U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Rail Decarbonization – VTO Strategy and R&D

Siddiq Khan, Ph.D.
Technology Manager, Decarbonization of Off-road, Rail, Marine, and Aviation
Vehicle Technologies Office (VTO)
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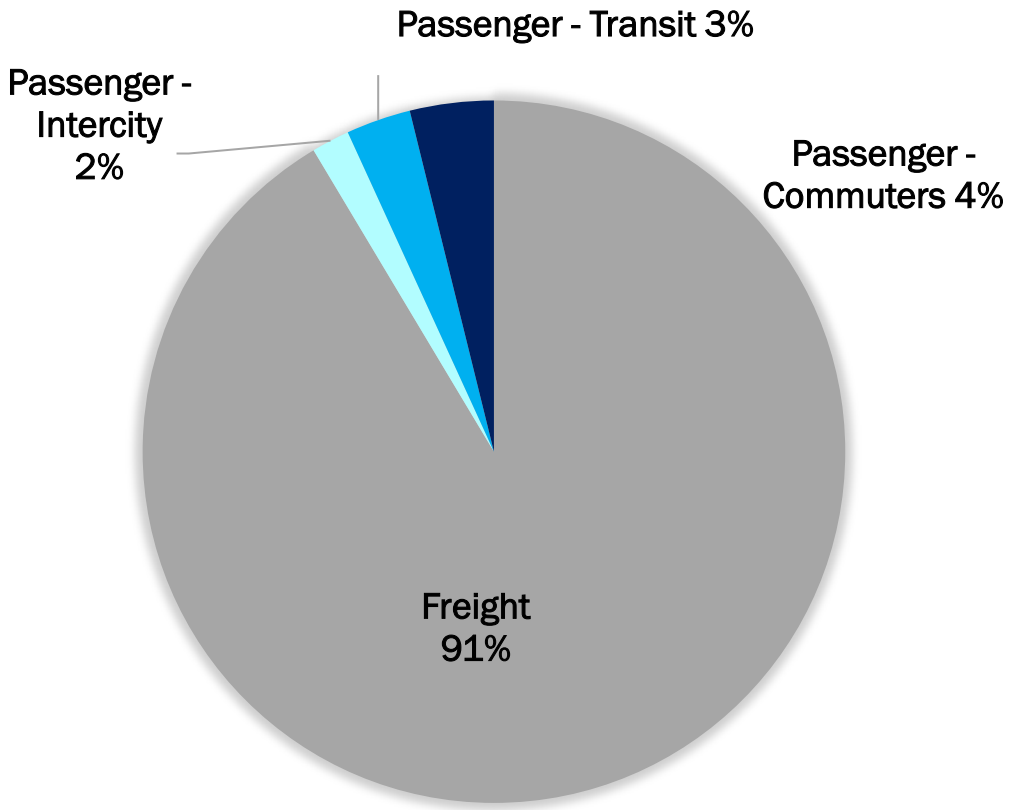
Rail Decarbonization Principles

