2017 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Greenhouse Gas (GHG) Emissions and Petroleum Use Reduction of Medium- and Heavy-Duty Trucks

Dong-Yeon (D-Y) Lee, Amgad Elgowainy, and Michael Wang

Argonne National Laboratory

June 6, 2017

SA064

Overview

Timeline

- ❑ Start: FY2017
- ❑ End: Determined by DOE
- ❑ % complete (FY17): 60%

Budget

- ❑ Funding for FY17: $100K

Barriers to Address

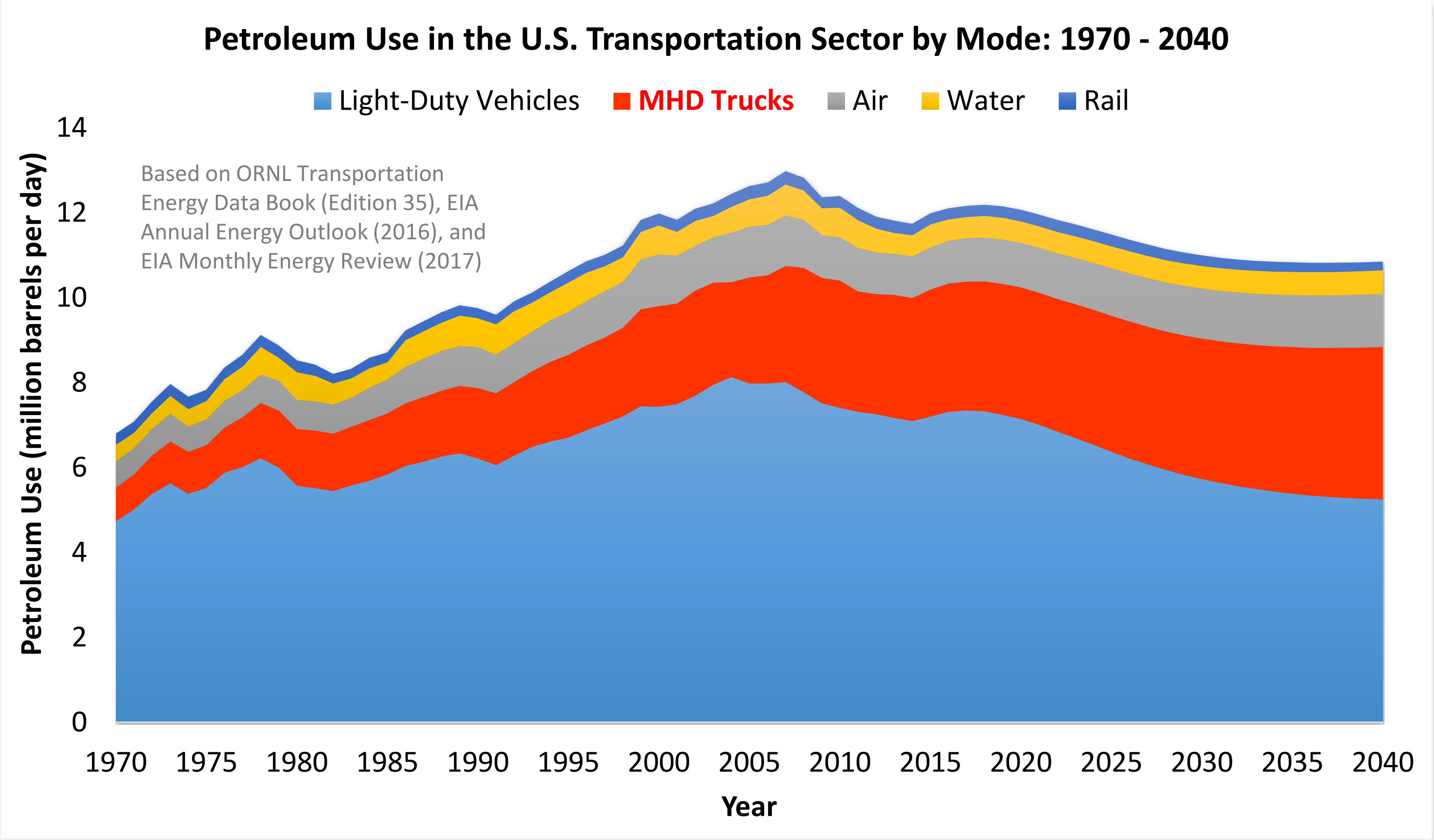
- ❑ Inconsistent data, assumptions, and guidelines
- ❑ Insufficient suite of models and tools

Partners/Collaborators

- ❑ ANL Autonomie Team
- ❑ ANL APRF
- ❑ NREL
- ❑ TransPower
- ❑ Motiv Power Systems
- ❑ TA Engineering
- ❑ City of Chicago
- ❑ Clemson University

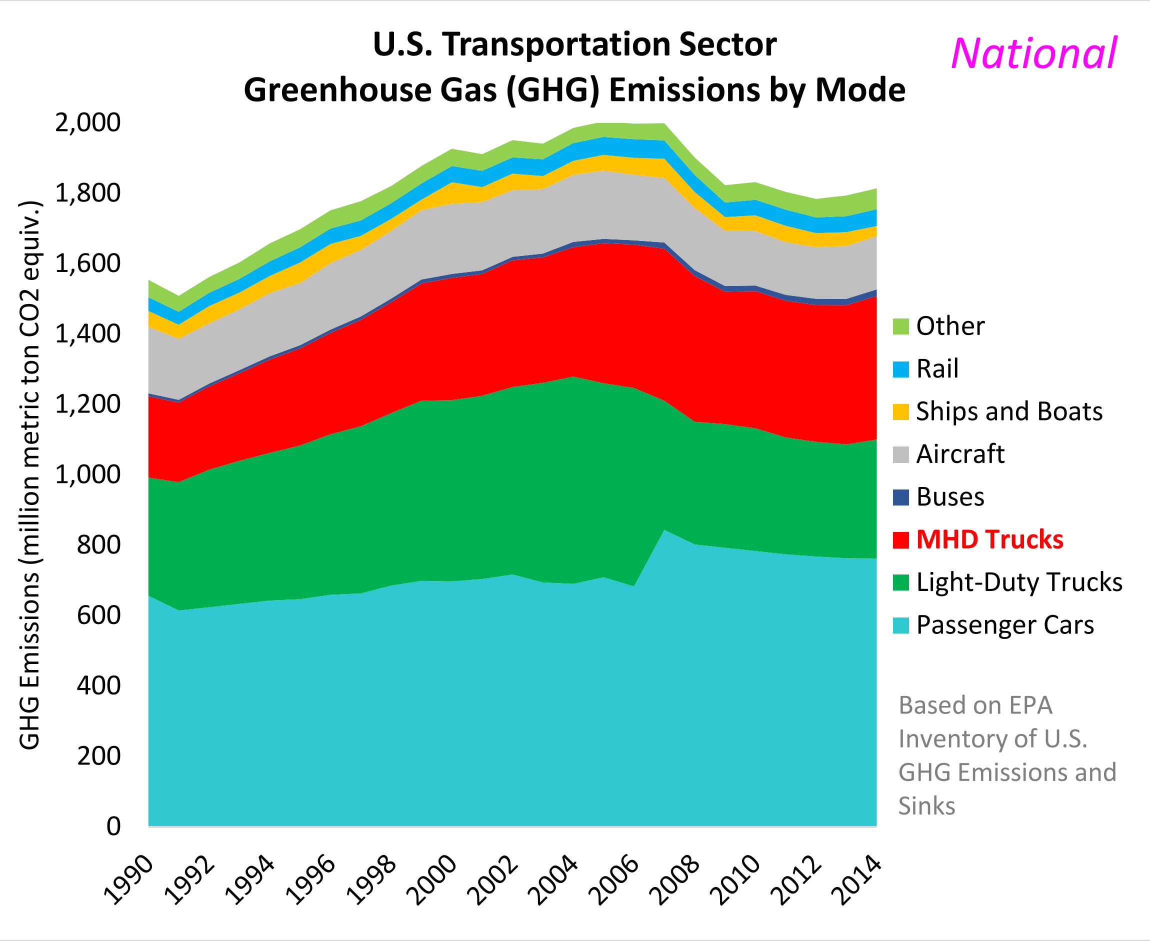
The increasing importance of medium- and heavy-duty vehicles in transportation sector – Relevance

- Medium- and heavy-duty vehicles (MHDVs) in the U.S. transportation sector:
  - The second largest and fastest growing energy (petroleum) consumer.



MHDVs represent significant share in both national and local air emissions – Relevance

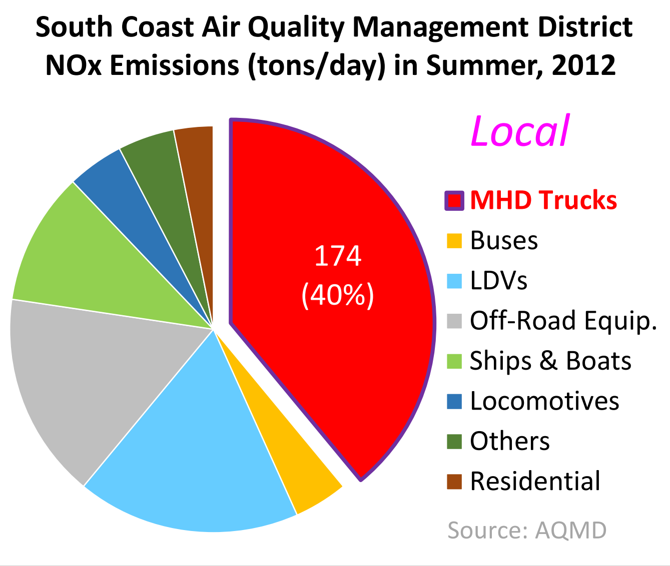
- The largest contributor to local air pollution in some areas (e.g., California South Coast AQMD).
- Disproportionate air emissions compared to light-duty vehicles, on a per-vehicle-and-energy basis.



U.S. Transportation Sector Greenhouse Gas (GHG) Emissions by Mode

National

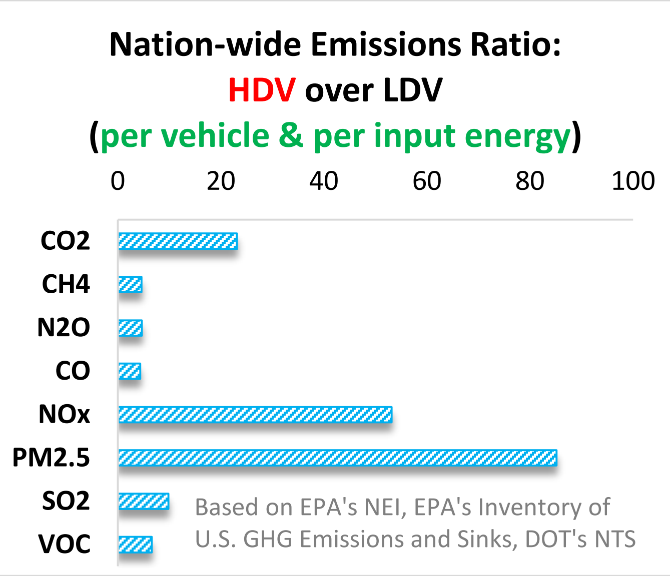
Based on EPA Inventory of U.S. GHG Emissions and Sinks



South Coast Air Quality Management District NOx Emissions (tons/day) in Summer, 2012

