Life Cycle Implications of Zero Emission Heavy Duty Vehicles

Presenter: Andrew Kotz, Ph.D.

NREL at a Glance

2,307

Employees,
plus more than
460
early-career researchers and visiting scientists

World-class
facilities, renowned technology experts

about 900

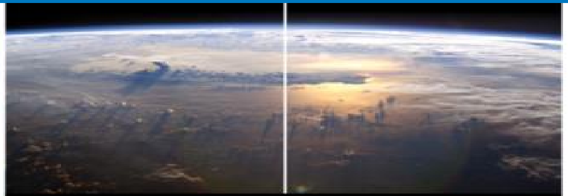
Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

Scope of Mission

Energy Efficiency

- Residential Buildings
- Commercial Buildings
- Personal and Commercial Vehicles



Renewable Energy

- Solar
- Wind and Water
- Biomass
- Hydrogen
- Geothermal

Systems Integration

- Grid Infrastructure
- Distributed Energy Interconnection
- Battery and Thermal Storage
- Transportation

Market Focus

- Private Industry
- Federal Agencies
- Defense Dept.
- State/Local Govt.
- International

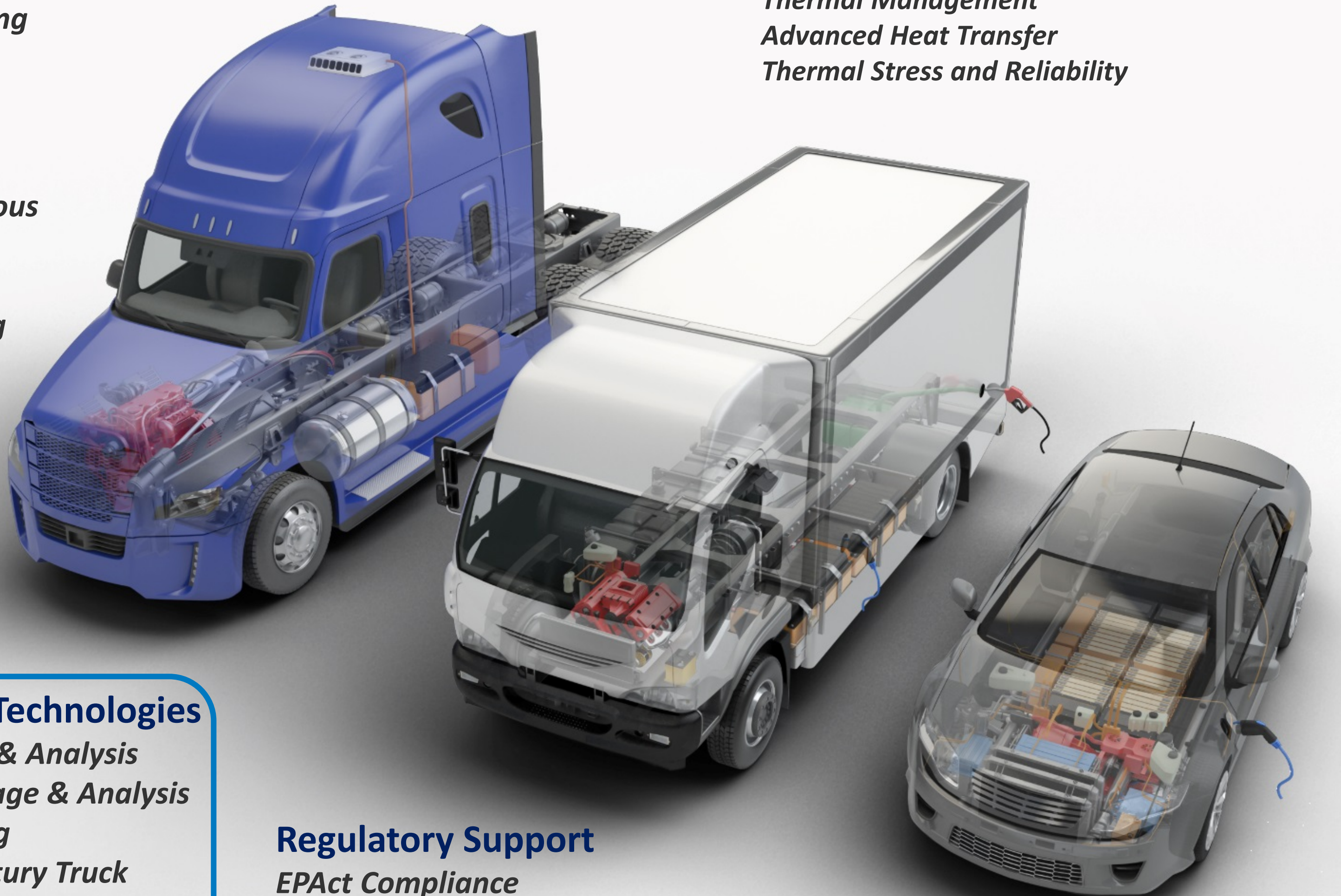
NREL Transportation and Vehicle R&D Activities

Advanced Combustion / Fuels
Advanced Petroleum and Biofuels
Combustion / Emissions Measurement
Vehicle and Engine Testing
Co-Optima

Advanced Power Electronics and Electric Motors
Thermal Management
Advanced Heat Transfer
Thermal Stress and Reliability

Advanced Energy Storage
Thermal Characterization / Management
Life/Abuse Testing and Modeling
Computer Aided Engineering
Electrode Material Development

Mobility Systems
Connected and Autonomous Vehicles
Multi-Modal Freight
Vehicle Systems Modeling
Technology Adoption
Total Cost of Ownership Modeling



Infrastructure and Impacts Analysis
Vehicle-to-Grid Integration
Integration with Renewables
Charging Equipment & Controls
Fueling Stations & Equipment

Hydrogen and Fuel Cells
Fuel Cell Electric Vehicles
Fuel Cell Buses
Fueling Infrastructure
Hydrogen Systems and Components
Safety, Codes and Standards

Commercial Vehicle Technologies
Technology Field Testing & Analysis
Big Data Collection, Storage & Analysis
Vehicle Systems Modeling
Super Truck and 21st Century Truck
Vehicle Thermal Management