2019 U.S. Rail Transportation Energy Use (0.5 Quads)

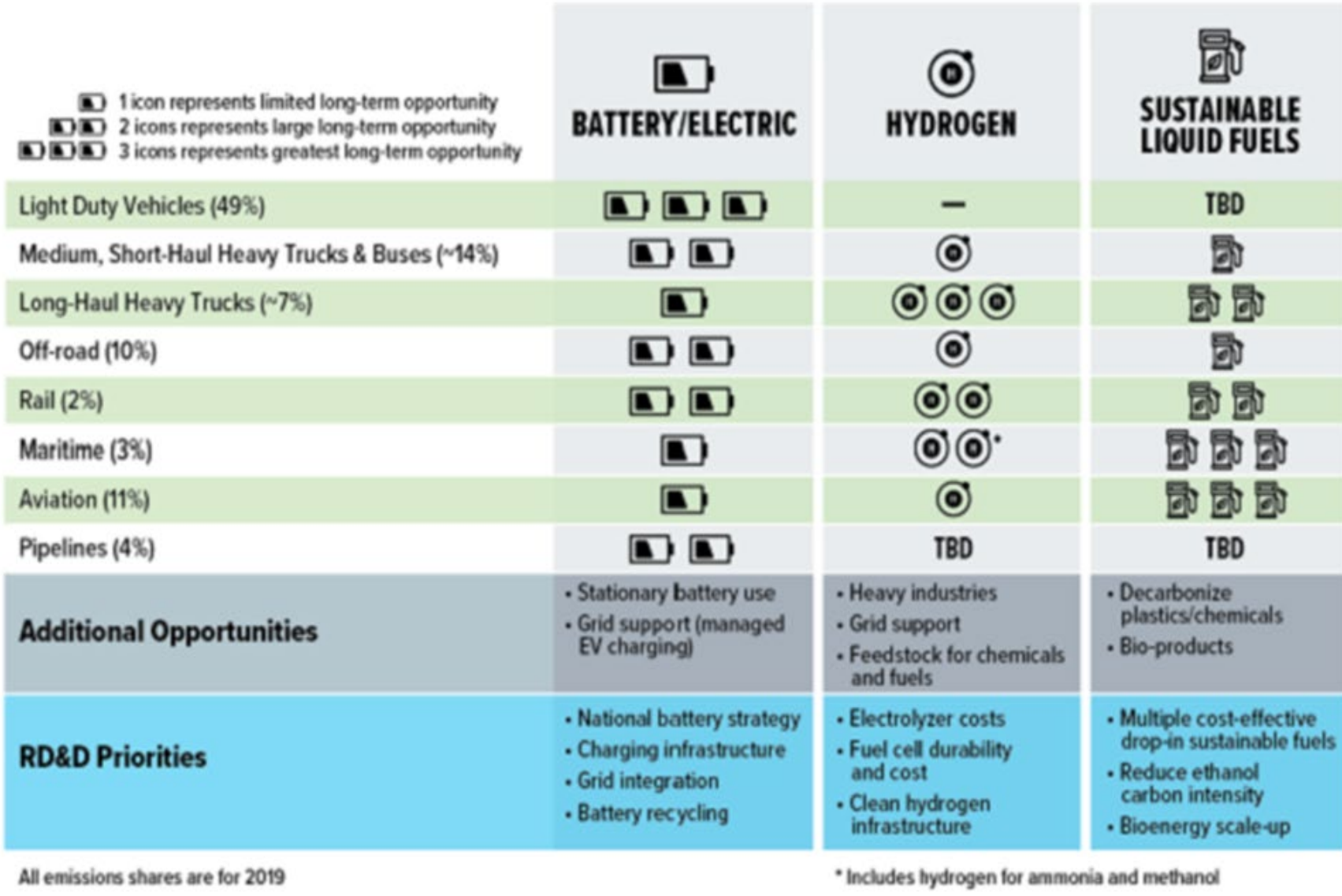


- Our focus is freight rail as they consume the most fuels.
- We are working on all plausible solutions that can be incrementally deployed:
  - delivering results by 2030
  - Preparing for zero-emission in 2050
- Multiple technology solutions are needed to decarbonize rail sector
- Collaboration with stakeholders and other agencies, especially FRA
- Full lifecycle emissions must be addresses

Transportation Decarbonization Blueprint, January 2023

Strategies:

- Work to establish specific targets
- Focus resources to develop technology pathways and set efficiency and zero-emissions vehicle targets
- Encourage greater use for intermodal to reduce emissions from road vehicles



1 icon represents limited long-term opportunity 2 icons represents large long-term opportunity 3 icons represents greatest long-term opportunity	BATTERY/ELECTRIC	HYDROGEN	SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)		–	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)			
Long-Haul Heavy Trucks (~7%)			
Off-road (10%)			
Rail (2%)			
Maritime (3%)		*	
Aviation (11%)			
Pipelines (4%)		TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

All emissions shares are for 2019

* Includes hydrogen for ammonia and methanol

Stakeholder Engagement, 2021-2023

- **Our rail decarbonization work started in 2021**
- **Our program, Advanced Combustion Engines and Fuels was renamed as Decarbonization of Rail, Marine, and Aviation**
- **We reached out to industry**
  - One-to-one meeting with diverse stakeholders including industries, suppliers, national labs, associations, academics, NGOs, state and federal agencies
  - Inter-agency briefings
  - Rail survey
  - Rail Workshop

