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H2@RailSM Workshop

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ABSTRACT

This report serves as the proceedings of the H2@RailSM Workshop held by the US Department of Energy's (DOE's) Fuel Cell Technologies Office (FCTO) and the US Department of Transportation's (DOT's) Federal Railroad Administration (FRA) on March 26-27, 2019 at Michigan State University in Lansing, MI. The workshop was specifically held to help identify needed research to accelerate technology development and industry commercialization regarding the use of hydrogen fuel cell systems in locomotives and rail applications. Experts and stakeholders from academia, government, and industry met at the workshop to assess the state of the art on rail propulsion. Discussions focused specifically on using fuel cells, operational requirements, and lessons learned about early fuel cell rail projects, and the identification of current technology gaps and collaborative R&D needed to close these gaps. This report summarizes the diverse perspectives and constructive ideas generated by the dedicated individuals who attended the workshop.

Prepared by: Sandia National Laboratories

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We are grateful of Sanjay Gupta of Michigan State University for delivering the opening remarks that inspired and helped frame this workshop and Andreas Hoffrichter of Michigan State University's Center for Railway Research and Education.

The workshop organizers wish to thank those who presented informative briefings at the workshop on the status of relevant technologies and key challenges, including Mark Maday, Phani Raj, Momoko Tamaoki, Carrie Schindler, Elena Hof, Leanna Belluz, Seky Chang, Michael Fore, Michael Cleveland, Mark Duve, Scott Nason, Reid Larson, Alan Mace, Rob Harvey, Jens Steger, Andreas Frixen, Andreas Hoffrichter, Rajesh Ahluwalia, Brian Ehrhart, and Lynn Harris.

We gratefully acknowledge the valuable ideas and insights contributed by the stakeholders who participated in the H2@RailSM Workshop. The willingness of these experts to share their time and knowledge has helped to identify current and emerging opportunities to accelerate the development and deployment of hydrogen rail technologies. Participating organizations are listed in Appendix B of this report.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AAR	Association of American Railroads
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CNG	compressed natural gas
DMU	diesel modular unit
DOE	US Department of Energy
DOT	US Department of Transportation
DOT-MARAD	US Department of Transportation Maritime Administration
DOT-FRA	U.S. Department of Transportation Federal Railroad Administration
EERE	Office of Energy Efficiency and Renewable Energy
EMU	electric multiple unit
EPA	US Environmental Protective Agency
FCTO	Fuel Cell Technologies Office
FLIRT	Fast Light Intercity & Regional Train
GHG	greenhouse gas
HMU	hybrid (diesel/hydrogen) modular unit
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
ISO	International Organization for Standardization
kg	kilogram
km	kilometer
KRRI	Korea Railroad Research Institute
kW / kWhr	kilowatt / kilowatt hour
LNG	liquid natural gas
M&O	maintenance and operations
mph	miles per hour
MW	megawatt
NCDOT	North Carolina Department of Transportation
NOW	National Organization for Hydrogen and Fuel Cell Technology, Germany
OCS	overhead catenary systems
PEM	proton exchange membrane
R&D	research and development
RD&D	research, development, and demonstration
RD&T	Office of Research, Development, & Technology
SBCTA	San Bernardino County Transit Authority

Abbreviation	Definition
SOFC, SOFC-GT	solid oxide fuel cell, solid oxide fuel cell-gas turbine
TCO	total cost of ownership

EXECUTIVE SUMMARY

Introduction

The workshop on hydrogen rail applications was attended by representatives from over 40 organizations across academia, government, and industry. The workshop agenda is provided in Appendix A, and a list of workshop organizations is provided in Appendix B.

The first day of the workshop focused on domestic and international government agency perspectives. The second day highlighted technology status and development, R&D topics, and industry perspectives on hydrogen rail activities. Topic sessions were followed by panel discussions on relative challenges and issues.

This report captures the key themes discussed by the workshop participants and provides details on specific recommendations and collaborative opportunities. The report includes presentation overviews, panel discussion summaries, and a summary of major outcomes, recommendations, and envisioned pathways forward in the development and deployment of hydrogen rail technology and international collaboration.¹

Current Status/State-of-the-Art for Hydrogen Rail Applications & Technology

The panels showcased a need for collaboration and information sharing, hydrogen research needs, the role of government funding in hydrogen rail technology development, the importance of public education regarding hydrogen and its applications, the state of hydrogen safety codes and standards, and infrastructure needs for hydrogen rail technology.

- Technology, economics, and safety are among the foremost challenges facing hydrogen applications for rail. Economics—the cost of fuel, power system acquisition and operations, and maintenance—must be competitive with costs for diesel power. In addition, the reliability of the fuel cell power system is also critical.
- Additional research and related activities are needed in multiple areas, including:
 - Cost assessment: as the predominate factor in the total cost of ownership, fuel cost requires more analysis and regional, national, and international strategies. Financial and technical assistance for hydrogen and fuel cell system technologies in rail applications is needed near term to achieve technical-economic parity with diesel locomotives.
 - Public education and perception: activities that increase public awareness and understanding of hydrogen and fuel cell technologies are needed to facilitate the implementation of technology demonstration projects and lead the way for long-term commercial adoption.
- Safety codes and standards have yet to be developed specifically for hydrogen fuel and power systems for rail applications. Harmonizing international standards might expedite the spread and use of hydrogen fuel and fuel cell power systems for rail applications. The time frame required to develop standards may also be shortened based on lessons learned from liquid natural gas (LNG) tender (i.e. fuel car) specifications that have been established by the US rail industry.
- Establishing a fueling infrastructure remains an important and immense endeavor, which is essentially undeveloped.
- Workshop participants also emphasized the importance of maintenance. Railroad operators aim to maximize operating time for their locomotives—more time in maintenance shops translates

¹ Participants were asked to provide copies of their presentations. The full presentations are available at the [workshop website](http://www.energy.gov/eere/fuelcells/h2rail-workshop) (www.energy.gov/eere/fuelcells/h2rail-workshop).

to more equipment cost. Other factors, such as replacement parts availability, pose a concern. Existing technology offers a well-understood design, replacement parts in easy supply, and high degree of reliability.

Panel Session Highlights

The following topics and research areas were suggested as priorities for advancing hydrogen and fuel cells in rail applications.

- R&D related to on-board storage, refueling infrastructure, and fuel cell power systems
- Hydrogen safety and safety codes and standards development for hydrogen fuel
- Reduced cost for hydrogen fuel

Accelerating Progress

Attendees suggested the following steps to accelerate progress:

- Conduct R&D to develop rugged fuel cell systems and liquid hydrogen fuel tender car technologies.
- Conduct demonstration projects to accelerate the progress of hydrogen technology and use.
- Some workshop attendees suggested next steps should include the development of international safety codes and standards.
- Improve public acceptance of hydrogen technology through public education and outreach, leverage the success of existing demonstration and deployments, and disseminate the results of hydrogen rail projects to the public.

A Closer Look at Total Cost of Ownership

The total cost of ownership (TCO) analysis of diesel and fuel cell locomotives presented at the workshop described the levelized costs of drive train and fuel storage, lifetime fuel cost, and the cost of engine maintenance, including overhaul costs for three different types of locomotives: long-haul freight (also known as line-haul), regional commuter passenger locomotives, and yard switchers (also known as shunters). Compared to the freight diesel locomotives, the initial capital cost of the fuel cell locomotive is 30% higher largely because a liquid-hydrogen refueled tender car is needed. Even though fuel cells have 30% higher efficiency on an EPA freight duty cycle, the break-even cost of delivered hydrogen relative to diesel at \$2.25/gal is \$2.20/kg. Cryogenic hydrogen storage is also preferred for regional commuter passenger locomotives, and the hydrogen can be stored on-board without the need for a dedicated tender car. The fuel cells are projected to have 37% higher efficiency on a representative regional duty cycle, and the break-even hydrogen cost to be competitive with diesel technology is \$3.50/kg. Fuel cells are attractive for deployment in yard switchers because hydrogen can be stored as a compressed gas at 350 bar and have 77% higher efficiency on EPA duty cycles for switchers. These analyses are preliminary and need to be further developed.

Conclusion

The workshop resulted in some clear direction for moving the technology forward. Of the three applications discussed (i.e., commuter passenger, yard switchers, and line haul freight locomotives), freight locomotives for long distance hauling is the most technically challenging but has the highest societal value in that the diesel volume displacement with hydrogen fuel would add significantly to

economies-of-scale and reduced fuel cost. Also, a hydrogen fuel cell locomotive for line haul service will require the design and development of a hydrogen fuel tender car either by industry alone or by industry with government assistance.

Future critical developments needed to move the technology forward include higher efficiency fuel cell systems, taking advantage of lower projected costs and modularity, higher durability membrane electrode assemblies using advanced materials, tighter system controls and optimized operating conditions, and the ability to deliver hydrogen to the locomotives at a competitive cost.