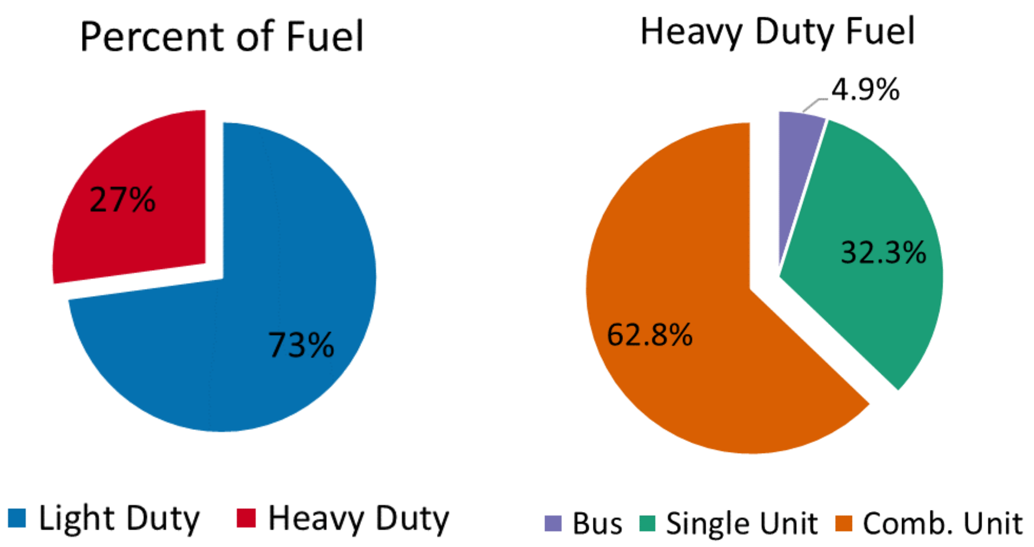
Regulatory Support
EPAct Compliance
Data & Policy Analysis
Technical Integration
Fleet Assistance

Technology Integration
Clean Cities
Guidance & Information for Fleet Decision Makers and Policy Makers
Technical Assistance
Online Data, Tools, Analysis

Motivation

Medium-, heavy-duty (MHD) vehicle electrification

- MHD vehicles have substantial energy requirements
  - 4.5% of U.S. vehicles
  - 27% of fuel use
  - Avg. 24,000 miles annually (~39,000 km)
- Impact per vehicle
  - @ 6.4 MPG = 3,744 gal/year
  - 83,500 lbsCO_2/year
- Fleet: 510million tonsCO_2/year
- 30% of NO_X & PM



https://www.fhwa.dot.gov/policyinformation/statistics/2017/vm1.cfm

Large per-vehicle impact

Life Cycle Analysis

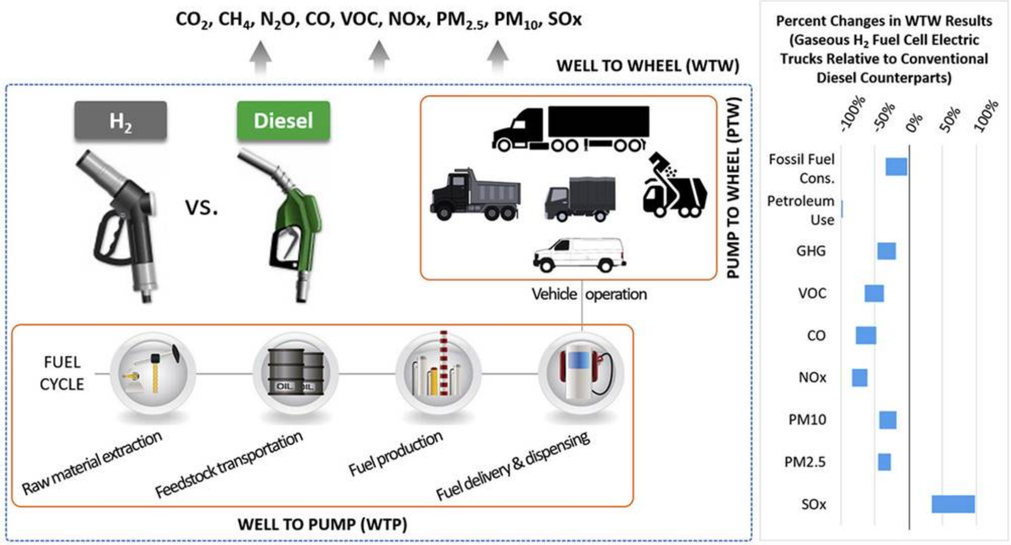
U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

- Internal combustion alternatives
  - Battery electric trucks (BET)
    - Higher efficiency
    - Low cost fuel
  - **Hydrogen fuel cell**
    - **Higher energy density**
    - **Faster fueling than BET**
  - Benefits
    - Effectively no heat rejection
    - No tailpipe emissions
- D.O.E. Fuel Cell Technology Office
  - Contract: DE-AC02-06CH11357
  - Examine real-world LCA

D.-Y. Lee, A. Elgowainy, A. Kotz, R. Vijayagopal, and J. Marcinkoski, “Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks,” *J. Power Sources*, vol. 393, no. April, pp. 217–229, 2018.



Transit Buses (not covered here): https://www.sciencedirect.com/science/article/pii/S0301421519300217