DOE-ORNL Survey 2021

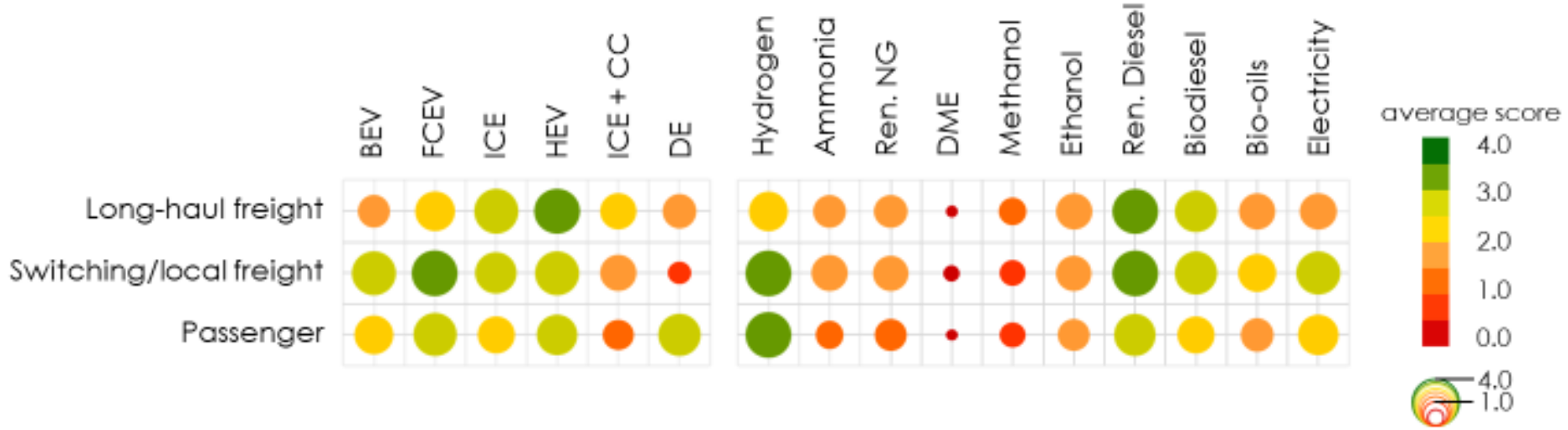
Survey was intended to get an informed perspective on decarbonization and identify key barriers to achieving decarbonization

1. Please indicate the importance of each powertrain configuration to achieving decarbonization of each rail sector by 2050 (? = I don't know, 0 = unimportant, 4 = extremely important)

	Long haul freight	Switching/local freight	Passenger
1.1 Battery electric (BEV)	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐
1.2 Fuel cell electric (FCEV)	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐
1.3 Internal combustion (IC) engine	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐
1.4 IC engine/battery hybrid (HEV)	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐
1.5 IC engine with onboard carbon capture	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐
1.6 Direct wired or wireless electric power	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐	? 0 1 2 3 4 ☐ ☐ ☐ ☐ ☐ ☐

DOE-ORNL Survey 2021

Rail: Powertrains & Fuels



Sector	Powertrains	Fuels
Long-haul freight	HEV, ICE, FCEV	Ren. Diesel, Biodiesel, Hydrogen
Switching/local freight	FCEV, HEV, BEV, ICE	Hydrogen, Ren. Diesel, Electricity, Biodiesel, Bio-oils
Passenger	FCEV, DE, HEV, BEV, ICE	Hydrogen, Ren. Diesel, Electricity, Biodiesel

BEV: battery electric vehicle | **FCEV:** fuel cell electric vehicle | **HEV:** hybrid electric vehicle
ICE: internal combustion engine | **ICE + CC:** ICE with CO_2 capture | **DE:** direct electrification

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

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ANL-DOE Rail Decarbonization Workshop, May 2022

Objectives:

- To bring together experts from relevant rail industry, academia, and government agencies backgrounds to review the decarbonization challenges and identify collaborative opportunities to address them.
- Produce a cross disciplinary recommendation for the role of government agencies to contribute meaningful research to address current technology gaps.