1. TECHNICAL SESSIONS

Along with the introductory remarks, four technical sessions were held over the course of the two-day H2@RailSM Workshop. Session topics focused on hydrogen fuel cells for powering rail vehicles:

1. Domestic government perspectives
2. International status
3. Industry perspectives
4. Hydrogen rail assessments

Each technical session included between three and seven panelists, who provided an overview of their relevant work or areas of expertise followed by a panel discussion. Following the sessions, workshop participants had the opportunity to network informally and continue their discussions with the presenters.

1.1. Introductory Remarks

Introductory remarks were provided by Sanjay Gupta, Dean of the Broad College of Business within Michigan State University, and Sunita Satyapal, Director of the Fuel Cells Technology Office within DOE.

1.1.1. Welcoming Remarks from Michigan State University

Sanjay Gupta - Dean of the Broad College of Business, Michigan State University

It is hoped that these workshop discussions lead to sustainable solutions, enabling attendees and others to consider and address climate issues and initiate larger efforts. Michigan State University's experience with DOE-funded research, its strong supply chain management program, and the Center for Railroad Research and Education at Michigan State University make it a suitable venue for these discussions.

1.1.2. Welcoming Remarks from Fuel Cell Technologies Office

Sunita Satyapal, Director, US Department of Energy's Fuel Cell Technologies Office

The DOE H2@Scale program explores the potential for wide-scale hydrogen production and use in the United States. In alignment with H2@Scale, two existing initiatives—H2@Rail (with the U.S. Department of Transportation Federal Railroad Administration, or DOT-FRA) and H2@Ports (with the Department of Transportation Maritime Administration, or DOT-MARAD)—conduct R&D to assess the technical and economic potential of hydrogen use for prime propulsion and auxiliary power for rail and maritime applications. If hydrogen technology and cost targets are met, they could compete with diesel-powered equipment for various rail applications. Most US regions have sufficient hydrogen resources to meet demand, with clusters of potential demand along freight routes.

Using hydrogen for large-scale applications across sectors aligns with the H2@Scale initiative and can enable energy security, provide economic value, and offer environmental benefits. Examples exist of fuel cell activities for rail applications such as the BNSF Fuel Cell Shunter in California (2008), the CRRC Fuel Cell Tram in China (2015), and the Alstom Coradia iLint in Germany (2017). In the United States, interest in hydrogen and fuel cells is increasing, with states investing more than \$180 million in hydrogen infrastructure in the last decade. Collaboration, as well as additional research and development, is still needed to realize the potential of hydrogen production and use.

Large-scale end-use applications such as heavy-duty trucks, marine, and rail, and industrial applications (such as steel and ammonia manufacturing) can help achieve economies of scale, reduce cost, and spur infrastructure development.

2. SESSION I: DOMESTIC GOVERNMENT PERSPECTIVES

The first workshop session focused on federal agencies and state entities involved in hydrogen rail applications. The presentations covered trends, related initiatives, relevant past and ongoing alternative fuel projects, and processes.

2.1. Federal Railroad Administration Program R&D Overview

Melissa Shurland, Program Manager, US Department of Transportation - Federal Railroad Administration (DOT-FRA), Office of Research, Development, and Technology

The FRA seeks to ensure that passengers and goods are transported as safely as possible. The Office of Research, Development, and Technology (RD&T) provides science-based data for regulatory decisions by the agency. While safety is their main driver, the FRA also strives to support innovation and industry.

Within the RD&T, the Rail Energy, Environment, and Engine Technology Research Program advances the modernization of rail transportation through research, development, and demonstration efforts. FRA collaborates through the DOE national laboratories to work closely with industry and promote the safe use of innovative technology.

The FRA has conducted alternative fuels research—including a collaboration with the Association of American Railroads (AAR), DOE national labs, and rail equipment manufacturers—resulting in natural gas as an alternative fuel of interest for rail. This collaboration has supported the development of AAR specifications for natural gas fuel tender cars. Currently, the program is assessing the crashworthiness of a liquefied natural gas fuel tender built structurally to the AAR specifications. From 2014-2016, FRA investigated solid oxide fuel cells for rail applications. They are currently looking into hydrogen and fuel cell technologies for rail applications via an impact study on the applicability and safety of hydrogen for rail.

2.2. Federal Railroad Administration Locomotive Alternative Fuels and Cryogenic Commodity Transportation Projects and Regulations

Mark Maday, US Department of Transportation-Federal Railroad Administration, Hazardous Materials Division
Phani Raj, General Engineer, US Department of Transportation-Federal Railroad Administration, Office of Safety

Several examples of LNG usage on rail exist, including two pilot projects that tested the use of LNG as a locomotive fuel, and one project for the shipment of LNG in portable tanks. It is anticipated that hydrogen usage on rail would follow the same FRA Alternative Fuels Program approvals set forth in 2013. The program requires approval by the Associate Administrator of Railroad Safety and is the responsibility of the host railroad. Applicants should expect a multi-year program which would include a validation period. Standards would be developed by industry initially (AAR), with rule-making likely the last step in the process. The FRA can provide technical assessments; for example, a recent assessment studied how much hydrogen would be needed for a given scenario on a commuter train.

Presently, regulations authorize hydrogen for transport in DOT-113 tank cars, but (as of this session) there are no rail cars designed for hydrogen specifically, and any proposed design would be subject to AAR approval. Hydrogen is authorized in UN-T75 tank containers but requires approval from the FRA.

The FRA maintains policies and guidelines for LNG shipments on rail. Railroads must assure the FRA that proposed shipments are safe and provide information and assistance to communities and emergency responders along rail corridors. FRA's major safety concerns surrounding hydrogen include:

- Crashworthiness
- Performance of double-walled tanks
- Reliability and performance of valves, gaskets, and other equipment in cryogenic environments
- Performance of shut-off valves and devices under crash scenarios

2.3. California State Perspectives

Momoko Tamaoki, Office Chief of Assets and Equipment, California Department of Transportation (Caltrans)

California has multiple state stakeholders with interest in hydrogen as an alternative fuel. A state railway system would further mitigate greenhouse gas (GHG) emissions and support the state's goals in addition to offsetting infrastructure impacts. California's targets require sustainable, community strategies.

Currently, California has several state-supported rail corridors. Challenges in the rail system include uncertain short- and long-term demand, incongruence of operations and maintenance standards across industries, handling of a non-electrified network, and an aged and fragmented fleet.

Recent work with Sunline Transit Agency and their hydrogen fuel cell buses have provided a test bed for hydrogen technology development, infrastructure, and commercial operations. The San Bernardino County Transit Authority (SBCTA)'s low-emission Diesel Multiple Unit Conversion Project provides an additional example of hydrogen technology explored within the state. Further R&D is of interest to Caltrans, specifically prototype construction and testing. Caltrans is looking for the opportunity to partner with multiple agencies and entities. They appreciate that hydrogen is flexible, adaptable, and modular.

The California Air Resources Board (CARB) has expressed concern about locomotive emissions, particularly high NO_x and PM_{2.5} emissions from line haul locomotives. California state agencies have established a sustainable freight action plan which emphasizes improved freight efficiency, transitioning to zero emission technologies, and increased economic competitiveness. A CARB technology assessment found no clear path to zero emissions, observing major challenges in line haul applications. They found that line haul requirements may not be met by batteries alone due to the long range and heavy-duty cycle requirements. They also identified that public incentives remain an important part of encouraging hydrogen technology and its adoption. The California Energy Commission is interested in several areas of hydrogen R&D, namely long-term energy storage, and the potential for hydrogen to electrify sectors otherwise difficult to address with battery-electric systems (e.g., rail or marine sectors).

2.4. San Bernardino County Transportation Authority

Carrie Schindler, Director of Transit and Rail Programs, San Bernardino County Transportation Authority

San Bernardino County Transportation Authority (SBCTA) has embarked on the Redlands Passenger Rail Project which will extend a nine-mile passenger rail service from the City of Redlands to San Bernardino. For the project, SBCTA has received funding to assess the most suitable technology for the conversion of a diesel multiple unit to a zero-emission multiple unit.

As part of the project, SBCTA selected their preferred technology by evaluating cost, infrastructure, environmental considerations, operations, regulatory compliance, implementation schedules, and risk. The project team toured nearby hydrogen facilities and investigated other available hydrogen technologies. As part of the next key task in the project, they have assembled energy usage and modeling scenarios. The SBCTA has engaged the FRA and outlined next steps to the request for proposal stage and beyond.

2.5. Panel Discussion

Following the session presentations, presenters participated in a panel discussion moderated by Pete Devlin, DOE-FCTO.

Panel Discussion Summary:

When considering the investment into and commercial use of hydrogen, it is important to understand that passenger rail is not profitable, but highly needed; line-haul/commercial haul is the “best bet” for high environmental impact.

For government organizations to coordinate and collaborate in order to successfully commercialize hydrogen for rail, there are several factors for success:

- The transparent sharing of technical information.
- Funding to overcome roadblocks to technology development that meets safety and cost requirements. (Partnerships play an important part in funding.)
- Coordination of activity and communication. (Standards development provides cohesion among stakeholders.)