Battery Electric Challenges

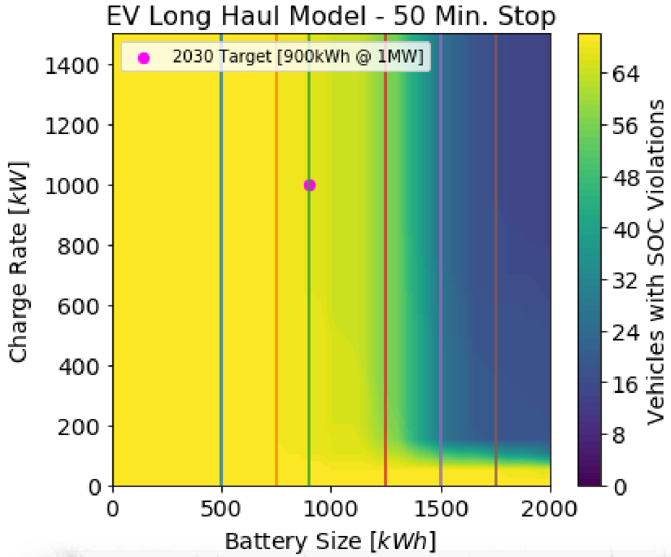
Example: Class 8 Long Haul EV

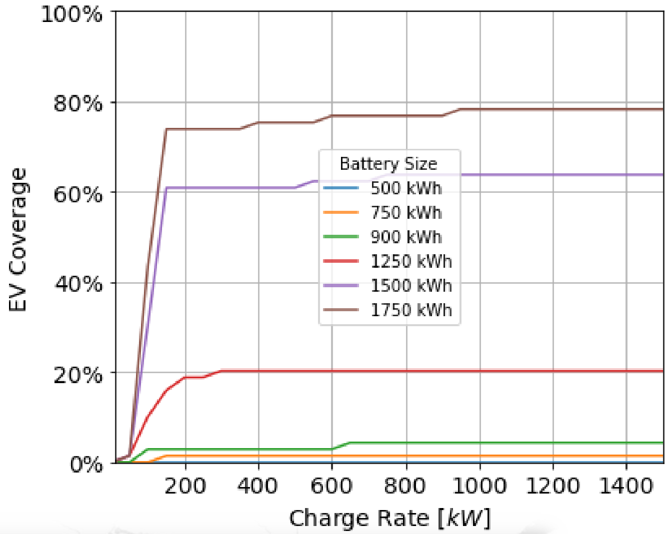
NOTE: This is preliminary modeled data

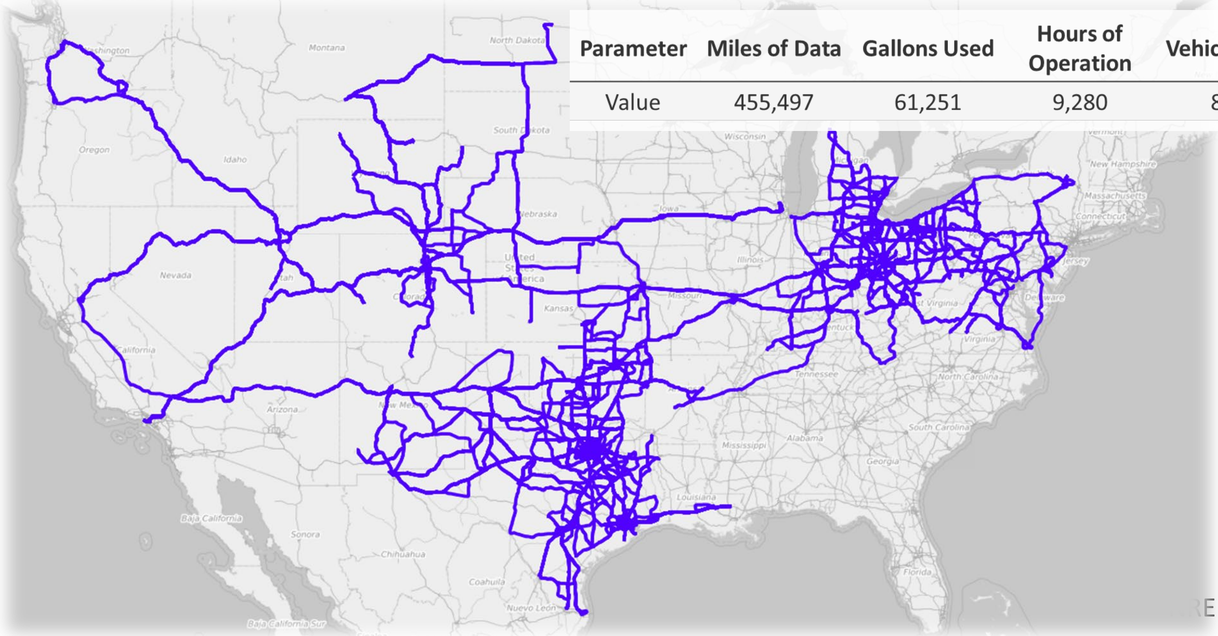
Challenges exist with battery technology in certain heavy vehicle application

- Use simplified EV model
  - Charges when stopped for > 50 min
  - 90% conversion eff. - No Regen
- Data from Fleet DNA
- Limited penetration in EV's under existing technology

There is a need for higher energy density and faster refill times to reach zero-emissions







Parameter	Miles of Data	Gallons Used	Hours of Operation	Vehicle Days
Value	455,497	61,251	9,280	869

Fleet DNA

Methodology

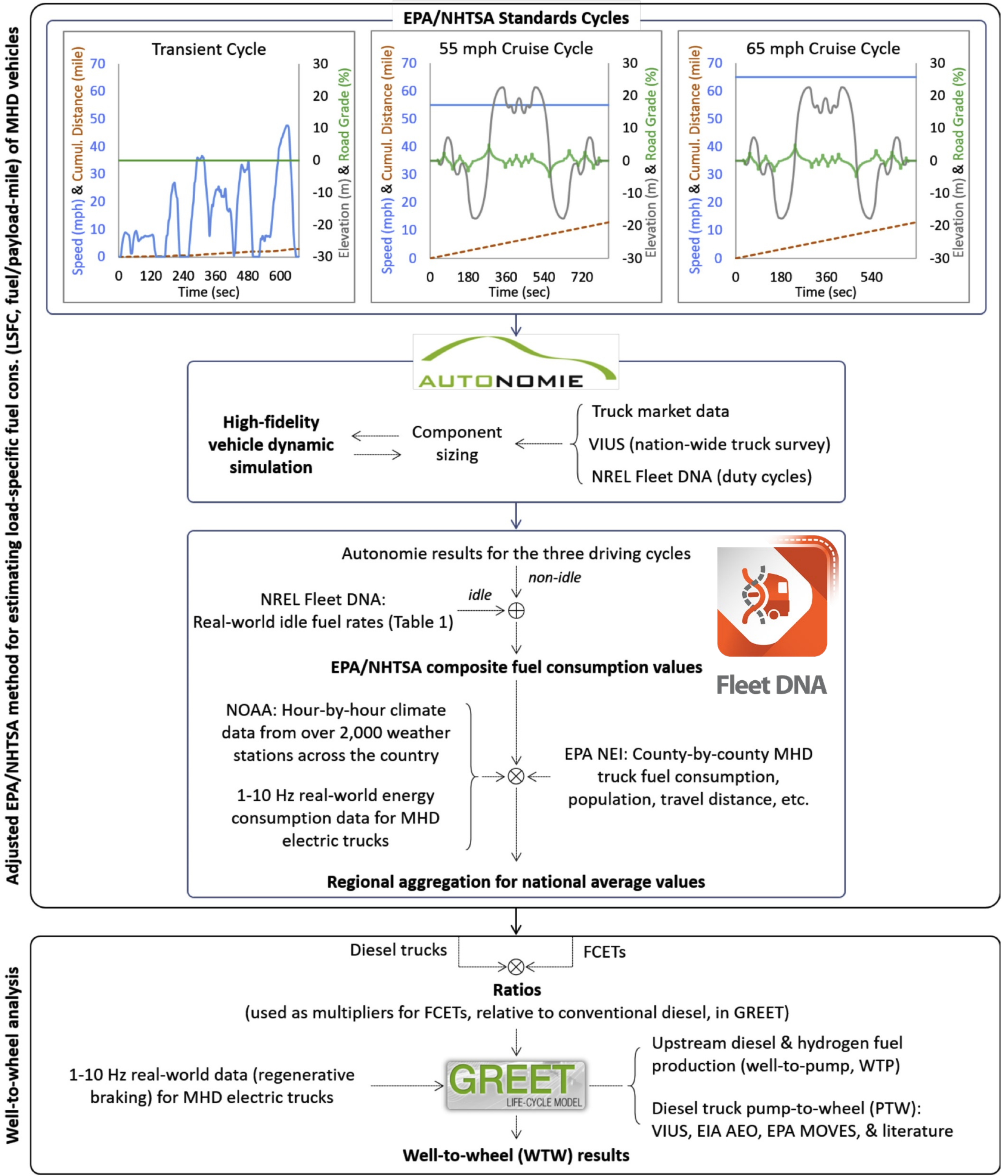
- Use EPA GHG Phase 2 Cycles
  - Spatio-temporal adjustment
- Develop vehicle dynamics model with and simulate with real-world operational data
- **GREET used for wheel-to-pump (WTP) analysis**
- **EPA MOVES for pump-to-wheel (PTW) tailpipe, tire and brake wear**