Almost 200 people attended this virtual workshop

ANL-DOE Rail Decarbonization Workshop, May 2022

Top-level Summary:

- Rail Industry has a very high interest in biofuel for near-term decarbonization
- Long term needs included decarbonized grid, green hydrogen for FC & ICEs, and high-speed charging for batteries, but the timing is a concern.
- Renewable diesel and biodiesel provide “drop-in” options for railroads GHG reductions. Dual-fuel locomotives considered as a near term GHG reductions and diesel option allows for reliable operation while infrastructure is built out.
- Electrification will play an important role to decarbonize rail.
- Retrofitting is very important for rail sector in the short term.
- New powertrains and fuels need to be tested and proven reliable in real operations.
- No silver bullet solution to decarbonized rail sector. This sector will likely see a fit and use for “all of the above” solutions.

Rail R&D Strategy (Preliminary)

- Rail decarbonization is challenging, specifically for freight
- Demonstration and durability will be key
- Battery electric locomotives for Switch yard rail.
  - Worksite charging
  - Promotes environmental justice
- Low carbon fuels including H2 for regional and long-haul freight
  - Use existing locomotives
  - Readily use low-carbon fuels
    - Liquid: BD, RD100, E100, M100
    - Gaseous: Green H_2 –H2ICE
  - Facilitates transition to H2 economy
  - Long-term potential for battery/hybrids and fuel cell
- Detail R&D strategies are being prepared

ORNL- DOE and DOT Collaborating on Research Efforts for Rail Decarbonization

CRADA between Wabtec and ORNL for single-cylinder engine (SCE) studies with LLCFs (e.g., hydrogen, methanol, ammonia, renewable diesel, etc.)

- Install and commission Wabtec SCE locomotive research engine at ORNL
- Establish maximum level of LLCF substitution for dual-fuel retrofit strategies while maintaining performance, emissions, and operability with 100% diesel
- Develop and evaluate direct-injection strategies that approach 100% substitution to enable next-generation locomotive solutions

CRADA between Wabtec, Argonne NL, and Convergent Science for CFD studies using digital twin of engine at ORNL

- ORNL project will provide experimental data for model development and validation

- **CFD results will provide:**
  - Insight on mixing and guidance on limits for injection timing, fueling rates, etc.
  - Guidance on hardware and operating strategies for candidate direct-injection approaches