Local

Source: AQMD

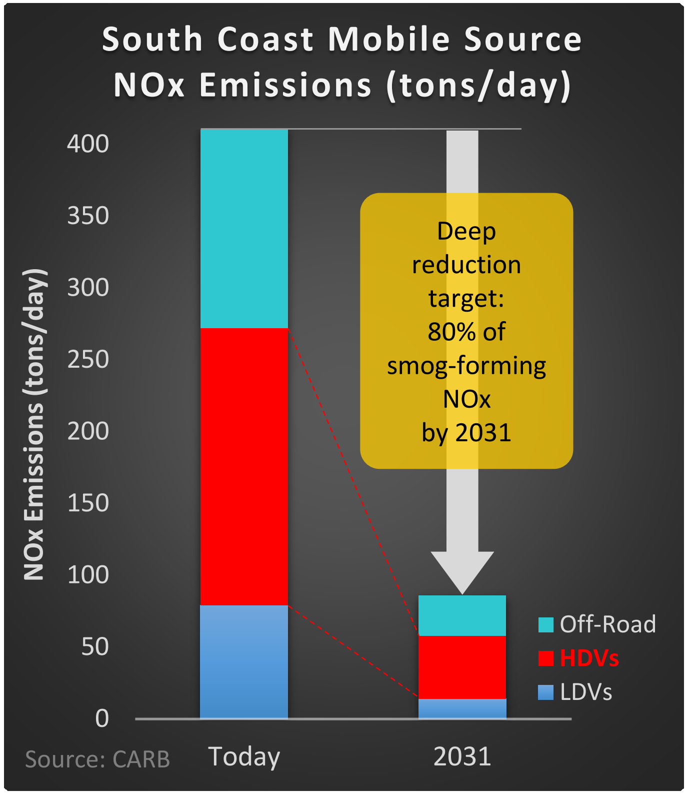


Nation-wide Emissions Ratio: HDV over LDV (per vehicle & per input energy)

Based on EPA's NEI, EPA's Inventory of U.S. GHG Emissions and Sinks, DOT's NTS

Relevance/Impact

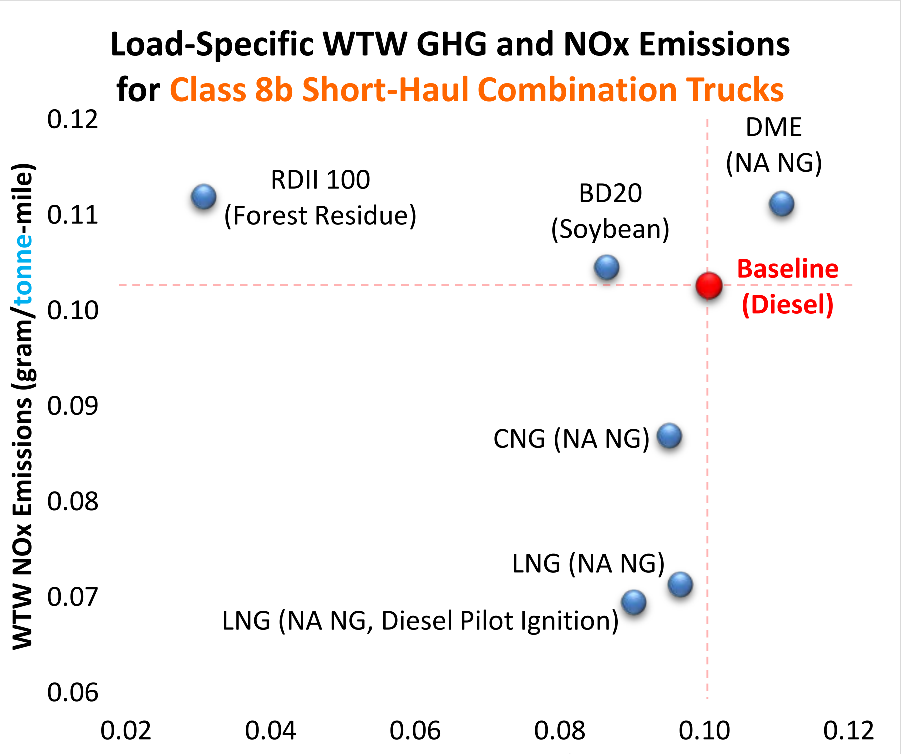
- There has been growing interest in hydrogen fuel cell electric vehicle (FCEV) technology in medium- and heavy-duty vehicle sector.
  - Multiple U.S. manufacturers are producing fuel cell electric trucks and buses, and demonstration is underway in various locations.
  - Gaining a better understanding of overall benefits and trade-offs can guide FCEV research, development, and demonstration (RD&D).
- Hydrogen fuel cell electric vehicles (FCEVs) create zero tail-pipe emissions of air pollutants, which can significantly contribute to local air quality improvement (e.g., South Coast in California).
  - For a fair and holistic comparison with other alternatives, it is crucial to account for not only direct (tail-pipe) but also indirect greenhouse gases and criteria air pollutants emissions on a life-cycle basis.
  - Potential benefits of medium- and heavy-duty hydrogen fuel cell vehicles may vary depending on duty cycles among others. Apples-to-apples comparison requires caution with regards to the duty cycles.



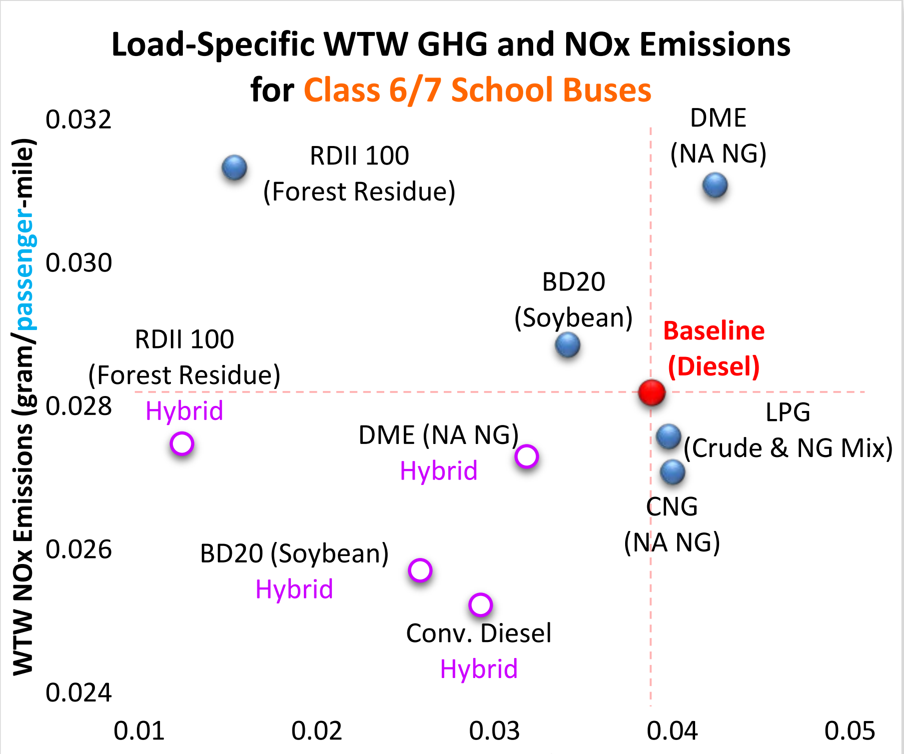
Source: CARB

Assessing the life-cycle benefits of alternative vehicle and fuel technologies in MHDV sector – Relevance

- GREET provides a comprehensive comparison of baseline diesel and alternative MHDV technologies on a well-to-wheel (WTW) basis.
- Hydrogen fuel cell electric vehicle (FCEV) technology is ***currently lacking*** in alternative MHDV technology portfolio in GREET.



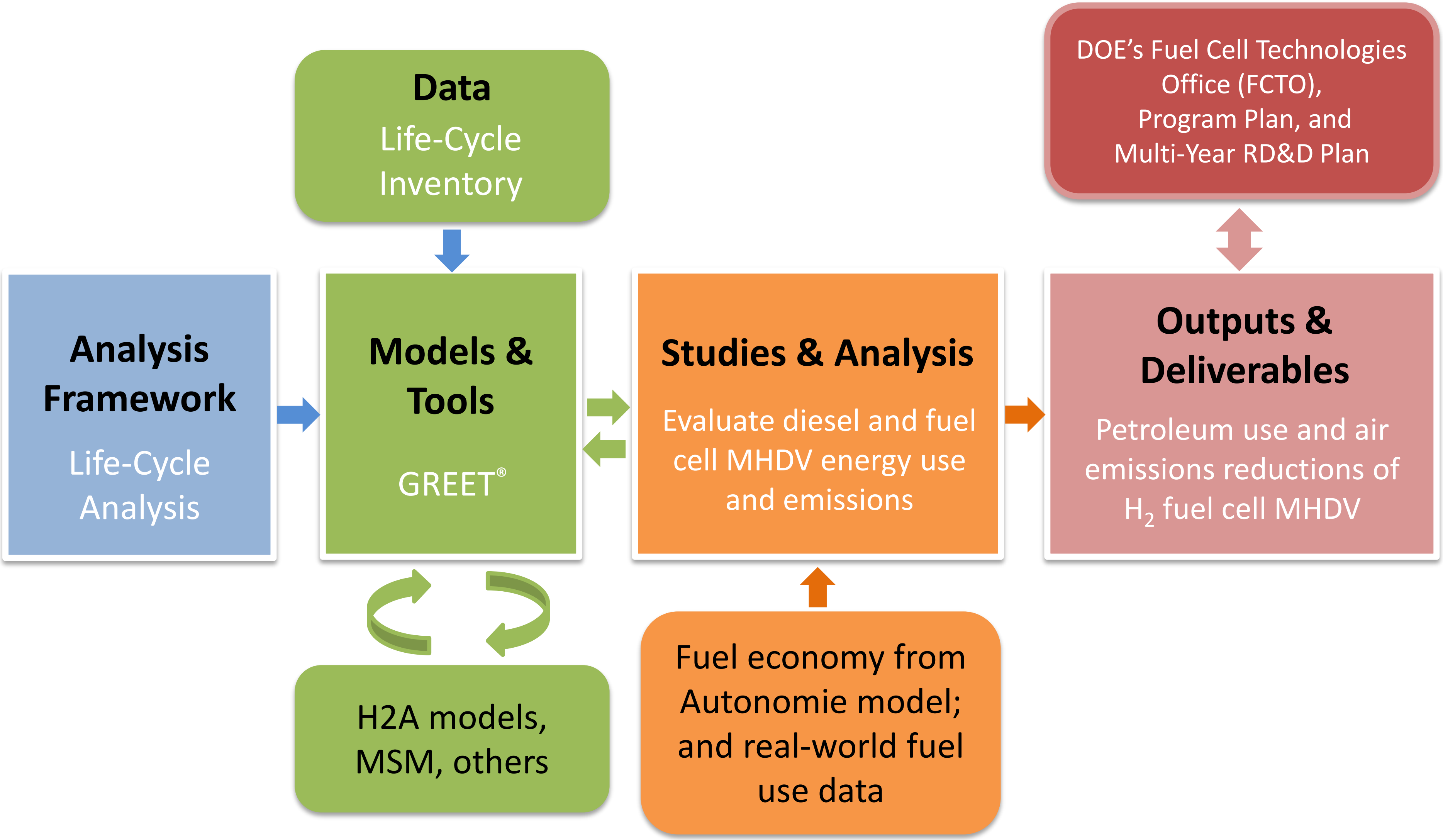
Source: GREET



Source: GREET

How does H2 FCEV technology compare in terms of air emissions and petroleum use?

LCA of GHG Emissions and petroleum use for hydrogen production pathways – Relevance



Data

Life-Cycle Inventory

DOE's Fuel Cell Technologies Office (FCTO), Program Plan, and Multi-Year RD&D Plan

Analysis Framework

Life-Cycle Analysis

Models & Tools

GREET®

Studies & Analysis

Evaluate diesel and fuel cell MHDV energy use and emissions

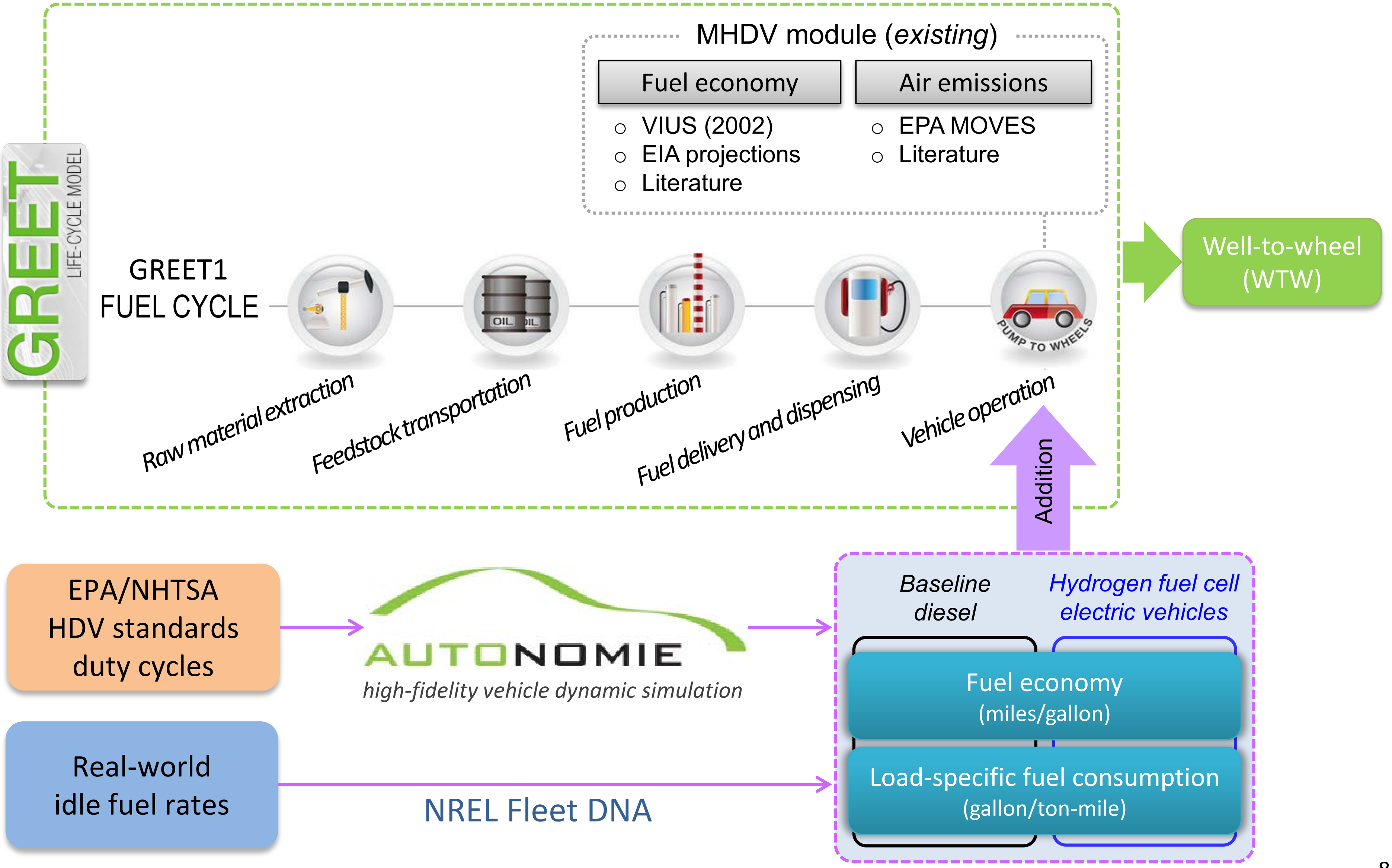
Outputs & Deliverables

Petroleum use and air emissions reductions of H_2 fuel cell MHDV

H2A models, MSM, others

Fuel economy from Autonomie model; and real-world fuel use data

Expanded GREET to include H2 fuel cell technology for medium- and heavy-duty vehicles – Approach



MHDV module (*existing*)

Fuel economy
- ○ VIUS (2002)
- ○ EIA projections
- ○ Literature

Air emissions
- ○ EPA MOVES
- ○ Literature

EPA/NHTSA HDV standards duty cycles

high-fidelity vehicle dynamic simulation

Real-world idle fuel rates

NREL Fleet DNA

Baseline diesel

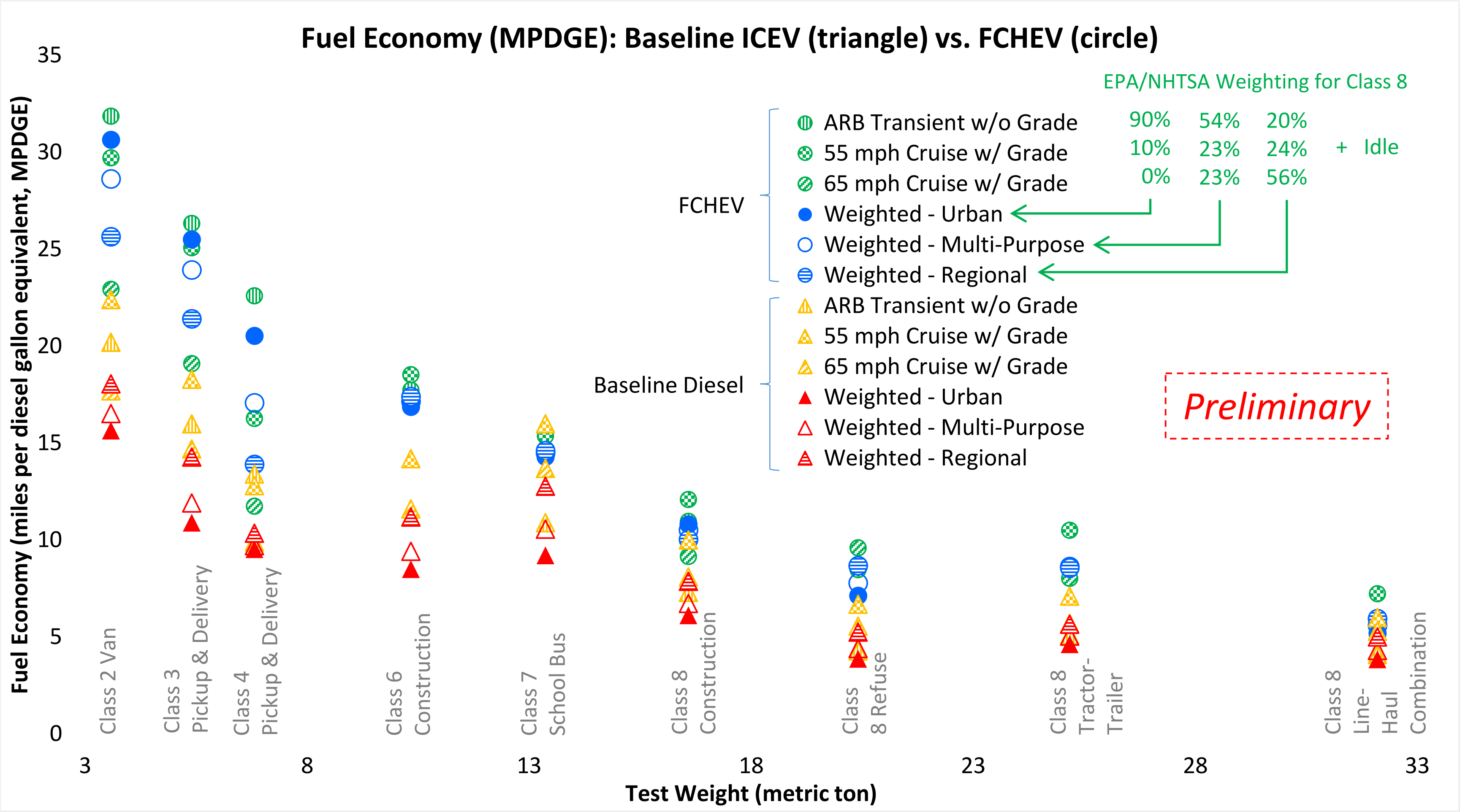
Hydrogen fuel cell electric vehicles

Fuel economy (miles/gallon)

Load-specific fuel consumption (gallon/ton-mile)

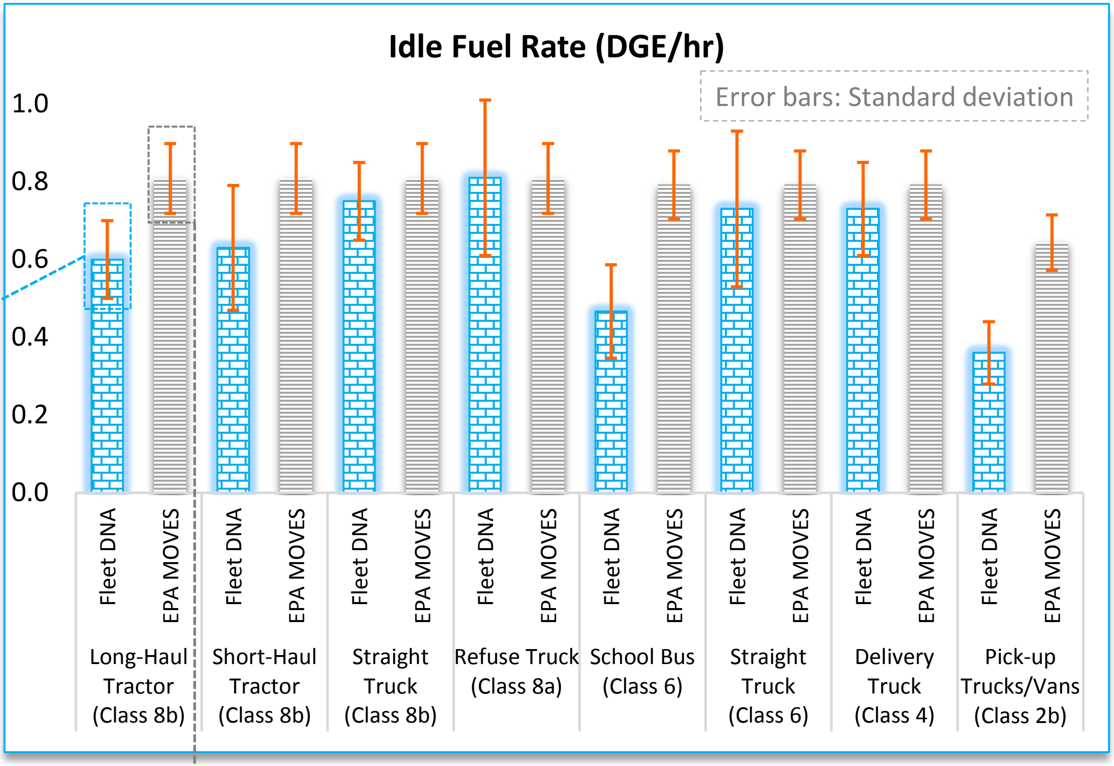
Fuel economy of diverse MHD vehicle weight classes and vocations – Accomplishment

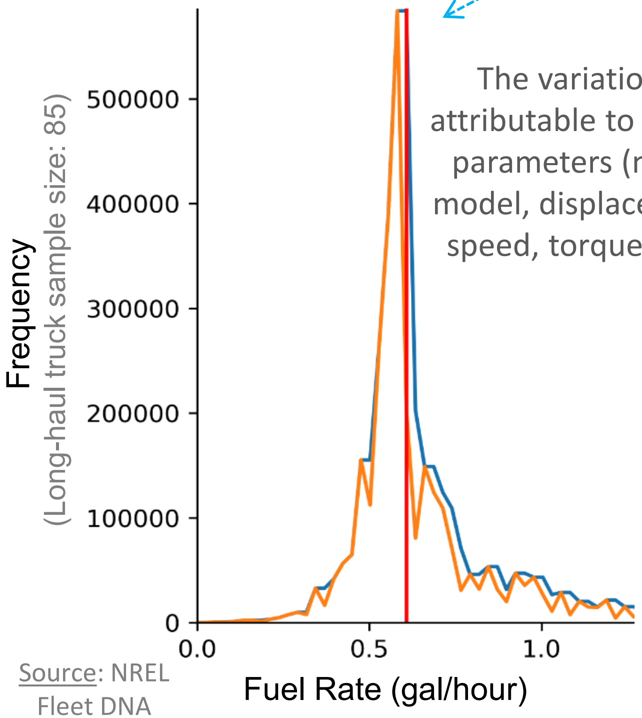
- Leveraged ANL's Autonomie model to estimate fuel economy for baseline diesel and fuel cell hybrid-electric vehicles (FCHEVs), based on EPA/NHTSA standards (Phase II) duty cycles.



Real-world idle fuel rates for baseline diesel trucks and buses – Accomplishment

- Incorporated real-world idle fuel rate data from NREL’s Fleet DNA team for different vehicle types and classes:
  More detailed, transparent, and reliable compared to EPA MOVES, CARB EMFAC, etc.

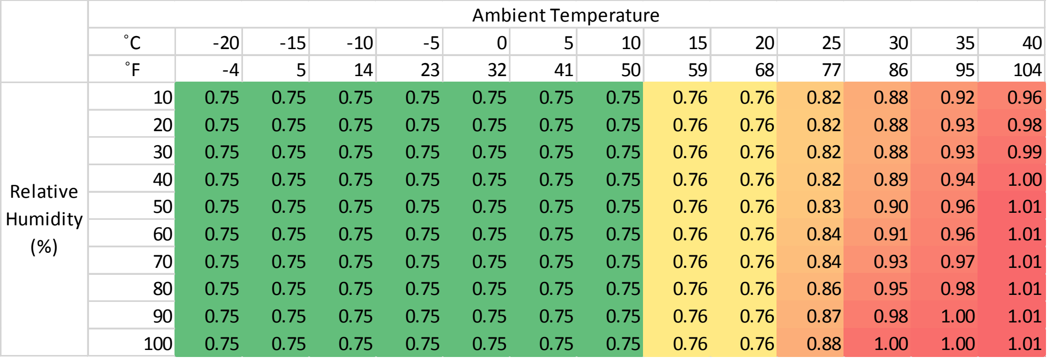




The variation is attributable to engine parameters (make, model, displacement, speed, torque, etc.)

Source: NREL Fleet DNA

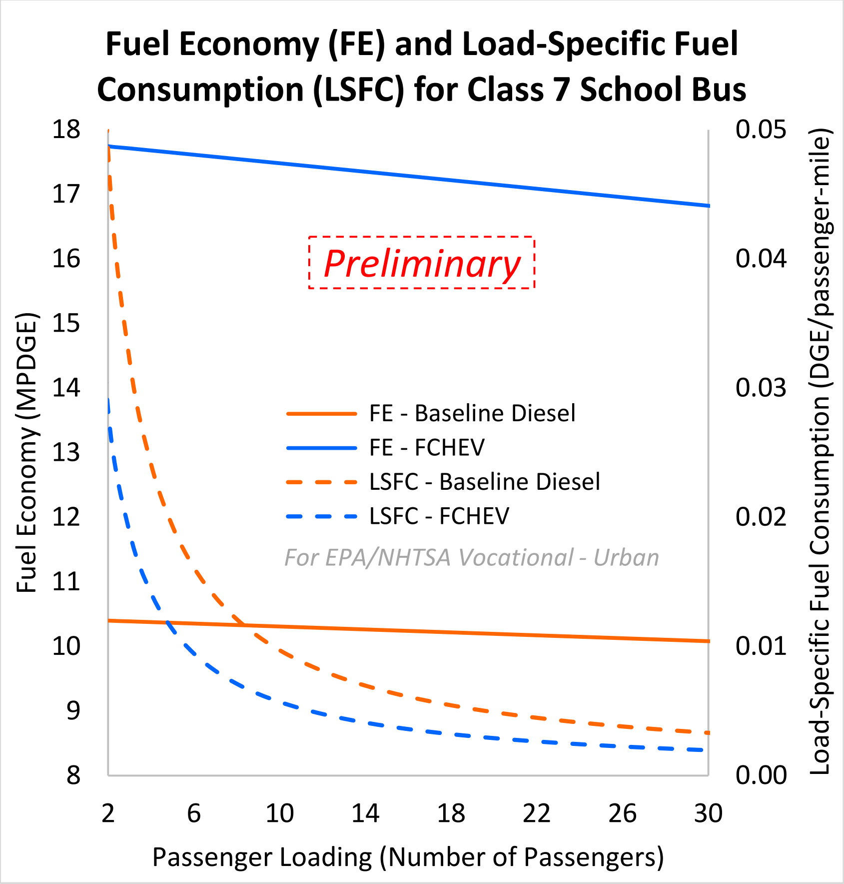
Source: EPA MOVES

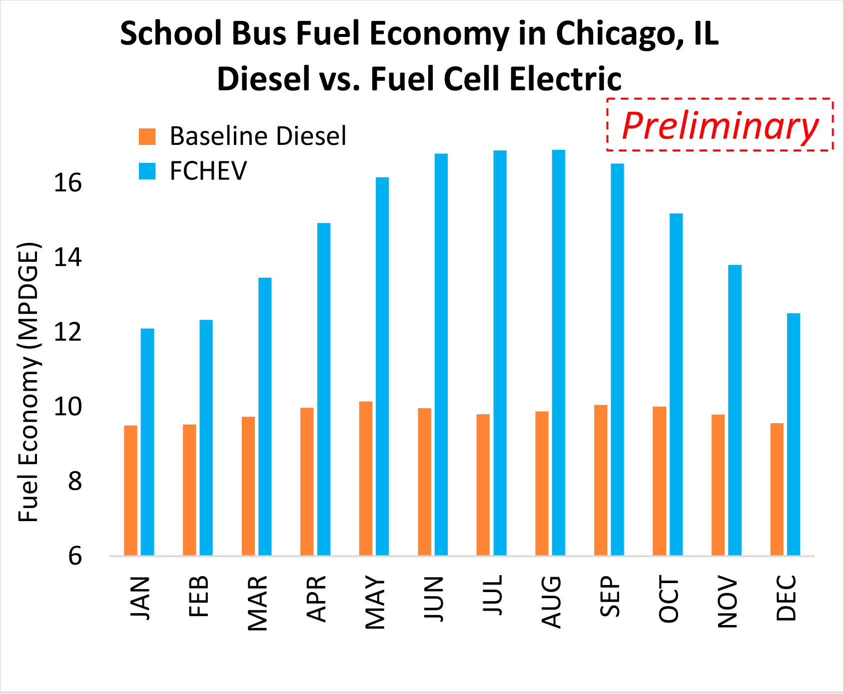


		Ambient Temperature												
	˚C	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40
	˚F	-4	5	14	23	32	41	50	59	68	77	86	95	104
Relative Humidity (%)	10	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.82	0.88	0.92	0.96
	20	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.82	0.88	0.93	0.98
	30	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.82	0.88	0.93	0.99
	40	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.82	0.89	0.94	1.00
	50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.83	0.90	0.96	1.01
	60	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.84	0.91	0.96	1.01
	70	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.84	0.93	0.97	1.01
	80	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.86	0.95	0.98	1.01
	90	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.87	0.98	1.00	1.01
	100	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.88	1.00	1.00	1.01

Examined the impact of different operating conditions – Accomplishment

- GREET adopts a ratio-based approach for medium- and heavy-duty vehicles (e.g., baseline diesel vs. FCHEV fuel economy ratio).
- Whether it's fuel economy (FE) or load-specific fuel consumption (LSFC), the ratio varies with operating conditions (e.g., payload, climate, driving behavior, route characteristics, etc.).
- Calculations show that some conditions (e.g., climate) affect FCHEV more severely compared to diesel.



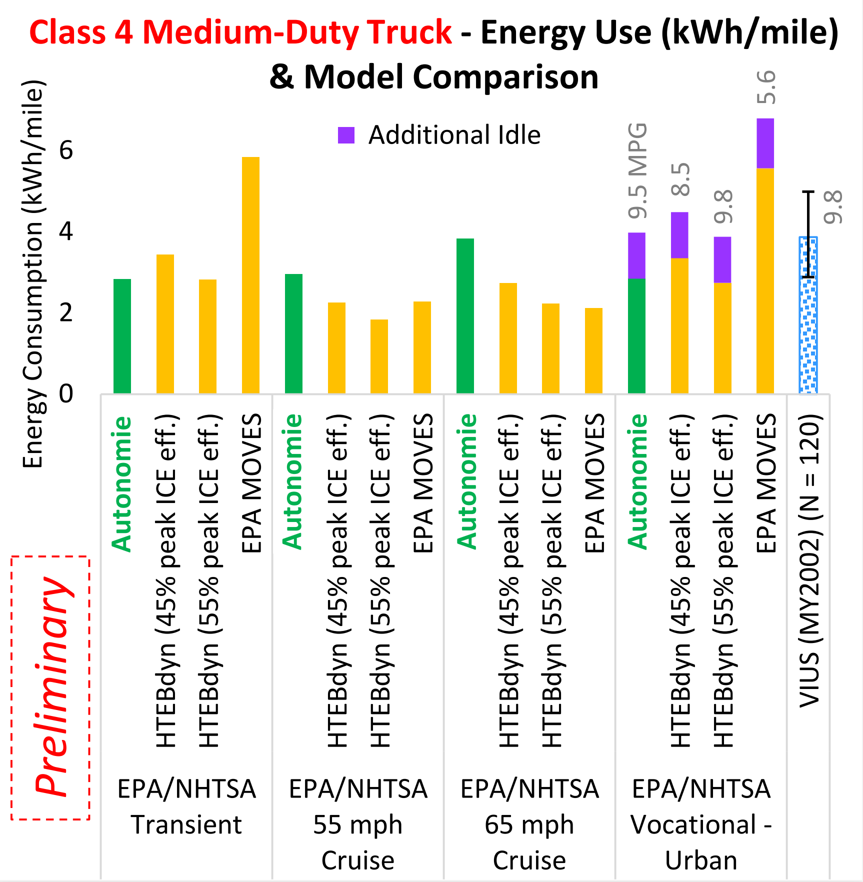


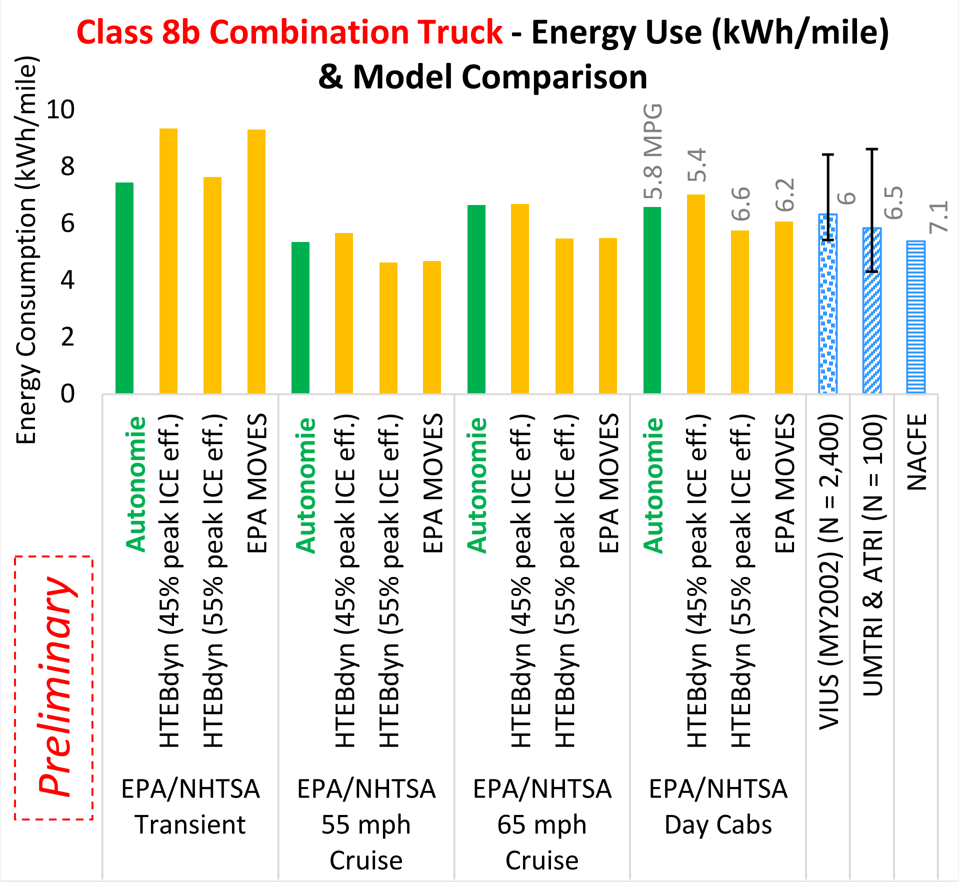
Based on 6-9 am and 3-6 pm operation time window and local hour-by-hour climate profiles. Passenger loading = 60.

✓ **FCHEV is more efficient than diesel counterpart but more sensitive to severe climate condition.**

Cross-evaluated different models and approaches – Accomplishment

- Model selection: Autonomie provides more consistent results (with real-world survey data) across vehicle weight classes, compared to other alternative tools.
- Idle fuel consumption is significant for EPA/NHTSA cycle weighting and aggregation, showcasing the importance of "real-world" idle fuel rates data (NREL's Fleet DNA).


Class 4 Medium-Duty Truck - Energy Use (kWh/mile) & Model Comparison

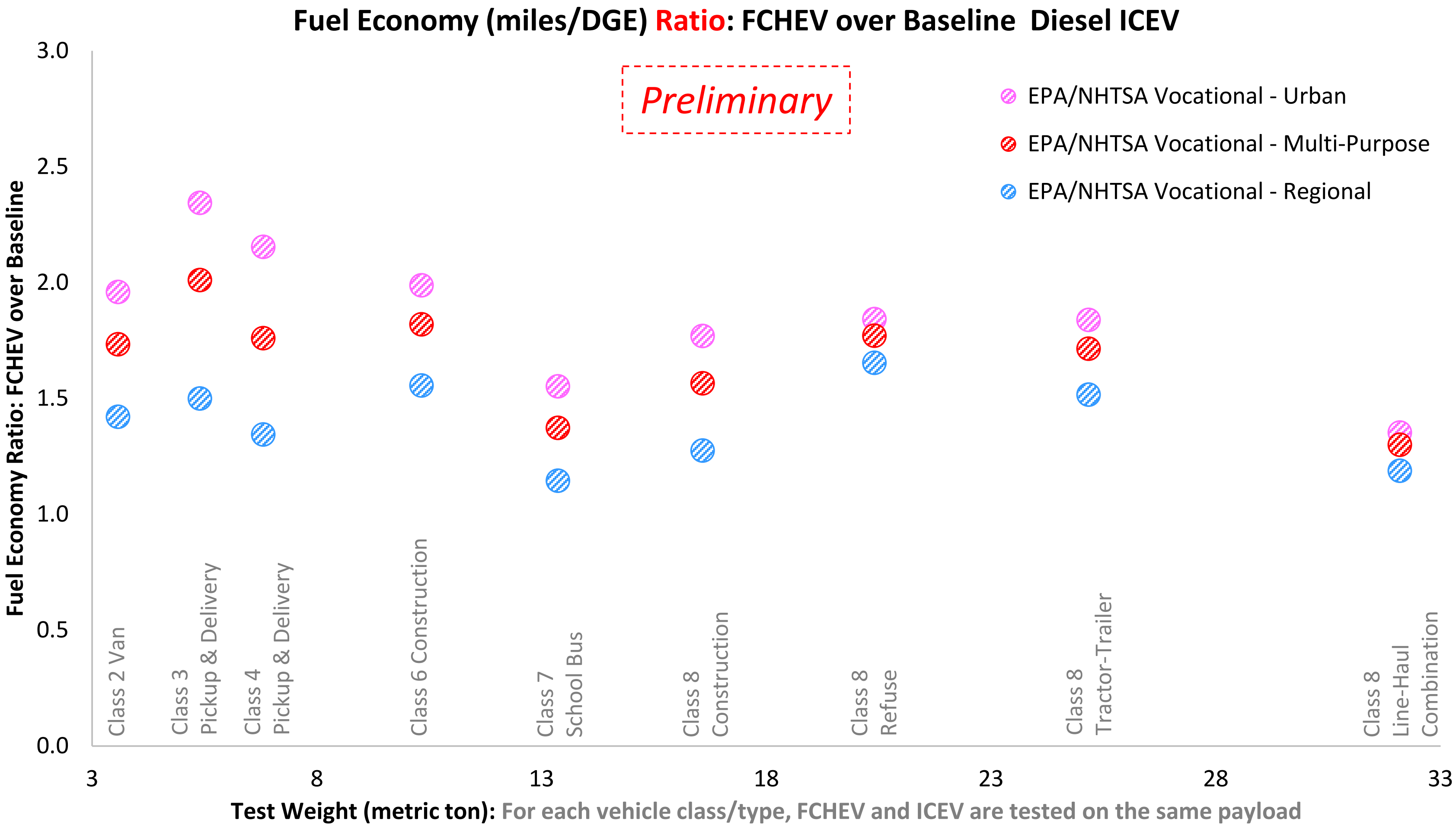

Class 8b Combination Truck - Energy Use (kWh/mile) & Model Comparison

HTEBdyn (TA Engineering): Used for DOE's Vehicle Technologies Program Government Performance and Results Act (GPRA) Report.

Fuel cell MHD vehicles achieve around 1.7 times better fuel economy than diesel – Accomplishment

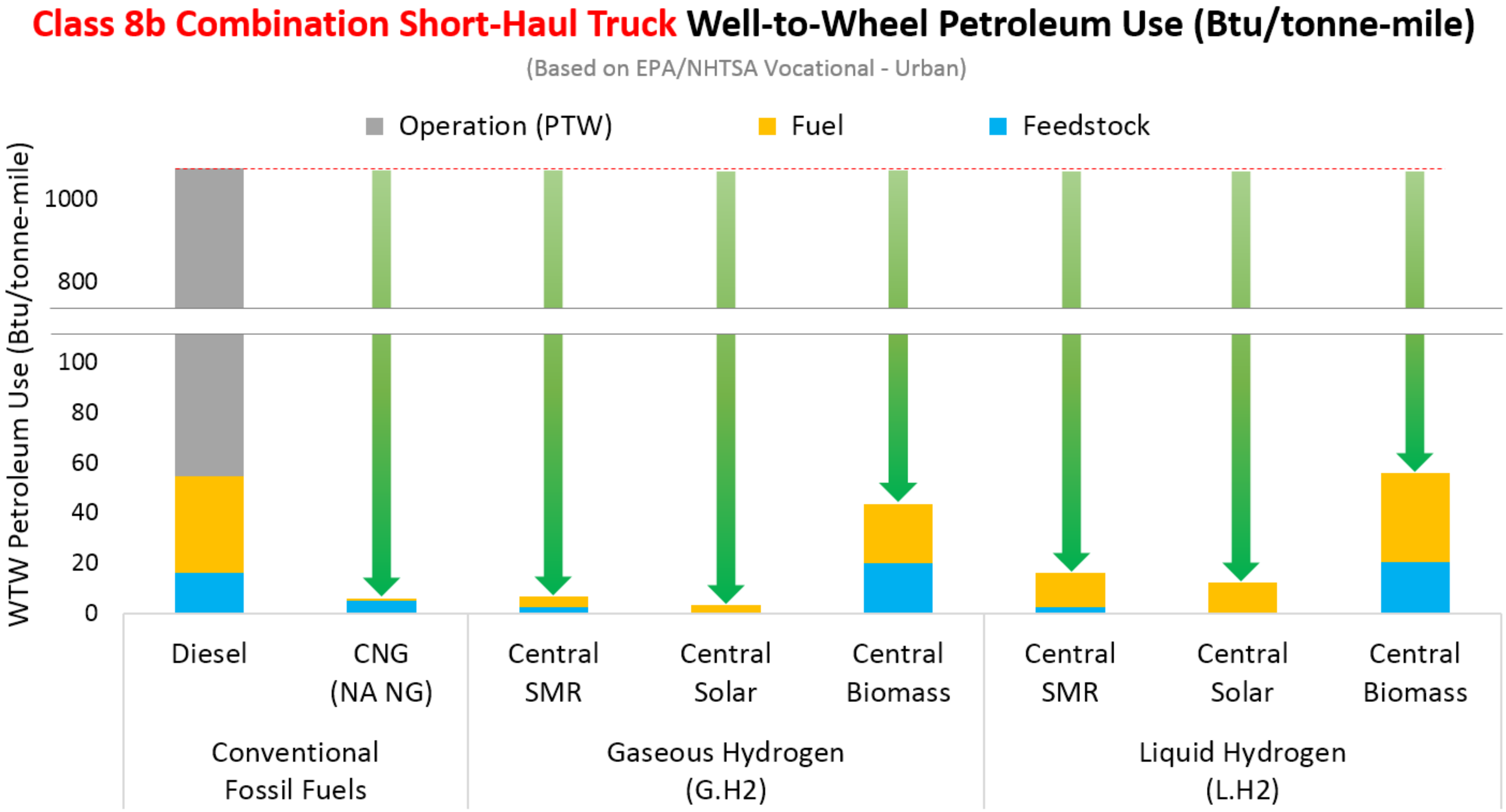
- Estimated fuel economy (FE in miles/gallon) and load-specific fuel consumption (LSFC in gallons/tonne-mile) ratios for GREET based on Autonomie simulations & idle fuel rates.

FE ratio relative to diesel is ~1.7 (1.2 – 2.3) → Vary with vocations & duty cycles.



Fuel cell freight trucks provide significant petroleum use reduction benefits – Accomplishment

Compared to baseline diesel trucks, hydrogen fuel cell trucks
reduce 95-99% of petroleum consumption.

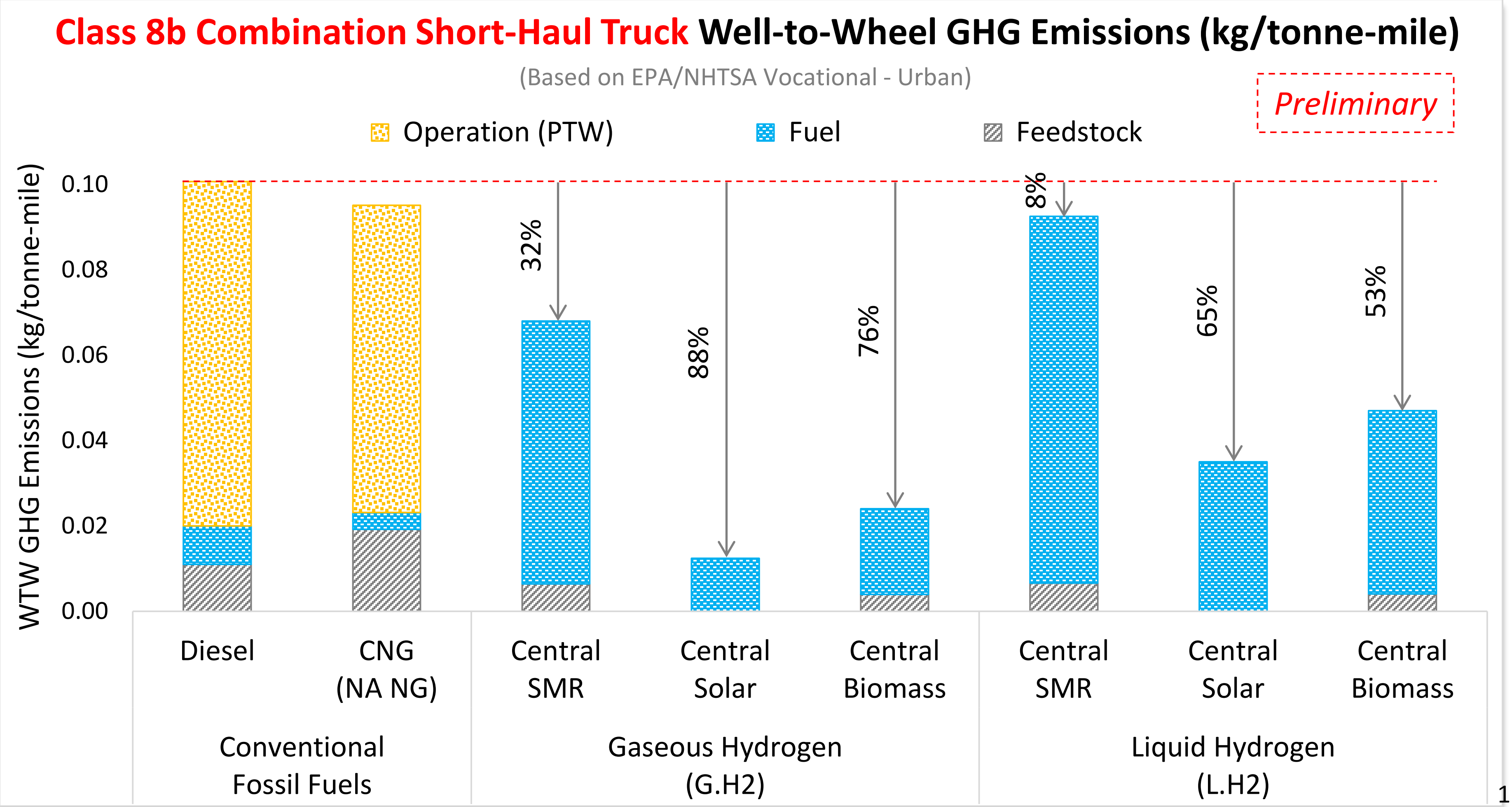

Class 8b Combination Short-Haul Truck Well-to-Wheel Petroleum Use (Btu/tonne-mile)

(Based on EPA/NHTSA Vocational - Urban)

Well-to-wheel analysis of GHG emissions of freight trucks – Accomplishment

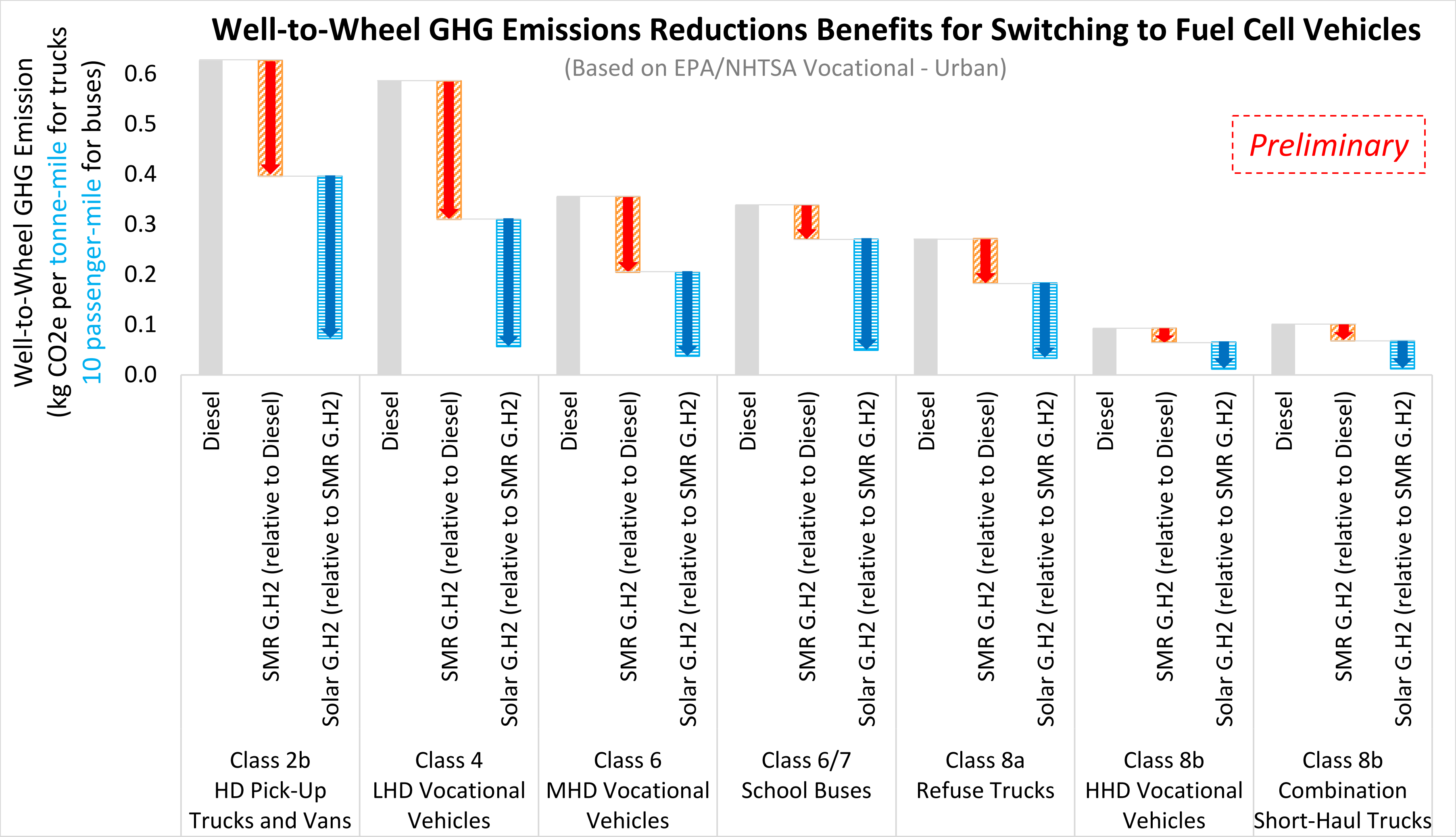
- On a tonne-mile basis, whether gaseous (G.H2) or liquid (L.H2), hydrogen fuel cell hybrid-electric trucks generally emit less WTW GHGs in comparison with baseline diesel.

Gaseous hydrogen FC trucks achieve ~30-90% GHG emissions reduction over diesel trucks.



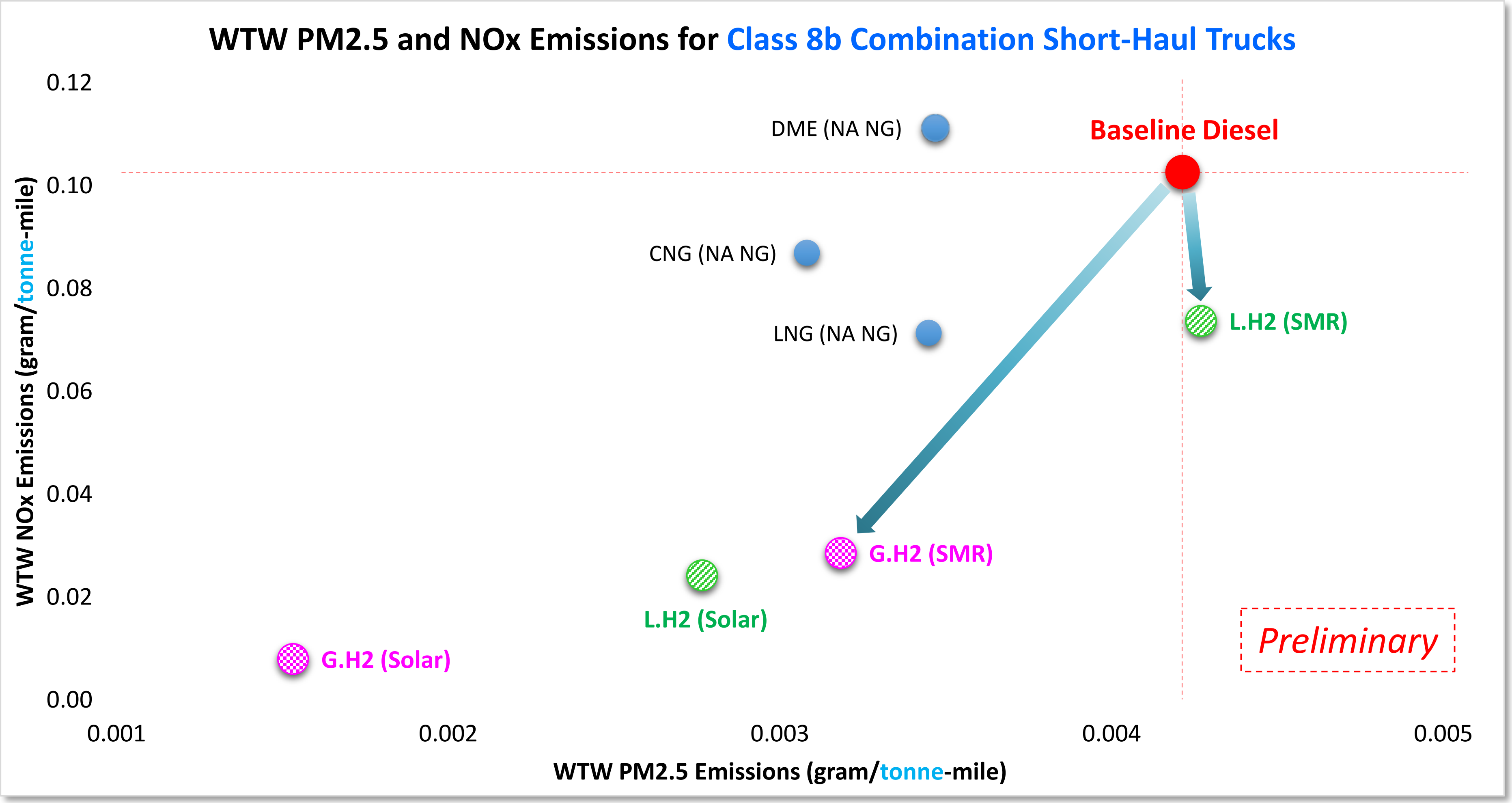
GHG emissions reductions for different MHD vehicle types and vocations – Accomplishment

Compared to diesel counterparts, medium- and heavy-duty (MHD) hydrogen fuel cell vehicles create much less GHG emissions across the board.



Well-to-wheel analysis of criteria air pollutants (CAP) emissions – Accomplishment

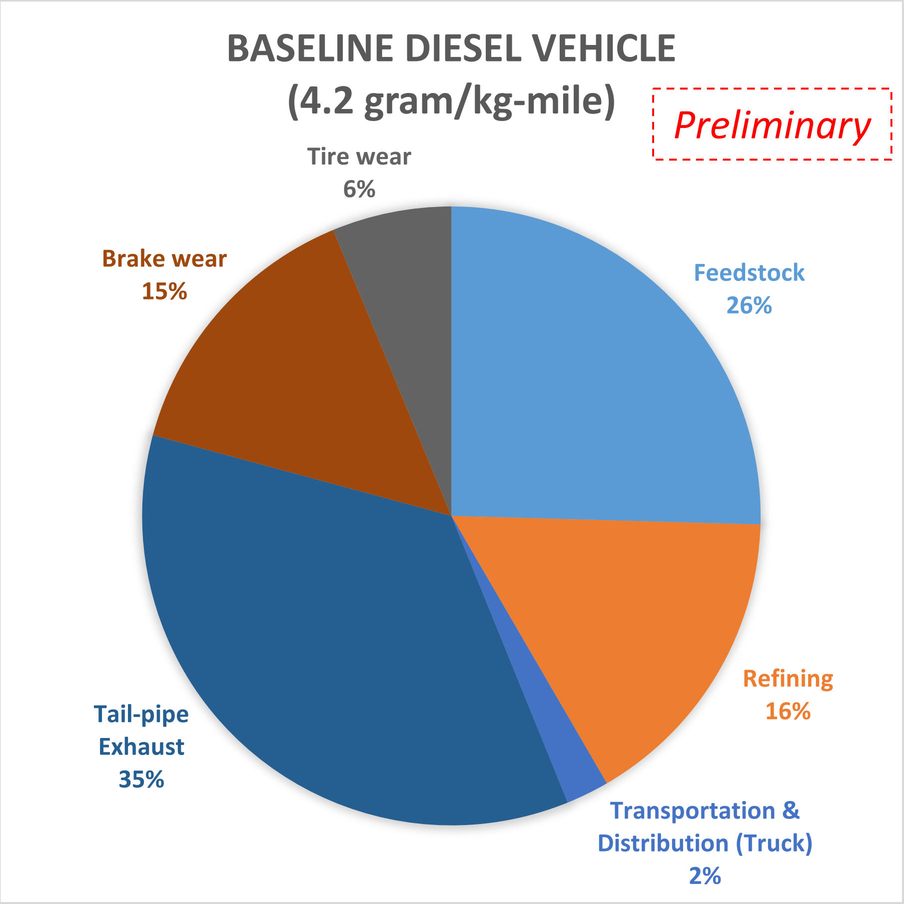
Gaseous hydrogen (G.H2) fuel cell electric trucks
reduce overall NOx and PM2.5 emissions compared to baseline diesel

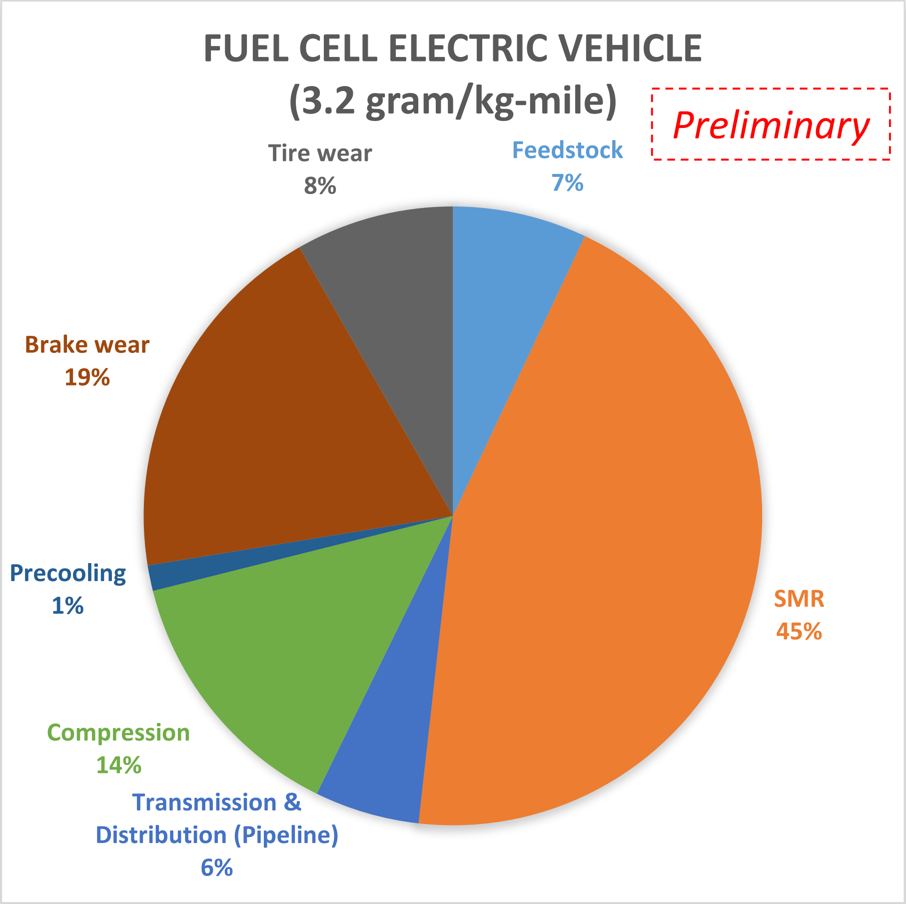


Lower PM2.5 emissions and different compositions along the well-to-wheel chain – Accomplishment

- For WTW PM2.5 emissions, tail-pipe and brake/tire wear account for more than half of total for baseline diesel, whereas upstream (WTP) is the largest element for FCHEV.

Well-to-wheel PM2.5 emissions for class 8b combination short-haul trucks: Diesel > FCHEV





Summary – *Accomplishment*

- Examined different models and approaches for estimating fuel economy of baseline diesel and fuel cell vehicles under various operating conditions.

- Estimated fuel economy and load-specific fuel consumption inventory for medium- and heavy-duty fuel cell electric trucks and buses.
  - ✓ Leveraged Autonomie model capabilities with Phase II EPA/NHTSA cycles.

- Employed high-fidelity vehicle dynamic simulation software and real-world data (idle fuel rates).

- Compared diesel and fuel cell vehicles on a common basis using the EPA/NHTSA standards (Phase II) duty cycles.

- Expanded GREET to include medium- and heavy-duty fuel cell electric vehicle technology.

- Evaluated comparative petroleum use and air emissions (greenhouse gases and criteria air pollutants) for baseline diesel vs. fuel cell electric vehicle technologies for diverse medium- and heavy-duty vehicle classes and vocations.

Collaborations and Acknowledgments

- ☐ Ram Vijayagopal and Aymeric Rousseau of ANL Autonomie team provided fuel economy values for phase II EPA/NHTSA driving cycles (in kind).
- ☐ Kevin Stutenberg and Forrest Jehlik of ANL APRF shared vehicle test data.
- ☐ Thomas Stephens of ANL and James S. Moore of TA Engineering helped run HTEBdyn simulations.
- ☐ Robert Prohaska, Kevin Walkowicz, Andrew Kotz, and Kenneth Kelly of NREL Fleet DNA team supplied idle fuel rates and in-use vehicle energy consumption data.
- ☐ Frank Falcone and Joshua Goldman of TransPower provided in-service vehicle energy use data.
- ☐ Samantha Bingham and Paul Payne of City of Chicago as well as Caleb Lander of Motiv Power Systems helped collect in-use truck fuel economy.
- ☐ Zoran Filipi and Andrej Ivanco of Clemson University shared real-world truck operation data.

Future Work

- Collect comprehensive in-service fuel economy data and examine real-world duty cycles
- Fully utilize the advanced vehicle dynamic simulation tool (i.e., Autonomie) by integrating with real-world duty cycles and developing statistical fuel economy data
  - Important for re-evaluating and updating baseline (diesel) data across different vehicle classes and vocations.
  - Crucial for making predictions on future model year's fuel economy
- Include missing classes/vocations (e.g., transit bus) for fuel cell electric vehicle technology
- Conduct an in-depth investigation of uncertainty and variations in fuel economy, focusing on model selection and operating conditions (e.g., route characteristics, driving behavior, grade, payload, climate, etc.)
- Update tail-pipe and non-exhaust emissions factors for baseline diesel
- Harmonize a suite of models and approaches to arrive at consistent results
- Investigate the impact of different fuel cell electric vehicle design strategies (e.g., battery dominant vs. fuel cell dominant)
- Update GREET model and document research findings in a publication for peer-review

Project Summary

- **Relevance:** Evaluate comparative petroleum use and air emissions of fuel cell electric vehicle technology and baseline diesel for diverse medium- and heavy-duty vehicles. Well-to-wheel (WTW) accounting method is essential to account for not only direct (tail-pipe and brake/tire wear) but also indirect emissions burden along the fuel supply-chain.
- **Approach:** Expand the GREET model to assess life-cycle petroleum use and air emissions (greenhouse gas and air pollutants) of medium- and heavy-duty fuel cell electric vehicles in comparison with baseline diesel, based on high-fidelity vehicle dynamic simulation, real-world idle fuel rates, and the most recent heavy-duty vehicle standards duty cycles.
- **Collaborations**: Sought data and guidance from an array of experts in medium- and heavy-duty vehicle industry, academia, and DOE national labs who provided guidance and valuable input on the performance of fuel cell electric and baseline diesel vehicles.
- **Technical accomplishments and progress:**
  - Estimated fuel economy, petroleum use, and air emissions for medium- and heavy-duty fuel cell electric vehicles of various weight classes and vocations
  - Compared different models and approaches for fuel economy estimation and gained confidence in the results
  - Examined the impact of different operating conditions as well as fuel production pathways
  - Identified the needs of more recent data for well-to-wheel analysis (e.g., SMR for H2 production)
- **Future Research**:
  - Incorporate fuel cell electric transit bus into analysis
  - Utilize a large set of real-world vehicle operation data
  - Develop statistical distributions of fuel economy and emissions
  - Assess spatial and temporal variations

Argonne NATIONAL LABORATORY

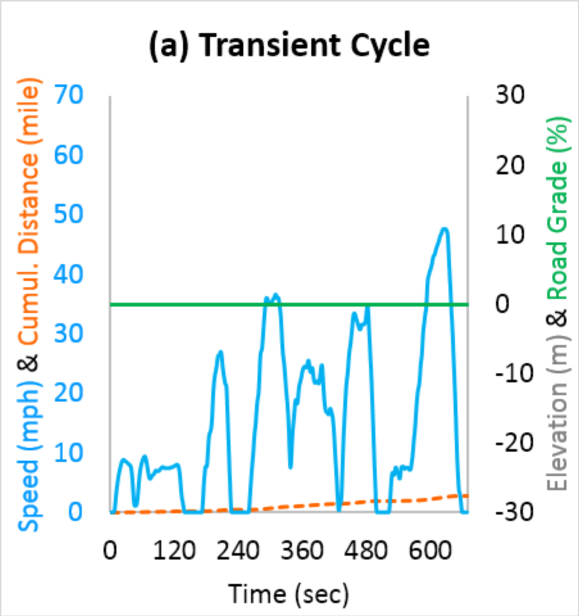
Acronyms

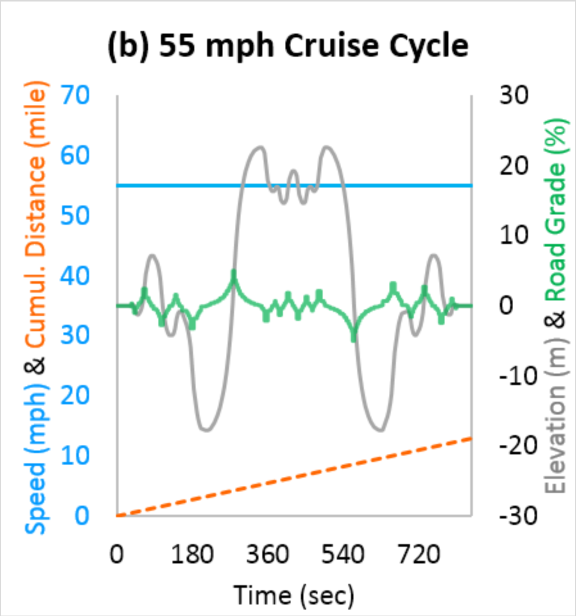
- ANL: Argonne National Laboratory
- APRF: Advanced Powertrain Research Facility
- AQMD: (South Coast) Air Quality Management District
- ATRI: American Transportation Research Institute
- BD20: Biodiesel (mixture of 20% biodiesel and 80% diesel by volume)
- CAP: Criteria Air Pollutant
- CARB: California Air Resources Board
- CH4: Methane
- CNG: Compressed Natural Gas
- CO: Carbon Monoxide
- CO2: Carbon Dioxide
- CO2e: Carbon Dioxide Equivalent
- DGE: Diesel Gallon Equivalent
- DME: DiMethyl Ether
- DOE: Department of Energy
- DOT: Department of Transportation
- EIA: Energy Information Administration
- EMFAC: EMission FACtors
- EPA: Environmental Protection Agency
- FC: Fuel Cell
- FCEV: Fuel Cell Electric Vehicle
- FCHEV: Fuel Cell Hybrid-Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- FE: Fuel Economy
- FY: Fiscal Year
- G.H2: Gaseous Hydrogen
- GHG : Greenhouse Gases
- GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- H_2: Hydrogen
- HD: Heavy-Duty
- HDV: Heavy-Duty Vehicle
- HHD: Heavy Heavy-Duty
- HTEBdyn: Heavy Truck Energy Balance Dynamic Model
- ICE: Internal Combustion Engine
- ICEV: Internal Combustion Engine Vehicle
- LDV: Light-Duty Vehicle
- LHD: Light Heavy-Duty
- L.H2: Liquid Hydrogen
- LNG: Liquefied Natural Gas
- LPG: Liquefied Petroleum Gas
- LSFC: Load-Specific Fuel Consumption
- MHD: Medium- and Heavy-Duty
- MHDV: Medium- and Heavy-Duty Vehicle
- MOVES: MOtor Vehicle Emission Simulator
- MPDGE: Miles Per Diesel Gallon Equivalent
- NA: North America
- NACFE: North American Council for Freight Efficiency
- NEI: National Emissions Inventory
- NG: Natural Gas
- NHTSA: National Highway Traffic Safety Administration
- N2O: Nitrous Oxide
- NOx: Nitrogen Oxides
- NTS: National Transportation Statistics
- ORNL: Oak Ridge National Laboratory
- PM: Particulate Matters
- PTW: Pump-to-Wheel
- RDII 100: Renewable Diesel 2 (100% by volume)
- SMR: Steam Methane Reforming
- SO2: Sulfur Dioxide
- UMTRI: University of Michigan Transportation Research Institute
- VIUS: Vehicle Inventory and Use Survey
- VOC: Volatile Organic Compounds
- WTP: Well-to-Pump
- WTT: Well-to-Tank
- WTW: Well-to-Wheel

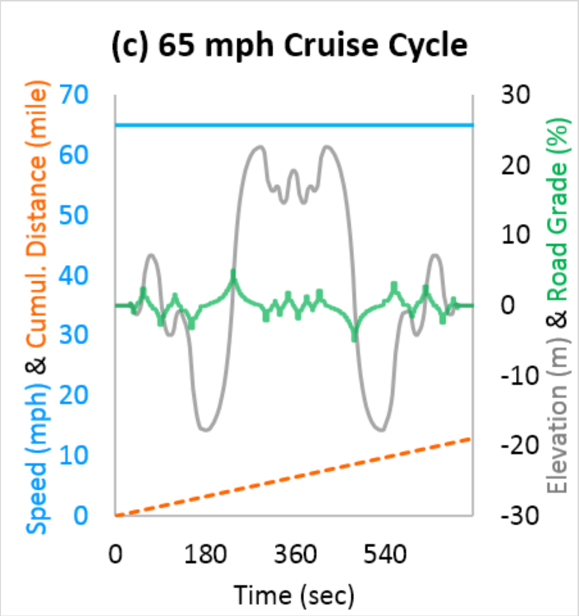
Technical Backup Slides

Adopted EPA/NHTSA heavy-duty vehicle standards (Phase II) duty cycles

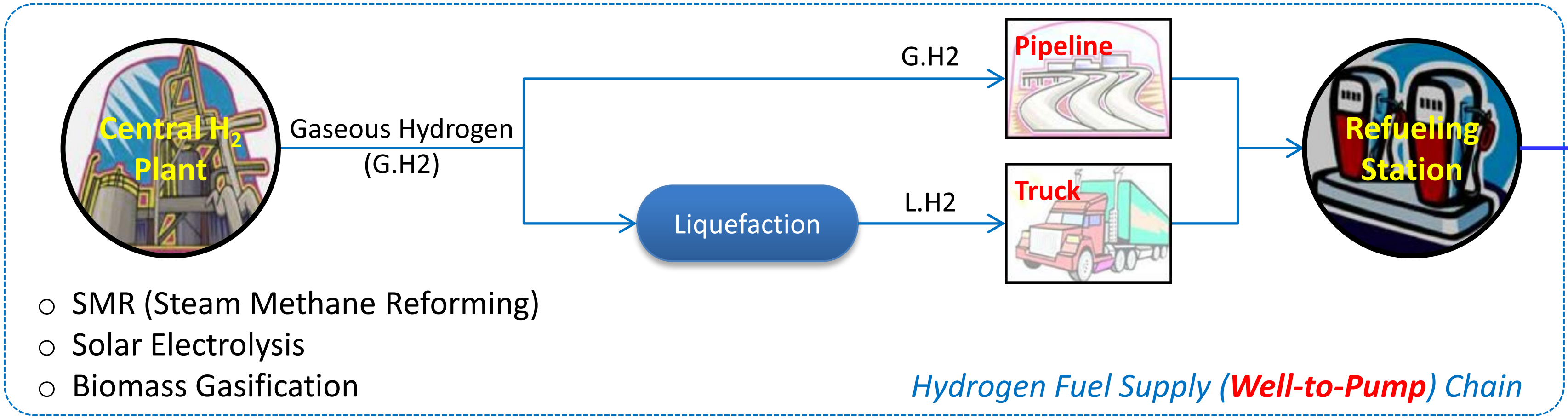
- To compare baseline diesel vs. fuel cell on a level ground: Used EPA/NHTSA HDV standards (Phase II) duty cycles.
- EPA/NHTSA takes a weighting approach based on both distance (non-idle) and time (idle).
    - Non-idle conditions (shown below):
        - (a) Transient without road grade
        - (b) 55 miles/hour steady-state cruise with (± 5%) road grade
        - (c) 65 miles/hour steady-state cruise with (± 5%) road grade
    - Idle conditions: parked & drive


(a) Transient Cycle


(b) 55 mph Cruise Cycle


(c) 65 mph Cruise Cycle

Medium- and heavy-duty hydrogen fuel cell electric vehicle (FCEV) system configuration



Central H_2 Plant

Gaseous Hydrogen (G.H2)

G.H2

Liquefaction

L.H2

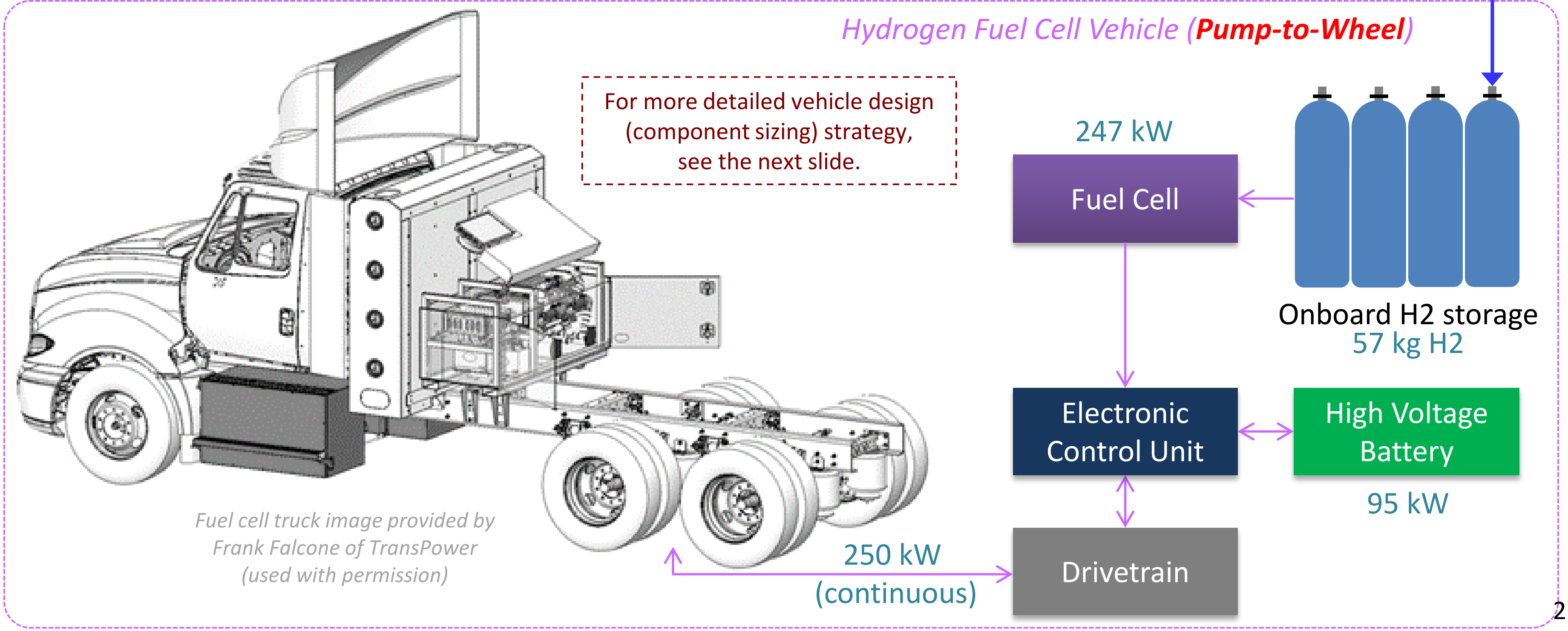
Pipeline

Truck

Refueling Station

- SMR (Steam Methane Reforming)
- Solar Electrolysis
- Biomass Gasification

*Hydrogen Fuel Supply (**Well-to-Pump**) Chain*



*Hydrogen Fuel Cell Vehicle (**Pump-to-Wheel**)*

For more detailed vehicle design (component sizing) strategy, see the next slide.

247 kW

Fuel Cell

Onboard H2 storage

57 kg H2

Electronic Control Unit

High Voltage Battery

95 kW

Drivetrain

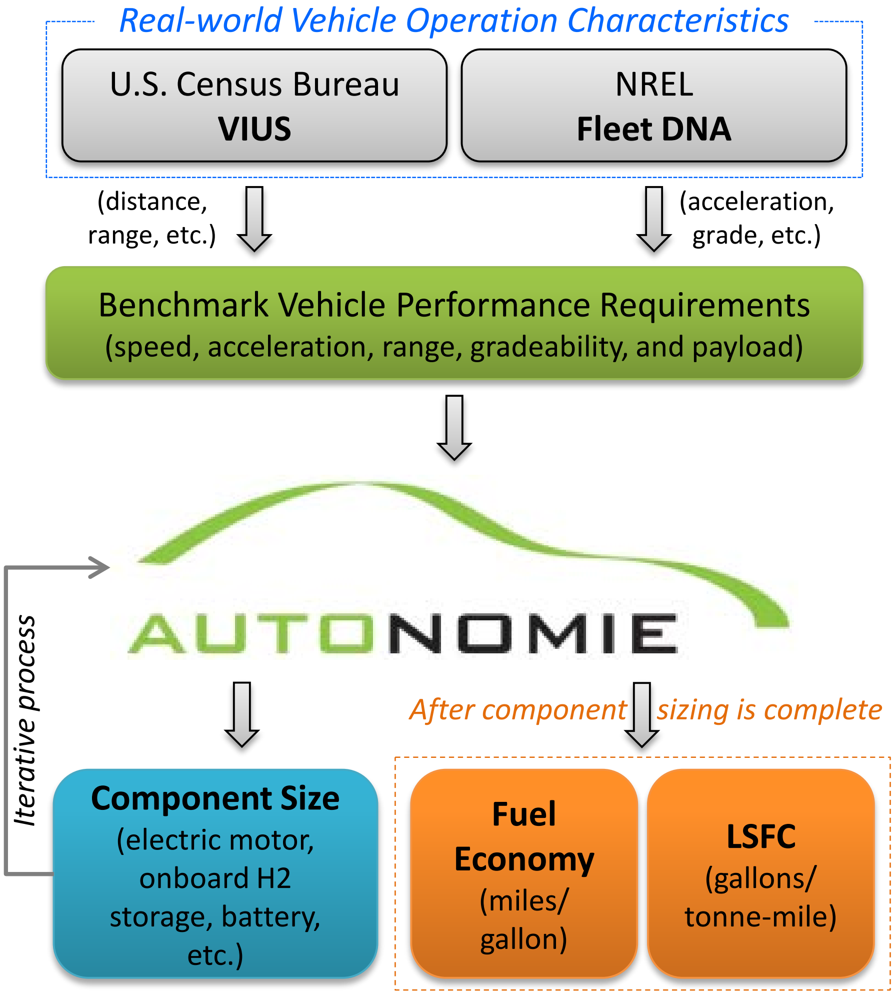
250 kW (continuous)

Fuel cell truck image provided by Frank Falcone of TransPower (used with permission)

Component sizing of medium- and heavy-duty hydrogen fuel cell hybrid-electric vehicles (FCHEVs)

Leveraged the vehicle component sizing and other relevant projects outcome.

- 2016 AMR → Project #TV-032: Fuel Cell Electric Truck Component Sizing (Supported by FCTO in FY16)
- 2017 AMR → Poster VAN023: Assessing Energy and Cost Impact of Adv. Tech. through Model Based Design



Real-world Vehicle Operation Characteristics

U.S. Census Bureau **VIUS**

NREL **Fleet DNA**

(distance, range, etc.)

(acceleration, grade, etc.)

Benchmark Vehicle Performance Requirements (speed, acceleration, range, gradeability, and payload)

AUTONOMIE

Iterative process

After component sizing is complete

Component Size (electric motor, onboard H2 storage, battery, etc.)

Fuel Economy (miles/gallon)

LSFC (gallons/tonne-mile)

Key assumptions:

- The same vehicle performance (speed, range, etc.) for baseline diesel and FCHEV.
- Fuel cell is sized so as to provide 100% continuous power requested.
- Electric motor must be able to meet both continuous and peak power demand.
- Battery provides additional power during acceleration.
- Battery state-of-charge (SOC) in hybrid configuration: Net SOC change over the test cycle is zero.
- Battery is sized to provide energy for one acceleration event.

Class	Vehicle Type	Motor Power (kW, cont.)	Fuel Cell Power (kW)	Battery Power (kW)
2	Van	128	147	6
3	Pickup & Delivery Van	157	149	62
4	Pickup & Delivery Van	151	166	59
6	Construction Truck	151	170	30
7	School Bus	146	145	56
8	Construction Truck	186	139	57
8	Refuse Truck	256	273	94
8	Tractor-Trailer	250	247	95
8	Line Haul Combination Truck	349	363	47

Response to Reviewers' Comments from 2016 AMR

This project is new and thus was not reviewed last year.