$$FC_{composite} = FC_{NI} + \frac{1}{\alpha_I \overline{V}_{moving}} FR_I \quad (1)$$

$$FC_{NI} = w_{NI,Transient}\left(\frac{G_{Transient}C_{climate} + \overline{P}_{ESS,Out,HVAC}T_{Transient}}{D_{Transient}}\right) + w_{NI,55mph}\left(\frac{G_{55mph}C_{climate} + \overline{P}_{ESS,Out,HVAC}T_{55mph}}{D_{55mph}}\right) + w_{NI,65mph}\left(\frac{G_{65mph}C_{climate} + \overline{P}_{ESS,Out,HVAC}T_{65mph}}{D_{65mph}}\right) \quad (2)$$

$$FR_I = w_{I,drive}\left(\overline{FR}_{I,drive} + \overline{P}_{ESS,Out,HVAC}\right) + w_{I,parked}\left(\overline{FR}_{I,parked} + \overline{P}_{ESS,Out,HVAC}\right) \quad (3)$$

$$\overline{P}_{ESS,Out,HVAC} = \frac{\overline{P}_{HVAC}}{\overline{\eta}_{FuelCell}} \quad (4)$$



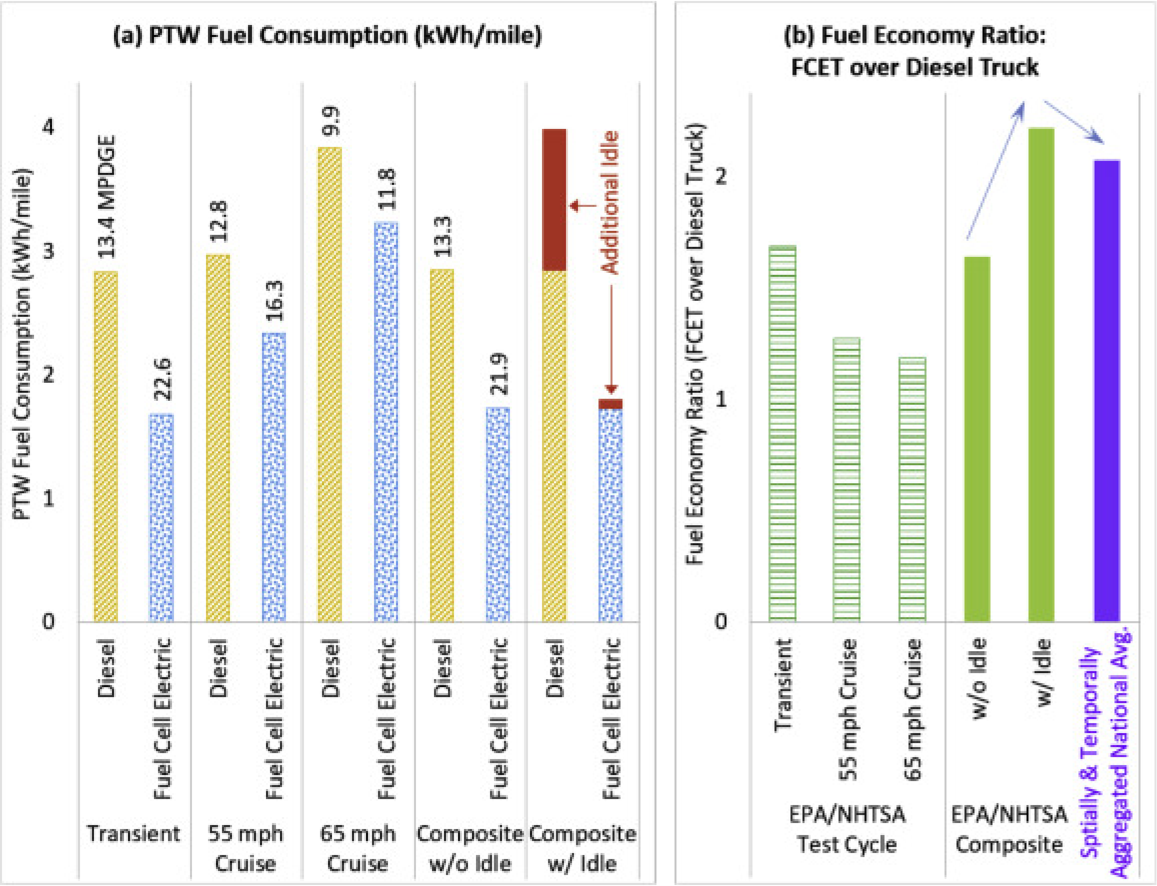
PTW Results for Regulatory Drive Cycles

Modeling Background

- Fuel economy generated over three cycles using Autonomie
- Fleet DNA used for idle fuel
  - Extensive in-use data

Example

- Class 4 straight truck
  - Idle fuel has larger impact on diesel - increases FCEV advantage
  - Spatiotemporal aggregation decreases ratio
    - HVAC power demand