Wabtec single-cylinder locomotive research engine installed at NTRC

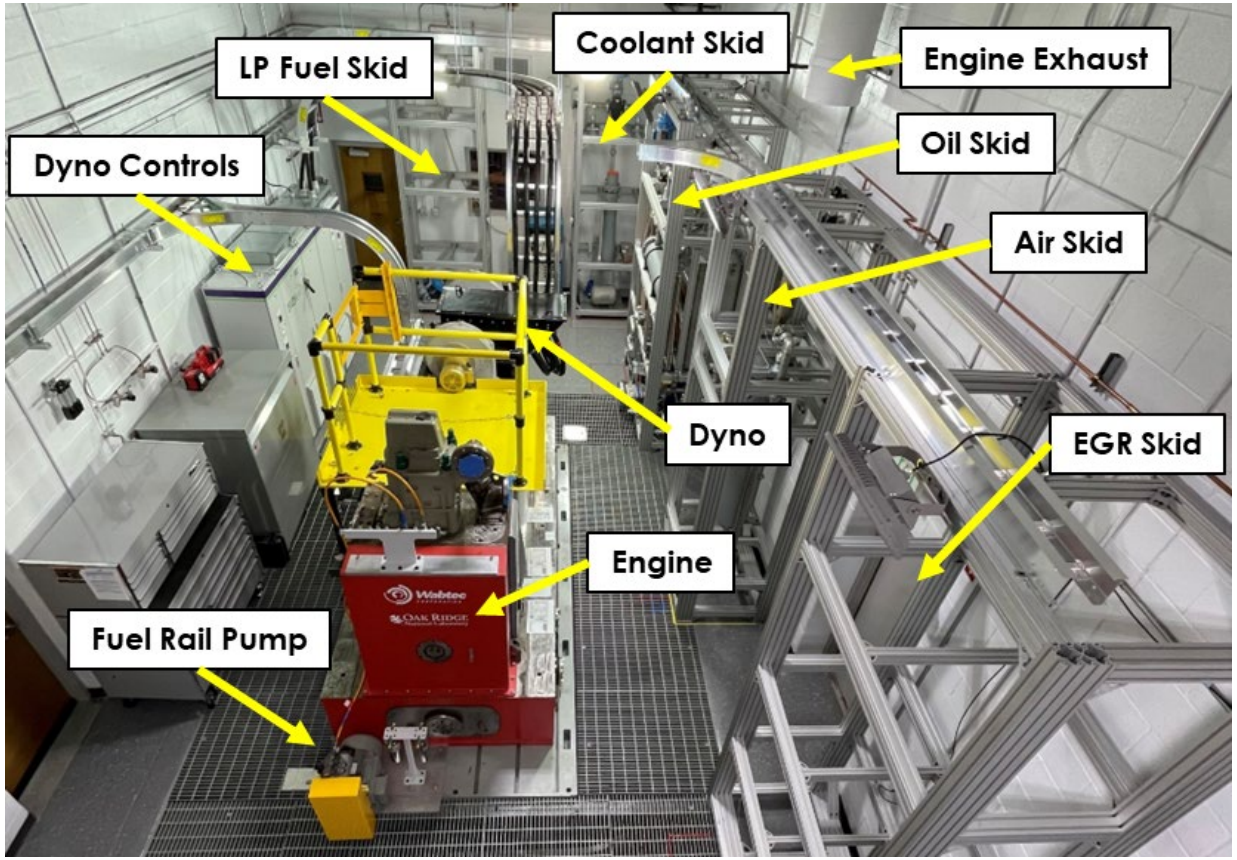
- **Based on production hardware (not scaled) for Wabtec 12-cyl EVO**
- 15.7-L displacement (250mm bore)
- 375 hp at 995 rpm
- Entire assembly is 8.5-ft tall, 41,000+ lbs.

Establishing a Rail Decarbonization Research Facility at ORNL

Installation and commissioning of a new research facility for decarbonization of locomotive applications is underway

- **Installed Wabtec single-cylinder locomotive research engine**
- **Performing infrastructure upgrades to support larger engine**
- **Building and upgrading support systems**

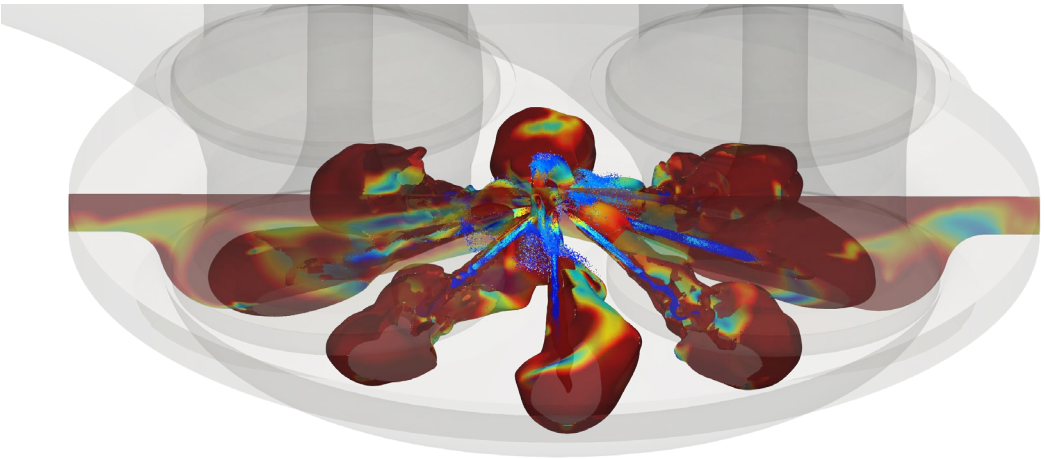
Targeting first fire in summer of 2023



H_2 Combustion Research at ANL – CRADA with Wabtec

Objectives:

- Develop and validate computational tools for combustion of low-carbon fuels, with a focus on hydrogen
- Use simulations to assist in evaluating different technologies and fuel injection options to enable up to 100% operation on hydrogen and low-carbon fuels



Progress in FY23:

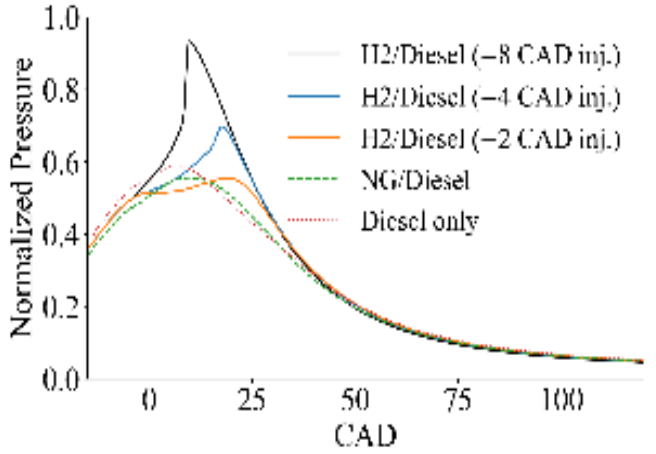
- Completed validation of CFD setup for modeling Wabtec SCE under Diesel/NG dual-fuel operation
- Performed CFD simulations to evaluate the effect of H_2 injection rate and injection timing
- Evaluated the effect of diesel injection timing on the in-cylinder pressure and heat release rate for H_2/diesel combustion

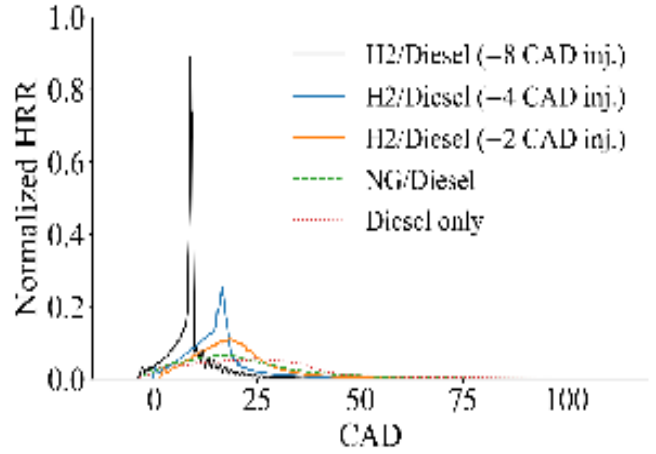
Major Findings from Simulations

Major Findings:

- Higher H_2 injection rates leads to more balanced H_2 mass flow rates
- H_2/Diesel operation shows faster combustion rates as compared to Diesel-only and Diesel/NG
- Diesel injection timing provides a strong control knob to control the pressure rise rate