Discussion also delved into synergies between hydrogen use and development for rail and marine ports. Panelists observed similarities related to how LNG vessels are performing maintenance and operations (M&O) requirements for the Coast Guard and how LNG conversion utilizes dual purpose energy sources.

Technology is not the sole issue for hydrogen rail development; it is simultaneously the technology, legal system, economics, safety, and public perception. International implementation and acceptance may help encourage US implementation and acceptance.

3. SESSION II: OVERVIEW OF INTERNATIONAL STATUS

The second workshop session focused on the status of hydrogen rail internationally. The presentations covered trends, related initiatives, relevant past and ongoing alternative fuel projects, processes, successes, and continued international needs.

3.1. Hydrogen Rail Status in Germany

Elena Hof, Program Manager, National Organization for Hydrogen and Fuel Cell Technology, Germany

Hof is a program manager within NOW, the National Organization for Hydrogen and Fuel Cell Technology, which serves as a link between industry and government. Currently in Germany, hydrogen-powered rail holds significant potential as a large portion of the rail network is powered by diesel and electrification can be costly. Germany expects increased rail traffic and sees particular potential for fuel cells in heavy duty applications (e.g., freight) where longer distances without catenaries and inexpensive hydrogen sources may make fuel cells profitable.

Germany has embarked on multiple fuel cell and battery electric train R&D projects, including the Coradia iLint project, which developed and validated a fuel cell electric train for passenger service in Lower Saxony, Germany. When examining rail propulsion options in Europe, in areas where much of the rail system is already electrified, hydrogen fuel cell technology may not make sense, such as in Switzerland and the Netherlands. However, in countries where much of the track is not electrified, hydrogen fuel cell powered trains may hold significant potential.

Common hydrogen rail project challenges include costs, financing, and regulatory and legal aspects of hydrogen. Risk surcharges pose an additional challenge. Furthermore, battery and fuel cell technology remain more expensive and it remains unclear which entities are responsible for hydrogen infrastructure in terms of costs and risks. Due to levies, costs remain high for 'green' hydrogen production through electrolysis. Hydrogen rail projects face lengthy approval and application procedures, require access to infrastructure owned by the train supplier, and encounter the legal aspects of tendering procedures.

Funding requests have overwhelmed the demand for train acquisition and NOW is currently conducting a detailed market analysis of their tracks to identify the optimal technologies and tender options for specific applications. The analysis will be used to guide funding decisions and expectations for applications.

3.2. Hydrogen Rail Status in Canada

Leanna Belluz, Senior Engineer, Transport Canada Innovation Centre

Many projects with the intention of improving rail transport and its environmental impact are underway in Canada:

- Transport Canada's new Innovation Centre works on alternative fuels research resulting from government directives.
- The Metrolinx Hydrail Feasibility Study examined the potential for a hydrogen fuel cell system in passenger rail networks, and made recommendations regarding risks, codes, and standards.
- Transport Canada's Rail Safety Group is evaluating regulations in the hydrogen space.

- CSA Group Hydrail is developing a standards and codes roadmap for hydrogen rail application.

3.3. Hydrogen Rail Status in South Korea

Seky Chang, Chief Researcher, Korea Railroad Research Institute

The Korea Railroad Research Institute (KRRI) has begun a hydrogen fuel cell-powered train project in response to the 2015 Paris climate agreement. Hydrogen fuel cell-powered automobiles and buses are popular—but their application to railways have been limited. As of this workshop, there are no hydrogen fuel cell-powered trains in South Korea. In KRRI’s proposed hydrogen fuel cell train system, power is generated from the 1.2MW fuel cell stack, which travels through a DC-DC converter to power a battery pack for both prime propulsion and auxiliary power. During braking, the battery also provides regenerative braking for the system. The KRRI’s primary goal is a hydrogen fuel cell train with a hybrid power system. KRRI is in the early stages of the project—designing and manufacturing devices, analyzing operations, and planning the fueling infrastructure—and anticipates the technology developed could be applied to light rail or tram operations or replace diesel locomotives. Hydrogen can reduce costs, improve safety, and be integrated easily with respect to light rail and tram applications.

Major challenges include public perception of safety, regulatory changes, and cross-sector collaboration. The KRRI is interested in and still sees a need for international joint research, hydrogen fuel cell train authentication process and standards, a road map for hydrogen economy and policy in the United States, and economic analyses for hydrogen fuel cell train systems.

3.4. Panel Discussion

Following the session presentations, presenters participated in a panel discussion moderated by Dr. Shuk Han Chan, DOE-FCTO.

Panel Discussion Summary:

Major areas of international interest are hydrogen for heavy duty use and synergy with freight trucks using hydrogen. Some feasibility studies have been completed and have concluded that government support of hydrogen and hydrogen R&D is crucial. To address public perception, which is a major hurdle, increased education, transparency of codes and standards, stakeholder input, and first responder trainings were recommended. Establishing a unified language for codes and standards has been slow, but international groups like IPHE and FCHJU are fostering harmonization.

4. SESSION III: INDUSTRY PERSPECTIVES

The third session of the workshop focused on industry perspectives on hydrogen rail—first from operators, then technology developers. The presentations covered trends, related initiatives, relevant past and ongoing alternative fuel projects, processes, successes, and continued needs.

4.1. Operator Perspectives

4.1.1. The American Association of Railroads

Michael Fore, Director of the Technical Services Group/Locomotive Committee Manager, American Association of Railroads

The American Association of Railroads (AAR) focuses on the safety and productivity of the US rail industry. The AAR's recent project, "AskRail," provides information for first responders. The AAR has several dockets for the reporting and review of developments in alternatives fuels. The docket LM-121, "Natural Gas Fuel Tenders" addresses standards for natural gas fuel tenders for the railroad industry. Chapters on requirements for LNG, CNG, and other alternative fuels were covered, including instructions to access these emerging and revised specifications. Under a related alternative fuels docket, LM-126, a task force exists to address concerns with the effects of hydrogenation derived renewable diesel on locomotive equipment.

Safety, energy density, and infrastructure pose the primary challenges to hydrogen rail implementation.

4.1.2. BNSF Railway

Michael Cleveland, Senior Manager, Emerging Technology, BNSF Railway

BNSF has conducted multiple hydrogen or alternative fuel demonstration projects. In 2008-2009, BNSF partnered with Vehicle Projects and the US Army to build and conduct tests on hydrogen-powered switcher cars. BNSF is also developing a hybrid battery electric locomotive demonstration with General Electric, which will have two operating modes—mainline operating mode and yard operating mode—to target fuel and emissions reductions.

Rail faces multiple key hydrogen fuel challenges:

- Safety, due to the ruggedness and rough handling of the railway environment
- Energy density to cross long distances
- Infrastructure investment, as rail has a large, decentralized physical footprint

4.1.3. Norfolk Southern Railway

Mark Duve, Locomotive Engineering Manager, Norfolk Southern

Norfolk Southern has an older fleet with low fleet maintenance costs, so it can be difficult to justify technology substitutions or replacements. However, Norfolk Southern has worked with several US states to "repower" locomotives, meaning that they put newer engines on existing locomotives.

While Norfolk Southern collected multiple lessons from its use of genset locomotives, they encountered issues with replacement part availability, training, dealer maintenance, and the new technology not being rugged enough for the railroad's operating conditions.

Hydrogen must meet or exceed the performance, reliability, maintenance requirements, economic expectations, and safety requirements of current locomotives.

4.1.4. Panel Discussion

Following the session presentations, presenters participated in a panel discussion moderated by Phani Raj, DOT-FRA.

Panel Discussion Summary:

The biggest challenges for hydrogen and fuel cell technologies in rail include issues of safety and concerns in an abusive, railroad environment. Safety, infrastructure, implementation, and costs are key considerations for rail. To address these challenges, it may be helpful to look to natural gas and other alternative fuel technologies for ways to handle them. It may also be helpful if other applications ruggedize and develop the technology to a point that rail can duplicate the successes in their own industry.

Hydrogen-related innovations in Europe, small-route passenger rail in California, and elsewhere are exciting to the industry and there is the desire to see more such projects in North America. Small-route passenger service may provide a good starting point where small passenger vehicles, with shorter routes and less rugged use, pave the way for other uses.

A collaborative effort between railroads, first responders, suppliers, FRA, AAR, and other stakeholders would ensure the safe deployment of hydrogen technologies. The safety codes and standards effort supporting CNG/LNG provided a good foundation for hydrogen fuel cell technologies, particularly as a place to start. The rail industry tends to be slow moving, and capital costs are high, so rail operators do not tend to adopt new technology early and prefer to adopt technology developed or proven in another industry first. Cost is a key factor with regard to fuel choice. Price volatility and absolute value were both factors for the panelists. Unaddressed areas of discussion include segments of laws, zoning, property rights and ownership, and space constraints.

4.2. Technology Developer Perspectives

4.2.1. Chart Industries

Scott Nason, Product Manager, Chart Industries, Rail Products Group

Reid Larson, LNG Product Manager, Chart Industries

The use and presence of LNG on railways may be a precursor to liquefied hydrogen (cryogenics) on rail. Railroads have begun using LNG, relative to conventional fuels, because it costs less, burns cleaner, and is abundantly available. Hydrogen has similar advantages, but the cost is not yet lower than competing fuels.

When it comes to fueling, LNG offers advantages over CNG for heavy duty applications, such as a higher energy density, faster filling speeds, easily scalable infrastructure, and lower maintenance costs. Currently, most natural gas fueling is done via pumping whereas most hydrogen fueling today is done via pressure transfer. Hydrogen's physical properties make it difficult to pump, with liquid hydrogen being slightly easier. However, fewer liquid hydrogen pump options exist than gaseous hydrogen compression options. For hydrogen rail, some fueling options include using liquid hydrogen tenders, using bulk trailers or tanks to fuel the locomotive, or gaseous hydrogen tenders, using tube trailers or liquid-to-gaseous hydrogen fueling enabled via pumps.

4.2.2. Ballard

Alan Mace, Market Manager, Ballard

Hydrogen offers the benefits of electrification without as significant of an infrastructure investment as electric catenary, and retains the flexibility of diesel fuels. Rail environments require technology developers to consider the shock, vibration, noise, modularity, and flexibility of design. Ballard has embarked on many projects—past and present—that outline their work with hydrogen or hydrogen-related efforts on rail, both commuter and freight:

- A fuel cell tram demonstration project in Tangshan, China which will be the world's first hydrogen-powered tram in pilot test phase. The project uses two 150 kW power modules.
- A tram line in Foshan, China that will make use of ten rooftop-mounted 200 kW modules.
- The HydroFlex project in the United Kingdom, which converted an existing train to hydrogen, dual/hybrid capability with 100 kW modules.
- The hydrogen-powered electric multiple units (EMUs), a partnership with Siemens, which will include rooftop-mounted 200 kW modules.

Fuel cells and hydrogen provide an appealing solution for zero-emission rail.

4.2.3. Hydrogenics

Rob Harvey, Director of Energy Infrastructure, Hydrogenics

The business case from Hydrogenics uses the combined total cost of ownership (TCO) of rolling stock and energy infrastructure. In comparison to overhead catenary systems (OCS), hydrogen rail's advantages include a lower upfront capital expenditure and lower TCO over time, as well as faster implementation than OCS, thus faster revenue capture. Hydrogen rail also offers greater operational flexibility, is scalable, and avoids the negative aesthetics or visual impact of additional wires in urban areas.

The Hydrogenics fuel cell module includes integrated software and mechanical control, a self-humidified low-pressure stack, an unlimited start/stop and sub-zero operation, and a scalable stack for mobile and stationary applications. To address the rail environment, Hydrogenics incorporates safety and predictive maintenance into their designs, as well as onboard controls and diagnostics. Hydrogenics has developed multiple power modules for mobility applications.

For commuter hydrogen rail deployment, scaling of hydrogen fueling infrastructure and maturation of the hydrogen supply chain will be necessary. Passenger or commuter hydrogen rail takes advantage of shorter operating ranges, onboard gaseous fuel storage, overnight fleet stabling, and centralized fuel depots. Meanwhile, freight hydrogen rail would need to account for long haul freight routes, a lack of feasibility of gaseous hydrogen, North American-wide operator logistics, and the massive investment required to establish a hydrogen fueling infrastructure network, even with onboard liquid hydrogen. Research could examine other ambient onboard liquid fuels such as methanol, liquid organic hydrogen carriers, or ammonia.

4.2.4. Stadler US

Jens Steger, Technical Program Management, Stadler US

Stadler has recently developed and deployed a variety of power configurations. The Stadler Fast Light Intercity & Regional Train (FLIRT) can support multiple propulsion system configurations, such as electric, diesel, hydrogen, battery, or hybrid configurations.

In terms of alternative propulsion systems, Stadler's work with the San Bernardino County Transit Authority will be among the first hydrogen rail technologies in the United States.

A FLIRT offers multiple alternative propulsion systems and advantages:

- Electrical multiple units (EMU)
- Diesel multiple units (DMU)
- DMUs with super capacitors
- Bimodular multiple units (BMU)
- Hydrogen multiple units

Stadler is helping SBCTA reach longer passenger train routes (from Los Angeles to Redlands), and has found that hydrogen technology provides certain advantages, such as eliminating the need to electrify the train lines and the charging times required by trains powered solely by batteries. The equipment requires more frequent replacement compared to conventional technology, but the small corridor, combined with the willingness of SBCTA to implement alternative propulsion technology, offers the best "first application" to learn and advance.

4.2.5. Alstom

Andreas Frixen, Hydrogen Refueling Stations and Hydrogen Supply Expert, Alstom

Hydrogen, not diesel, may be the future of train service, considering the low rate of rail electrification (90% of US rail is not electrified), the greater resiliency hydrogen offers, the increasing price of diesel fuel, the air quality and noise reduction offered, progressive urbanization and the need to reduce pressure on grid at peak times, and hydrogen's higher energy density than diesel.

Alstom manufactured the Coradia iLint, the world's first hydrogen-powered train, which started daily passenger service in 2018 and serves 75 miles of track. The project underwent the process to convert the fuel cell train from a diesel modular unit (DMU) to a hybrid (diesel/hydrogen) modular unit (HMU). The resulting design criteria for fuel cell trains included:

- Retention of train dimensions
- Retention of weight/point of gravity
- Re-use of main components (e.g., bogie)
- Retention of performance (availability, reliability, acceleration, range, etc.)
- Avoid technical equipment in passenger areas
- Avoidance of adverse impact on passenger experience and comfort
- Achievement of high energy efficiency
- Scalability (retrofitting, freight/passenger mode)
- Interoperability (mixed fleet)

Hydrogen and battery use is not an either/or question but rather requires an understanding of when one makes sense or when a combined use of both technologies is best. Alstom's work in Germany led to the creation of a strategy for the validation and certification process, which involved starting with risk analysis.

If the industry proceeds with a global perspective, hydrogen can provide many benefits, including increased resiliency.

4.2.6. Panel Discussion

Following the session presentations, presenters participated in a panel discussion moderated by Dimitrios Papageorgopoulos, DOE-FCTO.

Panel Discussion Summary:

Currently, some of the primary barriers are large-scale refueling infrastructure, cost of hydrogen fuel, integration, and public perception. The industry needs to focus on increased storage capacity, increased efficiency, optimization, and combining efforts cross-industry. Collaboration, partnerships, and open discussion play key roles in finding paths and leveraging similar work done in the past.

From a regulatory perspective, it will be crucial to learn from CNG/LNG projects what makes sense and what doesn't, which standards need to be developed, and ways to find opportunities for new paths forward. Economically, hydrogen's competitiveness as a fuel is partly about delivery and production, both of which could benefit from improvements. Hydrogen costs are expected to become more competitive as time goes by.

5. SESSION IV: HYDROGEN RAIL ASSESSMENT

The fourth workshop session focused on recent hydrogen rail assessments. The presentations covered research on hydrogen rail development, the total cost of ownership estimates, and a metric for weighing technology advantages and disadvantages.

5.1. Hydrogen Rail Development

Andreas Hoffrichter, Professor & Executive Director, Center for Railway Research and Education

Currently, a shift from road to rail freight transportation would decrease criteria pollutants significantly. Due to the economics of North American freight rail, railroad interest in alternative fuels often tracks the cost of diesel. Fuel is typically among freight rail's top three operating expenses.

It has been observed that regenerative braking still makes sense for passenger rail, switchers, and freight with changing terrain. Based on analyses, diesel rail energy efficiency is typically 30-34%, whereas fuel cell system efficiency varies between 30-60%.

The Center for Railway Research and Education is currently researching freight switchers, regional passenger rail, and intercity type passenger rail. They also oversee graduate and PhD research involving heavy commuter, and mainline freight research, including a project which estimated energy consumption reduction for a hydrogen hybrid for the Capitol Corridor in California. The center found that a ballast may be needed for hydrogen fuel-cell-only locomotives. Hydrogen rail technology may be suitable for many railway services, but there is a need for technology demonstrators and government funding to advance hydrogen rail development.

5.2. Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives

Rajesh Ahluwalia, Fuel Cell and Hydrogen Group Manager, Argonne National Laboratory

Fuel may account for up to 80% of the total cost of ownership (TCO) of rail applications. Besides engine reliability and availability, fuel economy and cost are extremely important for freight and regional locomotives. For switchers, fuel may account for 55% of TCO. Capital, maintenance and refurbishment, and fuel costs are important.

An Argonne study found a preliminary TCO of fuel cells could be more favorable for yard switchers than freight or regional use. When compared to diesel electric systems, the higher cost of proton exchange membrane (PEM) power systems currently is attributable to the cost of delivered hydrogen fuel according to preliminary analysis. On a TCO basis, fuel cells could be 15% cheaper than diesel systems if developed to meet the DOE performance and cost targets.

To break even relative to a cost of \$2.25 per gallon for diesel, the cost of delivered hydrogen would potentially need to be as follows:

- Freight locomotives: \$2.20/kg
- Regional passenger locomotives: \$3.50/kg

Areas for further development may include studying membrane electrode assembly durability, the availability and reliability of fuel cell system components, the benefits of single stacks, and methods to meet or exceed the critical cost targets for delivered hydrogen.

5.3. Hydrogen for Rail Applications

Brian Ebrhart, Chemical Engineer, Sandia National Laboratories

Current research highlights three priorities disclosed to stakeholders: safety, operational efficiencies and network congestion, and emissions controls. These concerns were used to develop a framework to compare locomotive technology (diesel, electric track, hydrogen) to applications (freight, commuter, switcher), in order to compare the benefits of each pairing. Preliminary analysis results highlight trade-offs between all technologies; some technologies, such as renewable hydrogen, have large emissions reductions, but may require large infrastructure investment.

Future work will focus on quantifying trade-offs, evaluating specific US areas that hydrogen rail could benefit, and a liquid hydrogen assessment.

5.4. North Carolina Department of Transportation Rail Division Clean Propulsion Initiatives

Lynn Harris, Senior Project Engineer, North Carolina Department of Transportation

The proposed tier 5 EPA regulations would align with North Carolina Department of Transportation (NCDOT) plans. An assessment performed by Michigan State University indicated that hydrogen rail and battery technology may be the “best fit” for NCDOT needs. They anticipate expanding their zero-emission technology from passenger rail to switchers and other rail uses once they have a viable system. Passenger rail needs to be included when discussing new technology as passenger rail provides the opportunity to test and demonstrate new technologies.

5.6. Additional Participant Input

Workshop participants were given notecards in order to contribute any thoughts, ideas, and suggested activities relative to the workshop objectives. These responses can be found in Appendix D.

APPENDIX A. WORKSHOP AGENDA

H2@RailSM Workshop Agenda

March 26-27, 2019

The James B. Henry Center for Executive Development | Lansing, Michigan

Workshop Introduction and Objectives

Government and industry technology developers world-wide are realizing the potential for hydrogen rail applications, and this workshop will help identify needed research to accelerate technology development and industry commercialization.

In collaboration with the Department of Transportation's Federal Railroad Administration and as part of the Department of Energy's H2@Scale Initiative, we welcome workshop participants and look forward to exploring opportunities for cooperation and collaboration on hydrogen rail areas of interest.

The objectives of this workshop are to:

- Assess the state of the art on electric rail power propulsion specifically using fuel cells
- Discuss operational requirements and lessons learned on early fuel cell rail projects
- Understand current technology gaps and identify collaborative R&D topics

Tuesday, March 26 | Day 1

Session I - Domestic Government Perspectives on Hydrogen Rail

Moderator: Pete Devlin, DOE-FCTO

1:00 PM

Welcoming Remarks from Michigan State University

Sanjay Gupta, Dean of the Broad College of Business, Michigan State University

1:10 PM

Welcoming Remarks and H2@Scale/H2@Rail Overview

Sunita Satyapal, Director, U.S. Department of Energy Fuel Cell Technologies Office (DOE-FCTO)

- 1:40 PM **FRA Program R&D Overview**
Melissa Shurland, Program Manager, Rolling Stock Research, U.S. Department of Transportation Federal Railroad Administration (DOT-FRA)
- 2:10 PM **Mark Maday and Phani Raj**
Staff Director – Hazardous Materials and General Engineer, DOT-FRA
- 2:40 PM **Break & Network**
- 3:00 PM **Momoko Tamaoki**
Office Chief of Rail Equipment and Procurement, California State Transportation Agency
- 3:30 PM **Carrie Schindler**
Director of Transit and Rail, San Bernardino County Transportation Authority
- 4:00 PM **Session I Panel Discussion**
- 4:30 PM **Wrap Up and Next Steps**
- 5:00 PM **Adjourn**

Wednesday, March 27 | Day 2

7:30AM **Breakfast**

Session II - Hydrogen Rail International Status Overviews

Moderator: Shuk Han Chan, DOE-FCTO

8:00 AM **Elena Hof**
Program Manager, German National Organization for Hydrogen and Fuel Cell Technology

8:20 AM **Leanna Belluz**
Senior Engineer, Transport Canada

8:40 AM **Seky Chang**
Chief Researcher, Korean Railroad Research Institute

9:00 AM **Session II Panel Discussion**

9:30 AM **Break & Network**

Session III – Industry Perspectives Operators’ Perspectives

Moderator: Phani Raj, DOT-FRA

9:50 AM **Michael Fore**
Director – Technical Services, American Association of Railroads

10:10 AM **Michael Cleveland**
Senior Manager of Emerging Technology, BNSF Railway

10:30 AM **Mark Duve**
Manager of Locomotive Engineering, Norfolk Southern

10:50 AM **Session III Panel Discussion**

Technology Developers’ Perspectives

Moderator: Dimitrios Papageorgopoulos, DOE-FCTO

11:20 AM **Reid Larson and Scott Nason**
Product Manager - Fueling System and Product Manager, Chart Industries

- 11:40 AM **Alan Mace**
Product Manager, Ballard
- 12:00 PM **Lunch & Network**
- 1:00 PM **Rob Harvey**
Large Scale Infrastructure Project Manager, Hydrogenics
- 1:20 PM **Jens Steger**
Vehicle Lead Engineer, Stadler US Inc.
- 1:40 PM **Andreas Frixen**
Tender Manager Fuel Cell Trains, Alstom
- 2:00 PM **Session III Panel Discussion**
- 2:30 PM **Break & Network**

Session IV – Hydrogen Rail Assessment

Moderator: Pete Devlin, DOE-FCTO

- 2:50 PM **Andreas Hoffrichter**
Burkhardt Professor in Railway Management, Michigan State University
- 3:10 PM **Total Cost of Ownership for Line Haul, Yard Switchers and Regional Passenger Locomotives**
Rajesh Ahluwalia, Senior Engineer, Argonne National Laboratory
- 3:30 PM **Hydrogen for Rail Applications**
Brian Ehrhart, Chemical Engineer, Sandia National Laboratories
- 3:50 PM **Session IV General Discussion**
- 4:20 PM **Wrap Up and Next Steps**
- 4:40 PM **Adjourn**

APPENDIX B. PARTICIPATING ORGANIZATIONS

The workshop convened a diverse group of representatives (from government agencies, academia, original equipment manufacturers, rail operators, and national laboratories), including international experts, who are participating in hydrogen rail applications.

- A.V. Tchouvelev & Associates Inc.
- Alstom
- Appalachian State University
- Argonne National Laboratory
- Association of American Railroads
- AVL Powertrain Engineering Inc.
- Ballard Power Systems
- BNSF Railway
- Chart Industries
- CNGmotive Inc.
- CSRA Support to US Department of Energy via Oak Ridge National Laboratory
- Cummins Inc
- ENGIE (Hydrogen Business Unit)
- General Electric Transportation
- General Motors
- Ground Vehicle System Center
- Hexagon RailGas
- Hydrogenics Corp.
- Jacobs Engineering
- McDowell Engineers & Associates / North Carolina Department of Transportation
- Michigan State University - Center for Railway Research and Education
- Mooresville Hydrail Initiative
- Mott MacDonald
- National Renewable Energy Laboratory
- Norfolk Southern
- NOW GmbH
- Pacific Northwest National Laboratory
- Plug Power
- PSI
- San Bernardino County Transportation Authority
- Sandia National Laboratories
- Savannah River National Laboratory
- Stadler US
- Telligence Group
- TML Consulting
- Transport Canada
- US Department of Energy Fuel Cell Technologies Office
- US Environmental Protection Agency, Office of Transportation and Air Quality
- UBC School of Engineering
- University of California Davis
- University of California, Irvine
- US Department of Transportation Federal Railroad Administration
- US Environmental Protection Agency

APPENDIX C. WORKSHOP PANELIST BIOGRAPHIES

Alan Mace, Market Manager, Ballard

Alan Mace has over 18 years' experience within the fuel cell industry in engineering, service and product management roles. In his current position as Market Manager, he is responsible for market development activities for the FCveloCity® Heavy Duty power modules including definition of customer requirements and value analysis, along with market analysis. Mace has held a broad range of roles in engineering, customer relationship management and marketing during his years of service at Ballard and IdaTech. His experience includes a strong technical background on fuel cell products and applications. Mace holds a Bachelor of Science in agricultural engineering from Washington State University. Prior to his current fuel cell activities, Mace has designed high-speed machine vision systems for food processing, along with design of machinery for pulp, paper and web processing.

Andreas Frixen, Hydrogen Refueling Stations and Hydrogen Supply Expert, Alstom

Andreas Frixen studied mechanical engineering and railway engineering at the University of Hannover, Germany and has over 20 years of experience in the rail industry. Frixen is the expert in Alstom for hydrogen refueling stations and hydrogen supply as it pertains to rail vehicles.

Andreas Hoffrichter, Professor & Executive Director, Center for Railway Research and Education

Andreas Hoffrichter is the Burkhardt Professor in Railway Management and the Executive Director of the Center for Railway Research and Education (CRRE) in the Broad College of Business at Michigan State University. His research expertise is in low- and zero-emission technologies for railway motive power, including discontinuous electrification, hybrid, battery-power, and hydrogen fuel cell options. He has been involved in multiple zero-emission motive power rail projects, globally, and leads several ongoing projects in this field at CRRE. Andreas studied transport management at Aston University, England, and completed the course with a first class, Bachelor of Science, honours degree. He has a master's degree in railway systems engineering and integration from the University of Birmingham, England. In his doctoral research at Birmingham, he investigated the suitability of hydrogen as an energy carrier for railway traction, which led to the development of a narrow-gauge prototype hydrogen-hybrid locomotive; the first practical hydrogen-powered railway vehicle in the United Kingdom. After completion of his PhD, he was employed as a Teaching and Research Fellow in the Birmingham Centre for Railway Research and Education at the university. In 2014, Andreas moved to the WMG within the University of Warwick, England, where he led the research activity related to drive systems for railway vehicles, including energy storage hybrids and hydrogen fuel cell systems. His research concentrated on railway traction, conceptual drive-system development, and subsequent vehicle performance evaluation. In 2016, he joined Michigan State University to lead their railway education and research activities.

Brian Ehrhart, Chemical Engineer, Sandia National Laboratories

Brian Ehrhart is a chemical engineer at Sandia National Laboratories. Since 2017, he has worked in the Risk and Reliability Analysis group supporting technical analyses for safety codes and standards for alternative fuels, particularly hydrogen. His current and past work has focused on assessing risk for hydrogen vehicles and infrastructure, developing software codes for various fire and thermal scenarios, and working to improve the National Fire Protection Association (NFPA) 2 Hydrogen Technologies fire safety code.

Carrie Schindler, Director of Transit and Rail Programs, San Bernardino County Transportation Authority

Carrie Schindler is Director of Transit and Rail Programs for the San Bernardino County Transportation Authority where, since 2015, she has been responsible for delivering the promises of Measure I, San Bernardino County's half-cent transportation sales tax as it relates to transit and rail efforts. She joined SBCTA in 2012 as Chief of Fund Administration after spending ten years with the County of San Bernardino where she served in many capacities including Resident Engineer and Chief of Transportation Planning. Prior to joining the public sector she worked in the private sector on transit related efforts in the San Diego area. Carrie is a graduate of San Diego State University in Civil Engineering and a registered Professional Engineer in California.

Elena Hof, Program Manager, National Organization for Hydrogen and Fuel Cell Technology, Germany

Elena Hof is one of the program managers for the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP) at the National Organization for Hydrogen and Fuel Cell Technology (NOW gmbH), in Berlin. As program manager, Hof supports hydrogen and fuel cell technologies. Previously, Hof interned at the German Association for International Cooperation (GIZ GmbH) as part of the project titled "Strengthening governance in Central Africa's extractive sector." Her experience also includes working as a student assistant at the Institute of Highway and Railroad Engineering at Karlsruhe Institute of Technology (KIT), Karlsruhe. Hof has studied civil engineering, and applied geosciences, and possesses a Master of Science in Georesources management. Her master's thesis is titled, "Power-to-gas for rail transport: Economic evaluation and concept for cost-optimal hydrogen supply."

Jens Steger, Technical Program Management, Stadler US

Jens Steger is responsible for the technical program management at Stadler US, currently in charge of leading the San Bernardino County Transit Authority Redlands Program. He oversees all Stadler US projects on technical aspects to ensure compliance according to internal and external requirements. He is also an expert on the Stadler FLIRT Platform and leads the effort to implement alternative propulsion technology in the U.S. market. Jens joined Stadler in 2016, where he was part of the project management team that first introduced a fully Alternate Vehicle Technology (AVT)-compliant Diesel Multiple Unit (DMU) to the U.S. market.

Leanna Belluz, Senior Engineer, Transport Canada Innovation Centre

Leanna Belluz has been working in the engineering field for over 19 years. She has a bachelor's degree in civil engineering from Lakehead University and a Master of Applied Science in civil engineering with a specialization in transportation from Carleton University. She started her career in the road safety field at Transport Canada conducting research on engineering safety countermeasures to prevent motor vehicle collisions. She then worked for the ecoTECHNOLOGY for Vehicles Program, managing testing and evaluation programs on new and emerging vehicle technologies that reduce emissions and increase safety. Leanna now works as a senior engineer in Transport Canada's Innovation Centre conducting research on rail transportation technologies.

Lynn Harris, Senior Project Engineer, North Carolina Department of Transportation

Mr. Lynn Harris has a Bachelor of Science in nuclear engineering from North Carolina State University and is employed by McDowell Engineers & Associates as an embedded consultant on rail equipment engineering in the North Carolina DOT Rail Division. Mr. Harris has been the lead project engineer on locomotive rebuilds and railcar refurbishments and lead quality/reliability engineer for NCDOT rolling stock. He has also been project manager on multiple projects including

biodiesel fuel testing, implementation of cutting-edge emissions improvement systems, and implementation of Wi-Fi on the NCDOT Piedmont passenger rail service.

Mark Maday, US Department of Transportation - FRA, Hazardous Materials Division

Mark A. Maday is the staff director of the Hazardous Materials Division within the Federal Railroad Administration Office of Technical Oversight. The FRA's Office of Railroad Safety, which includes the Office of Technical Oversight, promotes and regulates safety throughout the nation's railroad industry. The office executes its regulatory and inspection responsibilities through a diverse staff of railroad safety experts.

Mark Duve, Locomotive Engineering Manager, Norfolk Southern

Mark Duve is the locomotive engineering manager at Norfolk Southern. He began his career in locomotives in the Electro-Motive Division of EMD in 1994, and continued in various departments including purchasing, engine group, and locomotive systems engineering. In those departments, Mark worked on connecting rods, piston pin carriers, fuel economy testing, adhesion testing, and locomotive configuration management. In 2010, Mark took a position as a mechanical engineer in locomotive design at Norfolk Southern and has since worked as System Manager, Locomotive Reliability Manager, and now Manager of Locomotive Engineering. Mark has worked on various projects such as the ECO locomotives, DC to AC conversions, the natural gas mother slug, and locomotive reliability. He is the chairman of the Association of American Railroads Locomotive Committee and the Natural Gas Tender Committee. He also serves as chairman of the Locomotive Maintenance Officers Association Mechanical Committee. Mark's post-high school education includes a bachelor's degree in marketing from Colorado State University, a bachelor's degree in engineering from Stevens Institute of Technology, and a master's degree in mechanical engineering from Illinois Institute of Technology.

Melissa Shurland, Program Manager, U.S. Department of Transportation – FRA, Office of Research, Development and Technology

Melissa E. Shurland is a program manager at the Federal Railroad Administration's Office of Research, Development and Technology. Melissa manages the Rail Energy, Engine and Environment Research program. Her research projects focus on issues related to advancing locomotive efficiency technologies that are safe and can reduce emissions, as well as projects assessing alternative fuel usage in the rail industry. Melissa joined the FRA in 2007 following a six-year career as a car equipment engineer at the Metropolitan Transportation Authority, New York City Transit. *Michael Cleveland, Senior Manager, Emerging Technology, BNSF Railway*

Michael Cleveland is Senior Manager of Emerging Technology for BNSF Railway. He has been with BNSF Railway since 2010 holding a variety of positions related to locomotive maintenance, repair, and technology. In his current role, he focuses on the evaluation and implementation of new technologies related to locomotives, cargo handling equipment, and energy management. Additionally, he manages BNSF's evaluation of alternative locomotive fuels and emissions technologies. He received his master's degree in mechanical engineering from Texas A&M University and his bachelor's degree in physics and mathematics from Austin College.

Michael Fore, Director of the Technical Services Group/Locomotive Committee Manager, American Association of Railroads

Michael Fore is Director of the Technical Services Group and Locomotive Committee Manager for the American Association of Railroads. Fore has been with the AAR 25 years and has served as Locomotive Committee Manager for five years. On behalf of the committee, Fore helps to establish, improve, and maintain locomotive standards and rules. The committee develops and maintains standards, specifications, and recommended practices in Section M, Locomotives and Locomotive Equipment, of the *Manual of Standards and Recommended Practices*. These standards, specifications, and recommended practices are for the purposes of safety and interoperability. Fore also manages the Locomotive Repair Billing & Interchange Rules Committee as well as the review and oversight of AAR/Transportation Technology Center, Inc.'s Mechanical Inspection Department inspection result notices to repair facilities that service and repair freight and locomotive equipment.

Momoko Tamaoki, Office Chief of Assets and Equipment, California Department of Transportation (Caltrans)

Momoko Tamaoki is Office Chief of Assets and Equipment in the Division of Rail and Mass Transportation at Caltrans, the California Office of Transportation. Prior to being promoted to the position, Tamaoki led two large, nationally significant, high-profile projects as Branch Chief of the Rolling Stock Procurement. Tamaoki is a dynamic state government transportation professional with more than 10 years of increasingly responsible experience pertaining to rail and mass transportation.

Phani Raj, General Engineer, US Department of Transportation - FRA, Office of Safety

Phani K. Raj is a general engineer in the Office of Safety at the Federal Railroad Administration (FRA) in Washington, DC, where he is involved in monitoring several pilot projects on the use of LNG and CNG tenders for locomotive fueling. He represented the FRA in the Association of American Railroads' Technical Assessment Group that developed new standards for the design and operation of natural gas (including LNG & CNG) tenders for locomotives. He has also evaluated the safety issues related to permitting in-commerce transportation of LNG by rail, based on which work both Alaska Railroad and Florida East Coast Railway have been granted FRA approval. Raj is actively involved in many aspects of the safety of hazardous material transportation in tank cars (risks in crude shipments, pressure relief valve failure causes and tests, thermal protection systems performance, tank car design enhancements, design and testing of full scale LNG portable tanks exposed to fire, etc.). Raj holds master's and Ph.D. degrees in mechanical engineering from Harvard University and an MBA from Northeastern University. He has published over 65 technical papers in archival journals and has authored over 150 reports.

Rajesh Ahluwalia, Fuel Cell and Hydrogen Group Manager, Argonne National Laboratory

Rajesh Ahluwalia manages the Fuel Cell and Hydrogen group in Argonne National Laboratory's Energy Systems Division. He is a co-developer of GCTool (General Computational Toolkit), a software package that helps design, analyze, and optimize automotive and stationary distributed fuel cell power generation systems, as well as other power-plant configurations.

Reid Larson, LNG Product Manager, Chart Industries

Reid Larson is a liquefied natural gas (LNG) product manager for Chart Industries and has been instrumental in developing and bringing to market multiple products for fueling natural gas-powered vehicles, both on and off-road. He has worked for Chart Industries in multiple roles, developing expertise in managing and engineering products for stationary and mobile applications in the natural gas market. Chart is a leading independent global manufacturer of highly engineered equipment used in the production, storage and end-use of hydrocarbon and industrial gases. Chart's products are used throughout the LNG supply chain for purification, liquefaction, distribution, storage, and end-

use applications. Larson holds a master's degree in mechanical engineering from the University of Minnesota and a Bachelor of Science in physics from Augsburg College.

Rob Harvey, Director of Energy Infrastructure, Hydrogenics

Rob Harvey is the Director of Energy Infrastructure at Hydrogenics, a leading hydrogen cleantech technology enterprise which designs and builds fuel cell power modules and electrolyzers for zero-emission fleet mobility. Harvey was the company project leader for the Markham Energy Storage Facility, a 2.5MW power-to-gas project to provide regulation services for the Independent Electricity System Operator and the first utility scale project of its kind in North America. Harvey has worked over 20 years in the energy sector as a former principal with PHB Hagler Bailly and consultant with Oliver Wyman, and in startup ventures in waste-to-energy and biogas CHP. Harvey is one of the founding members of Energy Storage Canada and served as board chair from 2015–2017. He is a graduate in systems design engineering from the University of Waterloo and is a member of Professional Engineers Ontario.

Sanjay Gupta - Dean of Michigan State University Broad College of Business

Sanjay Gupta is the Eli and Edythe L. Broad Dean of the Eli Broad College of Business. He joined the Broad College in 2007 as the Russell E. Palmer Endowed Professor of Accounting and chair of the Department of Accounting and Information Systems. He was appointed associate dean for the MBA and professional master's programs in July 2012. As associate dean, Gupta instituted curricular innovations, such as BroadWeeks, in the full-time MBA program, led a task force to evaluate the weekend MBA program, and facilitated the launch of new master's programs in business analytics and management, strategy, and leadership. Average GMAT scores of entering students rose by 25 points during his tenure, and the MBA program increased its position in global and national rankings. Previously, he held several positions in the W. P. Carey School of Business at Arizona State University, including the first Henry & Horne Professorship in Accountancy, Dean's Council of 100 Distinguished Scholars, and faculty director of the master of accountancy and information systems and the master of taxation programs.

Scott Nason, Product Manager, Chart Industries, Rail Products Group

Scott Nason is the product manager for Chart Industries' Rail Products Group. He concentrates on LNG rail tender and tank car opportunities as well as opportunities for the use of ISO containers to transport and store LNG. Prior to this position, Nason spent several years as a product manager of mobile equipment for Chart, focusing on rail cars, highway trailers, ISO containers, and a variety of cryogenic liquid transportation equipment. He also worked as an engineering manager for Chart's process engineering (acquisition), working on bulk tanks and systems for all cryogenic liquids. Nason has 35 years of experience in design engineering, product management, and business development of cryogenic liquid systems and transportation equipment.

Seky Chang, Chief Researcher, Korea Railroad Research Institute

Seky Chang, Ph.D, is a chief researcher at Korea Railroad Research Institute, a government-funded research institute. One of his research interests is the application of hydrogen fuel cell system to railway. KRRRI has been established to contribute to the development of state and business industries through continuous R&D in the fields of railroad, public transportation, logistics, and the spreading of its work.

Sunita Satyapal, Director, US Department of Energy's Fuel Cell Technologies Office

Sunita Satyapal is the director of the US Department of Energy's Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy. In this capacity, she is responsible for the overall strategy and execution of hydrogen and fuel cell activities, including oversight and coordination of more than \$120 million per year of R&D programs, as well as staff. Her two and a half decades of experience, includes academia, industry and government. Prior positions within the office included chief engineer, deputy program manager, and hydrogen storage team leader, and she has coordinated hydrogen and fuel cell activities across DOE, with other agencies, and with international stakeholders, including 18 countries and the European Commission through the International Partnership for Hydrogen and Fuel Cells in the Economy.

APPENDIX D. ADDITIONAL PARTICIPANT INPUT

The panels on the second day were followed by a brainstorming session that solicited input on three topics:

1. Technology R&D priorities
2. Next steps to accelerate progress (e.g., government actions and collaborations)
3. Public acceptance progress (e.g., operators, communities) nationally and worldwide

Attendees' written responses were collected and included in the sections below.

Technology R&D Priorities

During the brainstorming session, attendees listed their technology R&D priorities. When grouped, these responses provided suggested R&D priorities related to fuel and fueling infrastructure, safety and safety codes and standards, fuel cells, demonstrations or test sites, potential analyses, and additional priorities.

Fuel and Fueling Infrastructure

Some workshop attendees suggested the following R&D priorities related to fuel and fueling infrastructure:

- Research fuel dispensing for high-volume fills (e.g., 1000 kg)
- Study liquid hydrogen options
- Research cryo-compressed pump development
- Research and develop cheap and efficient hydrogen liquefaction
- Research and develop large-scale high volumetric flow hardware and fueling protocol for heavy duty rail, port, and truck fueling
- Research and develop low-pressure storage as well as hydrogen storage on a scale applicable to rail for cryo- and cryo-compressed hydrogen
- Prioritize R&D related to fueling, fueling infrastructure, maintenance requirements, and reliability of hydrogen
- Pay more attention to on-locomotive hydrogen storage and refueling facilities
- Develop fast-fill hydrogen rail fueling stations

Hydrogen Safety and Safety Codes & Standards

Some workshop attendees suggested R&D priorities related to hydrogen safety and safety codes and standards, both generally and in specific terms or for specific scenarios:

- Prioritize R&D for hydrogen safety and codes
- Adapt risk assessment methods and tools for rail scenarios
- Identify all codes, standards, and regulations for hydrogen fuel cells for rail
- Develop safety codes, and standards for high-volume hydrogen dispensing, including unique hydrogen fueling technologies for line-haul and regional passenger rail
- Study the safety impact of loss of containment of hydrogen and liquid hydrogen

Fuel Cells

Some workshop attendees suggested R&D priorities related to fuel cells, both generally and for specific components or specific applications:

- Invest in the research, development, and implementation of solid oxide fuel cell (SOFC) and PEM fuel cell systems for passenger and freight rail
- Prioritize R&D for fuel cells on passenger rail applications
- Consider the SOFC-GT (gas turbine) system again because system modeling is promising and shows over 50% efficiency
- Conduct shock load testing per US freight load spectrums for fuel cells and related systems

Demonstrations & Test Sites

Some workshop attendees suggested R&D priorities related to demonstrations and test sites, both generally and for specific regions or applications:

- Study demonstrations/test sites
- Conduct switcher demonstrations at ports or rail yards in severe, non-attainment areas such as Southern California
- Demonstrate the feasibility of the technology as a system and not of individual components via demonstration projects on rail
- Conduct small yard switcher projects and small passenger line projects (0-20 miles) to assist with public learning and confidence; learn to walk before you run
- Focus on bringing a prototype hydrogen rail car or locomotive into existence in North America; this procedure could be via a European original equipment manufacturer or a “skunk works” effort in North America

Costs

Some workshop attendees suggested that their R&D priorities were related to costs. During the brainstorm session, attendees prioritized R&D that reduces:

- The cost for fuel and infrastructure rollout
- The cost of hydrogen fuel
- The cost of hydrogen storage
- The cost of fuel cells

Potential Analyses

Some workshop attendees suggested R&D priorities related to potential analyses, both generally and for specific regions or applications:

- Identify and prioritize various hydrogen technologies for rail applications based on cost, safety, and effectiveness (volume need based on exemplar railroad range)
- Evaluate other scenarios to use tenders to support hydrogen station build-out through delivery of hydrogen
- Conduct a technology needs assessment for locomotives as well as hydrogen supporting rail infrastructure
- Work with industry to vet DOE analytics on TCO

- Continue TCO study and include battery electric locomotives with wayside charging
- Study marginal trade curves

Additional Suggested R&D Priorities

Some workshop attendees suggested additional R&D priorities which spanned multiple aspects of rail technology and operations:

- Develop technology for line-haul locomotives
- Ruggedize safety appliances and equipment
- For freight, research and develop onboard storage technology and a combination of technologies
- For passenger rail, research and develop value stream components (e.g., hydrogen price from higher volume demand—hub anchor, increase mass transit, etc., systems [electrolysis])

Next Steps to Accelerate Progress (e.g. Government Actions and Collaborations)

During the brainstorming session, attendees listed potential next steps to accelerate progress towards the use of hydrogen for rail applications. Workshop attendees suggested next steps that included:

- Improved or specific public education and outreach efforts
- Demonstration projects and approaches
- Continued codes and standards work
- Resources to accelerate hydrogen implementation
- Steps to target costs
- Collaborations, incentives, and government funding

Public Education & Outreach

Some workshop attendees suggested next steps to improve public acceptance of hydrogen technology through public education and outreach:

- Create a public acceptance program (e.g., operators, regional/communities, nation, and worldwide)
- Help overcome the perceived risks and risk aversion towards new technologies through awareness, education, and professional training
- Get public attention (from test sites) by publishing success stories in mainstream media
- Conduct an open online forum or Slack channel; it would be possible to have different conversation topics and then have the comments archived/visible/searchable for viewers to look through and learn from

Demonstration Projects

Some workshop attendees suggested demonstration projects to accelerate the progress of hydrogen technology and use:

- Test Megawatt-scale equipment so that railroads get comfortable with the hardware needed for locomotives
- Conduct a multi-modal demonstration (e.g., at a port where multi-modes of transportation can leverage a single, larger refueling station or electrolyzer); the demonstration projects should

include switcher and/or passenger applications and other applications in the port, such as for trucks, material handling, or cold-ironing

- Perform a demonstration in the United States to raise visibility and grow the market for hydrogen; promote more demo or pilot programs to build experience and confidence in hydrogen rail solutions
- Provide more information about likely candidates for fuel cell demonstrations, passenger lines, and train manufacturers

Safety Codes and Standards

Some workshop attendees suggested next steps involving safety codes and standards to accelerate the progress of hydrogen technology and use. Comments ranged from general in nature (e.g., simply citing “codes and standards” as a next step) to more specific guidance, such as initiating steps to harmonize codes and standards.

- Set federal zero-emission standards and safety requirements
- Identify all codes, standards, and regulations for the use of hydrogen fuel cells for rail
- Craft hydrogen regulations and standards and initiate steps to harmonize and develop a common set of standards
- Centralize the ownership of translation of foreign regulations, policies, acceptance procedures, and testing procedures
- Create a centralized listing of hydrogen/rail organizations
- Centralize the ownership of government policies (national, state, local, international) related to hydrogen
- Facilitate the coordination and collaboration of R&D and codes and standards activities
- Sponsor the development of risk assessment approaches for rail
- Interested railroads should petition the FRA for hydrogen rail testing through processes the FRA has disseminated to industry
- Consider and discuss setback distances for storage and dispensing
- Work with interested parties to unify regulations
- Create a repository for supporting regulations, codes, and standards for passenger rail hydrogen applications and develop those standards with the audience in mind (particularly those in charge of approving regulations, codes, and standards) and in consultation with the FRA

Resources to Accelerate Progress

Some workshop attendees suggested resources that that might accelerate the progress of hydrogen technology and use.

- Create a listing/clearinghouse of grants for R&D rail-oriented projects
- Develop a strategic multimodal plan for hydrogen fuel cells in intermodal transportation systems (e.g., “exemplar” design of mixed-use fueling infrastructure)
- Centralize the monitoring and collection of data as hydrogen passenger rail operations are advanced and collect lessons learned and the current statuses of development

Addressing Costs

Some workshop attendees suggested steps to address costs that might accelerate the progress of hydrogen technology and use.

- Strive for cost targets or performance targets that are cost-competitive with diesel locomotives to enable railroads to maintain competitive edge over trucking industry
- Use peer review for TCO estimates
- Explore the lower cost of maintenance for fuel-cell/hybrid engines over diesel engines; large costs/downtime savings drove the change from steam to diesel 100 years ago
- To accelerate progress, the economics must be cost-effective on the basis of the system and total cost of ownership

Collaboration, Incentives, and Government Funding

Some workshop attendees suggested collaborative opportunities, incentives, and government funding that might accelerate the progress of hydrogen technology and use.

- Identify working groups and focus topics; ideally include within existing FRA and AAR committee structures
- Argue for coordination with the renewable, electrical grid via power to gas
- Provide government funding for demonstration projects; freight has the biggest impact!
- Ramp up economic incentives for implementing hydrogen projects
- Facilitate the sharing of hydrogen resources between public and private entities to offset cost of delivery and manufacturing

Additional Steps

Some workshop attendees suggested additional steps to accelerate the progress of hydrogen rail technology and applications which spanned multiple approaches and aspects of rail technology and operations:

- Learn from success of lift truck market with seed DOE funding
- Prioritize and consider adopting a focus for commercialized technology (i.e., passenger/light rail) and an emissions focus for near-term technology (i.e., switchers)
- Identify and prioritize various hydrogen technologies for rail applications based on cost, safety, and effectiveness (volume need based on exemplar railroad range)
- Assess the opportunity for other storage options (e.g., metal hydrides, liquid organic hydrogen carriers) as propulsion sources on trains
- Address infrastructure needs for hydrogen storage (on- and off-board), hydrogen carriers, and hydrogen liquefaction
- Consider methanol or ethanol onboard reforming to make hydrogen
- Identify the potential hydrogen demand for locomotive/rail yard applications
- Address the potential problem regarding the probable future life of the existing technology. The present worth of expenses is related to legacy tech decline e.g., the difficulty of obtaining parts, human resources leaving and not being replaced, vendors anticipating the market and leaving, public rejection of diesel, catenary
- Include fueling infrastructure suppliers in discussions; a cross-modal use of fueling infrastructure should reduce cost

Public Acceptance Progress (e.g. Operators, Regionals, And Communities) Nationally and Worldwide

During the brainstorming session, attendees also listed steps to advance the public acceptance of hydrogen for rail applications. Workshop attendees focused on demonstration projects, further analysis and research, and the continued importance of education and outreach. To advance the public acceptance of hydrogen for rail applications, attendees proposed:

- Leverage the success of Coradia iLint
- Demonstrate HyRail with public transit systems
- Facilitate the coordination and collaboration of R&D and codes and standards activities
- Improve public acceptance by focusing on economics and safety
- Demonstrate, test, document, and disseminate hydrogen rail efforts
- Integrate and socialize hydrogen in existing ports-related activities, e.g. EPA Ports Initiative

Analyses or Research for Public Acceptance

Some workshop attendees suggested additional analysis or research that might promote public acceptance:

- Address operators' concerns about why hydrogen rail might not work, particularly for long-haul applications
- Begin to understand the safety codes and standards barriers for rail applications
- Understand how first adopters of fuel cell technology would proceed
- Compile a report of DOE and FCTO publications, including Argonne National Laboratory and Sandia National Laboratories' publications

Education and Outreach

Workshop attendees also suggested additional education and outreach efforts to promote public acceptance. Comments identified the following audiences: public, industry, first responders, and local governments, as well as suggesting more segmented strategies such as focusing on outreach to university and high school students. The comments addressed using prior examples (hydrogen vehicles) as a guide and the importance of consistency (working from the same facts) and use of experts with strong communication skills during outreach and education.

- Follow the lead of the on-road hydrogen vehicles market in public education and outreach
- Educate the public, industry, and first responders, including education about hydrogen risks and safety. Foster discussions with local emergency responders and local governments
- Initiate public outreach workshops, forums, and meetings
- Publicly disseminate brochures on the merit of hydrogen for rail
- Promote general awareness as it relates to all hydrogen technologies. This will support the H2@Scale mission
- Work from the same facts in all public communications regarding hydrogen and hydrogen safety
- Get university and high school students to endorse and think hydrogen fuel cells are "cool." Try to address negative perceptions via social media
- Use experts with strong communication skills to perform outreach and education

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