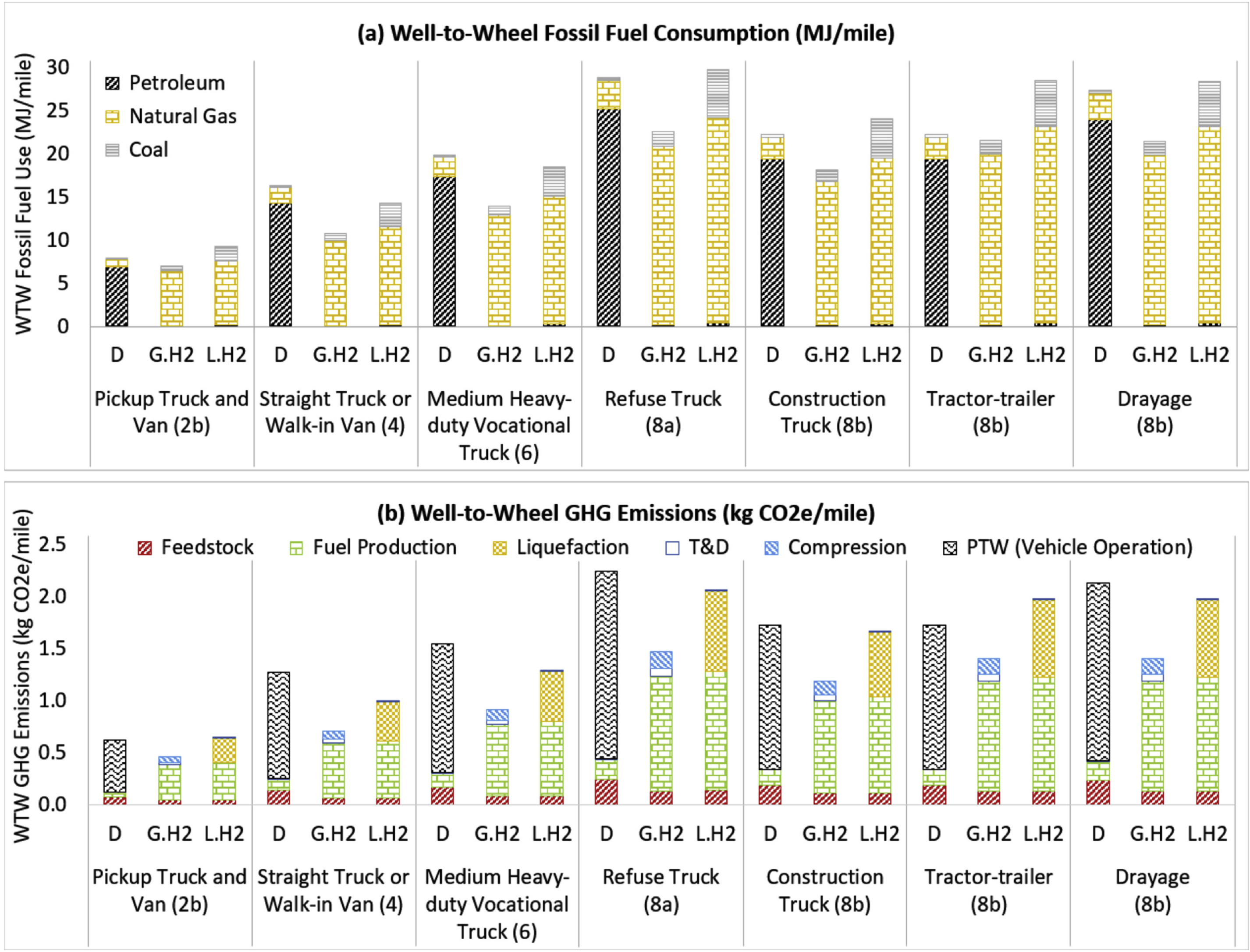
Carbon & Energy

Examine three fuels & seven vehicles

- Diesel (baseline)
- Gaseous hydrogen (G.H2)
- Liquified hydrogen (L.H2)
- *Assume steam methane reforming (SMR)*

Results

- Hydrogen eliminates petroleum
  - Shift to natural gas
  - Some increase in energy use
    - Drive cycle dependent – highway speed more efficient
- G.H2 provides largest CO_2 reduction
  - 19-45% reduction
- L.H2 provides mixed CO_2 benefit
  - Energy for liquefaction



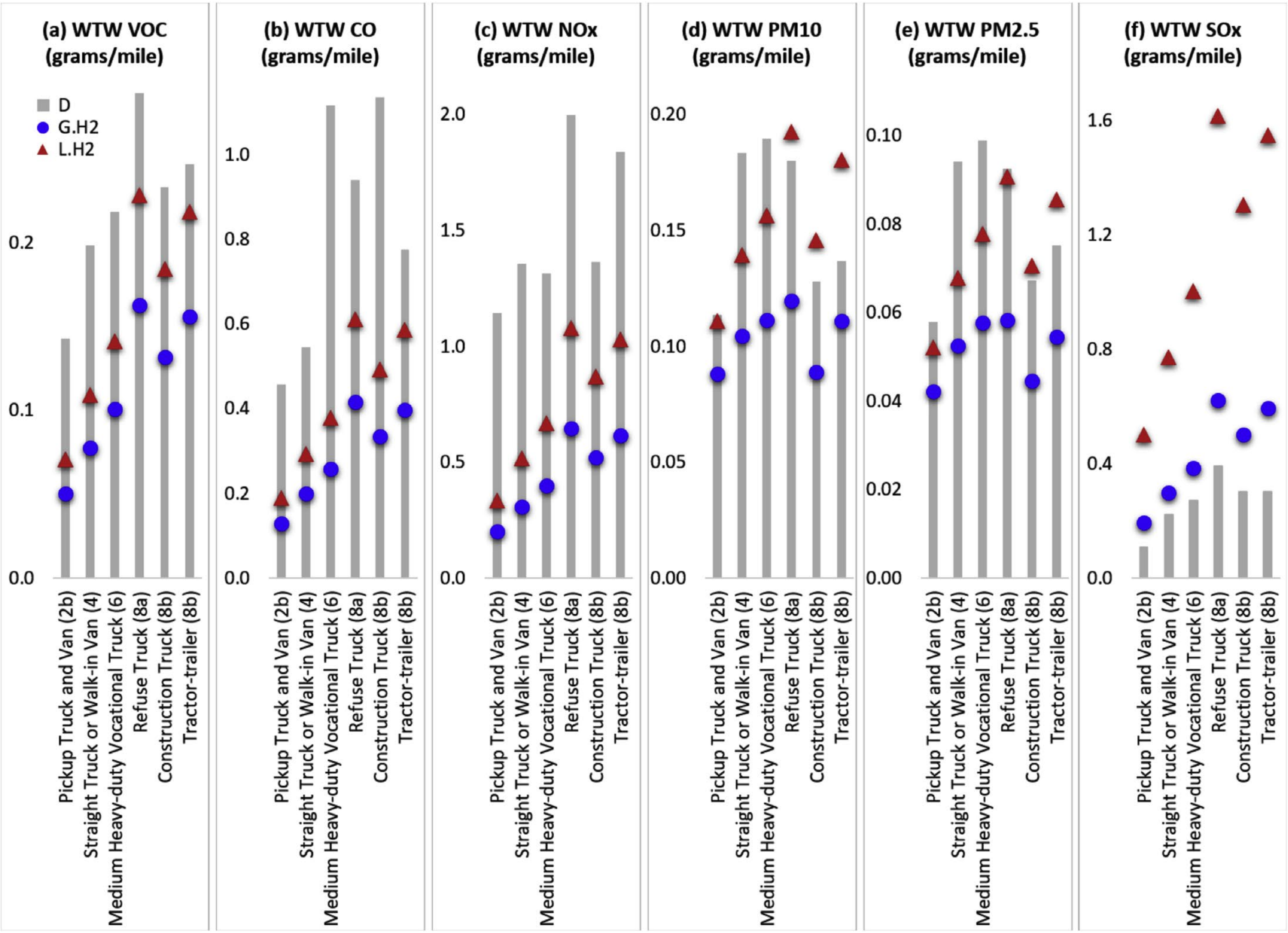
Criteria Pollutants

VOCs, CO, NO_X, PM 2.5 & PM10

- G.H2 provides largest reduction
- Lesser reductions for L.H2
  - Increase for construction & tractor-trailer
- Results vary based on duty cycle
- Can provide major SMOG reduction in non-attainment area
  - Ex) Los Angeles, Denver

