# 2022 Advertisers Index

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# 2022 TOC and Index

# 2021 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 2021.

| NAME | COMMITTEE | COMPANY |
|---|---|---|
| Patrick Roach | Mechanical Maintenance | Interstate McBee |
| Chris Miller | Fuel, Lubricants & Environmental | Wabtec (formerly with Canadian National Railway) |
| Rodney Myers | Electrical Maintenance | Wheeling & Lake Erie RR |
| Brandon Teal | Facilities, Material and Support | NSH USA |
| David Caron | Locomotive Software and Systems | Ekyrail Enterprises |

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

**LMOA EXECUTIVE COMMITTEE**

**THE LMOA EXECUTIVE BOARD WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO EDWIN BOHR ELECTRONICS FOR HOSTING THE ANNUAL JOINT TECHNICAL COMMITTEE MEETING IN CHATTANOOGA, TENNESSEE IN EARLY MAY 2022.**

**SPECIAL THANKS GO TO SETH CULLERS FOR MAKING ALL THE ARRANGEMENTS AND FOR CONDUCTING A TOUR OF THE EDWIN BOHR FACILITIES.**

# PAST PRESIDENTS

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

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

# Our Officers

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**Global Railroad Technical Liaison**
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# Our Past Presidents

**TOM KENNEDY**
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**TAD VOLKMANN**
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**Chief Consultant**
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**LES WHITE**
**Application Specialist**
Bach Simpson
London, Ontario

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**MARK DUVE**
**Principal Consultant**
Southeastern Locomotive Consultants
Alpharetta, GA

**COREY RUCH**
**Director-Technical Research & Development**
BNSF Railway
Topeka, KS

# 2021 State of the Union Address

**Tom Kennedy**
*October 4, 2021*
*Fort Worth, Texas*

Good afternoon, ladies, and gentlemen. Thank you all for attending.

It has been an interesting and challenging two years for LMOA and the railroad industry with the Covid shutdown and the implementation of PSR.

First, I want to thank Ron Pondel and Tom Gallagher for all their efforts and support in getting this conference held. With the RSI cancellation of the conferences in Chicago in 2020 and in Indianapolis this year we felt that LMOA needed to conduct a face-to-face meeting to best continue the work of LMOA. Many alternatives exist for meetings such as Zoom, Webex, Microsoft Teams, etc. but feedback from members after the RSI on-line conference last year further convinced us that a face-to-face meeting was the best option. Two-way communication, both verbal and non-verbal, was missing with on-line meetings.

Secondly, I want to thank all the committees and their Chairs and Vice Chairs for all their great work in getting the technical papers prepared and supporting the onsite conference.

There are many challenges that face LMOA and the railroad industry, as a whole. To remain a viable resource and value to the industry LMOA needs to address these challenges and take appropriate actions to improve our services and adapt and change where required, all to remain relevant and valuable to the railroad industry.

The biggest area where LMOA can provide value is in knowledge sharing and training. With PSR and retirements the railroads have lost a lot of technical knowledge and experience. This isn't a surprise as this "brain drain" was presented in a 2007 LMOA Mechanical paper presented by Don Freestone of Alaska Railroad, retired. Don's paper showed that there's a major age gap in experience in the railroad industry and within ten to fifteen years the average experience time would decay significantly. This decay has accelerated with the implementation of PSR. I highly encourage you to read this paper as it demonstrates LMOA's value.

To address the loss of technical knowledge and experience within the railroads LMOA has resources available, thanks to the many LMOA members who have remained engaged and supportive after their retirement, that can be deployed in education and training programs. Resources that we can deploy to develop training material and standard work development address the following areas, as a minimum:

- Safety and Asset Protection
  - Safety is the number one priority and asset protection is at times overlooked or neglected. We have resources available to develop safety and asset protection programs to reduce the risk of litigation and the loss of assets.

- Emission Regulations
  - We have members with thorough knowledge of the EPA 1033 regulations and the application of them.

- FRA Regulations
  - We have members with thorough knowledge of FRA requirements and the inspection criteria.

- Systems Engineering
  - Complex and highly integrated products require that all disciplines coordinate and work and communicate well together to ensure that there are no adverse interactions. This requires the disciplined application of a Systems Engineering process. The INCOSE (International Council of System Engineer's) organization is an excellent resource to learn more about Systems Engineering principles and practices.

- Product Development
  - This closely ties in with the discussion on Systems Engineering but for this area I want to highlight two significant historical issues effecting fielded product performance. First products have been released to the field with inadequate performance verification (i.e., RGT) leaving reliability testing and modifications for improvement to the end user. Secondly, products are often designed for producibility while neglecting maintainability which is a major impact to the end user's maintenance program.

- Field Experience
  - Again, related to Systems Engineering, it is imperative that the voice of the customer is heard during the product design and one of the best sources available to the suppliers are their own field service personnel. Far too often engineers and designers are at their CAD terminals developing product not fully understanding the field environment of how a railroad uses, misuses, and abuses the product. Again, LMOA has members with significant field experience that can be deployed.

- Problem Solving
  - Effective Problem Solving is an area where many struggle, both the railroads and the suppliers. Far too often the root cause of

the problem is not identified, and a corrective action gets applied to a symptom not the root cause. Additionally, oft times the corrective action is inadequately verified.

To sum up, LMOA is a deep resource for continuous improvement of the railroad industry. These are major areas effecting current products and we should offer help to the railroads and suppliers. We can add areas where we can provide support as they are identified.

Thank you for your time today.

# 2021 Acceptance speech

**Tom Gallagher**
*October 4, 2021*
*Fort Worth, Texas*

I request we take a moment of silence in remembrance of loved ones, friends & colleagues who have been negatively affected by COVID during the past 18 months. Thank you.

Ron Pondel was kind enough to share some of his learned wisdom, acquired during the past 30 odd years with LMOA, to aide my efforts today. He advised "less is more" and I will endeavor to follow his sage advice.

First let me start off with thanking Tom Kennedy for his leadership as President of LMOA during the past two years. Tom has the distinct privilege of being only the 4th person to serve as president for more than a single one-year term. Feel free to fact check me on pages # 8 – 10 of LMOA's annual proceedings. Tom has strived to strengthen communications, collaboration and coordination of efforts amongst key industry stakeholders (i.e. Class 1 RRs, Short Lines, CMOs, AAR, FRA, EPA, CARB) and inspire individual LMOA members to do the same. His vision was influenced by the efforts of our past presidents, many of whom are here today, and the dynamic factors the Railroad Industry is facing.

Looking forward, I would be remiss if I were not to acknowledge being a poor student of history. In late 2019, I professed the "Roaring 20s" were before us in terms of health and prosperity for the upcoming decade to family, friends, and colleagues. At the conclusion of World War 1 (WWI) in 1918, the global pandemic known as the "Spanish Flu" was underway thru Spring 1920 and the United States of America witnessed a severe recession in 1920 and 1921 while the global economy declined sharply. And yes, we had "Prohibition" in the USA from 1920 thru 1933. Through it all, innovative and cultural advancements persevered (i.e. automotive, moving pictures, aviation, radio, sanitation, jazz, rapid expansion of electric utilities, local & long distance telephone communications, etc.). This can-do attitude is alive and well today and will propel us forward in 2022 and beyond.

The following quote from Theodore Roosevelt, titled "The man in the Arena" may best represent the spirit of LMOA's mission and individual organizations represented within to effectively address environmental, technical, and operational challenges on the horizon for the Railroad industry:

"It is not the critic who counts; not the man who points out how the strong man stumbles, or where the doer of deeds could have done them better. The credit belongs to the man who is actually in the arena, whose face is marred by dust and sweat and blood; who strives valiantly; who errs, who comes short again and again, because there is no effort without error and shortcoming; but who does actually strive to do the deeds; who knows great enthusiasms, the great devotions; who spends himself in a worthy cause; who at the best knows in the end the triumph of high achievement, and who at the worst, if he fails, at least fails while daring greatly, so that his place shall never be with those cold and timid souls who neither know victory nor defeat."

The quote above illustrates the tireless dedication our LMOA members perform routinely to provide relevant knowledge and expertise on emerging issues:

- ESG (Environmental Social Governance) matters
- Continuous Improvement of Operating Efficiencies
- Lowering Carbon Intensity
- Consumption of Alternative Fuels
- EPA Emissions Standards (Tier 5 Rulemaking)

In closing, I look forward to progressing the constructive efforts of our former LMOA Presidents and ensuring the collective energies of our 5 technical committees (Electrical / Facilities, Materials & Support / Fuel, Lubricant & Environmental, Mechanical / Locomotive Software and Systems) remain focused and pragmatic. Thank you for this honor.

*Outgoing President Tom Kennedy hands gavel to newly elected President Tom Gallagher*

*Past President Ian Bradbury places LMOA blazer on newly elected Third Vice President Keith Mellin*

*Past President Dwight Beebe presents Past President's Pin to Outgoing President Tom*

*Past President Ian Bradbury presents LMOA watch to Outgoing President Tom Kennedy*

*Secretary-Treasurer Ron Pondel, newly elected 1st Vice President Mike Hartung, new Chairperson of Fuel Lubricants &Environmental Committee Jerainne Heywood, newly elected President Tom Gallagher, new Chairperson of Facilities, Material and Support Committee Brandon Teal, Past President Ian Bradbury, Outgoing President Tom Kennedy, chairperson of Mechanical Maintenance Committee, John Hedrick, Past President Dave Rutkowski, newly elected second Vice President, Tim Standish, newly elected third Vice President Keith Mellin, outgoing chairperson of FL&E committee, Anju Singla, and Past President Tad Volkmann*

*Picture of new Chairperson of the Fuel, Lubricants and Environmental Committee, Jerainne Heywood and outgoing Chairperson, Anju Singla*

*Picture of Past President Dave Rutkowski (l), Sarah Nott, and Past President Tad Volkmann holding Locomotive Bell in recognition of deceased Past President Dennis Nott for his long time service and dedication to LMOA*

*Picture of Secretary-Treasurer Ron Pondel and his wife, Lijana at the 2021 Fort Worth Conference*

# Report on the Committee on Electrical Maintenance

WEDNESDAY, OCTOBER 12, 2022
10:50 am

*Chair*

**Amarjit Soora**
Senior Product Manager
ZTR, London, Ontario

*Vice Chair*

**Jason Fox**
Control Systems Reliability Engr
Union Pacific Railroad, Omaha, NE

*Commitee Members*

| | | | |
|---|---|---|---|
| M. Ablett | Product Development Engr | Central Railway | Jacksonville, FL |
| S. Alessandrini | Senior Reliabiility Specialist | Canadian National Railway | Concord, Ontario |
| S. Bakker | President | Transportation Prod Supply Co | O'Fallon, MO |
| S. Bendriss | Senior Electrical Engineer | Amtrak | Miami, FL |
| T. Bourbeau | Vice President | Enerpro | Goleta, CA |
| B. Brown | Account Executive | Transportation Prod Supply Co | O'Fallon, MO |
| D. Caron | VP-Business Development & Sales | Ekyrail Enterprises | Chateauguay, Quebec |
| F. Carrion | Engineering | Ferrocarril Central Andino (FCCA) | Lima, Peru |
| J. DeLaurentis | VP / GM | Magnetech Industrial Services | Massilon, OH |
| D. Ferendeci | Principal Consultant | FEC Internatiional | Cleveland, OH |
| M Drylie | | LMOA | Jacksonville, FL |
| M. Fitzpatrick | President | Making Tracks Media LLC | Lyndhurst, OH |
| B. Gaudet | VP-Engineering and Quality | PowerRail, Inc. | Duryea, PA |
| E. Grecu | Senior Electrical Engineer | ViaRail-Canada | Montreal, Quebec |
| R. Honc | Senior Research Engineer | Southwest Research Institute | San Antonio, TX |
| D. Johnson | Design & Application Engineer | Morgan Advanced materials | Greenville, SC |
| J. Jovenall | Product Manager | Cattron | Warren, OH |
| B. Locklear | Manager-Electrical Systems | CSX Transportation | Huntington, WV |
| J. Madzar | President | Smart Light Source | Brooklyn, NY |
| M. Mailloux | Vice President-Operations | Distribution Laurent Leblanc | St. Jean Richelieu, Quebec |
| S. Meade | Mining Sales Manager | East Penn Manufacturing | Lyon Station, PA |
| K. Mellin | NE Sales Manager | Peaker Services Inc | Brighton, MI |
| S. Mueting | Field Service Manager | Siemens Mobility | Aurora, CO |
| C. Muir | Sales Representative | East Penn Manufacturing | Lyon Station, PA |
| D. Myers | Quality Manager | Edwin Bohr Corp | Chattanooga, TN |
| R. Myers | Asst Superintendent Motive Power | Wheeling & Lake Erie Rwy | Brewster, OH |
| J. Paxton | Owner | T&J Consulting | Springfield, MO |
| D. Pettengill | Account Manager | Dayton-Phoenix Group | Salem, VA |
| B. Reynolds | Retired | Amglo Kemlite Labs | Calgary, Alb Past President |
| B. Runyon | | Consultant | Roanoke, VA Past President |
| K. Rutkowski | General Manager-Sales | Illinois Auto Electric | Naperville, IL |
| H. Schafer | Superintendent-Topeka SMT | BNSF Railway | Topeka, KS |
| S. Sledge | Engineer-Locomotive Reliability | Norfolk Southern Corp | Atlanta, GA |
| C. Taylor | Product Manager-Monitoring | Bach-Simpson | London, Ontario |
| B. Wheless | Account Executive | Transportation Prod Sales Co | Fleming Island, FL |
| L. White | Applications Specialist | Bach-Simpson | London, Ont Past President |
| J. Whitmer | Electrical Specialist | Dakota, Missouri Valley & Western RR (DMVW) | Bismarck, ND |

PERSONAL HISTORY

## Amarjit Soora, P. Eng

Senior Product Manager
ZTR, London Ontario

Amarjit (Am) was born in London England but has spent most of his life in London Ontario, where he went to the University of Western Ontario. After obtaining a Bachelor of Science degree in Electrical Engineering in 1996, Am went to work with the Electromotive Division (EMD) in London. While there he had roles within the Engineering team, including Manufacturing Engineering and the Controls Group.

After three years Am joined ZTR, with whom he has been with for the past 20 years. While at ZTR Am has had several roles within engineering including R&D, Applications Engineering and Product Management. For the past ten years Am has managed various teams for domestic and export development projects, and has also led several long term control system programs.

Am currently lives in London with his wife Kulvinder of 25 years, and his daughter Parveen and son Amit. His passions outside of family and engineering include fitness, photography, soccer and the Indian Classical Instrument the Tabla.

**THE ELECTRICAL MAINTENANCE COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO THE UNION PACIFIC FOR HOSTING OUR COMMITTEE MEETING IN NORTH LITTLE ROCK, AR ON MARCH 8, 2022. THE COMMITTEE WAS GIVEN A SHOP TOUR BY DIRK DULL WHICH WAS VERY INFORMATIVE SPECIAL THANKS TO ELECTRICAL COMMITTEE VICE CHAIR JASON FOX FOR MAKING THIS POSSIBLE.**

**THE COMMITTTEE WOULD ALSO LIKE TO GIVE A BIG THANKS TO THE WHEELING & LAKE ERIE RWY CO FOR HOSTING OUR SUMMER MEETING IN BREWSTER, OHIO ON JULY 19, 2022. COMMITTEE MEMBER RODNEY MYERS EXTENDED THE INVITATION TO THE COMMITTEE AND WE RECEIVED A TOUR OF THEIR FACILITY. LUNCH WAS SERVED AT THE AMISH DOOR AND W&LE SOUVENIRS WERE PRESENTED TO COMMMITTEE MEMBERS.**

**THANK YOU VERY MUCH TO THE UNION PACIFIC AND WHEELING & LAKE ERIE FOR BEING SUCH GRACIOUS HOSTS.**

# Emission Reduction Technologies

*Prepared by:*
*Amarjit Soora, ZTR LLC*

## Introduction

Over time rail has developed into the most efficient means of transporting goods, as well as connecting communities with passenger rail service. Even then, rising fuel costs and legislative requirements (i.e. EPA) that have been in place for several years have driven all transportation industries to implement technologies to reduce emissions.

Recent focus on Environmental, Social, and Governance has brought emissions under increased focus. Railroads have set aggressive targets over the next few decades.

Working together over the decades, railroads and suppliers have found innovative ways to reduce locomotive emissions (more efficient engines, electronic fuel injection, control add-ons, cleaner fuels), however with the recent focus railroads are under pressure to show increased almost immediate improvements.

The future is exciting with alternative propulsion locomotives such as battery, electric, hydrogen/battery hybrid and liquid natural gas (LNG) to name a few. However, diesel electrics are part of the foreseeable future and technologies should continue to be leveraged to meet corporate goals.

This paper will cover common technologies currently in the market, with a general overview of emission reduction technologies (quick wins and large projects). There are also best practices and ways to ensure the control add-ons stay optimal.

Please note that the actual emission reduction targets are covered in a paper from the LMOA Mechanical Maintenance and Fuel, Lubricants and Environmental Committee's joint presentation entitled GHG Emissions for North American Railroad Commitments for Decarbonization.

## Ways of reducing Emissions and Increasing Sustainability

Although there are many clever and unique ways railroads are looking to reduce emissions, listed below are some commonly deployed strategies used by the different classes of railroads in North America.

- Idle Reduction
- Extend engine shutdown time
- Locomotive Propulsion Efficiency
- Optimize Locomotive Utilization
- Reduce Recycling and Waste
- Data services and insights

## Idle Reduction

**Automatic Engine Stop / Start System**

For various reasons locomotives spend a large amount of time dwelling and idling. For this reason, Automatic Engine Stop / Start (AESS) systems were introduced approximately 30 years ago. Prior to AESS, fuel prices were low and emission standards were not in place, and given the risk of freezing a water-cooled engine block it was easier to simply leave the engine running rather than shutting it down. However, rising fuel prices and tighter legislative requirements led to the need to reduce fuel consumption and emissions, and reducing unnecessary engine idle time. There are several utilization factors to consider, but an AESS along with well-maintained locomotive can result in massive reduction in engine idle time with savings of 5,000-8,000 gallons per locomotive per year.

There are many different varieties of AESS systems in the industry. Original variants were stand alone and easily integrated with just about any diesel electric locomotive. Over time, AESS functionality became more common on new OEM locomotives. Today, due to EPA requirements all new locomotives in North America are equipped with AESS technology.

AESS operation is outlined in the American Association of Railroads standards S-5502. Although the operation and setpoints may slightly vary, general operation is outlined as follows:

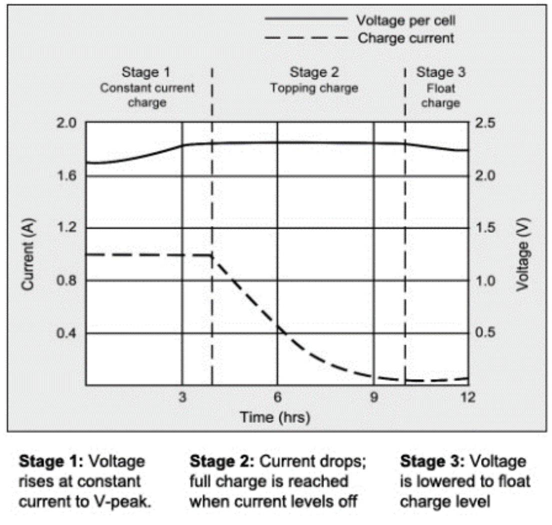
- During engine idle state, key parameters such as (but not limited to) indicated below are actively monitored.
- Systems are typically looking to see that safety (brake pressure) and parameters impacting the engine's ability to start (temperature and battery charge) are in a good state. Signals from the control stand (or trainline) are also monitored to ensure the locomotive is not being used.
- When the parameter readings are deemed "satisfactory", the system will automatically shutdown the locomotive engine
- If any key parameters become "unsatisfied" then the system restarts the engine. Important to note that the AESS system setpoints should be such that the setpoints have plenty of buffer to ensure the engine can start successfully, and the locomotive is in a "ready to use" state. This is especially important for road locomotives.


A good working AESS application can significantly reduce engine idle time (around the 50-60% mark), leading to anywhere from 5,000 to 8,000 gallons of fuel savings per year, per locomotive. Savings could be even further increased by optimizing the application.

**Optimizing AESS Performance**

Based on the operation outlined above, it's clear the AESS depends on other factors for optimal performance. In some cases, if left unchecked several factors can lead to deteriorated performances and, in extreme cases, complete loss of idle reduction time. As noted above several factors dictate when the engine will start and shutdown.

- The first and most common culprit that leads to extended idling and restarts is related to the air system:
    - Leaky air systems can cause frequent restarts. It is important to know when the air system should be inspected to minimize AESS disruptions. Please note the paper from the LMOA Mechanical team will cover this in further detail.
    - Systems will monitor the Main Reservoir and initiate restarts if the pressure drops too low. Some AESS systems offer Lead/Trail pressure switches that detects if the unit is leading or not. If not, it will ignore the MR pressure and not restart, thereby extending engine shutdown time.
    - If the locomotive is equipped with a parking brake capable of monitoring applied status, depending on the position of the Isolation Switch and Lead/Trail status, the AESS may not trigger an engine restart due to the Main Reservoir (MR) pressure dropping below the restart trigger point (please refer to the standard referenced at the end of this paper for exact details).
- Batteries can lead to extended idling and reduced engine shutdown time (idling waiting to charge and interruptions to shutdown time due to excessive restarts triggered by low battery voltage). Consider the following technologies:




- **Three stage charging** – to get the most out of starting lead acid batteries, specific charging profiles and setpoints are required per the battery manufacturer's guidelines. Earlier locomotive voltage regulation (VR) systems often had single stage (fixed voltage) or dual stage charging. In most cases, charge current and battery or ambient temperate were ignored. These earlier variants lead to undercharging and, in other cases, overcharging which lead to gassing of the batteries. Inadequate charging may also lead to operational disruptions (failure to start the engine) and premature battery end-of-life. Modern charging systems with configurable setpoints will improve battery health, state of charge and extend locomotive shutdown time as it relates to battery restarts. The figure shown is an example of what a three stage charge profile may look like.
- **Battery load shedding** – some AESS systems offer "load shedding" where non-essential loads are disconnected, reducing battery drain and extending shutdown time.
- **Energy sources to aid the lead acid batteries** –technologies such as super capacitors that boost cranking performance and offload the batteries at the same time. Over time this leads to less idle time to charge the batteries, potentially, extending engine shutdown time. Another added benefit is reduced engine crank time which leads to less wear on the starting equipment (motors).
- **Alternative battery technology** suited to hotel loads when engine is shutdown. Lithium batteries are gaining strong interest and application

in the industry. There are alternatives but one must also consider that typical AESS systems monitor state of charge by looking at the voltage. Lithium batteries have a flat voltage profile that tend to drop off very dramatically when nearing a low state of charge, so AESS systems will need to be enhanced to be able to adequately detect the battery's state of charge and know when to trigger an engine restart to avoid dead batteries.

- Increase maximum shutdown/start point – most AESS systems have a fixed number of shutdowns per day to protect the batteries and starting equipment. With enhancements to the battery control noted above and addition of starting assist technologies the number of shutdowns and restarts per day could be increased leading to reduced emissions.
- Engine water temperature setpoint – depending on operational requirements, some operators are reducing this shutdown/restart setpoint to extend engine shutdown time. More information regarding effectiveness and potential challenges with this will be discussed in a future paper.
- If your AESS system has been installed for some time, check with the vendor and see if updates are available that can lead to fuel savings. As an example, original AESS may have used digital switches but analog sensors are now more commonly used along with a software update for more intelligent decision making on start up / shut down criteria.

## Extend Engine Shutdown Time

Auxiliary Power Units (APU) have been deployed to extend engine shutdown time, whether the engine is shutdown with an AESS or manually. In principle, the main goal of these units is to keep key locomotive parameters in a "ready to start and use" state, such as engine water temperature, batteries, air system to name a few. By keeping these parameters in the "safe" operating regions, and as long as the locomotive is not needed for operation, the locomotive engine shutdown time may be significantly extended. It is important to note that APU's in different variants may only target specific areas but not all.

There are different styles of APUs that will be covered here, with the primary distinction being on-board and wayside systems.

### <u>**Onboard APU**</u>

With varying degrees of equipment and locomotive integration, listed below are examples of systems that would be installed on the locomotive.

- Diesel engine powered APU – these have their own diesel generator set that power equipment to do one or more of the following:
    - Heat and recirculate engine oil
    - Heat and recirculate engine water coolant
    - Maintain 74VDC system

- Trickle charge on-board batteries (leads to extended engine shutdown time and improves starting reliability)
- Maintain cab comfort by powering the HVAC system
- Maintain lighting system
- Offer a small compressor to maintain air reservoir pressure

- There are also APU's that are powered by diesel burner technology that pulls fuel directly from the fuel tank. Some models also have a mode when plugged in to shore power offer battery charging and compressor function to maintain air reservoir pressure

These types of systems may be best suited for locomotives that are often away from yards and have AESS operation kick in anywhere.

**Wayside APU (Shore Power)**

There are wayside or "shore power" systems where the power sources are external. The locomotive parks beside these stations and typically receives power to charge batteries (or the entire 74VDC system) and drive water and oil pumps. Some benefits with these include minimal locomotive modifications and not requiring a separate power source on the locomotive (engine or otherwise).

Unlike onboard APU's these types of applications require less locomotive modifications and may be best suited to captive units where they shutdown overnight or for extended periods of time.

**APU Integration with AESS**

Note that many of these factors impacted by the APU are also monitored by the AESS. Although manually shutdown engines will benefit from the APU, it's best to be paired with an AESS. Doing so will offer some positive options:

- AESS setpoints may be altered to extend shutdown time. For example, many AESS systems won't shutdown the engine below a temperature of 32F (0C). However, if the AESS knows an active APU is heating the coolant then the ambient temperature settings may be lowered (or bypassed) to extend engine shutdown time.
- The AESS can act as a backup to the APU in the event of a malfunction. Some examples:
    - If there is an "APU health" or "APU active" signal that can be monitored by the AESS it will know when to adjust setpoints or revert to standard settings.
    - If there is a malfunction with any of the equipment that pertains to heating of the water or charging the air compressor that goes undetected, the AESS will still trigger a restart if any of the parameters drop off.

Fuel savings with the applications of APUs will depend on several factors such as climate, operation, manual shutdown policy and effectiveness of integration with the AESS system (if equipped).

## Locomotive Propulsion Efficiency

Increasing the efficiency of the locomotive propulsion system offers key benefits:

- Pull more with less – with enough gains you may be able to reduce the number of locomotives in the consist, which means fewer locomotives idling and more efficient conversion of the diesel power to Tractive Effort. The actual efficiency gains are impacted by several factors such as operation, utilization, and operating speeds.
- Increased reliability – increased locomotive availability leads to less in-service failures, operational disruption and trucks/locomotives being sent out for rescue.

As an alternative to buying new locomotives, many railroads are electing to implement Control System overhauls, which is often referred to as "life extension" or "locomotive modernization". In addition to gains discussed below, it has the added benefit of recycling the locomotive hull and other components that can be reused, reducing waste and recycling.

- Most modernized control systems will add, replace and/or improve on existing functions that either directly or indirectly lead to efficiency gains. Some of these include:
  - **Increased Adhesion** – as mentioned earlier gains with Tractive Effort lead to gains such as increased velocity and potentially reducing the number of locomotives in a consist. DC motor armatures can be severely damaged during uncontrolled wheelslip, so elimination of slips will lead to increased motor life and less wear on the wheel and rail sets. The same applies to improved Braking Effort control, as better control prevents wheelslide and therefore wheel flat spots and damaged rail.
  - **Integrated AESS function** – most if not all modernized systems include the AESS functionality. Integrated solutions have the added benefit of tying in with further system inputs and outputs (I/O) which may lead to increased functionality and other benefits.
    - Should also include the ability to update settings, along with latest AESS features (load shedding, battery saver etc)
  - **Multi-stage Battery Charging and Voltage Regulation** – older locomotives are typically equipped with single stage voltage regulation i.e. one constant voltage without current regulation or temperature compensation. Common issues associated with these types of systems are:
    - Overcharge – voltage is too high leading to high current which will boil the electrolyte, causing gassing, grid corrosion and premature degradation of the battery
    - Undercharge – prolonged periods of partial charge on lead acid batteries leads to permanent sulfating (reduced capacity)

- **Remote monitoring** – critical to identify issues related to fuel and operational efficiency.

Many railroads have or are turning to Alternating Current (AC) Traction Motor propulsion. This technology has been available on freight locomotives in North America for decades. Some railroads have programs to upgrade older Direct Current (DC) locomotives to AC propulsion (a fine example of recycling and reducing waste).

Some key benefits associated with AC propulsion include longer motor life, less maintenance and, of course, increased adhesion.

Another solution commonly seen on high horse power (HP) locomotives is the Rail Cleaner solution. Locomotive adhesion is often adversely affected by not only liquid on the track (water, oil) but also debris such as wet leaves and insects such as millipedes. These Rail Cleaner solutions use compressed air from the locomotive air reservoir to blast compressed air in front of the lead locomotive axle to clear debris and allow for increased friction between wheel and rail.

## Operation Efficiency

Railroads have increasingly turned to Energy Management Systems (EMS) to reduce fuel consumption, improve train handling, and improve operational efficiency. Vendors have claimed fuel savings of up to 10%, but each railroad will have different results and monitoring systems should be used to verify the actual results.

These systems look at several key items for the trip such as the consist make up, the train length and car tonnage, and other locomotives that are operating in remote Distributed Power (DP) mode. Trip factors such as the rail profile, curves, grades, speed limits and track signalling are factored into the control algorithms that are calculated for each trip.

The EMS control algorithm uses track profile and train makeup information to constantly calculate the draft and draw ("push" and "pull") forces exerted on the couplers between cars. It determines the optimal throttle and braking operation to minimize train "bucking" or "slinky" action that may cause break-in-twos during operation over hill or curvy terrain, all while maintaining a higher average speed than would be otherwise possible.

Early versions of these systems informed the crew recommended throttle/brake settings via in-cab displays. Current EMS systems provide fully automated throttle control. In other terms, adaptive cruise control. Most current systems only offer the fully automated cruise control above certain speeds, and manufacturers are now developing so called zero-to-zero.

Optimal throttle and braking are the key drivers to the efficiency gains and train handling improvements. To give an example of where these systems can shine, consider driving an automobile. You are driving 75MPH, however

10 miles ahead there is traffic congestion causing a 20 minute delay. Do you need to continue at 75MPH only to stop? Or to save fuel are you better off at a slower speed reducing fuel consumption to get to that point? These are the type of situations where EMS control will improve operational efficiency. Of course, this is only one example.

There are other EMS solutions used on road locomotives that will be discussed in a future paper.

## Some Points on Recycling and Sustainability

To help with environmental sustainability, railroads are recycling as much as they can such as scrap steel, used oil and overflow fuel that will be recycled into a separate drum that will get pumped by an oil recycler.

Batteries – as noted above technologies and improvements to charging schemes are an excellent way to extend the life of lead batteries. However, when the battery comes to it's end of life, it is imperative that railroads continue to work with local networks of retail stores, service and distribution centers, to ensure spent batteries are collected, sorted and transported to recycling facilities for processing. This is especially important as there are an estimated 30,000 sets of Lead Acid batteries across the North American Rail Market.

Consider some key points with regards to lead acid battery recycling:

- For an estimated average life of 5 years, 99% of 12,000 tons of lead is recycled and reused in new battery manufacturing. Only 1% of Lead Acid Batteries reach landfill.
- A lead acid battery in the U.S. is typically constructed from more than 80% recycled raw materials. This also helps with supply chain for manufacturing of new batteries, as recycled lead and plastic is readily available.
- The plastic casing and the electrolyte from the battery are also recycled. The casing materials are melted for recycling and new battery casings. Used battery electrolyte is processed into sodium sulfate, which is used in laundry detergent, glass and textile manufacturing.

Paper use – railroad shops are proliferated with countless forms of documents and instructions: installation, testing, commissioning, maintenance, troubleshooting guides, schematics, wire running lists, piping diagrams to name a few. Some railroads are turning to the use of tablets for their personnel where they can not only do away with paper and the waste/recycling, but also have access to the most up to date documents at their fingertips. Of course, this may require updates to the locomotives (i.e. USB chargers for the tablets) but a small price to pay in increasing environmental sustainability.

Mentioned earlier in the paper were methods to improve the reliability of the locomotive by extending the life of many components such as traction motors and other rotating equipment. This leads to less waste and recycling of this equipment.

## Remote Monitoring and Cloud Based Information

Put simply, having easy and immediate access to your locomotive and it's subsystems are the easiest ways to protect the investment in these technologies and ensure your return on investment (ROI) is as expected. More importantly, if the ROI is not being achieved, then it's important to know why and how action can be taken.

Breaking it down further below are some further examples of benefits gained from this technology:

- Centralized information – all stored in a cloud/database and no need to send and track data through email and other cumbersome methods
- Track technology performance against measurable science-based targets.
- Having invested significant funds and resources into some of these fuel reduction technologies, it's important to know the status of the applications on a regular basis to ensure targets are being achieved.
- Some monitoring systems provide individual locomotive and fleet analysis, along with average numbers, top 10%, bottom 10%. This is helpful if looking for positive or negative trends with performance, and identify the worst performers that need action.
- If targets are not achieved, having actionable information for shops and crews is essential. With this information available with the locomotive anywhere, maintenance actions can be proactively setup for the next shopping of the locomotive
- Immediate record keeping for legislative purposes (EPA)

Another key and often overlooked benefit of remote monitoring is the ability to monitor pilot projects. This way, with minimal quantities and investment, the railroad can verify the effectiveness of technologies they are interested in with real data and verifying the needs are met prior to committing to a large program.

## Conclusions and Recommendations

This paper only covers the most commonly deployed technologies in the industry. There are others, and the current push to reduce carbon footprint in the industry will surely introduce more and innovative technologies as we continue to work with diesel engines.

An important point of consideration is the locomotive maintenance itself. The effectiveness of some of these solutions depend heavily on the state of the locomotive equipment such as batteries, air system etc.

It is also important to remember "not one size fits all". For example, a road unit that rarely stays in one part of the country may not benefit from a wayside APU charging system, with an onboard APU providing a better option. On the other hand, a wayside APU system would be more practical for a yard unit, requiring fewer locomotive modifications.

As indicated earlier, remote monitoring is a great method to protect the investments made into these technologies and ensure they are performing as expected without using up valuable shop time. Railroad employees are extremely busy, and suppliers should make every effort to provide monitoring and services that offload/alleviate the burden placed on the railroads as much as possible.

## Contributors:

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*Sid Bakker, Transportation Products Sales Company*
*Rodney Myers, Wheeling & Lake Erie*

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AAR Manual of Standards and Recommended Practices S-5502

# DC Traction Motors Reliability Solutions

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This paper will cover an insight into failure modes and provide reliability solutions with the primary focus on DC traction motors most currently in use

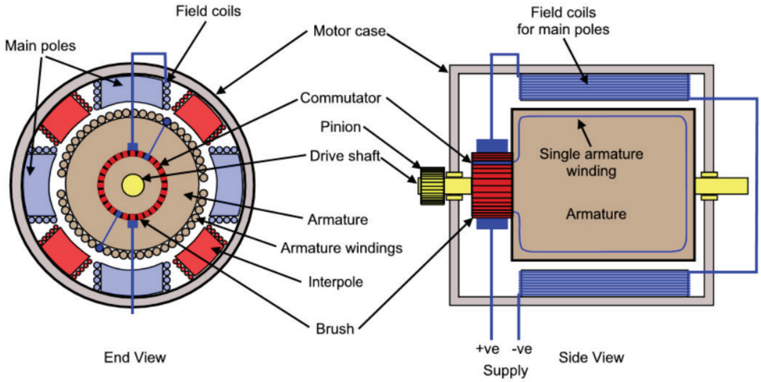
- EMD D77, D78, D87 and D-100
- GE AH-752

## The failure modes to be discussed are as follows:

- Internal connections
- Ingress of water and debris
- Flashovers

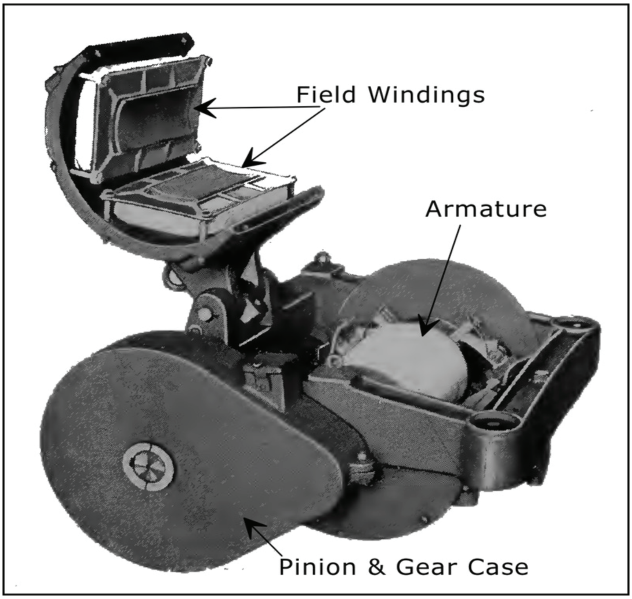
## A basic review of DC traction motors will be covered:

- Main field coils
- Interpole coils. Improve commutation.
    - Nullify the effect of armature reaction
    - The compensating mmf (magnetmotive force)in the interpolar zone is proportional to the armature current
    - Reduce (cancel) sparking between brushes and commutator, thus extending the motor's life
    - Reduce heat developed in the short-circuited coils
    - Reduce damaging back emf (electromagnetic force) that can adversely affect the switch gear and power supply.
- Armature, wound, equipped with a commutator
- Brushes
    - Placed at the magnetic neutral axis, where the emf is zero, and the resulting current is also zero




## Westinghouse

- 1890 – starts designing motors, taking into considerations the experiences of other suppliers
- 1891 – makes first enclosed motor to protect against snow, water, mud and dust.
- Designed the series wound motor. Speed controlled with series resistors, which when cut out in a few steps increase speed. This design has lasted throughout the remaining history of DC traction motors.



## Modern DC traction motors

- EMD
  - D77, D78, D79, D87, D100
- GE
  - 752-AH

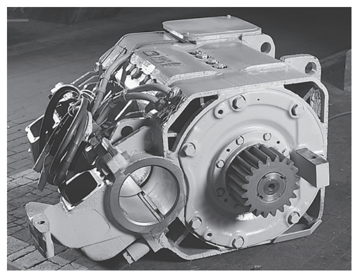
## Failure Modes:

**FAILURE MODE 1: INTERNAL INTERPOLE CONNECTION FAILURES**

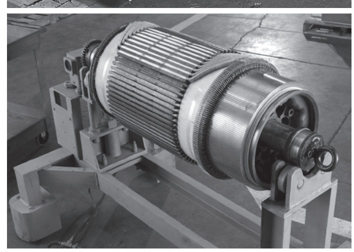
- Failure modes:
  - Open field
  - Connections breaking-off
  - High resistance interpoles
- Risk factors:
  - Shock and vibration
  - Temperature variations
  - Manufacturing process
- Interpole connections solutions:

It was observed that D90 interpole connections were commonly breaking at the #1 interpole connection tab (closest to the armature). The cause was that there was insufficient space to secure/clamp the cable close to the connection point and the vibration would cause the connection to break.

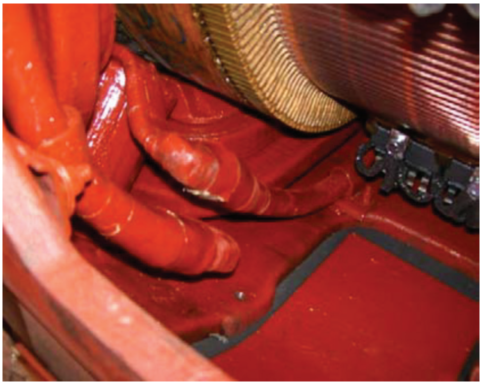


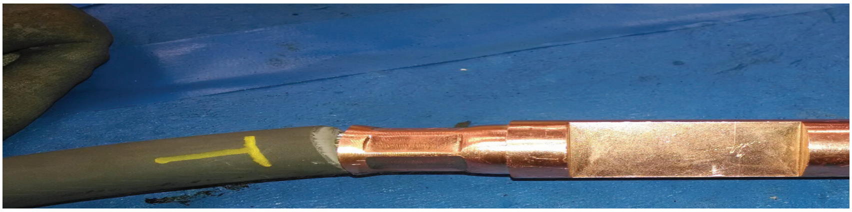


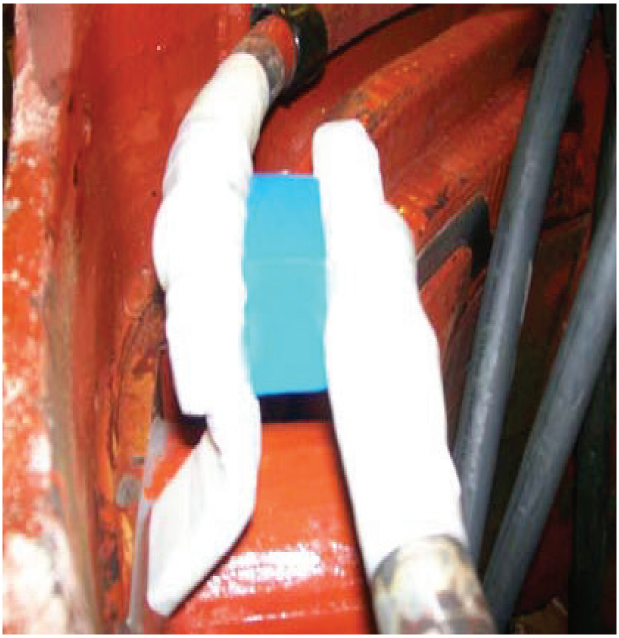




The solution was to insert a rubber insulating block between the two interpole cables and secure it into place allowing the #2 interpole cable to brace #1.







This process greatly reduced the failures at this connection point.

**FAILURE MODE 2: INTERNAL CONNECTION OPEN FIELDS FAILURES**

- Failure modes:
- On motors equipped with flexible jumpers
  - Degradation of lug/wire resistance due to shock and vibration
- On motors equipped with jumper bars
  - Connection bars failing due to fatigue caused by shock and vibration

**FAILURE MODE 3: HIGH RESISTANCE FAILURES**

- Failure Modes:
- On motors equipped with flexible jumpers
  - Degradation of lug/wire resistance due to:
    - Shock and vibration
    - Temperature variations
- Risk Factors:
  - Crimped lug copper annealing during brazing operation
- Solutions:
  - Use of brazed lugs instead of crimped

**FAILURE MODE 4: INGRESS OF WATER AND DEBRIS FAILURES**

- Failure modes:
  - Ineffective seals
  - Bent access covers
  - Loose access covers
  - Air intake location
- Risk factors:
  - Aging seal material (rubber)
  - Flying objects under the frame
  - Insufficient/improper maintenance
- Solutions:
  - GE TMs – RTV around rubber grommets
  - Inertial filters
  - Modify access ports and covers

It is extremely important to ensure that the inside of the motor is kept dry. One method of preventing water ingress is to apply RTV seal to the grommets where the TM leads enter the TM frame.

Note the gap between the grommet and the cable.:

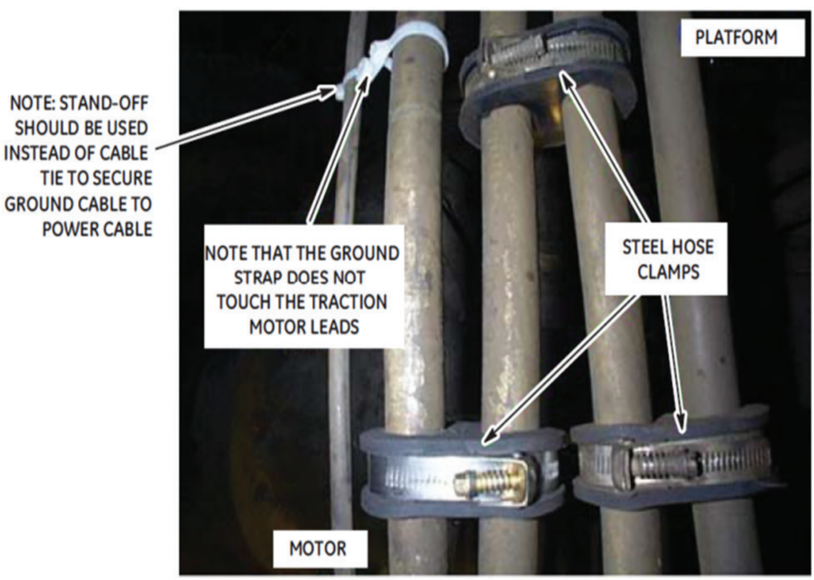
- RTV Silicone is used to seal that gap and prevent water ingress. This is a cost effective practical solution to prevent water ingress.

It does not have to be pretty, function over artwork.

**FAILURE MODE 5: RUB THROUGH GROUNDS & SHORTS FAILURES**

- Failure Modes:
  - High voltage grounds to frame
  - Possible intermittent high voltage ground
- Risk Factors:
  - Poor cable routing
  - Worn/deteriorated cables
- Solutions:
  - Route cabling properly
  - Use of OEM cable brackets

Proper method of ensuring TM leads do not rub together or short to the Locomotive undercarriage.


PLATFORM
NOTE: STAND-OFF SHOULD BE USED INSTEAD OF CABLE TIE TO SECURE GROUND CABLE TO POWER CABLE
NOTE THAT THE GROUND STRAP DOES NOT TOUCH THE TRACTION MOTOR LEADS
STEEL HOSE CLAMPS
MOTOR

**FAILURE MODE 6: COMMUTATOR & ARMATURE IMPROVEMENTS**

- Analysis of TM failures due to armature grounds identified that moisture could migrate from the commutator to the armature termination points. This realization led to processes that could seal the commutator surface preventing water from reaching critical areas on the armature.

**FAILURE MODE 7: POOR CLEANING MAINTENANCE FAILURES**

- Failure modes:
  - Poor maintenance/inspection
  - Dirtier than normal environments
- Risk Factors:
  - Excessive locomotive downtime
  - Premature failure of components
- Solutions:
  - Better maintenance practices

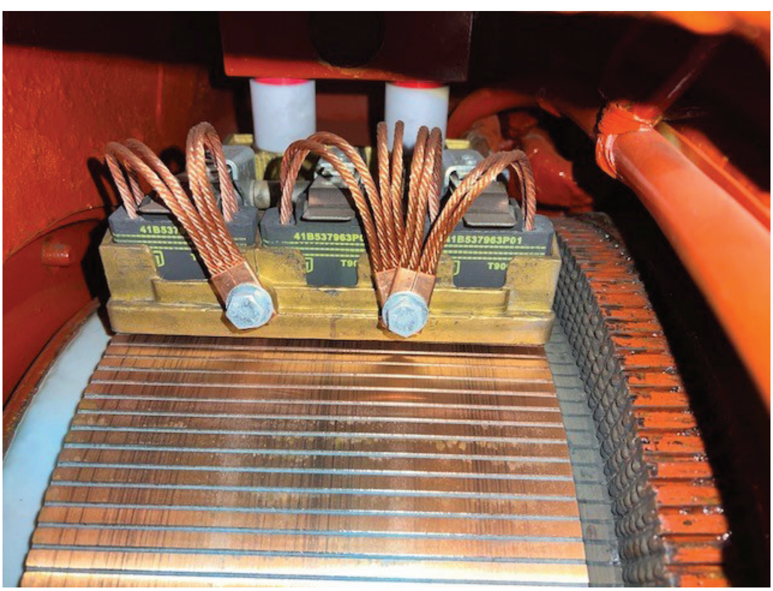
Proper cleaning of string band and insulators as well as creepage surfaces are another way of preventing High Voltage grounds.

It is very important to have Quality Control measures as part of your maintenance practice. Below are a few examples of poor workmanship that may contribute to TM failure.

This motor was just inspected and allegedly cleaned.

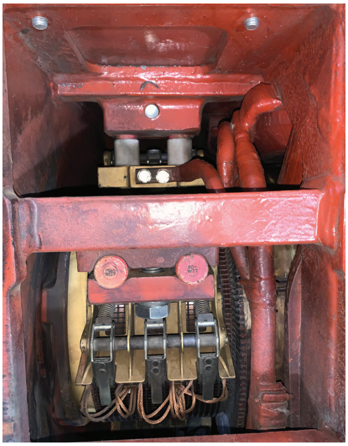

How a Teflon band should look before and after a proper cleaning.

Proper routing of pigtails to prevent damage is important.

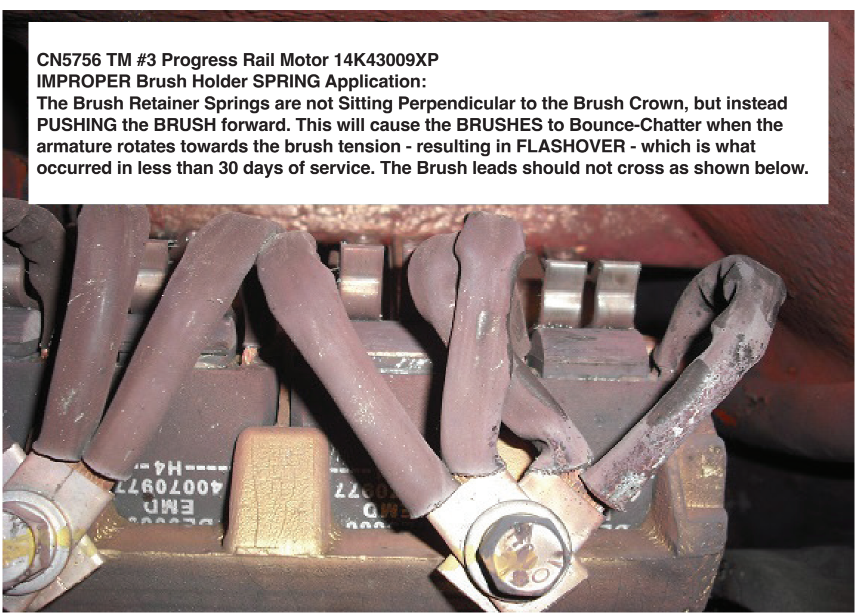
**FAILURE MODE 8: Flashover Failures**

- Failure Modes:
  - Light flashovers
  - Severe flashovers
  - High voltage discharges
    - Back emf due to open circuit under load
    - Contaminated creeping area
  - Open circuit under load
    - Severe impact and vibration due to road conditions
    - Low brush pressure due to weak springs
    - Weak springs
    - Rusted brush holder pivots and brush arms
- Risk factors:
  - High voltage discharges
  - Commutator with high bars or out of round
  - Dirty creep area
  - Shock and vibration
  - Road conditions
  - Brush holder maintenance practices
  - Excessively worn brushes
- Solutions:
  - TM Protection Panel
  - Improve resilience to shock
  - Keep commutator area clean
  - For operation in worse impact and vibration conditions, build brush holders with:
    - 3-leaf spring cells (EMD motors)
    - Extended brush pressure fingers



Proper Brush and pigtail application is also very important. If not applied properly you may not have the proper brush to commutator pressure and pigtails can become damaged and cause flashover.

**CN5756 TM #3**
**PROPER SPRING APPLICATION:**
**Flat Surface of Spring is SITTING on V-Shaped CROWN of the Brush; however, the brush leads could be positioned better.**
**FLASHOVER caused by Spring Application on another Brush Holder**



**CN5756 TM #3 Progress Rail Motor 14K43009XP**
**IMPROPER Brush Holder SPRING Application:**
**The Brush Retainer Springs are not Sitting Perpendicular to the Brush Crown, but instead PUSHING the BRUSH forward. This will cause the BRUSHES to Bounce-Chatter when the armature rotates towards the brush tension - resulting in FLASHOVER - which is what occurred in less than 30 days of service. The Brush leads should not cross as shown below.**

**FAILURE MODE 9: Traction Motor Protection Panel**

- Failure modes:
    - Stall burns
    - Overcurrent
    - Commutator failures
- Risk Factors:
    - Stall burns can occur when too much current is run through a traction motor at stall or low speeds.
    - Overcurrent can overheat the armature and commutator and brushes. One of the effects of the excessive current is to distort commutator segments and cause the comm to be out of round or have a high bar situation. This can also later result in poor brush to commutator contact and broken brushes causing flashover or grounds.
- Solutions:
    - Today's software is used to regulate the amount of current at various speeds. But on older non Microprocessor controlled locomotives there are devices that can be purchased to limit the time high current is put through a stalled traction motor. One such panel is the Traction Motor Protection Panel.
    - The control algorithms of the TMPP incorporate traction motor cooling air temperature compensation. Therefore, the TMPP must be mounted inside the main electrical cabinet of the locomotive. Since the auxiliary generator traction motor blower cools the cabinet, the TMPP is able to monitor the same air temperature as the cooling air for the traction motors. The TMPP manipulates control voltage between the locomotive's throttle response and rate control modules. Traction Motor current signals are received from the Q1200 Traction Motor Current Module (TMC). It will also function with CM-03 or CM-05 modules manufactured by other vendors. Simply put, when motor current exceeds short time rating and it becomes necessary to reduce generator excitation, the signal to the rate control module is decreased reducing generator output. This reduces current and allows traction motors to operate at continuous rating.

**FAILURE MODE 10: Moisture Failures**

- Failure Modes:
  - Moisture in the traction motors
- Risk Factors:
  - Moisture can be introduced into the traction motors through the Traction Motor blowers. This air is sometimes filtered however depending on weather and humidity the air used to keep the motor cool, dry and clean can contain a lot of moisture. This moisture can cause grounds that may result in the cutting out of traction motors thereby reducing adhesion.
- Solutions:
  - Some locomotives are equipped with software and relays that can re-position the ground reference point and temporarily increase the voltage to ground requirements. This gives the blowers an opportunity to clear moisture out of the motors and prevent the cutting out of a traction motor. The ground detection circuit is commonly automatically reconfigured after the first power circuit ground is detected.

## Conclusion:

With proper maintenance and a few upgrades, these failure modes can be eliminated or decreased.

**SD70M**

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# 27-Point MU Control Trainline Connectivity Issues

*Prepared by:*
*Saad Bendriss - Amtrak*

## Abstract

This paper constitutes an introduction to the 27-Point MU Control Trainline System, and the issues impacting the train Consist set up in Multiple Units (MU) Configuration, such as loss of traction and dynamic brake commands, as well as false and contradictory indications originating from trail equipment.

The MU System issues can mostly be divided into three categories: Receptacle(s), Jumper Cable(s), and Junction Boxes/Undercar Wiring.

Each category will be discussed, and basic recommendations will be explained.

## Background

Train consists, set in Multiple Units (MU), are seeing loading, traction/braking, false indication or alerts, because of overlooked MU System. By shedding the light on this MU System, those problems will be diminished, increasing the fleet's availability and decreasing downtime.

## 27-Point MU Control Trainline

**Definitions**

✓ **27-Point Fixed Jumper Cable**: A cable assembly, made of twenty-seven (27) Conductors, terminated on one end, to a plug, and permanently fixed to the Equipment on the other end, and providing a flexible electrical connection between two (2) pieces of equipment.

✓ **27-Point Portable Jumper Cable**: A cable assembly, made of twenty-seven (27) Conductors, terminated on both ends to a plug, and provides a flexible connection between two (2) pieces of equipment.

✓ **27-Point Receptacle**: A Receptacle(s) mounted on the ends or corners of an Equipment, and where the 27-Point Fixed Jumper Cable or Portable Jumper Cable mate.

✓ **27-Point Trainline**: An Electrical Wiring network that allows Electrical signals (Power, Control, Communications, etc.) to be sent over the entire length of a Train Consist.

✓ **27-Point Trainline Control & Communication**: Also known as "COMM Trainline", is a wiring network, dedicated to transferring Control and Communication Signals (Public Address, Door Controls, Brake Applied/Released, etc.) throughout a Train Consist.

✓ **27-Point Trainline Multiple Unit**: Also known as "MU Trainline", is a wiring network, dedicated to transferring Traction and Dynamic Brake Controls and various Indications between Locomotives coupled together, Cab cars and Locomotives, and Locomotives or power cars placed at the opposite ends of a Train Consist.

**Industrial Standards (AAR, APTA)**

Several Standards are being used to ensure maximum electrical and mechanical compatibility while mixing Equipment. Those Standards are as follows:

✓ **AAR S-512**: 27-Point Control Plug and Receptacle Standard.

✓ **APTA RP-E-017-99:** Recommended Practice for 27-Point Control and Communication Trainlines for Locomotives and Locomotive-Hauled Equipment.

✓ **APTA PR-E-RP-019-99**: Recommended Practice for 27-Point Jumper and Receptacle Hardware for Locomotives and Locomotive-Hauled Equipment.

**Purpose of 27-Point Trainline**

The 27-Point Trainline is dedicated to simultaneously issuing commands from one single point in the train Consist to some or all the equipment in the Train Consist. It also receives feedback signals or indications from one or more points in the consist, back to the leading Equipment, or centralized monitoring unit.


**Figure 1: P42 Locomotives in MU Configuration**

There are two types of 27-Point Trainlines:

✓ **Communication Trainline (COMM):** Send Control and indication signals, and audio signals for the PA/IC System, mostly for Passengers Cars. However, several other signals are sent to the Locomotive and Cab Car to indicate train status such as brake applied/ released, hot journal bearing, etc. (Table 1)

27 POINT COMMUNICATION FUNCTION CHART (BLUE RECEPTACLE)

| PIN# | WIRE DESIGNATION | WIRE GAUGE | FUNCTION NAME | VOLTAGE RANGE (VDC) | FUNCTION | CURRENT REQUIRED (MA) |
|---|---|---|---|---|---|---|
| 1 | SHLD | | SHIELD (COMMON) | NA | NA | XX |
| 2 | TB– | 10 | BATTERY NEGATIVE [4] | 0 | COMMON | XX |
| 3 | PA1 [1] | 14┐ | PA/TAPE MUSIC–1 (BLK) | [3] OdB* | A | XX |
| 4 | PA2 | 14┘ | PA/TAPE MUSIC–1 (WHT) | | A | XX |
| 5 | PA3 | 14┐ | INTERCOM (BLK) | OdB* | A | XX |
| 6 | PA4 | 14┘ | INTERCOM (WHT) | | A | XX |
| 7 | PA5 | 14┐ | PA CONTROL (BLK) | ±13┐ [2] | C | XX |
| 8 | PA6 | 14┘ | PA CONTROL (WHT) | ±13┘ | C | XX |
| 9 | RA1 | 14┐ | MUSIC–3 (RADIO) (BLK) | OdB* | A | XX |
| 10 | RA2 | 14┘ | MUSIC–3 (RADIO) (WHT) | | A | XX |
| 11 | EP1 | 12 | BRAKE APPLICATION | ■ 74 | C | XX |
| 12 | EP2 | 12 | BRAKE RELEASE | ■ 74 | C | XX |
| 13 | EP3 | 12 | BRAKE NEGATIVE | ■ 0 | COMMON | XX |
| 14 | D1 | 12 | OPEN DOORS RH | 74** | C | XX |
| 15 | D2 | 12 | OPEN DOORS LH | 74** | C | XX |
| 16 | D3 | 12 | CLOSE DOORS RH | 74** | C | XX |
| 17 | D4 | 12 | CLOSE DOORS LH | 74** | C | XX |
| 18 | DC1 | 12 | DOOR CLOSED LT | 74 | I | XX |
| 19 | BR | 12 | BRAKE RELEASED LT | 74 | I | XX |
| 20 | BA | 12 | BRAKE APPLIED LT | 74 | I | XX |
| 21 | HJ | 12 | HOT JOURNAL LT | 74 | I | XX |
| 22 | CS | 12 | CONDUCTOR SIGNAL | 74 | C | XX |
| 23 | DC2 | 12 | DOOR CLOSE LT | 74 | I | XX |
| 24 | PA7 | 14┐ | TAPE–MUSIC 2 | OdB* | A | XX |
| 25 | PA8 | 14┘ | TAPE–MUSIC 2 | | A | XX |
| 26 | BLS | 12 | CONDUCTOR DOOR LT FEED | 74 | I | XX |
| 27 | AN | 12 | ATTENDANT CALL | 74 | C | XX |

NOTES :

UNLESS NOTED, ALL SIGNALS ARE OFF–ON MAINTAINED AT 0 OR 74 VDC DERIVED FROM CAR BATTERY SYSTEM.

■ THESE 3 ARE POWERED FROM LOCOMOTIVE BATTERY SYSTEM.

* COMMUNICATION LINE MEASURED IN dB.

** MOMENTARY +74 V SIGNAL (PUSH BUTTON).

] 2–CONDUCTOR SHIELDED

NOTES :

1. SHIELD COMMON FOR ALL 5 SHIELDED PAIRS 1–POINT GROUND TO CARBODY; SHIELD IS CONTINUOUS OVER LENGTH OF LOCOMOTIVE / CAR.
2. DERIVED FROM PA UNIT
3. TRANSFORMER COUPLED → 600 OHM BALANCED LINE (4 PLACES)
4. THE NEGATIVE SIDE OF EACH CAR 74 VDC SYSTEM IS COMMON TO ALL CARS VIA THIS WIRE. THE NEGATIVE IS GROUNDED TO THE CARBODY IN EACH CAR AT THE BATTERY.
5. #14/15, 16/17, 18/23 CROSS WITHIN THE CAR AND ALSO IN THE COMMUNICATION JUMPER.

FUNCTION
C=COMMAND
I=INDICATION
A=AUDIO
F=FUTURE

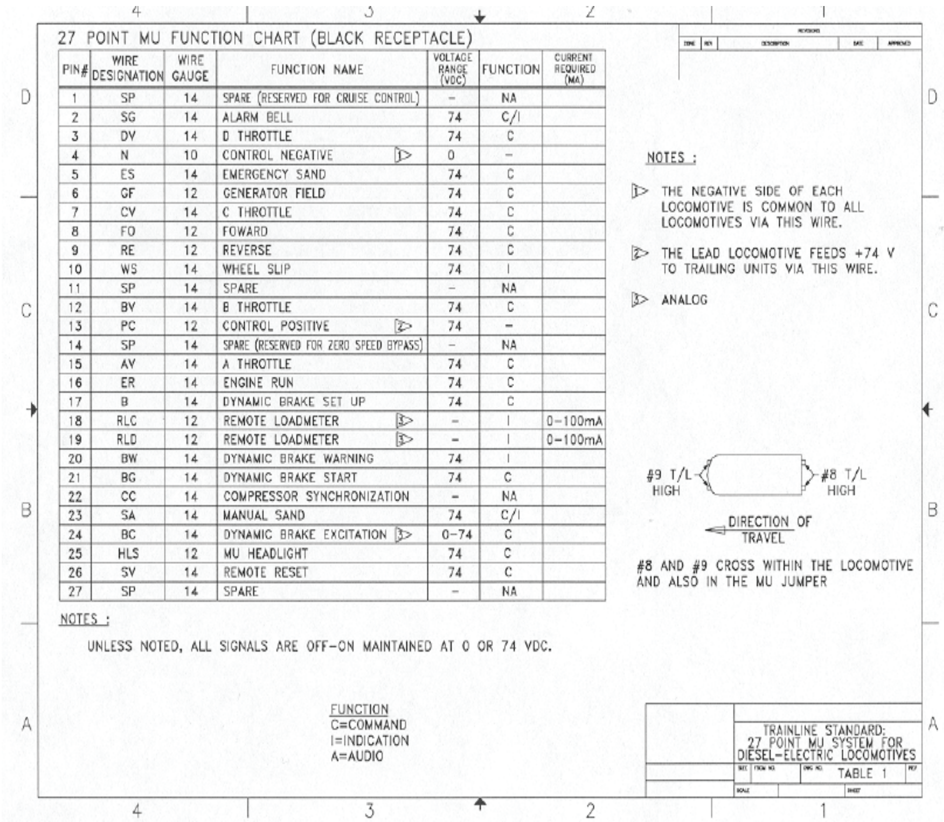
TRAINLINE STANDARD: 27 POINT COMMUNICATION SYSTEM FOR INTERCITY EQUIPMENT

TABLE 8

**Table 1: Example of Intercity Communication Trainline Signals**


Figure 2: 27 Point Trainline Communication Cable (Blue)

✓ **Multiple Units Trainline (MU):** Send Control and Indication Signals, related to traction, dynamic braking, and traction/locomotive status indication between Equipment such as Locomotives coupled together, Cab Car and Locomotive, Locomotives, or Power cars in a push-pull configuration (Table 2).



27 POINT MU FUNCTION CHART (BLACK RECEPTACLE)

| PIN# | WIRE DESIGNATION | WIRE GAUGE | FUNCTION NAME | VOLTAGE RANGE (VDC) | FUNCTION | CURRENT REQUIRED (MA) |
|---|---|---|---|---|---|---|
| 1 | SP | 14 | SPARE (RESERVED FOR CRUISE CONTROL) | – | NA | |
| 2 | SG | 14 | ALARM BELL | 74 | C/I | |
| 3 | DV | 14 | D THROTTLE | 74 | C | |
| 4 | N | 10 | CONTROL NEGATIVE ▷1 | 0 | – | |
| 5 | ES | 14 | EMERGENCY SAND | 74 | C | |
| 6 | GF | 12 | GENERATOR FIELD | 74 | C | |
| 7 | CV | 14 | C THROTTLE | 74 | C | |
| 8 | FO | 12 | FOWARD | 74 | C | |
| 9 | RE | 12 | REVERSE | 74 | C | |
| 10 | WS | 14 | WHEEL SLIP | 74 | I | |
| 11 | SP | 14 | SPARE | – | NA | |
| 12 | BV | 14 | B THROTTLE | 74 | C | |
| 13 | PC | 12 | CONTROL POSITIVE ▷2 | 74 | – | |
| 14 | SP | 14 | SPARE (RESERVED FOR ZERO SPEED BYPASS) | – | NA | |
| 15 | AV | 14 | A THROTTLE | 74 | C | |
| 16 | ER | 14 | ENGINE RUN | 74 | C | |
| 17 | B | 14 | DYNAMIC BRAKE SET UP | 74 | C | |
| 18 | RLC | 12 | REMOTE LOADMETER ▷3 | – | I | 0–100mA |
| 19 | RLD | 12 | REMOTE LOADMETER ▷3 | – | I | 0–100mA |
| 20 | BW | 14 | DYNAMIC BRAKE WARNING | 74 | I | |
| 21 | BG | 14 | DYNAMIC BRAKE START | 74 | C | |
| 22 | CC | 14 | COMPRESSOR SYNCHRONIZATION | – | NA | |
| 23 | SA | 14 | MANUAL SAND | 74 | C/I | |
| 24 | BC | 14 | DYNAMIC BRAKE EXCITATION ▷3 | 0–74 | C | |
| 25 | HLS | 12 | MU HEADLIGHT | 74 | C | |
| 26 | SV | 14 | REMOTE RESET | 74 | C | |
| 27 | SP | 14 | SPARE | – | NA | |

NOTES :

UNLESS NOTED, ALL SIGNALS ARE OFF–ON MAINTAINED AT 0 OR 74 VDC.

FUNCTION
C=COMMAND
I=INDICATION
A=AUDIO

NOTES :

▷1 THE NEGATIVE SIDE OF EACH LOCOMOTIVE IS COMMON TO ALL LOCOMOTIVES VIA THIS WIRE.

▷2 THE LEAD LOCOMOTIVE FEEDS +74 V TO TRAILING UNITS VIA THIS WIRE.

▷3 ANALOG



Table 2: Example of Locomotive Multiple Units Trainline Signals


**Figure 3: 27 Point Trainline MU Cable (Black)**

27-Point Communication (COMM) and Multiple Units (MU) Receptacles and Jumper Cable Plugs are color-coded for Standardization purposes, as follows:

- ✓ **Multiple Units Control**: BLACK, labeled MU
- ✓ **Multiple Units Dummy (If required)**: YELLOW, labeled DUMMY
- ✓ **Communication Intercity:** BLUE, labeled COMM
- ✓ **Communication Commuter**: YELLOW, labeled COMM
- ✓ **Communication Dummy**: WHITE, labeled DUMMY

**27-Point MU Trainline Hardware**

The 27-Point MU Trainline Hardware includes:

- ✓ **Receptacles**

MU Receptacles are flange-mounted to the Equipment, through a waterproof seal. They have a contact block of 27 Contacts, with a spring-loaded hinged cover to provide a retention force to maintain the MU Jumper Cable secured in the Receptacle.

MU Receptacle housing and its spring-loaded hinged cover are made from a corrosion-resistant material. It has a durable gasket to seal off the MU Receptacle when the cover is closed.

MU Receptacle contact block has twenty-seven (27) contact pins, made from a copper alloy, and silver-plated, accepting # 10 AWG, # 12 AWG, or 14 AWG wire gauge. The wire is 600 V, 110 ° C, with a tinned conductor and cross-linked polyolefin insulation.

MU Receptacle quantity and location depend on the type of Equipment (Table 3):

| Configuration | MU Quantity | Location |
|---|---|---|
| Diesel Locomotives | 4 MU Receptacles | All four corners |
| Electric Locomotives | 4 MU Receptacles | Two Diagonal corners: Front Right and Left Rear |
| Power Cars | 2 MU Receptacles | Both Sides of the Train end the Power Car |
| Power Cars in Push/Pull Operation | 4 MU Receptacles | Two per end (one receptacle per end is allowed but not recommended) |

**Table 3: MU Receptacles Quantity and Location**

Figure 4: MU Receptacle (Black)


**Figure 5: MU Receptacle (Black)**

**Figure 6: MU Receptacle Pins Arrangement**

### ✓ Jumper Cables

Jumper Cable Assembly includes two (2) 27-conductor plugs, connected thru a flexible rubber conduit. Plugs are designed to be secured by the spring-loaded hinged receptacle cover to keep in place, independently of stretching movement, which can reach tensile pull forces higher than 600 lbs.

Plug heads are made from aluminum alloy and are corrosion resistant. The joint, at the plug head and the rubber conduit, is watertight.

The Jumper Cable contact block has twenty-seven (27) contact sockets, made from a copper alloy, and silver-plated, accepting # 10 AWG, # 12 AWG, or 14 AWG wire gauge. The wire is 600 V, 110 ° C, with a tinned conductor and cross-linked polyolefin insulation.

For Jumper Cable longer than 90", hangers are being used to support Jumper Cable mid-span.


**Figure 7: MU Jumper Cable installed between Locomotives**


Figure 8: MU Jumper Cable

- ✓ **MU Junction Boxes**

Stainless Steel junction boxes, located near the ends of each vehicle, provide connectivity between the Receptacle Pigtails and the Vehicle Wiring, using stud-type terminal blocks.

For protection purposes against projectiles, debris, and elements, the wiring connecting the 27-Point Receptacles from end to end of the Vehicle is running in conduits.

Figure 9: Undercar MU Junction Box

**27-Point MU Trainline Testing**

To ensure the correct operation of the MU Trainline System, the following tests have to be run:

✓ **MU Jumper Cable Testing (Continuity, Insulation)**

A Continuity Test must be run to ensure that continuity exists between all the 27 wires end to end of the MU Jumper Cable.

An insulation Test between each of the 27 wires to the ground, and between every wire must be run to ensure there is no short to the ground or short between any given pair of wires.

✓ **Equipment MU System Wiring Testing (insulation, Continuity)**

A continuity Test must be run to ensure that continuity exists between all the 27 wires of all the MU Receptacles

An insulation Test between each of the 27 wires to the ground, and between every wire must be run to ensure there is no short to the ground or short between any given pair of wires of the MU Receptacles.

✓ **Equipment MU System Functional Test**

Each conductor of the 27-Point Trainline must be simulated to ensure the equipment to which it is connected, transmits, and receives the signal correctly.

**27-Point MU Connectivity Issues**

Several 27-Point MU System issues are being reported as follows:

✓ **Receptacles Issues**

- Cover cracked, broken, or missing
- Cover springs loose, damaged, or missing
- Hardware missing
- Gasket damaged or missing
- Housing full of moisture, dirt, water, etc.
- Pins corroded, excessive wear/out-of-spec, and physically damaged

**Figure 10: MU Receptacle Issue: Water Ingestion**


**Figure 11: MU Receptacle Issue: Gasketing**

**Figure 12: MU Receptacle issue: Pin Damages**

✓ **Jumper Cables Issues**

- Plug cracked or broken
- Jumper Cable damaged or deformed Plug Heads
- Cable plug hardware loose or missing
- Cable flexible sleeve frayed, a deep cut, or damaged
- Cable sockets corroded, excessive wear/out-of-spec, physically damaged and burnt

**Figure 13: MU Jumper Cable: Insulation Integrity Damages**

**Figure 14: MU Jumper Cable Issue: Plug damages**

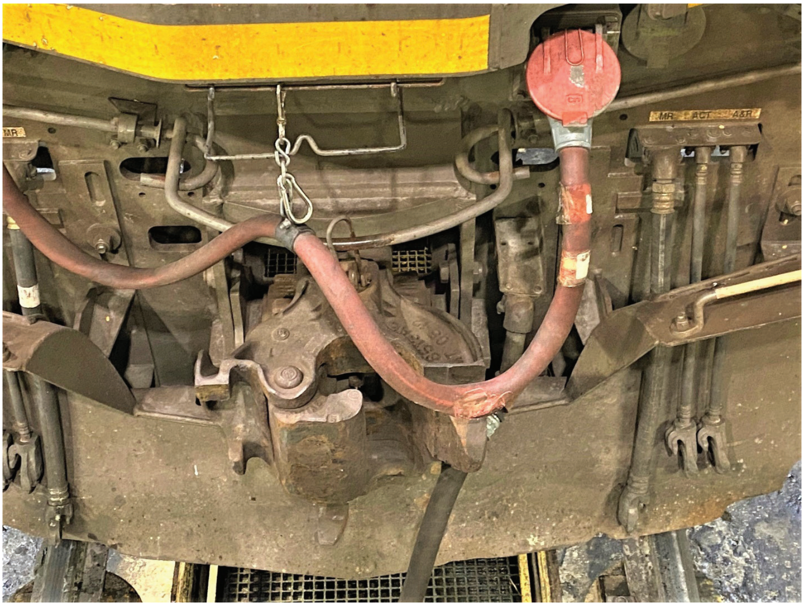


**Figure 15: MU Jumper Cable Issue: Hanger Stress damages**

✓ **Junction Boxes Issues**

- Cover damaged, corroded, or missing
- Cover hardware missing
- Junction box housing corroded or damaged
- Cover gasket damaged or missing
- Junction box full of dirt, water, etc.
- Terminal blocks corroded
- Terminal blocks hardware missing
- Wiring loose, damaged, broken, shorted, or open
- Wiring insulation compromised

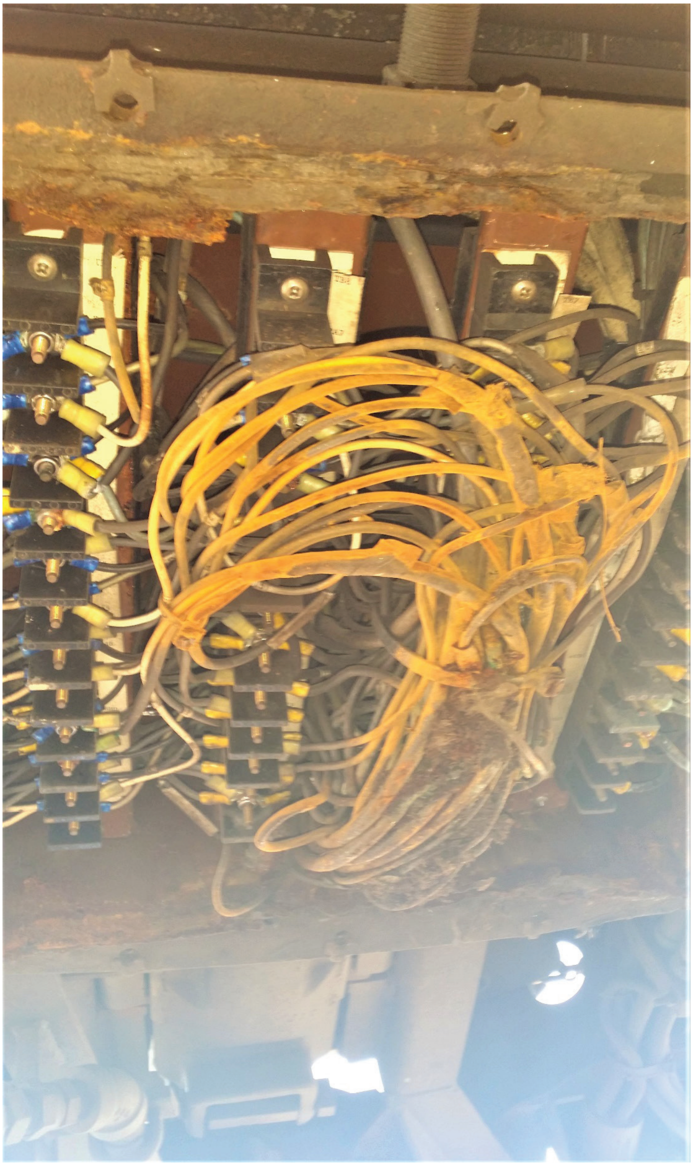


**Figure 16: MU Junction Box Issue: Water Ingestion and Corrosion**

✓ **Trainline Conduits**

- Trainline Conduits collapsed, deformed, or broken.

**27-Point MU Connectivity Issues Solutions**

A rigorous Preventive Maintenance is a key to solving 27-Point MU Connectivity issues. Preventive Maintenance includes Visual Inspections, Wiring Testing, and Functional Testing:

- ✓ **Visual Inspections** shall be conducted to identify failures such as Receptacle Housing & Cover damages, Receptacle Pins damages, Jumper Cable Plug damages, Jumper Cable Sleeve damages, Jumper Cable Plug Socket damages, Junction Boxes physical damages, Junction Box Terminal Block and Wiring damages, and Trainline Conduit damages.
- ✓ **Pins and Sockets** shall be checked using Pin/Socket Gauge.
- ✓ **MU Wiring** shall be tested for Continuity, Pin-Pin, and Pin-Ground Insulation using Multimeter, Megohmmeter (Megger), or an Automatic Multi-Point Tester.
- ✓ **MU Functionalities** shall be tested using a 27-Pin MU Tester.

Discrepancies can be addressed either by cleaning, using non-chlorinated solvent contact cleaner, jumper cleaning brushes (pin, socket), or tightening/ replacing compromised Receptacle, Jumper Cable, or Junction Box, and Wiring.

## Conclusion & Recommendations

To avoid Wheel Slip, Manual and Emergency Sanding, Braking, or propulsion problem, it is imperative to have MU systems maintained at a high standard, including Receptacles, Jumper Cables, Junction Boxes, and Wiring.

Jumper Cable can be improved by using enhanced Design and High flexibility Jumper Cable for easy field handling as well as field replacement contact from the front side with minimal effort and time as well as field replacement for the conductors.

**Figure 17: High Flexibility MU Cable**


**Figure 18: High Flexibility MU Jumper Cable**

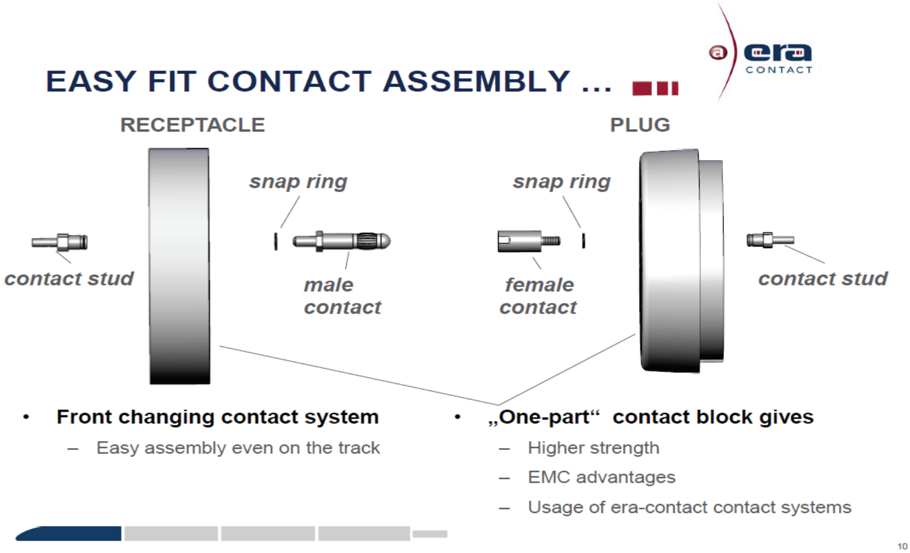



**Figure 19: Field Repairable MU Jumper Cable**

# References:


✓ **AAR S-512**: 27-Point Control Plug and Receptacle Standard.

✓ **APTA RP-E-017-99:** Recommended Practice for 27-Point Control and Communication Trainlines for Locomotives and Locomotive-Hauled Equipment.

✓ **APTA PR-E-RP-019-99**: Recommended Practice for 27-Point Jumper and Receptacle Hardware for Locomotives and Locomotive-Hauled Equipment.

✓ **AMTRAK MAINTENANCE PROCEDURES**

# Report on the Committee on Facilities, Material & Support

WEDNESDAY, OCTOBER 12, 2022
2:00 PM

*Chair*

**Brandon Teal**

**Product Mgr-Railway Machine Systems**

NSH USA Corporation, Albany, NY

*Commitee Members*

| | | | |
|---|---|---|---|
| Derek Barber | Railroad Services Director | Nabholz Corporation | North Little Rock, AR |
| Tim Bernat | Account Manager | Linkup International | Roanoke, TX |
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| *Past President* | | | |
| Michael Zerafa | VP-Business Process | PowerRail, Incorporated | Duryea, PA |

PERSONAL HISTORY

# Brandon Teal

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

Brandon is a native resident of Upstate New York. Brian has been married for 10 years to wife Farrah. Brandon enjoys travelling, German Sports Cars, motorcycles, physical fitness and home renovations.

**THE FACILITIES, MATERIAL AND SUPPORT COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO THE GENESEE & WYOMING RAILROAD FOR HOSTING AND SUPPORTING OUR 2022 WINTER COMMITTEE MEETING IN JANUARY IN JACKSONVILLE, FLORIDA.**

**THE COMMITTEE HAD A SUCCESSFUL MEETING DUE IN LARGE PART TO G&Ws HOSPITALITY.**

# Wheel Truing Technology Development and Innovation

*Prepared by:*
***NSH USA Corporation***
*David William Davis, President & COO*
*Eric Butler, VP, Engineering*
*Brandon Teal, Product Manager – Railway Machine Systems*
*Jason Steven Murphy, Machine Sales + Marketing Specialist*
*Michael Chu, Project Engineer*
*Simon Davies, Mechanical Project Engineer*

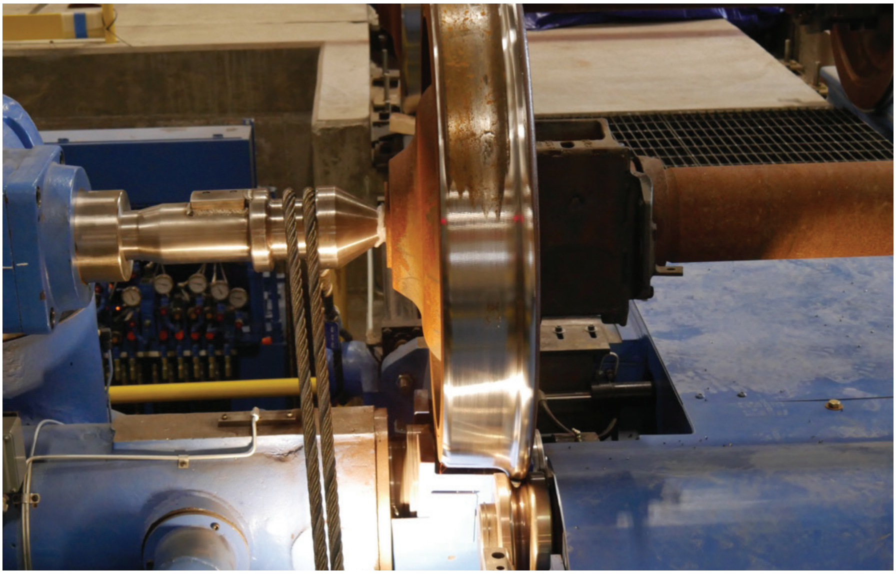
Wheel truing has long been a critical part of locomotive and railcar wheel set maintenance processes. Railroads depend on wheel truing machines to keep their wheel profiles in an optimal state. Maintaining the wheel profile extends the livelihood of the wheel set (a valuable asset) and allows for safe and efficient rail vehicle operation as well as less impact on the track infrastructure. It can also decrease vehicle dwell time needed to change out a wheel set.


**An above-floor wheel truing machine installation**

While much of the railway industry has implemented technological innovations to increase productivity, wheel reprofiling technology has largely languished – particularly cycle times. However, that has changed in the past several years. Looking to the general purpose machine tool industry as well as acknowledging industry demand for access to measurement data and process automation, wheel reprofiling is being brought into the 21st century.

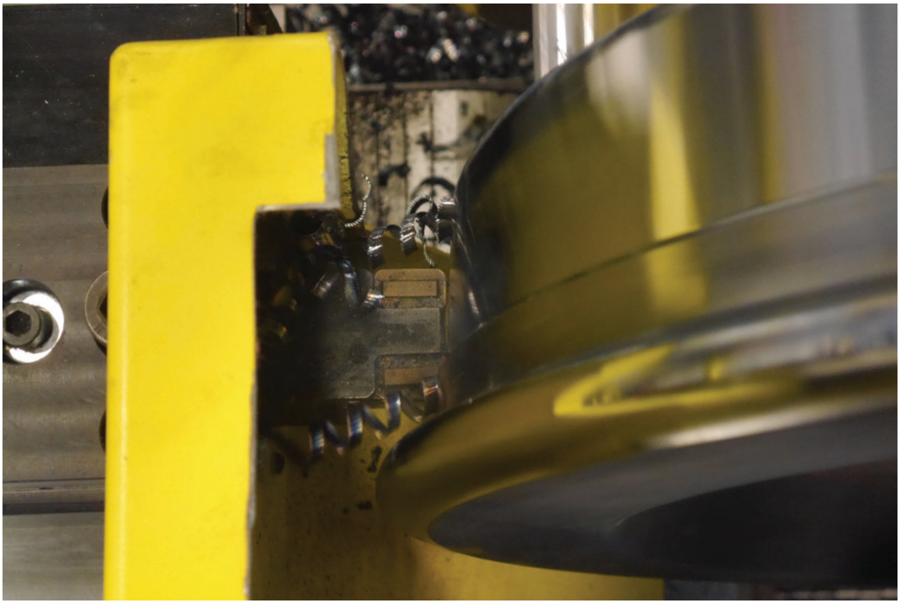
Wheel reprofiling is a machining process where metal is removed from the wheel to return the wheel profile to its optimal shape. During this process, defects such as flat spots, shelling, hard spots, and spalling are removed. Wheel reprofiling is part of the wheel set maintenance process not only to conserve the wheel set's useful life, but also to keep railway vehicles running safely and efficiently. Technologies for wheel reprofiling utilize one of two machining processes: milling or turning.

Milling, known historically throughout the railway industry as wheel truing, is a principal machining process whereby the cutting tool rotates rapidly while the workpiece is stationary, or in this case, the wheel, rotates very slowly. One revolution of a freight wheel is approximately 7 minutes. The traditional wheel truing cutting tool, which is referred to as the cutter, consists of a steel cutter body holding multiple removable steel blades that themselves contain multiple carbide inserts arranged with high precision across the length of each blade. In a wheel truing machine, the rotating milling cutter machines the full profile of the wheel in one axis of motion.



**The milling process**

Turning, also a principal machining process, is described as when the cutting tool is stationary while the workpiece (the wheel) rotates rapidly. The cutting tool consists of a single carbide insert which feeds across the wheel tread and flange. In the railway industry, a turning machine is referred to as a wheel lathe.



**The turning process**

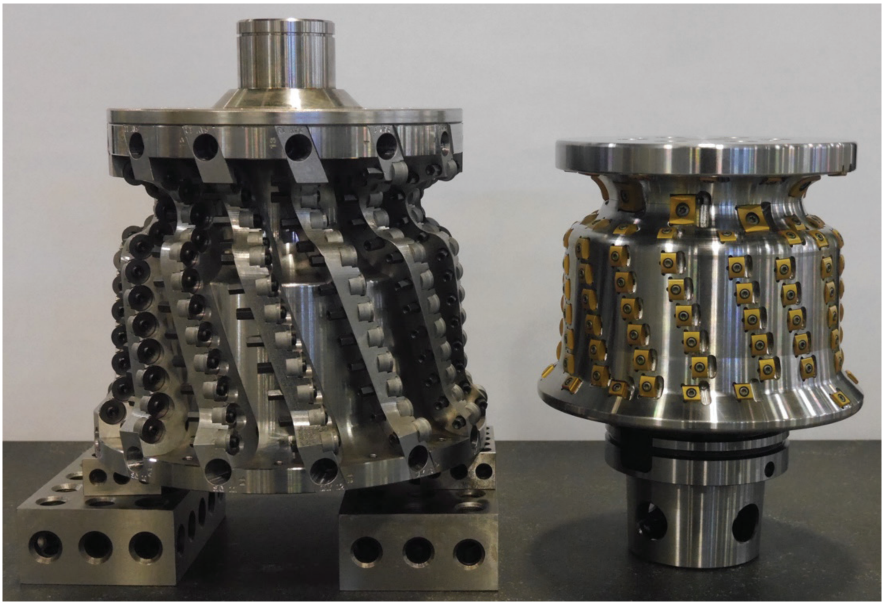
This paper will focus on the development and innovations related to the milling process (wheel truing) and will demonstrate that wheel truing offers significant opportunity for productivity growth and other advantages. The paper will further cover the most recent innovations to the next generation of wheel truing machines.

With turning, the only way to radically increase productivity is to rotate the wheel faster and increase the tool feed rate. In the manufacturing industry, this is achievable. But in a railway application, doing so amplifies the issues inherent in the turning process: the single point cutting tool is susceptible to damage or fracture when wheel wear conditions are present. Decreasing the feed rate allows for a safer, more controlled process, and a deeper depth of cut, but this tends to produce strands of metal called "stringers" (which are difficult to manage during the cutting cycle). It also increases cycle time, negating any productivity gains. The current proven way to increase productivity is to install more lathes running in tandem or larger groups, which requires a larger footprint for the system and substantially higher capital investment.

Through extensive research and experience with both reprofiling processes as it applies to the railway industry, it has been determined that milling is the technology that has additional opportunity for cost effective innovations. The process is ideally suited for railway wheel set maintenance operations, especially when wheel wear conditions are present. The full-profile milling process manages wheel wear conditions without operator intervention. Milling permits machining through wheel defects such as flat spots and shelling without decreasing workpiece rotational speed or changing cutter feed rates. There's also no need to undercut these wheel defects as required in the turning process, which means less service metal is removed. The slower rotational speed of the workpiece produces a more stable machining process by not inducing into the machining process dynamic forces caused by the large rotating mass of the wheel set.

With a high quantity of cutting inserts contained in each cutter, each insert is in the cut for a small fraction of each revolution of the cutting spindle, therefore it is impossible to make a continuous stringer like the lathe does. To increase material removal rate with the wheel truing machine, the depth of cut can significantly increase without drastically changing chip thickness or length. With the wheel truing machine, increasing the chip length by a factor of 2 or 3 means a 3/4 inch long chip instead of a 1/4 inch or 3/8 inch long chip – but never a stringer. Also, because milling inserts do not need a built-in chip break feature on the insert face (like turning), they can be designed and manufactured for toughness. The chips created by the milling material removal process are small, facilitating simple containment and collection.

By deploying digital manufacturing techniques, a new milling cutter design has been developed with two effective flutes or double helix. The double helix design permits twice as much material removal per revolution, which allows for increased performance. The outer diameter of the cutter has also decreased from 12 inches (305 mm) to 8 inches (203 mm). This change allows for an increased cutter RPM. When both of these design changes are implemented, the machining cycle time is immediately decreased, thereby permitting time to perform automated measurement without increasing overall cycle time when compared to turning.



**Older milling cutter next to new smaller cutter**

The new cutter design is further updated by placing the indexable carbide cutting inserts directly onto the cutter body as opposed to on removable blades. This change means less vibration is created throughout the tool during the machining process, creating a stiffer, stronger interface that extends the useable life of the inserts. The enhanced insert geometry as well as modern computer solid modeling lay-out tools also produce a more optimal wheel surface finish.

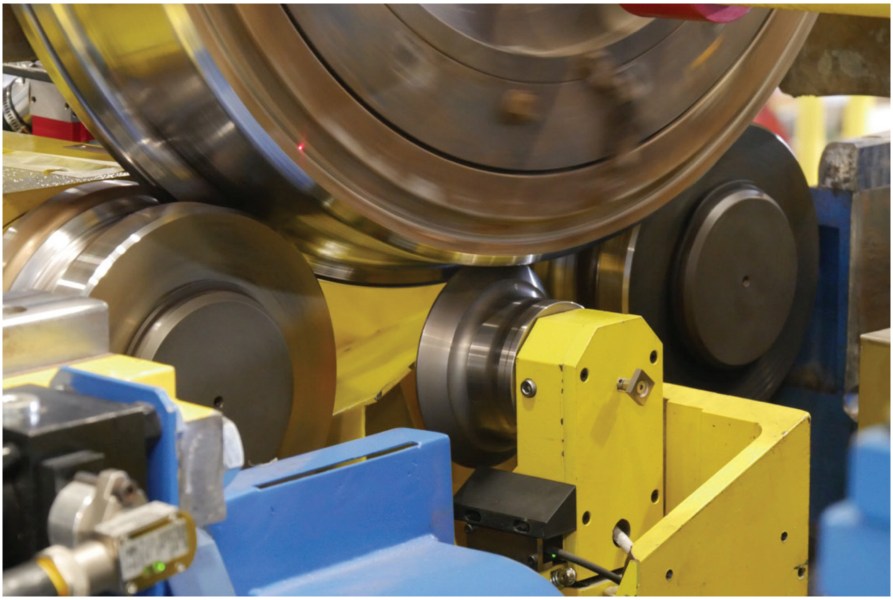
While the modifications to the milling cutter design appear to be the most transformative, there are other developments taking place in the wheel truing machine's design. One would be the wheel set clamping method.

The latest wheel truing machine design allows the wheel set center line to move while reprofiling. Instead of using heavy machine centers to clamp and hold the wheel set, a following probe monitors movement of the wheel set center line, and a closed loop servo system to keep the cutter at the correct radius. The axle centerline moves primarily vertically, but somewhat horizontally, as the wheel set rotates due to initial out-of-round condition, surface defects, a freshly cut surface contacting only one drive roller, etc. Our analysis shows that the horizontal movement has a negligible impact on the overall process. An integrated measurement system is used to find the initial location of axle center line with respect to cutter position. The cutter is then moved to the desired distance from axle centerline. If that centerline moves, the cutter moves with it, maintaining a constant distance. The process is therefore centerless (not requiring machine to

physically reference the axle centers) and completely independent of the condition (roundness) of the incoming wheels. Furthermore, this process will take an out of round wheel and ensure that it is trued round, regardless of wheel wear condition.

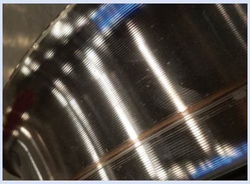
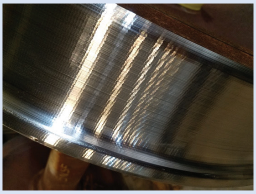
The wheel truing machine has historically relied on manual, external measurement tools to identify how much metal must be removed from the wheel. Measurement data from these tools can vary between operators based on simple human error. And while there have been some digital measurement tools introduced, they are still external to the machine.

Integrated automated measurement is now standard in the updated wheel truing machine design. As found throughout the railway industry, access to consistent and accurate measurement data has numerous benefits. The measurement data is collected prior to machining to influence a more precise reprofiling process. Parameters measured include wheel location (for cutter alignment), wheel diameter and width, the condition of the profile, flange height and width, wheel set back-to-back, and radial and axial runout. These parameters are also measured post-machining to confirm the wheel set has been trued to its target diameter. This data can be stored and evaluated later to better assess not just the state of the wheel truing machine, but also the state of the fleet's wheel sets. This data would prove invaluable when looking to implement a preventive maintenance program.



**Wheel measurement system**

One goal of updating the wheel truing machine cutter was to produce a better surface finish. Turning has long been viewed as producing a better surface finish than milling, which is largely based on a visual interpretation. As the data shows from a recent measurement exercise, the wheel lathe and legacy wheel truing machine produce largely the same surface finish. The new wheel truing machine, though, exceeded expectations with its surface finish measurement. And based on more recent anecdotal measurements as well as the refinements to the new wheel truing cutter, those measurements have been repeated and even exceeded!

| **Turning**<br>Underfloor Wheel Lathe | **Milling**<br>Legacy Wheel Truing Machine | **Milling**<br>New Wheel Truing Machine |
|---|---|---|
|  |  |  |

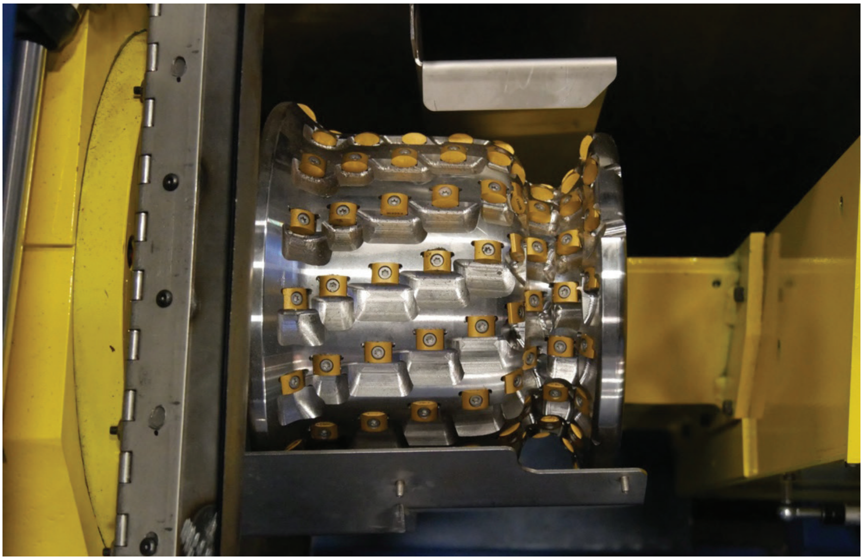
Based on measurements performed on "good" wheels individually machined in a controlled environment on a wheel lathe as well as a legacy and new wheel truing machine, assumptions made from visual interpretations look to be incorrect:

| | **Product Specification** | **Actual[1] [wheels][2]** |
|---|---|---|
| **Underfloor Wheel Lathe** | ≤ 472 $\mu$in Ra | 157 $\mu$-in. Ra [2] |
| **Legacy Wheel Truing Machine** | ≤ 200 $\mu$in Ra | 141 $\mu$-in. Ra [2] |
| **New Wheel Truing Machine** | ≤ 200 $\mu$in Ra | 54 $\mu$-in. Ra [4] |

1. Measured on tread surface in axial direction with Mahr Pocket Surf stylus-type profilometer (.195" stroke, 5 subgroups)
2. Number of wheels sampled based on in-house availability Feb. 2021

As an example of continuous improvement in engineering and design, the first iteration of the new wheel truing cutter included three different types of cutting inserts. The differences between the size and geometry of the three cutting inserts overtaxed the controls system. After several months of testing and evaluation, it was determined that reducing that number to just one type would allow for the same level of metal removal while allowing for more stable control. The change had the additional benefit of only needing to purchase one insert type in bulk quantity.

The first iteration of the new cutter also under-performed with chip evacuation. This started a process of designing wider pockets for the inserts as well as "gullets" running the length of the cutter. Both changes, while not impacting productivity, allowed for better chip evacuation and reduced insert wear during the machining process.



**Second iteration of new wheel truing cutter**

Another area of refinement has been the wheel set clamping process. The initial goal was to move away from requiring access to the wheel set's axle centers to hold the work piece on center. Not only does this add to the cycle time, but some modern vehicle design makes this method impossible. The new centerless clamping process has created a number of different clamping styles and specialized tools based on the end user's vehicle type. One positive occurrence has been that some rail vehicles do not need to be clamped at all, but rather are kept in place by the weight of the vehicle. The new wheel truing machine's following arms then monitor the position of the wheel and move the cutter to the wheel.

The development and improvement of wheel truing milling machine technology is a continuous process, and while early indicators show a move in a positive direction, more in service production is necessary. As the continuous improvement process develops, any worthwhile and updated findings will be reported to the LMOA.

# LMOA Facilities, Materials, and Support Committee Supply Chain Issues / Global Economy

*Prepared by:*
*Tim Bernat*
*LinkUp International*

**A complex web of issues has created global supply chain disruptions and impacts every phase of the supply network — from sourcing to manufacturing to last-mile delivery.**

## Past Supply Chain practices

In an interview conducted with a former Class I Sourcing Manager, in the past, Buyers had a tendency to buy particular materials from a Single Source. Often, the chosen Supplier may not have been the OEM but an Aftermarket Supplier. The OEMs would have been back-up Suppliers for larger locomotive components.

Buying and chosen Supplier decisions were made on Price – Quality – Delivery.


Buyers would spend more time traveling to Suppliers for Quality Audits - more so than today. In the past, Buyers often came from the field or shop level and knew more about locomotives and related components. In the early 2000s, there was a push to buy from Overseas Suppliers, which often caused longer lead times, lower quality components, and the lower pricing – not to mention lower quality parts. In the age of the internet, more material suppliers are available by searching the web and today's Buyers are more tech savvy in their searches.

## Role of Material in Locomotive Maintenance

Available materials are the life-blood of locomotive maintenance

- Right material, right place, right time is critical to locomotive performance
- The ability to upgrade, repair, and return a locomotive to service is time critical
- Managing inventory while controlling cost has always been a challenge
- No one wants to hear “Holding a Unit for Material”
- Last couple of years have been particularly difficult
    - Pandemic
    - Inflation
    - Labor shortage
    - Threat of war

## Current Supply Chain Issues

In the aftermath of the global pandemic, Russia-Ukraine War, fleet size reductions, manpower issues, inflation, and surcharges have all made managing Locomotive Material a more hostile environment.

Lead times have extended on most components used to repair, modernize, and build new locomotives. Due to pandemic factory shutdowns globally, the inability to manufacture steel and electronic components extended the lead times on raw and finished goods. Disruption to the flow of raw materials and parts sourced from China, India, and Mexico have seriously impeded global trade positions, forcing companies to reconsider their supply chain and partner ecosystems.

Global manufacturing capability, demand, and consumption patterns have bucked historical trends. The COVID-19 pandemic continues to wreak havoc on manufacturing worldwide, even as consumer demand for goods — including via e-commerce — remains high. Ports, trucking, railroading, warehousing, and distribution centers continue to adapt to these unpredictable changes. The pandemic has contracted the U.S. economy to its deepest pace since World War II. A decline in consumer spending and business investment affected millions of Americans. Gross domestic product fell 3.5% in 2020, the biggest decrease since 1946.

Port and warehouse congestion cause ripple effects throughout the intermodal system. While major railroads operate 24/7, not all other participants in the supply chain do. The lack of port, drayage, long-haul trucking, and warehousing capacity, as well as different working hours among supply chain partners set off a chain reaction leading to less efficient operations system-wide.

The Russia-Ukraine war has caused a major impact on the global supply chain, interfering with the flow of goods, causing dramatic cost increases and product shortages, and creating catastrophic food shortages globally. The Russian invasion has triggered sanctions and other obstacles, disrupting critical logistics and trade route operations.

**Fleet size reductions**

Precision Scheduled Railroading (PSR) has been criticized on many fronts. Shippers complain about poorer service and delays. Railroad workers have raised concerns about safety due to reduced inspections and staffing. Under PSR, service is typically eliminated on shipping lanes and origin-destination pairs that have low traffic levels. Intermodal terminals have been consolidated, with the railroad relying on trucks for the last hundred miles. Fewer workers are needed, even with higher traffic volumes. As a result, over 20,000 railroad workers were laid off in 2019.

The inability of the rails to adjust to variables in supply and demand has compounded supply chain fragmentation. As U.S. ports are struggling with a backup of containers stacked on their premises, rail depots are wrestling with the very same problem. The dwell time for containers at 11 major railroad depots reached an average of 9.8 days. That is up from 6.7 days in May 2021 and 5.9 days in February 2021.

The most severe backups were in Los Angeles, where containers waited an average of 16 days to be picked up, and in Charleston, South Carolina and Detroit, Michigan, where containers waited an average of 13 days to be carted away. The median cost of shipping a standard rectangular metal container from China to the West Coast in October 2021 reached a record $20,586 - nearly double what it cost in July, and that was double what it cost in January 2020. The shortage of chassis that is complicating life for U.S. motor carriers and drivers is also hurting the depots' ability to move containers through intermodal facilities.

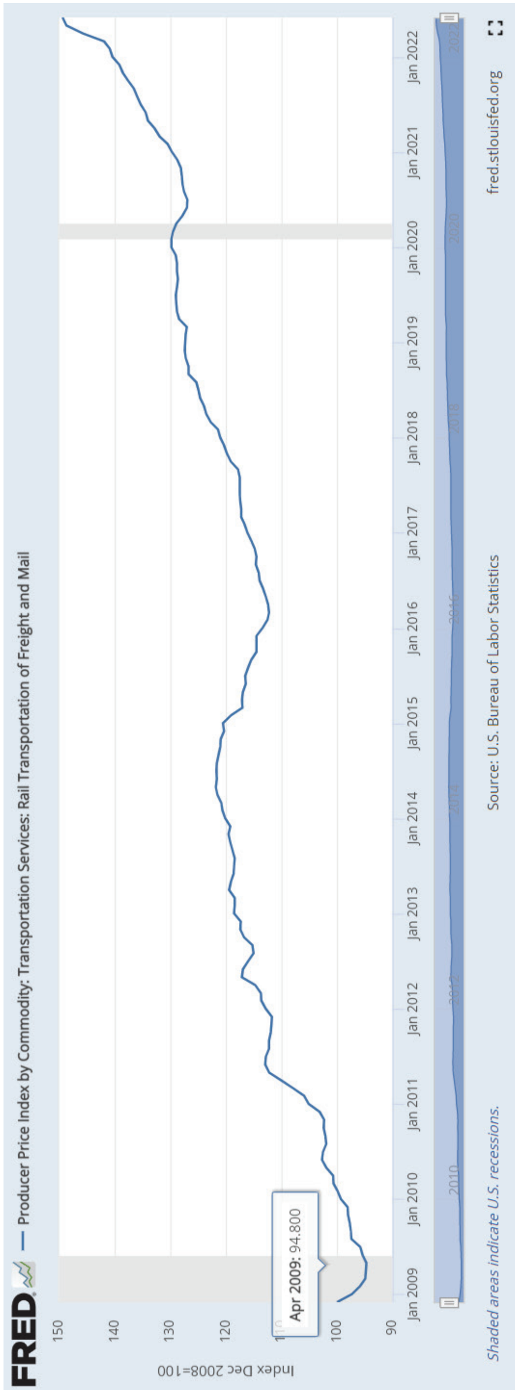
Unexpected increases in customer car orders hurt dwell time and network velocity. When demand grows, and rail capacity is in short supply, some customers increase their railcar orders beyond what they actually need. The influx of additional cars into an already congested system reduces the fluidity of the entire network.

**Manpower issues**

For railroads, the biggest challenge today is the nationwide challenge to recruit and retain qualified employees. Many industries — including railroads' largest competitor, the trucking industry — are having difficulty hiring and retaining employees to meet the surge in demand. As the STB recognizes, "carriers have reported hiring difficulties — difficulties that are not restricted to the rail industry."

**Inflation**

Increases in prices and the cost of living are at their worst level in 40 years. Material prices and the lead times have adversely affected the Rail Market negatively and have added to Supply Chain delays.


FRED
Producer Price Index by Commodity: Transportation Services: Rail Transportation of Freight and Mail
Index Dec 2008=100
150
140
130
120
100
90
Apr 2009: 94.800
Jan 2009
Jan 2010
Jan 2011
Jan 2012
Jan 2013
Jan 2014
Jan 2015
Jan 2016
Jan 2017
Jan 2018
Jan 2019
Jan 2020
Jan 2021
Jan 2022
Shaded areas indicate U.S. recessions.
Source: U.S. Bureau of Labor Statistics
fred.stlouisfed.org

**Surcharges affecting Rail Transport**

With the fluctuation of fuel costs, some freight carriers are imposing fuel surcharges to cover the necessary fuel costs. Delivery and pick-up surcharges are common, and deliveries or pick ups in areas that are less accessible can cost more than others. Handling charges might occur if shipment exceeds a certain dimension, and oversize charges are applied to goods and items that are packed over the recommended volume. As these dimensions vary during transit, it is advisable to accurately measure items and get a quote from a few couriers, as such shipments can be expensive.

## Recommendations for Best Practices

Current Solutions to Combat Supply Chain Issues

- Increase inventory when available
    - If suppliers have available inventory and the end user has a firm demand/ forecast on future orders, it may be best to buy more inventory before the lead times are extended.
- Multiple suppliers – avoid single source
    - If short lead times are available and the product meets all quality and cost standards, it is recommended to consider alternative suppliers.
- Contracts and commitments to purchase materials allow manufacturers and distributors to buy inventory for stock so it is available when needed by the end user.

Supply chain managers need to think carefully about opportunities and risk when looking for new sources, while also considering how to coordinate the change from one source or mode to another. If it isn't coordinated carefully, it could lead to all kinds of adverse effects throughout their supply chain.

## SUPPLY CHAIN DEMANDS CONSISTENT INVESTMENT POST-PANDEMIC

The pandemic and the economic recovery from it have sparked supply chain disruptions. The global supply chain is complex, and freight railroads have limited ability to influence non-railroad entities within it. Nevertheless, freight railroads are working with customers and other transportation modes to find solutions by expanding network capacity.

The current state of the supply chain industry demands consistent investment in infrastructure and technology. End-to-end communication is vital to overcoming current supply chain issues.

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# Report on the Committee on Mechanical Maintenance

## WEDNESDAY, OCTOBER 12, 2022
## 3:00 pm

*Chair*

**John Hedrick**
Principal Analyst
Southwest Research Institute, San Antonio, TX

*Vice Chair*

**Eric Dillen**
Advanced Engineering Leader
Wabtec Corporation, Erie, PA

*Commitee Members*

| | | | |
|---|---|---|---|
| M. Abbott | Product Design Engineer | Hotstart | Spokane, WA |
| D. Abeywickrama | Manager-Mechanical Engineering | Canadian National Railroad | Montreal, Quebec |
| M. Ayette | Engineering Manager | LeBrand | Tipp City, OH |
| E. Baldaccini | President | Quality Turbocharger | Houston, TX |
| J. Bink | Sales-Customer Service | Mid America RR Supply Company | Belton, MO |
| D. Bellemare | Executive Account Manager | Ekyrail | Chateauguay, Quebec |
| I. Bradbury | President | Peaker Services | Brighton, MI |
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| T. Casper | Vice President-Operations | PowerRail, Inc. | Exeter, PA |
| M. Cleveland | Director-Advanced Energy | Progress Rail | Fort Worth, TX |
| W. Clevenger | Vice President-Locomotive Division | Metro East Industries | Fairview Heights, IL |
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| A. Duncan | Dir-Diesel Engine Compliance Center | US-EPA | Ann Arbor, MI |
| D. Fox | CSO | ACS Railroad Solutions | Norcross, Ga |
| C. Gibson | Asst Vice Preesident-Mechanical | Genesee & Wyoming | Webster, NY |
| F. Jalili | Supplier Consultant | FJ LLC | Plano, TX |
| T. Kennnedy | President | Kennedy Rail Consulting | Omaha NE |
| *Past President* | | | |
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| M. Kopitzke | National Sales Manager | JMA Railroad Supply | Seymour, IN |
| A, Meek | Manager-Rail Business Dev | Cummins, Inc | Broomfield, CO |
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| D. Parsons | Senior Manager Engiineering-Diesel | Amtrak | Chicago, IL |
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| G. Wilson | Superintendent of Cars | Iowa Interstate RR | Cedar Rapids, Ia |

PERSONAL HISTORY

## John Hedrick

Principal Scientist
Southwest Research Institute
San Antonio, TX

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

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

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

**THE MECHANICAL MAINTENANCE COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO THE FLORIDA EAST COAST RAILWAY FOR HOSTING THEIR 2022 WINTER COMMITTEE MEETING IN JACKSONVILLE, FLORIDA.**

**THE COMMITTEE WOULD ALSO LIKE TO THANK THE ALASKA RAILROAD FOR HOSTING THEIR 2022 SUMMER MEETING IN ANCHORAGE, ALASKA.  COMMITTEE MEMBER RUSTY POCHATKO OF THE ALASKA RAILROAD ARRANGED THE MEETING AND GRACIOUSLY GAVE A TOUR OF THEIR FACILITIES WHICH WAS AN EYE- OPENING EXPERIENCE FOR COMMITTEE MEMBERS.**

**THANK YOU VERY MUCH FEC AND ALASKA RAILROADS.**

# Systems Engineering - Product Development and Integration

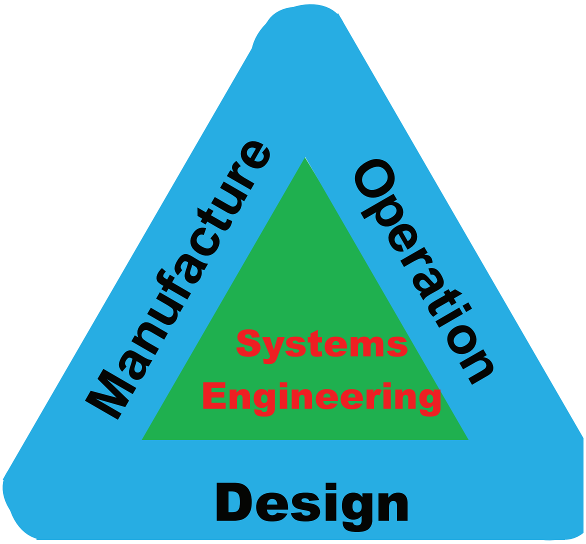
*Prepared by:*
*Tom Kennedy, Kennedy Rail Consulting*

Systems engineering is a structured approach for product development and integration. The practice of Systems Engineering incorporates specific tools such as requirement specification and allocation, reliability analyses, Failure Modes Effects Analysis (FMEA), Reliability Growth Testing (RGT), etc. For more detail of specific elements, reference the 2011 LMOA paper, Design for Reliability.

The discipline of Systems Engineering started in the late 1950's with the development of advanced military equipment and the US space program. Modern product designs are highly complex with high levels of integration of the technologies of mechanical, electrical, and software. In addition to the discussion of these technologies and their integration, Systems Engineering addresses, through a structured approach the integration of the disciplines of these technologies and the end user, the customer.

This paper describes a Systems Engineering Program, from a high level, to ensure successful product development, production, deployment, and asset disbursement at the end of its useful life. Included in this paper are two rail examples where systems engineering was not used or ineffectively used. This paper is designed to be a high-level introduction to Systems Engineering to facilitate future papers with more detail on Systems Engineering.

From a high level there are three program elements that describe a Systems Engineering program. These elements are the design process, the manufacturing process, and the product operation (customer). The successful integration of these elements is the objective of a Systems Engineering Program; the "Triad" graphic pictorially illustrates this. Test and verification activities are included in the Design, Manufacturing and Operation elements at lower indenture levels.



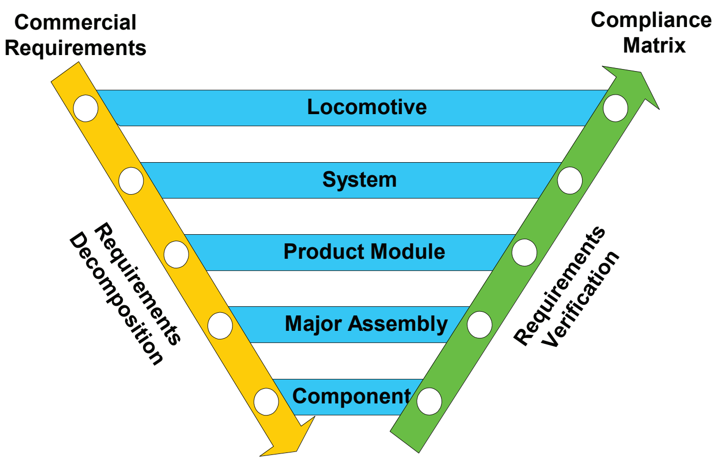

The integration of these three program elements is accomplished through a Systems Engineering Management Plan (SEMP) that defines the scope, schedule, and resources to achieve project objectives. This integration can be pictured as a three-legged stool, as shown in the graphic. If one of the legs is shorter than another the stool is unbalanced and subject to failure, thus as is a product development without Systems Engineering. Another way to look at this is if your program has more scope than resources or schedule then the program is unbalanced and subject to failure. Thus, if the program is not balanced it is subject to failure. The theory of constraints dictates that the element most limited needs to be adjusted to match the other elements or the other elements reduced to achieve balance.


The SEMP also contains significant detail such as, Quality Function Deployment, Design Requirements, Design Reviews, Hardware and Software Test, and Production Planning to support the program scope, schedule and resources identified in the SEMP. Design reviews are critical and an integral part of the SEMP to ensure that all the disciplines are working together to integrate all the required technologies. Typical design reviews (toll gates) used are:

SRR – Systems Requirements Review
SDR – Systems Development Review
PDR – Preliminary Design Review
CDR – Critical Design Review
TRR – Test Readiness Review
PRR – Production Readiness Review
SAR – Ship Authorization Review
PPR – Post-Production Review

Depending on the program size and criticality and risk these design reviews may be tailored to fit the program, but not eliminated. They are still essential.

At the heart of a Systems Engineering Program and central to the SEMP is the System "V" chart. This chart, shown in the pictorial below, illustrates how the commercial requirements are cascaded into specific design requirements for the locomotive, major systems, product modules, major assemblies and components. This decomposition is done down the left side of the "V". On the right side of the "V" is the requirements verification to ensure compliance to the requirements




Systems Engineering Process

This is a high-level illustration, and more detail is added to lower indenture levels.

As promised earlier here are two examples of where Systems Engineering was not used or not used well.

## Example 1: Idle reduction technology

When idle reduction, required by the EPA 1033 to reduce emissions, was implemented it created two problems. First, on electric motor start locomotives on one OEM these starter motors were never designed for this duty cycle and no changes were made to account for the increase in the number of engines starts. Prior to implementation of idle reduction, a locomotive may have experienced about ten starts a year. Now this number of restarts is possible in a matter of a few days depending primarily on-air loss, battery state of charge and the locomotive's software restart parameters. This requires the starter motors to be replaced yearly now instead of at the engine overhaul point.  The second issue is this created a shortened life of the lead acid locomotive start batteries due to the increased duty cycle of frequent discharges and potentially inadequate recharge due to AESS shutting the engine down before the battery was fully recharged. Testing that the

Union Pacific conducted at Fort Worth in 2009 in coordination with a railroad battery supplier showed that a 20 second engine roll consumed up to ten percent of the battery state of charge and that an idle time of approximately one hour was required to fully recharge the battery. There is a second OEM using generator start which had issues too. Although generator failure was not an issue, shortened battery life was still an issue. Also, the addition of contactors and inverters was an extra complication and reliability issue.

## Example 2: PTC and Off-board Communication

The installation of Positive Train Control and off board communication equipment in the locomotive cab is estimated to release approximately one thousand watts of thermal waste energy into the cab. For reference a road locomotive HVAC typically has a 30,000 BTU/HR air conditioner. One Kilowatt is 3412 BTU/HR so approximately 11.4% of the HVAC's air conditioner capability is consumed removing this thermal energy. This has undoubtedly contributed, not solely, to crew complaints of inadequate cab cooling. These complaints most likely generate engineer defects that require shop action to test and possibly replace the failed part. No Defects Found (NDF) at the railroad shops and HVAC's suppliers may have increased. Further analysis of this area is required—possible future LMOA paper.

In both of these examples if Systems Engineering had been effectively used all the effected design activities of mechanical, electrical and software would have been coordinated to identify all interactions and adverse effects and resolve them prior to implementation. Without coordination of all disciplines involved a sub-optimal design will be the result, with adverse consequences to the customer.

In conclusion, today's products are complex and highly integrated, and their development requires a strong and disciplined Systems Engineering program. It is highly recommended that a Systems Engineering department be established in your companies. It is further recommended that the Railroads develop and enhance their knowledge of Systems Engineering so they can participate and possibly partner with the OEM's and suppliers to ensure products are developed that meet their needs, requirements and expectations. Another benefit of Systems Engineering is that it will increase product financial knowledge and that basing decisions on the Total Cost of Ownership or Life Cycle Cost is superior to basing decisions purely on acquisition cost.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# Robust Validation
# Simultaneous Testing of Multiple Variables

*Prepared by:*
*Ian Bradbury, Peaker Services, Inc.*

## Introduction

Through most of human history, many of our discoveries have been made by perceptive observers seeing chance events (informed observation). The scientific method vastly accelerated our rate of learning with further acceleration becoming possible through use of statistically designed experiments (directed experimentation). Traditional thinking for product validation is to test a "sample" from the "population of interest", with larger "sample" sizes being required to have higher levels of confidence in our estimate of reliability. This approach is contrasted with use of fractional factorial designs where a directed experimentation approach can be used to systematically test across a broad range of conditions. It will be argued that the latter approach improves confidence in product validation and therefore real-world reliability when introducing new or redesigned products to market.

### How do we discover things?

If we consider how many discoveries have been made over human history, such as fire or champagne, they were mostly lucky accidents. The world presents us with chance events due to natural variation in environmental conditions. If we're lucky, a perceptive observer is around to observe the chance event and has the right state of mind (framework of perception) to realize that what they have seen is something new that's of value. Other than being directly taught ideas previously learned by others, this has been the most common way by which we have learned new things. We may increase the likelihood that this informed observation results in learning by methods such as the passive use of statistical control charts described in Bradbury (2020). For example, end of line performance testing is being performed on new locomotives. Brake Specific Fuel Consumption (BSFC) on the line haul cycle is recorded as part of the testing and recorded on an individual-moving-range chart as displayed in Figure 1. The noted point above the upper control limit (UCL) is a signal of special cause, so it makes sense to inquire into what was different about that particular locomotive or the conditions under which that particular measurement was taken. Examples of a special cause in such a case could be incorrect software loaded, error setting the timing pointer, bad fuel, or a transcription error.

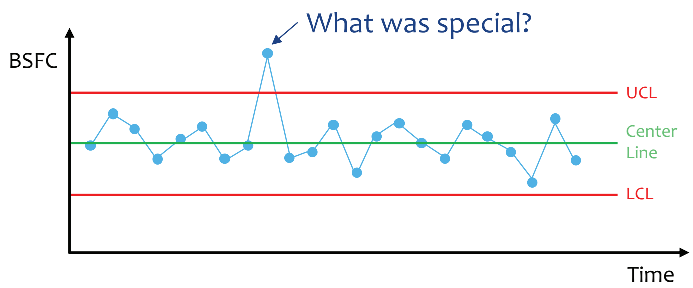


**Figure 1 – Individual-Moving-Range Statistical Control Chart of BSFC**

Philosophers debate origin of the Scientific Method, but the modern formulation which synthesizes both inductive and deductive inference appears to have emerged in the early 1800's (for instance in *Ørsted (1811)*). The advent of Scientific Method along with changes in dispersion of knowledge and reproducibility of experimental outcomes resulted in an explosion in the development of scientific knowledge and invention and corresponding material improvement of the human condition.

With Informed Observation, we aim to improve the chances that naturally occurring informative events are brought to the attention of the perceptive observer. With directed experimentation, we take deliberate action to try and increase the probability of an informative event occurring; actively testing our knowledge while taking action aimed at improvement. W. Edwards Deming, inspired by Walter Shewhart, formalized the process of simultaneous learning and improvement in the PDSA cycle (see *Deming (1994)*). This is the logical core of most problem-solving methods as described in *Standish (2019)* and is elaborated upon in Figure 2.

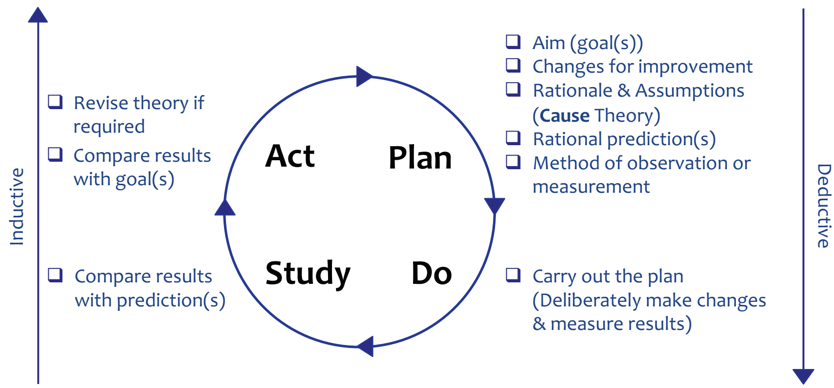


**Figure 2 – The Plan-Do-Study-Act Cycle for Learning and Improvement**

The PDSA cycle starts in the Planning stage with consideration of the question "What are we trying to accomplish?[1]" to establish the context and aim for improvement. The **Plan** consists of four components:

1. Changes that we can make which we predict will bring about the desired improvement.
2. The reasons we believe that the changes will bring improvement, any assumptions we are making and the reasoning behind the assumptions - this is our cause theory, no matter how tentative or improbable.
3. Prediction of the results we will get from carrying out the planned changes, based on our theory.
4. A method of observation or measurement which we will use to see whether the actual results of carrying out the plan were as predicted.

In the **Do** stage, the planned change(s) are carried out and the results are observed or measured.

The **Study** stage involves comparison of the results observed in the Do stage with the predictions made in the Planning stage. There are two possibilities (assuming the plan was carried out as intended):

1. The observed results and predictions do not correspond. This provides an opportunity to learn since we have cause to revise the theory used as a basis for the plan. It could be that the reasoning behind the prediction that the planned changes would bring about improvement is in need of revision. It could be that the reasoning behind the assumptions that were made is in need of revision.
2. The observed results and predictions do correspond. We do not have cause to revise the theory used for the plan, which increases our degree of belief in the

1 See API Model for Improvement in *Langley et al (2009)*

theory's usefulness. It does not, however, prove the theory to be true since the future may always present cause for revision.

In the **Act** stage the theory is revised (acted upon), if such a need were indicated in the Study stage, thereby providing a new foundation for any future cycles. The results achieved are also considered relative to the aim established in the Planning stage to determine whether further improvement is desired. If so, the next PDSA cycle starts with an answer to "What are we trying to accomplish?" that has adapted to past performance.

Figure 2 also illustrates how this formulation of the Scientific Method synthesizes deductive and inductive inference.

## Factors in Experimentation

When making changes to improve products or processes, we sometimes change more than one thing at a time. The problem with this is that the impact of the factors you've changed are "confounded" – you don't know which change had what effect. For instance, suppose that a friend tells you that "I changed to a new brand of oil filter as well as changing from single weight to multi-vis oil and I'm getting better oil life". You respond by asking whether it's the new oil filter or new oil that's improving oil life. The two factors – oil filter and oil type – were confounded in the experiment, so we don't know which factor had which effect. A common statement made in such a situation is that "the problem is that you changed more than one factor at the same time". The implicit thinking behind this statement is that the problem of factor confounding would be solved by changing one factor at a time. The experiment that your friend performed could be depicted as shown in the Figure 3 graph. Low and High levels of the oil filter factor are "Brand A" and "Brand B" respectively. Low and High levels of the oil type factor are "Straight Weight (SW)" and "Multi-Viscosity (MV)" respectively. Oil Life (the experimental response variable) was lower at the combination of Brand A oil filter with SW oil (low level of each factor) than it was with Brand B oil filter and MV oil (high level of each factor).

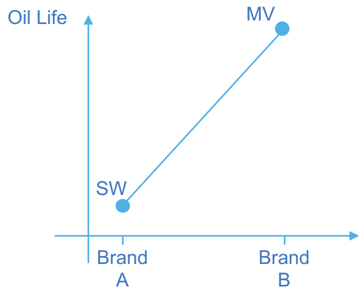


**Figure 3 – Oil Life Experiment as Performed**

If all we want to know is whether Brand A with SW oil is better or worse than Brand B with MV oil for oil life, there is no problem with the experiment. If we want to know what the relative contribution of oil filter type and oil type are and if one depends upon the other, we don't have enough information. Let's consider some of the possible scenarios. We could have the situation depicted in Figure 4; here Brand B oil filter gives better oil life whether you are using SW or MV oil, and the amount by which Brand B filter is better than Brand A filter is the same whether you are using SW or MV oil. Similarly, we can say that MV oil is better than SW oil for oil life whichever oil filter you're using and the amount by which it's better is independent of oil filter type. In such a situation, we say that the factors do not interact (the effect of either factor does not depend on the level you're at of the other factor).

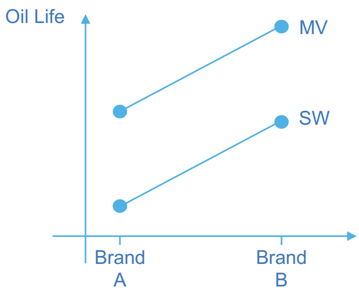


**Figure 4 – Experimental Scenario 1**

Alternatively, we might have the scenario depicted in Figure 5. This depicts an interaction between the factors – the effect of one factor depends on the level of the other factor. In this case, Brand B oil filter improves oil life over Brand A with SW oil, but it reduces oil life with MV oil. Equivalently, we can say that MV oil gives better oil life than SW oil, but the magnitude of improvement is larger with Brand A filter than it is with Brand B.

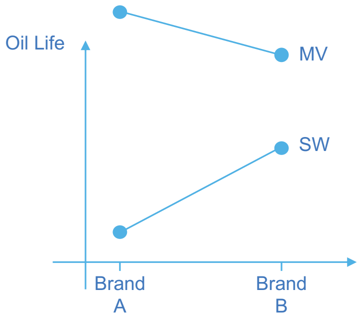


**Figure 5 – Experimental Scenario 2**

Figure 6 depicts a second scenario in which the factors interact – Brand B filter gives better oil life than Brand A whichever oil is being used, but the improvement in oil life is greater with SW oil than with MV. If using Brand A oil filter, use of MV oil increases oil life over SW whereas using Brand B filter, use of MV oil decreases oil life over SW.

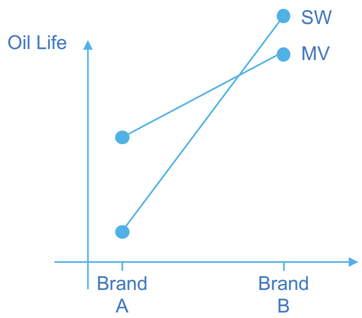


**Figure 6 – Experimental Scenario 3**

The last 3 examples illustrate that the original experiment cannot identify what the relative contribution of each factor is, whether the two factors are interacting with each other or what the best combination of factor levels is for oil life. With the benefit of these different possible scenarios, we can revisit the question of whether one factor at a time experimentation avoids the confounding problem. If, for example, we were to hold the oil filter factor constant at Brand A and just change oil type we would see the same type of experimental outcome – MV oil life is better than SW oil life with the Brand A filter. However, any of the 3 scenarios could be true with the Brand B oil filter. What we can say is that we know what the effect of oil type is conditional on holding filter type constant at Brand A, but this doesn't tell us what the effect of oil type might be with Brand B oil filter. This is really equivalent to the level of knowledge that we had for the original experiment. Looking at all the combinations is what allows us to see the relative effect of each factor and whether they interact.

## Factorial Experiments

In a complete factorial design, every combination of levels for each of the factors in the experiment is run at least once. In Figure 7 below, the vertices of the design represent each combination of factor levels that is run in the experiment. This is the underlying experimental design depicted in Figure 4 – Figure 6 where factor A is oil filter type (A(-) = Brand A; A(+) = Brand B) and factor B is oil type (B(-) = SW; B(+) = MV).

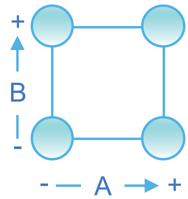


**Figure 7 – A $2^2$ Full Factorial Design**

A complete factorial design with 3 factors, each at 2 levels, known as a $2^3$ design is shown in Figure 8.

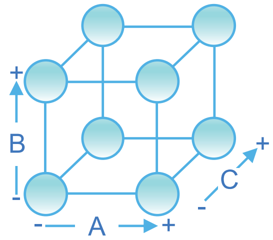


**Figure 8 – A $2^3$ Full Factorial Design**

As the number of factors and/or number of levels for each factor increases, the number of combinations required to perform a complete factorial design increases geometrically as we can see in Table 1, which does not include any repetition or replication.

**Table 1 – $2^k$ Design Size as the Number of Factors ($k$) Increases**

| # of factors ($k$) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| # of combinations ($2^k$) | 2 | 4 | 8 | 16 | 32 | 64 | 128 | 256 | 512 |

Naturally, it may seem impractical to consider a factorial experimentation approach if doing so would necessitate building and testing such a huge number of combinations when the number of factors increases. Fortunately, fractional factorial designs are often a practical solution.

## Fractional Factorial Designs

Fractional factorial designs are very helpful, particularly in the early stages of experimentation, where there are many possibilities (factors) that one wishes to explore. In these designs, a fraction of all possible combinations of levels for the factors are considered. The fraction is chosen in such a way that the confounding of effects is carefully controlled and balanced.

The graphic in Figure 9 depicts the combinations of a $2^3$ experiment which might be run for a ½ fraction ($2^{3-1}$ design). Either the shaded combinations would be run or the unshaded ones, reducing the number of test combinations from 8 for the full $2^3$ design to $½*(2^3) = 4$ for the ½ fraction. These particular combinations have the benefit that if any one of the 3 factors is unimportant, the design collapses into a complete $2^2$ factorial in the remaining 2 factors (this can be visualized in the projections shown in Figure 10 for the shaded vertices).

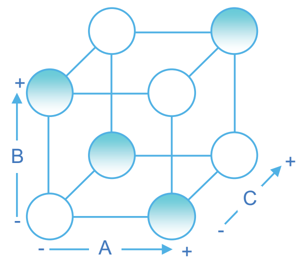


**Figure 9 – A $2^{3-1}$ Design**

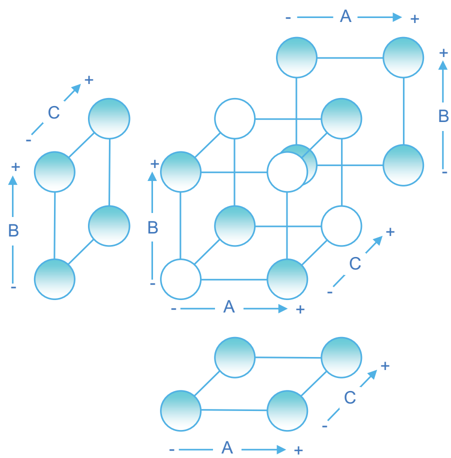


**Figure 10 – Projective Illustration that $2^{3-1}$ Design is a Complete $2^2$ if any Factor is Unimportant**

As we saw in the original example, there is a loss of information when all combinations of the factors are not run in the experiment – confounding is the price. What (designed) fractional factorial designs like the ½ fraction above do is control and balance the confounding according to an explicit theory/philosophy. In this case: the overall average I is the same contrast as the 3-way interaction ABC; A = BC; B = AC and C = AB. So, for instance, when we calculate the main effect of A, it is really A+BC. The general philosophy in designing fractional factorial designs is that main effects are more likely to be significant than 2-way interactions which in turn are more likely to be important than 3-way interactions and so on. Designs like this also lend themselves well to a building block approach to iterative experimentation – a question about interpretation of results may be resolved by adding a complementary design. In this example, running the complementary ½ fraction (the unshaded vertices if you ran the shaded ones) completely unconfounds the design – the combination is the complete $2^3$, so I, A, B, C, AB, BC, AC and ABC can then each be independently estimated.

A ½ fraction of a $2^4$ design is illustrated in Figure 11. Similar to the prior design, it can be seen that if any one of the factors is unimportant, the design becomes a complete $2^3$ design in the other 3 factors. As $k$ increases, it becomes increasingly likely that at least one of the $k$ factors in a $2^{k-1}$ design is relatively unimportant, so fractionation becomes less and less of an issue.

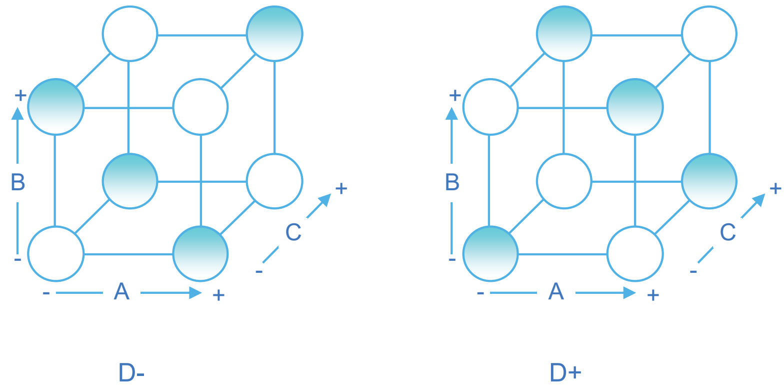


**Figure 11 – Illustration of a $2^{4-1}$ Design**

Equivalent logic may be applied for $1/p$ fractions; the likelihood that at least $p$ of the factors are relatively unimportant increases with $k$ for a $2^{k-p}$ design.

## Validation

The conventional approach to product validation is to test as many prototype parts as needed to failure or some other performance criteria. This is commonly stated in a form similar to: *To have 95% confidence that 90% of the population will exceed time to failure T (B10>T), a sample size of at least n is required.* Required sample sizes can be quite large and typically require assumptions about the distribution of time to failure. The biggest issue with such an approach in reality is that it assumes that you are drawing a random sample from the failure time distribution of interest. That distribution is time to failure of parts made on production equipment in customer use across the full range of production and customer use variation. Unfortunately, at the time of validation testing, parts typically have to be produced using prototype production methods and tested in lab conditions using methods intended to accelerate stress to speed time to failure. To the extent that prototype parts differ from production and lab test conditions differ from customer use, the accuracy of predicting reliability does not truly improve as sample size increases. You can study as much water as you want, it won't tell you how ice will behave.

A better approach[2] to increasing confidence in the results of validation is to think about the things expected to vary in production that might be expected to impact the performance of the part (control factors). Part specifications are often a good place to start since, by definition, variation has to be controlled to ensure satisfactory product performance. Another arena to consider are ways in which customer use might vary that are judged likely to impact durability (environmental factors). Both areas require the application of subject matter knowledge to come up with factors appropriate for deliberate inclusion in testing. Fractional factorial designs such as those introduced earlier provide an approach by which prototypes may be built and tested across a range of control and environmental factors. If the design elements are still under consideration, design factors can also be incorporated.

### Example

In the development of a locomotive emissions kit, the manufacturer has the design mostly complete. They are still considering whether they should use a standard or modified turbo design, whether or not to include exhaust blankets and whether or not to include a diesel oxidation catalyst. Inclusion in the final kit design will depend on relative contribution and necessity for kit robustness. Factors that vary in production with potential to impact emissions performance include injector calibration, inner diameter of the cylinder liner and lead wire reading (effective compression ratio). Factors varying under customer use conditions include cooling (radiator cleanliness) and ambient temperature. They formalized these into experimental factors as follows:

2 The Robust Design or Taguchi Method is similar in nature to what is being recommended here, but has some methodological differences. For instance, "noise" factors are typically crossed with the other factors.

- **Design**
    - Turbo (Standard vs. Modified)
    - Exhaust Blanket (None vs. Blanket)
    - DOC (None vs. DOC)
- **Production**
    - Injector Calibration (min. vs. max flow)
    - Liner Inner Diameter (min. vs. max. spec.)
    - Lead Wire (min. vs. max spec.)
- **Environment**
    - Cooling (clean vs. dirty radiators (simulated by restriction off vs. on))
    - Ambient Temperature ($0^0$F vs. $100^0$F)

If all combinations of the 8 factors were to be tested at each level, we would need to build $2^6 = 64$ engines with all the combinations of design and production factors and test them each across the $2^2 = 4$ test conditions of environmental factors for $2^6 * 2^2 = 2^8 = 256$ tests in total. Using the fractional factorial approach, they chose a $2^{8-4}_{IV}$ design instead as outlined in Table 2. This design is a 1/16 fraction of the full $2^8$ design; just 16 build/test combinations. As mentioned above, there is a price to pay in confounding of effect estimates with the fractional design – main effects are confounded with seven 3-way as well as higher order interactions; 2-way interactions are confounded with three other 2-way as well as higher order interactions. For each of the combinations of factors, criteria pollutants and BSFC were measured.

**Table 2 – Emissions Kit Validation $2^{8-4}_{IV}$ Design Matrix**

| TURBO | EXHAUST BLANKET | DOC | INJECTOR CAL | LINER DIA. | LEAD WIRE | COOLING | AMBIENT TEMP. |
|---|---|---|---|---|---|---|---|
| A | B | C | D | G | H | F | E |
| STD. TURBO | NONE | NO DOC | MIN FLOW | 9.0595" | 0.020" | CLEAN RADS | 0F |
| MOD. TURBO | NONE | NO DOC | MIN FLOW | 9.0620" | 0.068" | DIRTY RADS | 0F |
| STD. TURBO | BLANKET | NO DOC | MIN FLOW | 9.0620" | 0.020" | CLEAN RADS | 100F |
| MOD. TURBO | BLANKET | NO DOC | MIN FLOW | 9.0595" | 0.068" | DIRTY RADS | 100F |
| STD. TURBO | NONE | DOC | MIN FLOW | 9.0620" | 0.068" | DIRTY RADS | 100F |
| MOD. TURBO | NONE | DOC | MIN FLOW | 9.0595" | 0.020" | CLEAN RADS | 100F |
| STD. TURBO | BLANKET | DOC | MIN FLOW | 9.0595" | 0.068" | DIRTY RADS | 0F |
| MOD. TURBO | BLANKET | DOC | MIN FLOW | 9.0620" | 0.020" | CLEAN RADS | 0F |
| STD. TURBO | NONE | NO DOC | MAX FLOW | 9.0595" | 0.068" | DIRTY RADS | 100F |
| MOD. TURBO | NONE | NO DOC | MAX FLOW | 9.0620" | 0.020" | CLEAN RADS | 100F |
| STD. TURBO | BLANKET | NO DOC | MAX FLOW | 9.0620" | 0.068" | DIRTY RADS | 0F |
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| MOD. TURBO | BLANKET | DOC | MAX FLOW | 9.0620" | 0.068" | DIRTY RADS | 100F |

Analysis of results from an experiment like this are beyond the scope of the paper. As a result of such an experiment, it would be possible to learn a lot more than from a traditional validation test. For instance, it might be found that cooling and lead wire have an equivalent effect on NOx, so increasing the lead wire specification could be traded off against more frequent required radiator maintenance in the emissions M.I. It might be seen that, as expected, inclusion of a DOC consistently reduces PM but that PM compliance was consistently achieved at a lower system cost with the modified turbo and exhaust blanket.

Factorial experimentation can be used far more broadly than in validation or product development. For instance, in a problem-solving context where multiple potential causes of the problem you're trying to solve have been identified, a factorial or fractional factorial experiment can be used to focus in on those factors that really make a difference. In the following experiment, a problem-solving effort began due to high copper levels being experienced in engines after rebuild. An initial engine teardown eliminated potential sources of copper other than the power assembly thrust washers, so the focus became potential causes of thrust washer (accelerated) wear. Several factors emerged from brainstorming for testing:

- A: Piston Source: New vs. Rebuilt
- B: Thrust washer source: Current vs. Alternative Vendor (A vs. B)
- C: Should we polish the thrust washer? (As Received vs. Post Polish)
- D: Is there an engine location effect (Front vs. Rear end)
- E: Should we polish the piston thrust platform? (As Received vs. Post Polish)
- F: Is it caused by residual casting or rebuild grit? (Simulate – as is vs. soda blast)
- G: Is the thrust washer hanging up on the carrier wear step (Essentially no wear step vs. max requalifying step).

16 power assemblies were built and installed in an engine according to the design matrix shown in Table 3 and the engine was run for an extended load test.

**Table 3 – Thrust Washer $2_{IV}^{7-4}$ Design Matrix**

| Cylinder No. | Location | Thrust Platform Post Polish | Imbedded Grit | Thrust Washer Source | Thrust Washer Post Polish | Piston Source | Size of Carrier Pilot Wear Step |
|---|---|---|---|---|---|---|---|
| | D | E=BCD | F=ACD | B | C | A | G=ABD |
| 7 | Back End | As Shipped | As Shipped | Vendor A | As Shipped | New | None |
| 6 | Back End | As Shipped | Soda Blast | Vendor A | As Shipped | Rebuilt | Max |
| 13 | Back End | Post Polish | As Shipped | Vendor B | As Shipped | New | Max |
| 16 | Back End | Post Polish | Soda Blast | Vendor B | As Shipped | Rebuilt | None |
| 8 | Back End | Post Polish | As Shipped | Vendor A | Like Glass | Rebuilt | Max |
| 5 | Back End | Post Polish | Soda Blast | Vendor A | Like Glass | New | None |
| 15 | Back End | As Shipped | As Shipped | Vendor B | Like Glass | Rebuilt | None |
| 14 | Back End | As Shipped | Soda Blast | Vendor B | Like Glass | New | Max |
| 9 | Front End | Post Polish | As Shipped | Vendor A | As Shipped | Rebuilt | None |
| 3 | Front End | Post Polish | Soda Blast | Vendor A | As Shipped | New | Max |
| 4 | Front End | As Shipped | As Shipped | Vendor B | As Shipped | Rebuilt | Max |
| 2 | Front End | As Shipped | Soda Blast | Vendor B | As Shipped | New | None |
| 1 | Front End | As Shipped | As Shipped | Vendor A | Like Glass | New | Max |
| 10 | Front End | As Shipped | Soda Blast | Vendor A | Like Glass | Rebuilt | None |
| 12 | Front End | Post Polish | As Shipped | Vendor B | Like Glass | New | None |
| 11 | Front End | Post Polish | Soda Blast | Vendor B | Like Glass | Rebuilt | Max |

Thrust washers were weighed on a microgram scale and measured dimensionally before and after load test. They were also qualitatively assessed before and after load test by visual examination. The visual analysis showed a different pattern of wear – concentric circles for vendor A's thrust washers vs. a helical pattern for vendor B (shown in Figure 12 for the piston side of the thrust washers). The magnitude of flaking was also greater for vendor A's thrust washers.

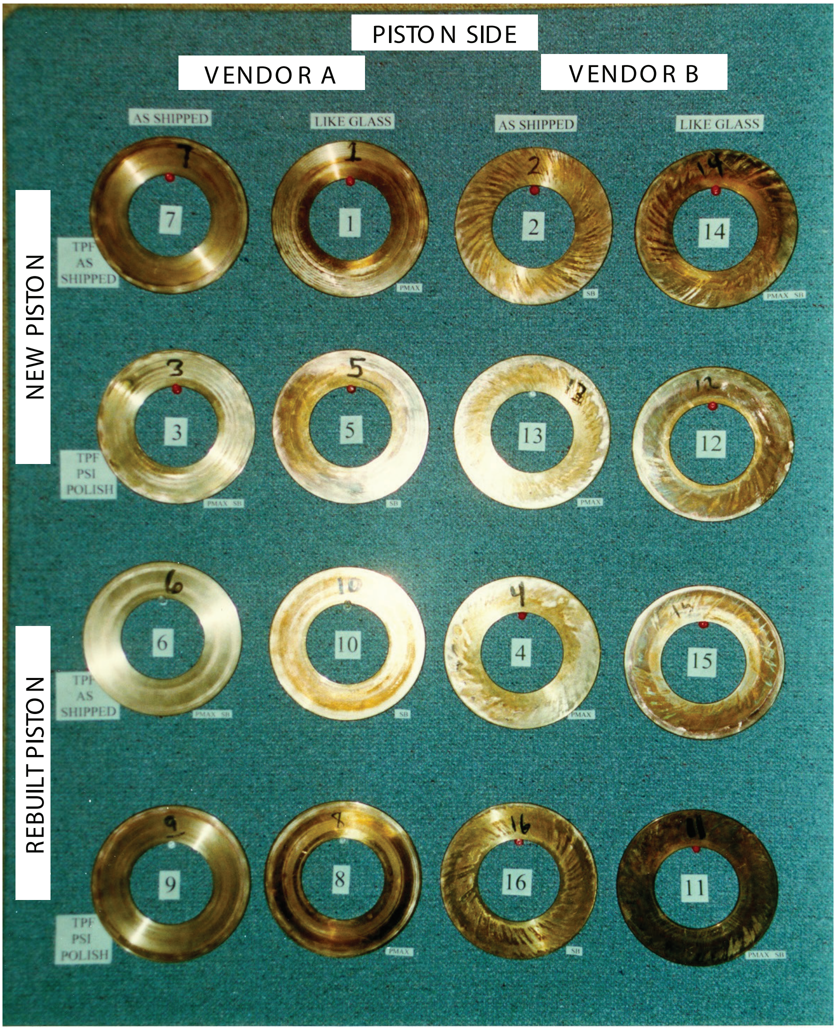


**Figure 12 – Visual Comparison of Thrust Washers Post Load Test**

With measured weight loss as a response variable, Figure 13 shows a Normal Scores Plot of the effect estimates. A Normal Scores Plot is a method to graphically distinguish between statistically significant and insignificant effect estimates – those that are likely significant fall away from a central 'noise' line. The indicated significant effects are B = Thrust Washer Source (+ ≥3-way interactions), C = Thrust Washer Post Polish (+ ≥3-way interactions) and FG+BC (+ higher order interactions). Given the significance of B and C, it is likely the BC interaction in the other string that's significant, so B and C have to be considered together as factors.

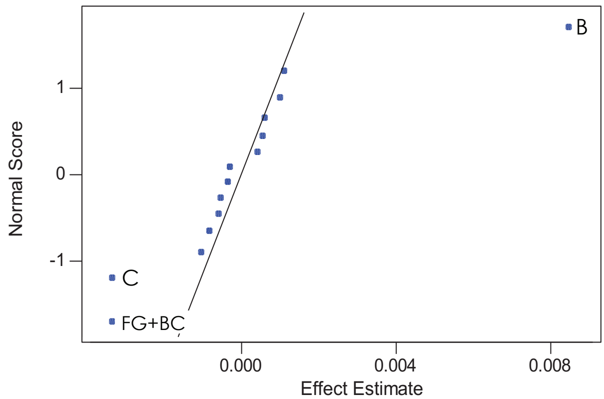


**Figure 13 – Normal Scores Plot of Experimental Effect Estimates for Weight Change**

Figure 14 shows the interaction plot for B and C. Vendor A's thrust washers gained weight whether polished or not (polishing didn't make a difference), which was a counter intuitive, particularly given the higher level of flaking.

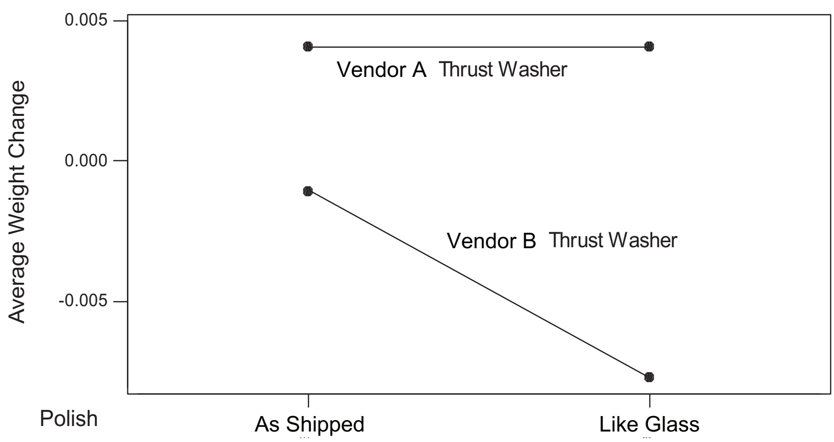


**Figure 14 – Thrust Washer Weight Change Interaction Plot**

This was subsequently concluded to be due to micro porosity absorbing oil. Vendor B's thrust washer did lose weight during load test, losing more weight if polished. Metallurgical analysis performed as a result of the testing confirmed vendor A and B's thrust washers differed in their chemical composition, microstructure and hardness. Use of vendor B's thrust washers resolved the problem of accelerated thrust washer wear as verified by normal copper levels in oil samples after instituting the change.

## Conclusions

Traditional validation testing is based on testing a large random sample from the "population of interest" (which is not actually possible). Using engineering judgment to identify factors expected to affect performance, then building and testing prototypes across a fractional factorial design matrix of control, manufacturing and environmental factors, provides a far greater opportunity to learn and gain higher real-world confidence in the reliability of a resulting design.

## Acknowledgments

The author appreciates the many constructive comments of the LMOA Mechanical Committee.

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# Autonomous Detection of Compressed Air Leaks on Trains

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## Abstract

Minimizing compressed air leaks on trains is one of the areas in which railroads can make significant gains towards reducing fuel consumption, which is necessary to meet current greenhouse gas reduction goals. While some awareness towards the cost of compressed air leaks exists[1,2] shop practices have generally not focused on fuel efficiency and have generally focused on safety and operability by allowing some level of leaks on certain compressed air systems on the train. While brake tests can sometimes tell you if you have a leak, they cannot tell you where within the train the leak is. Finding these leaks requires an employee to manually search, often going on, under, or between rolling stock to listen or feel for leaks. It is an inefficient and time-consuming process, which is why the Federal Railroad Administration (FRA) and railroads have defined acceptable leak rates. Automated detection of locomotive and train air leaks could reduce the time and labor necessary to find air leaks, reduce locomotive fuel consumption and exhaust emissions, and at the same time improve employee safety.

Southwest Research Institute (SwRI) was awarded a Transportation Research Board (TRB) Rail Safety IDEA project to develop a proof-of-concept wayside system that can autonomously detect compressed air leaks on trains and can relay the location of the leaks to mechanical department personnel for repair. This paper details the development of that system.

## 1.0 Background

Compressed air is vital for the safe operation of trains throughout the world. The compressed air, which is generated using air compressors on the locomotives, is used for vital purposes such as air brakes, valve actuation, radiator shutters, horns, bells, and more. Detection of air leaks is a difficult and time-consuming endeavor. With freight trains often stretching over a mile in length, safe brake pipe leak limits have been instituted by the FRA (49 CFR 232)[3] which allow for a 60 standard cubic feet per minute (SCFM) brake pipe leak rate for standard trains, and a 90 SCFM brake pipe leak limit for trains operating with Distributed Power (DP).

While these leaks are allowable by current safety regulations, testing has shown that these "allowable" leaks have significant effects on locomotive fuel efficiency. Initial testing has shown that even when well under the current limits, allowable leaks on trains produce an increase in traction specific fuel consumption (NTSFC). This means that power that would normally be sent to the traction motors is instead diverted to the air compressor, reducing vehicle efficiency. Air leaks also significantly reduce the effectiveness of Automatic Engine Stop-Start (AESS) systems, which not only means more unnecessary fuel burn, but reduces the lifespan of parts such as locomotive starters, air compressors, and batteries.

The wasted fuel spent overcoming air leaks is a significant environmental issue. Using overall fuel consumption data from the AAR Railroad Facts 2019 Edition[4], for every 1% increase in total fuel consumption on North American Class I railroads, it results in the following per year:

- 37,000,000 gallons of unnecessary fuel consumption
- 880,000,000 pounds of excess CO2 emissions
- 11,000,000 pounds of excess NOx emissions
- 110,000 pounds of excess PM emissions

Table 1 summarizes preliminary test data concerning the effects of air leaks on locomotive NTSFC. This data set includes data from a 2019 LMOA paper on the fuel efficiency impact of air leaks[(1)]. Testing to date has been completed on various locomotive models from Class I railroads. On each locomotive the initial test was done with the air compressor cut-out and the locomotive supplied compressed air from an outside source. This represents the ideal situation of no air compressed air leaks. The testing was then completed with the locomotive air compressor cut-in, with the compressor cut-in and a 30 SCFM brake pipe leak induced, and finally with the compressor cut-in and a 60 SCFM brake pipe leak induced. Note that not all configurations were tested on each locomotive.

All the leak rates tested are considered "allowable" leaks, meaning that current railroad regulations and practices will not flag the leaks as a problem. The average NTSFC increased by 2.0% from baseline with only a 30 SCFM brake pipe leak over the linehaul cycle and increased over 5% with a 60 SCFM leak. These increases in NTSFC more than double when calculated over the switch duty cycle, as shown in Table 2, with a 4.3% average increase in fuel consumption at 30 SCFM and an astounding 14.1% increase with a 60 SCFM leak.

**TABLE 1. Air Leak Effects on Linehaul Duty Cycle NTSFC**

| Test Locomotive | Baseline LH NTSFC - Air Compressor Cut Out [lb/THP-hr] | Change in LH NSTFC - Compressor Cut In [%] | Change in LH NTSFC - 30 SCFM Brake Pipe Leak [%] | Change in LH NTSFC - 60 SCFM Brake Pipe Leak [%] |
|---|---|---|---|---|
| Locomotive 1 | 0.389 | 1.3% | 1.6% | - |
| Locomotive 2 | 0.366 | - | 1.2% | - |
| Locomotive 3 | 0.352 | - | 2.2% | - |
| Locomotive 4 | 0.444 | - | 2.3% | - |
| Locomotive 5 | 0.409 | 1.1% | 2.1% | - |
| Locomotive 6 | 0.399 | - | 2.2% | - |
| Locomotive 7 | 0.403 | - | 2.1% | 5.2% |
| Locomotive 8 | 0.393 | - | - | 5.8% |
| | Average NSTFC Increase: | 1.2% | 2.0% | 5.5% |

**TABLE 2. Air Leak Effects on Switch Duty Cycle NTSFC**

| Test Locomotive | Baseline SW NTSFC - Air Compressor Cut Out [lb/THP-hr] | Change in SW NSTFC - Compressor Cut In [%] | Change in SW NTSFC - 30 SCFM Brake Pipe Leak [%] | Change in SW NTSFC - 60 SCFM Brake Pipe Leak [%] |
|---|---|---|---|---|
| Locomotive 1 | 0.416 | 2.9% | 4.1% | - |
| Locomotive 2 | 0.404 | - | 3.1% | - |
| Locomotive 3 | 0.398 | - | 4.7% | - |
| Locomotive 4 | 0.491 | - | 2.6% | - |
| Locomotive 5 | 0.505 | 2.56% | 5.4% | - |
| Locomotive 6 | 0.445 | - | 4.9% | - |
| Locomotive 7 | 0.445 | - | 5.2% | 14.1% |
| Locomotive 8 | 0.434 | - | - | 14.1% |
| | Average NSTFC Increase: | 2.7% | 4.3% | 14.1% |

There are standard air brake and main reservoir leak tests that are done to detect if air leaks are present on locomotives and railcars, but locating those leaks is a difficult process and is only attempted if the leaks are beyond the allowable limits. Locating leaks often requires an employee to move up and down the length of a train listening and feeling for air leaks. These investigations require multiple instances of employees going on, under, or between rolling equipment to try and locate the leaks.

If leaks could be detected and located autonomously, it could potentially reduce the number of times employees must go on, under or between rolling equipment and make repairing leaks much more efficient and reducing injury risk to employees. An overall reduction in air leaks will reduce fuel consumption and therefore reduce harmful exhaust emissions, increase the lifespan of parts, increase the effectiveness of AESS systems and will increase the factor of safety on air brake systems overall by reducing the onus on the consist air compressors to keep up.

## 2.0 Proof of Concept Development

Initial work to see if audio detection of air leaks was possible involved testing using equipment available with our noise, vibration, and harshness (NVH) team. SwRI then worked with Fluke Process Instruments and Sorama on a proposal to the Transportation Research Board (TRB) for the development of a proof-of-concept wayside system that can autonomously detect compressed air leaks on moving trains, which was submitted in September 2020 to the TRB Rail Safety IDEA program. The contract was awarded in October 2021 and work began on the development of the system.

The remainder of this paper describes the development, testing, and overall accuracy of that proof-of-concept system.

### 2.1 Hardware Selection

We worked to determine which sensor technology would be most appropriate for this application. It was determined that the Fluke SV600 Fixed Acoustic Imager (Figure 1) would be the ideal sensor option for this project. Table 3 shows the technical specifications of the SV600, which is a small form factor 64-microphone array with an integrated camera that functions at the frequencies needed for compressed air leak detection (30-45kHz).

**TABLE 3. Fluke SV600 Fixed Acoustic Imager Specs**

| | |
|---|---|
| Dimensions (LxWxD) | 170 x 170 x 65 mm |
| Weight | 0.85 kg |
| Frequency Range | 0-55 kHz |
| Microphone Count | 64 |
| Camera Resolution | 720p at 30fps |
| Operating Temperatures | -20°C to 50°C |


**Figure 1. Fluke SV600 Fixed Acoustic Imager**

While the acoustic imager is the main sensor, another imager was eventually added to the system. A Basler 1920-40gc visual spectrum camera was added to obtain an alternate image without audio overlay provided by the SV600. The camera is equipped with a Kowa LM25HC-SW 25mm F/1.4 lens. The specifications for the visual spectrum camera used during the project are listed in Table 4. The visual spectrum camera was used to allow for better part identification and leak location clarity, as it allowed for viewing behind the sound overlay map provided by the SV600 Sensor output

**TABLE 4. Visual Spectrum Camera Specs**

| | |
|---|---|
| Manufacturer | Basler |
| Model | 1920-40gc |
| Lens | Kowa LM25HC-SW, 25mm |
| Camera Resolution | 1920x1200 |
| Frame Rate | 42 fps |

Note that a thermal imaging camera was also included in testing, and while initial results were promising in seeing cooling effects from air leaks, the consensus at this time is that the SV600 is accurate enough that the thermal imaging camera is not necessary for further confidence in leak detection. As such, the thermal imaging results are not included in this publication.

## 2.2 Initial Assembly and Testing

A versatile mounting stand was constructed that was able to orient the sensor and cameras in different orientations for testing. With such large, desired ranges of motion, it was determined that a fixed stand would not be appropriate for the initial design so a portable stand was designed which could be moved and adjusted quickly and accurately to test various sensor positions in a rapid manner.

Once the stand was complete, initial testing began on a stationary locomotive running at Notch 3 in self load to determine ideal settings for the acoustic sensor. Air leaks were induced on a locomotive at multiple locations. As seen in Figure 2, the sensor could detect a compressed air leak at various distances with the locomotive engine running in self-load at Notch 3. The sensor height was set at 1.2 meters above the rail and the sensor distance was varied.

In Figure 2, one thing that isn't noted is that there is an additional air leak that was not being detected using the auto-range for the decibel settings on the sensor. The decibel minimum was tested at various levels to determine where the bottom cutoff was to detect smaller compressed air leaks. In Figure 3 the unit was auto-ranged with a minimum of 51 decibels. The second air leak was not detected at all with this minimum setting.

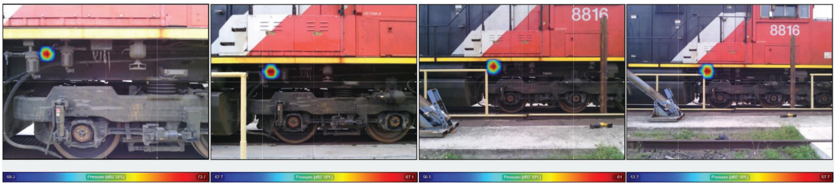

**Figure 2. Air Leak at 3.0, 4.5, 6.0, and 7.5 Meter Distances**


**Figure 3. Compressed Air Leaks at 51dB Minimum Detection Threshold**

The minimum range was set to 40 decibels (Figure 4), which is slightly louder than a whisper. The second leak becomes obvious in this range but note that there were significant artifacts sensed with this minimum which can be seen at the edge of the field of view below.

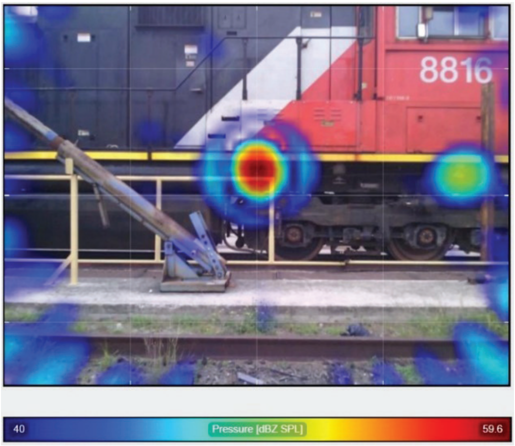


**Figure 4. Compressed Air Leaks at 40dB Minimum Detection Threshold**

The minimum detection threshold was then set to 45 decibels (Figure 5). This minimized the additional detections and gave a good, clean detection signal for both air leaks in the image. This was ideal to minimize potential false detections once the visual AI was implemented.

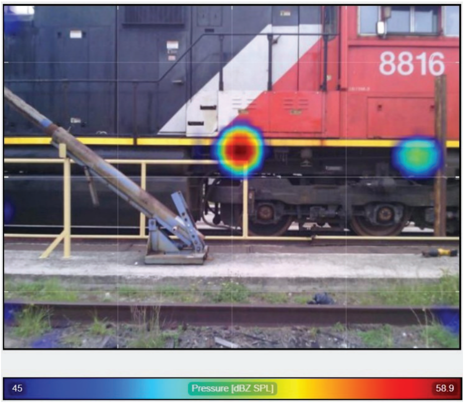


**Figure 5. Compressed Air Leaks at 45dB Minimum Detection Threshold**

Further testing was then completed using the acoustic sensor in concert with the visual spectrum camera on moving locomotives. Leaks were implemented at various locations and the locomotive speed was varied between 1mph and 10mph. This testing was completed multiple times, with various locomotives and locomotive consists to generate the data needed for implementation and training of the visual detection system.

While the acoustic sensor worked well and allowed for easy identification of air leak locations, there are other sounds that also occur in the same frequency range as air leaks so it requires a human with knowledge of the compressed air systems to watch the screen and make judgements based on the sensor display. In order to automate the process, a machine learning/machine vision system had to be implemented and trained.

The most important component for any machine learning and deep learning model to be successful is having a large and robust dataset with representative data for the task at hand. In this case we needed data from the SV600 of leaking compressed air components along with data from moving locomotives. Gathering data from operational equipment is very important in building a system that can not only detect leaks but reject other sources of noise, e.g. track ringing, compressor noise, engine noise, bells, horns, etc. To accomplish this task, testing was completed at SwRI's Locomotive Technology Center (LTC) in San Antonio, TX. Data was collected using both a single locomotive and locomotive consist, over multiple testing sessions. Air leaks were introduced in known locations to record and catalog ground truth data. The induced air leaks were sealed and opened as well as increased/decreased in intensity as the locomotive(s) were moved back and forth across the field of view of the sensors. In this instance more data was able to be collected on the intra-train connection components, such as knuckles and gladhands, which will serve as the basis for determining where a piece of rolling stock ends and the next one begins.

## 2.3 Data Annotation

Prior to training and evaluating a machine learning model, images collected from the acoustic sensors were manually annotated using CVAT, an open-source annotation tool. Regions including and around known leaks were labeled with closed polygons and the gladhands were labeled with bounding boxes (Figure 6). To separate unique runs of data collection, the start and end times of each data collection run was recorded for future use in the training pipeline. A held-out validation set was created by randomly selecting 20% of these runs, leaving the rest of the annotations as examples for training the model. Images collected from the Basler and Boson sensors were then registered to the SV600 image for each run to spatially align all images to the labels.

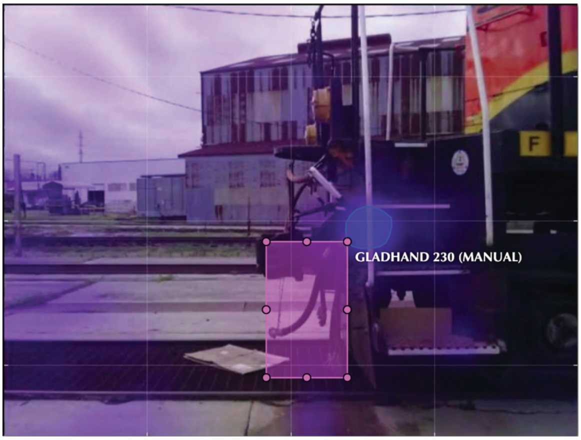


**Figure 6. Annotated frame in CVAT**

## 2.4 Machine Learning Model

Convolutional neural networks (CNNs) have shown state-of-the-art performance in a variety of image-based tasks in the past decade due to their ability to learn hierarchical patterns in image data with significantly fewer parameters than fully connected networks. For this project, two types of CNN architectures were trained and evaluated for the detection of air leaks. The first was a mobilenetV3 based segmentation model, which classifies each pixel in an image as either belonging to an air leak or a part of the background as shown in Figure 7. Segmentation models have the benefit of producing sharp predictions with the precise location of leaks at the cost of requiring advanced post-processing algorithms to determine which groups of pixels belong to an individual instances of a leak. The second model implemented was YOLOv5, an object detection architecture that holistically locates the centers of the leaks and bounds them using a standard geometry (boxes or circles). This method allows for the identification of individual instances to be a part of the deep learning process, though reduces the granularity of the predictions.

Development of the leak detection algorithm began with training the segmentation model on the images from the first data collection. While this model was able to detect larger leaks with confidence, it frequently reported smaller leaks as background. These false positives were determined to be inherent to the segmentation approach as larger leaks were given significantly more importance than smaller ones. This issue was further compounded by the ambiguity of what constitutes a leak on a pixel level. The visible and longwave images were also introduced as inputs to the model during this iteration of model development. While telling features of a leak were present in this data, poor overlap in the field of view of the cameras did not provide sufficient information for model to increase performance.

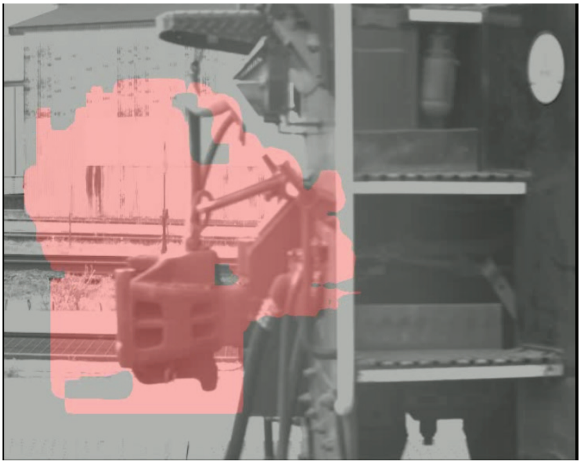

**Figure 7. Pixelwise Semantic Segmentation Mask of Air Leak**

Following the second round of data collection, the YOLOv5 model was implemented and trained. A python script was written to convert the air leak labels into the bounding box format required by the model (Figure 8). To reduce the errors from ambiguous labels seen previously, the identification of leaks was weighed relatively higher than bounding task in the training process. Results from this model showed a large improvement in the detection of smaller leaks and a higher confidence when detecting larger leaks. More false positives were found than with the previous model, though they lacked consistency between frames and could be filtered out with post-processing methods. The YOLOv5 architecture also enabled the inclusion of new features to be detected, such as gladhands, with only a marginal increase to the model size. Additional annotations were created for the past data collections to include the presence of gladhands and the model was retrained using both classes of labels.


**Figure 8. YOLOv5 Detection of an Air Leak**

An important feature of leaks not captured by the machine learning models is their persistence through time. While potential false positives could be filtered out by the models based on their shape and relative location to the locomotive, post-processing methods can be used to increase the confidence in detected leaks by looking at frames sequentially in time and tracking them while within the frames. An object tracking algorithm was used to identify and track detections across multiple frames. This technique allows the system to build an improved confidence score and measure the amount of time a leak is seen in the frame (Figure 9). Leaks with a probability over 50% were tracked by this algorithm and had to be present for 0.5 seconds to be a reported leak. While these thresholds were used for the reported metrics, they could be easily adjusted to fit different use cases and sensitivities.

An alerting system was developed to notify users of a detected leak and provide visualizations of their locations. A composite image is generated for each piece of rolling equipment, with the post-processed leaks being overlayed on the image. This image is then reported to the appropriate mechanical personnel for further investigation and repair as time permits. Figure 10 shows an example of the automated notification system. Note that this notification system is just an example and can be adapted as necessary to meet the needs of each railroad.

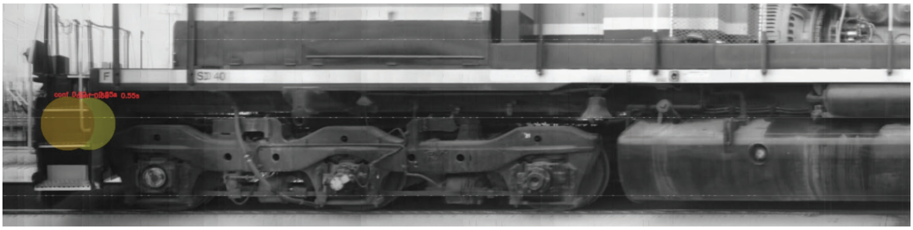

Figure 9. Example Composite Image of Passing Locomotive with Detected Air Leaks

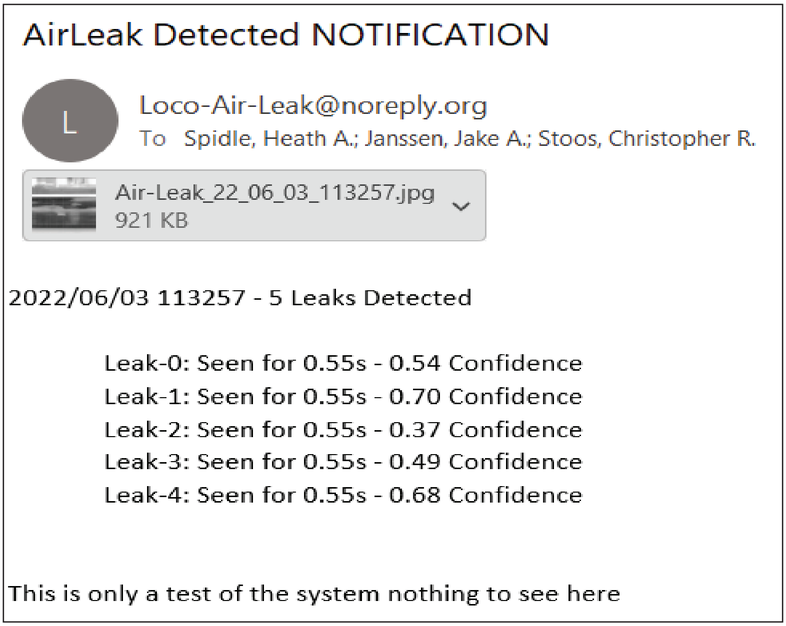


Figure 10. Example Air Leak Notification Alert

## 2.5 Results

Figure 11 shows validation metrics for the object detection deep learning network. The Y-axis is the normalized score between 0 and 1; the X-axis is the epoch. As the model is trained and subsequently evaluated after each epoch, the precision, recall, and mean average precision improve and change. As the model learns, it starts to reach a stabilized state where the validation metrics stop changing which means the model has fit itself to the data as much as it can with the currently available input data, hyperparameters and architectures used. These results are summarized in Table 5. The metrics that are used in reporting are defined below:

True Positive ($t_p$): Algorigthm identified a leak when there was a leak present (1)

True Negative ($t_n$) : Algorithm did not trigger when there was no leak present (2)

False Positive ($f_p$): Algorithm Identified a leak when there was no leak present (3)

False Negative ($f_n$): Algorithm did not trigger when there was a leak present (4)

Precision = $\frac{t_p}{t_p+f_p}$ : measures how accurate is your predictions. i.e. the percentage of your predictions are correct. Maximizing precision will minimize the false-positive errors (5)

Recall = $\frac{t_p}{t_p+f_n}$: measures how well you find all the positives. Maximizing recall will minimize the false-negative errors (6)

Mean Average Precision (mAP) = $\int_0^1 p(r)dr$ : Area under the precision recall curve. (7)

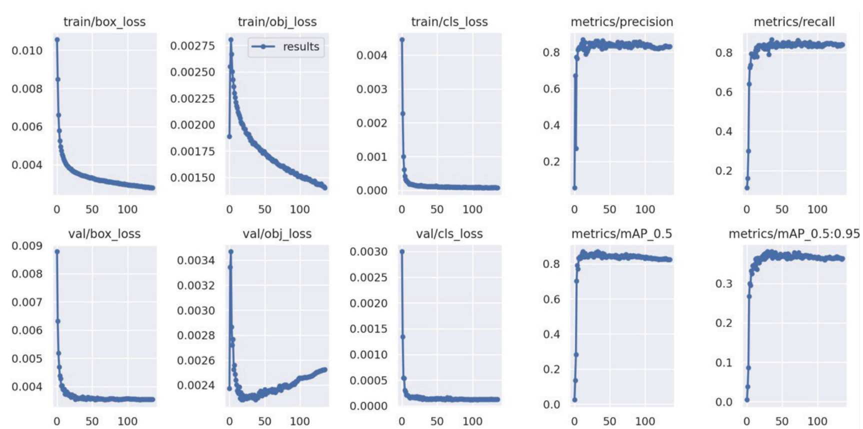


**Figure 11. SSD Training and Validation Metrics**

The selected model has a precision of 0.786 and recall of 0.846 with a mAP of 0.745. mAP_0.5 refers to the model's ability to detect and classify objects with at least a 50% overlap in the object detection region vs. the ground truth label. mAP_0.5:0.95 is the average of the mAP scores between 50% and 95% overlap with steps of 5%. Table 5 shows results from the validation process.

**TABLE 5. Model Validation Results**

| Class | Images | Labels | P | R | mAP@.5 | mAP@.5:.95 |
|---|---|---|---|---|---|---|
| all | 14037 | 2901 | 0.652 | 0.797 | 0.745 | 0.337 |
| leak | 14037 | 852 | 0.813 | 0.468 | 0.687 | 0.354 |
| gladhand | 14037 | 2049 | 0.835 | 0.780 | 0.803 | 0.319 |

Figure 12 shows the confusion matrix over the selected classifier. This matrix is a heatmap of how the classifier is predicting based on the labels. The Y-axis is what the classifier said was in the image. The X-axis is the ground truth. A perfect classifier would have a diagonal line from top left to bottom right. In the case of this classifier, we can see that it does very well at identifying gladhands with little false negatives. With Air leaks it predicts correctly 65% of the time, there is some confusion when the air leaks are on top of gladhands and there are cases where some air leaks were missed entirely. This matrix also shows that all the reported false positives the model reported were for air leaks. The performance and metrics of the model could be improved over time with more training, testing and validation data.

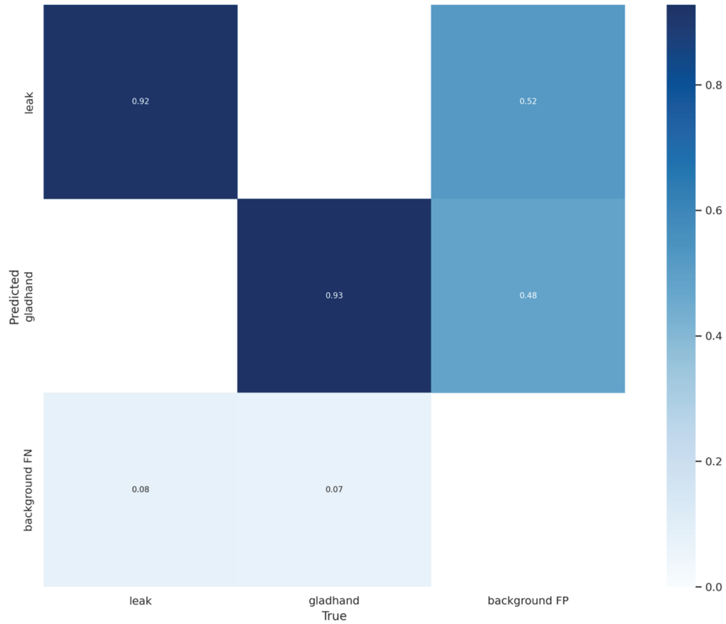


**Figure 12. SSD Confusion Matrix**

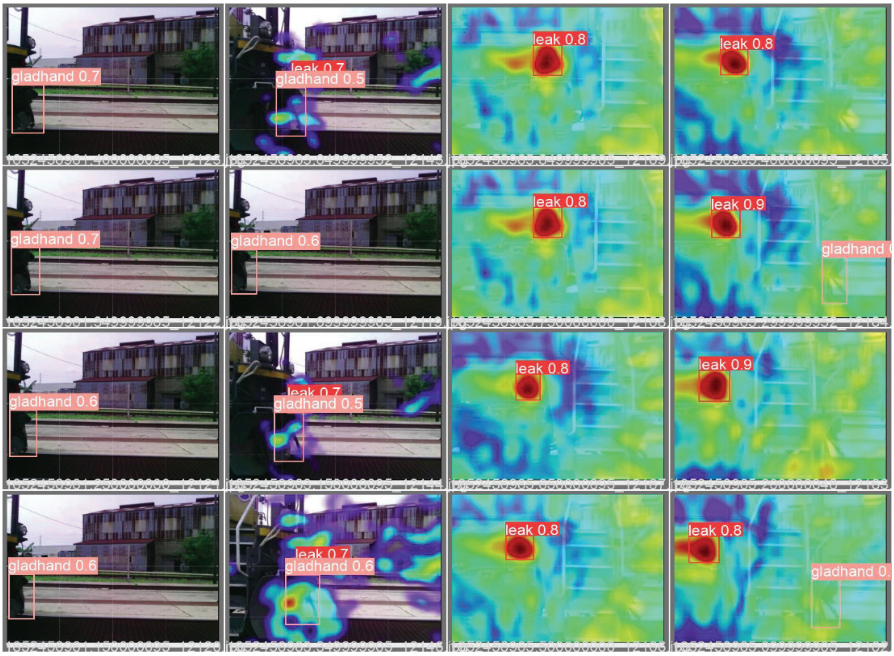


**Figure 13. SSD Validation Examples**

The metrics discussed above are pointwise metrics, meaning they are calculated and aggregated over every image in the validation dataset and do not consider the temporal and spatial relationships of an air leak as it progresses through the field of view of the camera (Figure 13). Using the object tracking techniques described above, we were able to reduce the false positives caused by track noise, bells, and blow offs. Additionally, the number of false negatives was reduced by allowing for infrequent missed detections while tracking a leak. Figure 14 depicts the tracking of an air leak. As the locomotive passes the ID value of the leak is tracked.


**Figure 14. Spatial and Temporal Tracking of an Air Leak**

The metrics below were calculated using the same validation set previously used for the pointwise metrics. The individual frames were first processed by the object detection model to create leak predictions for each image. These predictions and images were then used as inputs to the tracking algorithm to determine the presence of persistent leaks, the occurrence of a new locomotive, and the direction of the locomotive. Prior to running the tracking algorithm, 215 false positive leaks were predicted over the 1732 images, leading to a false positive per image rate of 12.4%. After applying the tracking algorithm, only 4 false leaks were persistently tracked over the validation set reducing this rate to 0.03%. Within the validation set, 8 unique air leaks were identified and used as the ground truth. The algorithm properly detected and tracked 7 of these leaks, with one leak being missed due to saturation of the acoustic image. The 4 false positives were found to be caused by persistent noise along the tracks which could potentially be filtered out by additional post-processing or higher confidence thresholds used within the tracking algorithm. The F1 score was additionally used to give a holistic evaluation of the full system's accuracy.

F_1 Score= t_p/(t_p+ 1/2(f_p+f_n)) : measures accuracy of predictions, i.e. the harmonic mean of precision and recall (8)

**TABLE 6. Air Leak Tracking Metrics**

| | |
|---|---|
| Precision | 0.786 |
| Recall | 0.846 |
| F1 Score | 0.815 |

As shown in Table 6, the accuracy of the system in identifying leaks in the reserved validation runs was 84.6%. This means that currently the system accurately detects roughly 11 out of every 13 leaks on a passing train. After the addition of the various models and tracking system discussed above, the proof-of-concept detection system was able to detect air leaks with very limited false positives and autonomously notify staff of the leak locations. With further development of the system in the field, autonomous wayside detection of rail air leaks can be refined and should provide railroads with significant opportunity at reducing fuel consumption, emissions, and improving employee and operational safety.

## 3.0 Lessons Learned

This proof-of-concept system was trained with a relatively small amount of data and the data contained only locomotives on a ~1/4 mile stretch of track. To improve the generalizability and reliability of the model more data is needed of longer trains with varied rail cars and equipment at various operation speeds. This cannot be achieved in a lab or shop setting and will require field testing on an active rail line.

Additionally, the inputs to the model were constrained by available access to the SV600 camera feeds. A notable improvement could be achieved with access to the SV600's raw camera stream and Audio mask. The current iteration relied on recording the screen from the sensors web dashboard and then cropping it and feeding it into the model, which prohibits any real-time capabilities. This means that all data had to first be saved, then post-processed. This likely wouldn't affect overall system capabilities as post processing can occur immediately after a train passed. In future development we will work with equipment manufacturers to implement those abilities. Additionally, separating the audio mask and video streams could eliminate the need for the visual spectrum camera as a separate sensor.

The SV600 sensors were accurate enough that it was determined that the thermal imaging camera was not needed for leak verification, even though it did tend to show some cooling effect at leak locations. It may still be necessary in a final product for identification in darkness, as the visual spectrum camera and the fluke image will not show clear images at night. Which camera is used has little impact on the machine vision system design.

Initial testing was limited in track speed of <10mph. Additional testing at a suitable location will be required to determine the upper limits of track speed at which accurate detection could occur. Detection is limited by sensor frame rate, distance from the track, and train speed. As speed increases or distance from the sensor to the train decreases, the number of frames that a suspected leak will be in the detection zone of the sensor decreases. If it is possible to increase the frame rate of the system, detection could occur at significantly higher track speeds.

There are additional complications with detecting leaks without direct line of sight and how to address those leaks. As you will note in Figure 15, the sensors are capable of detecting air leaks behind closed car body doors. Leaks in areas like compressor compartments, air brake compartments, etc. are all very common on locomotives. In these situations, neither the SV600 nor the visual spectrum camera will be able to identify the exact location of these leaks, which means component identification is impossible. It is therefore difficult to determine if the leak is a purposeful leak such as the J1 Relay releasing brake cylinder air or an actual leak at a mag valve or something similar on a single pass and may require multiple passes of the same piece of equipment to determine.

Similar situations will arise on rail cars with brake pipe piping that is not exposed. On rail cars we can assume that any leak is unintended (outside of brake release situations), so there is less concern with false positives in these situations. Work will need to go into determining how to approach this issue on locomotives though, as there are more complications in the compressed air system. While both leaks shown in Figure 15 were indeed unintended leaks, without further inspection this may be difficult to determine on a single pass by the sensors.

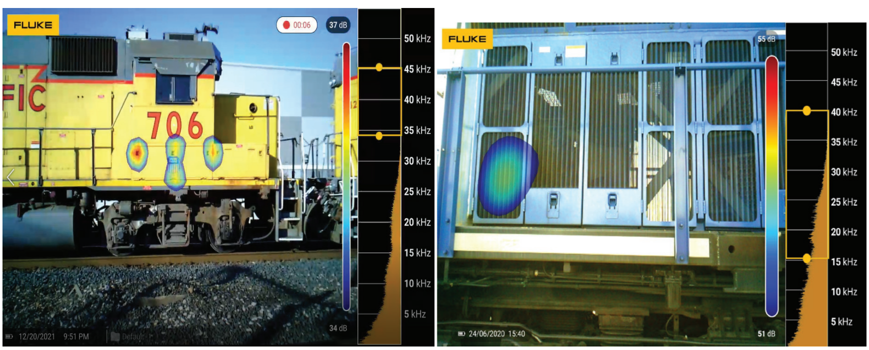


**FIGURE 15. Air Leaks in Air Brake Compartment Below Cab (left) and Rear Sander Mag Valve (right)**

## 4.0 Next Steps

The work completed in this project has demonstrated that autonomous detection of air leaks on moving trains is possible. Commercial implementation of this system will require further field development, as the air systems on trains are incredibly complicated with near infinite variations in train makeup. A high-level plan for final development and implementation of this design is outlined below.

1. Design and fabricate a field ready version of the system
   a. Railroads are not laboratories – Needs to be *everything* proof
   b. Final system will likely include two SV600 sensors per side of track at various heights and angles
   c. One high-definition visual spectrum camera per sensor (if necessary)
   d. AEI tag reader implemented for equipment identification
   e. Work with Fluke and Sorama to develop software to ease implementation of sensors into the system

2. Deploy prototype system on active rail line
   a. Preference would be a captive fleet
   b. Work with maintenance personnel on the ground to verify findings and use that information to train system

3. Data Collection
   a. Machine Learning systems require significant input data
   b. Length of time required is dependent on traffic. More trains = less time.

4. Prototype refinement
   a. The field trial will allow for improvements on both the system hardware and software designs
   b. System refinement will occur concurrently with the data collection

5. Revenue service implementation
   a. Once the technology is sufficiently matured through the field testing and system refinement, it will be available to railroads to implement

## 5.0 Conclusions

The proof-of-concept development of a wayside autonomous air leak detection system has showed great promise. The system was successfully able to detect air leaks at various locations with varying air leak rates with limited false positives and should greatly reduce the burden on mechanical personnel in finding air leaks on equipment. With further development the system could be improved by integrating AEI tag readers and implementing a machine learning system that can identify not just air leaks, but the individual components that are leaking further reducing the burden on mechanical personnel. These refinements will require significant data collection. This comprehensive data collection is planned in the next phase of this development effort.

As railroads strive to reduce their greenhouse gas emissions to meet their SBTi targets, improving overall vehicle efficiency through NTSFC reduction and AESS improvement is crucial. This system, if implemented correctly, could make significant improvements to both. While the system will significantly reduce the time spent locating air leaks, it cannot fix the leaks autonomously. As with many projects related to locomotive fuel consumption, it will initially require significant time and labor from mechanical department personnel to properly address air leaks. How that is accomplished will be the decision of the individual railroad, but support of mechanical department personnel will be required.

This technology will also reduce the number of times employees must go on, under, or between rolling stock which will in turn reduce the risk of injury to mechanical employees. Additionally, knowing where the leaks are on equipment can allow for repairs to occur in shop environments during periodic maintenance if desired, reducing the need for field repairs further reducing potential injury risk.

It is expected that, as the existing air leaks are addressed and fixed over time, the time necessary to maintain the fleet will gradually reduce. In time, properly addressing air leaks may even reduce overall mechanical labor burden as components such as air compressors, brake valves, air dryers, and starters should require less maintenance and need to be changed out less often.

As covered in detail above, even with limited data from a machine learning perspective, the system was able to positively identify air leaks with 84.6% accuracy and has a false positive rate of 0.03%. With these results we believe the proof-of-concept to be a success and believe that the system has the ability to greatly help railroads in their quest to improve employee safety, reduce emissions, and reduce fuel consumption.

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1. Hedrick, J. "AAR RP-589 Locomotive Air Compressor Load," LMOA – Proceedings of the 82nd Annual Meeting, pp. 186-200 (September 2020)

2. Brunson, J. "A Review of Compressed Air Systems" LMOA – Proceedings of the 80$^{th}$ Annual Meeting (2018)

3. 49 C.F.R. §232

4. Association of American Railroads "Railroad Facts 2019 Edition" Policy and Economics Department, Association of American Railroads (October 2019)

# Report on the Committee on Fuel, Lubricants and Environmental

THURSDAY, OCTOBER 13, 2022

8:30 AM

*Chair*

**Jerainne Heywood**

Senior Fuels and Lubricants Engineeer

Wabtec Corporation, Fort Worth, TX

*Co-Chair*

**C. Miller**

Senior Director-Service Product Management

Wabtec Corporation, Chicago, IL

*Commitee Members*

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| .A. Vanatta | Chief Engineer | Long Island Railroad | Glenwood Landing, NY |

PERSONAL HISTORY

## Jerainne Heywood

Senior Engineer
GE/Wabtec, Fort Worth, TX

Jerainne is a Senior Engineer at Wabtec Corporation, where she leads lubricants and fuels development utilized in Wabtec's various medium-speed diesel engine platforms and motorized gear wheels. She works closely with a global team of design engineers, service managers, product managers, fuel and lubricant suppliers to develop suitable engine products, resolve various fluid related issues and provide fuel and lubricant-related support.

Jerainne was born and raised in Kingston, Jamaica and migrated to the United States after completing her high school studies to pursue her passion in science. She received her B.S. in Chemistry from Morgan State University and her Ph.D. in Physical Chemistry from the University of Southern California. Her graduate work focused on characterizing and analyzing novel, macrocyclic polymers that have future applications in molecular-based solar cells. Subsequently, she completed her postdoctoral research at the National Institute of Standards and Technology (NIST), where she worked to develop a standardized method to evaluate the suitability of saccharide-based host materials to stabilize protein-based pharmaceuticals and therapeutics at room temperature.

In addition to serving as the Chair for the Fuels, Lubricant and Environment Committee, Jerainne also represents Wabtec on the American Society for Testing and Materials' (ASTM's) D02 and D03 committees, the Association of American Railroads (AAR) locomotive committee, the National Lubricating Grease Institute (NLGI) and the Society of Tribologists and Lubrication Engineers (STLE), where she serves as secretary for the North Texas Chapter.

Jerainne is also enthusiastically involved in serving to groom the next generation of scientists and engineers by actively participating in several student-based activities. She has served as program and application reviewer and judge for various student-based conferences, technical presentations and award programs. She also vigorously pursues her passion to influence young budding scientists by providing mentorship for students in K-12, undergraduate and graduate level programs. Jerainne currently sits on the External Advisory board for the Materials Science and Chemical Engineering department at Stony Brook University.

Jerainne currently lives in the Dallas Fort Worth Metropolitan with her husband and two daughters. She loves arts and crafts, is an avid gardener and home chef. In her spare time, Jerainne enjoys exploring the globe with her family, making hand-crafted jewelry, fruit and vegetable gardening and creating unique vegetarian dishes in her kitchen.

**THE FUEL, LUBRICANTS AND ENVIRONMENTAL COMMITTEE WOULD LIKE TO EXPRESS THEIR SINCERE APPRECIATION TO SOUTHWEST RESEARCH INSTITUTE FOR HOSTING THEIR 2022 COMMITTEE MEETING AT THEIR FACILITY IN SAN ANTONIO, TEXAS.**

**SPECIAL THANKS AND GRATITUDE TO COMMITTEE MEMBER STEVE FRITZ FOR BEING SUCH A GRACIOUS HOST AND FOR PROVIDING A TOUR OF THEIR CAMPUS.**

# Renewable Fuels Inter-Compatibility

*Prepared by:*
*Randy Garver, Innospec Fuel Specialties, USA*
*Brett Amen, Union Pacific, USA*
*Jerainne Heywood, Wabtec, USA*

Over the last few years, there have been strong initiatives across many industries to reduce GHG emissions and carbon footprint. Since the implementation of the Renewable Fuel Standard (RFS) in the United States in 2005, many fleets and large fuel consumers have increased their focus on renewable fuel alternatives. The intent of this paper is to inform readers of potential benefits and challenges associated with renewable fuel blends which would consist of a combination of ULSD, biodiesel, and renewable diesel (HDFD).

Fatty acid methyl esters (FAME), also known as biodiesel, became commercially available in 1991 in Kansas City, MO. Several states have implemented incentive programs that complemented the RFS, which greatly increased the rate of adoption of biodiesel blends and the concentration of the biodiesel in finished fuels. There is a strong awareness of the handling and physical properties associated with biodiesels and their associated feedstocks. Figure 1 and table 1 provide an illustration in the variability of the biodiesel properties based on feedstocks.

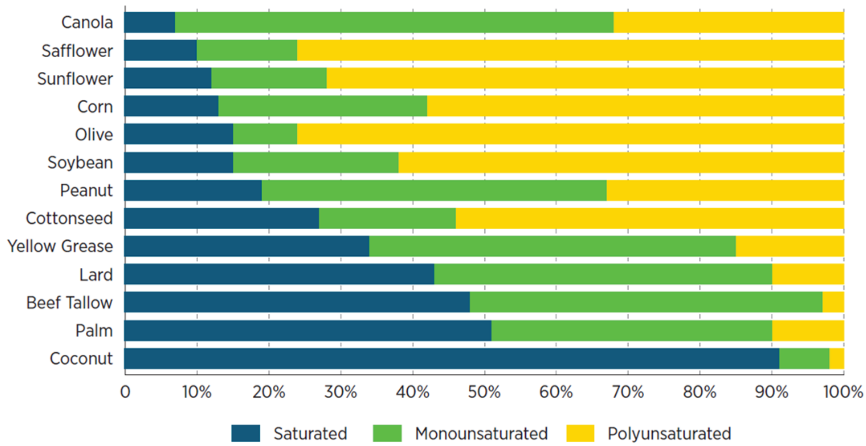



**Figure 1. Biodiesel Feedstocks and How they Affect Biodiesel Properties** [1]

**Table 1. Fuel Properties as a Function of Fuel Composition in Diesel Engines [1]**

| | Saturated | Monounsaturated | Polyunsaturated |
|---|---|---|---|
| Cetane Number | High | Medium | Low |
| Cloud Point | High | Medium | Low |
| Stability | High | Medium | Low |

Renewable diesel, also known as Hydrogen Derived Renewable Diesel (HDRD), became available to the global market in 2007. Several production facilities were built in the United States in 2011, which made this alternative fuel more available to the North American market. The financial incentives associated with the adoption of HDRD increased investment activity in HDRD production capacity in recent years. Figure 2 illustrates the current and planned HDRD production locations and financial incentive regions.

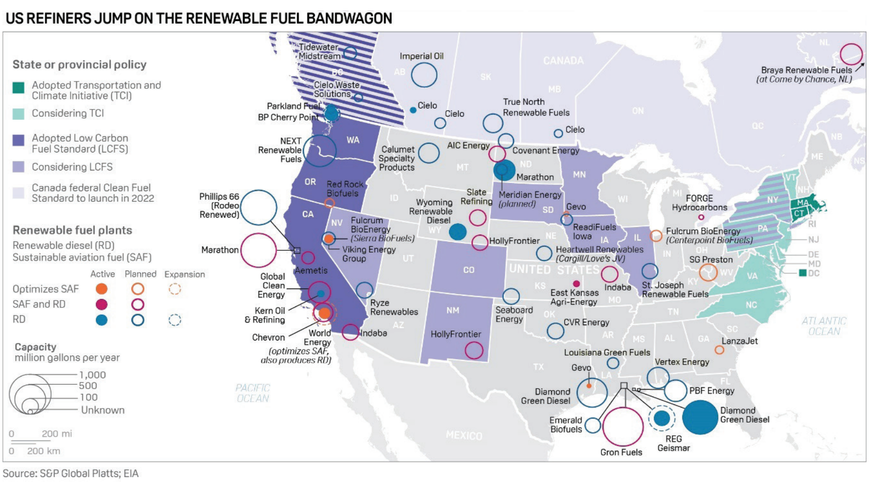



**Figure 2. Current and Planned HDRD Production [2]**

One of the limiting factors associated with renewable diesel and biodiesel has been feedstock availability. Soybeans are a popular feedstock and there is a high level of investment activity into soybean crushing plants to support the new and prospective production capacity. Figure 3 illustrates the investment in vegetable oil production capacity.

The composition and properties of renewable diesel can vary greatly, much of which is dependent on the chemical process utilized to produce the material. When evaluating renewable diesel products, the largest degree of variability commonly observed is the low temperature properties such as cloud point, cold filter plugging point, and pour point. Cloud points for HDRD can vary from +5.0°C (+41.0°F) to as low as -41.2°C (-42.2°F). Other common properties such as NACE corrosion, HFRR wear scar diameter, and electrical conductivity are similar to that of untreated ultra low sulfur diesel (ULSD).

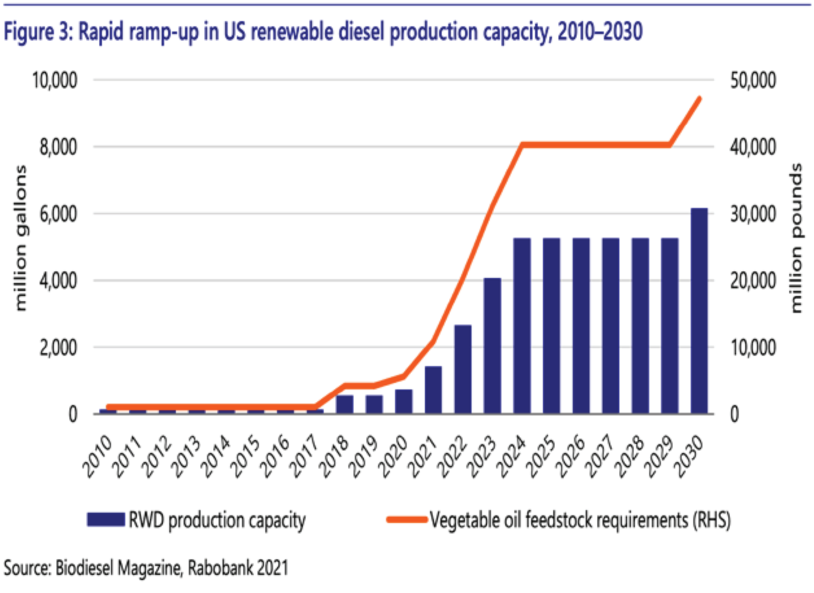



**Figure 3. Current Investment in Vegetable Oil Production Capacity [3]**

Additives traditionally utilized for improvement of lubricity, conductivity, stability, and corrosion in ULSD are also the primary technologies utilized in the treatment of renewable fuels. Given the unique composition of renewable fuels, affecting their low temperature characteristics is more difficult and work is currently in progress to identify the most effective additives for use in renewable diesel as well as blends made with renewable diesel.

Renewable diesels are different among several key properties when compared to petroleum derived ULSD. A comparison of several properties among renewable diesel and a typical ULSD is adapted from Smagala et al [4] are in table 2.

| Property | RD A | RD B | RD C | RD D | RD E | RD F | RD G | RD H | RD I | ULSD | ASTM D975 Limit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Density (g/mL), ASTM D4052 | 0.7751 | 0.7729 | 0.7850 | 0.7816 | 0.7770 | 0.7748 | 0.7784 | 0.7766 | 0.7950 | 0.8477 | -- |
| Net heat of combustion (MJ/L), ASTM D240 | 34.449 | 33.938 | 34.749 | 34.511 | 34.438 | 34.323 | 34.359 | 34.390 | 35.223 | 36.349 | -- |
| Cloud Point (°C), ASTM D2500 | -27 | -73 | -13 | -4 | -19 | -5 | -19 | -5 | 24 | -28 | Report |
| LTFT(°C), ASTM D4539 | -24 | -41 | -14 | -- | -16 | -5 | -- | -- | -- | -- | -- |
| CFPP(°C), ASTM D6371 | -25 | -48 | -15 | -- | -18 | -7 | -- | -8 | -- | -- | -- |
| T90 Distillation (°C), ASTM D86 | 287 | 246 | 315 | 292 | 292 | 338 | 289 | 293 | 305 | 300 | 282-338 |
| Flash Point(°C), ASTM D93 | 65 | 101 | 75 | 79 | 61 | 72 | 59 | >125 | >125 | 73 | 52 min. |

**Table 2. Selected Performance Properties for Renewable Diesel**

Renewable diesel properties can vary significantly in areas such as density and energy density. Cloud point, CFPP, flash point, and distillation can vary significantly as well. Please note, all the fuels in the table 2 meet ASTM D975 [5] specifications, except RD B which had a T90 below the lower specification limit.

As described by Smagala [2] the cold flow properties of renewable diesel samples are determined based upon the composition of n-alkanes, i-alkanes, and the degree of isomerization of the renewable diesel, where n-alkanes are straight chained saturated hydrocarbons and i-alkanes are branched saturated hydrocarbons. In general, renewable diesels which are comprised of a greater overall concentration of longer Cn (C14-C18) paraffins, and with a low degree of isomerization, will have a higher cloud point. Consequently, fuels with higher cloud points will have a higher cold filter plugging point (CFPP). Table 3 below provides a comparison of the n-paraffin, i-paraffin, and total paraffin content of two renewable diesels (Fuel I and Fuel E) described by Smagala and one ULSD analyzed by Innospec.

| | Fuel I | Fuel E | ULSD (2002-02185) | Fuel I | Fuel E | ULSD (2002-02185) | Fuel I | Fuel E | ULSD (2002-02185) |
|---|---|---|---|---|---|---|---|---|---|
| Carbon # | n-paraffin | | | iso-paraffin | | | total paraffin | | |
| <8 | 0.0 | 0.2 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.4 | 0.0 |
| 8 | 0.0 | 0.4 | 0.1 | 0.0 | 0.8 | 0.1 | 0.0 | 1.2 | 0.2 |
| 9 | 0.0 | 0.6 | 0.5 | 0.0 | 1.3 | 0.5 | 0.0 | 1.9 | 0.9 |
| 10 | 0.1 | 0.8 | 0.7 | 0.0 | 2.1 | 1.1 | 0.1 | 2.9 | 1.8 |
| 11 | 0.0 | 0.8 | 1.0 | 0.0 | 2.8 | 1.5 | 0.0 | 3.6 | 2.5 |
| 12 | 0.1 | 0.8 | 1.0 | 0.0 | 2.8 | 1.6 | 0.1 | 3.6 | 2.5 |
| 13 | 0.4 | 0.6 | 1.0 | 0.0 | 2.7 | 1.6 | 0.4 | 3.3 | 2.6 |
| 14 | 2.9 | 0.9 | 1.0 | 0.1 | 3.0 | 1.5 | 3.0 | 3.9 | 2.5 |
| 15 | 3.1 | 2.1 | 1.5 | 0.3 | 5.3 | 1.7 | 3.4 | 7.4 | 3.1 |
| 16 | 22.3 | 6.1 | 1.8 | 0.3 | 12.4 | 1.8 | 22.6 | 18.5 | 3.6 |
| 17 | 9.0 | 3.7 | 1.8 | 0.9 | 16.9 | 2.3 | 9.9 | 20.6 | 4.1 |
| 18 | 55.8 | 7.0 | 1.6 | 1.0 | 21.5 | 2.4 | 56.8 | 28.5 | 4.0 |
| 19 | 0.7 | 0.1 | 1.1 | 0.4 | 0.6 | 2.1 | 1.1 | 0.7 | 3.2 |
| 20 | 0.6 | 0.1 | 0.7 | 0.1 | 0.4 | 1.1 | 0.7 | 0.5 | 1.8 |
| 21 | 0.3 | 0.0 | 0.5 | 0.3 | 0.1 | 0.7 | 0.6 | 0.1 | 1.2 |
| 22 | 0.1 | 0.0 | 0.3 | 0.0 | 0.1 | 0.5 | 0.1 | 0.1 | 0.8 |
| 23 | 0.0 | 0.0 | 0.2 | 0.0 | 0.1 | 0.3 | 0.0 | 0.1 | 0.5 |
| 24 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.4 |
| 25 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.2 |
| >25 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 |
| **Total** | **95.4** | **24.2** | **14.9** | **3.4** | **73.1** | **21.2** | **98.8** | **97.3** | **36.1** |

**Table 3. Comparison of Weight Percent Paraffin Content of Two Samples of Renewable Diesel and a sample of ULSD [6]**

As can be seen from Figures 4 through 6 and Table 3, the composition of renewable diesels is primarily a distribution of n-paraffins and i-paraffins, while ULSD is comprised of only 14.9% n-paraffins and 21.2% i-paraffins. ULSD is comprised of a more complex and diverse range of compounds than renewable diesel.

The wide range of cold flow properties should be considered when sourcing HDRD and biodiesel for renewable diesel blends. Fuel components and/or the fuel blends could require heated storage tank capabilities. Cold Flow Improver additives should be applied at 10 degrees Fahrenheit above the cloud point of the fuel, which could be a challenge depending on the fuels supply chain and the fuel selected. Additionally, due to the high level of variability, Cold Flow Improver additive treatment efficacy should be considered for blends on a case-by-case basis.

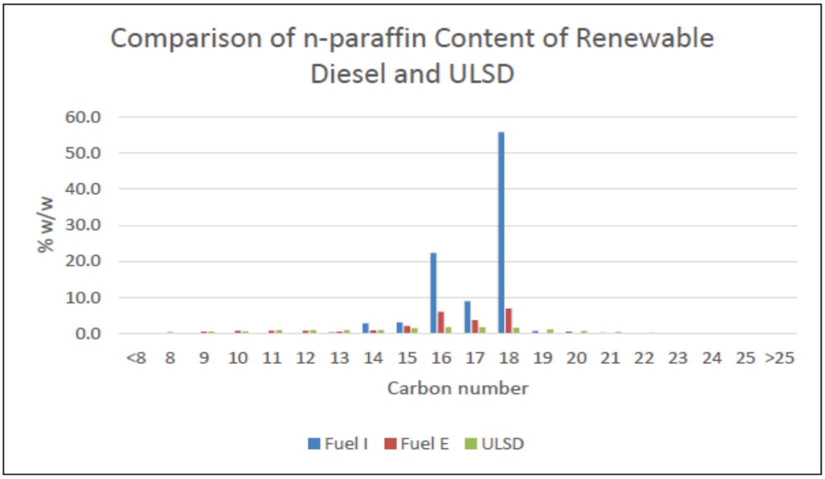



**Figure 4: n-paraffin Content for HDRD and ULSD [6]**

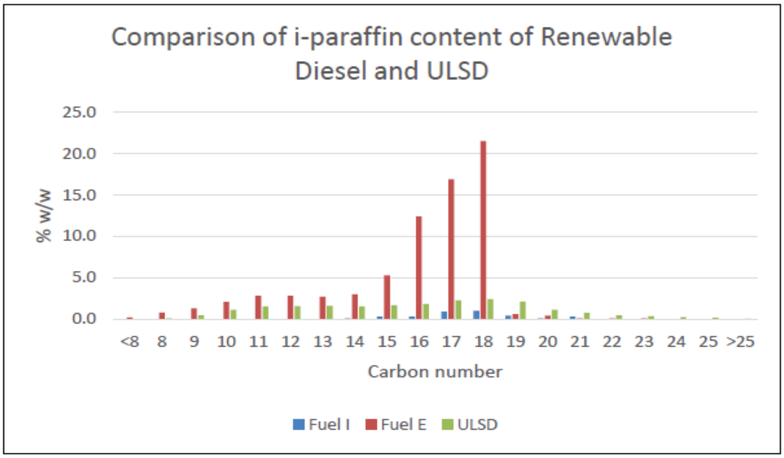



**Figure 5: i-paraffin Content for HDRD and ULSD [6]**

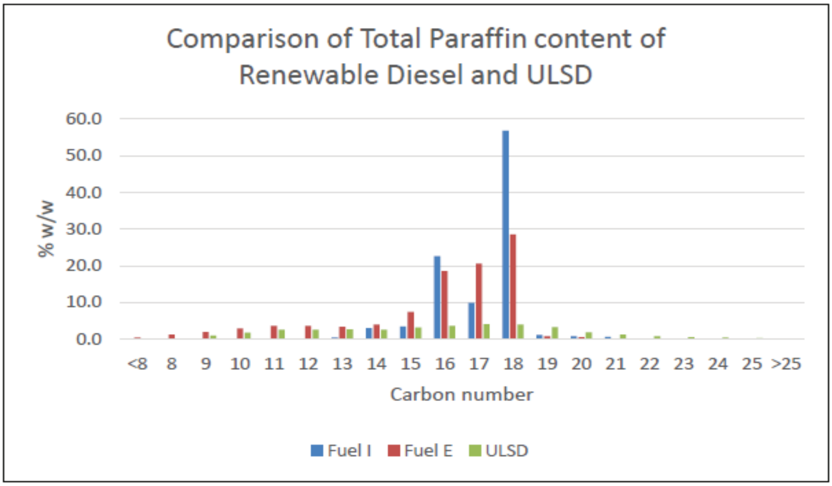



**Figure 6: Total Paraffin Content for HDRD and ULSD [6]**

## Results of Testing Renewable Diesel and Response to Additization

Innospec evaluated the base cold flow properties, lubricating properties, conductivity, and corrosivity of three samples of renewable diesel, with varying regional availability and feedstock. The results for each of the fuels are presented below in table 4.

| Fuel | Cloud Point (°C), ASTM D5773 | Pour Point (°C), ASTM D5949 | HFRR WSD (µm), ASTM D6079 | Conductivity (pS/m), ASTM D2624 | NACE Rating, TM 0172 | Corrosion (%), TM 0172 |
|---|---|---|---|---|---|---|
| 2008-06764 | -41.2 | -54 | 662 | 2 | C | 30 |
| 2110-06937 | -34.7 | -66 | 581 | 12 | D | 60 |
| 2106-05056 | 5.4 | 6 | 579 | 0 | D | 60 |

**Table 4: Base Properties of Several Samples of Renewable Diesel [6]**

The same samples of renewable diesel were also tested for their response to additives for lubricity, conductivity, and corrosion. Results for each of the fuels can be found in tables 5 through 7.

| Fuel | Treatment | Treat rate ppm v/v | HFRR WSD (μm), ASTM D6079 |
|---|---|---|---|
| 2008-06764 | Untreated | None | 662 |
| | OLI-9070.x | 200 | 632 |
| | | 225 | 410 |
| 2106-05056 | Untreated | None | 579 |
| | OLI-9103.x | 250 | 565 |
| | | 281 | 462 |
| | | 312 | 377 |
| 2110-06937 | Untreated | None | 581 |
| | OLI-9103.x | 200 | 592 |
| | | 225 | 548 |
| | | 250 | 447 |

**Table 5: Response of Several Renewable Diesel Samples to Lubricity Improver Additization [6]**

| **Fuel** | **Treatment** | **Treat rate** | **Conductivity (pS/m), ASTM D2624** |
|---|---|---|---|
| 2008-06764 | Untreated | None | 3 |
| | Stadis 425 ® | 0.212 ppm v/v | 53 |
| | | 0.424 ppm v/v | 108 |
| 2106-05056 | Untreated | None | 0 |
| | OLI-9103.x | 250 ppm v/v | 710 |
| | | 281 ppm v/v | 865 |
| | | 312 ppm v/v | 980 |
| 2110-06937 | Untreated | None | 12 |
| | OLI-9103.x | 200 ppm v/v | 562 |
| | | 225 ppm v/v | 615 |
| | | 250 ppm v/v | 720 |

**Table 6: Response of Several Renewable Diesel Samples to Static Dissipator Additization [6]**

| Fuel | Treatment | Treat rate | NACE Rating, TM 0172 | Corrosion, TM 0172 |
|---|---|---|---|---|
| 2008-06764 | Untreated | None | C | 30% |
| | DCI-4A | 5.4 ppm v/v | B++ | 25% |
| | | 10.8 ppm v/v | B++ | <0.1% |
| 2106-05056 | Untreated | None | D | 60% |
| | DCI-6A | 6 ppm v/v | B++ | <0.1% |
| | | 12 ppm v/v | B++ | <0.1% |
| 2110-06937 | Untreated | None | C | 60% |
| | DCI-6A | 6 ppm v/v | A | 0% |
| | | 12 ppm v/v | B++ | <0.1% |

**Table 7: Response of Several Renewable Diesel Samples to Corrosion Inhibitor Additization [6]**

The base properties of HDRD for lubricity, conductivity, and corrosion are similar to that of untreated ULSD. Additionally, traditionally utilized fuel additives are effective in HDRD at improving each of these properties.

Among cold flow properties of cloud point and pour point, there is far more variability in the values measured both for cloud point and pour point. As described in the introduction, this wide variability in the cold flow properties of the fuels is primarily due to the degree of isomerization. In general, iso-alkanes have superior low temperature flow properties, compared to the analogous n-alkane.

Many of the North American railroads have expressed a strong interest in adopting renewable diesel blends to help them reach their GHG reduction initiatives and commitments. Many of these blends could contain a combination of petroleum diesel, biodiesel, and renewable diesels. Figure 7 and table 8 illustrate prospective blends of interest for North American railroads.

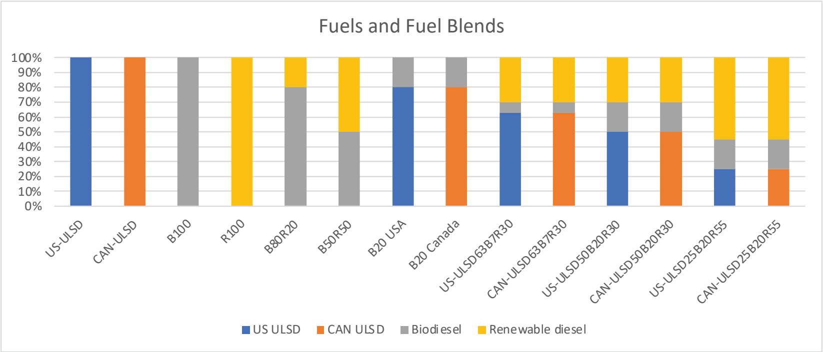



**Figure 7. Fuel Blends of Interest for North American Railroads**

| Fuel Desciption | US ULSD | CAN ULSD | Biodiesel | Renewable diesel |
|---|---|---|---|---|
| US-ULSD | 100% | 0% | 0% | 0% |
| CAN-ULSD | 0% | 100% | 0% | 0% |
| B100 | 0% | 0% | 100% | 0% |
| R100 | 0% | 0% | 0% | 100% |
| B80R20 | 0% | 0% | 80% | 20% |
| B50R50 | 0% | 0% | 50% | 50% |
| B20 USA | 80% | 0% | 20% | 0% |
| B20 Canada | 0% | 80% | 20% | 0% |
| US-ULSD63B7R30 | 63% | 0% | 7% | 30% |
| CAN-ULSD63B7R30 | 0% | 63% | 7% | 30% |
| US-ULSD50B20R30 | 50% | 0% | 20% | 30% |
| CAN-ULSD50B20R30 | 0% | 50% | 20% | 30% |
| US-ULSD25B20R55 | 25% | 0% | 20% | 55% |
| CAN-ULSD25B20R55 | 0% | 25% | 20% | 55% |

**Table 8. Fuel Blends of Interest for North American Railroads**

The fuels and fuel blends in the table 8 were evaluated for a number of properties to determine potential impacts on operability. Please note, this study was completed using the following fuels:

1> Midwest fungible ULSD from the pipeline, winter grade
2> Alberta winter grade Canadian Diesel
3> Biodiesel – Supplied by REG
4> Renewable Diesel, supplied by REG from the Geismar, LA production facility.

The cetane number is a measure of the ignition delay time in an internal combustion engine. A higher cetane number denotes faster auto ignition. Figure 8 illustrates the variation in the derived cetane numbers, which is measured in a constant volume combustion chamber and functionally equivalent to cetane number, based on different fuels and fuel blends. Neat renewable diesel, R100, shows the highest derived cetane number value. Figure 8 shows the derived cetane numbers for the biofuel and biofuel blends of interest.

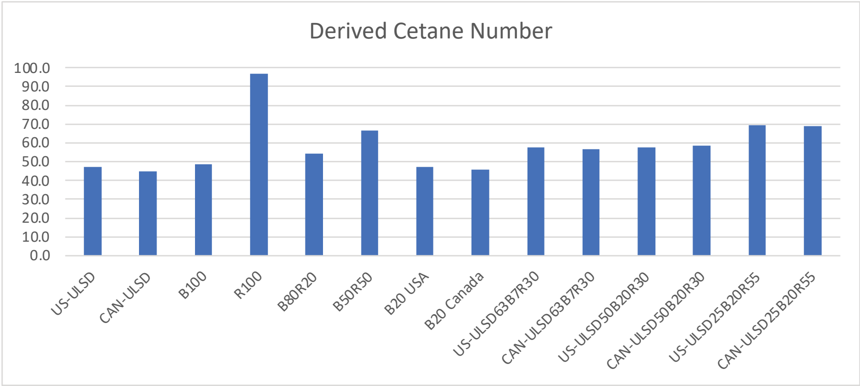
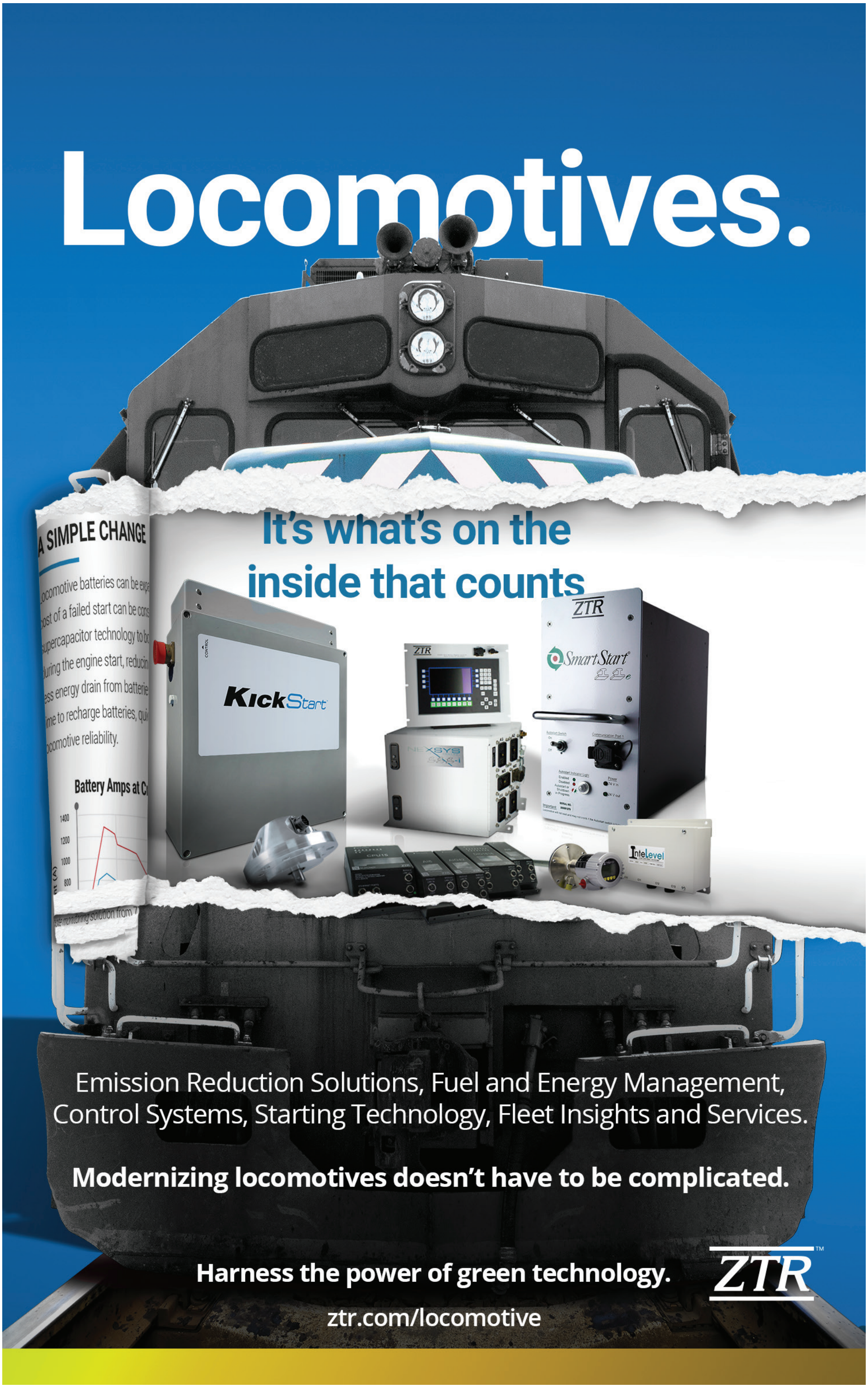



**Figure 8. Derived Cetane Number fo Various Fuel Blends**

Figure 9 shows the ignition and combustion delays from the fuels and fuel blends. The data is also summarized in table 9.


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

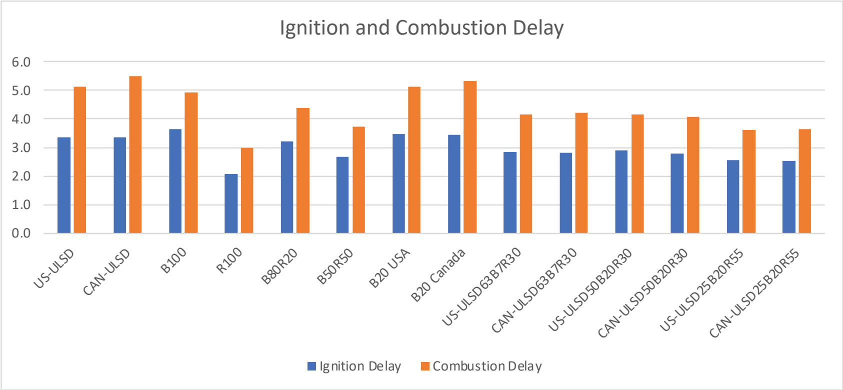



**Figure 9. Ignition Delay and Combustion Delay of Various Fuel Blends**

| Fuel Desciption | Derived Cetane Number | Ignition Delay | Combustion Delay |
|---|---|---|---|
| US-ULSD | 47.1 | 3.4 | 5.1 |
| CAN-ULSD | 44.7 | 3.4 | 5.5 |
| B100 | 48.8 | 3.6 | 4.9 |
| R100 | 96.8 | 2.1 | 3.0 |
| B80R20 | 54.4 | 3.2 | 4.4 |
| B50R50 | 66.3 | 2.7 | 3.7 |
| B20 USA | 47.2 | 3.5 | 5.1 |
| B20 Canada | 45.8 | 3.4 | 5.3 |
| US-ULSD63B7R30 | 57.7 | 2.9 | 4.1 |
| CAN-ULSD63B7R30 | 56.6 | 2.8 | 4.2 |
| US-ULSD50B20R30 | 57.7 | 2.9 | 4.1 |
| CAN-ULSD50B20R30 | 58.8 | 2.8 | 4.1 |
| US-ULSD25B20R55 | 69.4 | 2.6 | 3.6 |
| CAN-ULSD25B20R55 | 68.7 | 2.5 | 3.6 |

**Table 9. Ignition & Combustion Delay of Fuel Blends**

Figure 10 and table 10 provide the cloud points, cold filter plugging points, and pour points of the fuels and fuel blends. As discussed previously, the handling and operability of biodiesel, renewable diesel, and blends containing these products can be heavily impacted as temperatures decrease. Many of the prospective blends and components could require heated storage to be viable fuels for railroads. Fuel additive chemistries can positively impact the cold weather properties of the blend, but their efficacy is generally fuel specific.

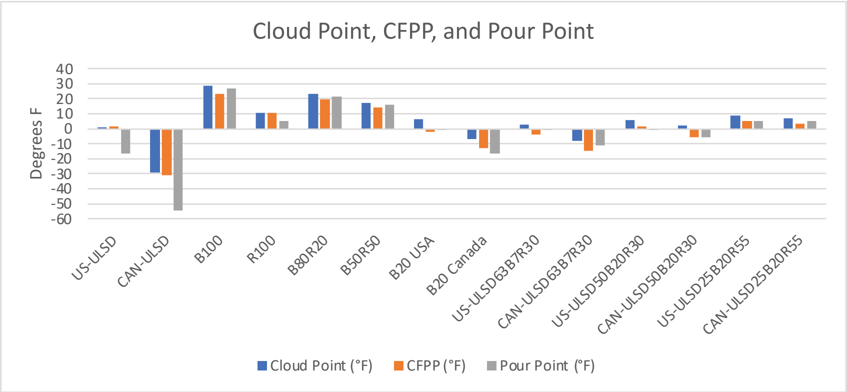



**Figure 10. Cloud Points, Cold Filter Plugging Points, and Pour Points of Fuel Blends**

| Fuel Desciption | Cloud Point (°F) | CFPP (°F) | Pour Point (°F) |
|---|---|---|---|
| US-ULSD | 1.2 | 1.4 | -16.6 |
| CAN-ULSD | -29.0 | -31.0 | -54.4 |
| B100 | 28.9 | 23.0 | 26.6 |
| R100 | 10.4 | 10.4 | 5.0 |
| B80R20 | 23.4 | 19.4 | 21.2 |
| B50R50 | 17.1 | 14.0 | 15.8 |
| B20 USA | 6.3 | -2.2 | -0.4 |
| B20 Canada | -7.1 | -13.0 | -16.6 |
| US-ULSD63B7R30 | 2.8 | -4.0 | -0.4 |
| CAN-ULSD63B7R30 | -7.8 | -14.8 | -11.2 |
| US-ULSD50B20R30 | 5.9 | 1.4 | -0.4 |
| CAN-ULSD50B20R30 | 1.9 | -5.8 | -5.8 |
| US-ULSD25B20R55 | 9.0 | 5.0 | 5.0 |
| CAN-ULSD25B20R55 | 6.8 | 3.2 | 5.0 |

**Table 10. Cloud Points, Cold Filter Plugging Points, and Pour Points of Fuel Blends**

Figure 11 and table 11 summarize the filter blocking tendency (FBT) of the fuels and fuel blends. For the fuels tested as part of this study, the FBT results are within specification (<1.40). In general, the FBT results of a finish blend are typically a direct correlation to the FBT of the components. Drag reducing agents, insolubles, and contamination can negatively impact FBT. FBT results can be improved in many cases with the correct fuel additive solution.

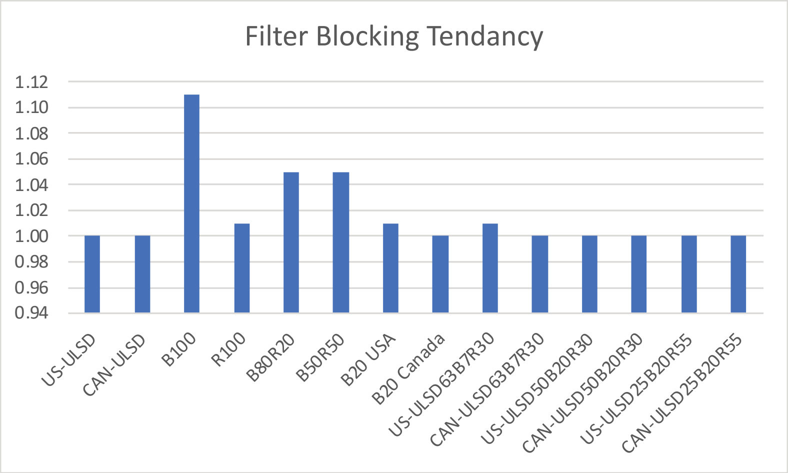



**Figure 11. Filter Blocking Tendancy of Various Fuels**

| Fuel Desciption | FBT |
|---|---|
| US-ULSD | 1.00 |
| CAN-ULSD | 1.00 |
| B100 | 1.11 |
| R100 | 1.01 |
| B80R20 | 1.05 |
| B50R50 | 1.05 |
| B20 USA | 1.01 |
| B20 Canada | 1.00 |
| US-ULSD63B7R30 | 1.01 |
| CAN-ULSD63B7R30 | 1.00 |
| US-ULSD50B20R30 | 1.00 |
| CAN-ULSD50B20R30 | 1.00 |
| US-ULSD25B20R55 | 1.00 |
| CAN-ULSD25B20R55 | 1.00 |

**Table 11. Filter Blocking Tendancy of Various Fuels**

Figure 12 and table 12 show the Rancimat results of the fuels and fuel blends. Rancimat is a good indicator of thermal and oxidative stability of biodiesel containing fuels. For best practices, most consumers target greater than 6 hours for a B100 and greater than 20 hours for any biodiesel blends. Figure 12 indicates that many of the blends are below the 20 hour Rancimat minimum. Rancimat results can be improved through the use of the correct additive solution.

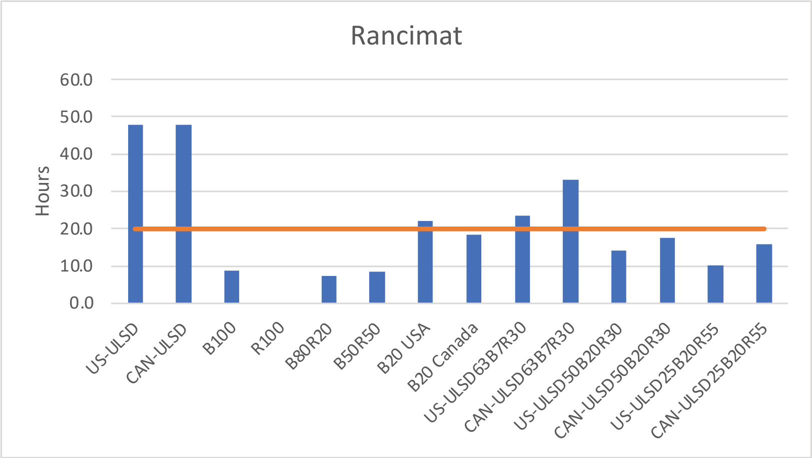



**Figure 12. Rancimat Results of Several Fuel Blends**

Figure 13 and table 12 summarize the PetroOxy results of the fuels and fuel blends. PetroOxy is a good indicator of oxidative stability of liquid fuels. For best practices, most consumers target greater than 60 minutes to ensure the fuel has sufficient reserve stability. Figure 13 indicates that many of the blends are below the 60 minute minimum. PetroOxy results can be positively impacted by the correct additive solution.

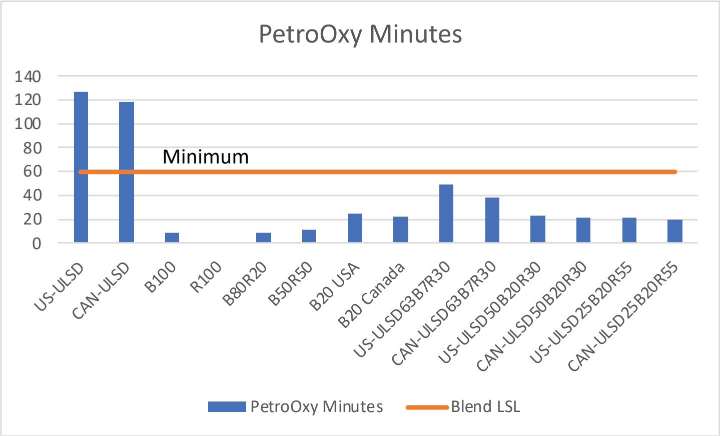



**Figure 13. PetroOxy Minutes of Several Fuel Blends**

| **Fuel Desciption** | Racimat Hours | PetroOxy Minutes |
|---|---|---|
| US-ULSD | 48.0 | 127.0 |
| CAN-ULSD | 48.0 | 118.0 |
| B100 | 8.7 | 9.0 |
| R100 | | |
| B80R20 | 7.5 | 9.0 |
| B50R50 | 8.4 | 11.0 |
| B20 USA | 22.0 | 25.0 |
| B20 Canada | 18.4 | 22.0 |
| US-ULSD63B7R30 | 23.4 | 49.0 |
| CAN-ULSD63B7R30 | 33.2 | 38.0 |
| US-ULSD50B20R30 | 14.1 | 23.0 |
| CAN-ULSD50B20R30 | 17.5 | 21.0 |
| US-ULSD25B20R55 | 10.2 | 21.0 |
| CAN-ULSD25B20R55 | 16.0 | 20.0 |

**Table 12. Rancimat and PetroOxy Results for Several Fuel Blends**

Figure 14 and table 13 summarize lubricity results of the fuels and fuel blends. Traditional lubricity improvers can be utilized in these fuel blends if required. Please note, several blends were not tested due to the high concentrations of biodiesel, which is known to reduce the HFRR results below the upper specification limits.

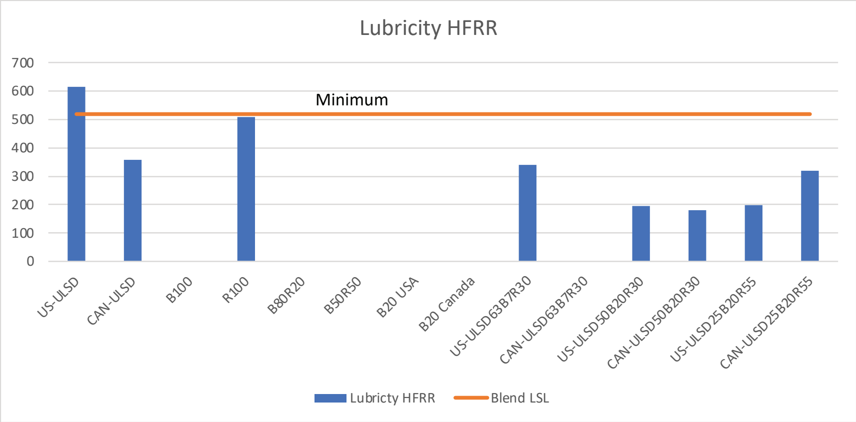



**Figure 14. Lubricity Results for Several Fuel Blends**

| **Fuel Desciption** | Lubricty HFRR |
|---|---|
| US-ULSD | 615 |
| CAN-ULSD | 357 |
| B100 | <460 |
| R100 | 508 |
| B80R20 | <460 |
| B50R50 | <460 |
| B20 USA | <460 |
| B20 Canada | <460 |
| US-ULSD63B7R30 | 340 |
| CAN-ULSD63B7R30 | <460 |
| US-ULSD50B20R30 | 194 |
| CAN-ULSD50B20R30 | 180 |
| US-ULSD25B20R55 | 197 |
| CAN-ULSD25B20R55 | 318 |

**Table 13. Lubricity Results for Several Fuel Blends**

Figure 15 and table 14 summarize the long term storage stability of the fuels and fuel blends. This test was completed at 100F for 4 weeks. Please note the significant increase in insolubles in the two fuels on the right. The Canadian Diesel 50:B20:R30 destabilized while the USA ULSD50:B20:R30 remained stable. Additionally, the B20 containing USA ULSD remained highly stable, while the ULSD25:B20:R55 destabilized, causing significant insoluble precipitants. The cause of the insolubles precipitation phenomenon can be explained through chemistry, and can be mitigated with the correct additive solution or sourcing/ blending practices.

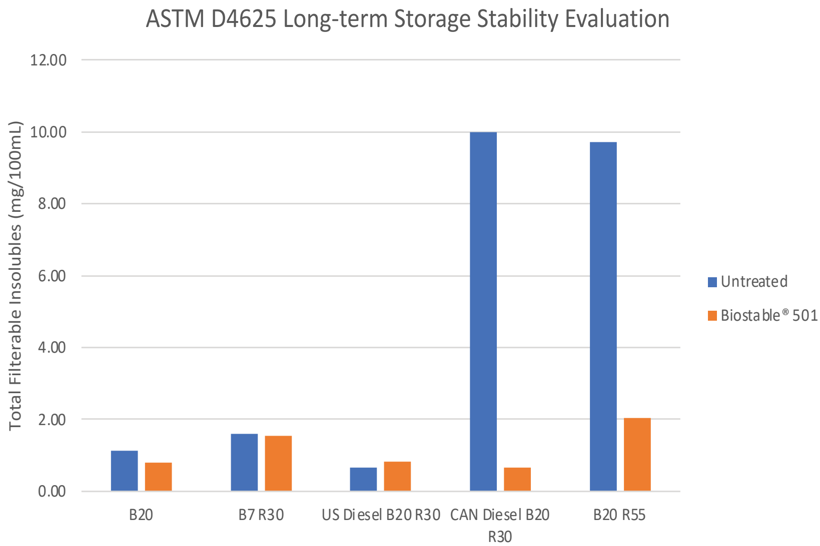



**Figure 15: Total Filterable Insolubles of Several Fuel Blends**

| Fuel | Treatment ppm v/v | Total Filterable insolubles (minus blank) (mg/100mL) |
|---|---|---|
| ULSD | 0 | 0.63 |
| B20 | 0 | 1.13 |
| B20 | 1000 | 0.80 |
| B7 R30 | 0 | 1.60 |
| B7 R30 | 1000 | 1.55 |
| US Diesel B20 R30 | 0 | 0.65 |
| US Diesel B20 R30 | 1000 | 0.83 |
| CAN Diesel B20 R30 | 0 | 10.00 |
| CAN Diesel B20 R30 | 1000 | 0.65 |
| B20 R55 | 0 | 9.73 |
| B20 R55 | 1000 | 2.03 |

**Table 14: Total Filterable Insolubles of Several Fuel Blends**

## Conclusions:

1> Biodiesel, while well established in the United States fuels market, has been limited to <5% in a finished fuel for the railroad industry. The adoption of biodiesel at higher concentrations could potentially impact operability and reliability. Strategic sourcing and quality control will be paramount in minimizing the impact on railroads.

2> The investment in renewable diesel production assets is currently very strong. Renewable diesel's cold weather handling and operability is dependent on the process capabilities of the producers. Cloud points for HDRD can vary from +5.0°C (+41.0°F) to as low as -41.2°C (-42.2°F). Strategic sourcing and quality control will be paramount in minimizing the impact on railroads.

3> Traditional fuel additive chemistries are highly effective for managing stability, lubricity, conductivity, and corrosion of renewable fuels. Cold Flow Improver treatment efficacy and dosages could be impacted by utilizing high concentrations of HDRD. Please note, HDRD typically has 3-4 times more wax than a traditional ULSD, and n-paraffins have much higher crystallization temperatures than paraffins found in USLD.

4> Many of the fuel blends tested had cetane numbers that exceeded 52. Special consideration may be required to efficiently consume these renewable blends in equipment with mechanical fuel injection.

5> The establishment of best practices to reliably store and transfer these fuel components and blends may be required. Heated storage may be required based on physical properties of the fuels sourced.

6> The inter-compatibility of ULSD, HDRD, and biodiesel could have challenges. The precipitation of insoluble material can be managed with the correct operational or additive solution.

## References

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[5] ASTM D975-21 Standard Specification for Diesel Fuel.

[6] Innospec Renewable Diesel Technical Bulletin, I2V2


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# Biomass-based Fuels Long-Term Durability and Emissions Testing

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## Abstract

Biodiesel (Fatty Acid Methyl Ester - FAME) and renewable diesel (Hydrogenation-Derived Renewable Diesel -HDRD) are likely to be a necessary part of North American railroads decarbonization initiatives. However, little is known about the long-term durability, fuel efficiency, and exhaust emissions from blends of FAME and HDRD used in heavy-haul North American freight rail operations. This paper outlines a testing template to help the industry understand the potential impacts of future broad scale use of these fuels. Understanding and controlling for variations in fuel quality is also a part of the proposed testing template. Stationary locomotive testing (load box) must be designed to understand emissions, fuel consumption, and engine power changes, while long-term revenue-service durability testing must be designed to understand lube oil, fuel system, filter, and engine impacts, along with wayside fuel storage, filtration, and dispensing systems. FAME and HDRD will have a positive impact on railroad GHG emission reduction but will ultimately need long term durability testing to better understand the impact on operations.

## Introduction

Use of higher blends of biodiesel (FAME) and renewable diesel (HDRD) is becoming a likely pathway for North American Class I freight railroads to meet their greenhouse gas (GHG) emissions reduction targets as submitted to the Science Based Targets Initiative (SBTI). The existing fleet of diesel-electric locomotives were purchased with expectations to be in service for upward of 30 years. To reduce the carbon intensity of their operations, railroads will likely increase the use of biomass-based fuels to fill in the gap before alternative “zero carbon” propulsion such as Battery Electric Locomotives (BEL) or Hydrogen ($H_2$) Locomotives are commercially available and widely used.

Biodiesel and renewable diesel are considered low carbon because the plant sources of the feedstocks for making biodiesel—such as soybeans or palm oil—absorb carbon dioxide ($CO_2$) as they grow which partially offsets the $CO_2$ emitted during production and burning of the fuel. Used vegetable oils and animal fats also qualify as low carbon as they are considered waste products that would otherwise be discarded rather than reused for fuel.

Both biodiesel and renewable diesel do bring challenges in how they differ from petroleum-based diesel. Biodiesel is hygroscopic (absorbs water) and can increase NOx emissions. Both fuels often have higher cloud points that can limit cold weather usage. Renewable diesel has very little to no aromatics which can negatively impact elastomers which are used in seals and gaskets in the locomotive fuel system and wayside fueling equipment. High cetane in renewable diesel can impact combustion (a concern for legacy engines with relatively advanced fuel injection timing), as well as low lubricity that can reduce component life cycles. Both biodiesel and renewable diesel have lower energy density (less BTU/gallon), which can impact volumetric fuel consumption and locomotive range.

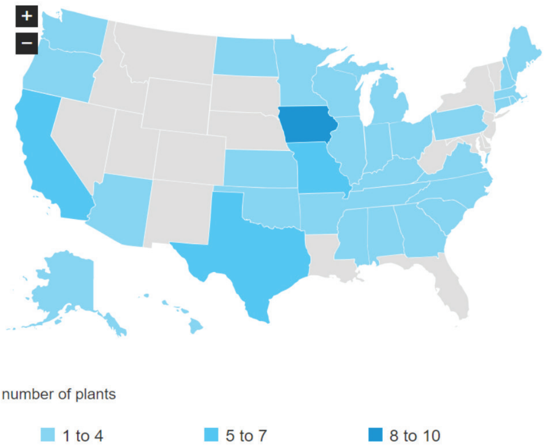
For the reasons listed above, a thorough test protocol for a comprehensive field study is needed to fully understand the many possible impacts of running these biomass-based fuels in locomotives. A 2012 LMOA paper authored by Dennis McAndrew titled "Locomotive Durability Test Protocol for Alternate Fuels and Biodiesel"[1] is recommended for context as it details the importance of each factor being tested in the system, which can be utilized as the foundation for any alternative fuel test. The purpose of this new paper, ten years later, is to define a specific template to use in determining locomotive durability, performance, fuel economy, and emissions while testing relatively high concentrations of biomass-based fuels.

## Scale and Scope of FAME and HDRD Blends

The availability and supply of biodiesel and renewable diesel fuels have been in flux as producers, regulators, and end users of diesel fuel work toward decarbonization. Biomass-based fuels tend to 'follow the corn' or soybeans – meaning availability and supply are generally good in the central Midwest and Great Plains areas but taper off toward the edges of the region. The west coast (California) areas typically enjoy moderate availability and supply of FAME fuel blends as well. On a state-by-state basis the Energy Information Administration (EIA) displays a list of approximately 75 FAME plants spread across 32 states, including Alaska and Hawaii (as of January 2021). These plants have a stated production capacity of approximately 2,409 million gallons per year. Figure 1 shows the distribution of biodiesel plant capacity.

1 McAndrew, D., "Locomotive Durability Test Protocol for Alternative Fuels and Biodiesel," Proceedings of the 74th Annual LMOA Meeting, pp. 131-145 (September 2012).

U.S. biodiesel plant count by state, 2021




**U.S. Biodiesel Plant Production Capacity as of January 1, 2021**

| PAD District | Number of Plants | Production Capacity (MMgal/year) | Production Capacity (Mb/d) |
|---|---|---|---|
| PADD 1 | 13 | 152 | 10 |
| PADD 2 | 37 | 1,483 | 97 |
| PADD 3 | 15 | 580 | 38 |
| PADD 4 | 0 | 0 | 0 |
| PADD 5 | 10 | 194 | 13 |
| **U.S. Total** | **75** | **2,409** | **157** |

**Biodiesel Production Capacity** is intended to measure estimated gallons of biodiesel that a plant is capable of producing over a period of one year (365 consecutive days) starting on the first day of each report month.

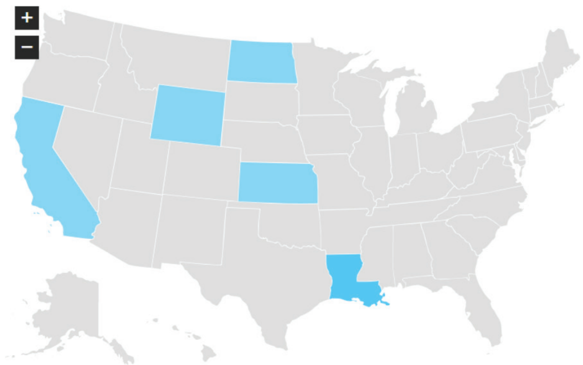
**Note:** Totals may not equal sum of components due to independent rounding.

**Source:** Form EIA-819, *Monthly Report of Biofuels, Fuels from Non-Biogenic Wastes, Fuel Oxygenates, Isooctane, and Isooctene.*

**Figure 1: Biodiesel Plant Count and Production Capacity**

Renewable diesel production displays a similar distribution shown in Figure 2 over the upper Midwest and Great Plains states, close to many sources of feedstock, but also includes Louisiana for its proximity to production refineries and the West Coast / California region for its end user proximity. On a state-by-state basis the Energy Information Administration (EIA) displays a list of only six renewable diesel plants spread across 5 states (as of January 2021). These plants have a stated production capacity of approximately 791 million gallons per year.

U.S. renewable diesel fuel and other biofuels plant count by state, 2021



number of plants

1 2

**U.S. Renewable Diesel Fuel and Other Biofuels Plant Production Capacity as of January 1, 2021**

| PAD District | Number of Plants | Production Capacity (MMgal/year) | Production Capacity (Mb/d) |
|---|---|---|---|
| PADD 1 | 0 | 0 | 0 |
| PADD 2 | 2 | 195 | 13 |
| PADD 3 | 2 | 437 | 29 |
| PADD 4 | 1 | 117 | 8 |
| PADD 5 | 1 | 42 | 3 |
| **U.S. Total** | **6** | **791** | **52** |

**Renewable Diesel Fuel and Other Biofuels Production Capacity** is intended to measure estimated gallons of renewable diesel fuel, renewable heating oil, renewable jet fuel, renewable naphtha and gasoline, and other biofuels (excluding fuel ethanol and biodiesel) and biointermediates that a plant is capable of producing over a period of one year (365 consecutive days) starting on the first day of each report month.

**Note:** Totals may not equal sum of components due to independent rounding.

**Source:** Form EIA-819, *Monthly Report of Biofuels, Fuels from Non-Biogenic Wastes, Fuel Oxygenates, Isooctane, and Isooctene.*

**Figure 2: Renewable Diesel Plant Count and Production Capacity**

Examination of the 2021 fuel production data in conjunction with the most recently available 2022 data (at the time of this publication) reveals that biodiesel production in the U.S. is holding consistently at 2,400 MMgal/yr with a slight drop in 2022 into the 2,200 MMgal/yr range. Conversely, domestic renewable diesel production has increased substantially from the previously mentioned 791 MMgal/yr at the start of 2021 to 1,468 MMgal/yr at the close of February 2022, an 85% increase in production over a 14-month period. Plotting the data on a graph and performing simple linear extrapolations suggests that in late 2023, if current trends continue, domestic renewable diesel production may equal, then surpass domestic biodiesel fuel production.[2]

**U.S. Biofuels operable production capacity**

million gallons per year

| Period | Fuel Ethanol | Biodiesel | Renewable Diesel and Other Biofuels[1] |
|---|---|---|---|
| **2021** | | | |
| January | 17,510 | 2,394 | 791 |
| February | 17,455 | 2,394 | 791 |
| March | 17,376 | 2,410 | 791 |
| April | 17,396 | 2,410 | 971 |
| May | 17,396 | 2,428 | 971 |
| June | 17,393 | 2,428 | 911 |
| July | 17,393 | 2,430 | 911 |
| August | 17,393 | 2,430 | 911 |
| September | 17,393 | 2,462 | 911 |
| October | 17,393 | 2,461 | 1,014 |
| November | 17,428 | 2,389 | 1,017 |
| December | 17,385 | 2,244 | 1,106 |
| **2022** | | | |
| January | 17,399 | 2,245 | 1,468 |
| February | 17,423 | 2,232 | 1,468 |

[1]Other biofuels include renewable heating oil, renewable jet fuel, renewable naphtha, renewable gasoline, and other biofuels and biointermediates.

Source: U.S. Energy Information Administration, Form EIA-819 "Monthly Report of Biofuels, Fuels from Non-Biogenic Wastes, Fuel Oxygenates, Isooctane, and Isooctene"

U.S. Energy Information Administration | Monthly Biofuels Capacity and Feedstocks Update

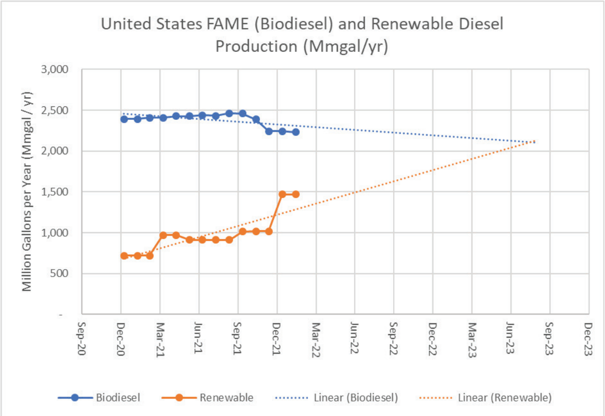



**Figure 3: Biodiesel and Renewable Diesel Production Capacity**

2 https://www.eia.gov/biofuels/renewable/capacity/

Overall, while geographic availability of both biodiesel and renewable diesel are similar, concentrated mainly in the center of the continental United States and along the west coast, the current quantity of renewable diesel available is approximately 1/3 that of biodiesel. It should be noted that nearly 800 million gallons per year of renewable diesel was produced at only six listed production plants in comparison to 2,400 million gallons of biodiesel produced at 75 plants. On average, a renewable diesel plant is producing on the order of 133 MMgal/yr of fuel and biodiesel plants are producing 32 MMgal/yr.

## Fuel Blends, Use, and Storage

There are several fuel specifications that are relevant to procuring the correct fuel for a biofuel test. The main fuel standard developing organization in North America is ASTM International (formerly the American Society of Testing and Materials). The standard for Ultra Low Sulfur Diesel (ULSD, also known as #2 diesel) is *ASTM D975 – Standard Specification for Diesel Fuel* currently allows up to 5% biodiesel. Table 1 highlights selected fuel properties and corresponding test methods applicable to ASTM D975 specified ULSD.

| | |
|---|---|
| D2500 | Cloud Point |
| D6304 | Water and Sediment |
| D524 | Ramsbottom Carbon Residue |
| D482 | Ash |
| D86 | Distillation |
| D445 | Viscosity |
| D5453 | Sulfur |
| D130 | Copper Corrosion |
| D613 | Cetane Number |
| D976 | Cetane Index |
| D5186 | Aromatics |
| D5001 | Lubricity |
| D2624 | Conductivity |

**Table 1. ASTM D975 Selected Fuel Properties and Corresponding Test Methods**

Neat biodiesel is defined in *ASTM D6751 – Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels*. *ASTM D7467 - Standard Specification for Diesel Fuel Oil, Biodiesel Blend (B6 to B20)* covers the range of biodiesel blended with petroleum diesel between 6 percent and 20 percent (by volume) of biodiesel. It's worth noting that there are no ASTM specifications for renewable diesel as it generally meets ASTM D975. However, there are significant differences between renewable diesel and conventional petroleum-based diesel fuel, mainly in aromatics, lubricity, and cetane. These differences are the reason for a conservative approach to introducing these fuels into the railroad fuel supply.

Before procuring fuel for a controlled railroad field test, it is important to consider how to both control and test the blend of fuels during testing. Controlling the blend may be as simple as specifying the required blend to the fuel supplier, or it may involve buying neat fuels and blending them before testing. Simultaneous inline blending (where both fuels are pumped together in the same line) is the recommended blending technique versus splash blending where biodiesel, renewable diesel, and petroleum-based fuels may not form a homogeneous blend due to slightly different densities. The fuel should be sampled regularly during fueling from both the source tank and the locomotive directly to ensure an accurate blend at all points of the test. The testing railroad and OEM should agree upon other parameters such as density, cloud point, flash point, aromatics, etc. that can affect the storage, handling, or performance of the fuel. Selected samples can also be sent to a specialty lab for ASTM D6866 biocarbon percentage analysis to confirm the renewable diesel content and ASTM D7371-14 analysis for biodiesel content.

Depending on the testing location and season, cold weather blend options may need to be considered. There are two key metrics available to understand when the test fuel may become unusable due to waxing or gelling when the fuel becomes too viscous to flow in the wayside filtration or locomotive fuel system; cloud point and freeze point. Cloud point (ASTM D2500) is the temperature when the paraffins in the fuel begin to visibly cloud due to wax crystal formation, while freeze point (D2386) is the lowest temperature at which the fuel remains free of hydrocarbon crystals. Freeze point is a more conservative measurement as it identifies when the first wax crystals will start to melt, not when there are enough of them to become visible. Cold Filter Plugging Point (CFPP) (ASTM D6371) can also be used. It is the lowest temperature at which diesel fuel passes through a standardized filtration device in a specified time when cooled. It estimates the lowest temperature at which a fuel will flow in most engine fuel systems. If the railroad testing the fuels is operationally risk averse, it is recommended to order fuels using the freeze point or CFPP. Ultimately, fuel logistics and cold weather blending are best left to the fuel supplier who has a deep knowledge of the feedstock and blend that could affect cold weather operations.

Fuel storage, usage, and sampling practices are important with petroleum diesel, but there are additional best practices to consider with the addition of biodiesel or renewable diesel to ensure the fuel used in the locomotive won't cause operational issues. The *Biodiesel Handling and Use Guide* from the U.S. Department of Energy (DOE/GO-102016-4875) is an excellent guide for understanding and developing action plans to minimize fuel quality issues due to storage. These issues can be easily addressed and include microbial/biological contamination, lower oxidation stability that can lead to high acid numbers, high viscosity, and the formulation of gums and sediments that can clog filters. As with testing in the locomotive, storage in low temperatures may require infrastructure upgrades to ensure fuel flow can be maintained at all times. Finally, it is important to note that federal and local codes and regulations may change with blends above B20.

## Template for stationary testing

Stationary (load box) testing of biodiesel and renewable diesel, and blends of these fuels, has historically been somewhat limited. The primary purpose of stationary testing is to identify and characterize changes in engine performance, fuel consumption, and exhaust emissions. Figure 5 summarizes locomotive models for which biodiesel and renewable diesel blends have been tested, and where the results are in the public domain. References are provided for the test reports and technical papers covering these tests. Most of these studies focused on relatively low concentrations of Biodiesel, generally 5% (B5) and 20% (B20). Only recently has there been interest in evaluating much higher concentrations of biofuels. For example, the CARB-funded locomotive work reported in the 2021 LMOA paper[3] included neat renewable diesel (R100), and a 50% blend of renewable diesel with CARB diesel (R50). In that same study, BNSF and UP funded testing of an additional fuel blend of 20% biodiesel, 30% renewable diesel, and the balance of the fuel blend being CARB diesel (B20/R50).

3 Fritz, S.G., C. Stoos, C. Ruch, and R. Flott, "Renewable Diesel Fuel Effects on Exhaust Emissions from a Tier 3 GE ES44C4 Locomotive," LMOA Proceedings of the 83rd Annual Meeting, pp. 35-54 (October 2021)

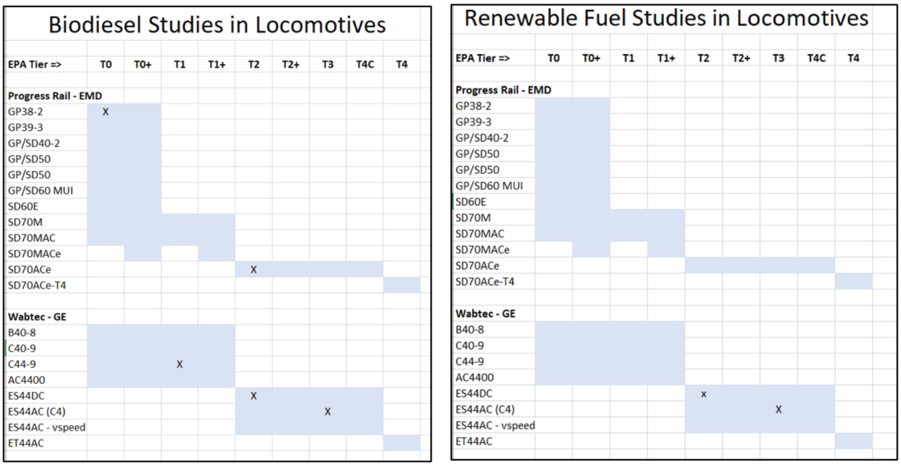



**Figure 4: Biodiesel and Renewable Fuel Studies in Locomotives**

One of the considerations for testing and using these biofuels is that they have a lower energy density on a volumetric basis, compared to conventional petroleum diesel fuel (lower BTU/gallon). Table 2 summarizes a sample data set from the 2021 LMOA paper. In this example, the renewable diesel had roughly 4% lower energy density compared to CARB ULSD, and biodiesel had roughly 8% lower energy density compared to CARB ULSD. The energy density correlates linearly with the blend ratio, so a "R50" fuel, 50% renewable diesel blended with conventional ULSD, would result in a 2% volumetric fuel consumption penalty. The C50/R30/B20 blend in Table 1 had a 3.7% lower volumetric heating value compared to the CARB ULSD fuel.

| ASTM | Property | Units | C100 | B100 | R100 | C50/R50 | C50/R30/B20 | EPA Cert. |
|---|---|---|---|---|---|---|---|---|
| D240G | BTU Heat | BTU/lb | 19,792 | 17,186 | 20,297 | 20,020 | 19,560 | 19,652 |
| D240N | BTU Heat | BTU/lb | 18,534 | 16,090 | 18,922 | 18,702 | 18,270 | 18,445 |
| | HHV | BTU/gal | 137,800 | 126,562 | 132,296 | 134,897 | 132,760 | 138,103 |
| | **HHV % change from C100** | | *** | **-8.2%** | **-4.0%** | **-2.1%** | **-3.7%** | **0.2%** |
| | LHV | BTU/gal | 129,041 | 118,491 | 123,334 | 126,016 | 124,004 | 129,621 |
| | **LHV % change from C100** | | *** | **-8.2%** | **-4.4%** | **-2.3%** | **-3.9%** | **0.4%** |
| D4052 | density | lb/gal | 6.96 | 7.36 | 6.52 | 6.74 | 6.79 | 7.03 |

**Table 2. Heating Value and Density of CARB-Funded Locomotive Test Fuels[4]**

4 Fritz, S.G., C. Stoos, C. Ruch, and R. Flott, "Renewable Diesel Fuel Effects on Exhaust Emissions from a Tier 3 GE ES44C4 Locomotive," LMOA Proceedings of the 83rd Annual Meeting, pp. 35-54 (October 2021).

Fuel consumption from controlled stationary locomotive tests is typically reported on a brake-specific mass basis, in units of lb/hp-hr. For renewable diesel, the heating value of the fuel (ASTM D240) is often higher than conventional ULSD on a mass basis (BTU/lb), resulting in an apparent improvement in fuel efficiency. However, railroads buy fuel on a volumetric basis in gallons (or liters). The density of the fuel is measured and reported in lb/gal, and the density of the renewable diesel is often notably lower than conventional ULSD. The lower density impacts the volumetric heating value of the fuel more than the higher mass-based heating value, such that the net volumetric heating value is lower than the CARB ULSD in our example by 4%. Therefore, it is important to not only report stationary locomotive fuel consumption with the conventional units of lb/hp-hr, but fuel consumption should also be reported in units of gal/hp-hr.

Depending on the locomotive model and associated fuel and engine control system, these lower energy density biofuels will affect performance. For example, on gross-horsepower controlled locomotives, horsepower will normally be unchanged, and the volumetric fuel flow will be higher by the same percentage as the volumetric energy density. In our example with R100 fuel, you would expect to use 4% more gallons of R100 compared to CARB ULSD at any given Notch position. This assumes that the fuel system has additional capacity to inject the additional volume of fuel needed to maintain the target power. Older EMD locomotives, generally with mechanical governors, regulate power at each Notch using a rack position signal to the load regulator, effectively controlling a volumetric fuel flow rate. With our R100 example, these EMD MUI locomotives would expect to see a 4% reduction in power, but the volumetric fuel rate would be unchanged.

## Template for Set-up and Baseline of Long-term Durability, Emissions, and Performance Tests

Long-term durability testing is needed to understand the impacts over time of a given biomass-based fuel blend on the various components of the locomotive. This includes any components that come in contact with the fuel as well as any components that come in contact with the lube oil as the oil's performance can be affected by the addition of biodiesel or renewable diesel. The changes in performance and durability can affect the railroads by changing component lifecycle costs, maintenance practices, and reliability. These changes can also affect the locomotive OEM as these same issues are often woven into Maintenance Service Agreements (MSA) that have defined metrics that an OEM must meet and costs of the agreement that must be controlled. A test period of two to three years is recommended to fully understand the long-term impact of biomass-based fuel usage and may be dependent on engine architecture.

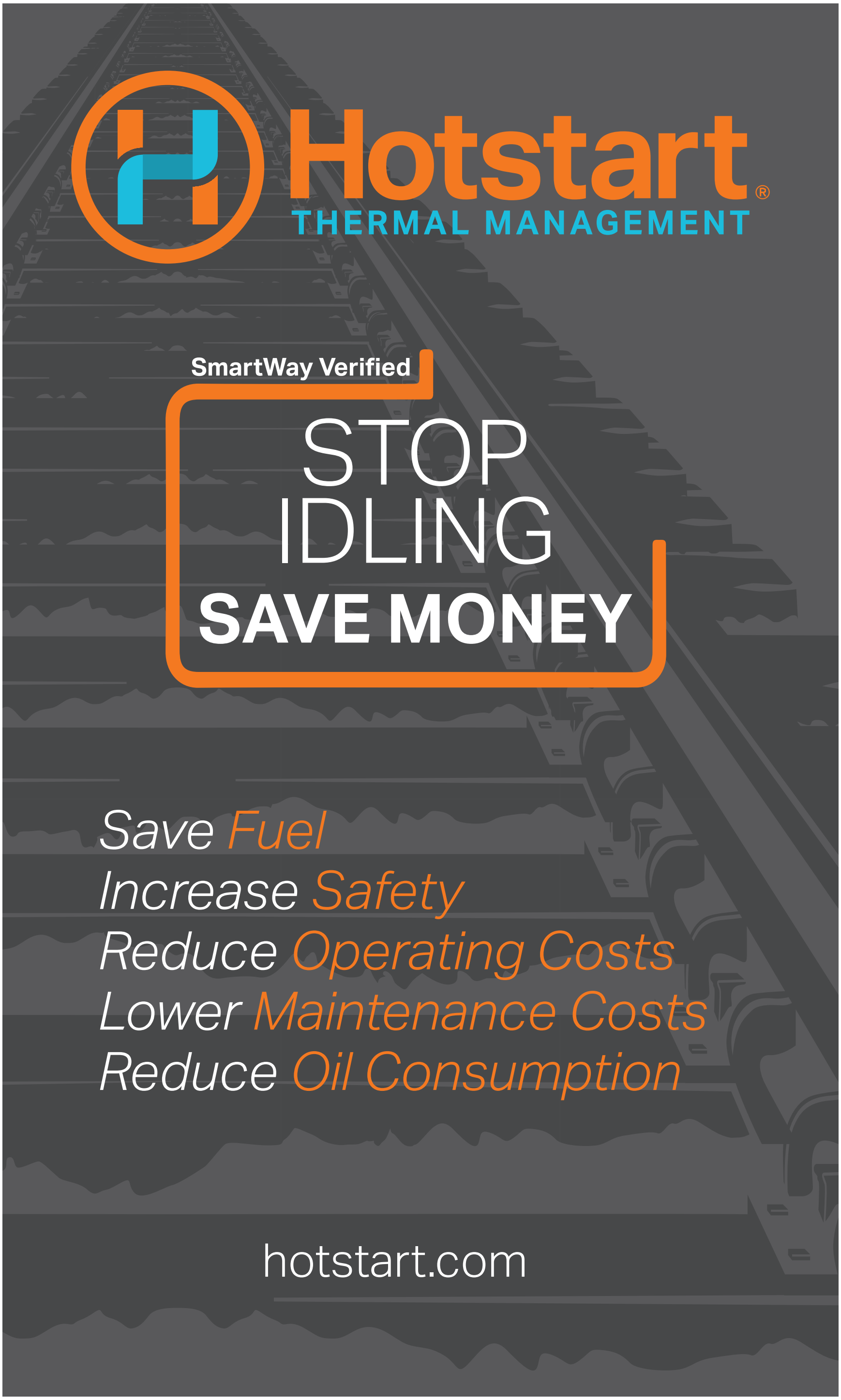
The first aspect of setting up a long-term test is to decide on sample size. It is very important that each core engine family and EPA tier designation is represented from a given manufacturer. The technology incorporated into the various engine families spans decades, so a single fuel blend may react very differently in a FDL engine than it would in a Tier 4 EVO. A test of Progress Rail (EMD) locomotives should consist of both Tier 0+ 645 engines, Tier 0+ and Tier 3 710 engines, and Tier 4 1010 engine configurations. A test of Wabtec (GE) locomotives should consist of Tier 1+ FDL and FDLA engines as well as Tier 3 and Tier 4 EVO engines.

Dennis McAndrew recommended a minimum of four locomotives in his 2012 LMOA paper, "Locomotive Durability Test Protocol for Alternate Fuels and Biodiesel." This number allows for a statistical evaluation of the locomotives while also accounting for possible locomotive failures that could reduce sample size. If available, it is recommended to use 5-7 locomotives for additional data points and fallout risk reduction. Of these locomotives, four should be available for baseline and follow up emissions tests. Components should only be changed on these locomotives if absolutely needed to fully understand the emissions deterioration factor (DF) over the course of the test. The remaining test locomotives should be used for mechanical testing. All locomotives should get an EPA exemption before beginning testing to account for the unknown effects to emissions when running biofuels.

Once the test locomotive population is established, a baseline should be recorded for each locomotive. Emissions, engine performance, and mechanical component baselines are needed for a holistic picture of locomotive health. An emissions test should be performed using EPA certification #2 ULSD fuel as a baseline for emissions. Testing should also be done with the test blend to understand the emission profile when the biofuels are being burned. This may not be required by law but is good practice for an OEM. Locomotive performance should be noted using the onboard control system to look at engine horsepower, pump pressures, fuel temps, exhaust temps, turbine speeds, etc. It is important to evaluate not just Notch 8 loading for power deration, but also to check load rate with biofuels when moving through the notches. Special attention should be paid to mid-notch transitions and fuel limits that could cause transient smoking or engine bogging.

Mechanical and software-based engine protection limits should be monitored to ensure there will be no nuisance shutdowns. The locomotive must stay within mechanical limits of Peak Cylinder Pressure (PCP) for reliability purposes. While the engine controller will protect the engine with derate strategies to lower PCP, the goal is to not experience any performance decrease with this fuel change. Other protective limits around fuel leak detection, fuel pressures, turbine speeds, exhaust temperatures, etc. should also be reviewed to ensure different fuel properties don't cause nuisance shutdowns.

Baseline testing should include the installation of new, UX, or measured components as well as a visual inspection. The component change-outs allow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for a known baseline in component wear. The list of components that should be changed at the beginning of a test may be dependent on what type of locomotive is being tested. In general, fuel injectors, fuel pumps (if applicable), fuel filters, oil filters, and the lube oil should be changed at the start of the test. The OEM may extend that list to include power assemblies, fuel preheater, fuel transfer pumps, or specialized Tier 4 components like EGR coolers that may be impacted by the test fuel. When testing existing power assemblies, a visual inspection should be completed to understand current conditions prior to testing. If applicable, inspect pistons and rings for wear and deposits, liner condition, cylinder head for valve deposits and seat wear, rod bearings, and air box deposits. Pictures are recommended to track condition changes over the length of the test since memories and team members may change over the course of a multi-year test.

A captured fleet is advised, but not required for testing. Dennis McAndrew points out in his 2012 LMOA paper the pros and cons of general revenue service versus using a captured fleet. While general revenue service allows the locomotive to be operated in the exact environment that the railroad's fleets operate, the logistics to make a specific fuel blend available to a specific fleet over the entire railroad network would be challenging at best. A captured fleet that either operates from a central fueling hub in a loop or in A to B to A service allows the railroad to focus test fuel operations to one or two locations. Even in captured service, though, special tooling or locking caps on the test locomotives should be utilized to ensure no fuel that isn't the specific test fuel is put in the locomotive fuel tank.

Regular sampling of both fuel and oil to correlate with MWHrs and dispensed fuel consumption is important throughout the test. Fuel sampling should occur each time the locomotives are fueled, ideally from the locomotive tank, but otherwise from the fuel filter housing to be certain the test locomotive is running on the expected test blend and no other fuels were used. Whoever fuels the locomotive should record the unit number and gallons added per unit. This data can be used with the MWHr data to understand the differences in fuel consumption for the test blend. The fuel samples should be tested per ASTM procedures for important metrics like bio content, lubricity, viscosity, water content, etc. Coordination is important between the OEM and railroad to ensure data relevant to each entity is collected, but with a process the railroad can maintain for the entire test period.

Oil sampling when testing biodiesel or renewable diesel fuels in locomotives is important to understand the effects the fuels may have on the oil and wear of the engine. Oil samples should be taken at regular intervals such as every 10 to 15 days as suggested by Dennis McAndrew in his 2019 LMOA paper, "Used oil analysis – is it reliable?"[5] OEMs may require more frequent sampling, especially at the beginning of new fuel testing to best understand the rate of any effects on the oil condition. These short sample intervals are easier for a railroad to achieve

5 McAndrew, D., "Used Oil Analysis – Is It Reliable?" Proceedings of the 81st Annual LMOA Meeting pp. 105-123 (September 2019).

in a captive fleet test while the nature of general revenue service makes these shorter collection intervals difficult.

The most important oil properties to measure are viscosity, BN (Base Number), TAN (Total Acid Number), soot, and elemental analysis. If unchecked the viscosity, BN, TAN, and soot levels can negatively affect the life of the engine. Elemental analysis serves to give visibility to the wear the engine is experiencing at a given time, the balance and health of the lubricating oil's additive system and can be used to alert the railroads or OEMs to changes in the lubricating oil between oil change intervals. Other important parameters to monitor are water content and fuel dilution. Water can be introduced by rain or condensation and retained by biofuels at higher levels than standard #2 ULSD fuel. Fuel dilution in the oil can present a performance and safety risk to the engine.

## In-use Testing

Once testing has begun, the test locomotives must be monitored to determine if maintenance needs should be adjusted based on conditions and concerns that occur during testing. The maintenance and inspection plan should be laid out and agreed upon by both the railroad and the OEM to ensure that the process is sustainable throughout the test period. It is also advised to align the biofuel test inspections with other scheduled inspections so the locomotive availability remains at standard levels. Most railroad inspection intervals fall into weekly servicing, 92-day inspections, 184-day inspections, and yearly inspections. Note that the semi-yearly and yearly inspections should include the tasks done during the weekly and 92-day inspections.

During servicing and fueling of the locomotives or at a maximum interval of one week, visible fuel system components like the fuel tank sight glass and hoses should be inspected for leaks or seepage. 92-day inspections vary in practice from railroad to railroad, but this inspection would be a good time to perform a N8 load test and review performance parameters like horsepower, exhaust temps, turbine speeds, etc. This information may also be available remotely to either the railroad or OEM through snapshots taken as the locomotive is used to pull freight. These snapshots can be used to look for trends over time. With either option, at 92 days the locomotive fuel filters should be changed and inspected for signs of plugging or biological growth.

The 184-day inspection will be the first major inspection for the biofuel test. Generally, there are two options for checking the state of the engine and engine support systems. The first option is to do only a visual inspection on the locomotive. The inspection would include pistons and rings for wear and deposits, liner condition, cylinder head for valve deposits and seat wear, rod bearings, turbo, and air manifold deposits. Support systems such as fuel hoses and jumper lines, fuel transfer pump, and water separators (if applicable) should also be included. This inspection should match the baseline inspection and be documented with pictures.

The second option is to remove certain components for inspection and possible tear-down analysis off board the locomotive. Removing components does add cost and time to the inspection but can provide more insight as the components can be sent to a lab or OEM facility for more thorough analysis.

Another optional task for the 184-day inspection is an emissions test. At a minimum, emissions should be tested yearly, but if the test plan allows, another data point to help determine the Deterioration Factor (DF) can be illuminating. The DF is defined by the EPA as "the relationship between emissions at the end of useful life and emissions at the low-hour test point, expressed in one of the following ways:

(1) For multiplicative deterioration factors, the ratio of emissions at the end of useful life to emissions at the low-hour test point.

(2) For additive deterioration factors, the difference between emissions at the end of useful life and emissions at the low-hour test point."

To avoid running emissions tests to support a biofuel program all the way to the end of useful life on a locomotive engine, typically around 7-10 years, the curve defined by the DF can allow for an accurate projection of emissions at end of life. The EPA states that the DF must be developed with "good engineering judgment" and so it is up to the engineers and regulatory group in an OEM to determine how many points should be tested, how often, and for how long.

The yearly inspection will be very similar to the 184-day inspection. It must include emissions testing that should be done yearly throughout the entire test period. As with the 184-day inspection the OEM of the test locomotives will determine what components and how many are required to be removed from the test locomotives to do a thorough analysis of wear. The group of locomotives used for emissions testing should be used only as a backup with minimal component changes since changing components could nullify the DF calculations and not allow for an updated emissions profile for the certification by the EPA. Again, best engineering judgment should be used and be defensible to the EPA.

## Looking Forward to Emission and Durability Impact

There are currently two public field tests running high percentages of biofuels in locomotives. The first field test was announced on November 3, 2021 and is taking place on the Bessemer & Lake Erie portion of the Canadian National Railway network. CN announced the test as a collaboration between Renewable Energy Group (REG), Progress Rail, and CN beginning on February 1, 2022. Per CN, "Tests will be performed over a period of approximately two years, as one objective is for CN and Progress Rail to better understand the long-term durability and operational impacts of renewable fuels on locomotives, especially in cold weather. Renewable Energy Group (REG) will supply high-percentage blends of biomass-based fuel, including both biodiesel (FAME) and renewable diesel (HDRD) for testing."

The second field test was announced March 9, 2022 to commence in Q2 of 2022 between Wabtec and both BNSF and UP. BNSF will be testing a 100% biofuel blend on Tier 3 and Tier 4 Evolution Series locomotives in between Barstow and Los Angeles, CA. BNSF stated that "rail is already the most carbon-efficient mode of land freight transport, and the use of these lower carbon fuels is another means for BNSF to reduce its emissions and help meet its carbon reduction goal." At the same time, Wabtec and Union Pacific are testing the same biodiesel blend on FDL and FDLA locomotives operating in California. UP states that "increasing the use of renewable diesels and biofuels currently represents the most promising avenue to help Union Pacific meet its environmental goals."

Due to the nature of both tests with Wabtec and Progress Rail starting early in 2022, the impact of biofuel on locomotive engines is not yet known. As such, this paper will be a two-part paper with the 2nd half releasing in 2023. That paper will document the fuel system impact (high-pressure fuel pumps, LP fuel pumps, injectors), filter maintenance intervals and filter spec changes, and any engine impacts (water separator, power assembly, elastomers, valves) that are seen during testing. The impact of running biofuels in the locomotives will also be better understood as there will be the opportunity to collect the yearly emissions test data for both Progress Rail and Wabtec field test locomotives. The second part will also include suggestions for rollout of wide-spread use of biofuels in a railroad's existing fleet containing locomotives in a variety of stages of wear out. Stay tuned for the results!

## List of Abbreviations

| | |
|---|---|
| ASTM | ASTM International (formerly American Society for Testing Materials) |
| BEL | battery-electric locomotive |
| BNSF | BNSF Railway Company |
| BTU | British Thermal Unit |
| Bxx | Percentage biodiesel in balance petroleum diesel. Eg: B5 = 5% biodiesel in 95% petroleum diesel |
| BxxRyy | Percentage biodiesel and percentage renewable diesel in balance petroleum diesel. Eg: B5R30 = 5% biodiesel and 30% renewable diesel in 65% petroleum diesel |
| CARB | California Air Resources Board |
| CFPP | cold filter plug point |
| CN | Canadian National Railroad |
| CP | cloud point |
| $CO_2$ | carbon dioxide |
| DF | deterioration factor |
| DOE | Department of Energy |
| EGR | exhaust gas recirculation |

| | |
|---|---|
| EIA | Energy Information Administration - https://www.eia.gov/ |
| EMD | Electromotive Division (now Progress Rail) |
| EPA | U.S. Environmental Protection Agency |
| FAME | fatty-acid methyl-ester |
| FP | freeze point |
| GE | General Electric (now Wabtec) |
| GHG | greenhouse gas |
| $H_2$ | hydrogen |
| HDRD | hydrogenation-derived renewable diesel |
| HP | high pressure |
| LMOA | Locomotive Maintenance Officers Association |
| LP | low pressure |
| MMgal | Million gallons liquid volume |
| MSA | Maintenance Service Agreements |
| MW-hr | megawatt-hour |
| OEM | original equipment manufacturer |
| PCP | peak cylinder pressure |
| PP | pour point |
| REG | Renewable Energy Group, Inc. |
| Rxx | Percentage renewable diesel in balance petroleum diesel. Eg: R30 = 30% renewable diesel in 70% petroleum diesel. |
| SBTi | Science-Based Targets initiative |
| ULSD | ultra-low sulfur diesel fuel |
| UP | Union Pacific Railroad Company |
| US | United States |
| UX | unit exchange |
| Yr | year |

## Stationary Test References


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These reduce
$CO_2$ emissions.

# GHG Emissions Reduction for North American Railroads

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## Abstract

This paper provides an overview of North American railroads fuel consumption trends, technologies and other initiatives implemented in recent years to improve fuel efficiency, and details the challenges set forth to meet the GHG reduction targets while simultaneously meeting ever-more stringent criterial emission limits (NOx and PM). Case studies of recent projects to improve the diesel engine fuel efficiency will be presented, along with a discussion of engine, locomotive, and train level fuel economy improvements that will likely need to be explored in the future. Finally, we will highlight low-carbon fuel options and carbon-free initiatives that the railroads have announced or are currently pursuing, such as battery electric and hydrogen fuel cell powered locomotives.

North American freight railroads are all non-government, publicly traded companies (with the exception of BNSF which is owned by Berkshire Hathaway), with seven large “Class 1” (annual revenue greater than $250 million) railroads that combined consume approximately 13.6 billion liters of diesel fuel each year. Each of these railroads have recently announced greenhouse gas (GHG) emissions reduction targets under the Science Based Targets initiative (SBTi) as a first step towards low-carbon freight transportation. These railroads have made consistent and steady improvement in fuel efficiency over the last decade, on the order of approximately 1% per year as an industry, but additional fuel efficiency gains will need to be even more aggressive to meet the SBTi goals of roughly 35% reduction of Scope 1 GHG emissions intensity by the year 2030.

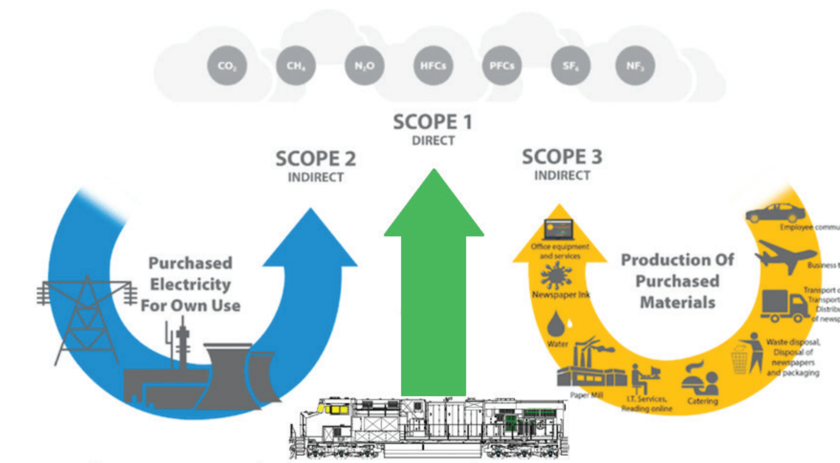
## SBTi Scope Emissions and Reduction Goals for the Industry

The Science Based Targets initiative (website sciencebasedtargets.org) was established in 2015 to help companies to set emission reduction targets in line with climate science and the Paris Agreement goals. The Paris Agreement’s long-term temperature goal is to keep the rise in mean global temperatures to well below 2 degrees Celsius above pre-industrial levels, and preferably limit the increase to 1.5

degrees Celsius.

Figure 1 shows the differing scopes and a brief description of each scope. Scope 1 covers direct emissions from owned or controlled sources, diesel fuel burned in locomotives in this case for rail. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the rail reporting company. Scope 3 includes all other indirect emissions that occur in a company's value chain which for railroads is significant regarding the production and transportation of diesel fuel, steel rail and track ties - three of the largest purchased commodity groups for railroads in general.

There are two main metrics used for GHG emission measures; an absolute metric which is directly tied to how much diesel fuel is burned and is referenced in metric tons of $CO_2$ equivalent, and the more common measure based on intensity using either gross ton miles or revenue ton miles, as a base measure producing an intensity rate which is volume neutral. Example units are $gCO_2e$/RTM (revenue ton mile).




Source: https://www.greenelement.co.uk/blog/carbon-footprint-scope-1-2-3/

**Figure 1 – Emissions Scope Definitions**

Table 1 is directly from the SBTi website and shows all Class 1 goals which have been approved (save BNSF which should have their goal approved in 2022). The goal dates vary but are mostly centered around the 2030 time frame. They have all chosen a "well below 2 degrees Celsius" goal for limiting long term global warming. You can further observe that the CN has committed to a Net-Zero goal by 2050, and UP has announced their intent to do so soon.

Under the Targets column in Table 1 the goals are stated as a percentage improvement from a base year, also whether the goal is Absolute, or Intensity based. Both BNSF and UP railroads have chosen the less common Absolute goal measure, where future growth and volume increases will make their GHG reduction goals more challenging to achieve.

## Class I Railroads and Description of GHG Emissions Reduction Goals

Further details for each railroad SBTi commitments include:

BNSF - Reduce absolute scope 1 and 2 GHG emissions by 30% by 2030 from a 2019 base year.

CN - Reduce scope 1 and 2 GHG emissions 43% per million Gross Ton Mile and scope 3 GHG emissions from fuel and energy related activities 40% per million Gross Ton Mile by 2030 from a 2019 base year – the target boundary includes biogenic emissions and removals from bioenergy feedstocks.

CP - Reduce Scope 1, 2 and 3 locomotive well-to-wheel GHG emissions 38.3% per Revenue Ton Mile by 2030 from a 2019 base year.

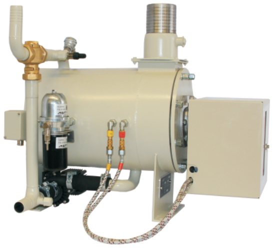
CSX - Reduce scope 1 and 2 GHG emissions intensity 37% per million Gross Ton Mile by 2029 from a 2019 base year.

NS - Reduce scope 1 and 2 GHG emissions 42% per million Gross Ton Mile by 2034 from a 2019 base year – the target boundary includes biogenic emissions and removals from bioenergy feedstocks.

UP - Reduce absolute scope 1 and 2 GHG emissions on a well-to-wheel basis from locomotive operations 26% by 2030 from a 2018 base year – the target boundary includes biogenic emissions and removals from bioenergy feedstocks.

KCS – Reduce scope 1 and 2 emissions 42% per million Gross Ton Mile by 2034 from a 2019 base year.

All railroads will need to submit more aggressive goals no later than 2025 to meet SBTi's preferred ambition moving from the current "well below 2 degrees Celsius" to a new "1.5 degree Celsius". The new strategy is being rolled out in response to increasing urgency for climate action and the success of science-based targets to-date.[1]



Near term | Long term | Net-zero | Location | North America × | Organisation type | Ground Transportati... × | Date

| COMPANY/FINANCIAL INSTITUTION | TARGETS | | | |
|---|---|---|---|---|
| | NEAR TERM | Goal Type | Amount | NET-ZERO |
| **BNSF Railway**<br>United States of America (USA), North America | COMMITTED | **Absolute** | **30%** | - |
| **Canadian National Railway Company**<br>Canada, North America | WELL-BELOW 2°C | Intensity | 43% | COMMITTED |
| **Canadian Pacific Railway Company**<br>Canada, North America | WELL-BELOW 2°C | Intensity | 38% | - |
| **CSX Corporation**<br>United States of America (USA), North America | WELL-BELOW 2°C | Intensity | 37% | - |
| **Norfolk Southern Corporation**<br>United States of America (USA), North America | WELL-BELOW 2°C | Intensity | 42% | - |
| **Union Pacific Railroad**<br>United States of America (USA), North America | WELL-BELOW 2°C | **Absolute** | **26%** | Announced Intent |
| **Kansas City Southern**<br>United States of America (USA), North America | WELL-BELOW 2°C | Intensity | 42% | - |

Source: https://sciencebasedtargets.org/companies-taking-action

**Table 1 – SBTi Goals by Railroad**

Figure 2 shows each Class 1 railroad and their base year and target year with associated percentage reduction. Note there are three different emissions measures being shown on this chart and the Variable Legend shows each emissions measure. Note mixed units on the Y-axis, so a ranking is not significant, rather the slope of the line and how each railroad has started in the early years.

Also note the "estimated" measures where applicable for 2020 and 2021 which have been calculated based on known annual diesel fuel consumption and prior year stated emissions measures from each railroad and using CO2e conversion factors that do not include any significant use of Biodiesel and/or Renewable diesel.

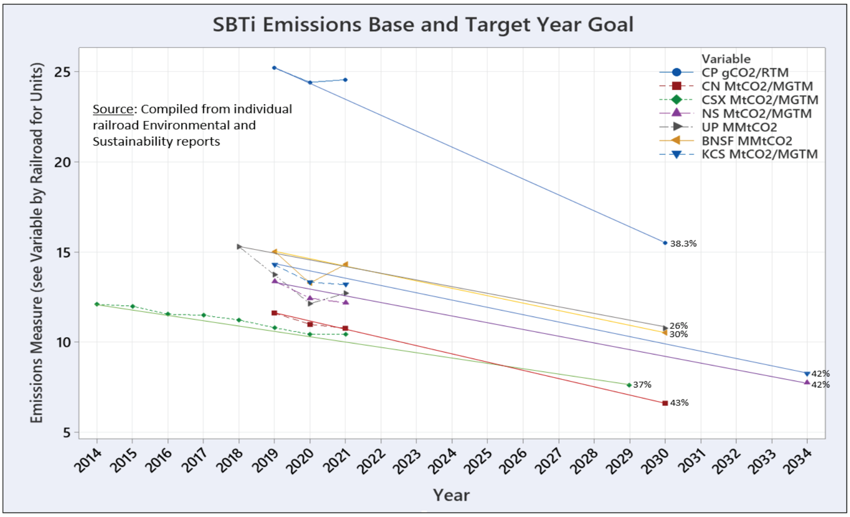



**Figure 2 – SBTi Emissions Baseline and Target Year for each Railroad with Associated Reduction Goal**

## Various Fuel Saving Approaches by Railroad

Table 2 highlights each railroad and their specific key initiatives that they have listed in their most recent ESG or Climate Action Plan reports from 2020 and 2021. It indicates the percentage of GHG coming from their locomotive fleets which are all very high in the 95% or higher range, with the exception of CN lower at 85% due to their ownership of both trucking and maritime fleets.

Some common approaches being used to reduce GHG emissions are Energy Management Systems (EMS) and lower Horsepower-Per-Trailing-Ton (HPTT) due to longer trains compliments of Precision Scheduled Railroading or PSR initiatives. Auto Engine Stop Start (AESS) and the use of Distributed Power (DP) technology is also listed as being in common practice. Less common approaches are the use of biofuels (biodiesel and/or renewable diesel) with UP having announced a goal of 10% biofuel use by 2025 and 20% by 2030. The use of data analytics, having a fuel dispatching desk as part of their network train dispatching process, track lubrication and mother-slug units are also considered less common fuel saving practices.

| Railroad | SBTi Goal | % GHG from Locomotives | Key Initiatives for GHG Emissions Reduction | Publication Date & Source |
|---|---|---|---|---|
| BNSF RAILWAY | 30% Absolute | 94% | Three key areas are newer locomotives, AESS and EMS. Utilization of lower HPTT optimization through speed-based throttle limitation. Reduced rolling friction and less stops/starts increasing network fluidity and speed (see pages 23-26) | (November 9, 2020) 2018/2019 Corporate Sustainability Report |
| UNION PACIFIC BUILDING AMERICA | 26% Absolute | 97.6% | More efficient train operations and a greater use of low-carbon fuels (20% by 2030) and adoption of alternative-propulsion technology. Overhauled 175 LHP locomotives with 220 more planned through 2022, Mother-Slugs, EMS and AESS (see pages 6 and 9) | (December 6, 2021) 2021 Climate Action Plan |
| CN | 43% Intensity | 85% | Five key strategic areas are 1. Upgrading locomotive fleets 2. Increasing fuel-efficient technologies (EMS, DP, HPTA) 3. Leveraging the use of big data 4. Enhancing operating practices (FMX, DSR) 5. Expanding the use of cleaner fuels (see pages 5-10) | (April 2021) 2020 Climate Action Plan |
| CSX | 37% Intensity | 96% | 24/7 Fuel Conservation Desk, EMS and MPP (Meet Pass Planner) for greater network fluidity, track lubrication. Climate-related Scenario Analysis performed for Short-term (0-3 years), Medium-term (3-10 years) and Long-term (10-30 years) (see pages 94-101) | (June 3, 2021) 2020 Environmental, Social & Governance |
| NS | 42% Intensity | 90% | Retired 1/3 of older fleet, modernized DC to AC propulsion, longer trains through PSR, EMS on 90% of HHP fleet, right size the locomotive fleet through reduced HPTT (see page 7) | (August 9, 2021) 2021 Environmental, Social & Governance |
| CP | 38% Intensity | 96% | Upgrading existing locomotives, software solutions for route and speed optimization, behavioral change initiatives, longer trains, DP and advancement of alternative fuels (Hydrogen) and emerging technologies (see pages 15-16) | (July 26, 2021) 2021 Climate Strategy Report |
| Kansas City Southern / Kansas City Southern de México | 42% Intensity | 95% | Lowering HPTT through PSR, AESS and reduced idle programs, EMS using Trip Optimizer, DP, rail track lubrication, Smart HPT, longer / heavier trains, better train handling techniques and evaluating new technologies (see pages 30-31) | (July 1, 2021) 2020 Sustainability Report |

Sources: Compiled from most recent individual railroad Environmental and Sustainability reports / Climate Strategy / Action Plan documents

**Table 2 – Various Fuel Saving Approaches by Railroad**

## Historical Fuel Savings Industry Performance

The rail industry commonly uses a fuel efficiency measure of Gallons per Thousand Gross Ton Miles which has been tracked for many decades. Figure 3 shows each of the seven Class 1 railroads going back to 2001 with KCS only disclosing their fuel efficiency metric starting in 2011. Notice the Canadian railroads have generally been the best performers and starting in 2013 both distanced themselves from their US peers. Most railroads stay in their own fuel efficiency "lane" except for CSX that now looks more like a Canadian railroad in terms of exceptional fuel efficiency. Still, there remains a 30% gap between the best and most challenged railroads looking at the most recent year of 2021.

Figure 4 shows the combination of all Gallons and all Gross Ton Miles, so it is an industry performance metric for the Class 1's that indicate a roughly 1% improvement per year the past decade. There are some slight anomalies such as 2018 underperforming and 2020 overperforming but notice that the most recent year of 2021 shows the same roughly 1% improvement. If we look at the aggregate SBTi goals out to 2030 and the glide slope required for the industry to achieve that goal, it will require from 2021 forward, a 2.5% year over year improvement in fuel efficiency to meet the SBTi targets. Whereas on the current historical glide slope, that would create an 18% percent gap between where railroads need to be and where they likely will be on their current trajectory or historical glide slope. Per the more challenging SBTi goals to be announced by 2025 mentioned earlier, this will likely mean the slope of the line shown in Figure 4 will be even steeper.

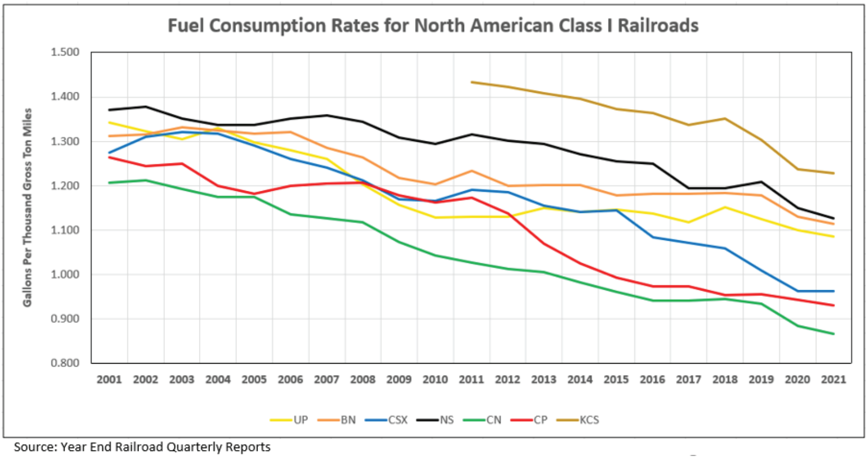



**Figure 3 – Fuel Efficiency for Class 1 Railroads**

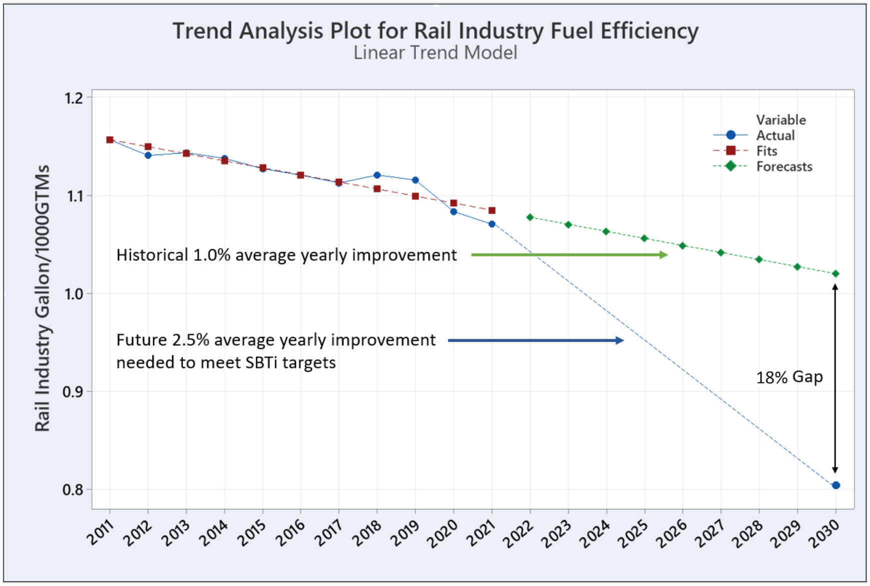



**Figure 4 – Historical Glide Slope versus SBTi 2030 Goal**

## Marginal Abatement Cost for GHG Emissions Reduction

Figure 5 shows for illustrative purposes, a sample of many individual fuel saving initiatives grouped into nine categories. The y-axis measures the abatement cost in US dollars per Metric Ton of $CO_2$ equivalent. For most initiatives that are below the x-axis, they deliver a positive ROI meaning the value of the fuel savings is more than enough to offset the cost and maintenance of the technology. The bar height for each project specifies the strength of the fuel savings or magnitude of the ROI. The x-axis measures the emissions intensity in Metric Tons of $CO_2$ equivalent per Million Gross Ton Mile, so the wider each bar, the more it moves the needle in reducing GHG emissions intensity. You'll notice some initiatives are above the x-axis meaning they will present a net cost to pursue, both biofuel initiatives and advanced technology projects fit into those categories.

The SCC or Social Cost of Carbon is also drawn in at the current $50 per Metric Ton and that value will likely increase in the future. The SCC is used to estimate in dollars all economic damage that would result from emitting one ton of carbon dioxide into the atmosphere. It indicates how much it is worth to us today to avoid the damage that is projected for the future.[2]

The social cost of carbon is used to help policy makers determine whether the costs and benefits of a proposed policy to curb climate change are justified. A higher SCC generally means that the benefits of a particular climate policy to cut CO2 justify its cost; a low SCC makes a policy seemingly cost more than the benefits it ultimately delivers. Theoretically, the SCC should increase over time because physical and economic systems will become more stressed as the impacts of climate change accumulate.[2]

A generic 2030 goal is shown on the chart and the takeaway is that railroads will not be able to pick and choose which projects to pursue. They will likely need to pursue all of them to achieve their 2030 emissions goals.

Figure 5 also shows that biodiesel and renewable diesel are projected to be expensive yet effective options for achieving the SBTi goals. They constitute the "easy button" – but should be used as a last resort.

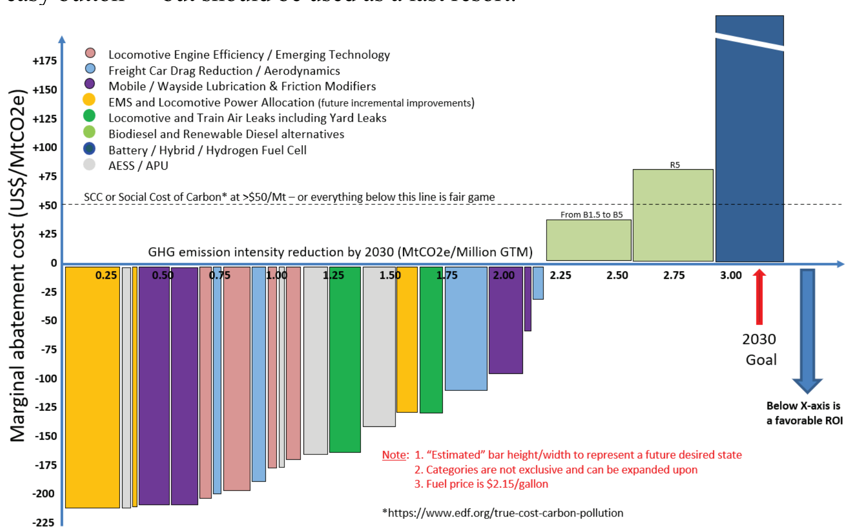


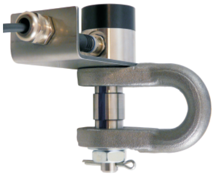

**Figure 5 – Sample Marginal Abatement Cost Chart**

**STOP** your locomotive AESS being in the hummingbird mode starting the engine excessively for main reservoir pressure built ups

**START** saving fuel with monitoring the handbrake applied status by **ABrake Sense** to inhibit unneeded AESS engine starts for main pressure build ups

**ABrake Sense** measures the correct parking brake applied force directly at the brake cylinder lever

*It complies to AAR AESS spec. S-5502: When the applied status of the handbrake is known, low main reservoir pressure is no longer a required engine start-up parameter for all units on trail operation and isolated lead units*



**ABrake Sense** retrofit handbrake sensor

**Clevis with load pin**

Idle Free

AST Gruppe®
Angewandte System Technik

Find out more on www.ast.de
A.S.T. - Angewandte Systemtechnik GmbH
Energie & Umwelttechnik
Hagertshausen 7 - 85283 Wolnzach - Germany
email: info@ast.de

## Case Study 1 – Replacement of EUI Fuel Injectors

Locomotive aftermarket parts sales is a very large business within the rail industry and fuel injectors are one particular piece that can play an outsized role in fuel conservation. A large Class 1 railroad was experiencing strong headwinds in their fuel conservation efforts and upon some investigation, it was learned that the sourcing department had decided a few years earlier to change to a lower cost fuel injector vendor without considering that there could be a difference in actual fuel consumption or emissions performance. It was discovered that there was a 3% difference in Brake Specific Fuel Consumption or BSFC as shown in Figure 6, between the two suppliers of fuel injectors.

At the same time, SwRI observed differences in NOx and fuel efficiency in locomotives of the same model and EPA Tier as part of the annual AAR-coordinated and EPA required "End of Useful Life" emissions testing.

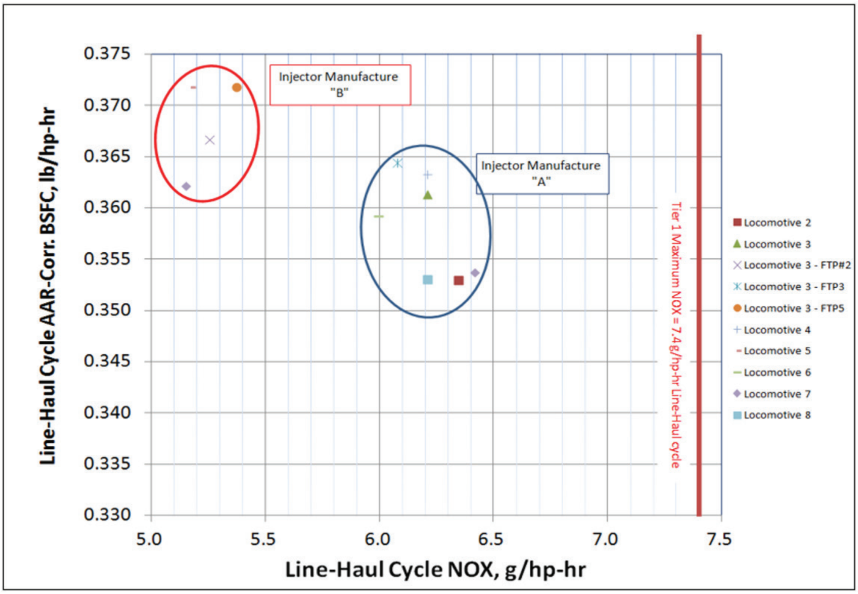



**Figure 6 – BSFC Performance for Injector Brand A versus Brand B**

Figure 7 shows benefits in HC, CO and PM emissions which all decreased with "A" injector, only NOx saw an increase, which was still well below the EPA required limit.

The lesson learned here is to ensure performance and fuel economy of emissions critical engine parts are comparable before changing suppliers – particularly those which have a strong determination on fuel consumption such as fuel injectors.

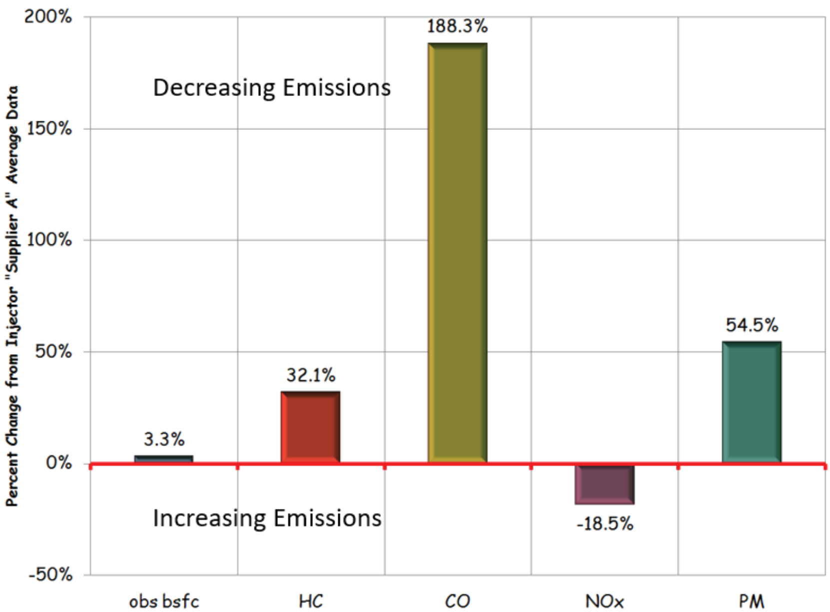



**Figure 7 – Emissions Difference for Injector Brand A versus Brand B**

## Case Study 2 – EUI Timing Optimization

While testing the various fuel injector vendors looking for the extent of the fuel consumption penalty described in Case Study 1, it was noticed that the NOx levels were quite low in comparison to the applicable EPA NOx limit of 7.4 g/hp-hr. In other words, the NOx compliance margin was very large, with an associated fuel efficiency penalty. Upon further investigation and working with the locomotive OEM, a modified and optimized EUI timing map was developed and added to the EPA certificate of conformity, which provided a smaller NOx compliance margin, but with a resulting 2.8% fuel efficiency gain. The new timing map was pushed through a software upgrade to the locomotive fleet.

Figures 8 shows the relationship between the BSFC and the Line-Haul duty cycle NOx emissions output.

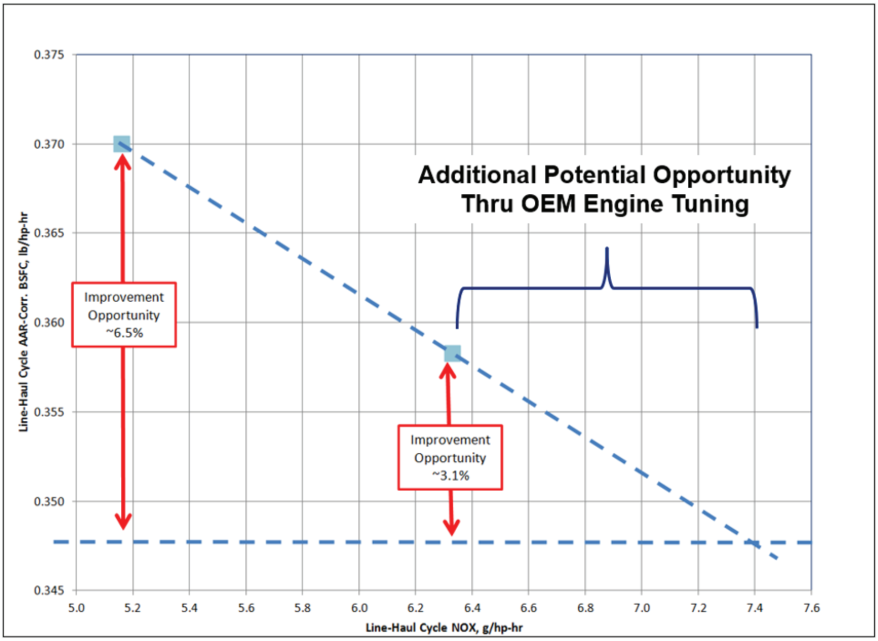



**Figure 8 – BSFC versus NOx Relationship**

Figure 9 shows both the BSFC for the railroad specific duty cycle in relation to the EPA Line-Haul NOx, with a potential fuel savings curve overlayed up to the NOx limit of 7.4 g/hp-hr. The better control over NOx emissions, the less NOx compliance is needed, and fuel efficiency can be optimized.

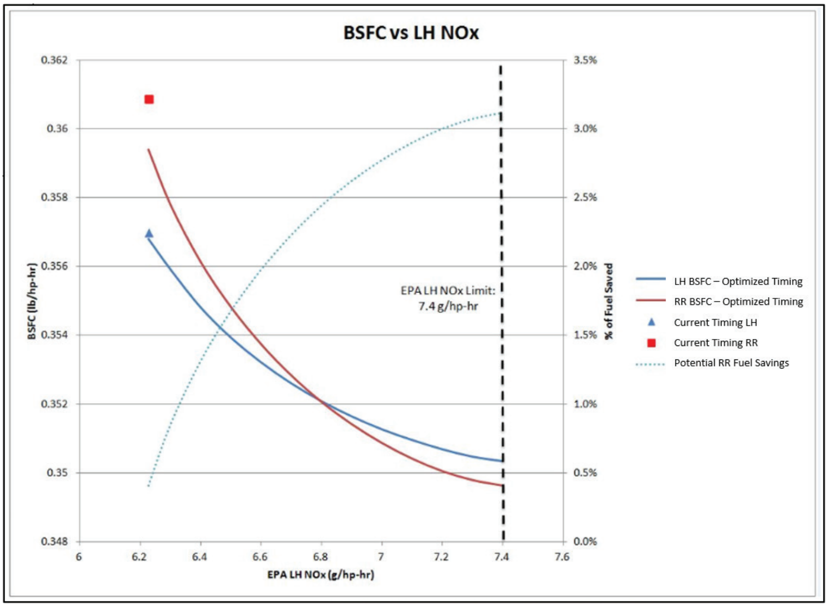



**Figure 9 – Optimized Timing Map Fuel Savings Curve versus Chosen NOx Limit**

## Case Study 3 – Locomotive and Train Line Air Leaks

Air leaks in train service are common and the locomotive compressor must make up for the resulting air loss. The air compressors in most locomotives are either shaft-driven or motor-driven, but both put extra load on the engine. The fuel penalty associated with the extra load due to running the air compressor to recover the loss of air pressure is significant, and methods need to be developed to easily identify, repair, and minimize the larger leaks both within the locomotive and the associated cars within the train line.

Figure 10 shows a reference from a 2020 LMOA paper[3]. The test measured the NTSFC difference both with and without a 30 SCFM induced air leak, which indicates an average NTSFC fuel penalty of 4.0% over the switcher duty cycle, 1.9% over the line haul cycle, and 1.8% over the AAR medium duty cycle.

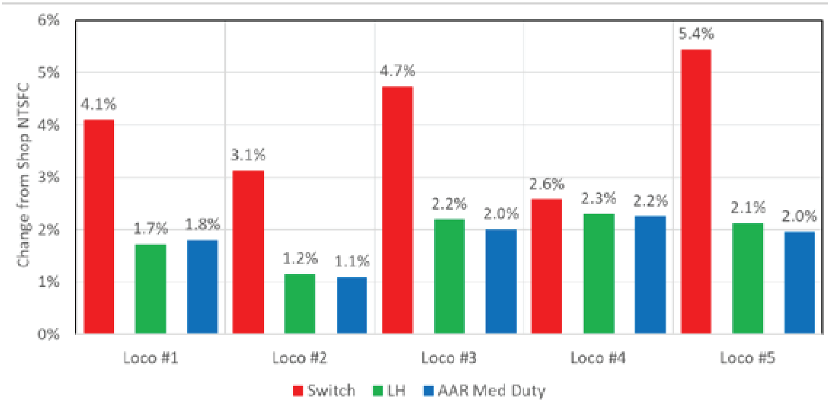



**Figure 10 – Locomotive Fuel Penalty with a 30 SCFM Air Leak**

A reliable and efficient method to locate and identify locomotive and train line air leaks is essential to addressing this source of fuel inefficiency. The effectiveness of the on-board AESS system is severely compromised due to locomotive air leaks, thus providing another source of needless and excessive fuel burn for no effective work performed.

SwRI is working on a TRB funded project to develop and demonstrate an autonomous system to identify compressed air leaks on locomotives and rail cars using acoustic imaging[4].

The Fluke ii900 industrial acoustic imager shown in Figure 11 provides an effective tool to identify air leaks a sample of which output is shown in Figure 12. Future optimization of the sensor into existing wayside inspection portals, along with the appropriate AI integration will provide an automated detection system for future use, to significantly decrease the number and size of air leaks on locomotives and car freight.

**Figure 11 – Fluke ii900 Industrial Acoustic Imager**

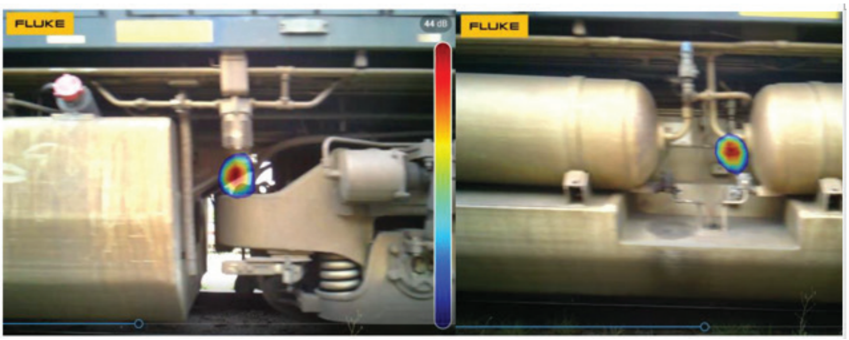



Figure 12 – Sample output of air leak identification using the Fluke ii900 device

## Case Study 4 – Locomotive NTSFC Benchmarking by Locomotive Model

Fuel consumption guarantee testing is performed periodically by some of the Class I railroads prior to and during delivery of new locomotive model fleets. While this data is proprietary to the customer and specific OEM, an overview of anonymous data points shown in Figure 13 clearly shows a large amount of variation in measured AAR-corrected NTSFC, a full 17% swing between the most and least fuel efficient within a similar Tier standard.

As an industry, railroads would benefit from pooling this valuable, credible, and independent fuel consumption data to help with decision making in terms of which units to store and which to deploy based on fuel efficiency measures.

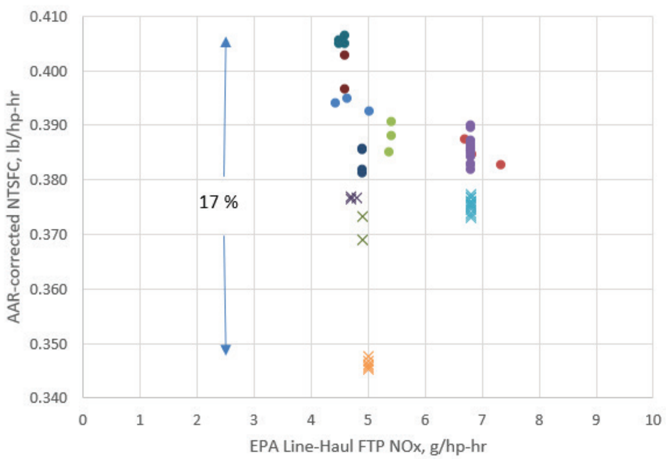



Figure 13 – AAR-corrected NTSFC Performance Across Multiple Locomotive Models

## Case Study 5 – Aerodynamic Improvements

The shape of rail cars and locomotives within the North American freight industry have not changed in many decades and it is evident that no consideration was made for aerodynamic efficiencies in the current and past designs being offered from the major OEMS for cars and locomotives.

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

Figure 14 shows the curve of aerodynamic and other forces and the resistance or power required for each, to move trains at various speeds. Given all railroads are focused on increasing network speed and providing stellar service to their customer base, rail aerodynamics must play a future role in helping conserve fuel as network velocity increases.

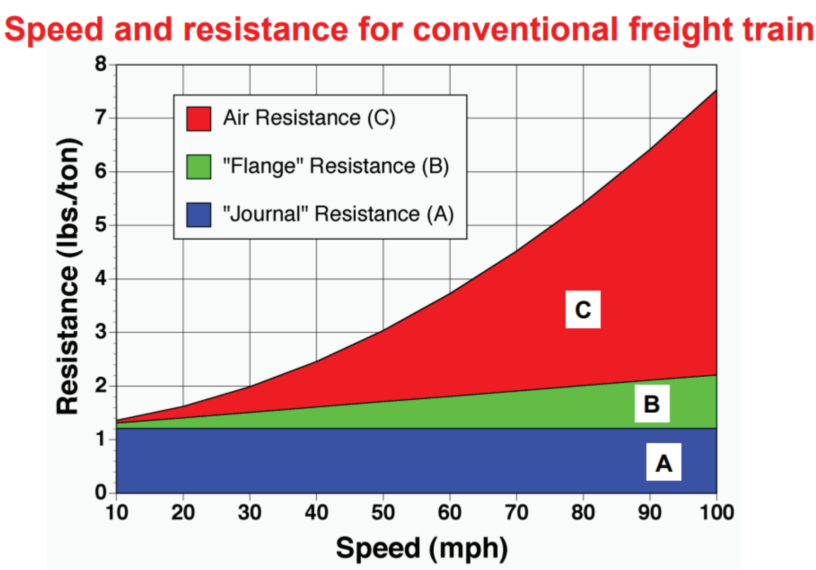


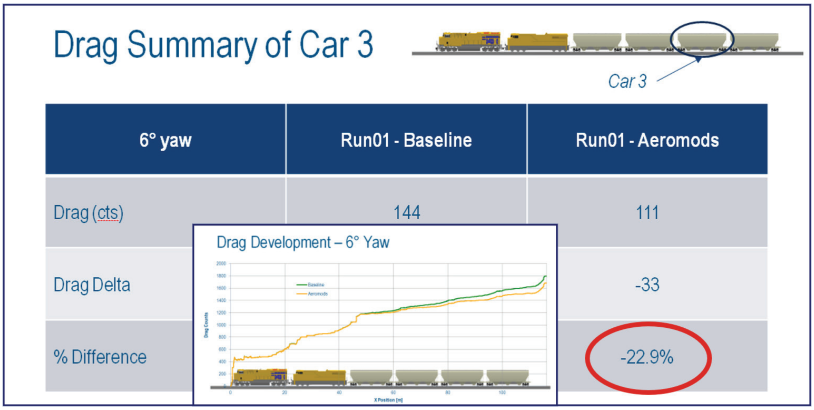

**Figure 14 – Resistance Forces for Freight Trains at Various Speeds[5]**

An example of simple modifications made to a new build of covered hoppers is shown in Figure 15 where both the cavities around the bottom hopper chute and top walkway supports have been enclosed providing a more aerodynamic running surface, removing sharp angles and open voids which create air turbulence and resulting excessive drag.

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


**Figure 15 – Covered Hopper with Aerodynamic Modifications Installed**

Through CFD analysis, with a representative 6 degree wind yaw, Figure 16 shows a 22.9% reduction in aerodynamic drag on the 3rd car which is considered representative of the remaining cars in a unit car train. A drag development chart is shown with clear separation between the baseline and modified train car consist with a drag count reduction of 33 from a baseline of 144 cts (a dimensionless unit drag count measure) due to the addition of the simple and inexpensive aerodynamic treatments.




| 6° yaw | Run01 - Baseline | Run01 - Aeromods |
|---|---|---|
| Drag (cts) | 144 | 111 |
| Drag Delta | | -33 |
| % Difference | | -22.9% |

**Figure 16 – Drag Summary of Car 3 at 6 degree yaw**

Surface pressure plots shown in Figure 17 indicate far less air impingement due to closing off the gaps between the dump gates. All these seemingly small details can add up to a big improvement in fuel efficiency.

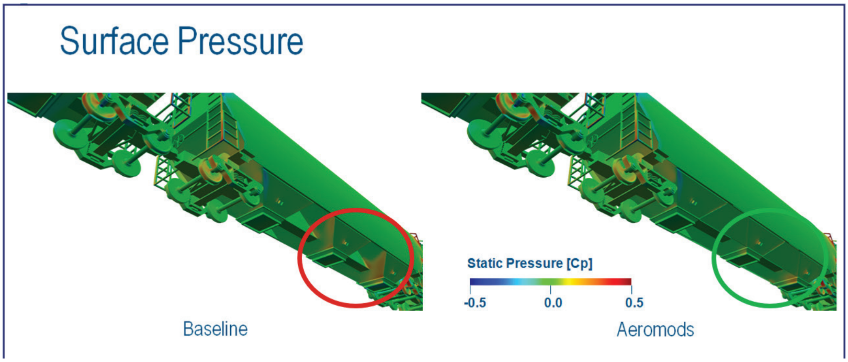



**Figure 17 – Surface pressure plot showing underbody impingement with and without aerodynamic treatment**

The wind tunnel used for testing is shown in Figure 18. Revenue field testing and Train Performance Simulator modeling all showed similar fuel savings from reduced drag. The range of savings from all four testing procedures ranged from a low of 6% to a high of 7.5% with close agreement between the various tests performed. This indicated a high degree of certainty that the simple aero treatments were successful in reducing drag and providing fuel savings in revenue service.

**Figure 18 – Wind Tunnel configured for G scale (1/29th) model testing (now owned by MxV Rail in Pueblo CO)**

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

This type of technology is agnostic to the fuel type being used to pull freight, so will be just as useful in the future for Battery Electric or Hydrogen Fuel cell powered locomotives pulling revenue freight trains.

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

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

## Biodiesel and Renewable Diesel Fuels

Biofuels usage is increasing as a method to reduce the carbon intensity of fuels to help meet the aggressive GHG reduction goals. However, there are challenges. Biodiesel, while available, has operability issues in cold weather which affect virtually all Class I railroads on portions of their network. Renewable diesel, has no such operability issues, though availability may be problematic given all transportation and other major industries which rely heavily on diesel fuel are looking to increase renewable diesel usage with a limited production volume increase forecast into the future.

Feedstocks for Renewable diesel are currently limited to the major sources of soybean and canola oil, animal fats, and used cooking oil, which are both somewhat finite in volume and only increase in direct correlation with population growth. Expansion for US Renewable diesel is limited not only by feedstock availability, but also by lack of support from existing Renewable fuel policies, per a new report from the clean fuel consultancy Cerulogy prepared for the International Council on Clean Transportation (ICCT)[6]

The price of biodiesel and renewable diesel may well become unattractive for railroads as many different industries both within and outside the transportation industry compete for a limited supply.

Table 3 shows the limited amount of publicly available locomotive biodiesel and renewable diesel test studies performed to-date. More research is required in this space to fully understand the operability of Biodiesel and the effect of lower energy content which affects both types of diesel biofuels.

Progress Rail has announced the approval of B20[7], while Wabtec is approved to B5.

**Biodiesel Studies in Locomotives**

| EPA Tier => | T0 | T0+ | T1 | T1+ | T2 | T2+ | T3 | T4C | T4 |
|---|---|---|---|---|---|---|---|---|---|
| **Progress Rail - EMD** | | | | | | | | | |
| GP38-2 | X | | | | | | | | |
| GP39-3 | | | | | | | | | |
| GP/SD40-2 | | | | | | | | | |
| GP/SD50 | | | | | | | | | |
| GP/SD50 | | | | | | | | | |
| GP/SD60 MUI | | | | | | | | | |
| SD60E | | | | | | | | | |
| SD70M | | | | | | | | | |
| SD70MAC | | | | | | | | | |
| SD70MACe | | | | | | | | | |
| SD70ACe | | | | | X | | | | |
| SD70ACe-T4 | | | | | | | | | |
| **Wabtec - GE** | | | | | | | | | |
| B40-8 | | | | | | | | | |
| C40-9 | | | | | | | | | |
| C44-9 | | | X | | | | | | |
| AC4400 | | | | | | | | | |
| ES44DC | | | | | X | | | | |
| ES44AC (C4) | | | | | | | X | | |
| ES44AC - vspeed | | | | | | | | | |
| ET44AC | | | | | | | | | |

**Renewable Fuel Studies in Locomotives**

| EPA Tier => | T0 | T0+ | T1 | T1+ | T2 | T2+ | T3 | T4C | T4 |
|---|---|---|---|---|---|---|---|---|---|
| **Progress Rail - EMD** | | | | | | | | | |
| GP38-2 | | | | | | | | | |
| GP39-3 | | | | | | | | | |
| GP/SD40-2 | | | | | | | | | |
| GP/SD50 | | | | | | | | | |
| GP/SD50 | | | | | | | | | |
| GP/SD60 MUI | | | | | | | | | |
| SD60E | | | | | | | | | |
| SD70M | | | | | | | | | |
| SD70MAC | | | | | | | | | |
| SD70MACe | | | | | | | | | |
| SD70ACe | | | | | | | | | |
| SD70ACe-T4 | | | | | | | | | |
| **Wabtec - GE** | | | | | | | | | |
| B40-8 | | | | | | | | | |
| C40-9 | | | | | | | | | |
| C44-9 | | | | | | | | | |
| AC4400 | | | | | | | | | |
| ES44DC | | | | | x | | | | |
| ES44AC (C4) | | | | | | | X | | |
| ES44AC - vspeed | | | | | | | | | |
| ET44AC | | | | | | | | | |

**Table 3 – Locomotive Studies Performed with Biodiesel and Renewable Diesel Fuels**

Figure 19 shows a bubble plot of the volume-weighted average carbon intensity from CARB certified fuel test samples for both Biodiesel and Renewable diesel. Note the very broad distribution for both types of biofuels. Not all biofuels are the same in terms of their carbon intensity – being able to choose fuels that are towards the lower end of the scale would help lower associated carbon emissions considerably.

**2021 Volume-weighted Average Carbon Intensity by Fuel Type for Liquid Fuels**

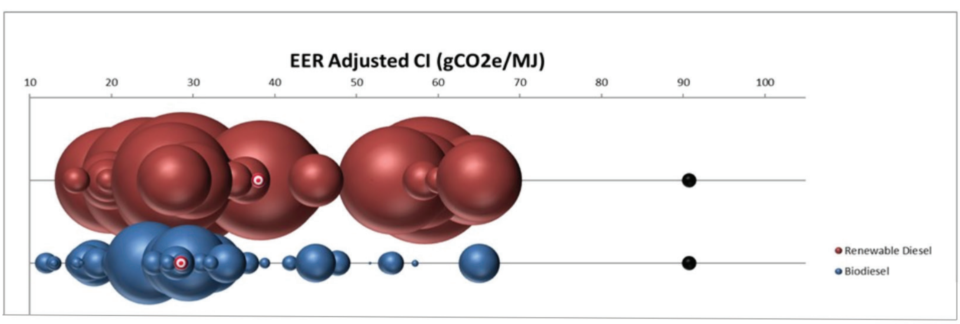



**Figure 19 – Bubble Plot of Energy Based Carbon Intensity of both Biodiesel and Renewable Diesel Fuels[8]**

## Getting to Actual Fuel Savings

Many technologies, regardless of their platform, advertise fuel savings that have been quantified through controlled testing, devoid of the typical operational variation that is freight railroading. Operational field testing, is by far the most realistic avenue to determine actual fuel savings and many factors will then need to be applied before an "actual" and "bankable" fuel savings amount can be quantified. Without an adequate "actual" fuel savings percentage, determining ROI (Return on Investment) becomes problematic and unrealistic.

Figure 20 shows five different technology platforms, including operational change and training programs all with the intent of saving fuel and reducing GHG emissions intensity. To the right of each different technology platform are different "hoops" that need to be progressively jumped through to arrive at a final realistic fuel savings. In the statistical world, this is often referred to as a "Rolled Throughput Yield" where the probability of success (percent fuel savings in this example) is dependent on passing through successive filters, or criteria to end up with a final end process, or actual fuel savings. This figure will often differ significantly from what is advertised by a vendor where testing has been performed in near laboratory conditions with little field variation being introduced.

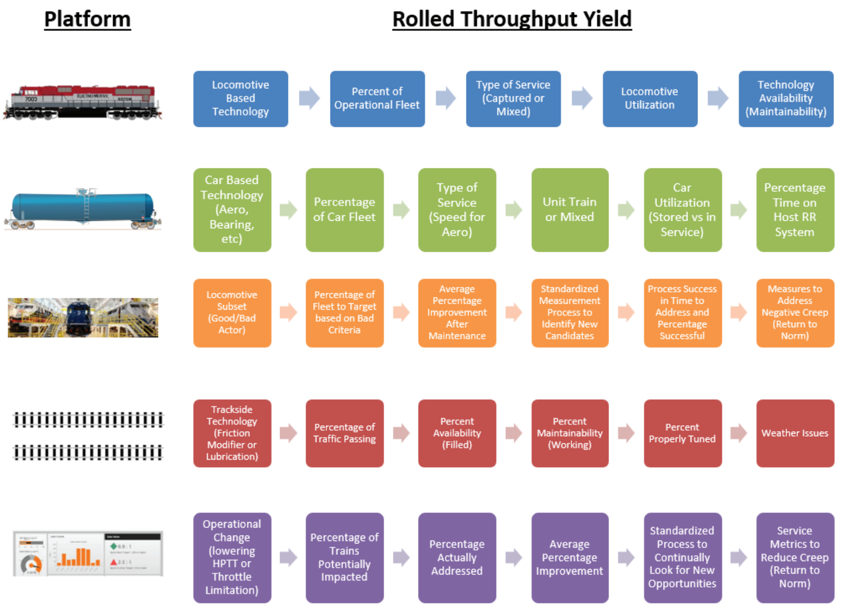



**Figure 20 – Rolled Throughput Yield for Various Fuel Saving Technology Platforms**

## Future Technology Progression

Figure 21 shows a pictorial timeline for various alternate locomotive fuel technologies such as natural gas (NG), battery electric (BEL) and hydrogen fuel cells (HFC). Virtually all Class I railroads have dabbled in natural gas technology, even sharing tender cars for various field tests over the last three decades. Hydrogen fuel cell powered locomotives have been attempted by BNSF and more recently championed by CP. Battery electric locomotives have a long history as switcher power, and both OEM vendors have various offerings for both yard and line-haul locomotives. UP made the largest splash by announcing the purchase of 20 yard switcher locomotives to be delivered in 2023 at two of their major yard facilities.

While the technology development for both BEL and HFC appear to have the upper hand at present, the power density of BEL is nowhere near what would be needed for a line-haul locomotive and the infrastructure for both technologies is still in the early stages of development with the AAR. As presented earlier, it's a certainty that both BEL and HFC driven fuel technologies will not be moving the needle significantly to achieve the aggressive SBTi goals out to 2029/2034.

As to the long term net zero 2050 emissions goal that CN has committed to thus far, and UP announced the intent to do so in the future, these technologies may indeed end up being the sole available paths to achieve those long term goals. This assumes the technology can be advanced and improved quickly and that it is likewise adopted quickly. For perspective, the transition from steam power to the current diesel-electric took more than four decades.

In the interim, many technologies and operational approaches exist to significantly reduce GHG emissions using the current diesel-electric installed fleet. This is likely sufficient to reach the near term goals, but it will require an "all hands on deck" and "what projects to pursue? – all of them" type mentality.


**Figure 21 - Technology Progression Pictorial from the 1980's thru to the Present Decade**

## Trucks versus Rail – Possible Threat?

The oft mentioned quote that "rail is three to four times more fuel efficient than truck" could be in jeopardy in the future depending upon how quickly the rail industry accelerates their fuel efficiency improvement glide slope and what new technologies the trucking industry adopts.  This may include electric or fuel cell vehicles with autonomous capability.

The obvious advantage that the trucking industry has over rail is their relatively quick comparative speed in introducing new technology due to turning over assets - every 2 to 4 years, on average for tractors and every 8 years on average for trailers.  Compare this to the rail industry where locomotives and freight cars can be in service for almost 50 years thus making new technology adoption very slow.

An excellent organization for the trucking industry is NACFE, the North American Council for Freight Efficiency which was formed in 2009.  Their mission is to "drive the development and adoption of (fuel) efficiency enhancing, environmentally beneficial, and cost-effective technologies, service and methodologies in the North American freight industry.[9]

Figure 22 shows a NACFE illustration[10] showcasing the 85 different technologies grouped into fifteen separate categories, all currently available for adoption into existing and new fleet purchases.


**Figure 22 – Technology Groupings for Tractor / Trailer Fuel Efficiency Technologies**

With so many different technologies to choose from, what type of mechanism exists to help with deciding which ones to adopt quickly and which ones to allow to mature for future adoption, or simply to leave alone? NACFE also provides confidence ratings and payback information per the graphic in Figure 23 which helps with the decision making process.

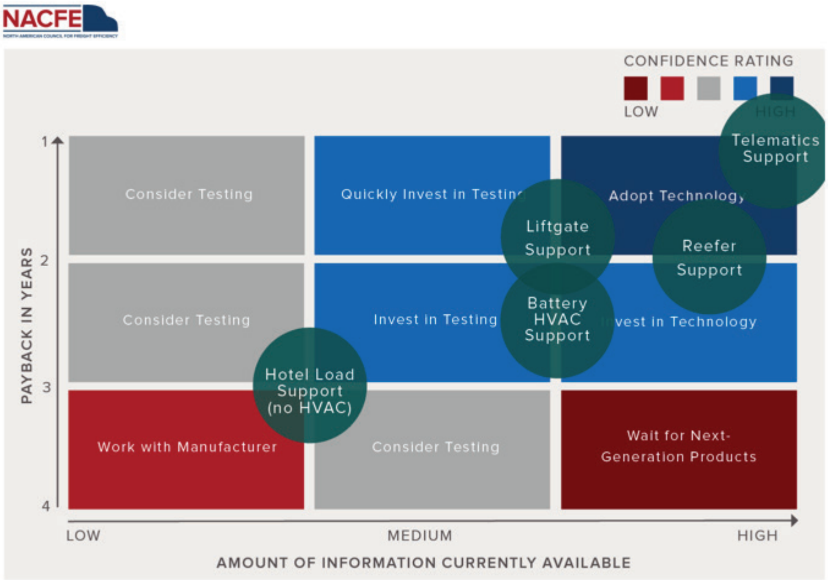



**Figure 23 – Technology Adoption Grid Showing Confidence Ratings, Payback and Available Information Metrics**

So, with all this plethora of information available from NACFE, do fleets that use this information actually perform better than fleets that do not? Figure 24 shows the difference, and it is significant. Further, the Department of Energy (DoE) has provided significant funding in the form of SuperTruck I, II and currently III to both assist in the development and research of future technologies, and the implementation of cutting edge technologies including battery electric vehicles.

Given technologies have been identified through DoE funding to almost double the existing fuel efficiency of the trucking industry and the fact that a sampling of SBTi and other GHG emissions goal reduction appear to be more aggressive than the goals that railroads have announced (39% to 55% for trucking versus 26% to 43% for rail within comparable time frames) – there could be a future threat from the trucking industry that would shrink that "three to four" fuel efficiency advantage for rail, more towards truck, which already has the built-in advantage of first / last mile convenience and improved service metrics with consistency and reliability enhancements over rail.

When will the rail industry develop an organization comparable to what NACFE provides for the trucking industry? Looking at the various Class I railroads and what initiatives they are working on to provide greater fuel efficiency, there does not appear to be a unified information sharing approach that can benefit the industry as a whole.

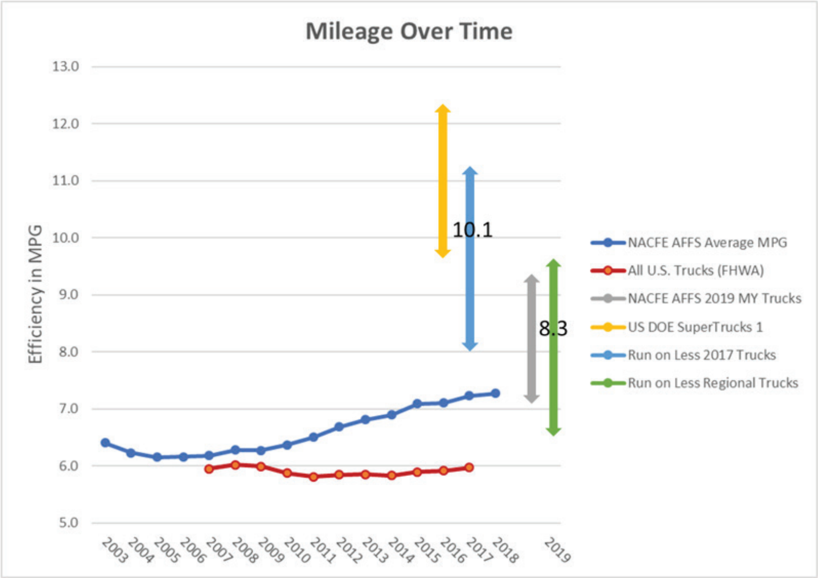



**Figure 24 – Fuel Efficiency Trends for Various Fleets and Future Possibilities from DoE SuperTruck Funding**

## Collaboration and Industry Leadership from the AAR

The AAR recently published an article "Freight Railroads & Climate Change"[11] which outlines various approaches to increasing fuel efficiency shown in Figure 25. Most of these initiatives have been in practice for many years and few are considered new technology. Aerodynamics is one bright spot of untapped capability though lacks the required plan and funding at present to move forward in a meaningful way to make this an industry strategic initiative.

The document highlights the need for "significant investments are essential to unlocking energy solutions capable of reducing GHG emissions" – hopefully the various committees already in place can take a NACFE approach to providing the needed leadership for the rail industry to attain their short term SBTi goals.

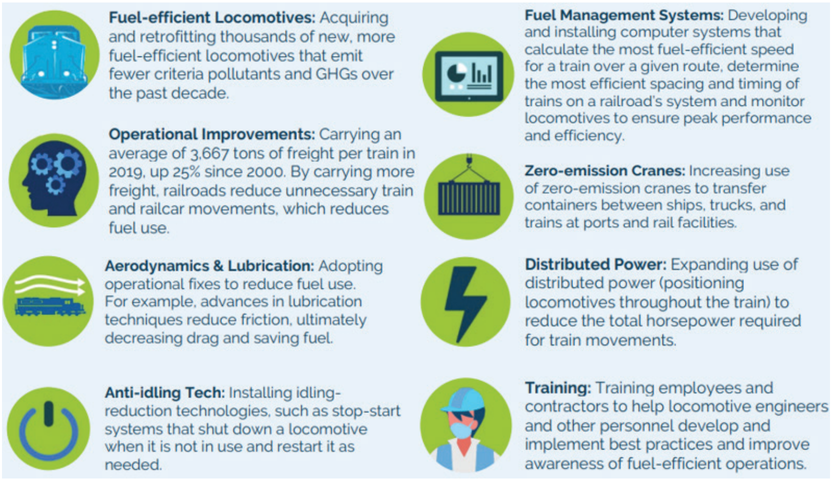



**Figure 25 – Various Technology, Training and Approach Initiatives for Rail Fuel Efficiency Improvement**

## Conclusion

The rail industry stands at a critical juncture in a post PSR world. The need for reliable, dependable and efficient customer service performance has never been greater, while new carbon-free locomotive technology to attain a 2050 long term net zero GHG emissions goal will be the largest motive power technology leap for the industry since moving from coal fired to diesel-electric locomotive power beginning in the 1930's, often referred to as Dieselization.

Even the near term SBTi goals out to 2030 seem very difficult to achieve with the current level of technology investment and operating practices, given the historical performance of a 1% per year improvement in fuel efficiency pales in comparison to the required 2.5% a year improvement needed immediately and continuing every year for the next 8 years.

A primer for accelerating GHG emissions reduction is summarized in the following steps:

1. Take an honest look at the inventory of fuel conservation initiatives planned, will they suffice for both short and long term SBTi goals? (the honest answer is likely - no)
2. Refer to Figure 5 – when asking which projects do we need? The answer is "all of them"
3. Industry and Government funding will be key
4. Some technology approaches need an industry push / support, such as aerodynamics, comprehensive track lubrication, air leak detection, and AESS effectiveness

5. Industry collaboration and leadership (NACFE like service) in conjunction with OEM support will be crucial for long term success
6. Biofuels will likely be an expensive stopgap solution for attaining a portion of a railroad's SBTi goals

A full-court-press and "all-in" approach, with full support from various critical railroad departments (Legal, Environmental, Operations, Finance, Purchasing, Fuel Management and the most important, Mechanical) will be able to yield not only the short term goals, but additional improvement as a net-zero goal is approached by 2050.

New approaches and new technologies outlined in this paper will be sufficient to meet SBTi goals if the railroads move quickly, but delay will quickly "eat up" the available runway to attain the aggressive goals outlined.

Leadership from the AAR and FRA, including targeted funding, and an industry mindset of "a rising tide lifts all boats" and best practices sharing will pave the way towards GHG emissions reduction success.

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