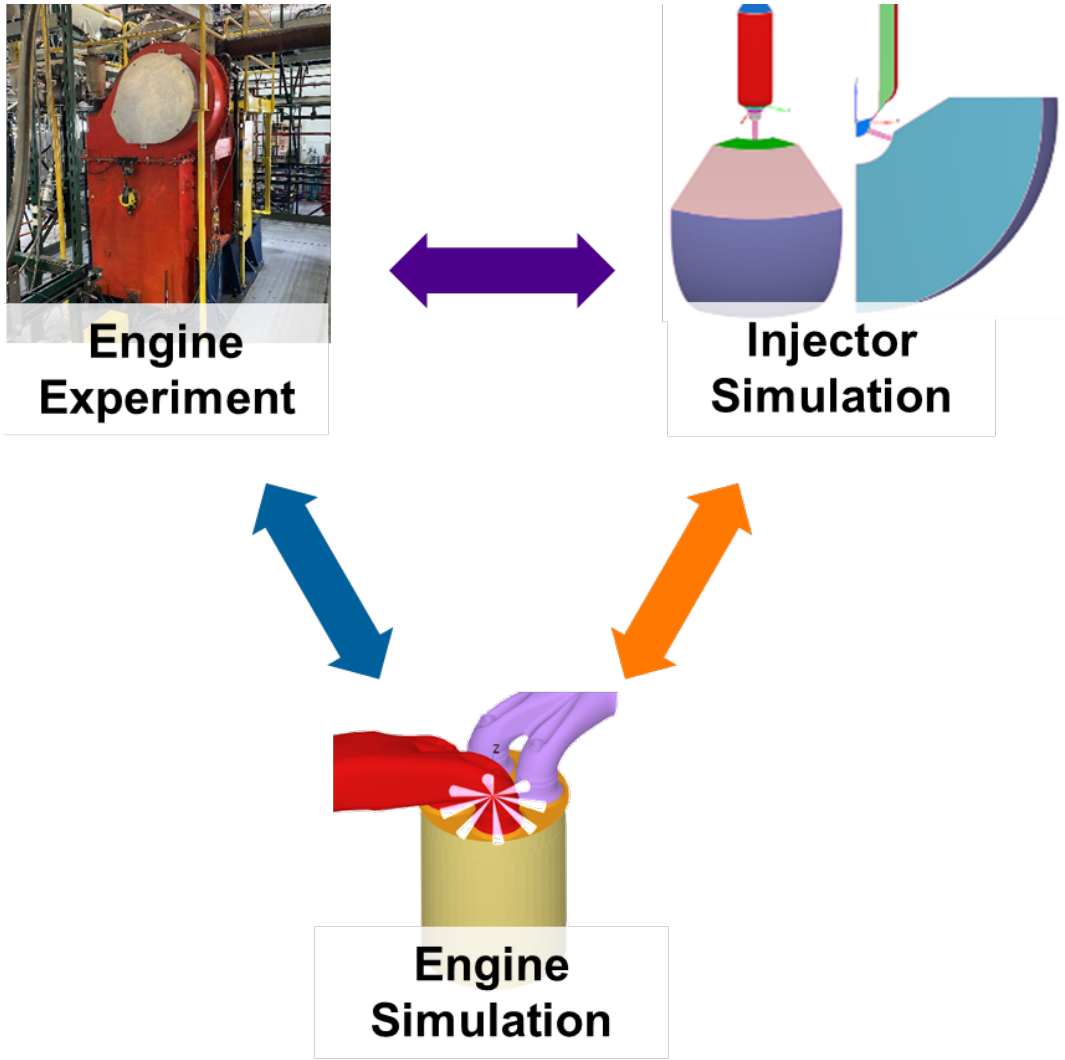
Effect of Diesel injection timing on combustion behavior





ANL- Enabling Higher Blends of Biodiesel and Renewable Diesel for Rail

- **Objective**
  - Assess rail engine performance with high blends of biodiesel and renewable diesel with joint funding by FRA and VTO
- **Approach:**
  - Engine tests on Progress Rail's 1010J engine
  - High-fidelity injection nozzle flow CFD
  - High-fidelity engine combustion CFD



High-Fidelity Nozzle Flow and Combustion CFD to Investigate the Effects of Injector Design and Fuel Properties

- Internal nozzle flow CFD
  - Developed the nozzle flow CFD model for common rail injector
  - *Next step:* investigate physical property effects of bio and renewable diesel

- **Engine Combustion CFD**
  - Developed an engine combustion CFD model for 1010 engine that accurately captures combustion characteristics for a wide range of operating conditions
  - *Next step:* develop fuel surrogates and reduced chemistry mechanisms for bio and renewable diesel blends

Areas for Additional Collaboration with Industry

- Better understanding of locomotive use and future of rail in a net-zero emissions environment (especially with changing freight demand)
- Deep dive into Battery Electric and Fuel Cell Electric use cases
- Information exchange and data sharing with feedback from industry and trade associations to develop detailed R&D for VTO
- Analysis of the total cost of ownership for different technology solutions based on real-world use data and technology cost/performance
  - Leading to development of technology roadmap
- Additional R&D and demonstration of various solutions to reduce GHG and criteria emissions

Thank You

Siddiq Khan, Ph.D.
Technology Manager
Decarbonization of Off-road, Rail, Marine, and Aviation
Vehicle Technologies Office
202-734-1449
siddiq.khan@ee.doe.gov