SO_X

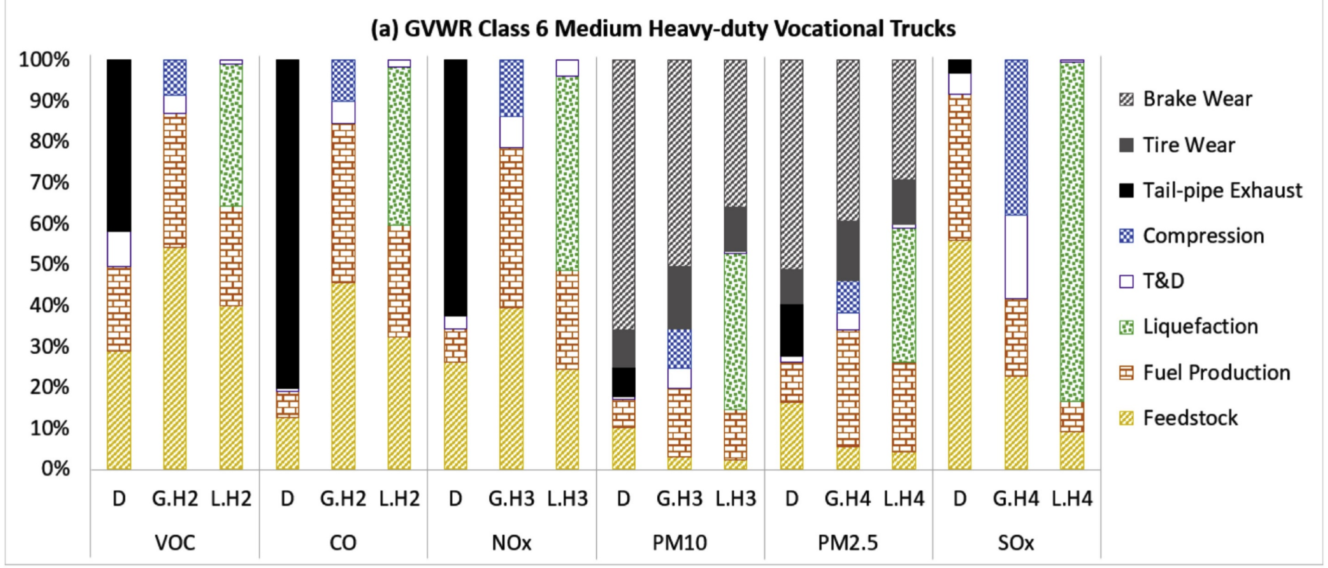
- Increases for hydrogen
  - Use of ultra-low sulfur diesel
  - **Electricity use for compression**
- Shift from tailpipe to fuel production electricity

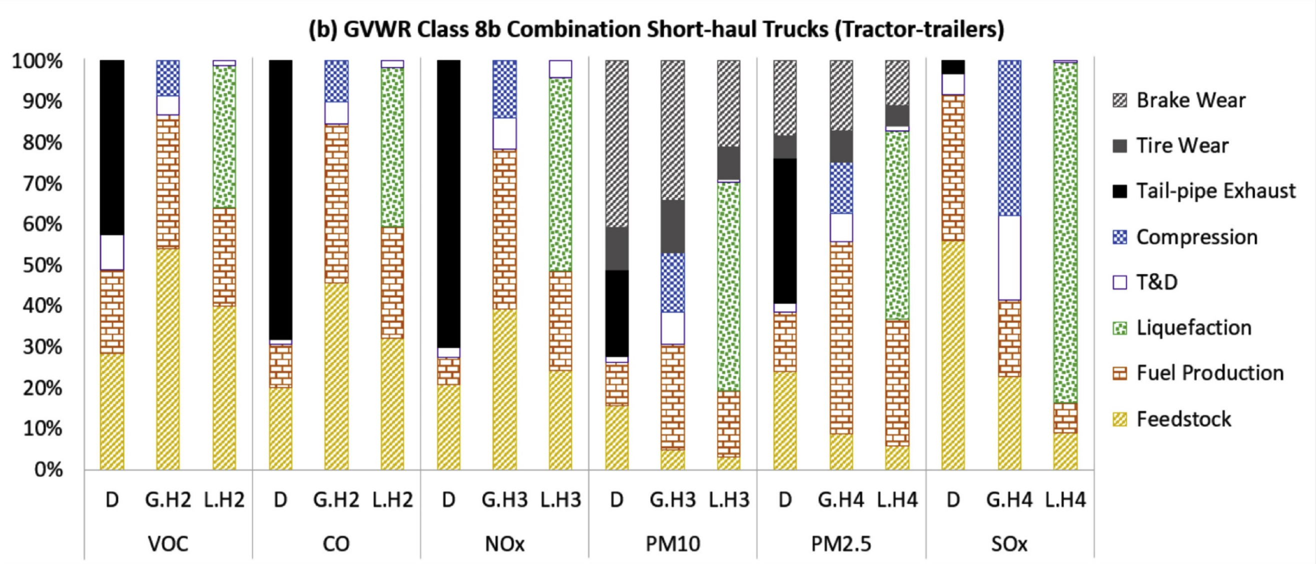


NOTE: no drayage due to limited data

Emissions by Source

- Less benefits for PM
  - Brake and tire wear + upstream fuel production
  - Diesel particulate filters (DPFs)
  - On-road low speed PM 2.5 reductions significant
    - 71% reduction for Refuse
      - 70% tail, 30% b&t wear
- SO_X higher
  - Electricity for liquefaction & compression
  - Dependent on grid mixture





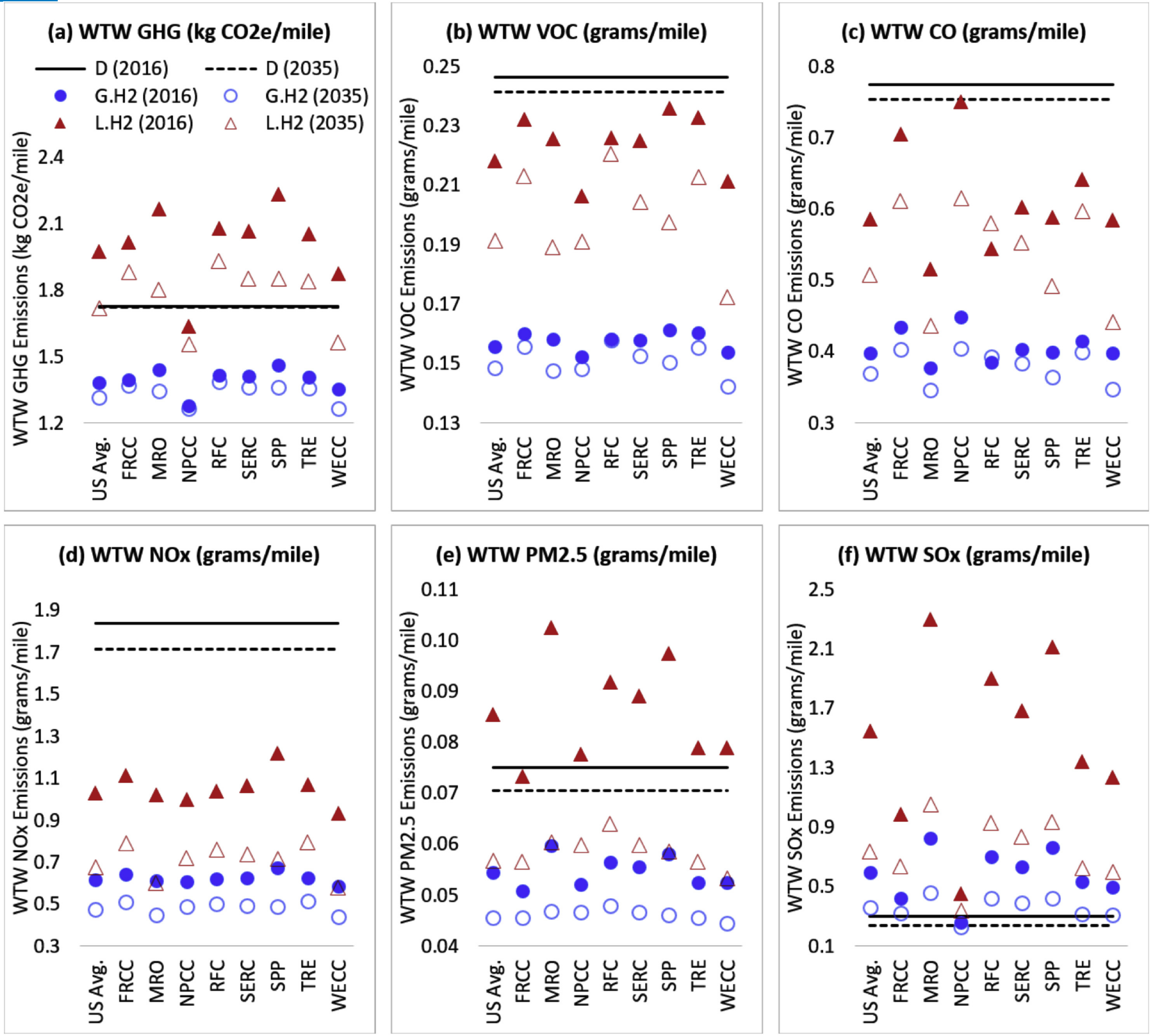
Grid Implications

Electric grid plays a major role in upstream emissions for production

- Anticipated shift to low-emission grid from 2016 – 2035
- Limited effects for diesel production
- Larger current benefit for:
  - WECC & NPCC
    - Includes CA where first FCET being deployed
  - CO increase on RFC grid in 2035
    - Increased natural gas use
- **Still assumes SMR in 2035**

Other notes

- Production plants located in less populated areas
  - Higher perceived benefit



Grid Impacts BETs Too

EV Class 8 Long Haul Example

Fuel economy benefit of battery electric trucks (BET)

- 2.5X improvement

Price:

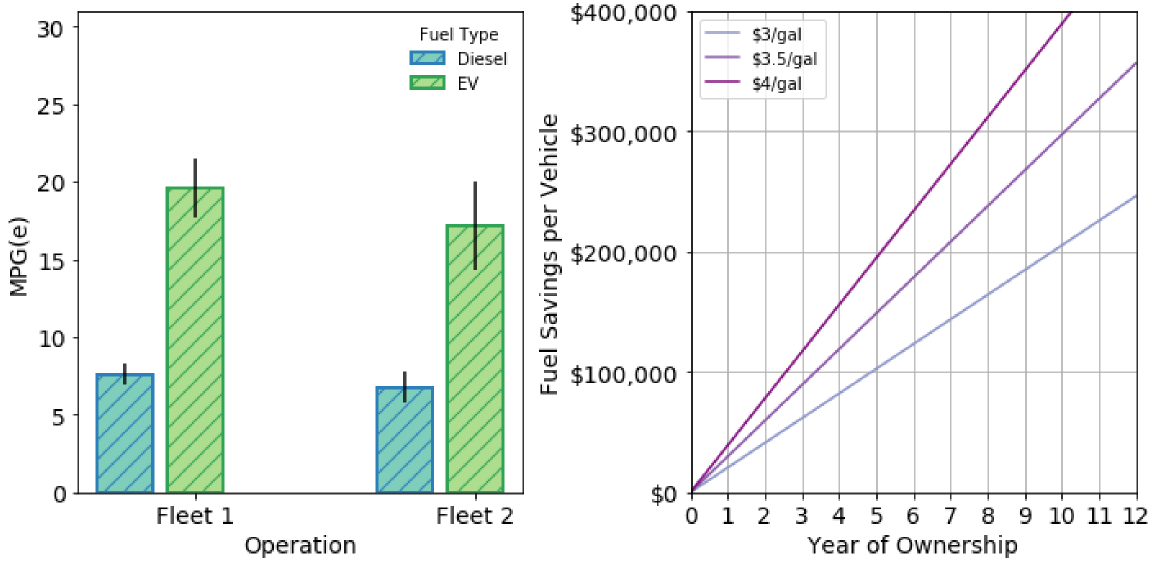
- Assume $0.12/kWh
- 135,855 miles per year @ 7.38 MPG
- 5 days per week

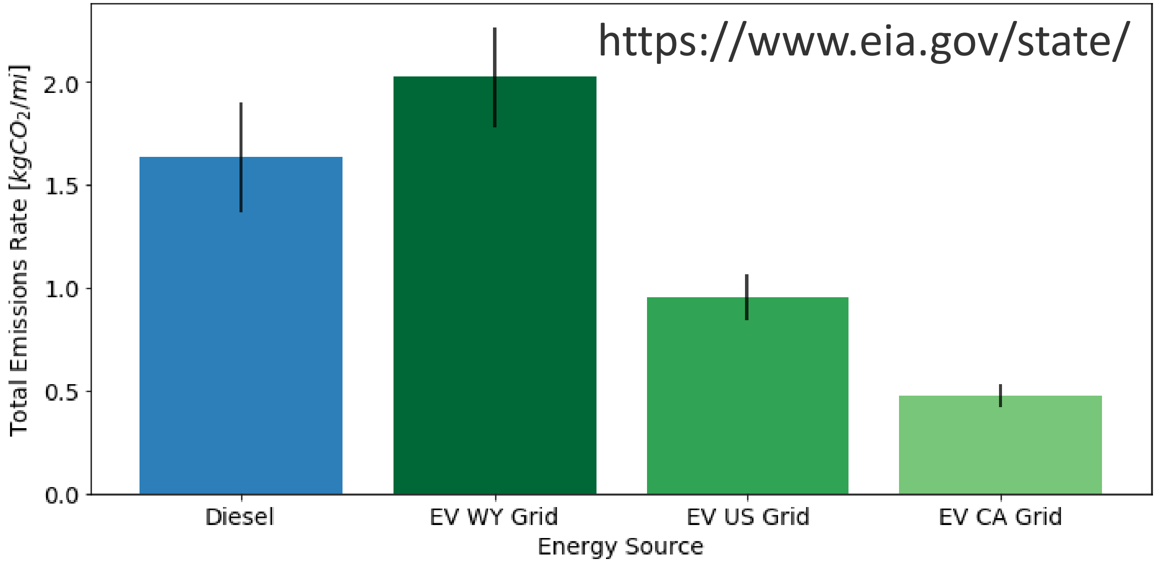
Emissions benefit depends where charged

- Assumptions
  - All carbon → CO_2 (10.1 kg/Gal)
  - Diesel production: 1.84 $kgCO_2$/Gal
  - US avg. grid: 0.448 $kgCO_2$/kWh
  - CA grid: 0.223 $kgCO_2$/kWh
  - WY Grid: 0.952 $kgCO_2$/kWh

Example: Class 8 Long Haul EV

NOTE: This is preliminary modeled data





https://www.eia.gov/state/

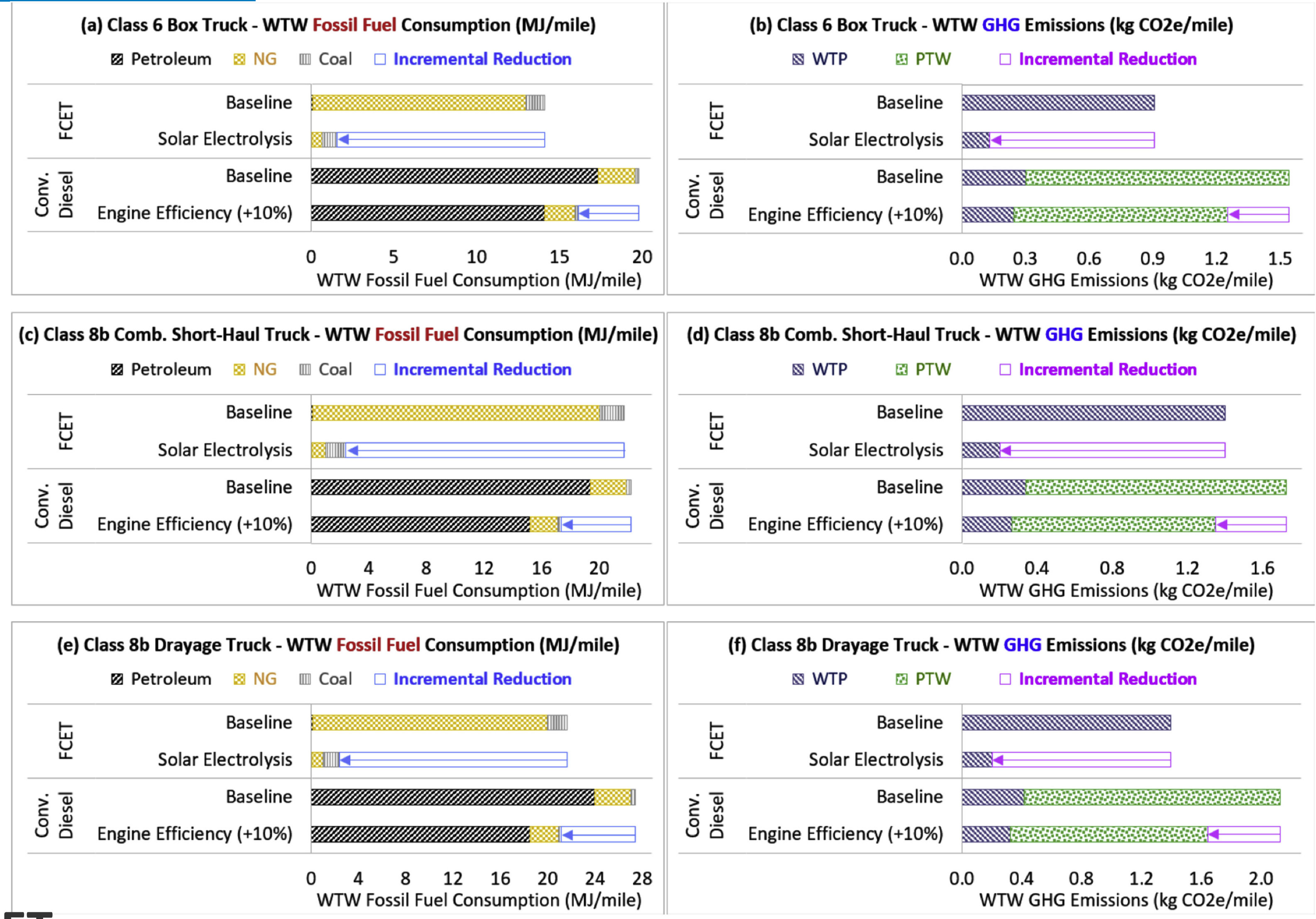
Technology Improvement

Examine powertrain improvements

- Chassis technologies work for both powertrains
- Diesel - 10% thermal efficiency improvement
- FCETs - Electrolysis via solar

Simulate using FASTSim

- Examine 3 vocations
- FCET Reductions:
  - 90% Fuel, 86% GHG
  - Grid used for compression
- Diesel Reductions:
  - 20% Fuel & GHG



FASTSim

Larger potential reduction for FCETs

Summary

Overview

- Vehicle dynamics modeling software was used to estimate energy use based on real-world data
- GREET & EPA MOVES used for WTW emissions
- Explore GHG, criteria pollutants, grid electricity and impacts from technology advances

Key Findings

- FCET provide substantial benefit over conventional diesel
  - Nearly eliminate petroleum
  - Electricity use for liquefaction and compression adds to life-cycle emissions
    - Electric grid is important in WTW emissions & future grids can reduce these emissions
  - Technological improvements will increase benefit of FCETs
  - Emissions shifted from tailpipe to production
    - Usually in less populated areas

Thank you

www.nrel.gov

andrew.kotz@nrel.gov

D.-Y. Lee, A. Elgowainy, A. Kotz, R. Vijayagopal, and J. Marcinkoski, “Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks,” *J. Power Sources*, vol. 393, no. April, pp. 217–229, 2018.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY