Key Findings: RFI on Medium- and Heavy-Duty Truck Research and Development Activities & SuperTruck Initiative

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Welcome

Today's session is being recorded.

- On October 9, EERE issued a Request for Information on research needs and opportunities related to medium and heavy-duty freight trucking across five categories.
- Sought feedback from industry, academia, research laboratories, government agencies, and other stakeholders.

Category	# of Responses
1: Freight Operational Efficiency and Systems	134
2: Internal Combustion Engine, Powertrain, Fuels, and Emissions Control	264
3: Batteries, Electrification, and Charging of MD/HD Trucks	283
4: Hydrogen and Fuel Cell Trucking	117
5: Other Important Considerations	69

867

Sustainable Transportation - ***Focus on research that will lead to more affordable, efficient and secure transportation energy.***

Vehicle Technologies
– David Howell, Acting Director

Hydrogen & Fuel Cell Technologies
- Sunita Satyapal, Director

Bioenergy Technologies
- Valerie Reed, Deputy Director

Today's Webinar

- Walk through each category and share the key findings.
- Each category will be followed by a short Q&A.
  - Submit questions using Webex's "Q&A" feature.
- A recording of today's webinar and PowerPoint will be posted at: https://www.energy.gov/eere/vehicles/events/webinar-discuss-key-findings-does-request-information-support-medium-and-heavy

- Our team continues to review the detailed responses.
- Responses will inform/guide EERE's medium and heavy-duty R&D portfolio including multi-year program plans, technology roadmaps.

Michael Berube

Acting Deputy Assistant Secretary – Sustainable Transportation

Office of Energy Efficiency and Renewable Energy (EERE)

TRANSPORTATION IS FUNDAMENTAL TO OUR WAY OF LIFE

11 Billion Freight Tons

3 Trillion Vehicle Miles

50% of the weight and 37% of the value of goods are moved less than 100 miles between origin and destination

In 2018, USPS shipped 6.2 Billion packages – up from 4 Billion in 2014

Technologies and fuel choices are expanding

Transportation costs are high—second only to housing expenses

CHANGING BUSINESS MODELS

1980's ->AIRLINE: Hub & Spoke

Source: Delta Airlines

Challenges / Opportunities in Freight:

- **Driver Shortages:** 50,000 in 2018
- **ATA TRAC study:** decreasing trip lengths
- **Traffic Congestion:** 1.2 billion hours
- **Fuel Efficiency & Operational Costs**

DOE EERE TRANSPORTATION SECTOR

Energy Affordability	Energy Integration	Energy Storage

Vehicle Technologies ($396M)

- Electrification
- Combustion engines
- Low cost lightweight materials
- New mobility & transportation systems

H2 & Fuel Cell Technologies ($150M)

- Hydrogen production (photoelectrochemical, electrolysis)
- Fuel Cell systems
- H2@Scale

Bioenergy Technologies ($259M)

- Biofuels and bioproducts
- New products, fuels, and chemicals from waste
- Energy crops

Agenda

Time	Topic	Speaker
1:00 – 1:05 PM	Welcome	David Howell, Acting Director Vehicle Technologies Office
1:05 – 1:15 PM	Introduction | Overview	Michael Berube, Acting Deputy Assistant Secretary Sustainable Transportation Energy Efficiency and Renewable Energy
1:15 –1:40 PM	1: Freight Operational Efficiency and Systems	David Anderson, Program Manager Energy Efficient Mobility Systems Vehicle Technologies Office
1:40 – 2:25 PM	2: Internal Combustion Engine, Powertrain, Fuels, and Emissions Control	Gurpreet Singh, Program Manager Advanced Engine and Fuel Technologies Vehicle Technologies Office
2:25 – 3:10 PM	3: Batteries, Electrification, and Charging of MD/HD Trucks	Steven Boyd, Program Manager Batteries and Electrification Vehicle Technologies Office
3:10 – 3:35 PM	4: Hydrogen and Fuel Cell Trucking	Mariya Koleva, National Renewable Energy Laboratory (Detailed to HFTO)
3:35 –3:55 PM	5: Other important considerations?	Mark Smith, Program Manager Technology Integration Vehicle Technologies Office
3:55 – 4:00PM	Conclusions	Kenneth Howden Director 21CTP

1. Freight Operational Efficiency

David Anderson, Program Manager

Energy Efficient Mobility Systems

Vehicle Technologies Office

1.) Freight Operational Efficiency

Freight Operational Efficiency and Systems: DOE has research interest in improving freight efficiency at the vehicle and **freight transportation system levels**. This includes the vehicle and how the vehicle is used within the context of the overall freight management system. It covers the role of **connectivity, automation, last mile delivery options and new operating patterns**. It recognizes that **freight moves through multiple vehicles and processes** to go from manufacturing to its end destination at a business or home. For this RFI, the following questions are posed to help understand the freight operational efficiency space and focus areas for research.

Total Responses (All Questions): 132

1.a.) Understanding Trends and Defining Metrics

Understanding the trends and defining metrics: Data and analysis identified by VTO highlights several trends:

(1) Average length of haul for dry van freight has decreased in recent years by 38% (to around 300 miles)

(2) 75% of freight by mass moves less than 250 miles

(3) Freight shippers are making more use of hub and spoke distribution systems

(4) Day cab tractors are becoming increasingly popular as an option to meet freight needs as a result of items 1-3.

Total Responses: 19

1.a.1.) Data Gaps / Data Sources / Data Collection

What are the most critical **data gaps** in understanding current freight operation and developing scenarios for future freight trends? What **data sources** might fill these gaps? Are there gaps that cannot currently be filled with existing data sources, so new **data collection** would be needed?

Response Summary

- Common methods for reporting, collecting, and analyzing real-world data (cloud-based telematics, open data platform)
- Gaps:

Load size	Time of travel	Travel Cost	Maintenance
Operating Cost	Labor	Distance	Type of freight
Duty cycles	Charging requirements	Power requirements	Miles/payload

- Broad range of vocations in MD/HD sector (not just freight)
- Loading/unloading, idling, fueling/charging time, rest periods
- Driver demographics/preferences
- Resale value, impact on Total Cost of Ownership (TCO)
- Effect of truck operation on other traffic (connectivity and automation)
- Updated Vehicle Inventory and Use Survey (VIUS)
- A comprehensive freight efficiency metric is difficult; If it can be measured, it can be improved

1.b.) How Will Trends Change? What are the Implications?

How will the **trends** for long-haul and regional-haul change in the coming years and what are the **implications** for the types of trucks and propulsion systems that will be used?

Total Responses: 51

1.b.1.) Better ways to measure system efficiency (ton-mpg)?

In the past, DOE focused on freight efficiency as a metric (**ton-miles/gallon**), looking at the benefit of changes to a single truck, operated over a prescribed duty cycle. In the future, are there **better ways to measure system level efficiency**? How could these metrics cover different technologies whose benefits may vary in different types of operational environments?

Response Summary

- Include fueling/charging times for productivity
  - Driver on-road time (moving vs. not moving)
- Measure productivity instead of tonnage (per unit of energy; per unit of TCO)
  - Include work trucks; broader than freight movement
- Time-based (unit of energy per hour; hours per ton-mile)
- Accommodate BEV technologies and include CO2 (CO2/ton-mile)
  - Consider weight (and displaced capacity due to new powertrain technology)
- Weight, volume, value of freight (impacts TCO)
- Apply to the fleet instead of to individual vehicles (deadheading vs. productive miles)
- Need for detailed nation-wide model for analysis

1.b.2.) Metric Change from Ton-MPG? Include Other Factors?

If DOE retained a freight efficiency metric, should it change from ton-miles/gallon? Should energy metrics be weight-based, volume-based, or both? Are cost metrics valuable to include, and if so, should they be total-cost-of-ownership based or cost of shipment based? Are time-based metrics valuable to include, and why or why not? Should Total Cost of Ownership (TCO) or CO_2-eq emissions metrics be included?

<u>Response Summary</u>

- TCO is fundamental, and should include:
  - Capital cost Fuel cost Maintenance cost Battery life Infrastructure cost
- Volume and weight metrics are important; Shipping costs must include value of freight
- Ton-miles/kWh is critical (but only meaningful for the ~10% of freight that is weight-constrained)
- Freight efficiency and TCO are both important, but cannot be combined
  - Metrics should consider total energy consumed to deliver goods with respect to time, TCO, and CO_2, but this becomes difficult
- Need to shift to a CO_2-equivalent on a Life-Cycle Analysis basis (including full fuel cycle)
- Shift to less-than-truckload shipments, changing duty cycles, e-commerce, warehousing should be considered

1.b.3.) Additional Opportunities? For Which Classes?

With these trends, are there **additional opportunities** to increase efficiency and decrease emissions across a broad range of trucks? **What classes provide the largest potential** from technological advancements?

Response Summary

- Connectivity and automation can increase productivity, but needs pull from the freight shipping industry
- Increase payload per trip using Long Combination Vehicles (LCVs)
- Class 7-8 is largest opportunity, but all classes benefit from low-cost solutions
- Managed lanes to alleviate congestion, facilitate efficient drive cycles
- Connected fleet management for pick-up and delivery (urban/regional)
- V2V and automation for long-haul full truck-load
- Application of light-duty components/research to MD/HD segment
- Need for complex systems-level modeling for measuring system efficiency

1.b.) What are Major Benefits, Opportunities, Barriers (CAVs)?

What are the major **benefits, research opportunities, and barriers** for developing system-level freight efficiency technologies (i.e., technologies with an effect beyond the efficiency of individual vehicles)? What are the research needs and barriers to **connectivity and automation** technologies to improving freight efficiency?

Total Responses: 8

Response Summary

- Electrification could become powertrain technology of choice, changing existing use-cases (trip-length, infrastructure)
- Hub/spoke models, drones and other new modes must be considered
- Data security is critical; benefits of CAVs highly uncertain
- Effect of structural materials on connectivity & automation (e.g., sensing)
- Opportunities for system efficiency through optimizing capacity utilization
  - Shared freight hubs, digital freight contracting platforms
- Impact of automation on driver, operating costs, utilization, refueling time requirements

1.b.) What are Major Benefits, Opportunities, Barriers (CAVs)?

Cont'd:

- Leverage existing liquid-fuel technology to enable switch to low-carbon fuels
- On/off-board computing requirements for vehicle/powertrain control
- Need for infrastructure development (lanes, charging, monitoring, control)
- Ensure full automation does not encourage an increase in energy use
- Fleet route optimization, predictive maintenance, emissions compliance, and driver coaching (longer time horizon)
- Additional barriers include network bandwidth, cybersecurity, algorithms for cloud/edge computing
- Advancements in AI/ML to manage freight operations
  - Barrier: access to data
- Driver behavior relative to CAVs, operational practices (e.g., hand-off between full automated control and driver operation)
- Need for large-scale modeling and simulation to understand opportunities

1.c.) Alternative Fuels? Changing Use-Cases? Infrastructure?

What **opportunities do these trends open up for alternative fuels** such as electricity, natural gas, biofuels, and hydrogen? Will the **use cases change** to fit the technology, or will **aggressive technology changes** be needed to make them fit the current use cases? What impact will **infrastructure** have on the uptake of these fuels, and what opportunities and barriers exist in the area of infrastructure?

Total Responses: 16

Response Summary

- Opportunities for clean electricity, natural gas storage, biofuels, H2-based fuels
- Benefits: cleaner air, lower emissions, lower cost, ease of operation
- Barrier: cost of new technology
- Different technologies based on application (no single solution)
  - Liquid fuels for long-haul; H2 for regional; BEV for short-haul; issues with NG
- Initial focus on centralized fueling infrastructure
  - Hub & spoke with shorter trip length supports electrification
- Class 7/8 represents the largest opportunity

1.c.) Alternative Fuels? Changing Use-Cases? Infrastructure?

Cont'd:

- Infrastructure and system-level planning enables right-sizing of powertrain
- GHG requirements will drive fuel mix
- Technology will have to change to meet use-cases and TCO – but operations are already changing
- Need for fleet-level optimization, assessment of energy for entire delivery chain

1.d.) Understanding System Constraints

Understanding System Constraints: To utilize the efficiencies of today's system and improve them, **building off existing assets** is necessary. These constraints may help identify the key needs and make **incremental changes** in efficiency while **breakthroughs that disrupt the system** are also developed in the longer term.

Total Responses: 38

1.d.1.) Typical Payload Capacity? Growth in Vocations/Classes?

Do trucks typically operate at maximum **payload capacity** (by weight or volume)? In the coming decade, are there any anticipated any **changes to the typical weight of payloads** on board trucks? In what truck vocations/class and/or regions of the country is there **anticipated market growth** in the coming years, and why?

Response Summary

- Payload capacity dependent many variables (density, size, packaging)
- Most Class 7/8 trucks are volume-limited (depends on industry); more data is needed
- Opportunities to increase payload to 91,000 lbs with addition of 6^{th} axle
- ZEVs may need different classification
- Opportunities to improve operational efficiency by increasing volume

1.d.2) Commercial Fueling Stations

Are commercial fueling stations for trucks commonly co-located with light-duty vehicle fueling stations? Are commercial fueling stations for trucks commonly located in regions where land area is a constraint (e.g., urban locations)?

Response Summary

- Colocation is common, but LD and MD/HD typically separated
- Future fueling stations will be far more complex than traditional gasoline/diesel stations
- EV charging will require high power (>350kW), leading to grid impacts for which more study is needed.
  - Colocation may not be dominant paradigm.
- In urban settings, colocation is not prevalent; H2 and EV may hinder colocation

1.d.3) Payback Period and Discount Rate

What is the typical **payback period** for capital equipment (e.g., fueling stations) for trucks? What is the associated **discount rate**?

Response Summary

- **Payback period is application-specific**
  - 1.5 – 3 years
  - 10 years or more
  - 18-24 months acceptable range for Class 8
- **Discount rate of 6-10%**

1.d.4) Benefits, Opportunities, and Barriers

What are the major **benefits**, **opportunities**, and **barriers** in this space and is this worthwhile to pursue?

Response Summary

- **EV infrastructure sharing and technology spillover significant in MD/HD sector**
- **New materials, AI-based vehicle/fleet control, low-carbon fuels, life-cycle analysis (LCA) models**
- **Infrastructure is a challenge/barrier**
- **Connectivity (between vehicles, infrastructure) is a major opportunity**
- **Infrastructure technology development opportunities:**
  - Grid-side technologies to enable rapid recharging
  - Vehicle-to-grid (V2G) services
  - Cost-effective H2 generation
  - Portable H2 refueling stations

1.d.5) Data on Distance/Payload/Drive Cycles/Fuel Use

Is there data available that shows **distribution of distance traveled versus payload**? Is there data sufficient to validate baseline truck models? This includes **drive cycle data** with grade as well as fuel consumption measurements and vehicle characteristics (tire rolling resistance, aero drag coefficient, frontal area, gross weight (including payload data).

Response Summary

- **Data gaps remain (truck configuration, usage, location, road conditions, weather, technologies, hours, driver skill, data ownership).**
- **Tire rolling resistance and aero coefficients subject to pavement surface and wind direction. Fleets do not have capability to measure this.**
- **Payload weight data not readily available.**
  - Publicly available aggregate data sets exist indicating distance traveled and average payload. Other data confidential.
- **Most data are considered highly confidential.**

2: Internal Combustion Engine, Powertrain, Fuels, and Emissions Control

Fuel choice has a significant impact on total cost of ownership and represents a significant and long-term commitment by fleets when options are available.

Gurpreet Singh, Program Manager
Advanced Engine and Fuel Technologies
Vehicle Technologies Office

2a: Understanding Fuel Choice

2.a.1. Are Spark Ignition (SI) fuels, such as gasoline, attractive for stand-alone ICE-powered vehicles in MD and HD vehicle classes? If so, in what specific applications and vehicle classes?

- 22 Responses: 4 OEMs, 3 Trade Assoc, 2 Tier 1 suppliers, 2 Energy companies, 1 National lab, 1 non-profit R&D, 4 university, 5 small business
- 21 yes, 1 no

Response Summary

- Vehicle Classes and Applications: Classes 2b-6, Urban/Regional Transit and Delivery, Lower Work Factor and Mileage applications, TCO benefit from lower fuel and aftertreatment costs
- Research Interest Areas: Higher SI efficiency (lower CO_2) for liquid and gaseous fuels (compression ratio, dilution tolerance, pumping work, friction losses), greater durability, lower cost hybridization, improved low-speed torque and launch performance.

2.a. Understanding Fuel Choice

2.a.2 Is there interest in using market gasoline for advanced compression ignition combustion strategies in MD or HD engines? Is there consideration to use of technologies such as an intake heater or additive injection to enable such a combustion strategy?

- 21 Responses: 3 OEMs, 3 Trade Assoc., 2 Tier 1 suppliers,1 Energy company 2 National labs, 1 non-profit R&D, 3 university, 5 small business
- 11 yes, 5 no, 5 maybe

<u>Response Summary</u>

- Reasons for interest: cost difference between gasoline and diesel is expected to widen with changing demand, which creates the potential to reduce TCO and lower GHG (due to lower C/H ratio fuel),
- Reasons for disinterest: sensitivity to variation in fuel, less compatible with modern aftertreatment that relies on thermal management to maintain effectiveness, too many barriers to production to warrant investment.

2.a: Understanding fuel choice

2.a.3. Are dual-fuel engines/vehicles of interest to industry and consumers? (These would include any system requiring two fuels to be available at all times, e.g., pilot-ignited gaseous fuels as well as systems that rely on advanced combustion such as reactivity controlled compression ignition. Please exclude bi-fuel systems which can provide full utility on either of two fuels.) If dual fuel systems are of interest, please specify applications, fuel pairs, and type of system of interest.

- 18 Responses: **3 OEMs, 2 Trade Assoc., 1 Energy company, 1 National labs, 1 non-profit R&D, 3 university, 7 small business.** 5 yes, 6 no, 4 maybe, 3 incomplete

<u>Response Summary</u>

- **Reasons for interest:**
  - Reduced operating cost (cheaper main fuel), potential higher cycle efficiency (e.g., RCCI), potential for lower GHGs.
  - Interesting fuel pairings: NG/Diesel, Ethanol/Gasoline. Most respondents who were supportive have, or are working on, dual-fuel approaches/systems.
- **Reasons for disinterest:**
  - Small & niche market at present, complicated systems, drivers don't like dual fuel, typically need full diesel EC, hardware cost/complexity.
  - RCCI generally complicated; general preference for single-fuel solutions (e.g., GCI).

2.a.: Understanding fuel choice

2.a.4. To what extent are gaseous alternative fuels, such as natural gas or LPG, of interest in the MD and HD vehicle classes - i.e., Class 3-8? If gaseous alternative fuels are of interest to industry and consumers, what specific fuel types are of interest for what engines/vehicle platforms and applications?

- **22 Responses: 5 OEMs, 3 Trade Assoc., 1 Energy company, 2 non-profit R&D, 2 university, 9 small business**
- **17 yes, 3 no, 2 incomplete**

Response Summary

- **Reasons for interest:**
  - Expected lower cost and simpler emissions control to reach low NOx levels, less weight than batteries.
  - Gaseous HCs still leading alternative to liquid HCs for HD, but H2ICE came up several times, but with caveat that renewable electricity is needed. Several supporters said, “only with renewable gaseous fuels”.
- **Reasons for disinterest/reservations:**
  - Small & niche market at present, cost of fuel storage (for NG or H2), low energy density of fuel storage, lower efficiency (for stoichiometric), lack of driver familiarity/comfort with gaseous fuels, lack of engines available in some sizes, reduced vehicle resale value, NG will be surpassed and replaced by H2 fuel cells.

2.a.: Understanding fuel choice

2.a.5. To what extent are biofuels of interest in the MD and HD vehicle classes - i.e., Class 3-8? If biofuels are of interest to industry and consumers, what specific fuel types are of interest for what engines/vehicle platforms and applications?

- **15 Responses: 4 OEMs, 3 Trade Assoc., 1 Energy company, 2 university, 1 national lab, 4 small business**
- **14 yes, 0 no, 1 maybe**

<u>**Response Summary**</u>

- **Reasons for interest:**
  - Carbon reduction as a corporate or social goal, public image, improved performance in some cases.
  - Types of biofuels: drop-in HCs, RNG, biodiesel (FAME-type), renewable diesel, ethanol (low-and high-blend). Generally applied to all HDV applications and size classes.
- **Reasons for disinterest/reservations:**
  - Cost, usually lower energy density, oxygen content.

2.b: Renewable and Biofuels for Trucking

2.b Truck OEMs, large truck fleet operators and large commercial customers have indicated a need to target low carbon dioxide equivalent (CO2-eq) emissions for future trucks. Given the ubiquity of liquid fuels, this has led to increased industry and commercial customer interest in drop-in renewable fuels such as biofuels that can deliver large reductions in CO2-eq emissions from conventional powertrains. DOE R&D has shown that CO2-eq reductions of 80% or more relative to incumbent fuels (gasoline or diesel fuel) are possible from renewable fuels.

- **Note: There was no question asked here. Respondents largely used these responses as an opportunity to speak in generalities about benefits or promote their own solutions.**
- **9 Responses: 1 OEM, 1 Tier 1 Supplier; 1 Trade Assoc., 3 universities, 3 small businesses**

Response Summary

- "ubiquity of liquid fuels… [provides] the most pragmatic way to reduce the GHG emissions from the heavy-duty trucking sector."
- There is significant interest from customers in reducing carbon footprint. Will require combination with hybridization to maximize impact of biofuels and other low-C liquids.
- LD sector can use fully electric; HD will require liquids for some time. California LCFS is a good example of how full-cycle carbon accounting can work.
- Universities and small businesses largely promoted their own systems and preferred fuels.

2.b: Renewable and Biofuels for Trucking

2.b.1. Is there an interest from industry or consumers in research into low lifecycle CO2-eq liquid fuels? How much CO2-eq reduction is sufficient to qualify as "low-carbon" and compete with other advance technologies? Is there value in expending additional R&D effort to reduce lifecycle CO2-eq emissions by greater than 80%?

- **14 Responses: 5 OEMs, 1 Tier 1; 2 Trade Assoc., 1 Energy company, 3 small business, 2 non-profit R&D**
- **12 yes, 1 no, 1 maybe**

Response Summary

- **Reasons for interest:**
  - Carbon reduction as a corporate or social goal, public image, customer demand for low-carbon approaches (for fleets), assumed lower hardware costs relative to other approaches (such as electric or gaseous fuels).
  - R&D should "demonstrate CO2 emissions by greater than 80%... [and] demonstrate implementation of the technology"; word "critical" came up a lot, esp. among OEMs
- **Reasons for disinterest/reservations:**
  - Not specified (e.g., not currently under consideration by this company).
  - Some approaches may be very expensive, at least initially.
  - Warranty concerns if fuels are not identical to conventional.

2.b: Renewable and Biofuels for Trucking

2.b.2 Low lifecycle CO2-eq liquid fuels have the potential advantage of not requiring vehicle, infrastructure or operational changes that could come with other options such as Battery electrification, Hydrogen Fuels, or Natural gas. How important are these benefits? If these fuels cost more per mile than today's fuels, how much does the benefit of less disruption offset that higher cost?

- **16 Responses: 5 OEMs, 1 Tier 1 supplier, 2 Trade Assoc., 2 energy companies, 2 universities, 3 small business, 1 national lab**
- **9 mainly positive, 1 mainly negative, 4 mixed, 2 incomplete**

Response Summary

- **Reasons for interest:**
  - More than just fuel cost; TCO more important than fuel cost; highly dependent on application and truck type (e.g., for MD work trucks); while drop-in simplifies things, $/ton CO2 abatement is the most-significant metric; several thought maintaining same infrastructure and vehicle architecture was a "huge benefit"; very important for a solution to be easily implementable.
- **Reasons for disinterest/reservations:**
  - Hybridization with conventional fuels can reduce CO2 by a lot & one may pay much more to achieve only with liquid/renewable fuels.
  - Fleet-specific TCO calculation is necessary to determine value of trade offs.

2.b: Renewable and Biofuels for Trucking

2.b.3. How important to industry and your customer's is the lifecycle CO_2-eq emissions of medium/heavy-duty trucks? Is CO_2-eq emissions accounting, if any, conducted on a tank-to-wheels or well-to-wheels basis? And is any accounting down [sic.] looking at the total movement of freight from manufacture to customer? Are customer/market/investor interests in CO_2-eq emissions reduction a major factors in industry's interest in CO_2-eq emissions reduction, or is it driven primarily by regulations? What is the relative importance of domestic markets vs. international markets for determining current and planned CO_2-eq posture?

- **10 Responses: 4 OEMs, 1 Trade Assoc., 1 energy company, 2 universities, 2 small business.**
- **4 very important, 4 mixed, 2 incomplete**

Response Summary

- Well-to-wheel basis for accounting near-universally endorsed.
- OEMs generally say that CO_2 metric is at or near the top of their corporate priorities. The dominance of TCO among their customers makes independent action difficult, despite customers also claiming CO_2 is a priority. One noted regulation is the primary driver.
- Energy company noted that while initially spurred by regulations they increasingly "have customers who are willing to pay a premium for low-carbon fuels as part of their corporate image and branding strategy."

2.c: Engine Design Tools leveraging computer science/AI

2.c. The capacity for high performance computing continues to increase at a rapid rate. Large, high-fidelity computer simulations of engine processes create massive datasets that can be coupled with emerging artificial intelligence methods, creating the potential for powerful tools to design engines. How interested is industry in creating engine design tools that can leverage advancements in computer science and artificial intelligence?

- 13 responses: 4 OEM, 3 tier 1, 2 national lab, 1 academia, 3 small business
- 12 yes, 1 maybe

Response Summary

- Co-simulating multiple systems (air handling, engine combustion, aftertreatment, electrical system) could provide a step-change in design process, but simulations must be predictive.
- Industry respondents interested in increases access to HPC resources at DOE labs.
- Artificial Intelligence can be applied to engine/powertrain controls to optimize performance
- Machine learning algorithms are needed to explore the full design space opened up with advanced manufacturing and speed new products to market.

2.d: Large-Bore Gasoline Engines

2.d. Manufacturers are actively considering gasoline fueled engines for commercial vehicles, specifically for class 3-6 vehicles. They also offer potential savings from low gasoline price compared to diesel and lower complexity emissions control requirements. How important is it to industry to conduct research focused on large-bore gasoline engines?

- 15 responses: 2 OEMs, 1 Tier 1, 3 Small Business, 2 National Labs, 3 Academia, 1 Trade Association
- 8 important, 1 maybe, 6 other priorities

Response Summary

- Large-bore gasoline engines could be a promising technology, offering lower operational cost and complexity. Lower gasoline engine cost could enable greater use of hybrid powertrains for greater efficiency.
- Challenges for gasoline engines versus diesel include lower specific power, knock-limited performance under high loads, and lower durability.

2.e Waste Heat Recovery

2.e. Waste heat recovery ("WHR") systems have demonstrated the ability to increase overall engine efficiency and are included in the EPA Phase 2 Rule as contributing to fuel economy improvements for future trucks. How interested is industry in further developing WHR systems or specific components for WHR?

- 15 responses, 4 OEMs, 3 Tier 1, 3 Small Business, 1 National Lab, 1 Academia, 2 Trade Associations, 1 unknown
- 9 yes, 4 no, 2 maybe

Response Summary

- WHR is a promising technology to improve system efficiency but challenges include weight penalty, design and integration complexity, and unfavorable ROI when compared to other GHG savings technologies
- Analysis of the potential energy savings for different applications will allow for proper use of WHR and right-sizing the components

2.f Further reduce NOx and PM emissions

2.f. Heavy-duty diesel and gasoline vehicles are under increasing pressure from regulators to further reduce their criteria emissions, specifically NOx and PM while minimizing efficiency losses. Regulators are also considering significantly increasing the warranty and full useful life requirements for these vehicles. While DOE has active research on low temperature NOx emissions and on technologies for low NOx and PM with the national laboratories, universities and industry, what additional research can DOE undertake to help further reduce NOx and PM emissions? What technical challenges are you envisioning with extended warranty and full useful life requirements and what are the research needs? Should DOE Metrics in initiatives like SuperTruck target current emissions or future?

- 24 responses: 6 OEMs, 7 Tier 1, 3 Small Business, 1 National Lab, 3 Academia/Institute, 3 Trade Associations, 1 unknown

Response Summary

- Comprehensive system level evaluations that identify strategies and potential benefits from coupling LTC with various lean NOx aftertreatment
- Further research on ducted fuel injection and Isolated small-nozzle-hole plume fuel injection as well as Sophisticated Engine Air Management such as Cylinder Deactivation

2.f Further reduce NOx and PM emissions (Contd.)

- "Co-co-optimization" of fuel-engine-aftertreatment technologies, to determine what combination of fuel, engine architecture, and aftertreatment system produces maximum benefits
- Research focusing on dual pollutant reduction and demonstration, such as the development of mild hybrid regenerative systems coupled with exhaust energy control
- Improved conversion efficiencies of TWCs, DOCs, SCRs, and Urea injection systems with colder exhaust temperatures as well as better/lower cost exhaust sensors
- Increase in emissions equipment should not compromise the functionality of standard work trucks
- R&D into advanced system modeling to help minimize validation testing
- SuperTruck projects going forward should include HD Low NOx final phase-in proposed emissions requirements
- DOE metrics need to account for higher costs associated with increased emissions warranties and useful life requirements

2.g. Aftertreatment

2.g CARB's low NOx project with Southwest Research Institute recently revealed an aftertreatment system for ultra-low NOx emissions that consisted of multiple SCR, dual DEF dosing, multiple NOx, NH3, and temperature sensors as well as catalytic converter for ultra-low PM emissions. What technical challenges and system requirements are you envisioning for this type of aftertreatment system and what research would be useful for DOE undertake in order to improve system efficiency and help commercialization?

- 23 responses: 5 OEMs, 7 Tier 1, 3 Small Business, 2 National Lab, 3 universities, 2 Trade Associations, 1 unknown

<u>Response Summary</u>

- Concerns with exhaust system performance under varying load conditions, SCR dosing control, light-off SCR, heat management, system packaging, truck usability, reliability, maintenance and service, and componentry failure rate as well as cost and weight increase
- Further research on aging protocol and in-use compliance as well as on optimization of aftertreatments with fuel injection, EGR control and boosting, and hybridization for advanced combustion strategies and their real-world demonstration
- Development of a more comprehensive, system level understanding of the interactions between engine out emissions, exhaust temp, and various aftertreatment options to optimized engine-aftertreatment systems

2.h. Additional Development

2.h At the engine systems level, what specific additional development is required in technologies such as air handling and boosting, combustion and aftertreatment sensors, fuel injection systems, and thermal management (including temperature-following thermal barrier coatings)?

16 Responses: 4 OEMs, 1 Trade Assoc., 5 Tier 1 suppliers,1 Energy company 2 National labs, 1 non-profit R&D, 2 small business

Response Summary

- Turbocharging (higher temperature materials and coatings, e-Booster, driving EGR),
- Fuel Injection (internal flow, sprays, Direct Injection of gaseous fuel),
- Thermal Barrier Coatings (increase exhaust temperature, pistons, material properties, Thermal Swing Coatings),
- Sensors (NOx, PM, Ammonia, on-board predictive diagnostics, durability,
- Valve control (VVA, CDA),
- Friction Reduction (lubricants, surface texture),
- High Temperature Materials (Pistons, turbochargers)

3. Batteries, Electrification, and Charging of MD/HD Trucks

Steven Boyd, Program Manager

Batteries and Electrification

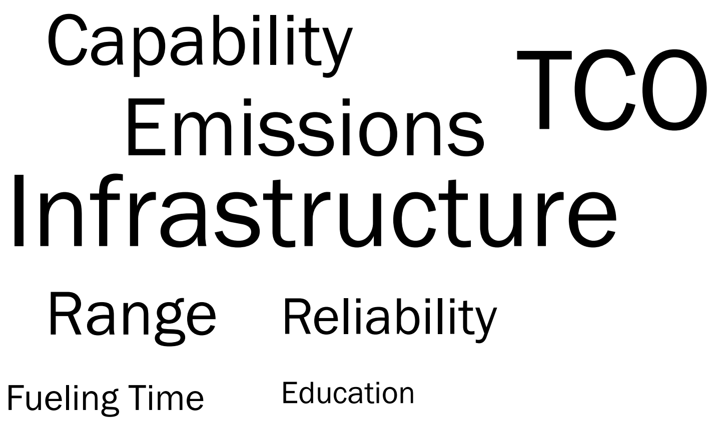
Vehicle Technologies Office

3. Batteries, Electrification, and Charging of MD/HD Trucks

3a) What factors are most important in motivating the choice to pursue powertrain systems for MD/HD trucks that are all-battery vs. battery dominant vs. fuel cell- or internal combustion-dominant?

Summary of 20 responses:

- Emissions can be general environmental, GHG or criteria regulations, or taxes. Includes corporate sustainability
- Infrastructure refers to any sort of fueling including fuel availability
- TCO includes any costs such as batteries and infrastructure costs
- Reliability is grouped with durability and/or warranty



> "At the moment, fuel cell and hydrogen infrastructure is still too immature to deliver a positive TCO for customers. All battery dominant vehicles also have challenges on TCO but are closer to a market solution than fuel cell. Additionally the TCO of charging infrastructure is much closer to a TCO for market acceptance than hydrogen infrastructure"
>
> \- *OEM response*

3b. MD/HD Trucks: Applications, Features, Range

3b. Please list three most ideal applications for battery electric heavy-duty trucks. What is the most probable entry-point for battery electric vehicle architectures in medium- and heavy-duty vehicles? What are the most attractive features of electrification across these applications? What range should be targeted for these applications?

"Ease of driver operation, less noise, less maintenance and zero tailpipe regulatory challenges all combine to make a battery electric, HD truck an interesting option for the future" - *OEM response*

Summary of 21 responses:

- **Delivery was #1, followed by drayage/short haul, urban buses**
- **Probable entry points and attractive features focused on these factors**
  - short routes/ranges/shifts
  - zero or low emissions, noise
  - stop and go operation
  - positive or similar TCO
- **Range estimates varied greatly with requirements, cycles, expectations, etc. Overall, 100 miles per day for MD, 100-200 per day for class 7/8. Many mentioned the use of on-route or opportunity charging.**

3b. MD/HD Trucks: Applications, Features, Range

Applications	Features	Range
Last mile/ middle mile delivery **(12)**	"High utilization of regenerative breaking benefits, vehicles return to the same depot for overnight charging, lower cost of lower range models, limited range requirements and consistent routes"	100 – 200 mi
Class 6/7 short/regional haul **(11)**	"High utilization rates and moderate daily duty cycles will provide maximum fuel savings, lower payload requirements improve vehicle efficiency and range, vehicles return to the same depot for overnight charging (Dwell times 6 to 9 hrs)", "Ease of driver operation, less noise, less maintenance and zero tailpipe regulatory challenges all combine to make a battery electric, HD truck an interesting option for the future"	<300 mi or <250 mi (response varied)
Urban transit **(8)**	"The defined routes and stops in the public transportation sector allow an accurate estimation of the use-case…The stops build potential charging points, which would enable quick charging throughout the route"	<250 mi
Class 3 local haul/ hub-to-hub **(7)**	"These routes would allow a full battery charge to be expended on an 8 hour shift and allow recharging at a return to base operation"	<200 mi
Refuse vehicles **(7)**	"Refuse HD trucks with many stop-start applications that allow regenerating torque to charge the batteries can help keep the battery size small and make these trucks less expensive and commercially viable for customers", "zero emissions at the vehicle level"	<300 mi
Drayage **(6)**	"Drayage (Classes 7 & 8), with a standard 400-mile availability for various applications "	<400 mi
Class 8 **(3)**	"An ideal range that could be targeted would be total round trip mission of around 400 miles. It can be smaller if some common delivery points have charging areas"	<400 mi
Utility Vehicles **(3)** (non-refuse/drayage)	"lower-range MD vocational applications requiring less than 200 miles/day "	<200 mi
Port operations **(3)**	"Supporting port operations and onsite depot operations with limited travel beyond the centralized hub and with easy access to on-site charging systems"	<100 mi
Eng/Gen+ Boost (1)	"low cost of operation related to fuel expenses"	500-1000 mi

3. Batteries, Electrification, and Charging of MD/HD Trucks

3c.) The mission of VTO is to fund early-stage, high risk R&D. What would be the most impactful R&D areas and/or results for industry or consumers in this area of batteries, electrification, and charging of MD/HD trucks?

Summary of 13 responses:

- Most responses fall into Batteries, EV Drivetrain, Charging. “many of the same technologies being developed for light-duty vehicles will also be applicable to MD/HD vehicles”
- For these components, reducing cost and improving reliability is cited, as is commonality/standardization across platforms and common charging solutions
- Battery R&D for cells, modules, and packs – including solid state and new chemistries without critical materials; focus on higher energy density, lower cost, faster charging, and greater cycle life.
- High voltage (1200-1700V) electric drive systems using Wide Bandgap devices. Electric motors with high torque, efficiency, and good thermal performance. Same for electric Heat pumps.
- Technologies for 1+MW DC fast charging for multiple trucks including scalable business models for charging

> “The medium and heavy-duty truck sector lacks the consistent research and demonstration funding typical to some vehicle categories such as public transportation.” - *Manufacturer*

3.d. Batteries for MD/HD Trucks - Costs

3.d.1 Cost: at what cost ($/kWh) do batteries attract interest for the MD/HD industry? How does this change across different truck classes?

Summary of 13 responses:

- Most responses centered around a cost of **$100/kWh - $125/kWh** for most heavy duty applications
- Some highlighted applications and classes (**class 6 & 7**) that could be viable with costs of **~$150/kWh**
- A few responses also stated that **urban-use vehicles** including refuse could tolerate battery prices up to **$200/kWh**
- A few responses stated desired costs below **$100/kWh**

- Many responses highlighted need for standardizing of cells/pack/modules in order to reduce costs and increase production scales

> "Because batteries are platform- and application-dependent, a commonized cell or pack could greatly reduce system costs and improve capabilities. This includes monitoring and mitigation along with the reliability of pack replacement, thus affecting TCO. Further work is required to address cost components, system optimization, and life-cycle and disposal factors."
>
> \- *Corporation Response*

3.d. Batteries for MD/HD Trucks – Production Volumes

3.d.2 Please comment on what production volume for any given medium- or heavy-duty application would be necessary to shift from battery cells designed for the light-duty market to seeking a tailored battery design for trucks.

Summary of 9 responses:

- Responses varied substantially
- Some interesting responses included projection suggesting that at least 20-25% of heavy duty vehicles may be electrified in the near term
- The need for **standardization** was highlighted
- Responders highlighted the challenge of keeping **total cost of ownership (TCO)** low for low volumes

"Widespread consideration for specific MD/HD-tailored battery cell designs may not occur until BEVs dominate overall light-duty vehicle market share.
- *Corporate Response*

"Production volume of approximately 10M cells (assuming a 50 A-h Li-ion cell) is needed to justify the production of a purpose-built cell."
- OEM Response

"By the 2030-time frame, we project **~50% of MD vehicles** will be EVs, with Class 7 and 8 vehicles reaching levels based on technology maturity and market acceptance. To properly address the scope and costs of changes needed to achieve production levels requires further consideration and analysis of a range of factors for each vehicle category. These include the ability of each vehicle class to use similar battery packs, the integration of components / systems, TCO, life cycle, applications, etc., to achieve customer adoption. "
- *OEM Response*

3.d. Batteries for MD/HD Trucks - Concerns

3.d.3 Are there aspects of presently commercial battery systems for light-duty vehicles that cause concern or could not be suitably adapted to medium- and heavy-duty applications? If so, what are those inherent features that will complicate that scale-up?

Summary of 14 responses (most cited concerns/barriers):

- Weight of battery/size of battery effect truck payloads/volumes
- Cycle life/battery lifetimes
  - These can be affected by fast charging requirements
  - May need cycle lives upwards of 4,000 cycles
- Thermal management challenges
- Needed power requirements greater than current technologies capabilities
- Needed energy densities greater than current technologies
- High operating voltages for total vehicle system

"The main issue with scaling up batteries for medium and heavy duty trucks is that the additional weight of the battery reduces the truck's payload capacity which reduces the profit available for the fleet operator.
- *OEM Response*

3.d. Batteries for MD/HD Trucks

3.d.4 Discuss the benefits and drawbacks of purpose-built battery-electric truck chassis. In the near-term, are purpose-built or conventional chassis likely to be the preferred architecture? If accommodating battery systems to conventional chassis is initially preferred, is this likely to change in the next decade?

Summary of 14 responses:

- Overall, purpose-built chassis were preferred
- **Purpose-built chassis:**
  - Pros:
    - Better battery pack & module integration into structure
  - Cons:
    - Higher product development costs
    - Longer lead times
    - Would require large enough volumes of production to achieve economies of scale
- **Utilizing existing chassis**:
  - Pros:
    - Lower costs
    - Ease of fast adoption
  - Cons:
    - Does not allow for optimization of battery pack size and weight

"We believe that purpose-built chassis is already the preferred architecture for MD/HD electric vehicles... This approach provides opportunities for economies of scale which can help bring costs down and make products more affordable and therefore accessible.

- *Nonprofit Response*

3.d. Batteries for MD/HD Trucks - Modules

3.d.5 Would a modular battery module that scales with truck size/vocation needs be preferable and possible across hybridization schemes and truck classes, or are customized battery designs preferable and required?

Summary of 14 responses:

- Most responses stated that **yes**, modules would be of benefit to adoption
- Responses noted that modular batteries can enable hybridization, battery swapping, scalable options, and ease of upgrading
- Some expressed concerns/barriers for modular systems including safety considerations with swapping modules, space and storage challenges, and potential operational challenges
- Some noted that beyond battery modules, **modular control systems** can also be a benefit toward battery swapping
- One responder noted that modular strategies could refer to a range of systems, and the modular design would effect the challenges and benefits

> "Modular strategy at the sub-pack level allows flexibility in pack configurations. If a battery module is effectively a standalone pack, handling multiple packs would require some engineering of the vehicle to accommodate this feature. "
>
> - OEM *Response*

3.d.6 Please comment on the trade-offs between designing for battery replacement, or modular repair, or requiring a single pack last the entire truck lifetime.

Summary of 14 responses (overall, full or modular battery replacement was preferred):

- Responders differed in in their preference of replacement (modular or full) or use of a single pack over lifetime

Modular battery replacement:

- Pros:
  - Lower costs compared to total battery replacements
  - Less overall downtime compared to total battery replacements
  - Extends total lifetime of truck
- Cons:
  - Would require rigorous safety protocols and regulations

Total battery replacement:

- Pros:
  - Easier replacement, less rigorous safety protocols compared to modular designs
  - Extends total lifetime of truck
  - More possible in the near term
- Cons:
  - Higher TCO compared to no battery replacement and modular replacements

Single pack for truck lifetime:

- Pros:
  - Low TCO compared to battery replacements
- Cons:
  - May limit truck lifetime
  - Feasibility of batteries achieving desired lifetimes

> "A single non-modular pack may save cost in terms of total bill-of-materials but has the potential drawback of increasing repair cost since it may be more difficult/labor intensive to replace a failed component." - OEM *Response*

3.d. Batteries for MD/HD Trucks

3.d.7 What are the expected volumetric and gravimetric penalties are expected for the pack design of the most attractive medium- and heavy-duty vehicles?

Summary of 4 responses:

- A pack volumetric density of **600 Wh/L** was suggested to allow for minimal penalties for MD/HD electrification

> “Currently, we’d estimate a **cell-to-pack ratio of 60%.** Depending on cell type (pouch, prismatic, cylindrical) this is an area for improvement and an area where improvements can be facilitated by a purpose-built chassis. “
>
> - OEM *Response*

3.d. Batteries for MD/HD Trucks

3.d.8 Are there any areas in the space of medium- and heavy-duty electrification for batteries that we are not considering in this RFI that would be useful to consider?

Summary of 11 responses:

- Consider **bidirectional power transfer** and vehicle-to-grid integration without creating local distribution issues
- **Factors limiting fast-charge** performance that will be a barrier to adoption
- Need for **standardization** of performance tests and safety regulations
- Need for **advanced battery mounting strategies**
- Innovative **battery financing models** and tools could be of benefit
- Opportunities for **APUs and power takeoff** on trucks

3.e. Electric Drive Technologies

3.e.1 Considering the traction inverter, traction motor, high voltage to low voltage dc-dc converter, and the electrified accessories, what are the greatest barrier(s) to the electrification of MD and HD vehicles? What are the primary R&D needs to overcome barriers?

Summary of 17 responses:

- **Responses varied but predominantly looked at the following areas:**
  - Price volatility and sustainability of rare-earth materials used in permanent magnets for traction motors
  - Improved efficiency, power density, cost, and size of power electronics
  - The high voltage (HV) traction motor and inverter thermal limitations and torque densities required for MD and HD vehicles
- **R&D identified for the following areas:**
  - High energy density, high temperature stability non-rare Earth permanent magnet for traction motors
  - Size and weight reduction of HV (>800 V) battery packs to improve system efficiency and overall volume
  - Tighter integration between the power electronics and the traction motor

> "It is therefore necessary for the traction motor(s) to have sufficient peak torque and continuous power capability in a reasonably sized package. Thus, improvements in traction motor power density are desirable. Improved methods to dissipate heat effectively from the motor rotor and stator would help continuous power capability."
>
> \- *Corporation Response*

3.e. Electric Drive Technologies

3.e.2 To what extent can commercially available, off-the-shelf products for inverters, converters, and motors can be used in current MD and HD vehicles? What are the gaps and challenges?

Summary of 17 responses:

- **Majority of responders felt available COTS wide-bandgap power devices/modules may be acceptable for MD & HD converters with caveats:**
  - Given that long-term reliability of the devices are demonstrated and accepted
  - High voltage (>1 kV) bus is utilized
  - Useful for prototyping and proof-of-concept systems for MD and HD vehicles
- **Further R&D of fully integrated electric powertrain systems for HD vehicles:**
  - Development of durable, cost effective, high speed electric machines suitable for integration with commercial electrified rigid axles meeting power density and size requirements for Class 8 HD vehicles
- **Other gaps and challenges include:**
  - Reduction in rare-Earth materials
  - Effective thermal management (thermal stresses)
  - COTS inverters operating lifetime is often more than 6x shorter than required for HD vehicles

"There are several Commercial off the Shelf (COTS) products that are developed for MD and HD truck applications, and many of them are actively utilized in demonstration vehicles and small fleet deployments. For larger scale production and full-scale market introduction, however, these products should be ruggedized and qualified for higher levels of functional safety, reliability, service life, as well as environmental compatibilities."
- *Corporation Response*

3.e. Electric Drive Technologies

3.e.3 Considering the roadmap for passenger vehicle electric drive technologies targets, are there any activities missing that would be needed for MD/HD Electrification? Any targets or requirements to add? Are there additional technology challenges or gaps that should be addressed?

Summary of 14 responses:

- **Companies suggest that targets for MD and HD vehicles should be further defined for a wider range of key applications**
- **According to multiple responses, multi-speed transmission and powertrain integration should be addressed**
- **Thermal challenges for MD and HD high power motors and drivetrains need to be further analyzed**
- **MD and HD targets could benefit from improved metrics such as those that address TCO or economy of scale (modularity or commonization).**
- **Multiple responses also indicate standardization of traction voltage systems could assist in long-term system development.**

"Durability, Higher Sustained Power, Smaller volume commercial offerings are all gaps from light duty products. The science is very similar, but the application engineering and commercial, long term availability are a challenge. Wider temperature tolerance in smaller volumes are a gap with these technologies. Also standardization of interfaces would be helpful."

- *Small Business Response*

3.e.4 All the power electronics components, power electronics systems, and electric motors require many iterations and lab testing of each iteration due to modeling accuracy problems of the commercial software. Are available high fidelity modeling tools sufficient to reduce the design cycle time or are additional design tools needed that are tailored to MD/HD applications?

Summary of 13 responses:

- **New platforms effectively combining electrical/electromagnetic, thermal, and mechanical analysis computationally are recommended**
- **Improvements in high fidelity tools could lead to a significant reduction in design cycle time for MD/HD electric drivetrains**
- **Improvements in modeling tools including electron flow and EMI/RFI would be helpful in packaging design efficiency.**
- **Reconfigurable, multi-physics models to permit change of fidelity & scope for different needs is also desired**
  - Calibration development, durability, control algorithm development, EMI, thermal etc.

"Existing high-fidelity modeling tools can be helpful in the design of electric motors, power electronic systems, and power electronic components. However, we believe there is considerable opportunity for improvement, and therefore significant reduction in design cycle time for MD/HD electric drivetrains."
- *Government Response*

3.f. Regenerative Braking

3.f Recovering the braking energy a.k.a. regeneration through electric braking is an important aspect of electrified transportation. Are the current technologies sufficient to recover all or sufficient amount of the energy generated without wasting it? Are other technologies required not to waste any recoverable energy?

Summary of 11 responses:

- **Multiple responses noted peak braking power of HD vehicles are greater than required maximum propulsion power**
  - Not all braking energy could be recovered using existing electric powertrains
- **Efficiency of recovering braking energy during a full battery pack was also a concern**
- **Better planning and repartition of the braking energy (spreading the same amount of energy over a longer duration) can allow to reduce power levels:**
  - Makes manageable for the electric powertrain
  - More energy is recovered.
- **MD and HD vehicles require significantly larger regenerative braking/torque power capacity than traction capacity**

> "Deficiency of recuperating braking power can be caused by hardware operational limits, especially with batteries having charge-current limits significantly lower than discharge."
> - *R&D org. response*

3.g. Charging for Electrified Trucks

3.g.1. How much down time do trucks typically have at stops (during which they can be charged)? If possible, please provide the vocation/class of the truck corresponding to a given amount of down time.

Summary of 13 responses:

- According to responders, the amount down time will vary with vocation and route
- Vehicles like drayage and refuse trucks have short downtimes during shifts and are better suited for overnight charging
- U.S. study citied by one responder noted that 44 % cargo drivers spent 2 hours or less during unloading.

MD/HD Truck Class	Vocation	Down Time
4 – 7	Food & Bev. Trucks	20 mins. To 40 mins.
7/8	Regional Haul	10 mins. to 1 hour
8	Refuse & Busses	Overnights
8	Terminal Tractor	30 mins. to 1 hour (break)

"These answers are dependent on the numerous variety of duty cycles and applications, therefore it is very difficult to define a typical stop. However for class 7/8 regional haul vehicles loading and unloading the trailer can provide anywhere from 10 minutes to 1 hour at a loading dock. For class 7/8 vocational vehicles i.e. refuse, approximately 50 stops per shift might last only 1 minute."

- *OEM Response*

3.g. Charging for Electrified Trucks

3.g.2. What charging rate(s) are you currently considering for electrified trucks? What information would help (e.g., validation, analysis, etc.) in determining future decisions to electrify further?

Summary of 7 responses:

- **Majority of responses looked at the maximum charging rate of the MD and HD vehicle battery packs as the constraint:**
  - 1.5 C batteries common for electrified trucks
  - 3 C ~ 6 C emerging battery technology could allow for extreme fast chargers, XFC: >1 MW
- **Currently, responders are utilizing charging rates ranging from 50 to 200 kWh**
- **Useful information for determining future decisions:**
  - Drive cycles, cell capabilities, and battery system efficiency
  - Charger capabilities, charging infrastructure, and ROI analysis
  - Cost implications of fast charging for fleets

"The chargers suitable for electrified trucks are able to charge 60kwh – 120kwh. The fast charging capability of the battery will determine future decisions to electrify. It depends on the customer drive cycle. 1C charging is possible with some electrified truck batteries, but if you increase the charging rate you decrease the cycle life."

- *Corporation Response*

3.g. Charging for Electrified Trucks

3.g.3. How is industry envisioning the future of charging infrastructure? Who would or should own charging infrastructure? Will they leverage publicly funded, publicly available stations? Will a minimum cluster or corridor of stations be required to support an initial rollout of technology? What is the minimum number?

Summary of 14 responses:

- **Many responders look at expanding charging infrastructure design along interstate routes to enable commerce and in-route charging**
- **Will ultimately depend on battery development and vehicle application**

Who should own charging infrastructure?

- Fleet owners/operators
- Fueling centers
- Distribution centers
- Utilities

Leveraging publicly funded, publically available stations:

- Initially a mix of publically/privately owned 125 kW to 375 kW stations
- Near term focusing on privately owned
- For long distance routes, publically high-capacity chargers will be necessary

Minimum cluster or corridor of stations required to support initial rollout?

- Convenient, available public stations will be key to adoption
- DCFC stations at rest areas, visitor centers, travel plazas, & "truck stops"
- Spaced within minimal distance of lowest range model

3.g.4. Are there Electric Vehicle Supply Equipment (EVSE) capabilities or technologies that are not currently being addressed in the market?

Summary of 11 responses:

- **Of the responses, the #1 EVSE capability needing further attention was the bidirectional energy flow capability of EVSEs:**
  - Further deployment of capabilities and services
  - Help enhance grid reliability and resilience
  - Location of transmission and/or feeder lines
- **EVSE networks ability to delay and modulate charging of vehicles to minimize the impact on the existing substation and grid**
- **Technologies to monitor the health condition and security of charging station in real-time are recommended for a reliable, trustable charging infrastructure network**
- **A few responders suggested further investigation of higher DC voltage (>1 kV) charging stations to reduce current levels:**
  - Reduces size, weight, and cost of power cables and conductors
  - Reduces losses along cables and conductors (I^2R losses)
  - Simplifies thermal management of connectors

> "Vehicle-to-Grid (V2G) capabilities should be addressed to a greater extent to further deploy these capabilities and services, and thereby help enhance grid reliability and resilience and leverage the capabilities of batteries on vehicles to help provide power to the grid, in addition to the grid and EVSE being used to charge batteries.
>
> \- *Trade Association Response*

4: Hydrogen and Fuel Cell Trucking

Mariya Koleva, National Renewable Energy Laboratory

4: Hydrogen and Fuel Cell Trucking

4.a. At what vehicle range (for each class/vocation), does hydrogen become a more cost-effective solution than other technology options such as diesel, biofuel, or battery vehicles (today, and in the future)?

Response Summary: Hydrogen becomes more competitive at higher mile ranges, i.e.:

- An even distribution of responses for vehicle range varied from 150 miles to 300 miles with an average of 220 miles
- Cost-effectiveness range depends on:
  - Vehicle duty cycle
  - Payload weight

4: Hydrogen and Fuel Cell Trucking

4.b. DOE is considering reference truck designs that do not need to meet the 6% grade for 11 miles (40 mph for single drive axle trucks and 30 mph for trucks with two drive axles). Is this appropriate for representing the requirements of the majority of trucks. What percentage of trucks experience 11 miles, 6% grade? DOE is considering a continuous-speed grade requirement of 1.25% at max cruising speed (65 mph for primarily highway vehicles, 55 mph for others) for truck modeling purposes.

Response Summary: The considerations may not be appropriate for all truck vocations.

- **Reference truck designs (grade and mileage) depend on the application:**
  - Short haul: 11 miles may be a longer than necessary with maximum 6% uphill gradeability at maximum 20-30 mph
  - Other vocational applications: maximum 10% uphill gradeability at maximum 25 mph
  - Maximum cruising speed: 0.5% grade at 65 mph and 1% continuous speed grade requirement
- **Standard depends on:**
  - Payload
  - Routes
  - Congestion
  - Propulsion architecture

4: Hydrogen and Fuel Cell Trucking

4.c. HFTO is considering the following target combining durability, performance, efficiency, and cost for membrane electrode assemblies (MEAs) for heavy-duty fuel cell trucks: 2.5 kW/gPGM power (total PGM loading 0.3 mg/cm2; equivalent to 1.07 A/cm2 current density) at 0.7 V measured after a 25,000 hour-equivalent accelerated durability test (MEA test conditions: 88°C, 2.5 atm, stoichiometric ratio: 1.5 cathode/2 anode, 40% RH). Is this combined target appropriate and reasonable?

Response Summary: The combined target may not be appropriate. The following targets are suggested:

- 5 kW/gPGM and higher maximum operating temperature (1 response)
- ≥ 0.3 mg/cm² PGM loading target (2 responses)
- Membrane durability of 25,000 h may be too high given current state of art for LDVs is 5,000 h (1 response)
- Stoichiometric ratio target of 2 for cathode and 1.5 for anode in the high-power operating region (1 response)
- Targets should allow for higher durability and efficiency goals

4: Hydrogen and Fuel Cell Trucking

4.d. Are there available data required for optimizing vehicle design around a specific use case for a vehicle class? This includes 1 hertz (Hz) drive cycle data (speed and grade vs. time) including payload, for a variety of regional geographical conditions, including urban, suburban, and rural; flat, mountainous conditions with hot and cold weather. Are there data available to map a distribution the number of trucks over regional conditions? What other data is needed?

Response Summary: Data is scarce and more reliable data is suggested for collection and calculations.

- **Limited data collected by NREL's Fleet DNA, OEM's, CARB, Ports of LA and Truck Association working group**
- **Literature and other open source data does not match up to parcel delivery routes data**
- **Suggested data and calculations:**
  - Reliable drive and duty cycles, road grade, GPS, vehicle mass, aerodynamics (e.g. frontal area, Cd and Cr)
  - Durability of current products to calculate total cost of ownership (TCO)
  - Residual value, maintenance life, component disposal/ reuse at the end of vehicle life

4.e. Fueling for Hydrogen and Fuel Cell Trucks

4.e.1. How much down time do trucks typically have in between shifts (during which they can be refueled)? If possible, please provide the vocation/class of the truck corresponding to a given amount of down time.

Response Summary: Depending on fueling time available, trucks are sorted into 3 groups.

- 3 major groups:
  - Vehicles/operations returning to base could charge overnight or vehicles/operations having 1-2 shifts have ample time for charging
  - Vehicles (e.g. refuse trucks) running 10-hour shifts could charge/fuel during the rest of the time
  - Vehicles (e.g. trucks on-call) running 24 hours are allowed only minutes to charge/fuel
- Time between shifts depends on:
  - Application
  - Class
  - Location
  - Truck-driving regulations

4.e. Fueling for Hydrogen and Fuel Cell Trucks

4.e.2. Are trucks commonly fueled at fueling stations in the middle of routes/during shifts? If so, approximately how long does the fueling process currently take?

Response Summary: Depending on application, trucks can refuel during a shift, where natural stops can be used, or return to central depots.

- **Depending on application, vehicles can refuel during their natural stops:**
  - Line haul trucks: 1 hour, 10 hours
  - Bulk tanker: 1 hour, 4 hours; during shifts
  - Regional haul: 1 hour, 14 hours; at their own facilities, central depos, etc.
- **Current form of refueling takes 10-15 minutes at approx. 14 gpm for diesel trucks**

4.e. Fueling for Hydrogen and Fuel Cell Trucks

4.e.3. Approximately what percentage of the market requires fuel fill time of less than 15 minutes?

Response Summary:

- **Distribution centers that run on 24-hour shifts**
- **Ports that have limited real estate to utilize for refueling/recharging and cannot have trucks sitting at multiple charging stations**

4.e. Fueling for Hydrogen and Fuel Cell Trucks

4.e.4. What fueling pressure will be considered? Is liquid hydrogen considered to be a viable fuel system choice? What information is still needed (e.g., validation, analysis, etc.) to determine the decision?

Response Summary: There is a general near-term consensus for gaseous hydrogen with a potential for liquid hydrogen in future subject to addressing key challenges.

- Near-term consensus for gaseous hydrogen (1 response)
- Liquid hydrogen can be a viable fuel system choice but in the “foreseeable” future it poses challenges (3 responses):
    - On-board storage
    - Boil-off
    - Added cost
    - Cooling below critical point
- 700-bar tanks for LDV, MDV and HDV applications (2 responses)
- 700-bar provides for extended MDV/HDV range (1 response)

4.e. Fueling for Hydrogen and Fuel Cell Trucks

4.e.5. How is industry envisioning the future of fueling infrastructure? Will stations be owned by hydrogen vehicle fleet owners? Will they leverage publicly funded, publicly available stations? Will a minimum cluster or corridor of stations be required to support initial rollout of technology? What is the minimum number?

Response Summary: Industry envisions a combination of options for the future fueling infrastructure.

- Fleets or third-party ownership
- Both, public and private investment are needed
- Both, minimum cluster and decentralized fueling along driving corridors
- Minimum number of stations between 2 and 10 and minimum fleet size of 10 trucks

4.e. Fueling for Hydrogen and Fuel Cell Trucks

4.e.6. Will Truck manufacturers develop their own fuel dispenser technology? What specific bottlenecks in the supply chain would industry be interested in addressing (e.g., nozzles, hoses, chillers, modular station designs, etc.)?

Response Summary: Efficient economic operations require standardization.

- Current priorities are:
  - Non-proprietary standards and costs for MDV/HDV 700-bar refueling
  - Developing industry standards
- Technologies needed include:
  - Fuel-fill nipples/couplings and pump/nozzle as vehicle-fill interface
  - Plug-in hybrid's charging-plug interfaces
  - High-pressure refill procedures
- Additional studies required:
  - Consistency and compatibility of fueling infrastructures
  - Incentivize supply chain to meet projected demand
  - Infrastructure design and implementation
  - Reducing hydrogen costs through protocols or hardware

5: Other Important Considerations

Mark Smith, Program Manager
Technology Integration
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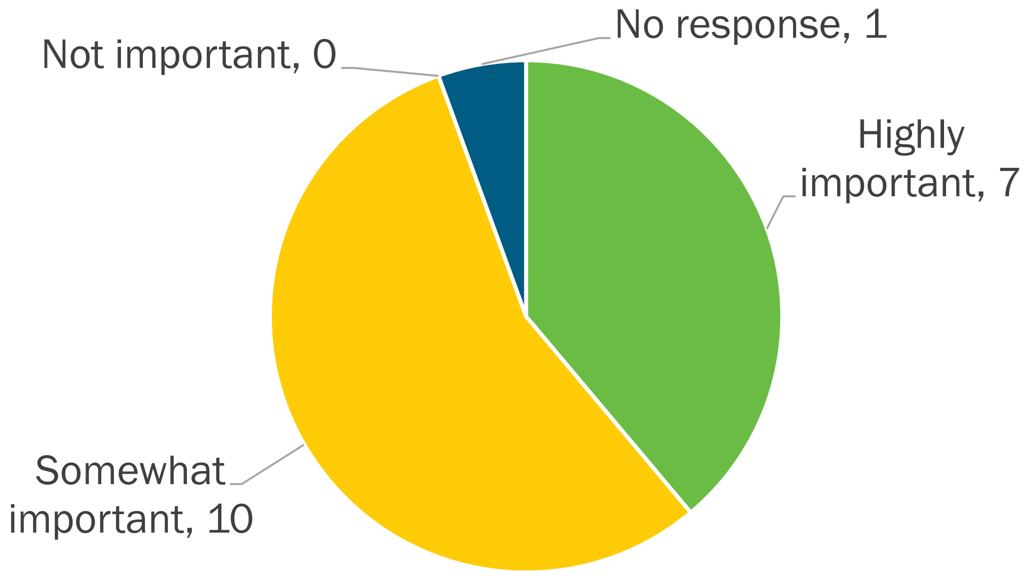
5. Other Considerations

5.a. How important are non-powertrain vehicle-level efficiency technology improvements (e.g., aerodynamics for certain trucks/duty cycles, tire rolling resistance, idling reduction, lightweighting)?

5.a. RESPONSE SUMMARY (1 of 2)

Level of importance of real-world testing



(18 total responses)

5. Other Considerations

5.a. RESPONSE SUMMARY (2 of 2)

- **Technologies of importance**
  - Aerodynamics (active aero, optimized tractor/trailer pairing)
  - Lightweighting (increase payload, offset new powertrain technology weight, compounding effects)
  - Composite materials (light weight, flexible geometry)
  - Vehicle energy management
  - Tire technology (rolling resistance, real-time state information)
  - Automation/connectivity/predictive controls
  - Electrification of accessories (synergy with broader powertrain electrification)
- **Other considerations for non-powertrain technologies**
  - Critical to work trucks (up to 80% of energy use is with truck not moving)
  - Can reduce electric vehicle cost/increase vehicle range
  - Benefit all powertrain types – more commercialization potential, higher customer ROI
  - Select best combinations through drive/duty cycle data

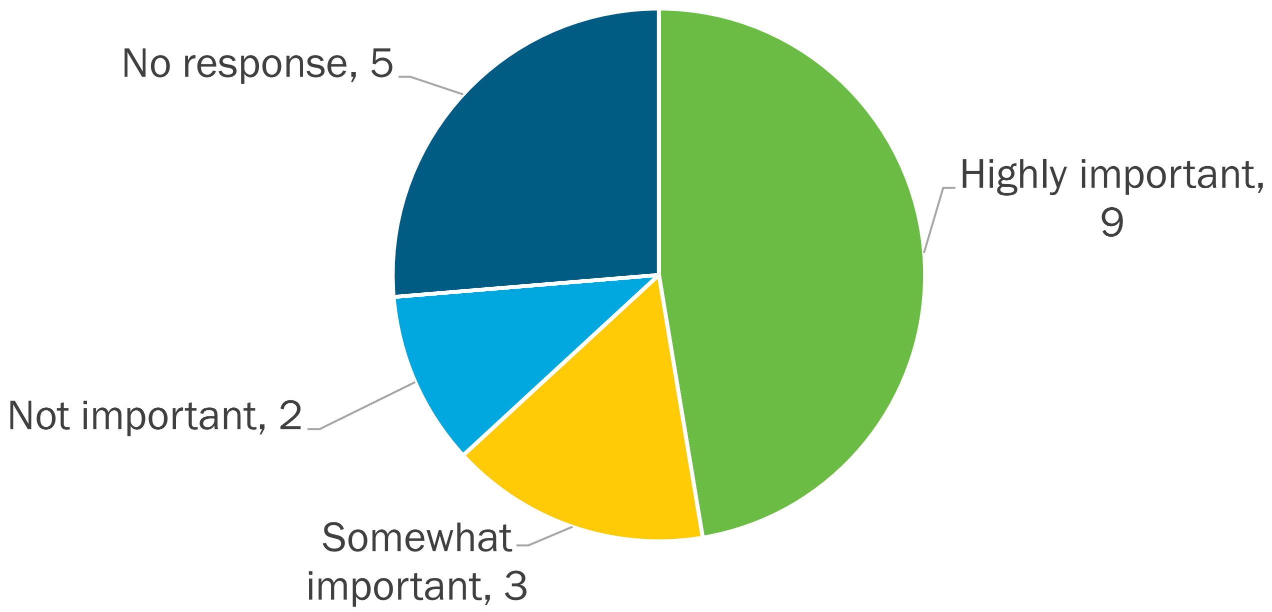
5. Other Considerations

5.b. What are best opportunities and mechanisms to validate, test and integrate advanced technologies into trucks? How important is it to demonstrate technologies in real world applications?

5.b. RESPONSE SUMMARY (1 of 4)

Level of importance of real-world testing

(19 total responses)



5. Other Considerations

5.b. RESPONSE SUMMARY (2 of 4)

- **Importance of real-world testing**
  - Technology development and deployment requires R&D effort beyond capabilities of individual companies, needs government support (complex trucks and many technologies)
  - Validate under actual use conditions to understand technology requirements, evaluate functionality, highlight benefits, get real-world feedback, and develop public awareness/safety expectations
  - Essential to validate in real-world conditions (wide variety of truck use cases)
  - Can validate models or analysis assumptions with demonstrations
  - OEMs should manage demos to maintain quality and reliability
  - Vehicle demos better for high-TRL technologies (many technologies in this space are not yet at this level)

5. Other Considerations

5.b. RESPONSE SUMMARY (3 of 4)

- **Opportunities to validate, test and integrate advanced technologies into trucks**
  - Improve cost-benefit analyses: new guidelines for soft costs; more fleet-specific metrics in DOE tools
  - Metrics for addressing grid impacts of charging MD/HD electric vehicles using managed charging and distributed energy resources
  - Ancillary benefits of distributed energy resources: resiliency and reliability
  - Provide advanced manufacturing facilities for prototyping, testing, and validation of innovation: entrepreneurs and startups can access latest equipment and interact with experts in technical fields
  - Research, data gathering, analysis to identify/validate efficiency improvements of technologies for EPA delegated assembly process (GHG regulation)
  - Hydrogen opportunities - higher temperature PEM operation; integration of technologies to reduce cost and improve manufacturability/reliability/serviceability (combine thermal management systems, develop higher voltage and higher current power electronics)

5. Other Considerations

5.b. RESPONSE SUMMARY (4 of 4)

- **Mechanisms to validate, test and integrate advanced technologies into trucks**
  - Federal support for technology demonstrations (SuperTruck or similar)
  - Federal support for zero emission commercial vehicles and infrastructure (voucher program for fleet owners for cost differential, technical assistance for local infrastructure partners)
  - Detailed drive and duty cycle analysis
  - Virtual design and simulation tools/analysis-led design to reduce design iteration cost and time, combine with real-world testing (validate tools/verify vehicle performance)
  - Lab testing of components and systems in simulated real-world conditions
  - Large scale field demonstrations of vehicles and systems (including associated infrastructure), using existing facilities at universities or other partners: choose demos to provide data to inform future projects across multiple use cases
  - Demonstration of material and component manufacturing at representative rates and scales (production/manufacturing demonstration)
  - End users define technology requirements and test technology in real-world application
  - Education and outreach to disseminate demonstration results/address fleet aversion to new technology

5. Other Considerations

5.c. What kind of collaborations and partnerships need to occur in order to ensure systems-wide efficiency gains are met? What role should trucking fleets play in these collaborations and partnerships?

5.c. RESPONSE SUMMARY (1 of 2)   (18 total responses)

Partners and Roles (as identified by respondents)

- Fleets/customers
  - Set technology requirements based on their needs/duty cycle demands
  - Data for modeling, use case understanding, and technology optimization
  - Testbed for new technologies (partnership with OEM)
  - Receive expanded understanding of technology benefits and duty cycle data gathering/analysis
  - Determine pace of technology adoption
- OEMs
  - Provide information on current/emerging technologies and barriers to using them
  - Develop new powertrains and vehicles to harness the potential of new technologies
- Tier 1 suppliers
  - Provide technical input during technology development
- Other component/materials suppliers

5. Other Considerations

5.c. RESPONSE SUMMARY (2 of 2)

Partners and Roles (as identified by respondents)

- Fuel producers/fuel suppliers/infrastructure providers (including utilities)
  - Produce/supply low carbon intensity/cleaner fuels
  - Data/understanding on well-to-tank emissions of fuel pathways
- National laboratories
  - Expertise in research, data acquisition and retention, analytical understanding of technology benefits
- Universities
  - R&D expertise through new connections to MD/HD industry (need to bridge this gap)
- Federal government agencies (DOE, DOT, EPA, etc.)
- State/local government agencies
- Policymakers
- Workforce development organizations
- Networks of any/all of the above partners

5.d. Artificial intelligence techniques are currently being used for design and control optimization. Would new tools and technologies using artificial intelligence help with industry technology challenges? Please specify.

5.d. RESPONSE SUMMARY (1 of 2) (12 total responses)

- **100% of respondents said new AI tools would help with challenges**
- **AI/machine learning tool ideas**
  - Onboard AI/ML
    - Dynamically optimizing control strategies
    - Engine controls to compensate for or mitigate component aging
  - Offboard AI
    - Optimizing fleet utilization
    - Mission-specific calibrations sent over-the-air to optimize vehicle for daily duty cycle
  - Edge computing and 5G networks to address low latency requirements for transportation

5. Other Considerations

5.d. RESPONSE SUMMARY (2 of 2)

- **How AI/ML tools and technologies would be helpful**
  - Systems with large number of inputs; cause-effect relationships and physics-based models difficult to create (nonlinear or stochastic systems); real-time predictions needed
  - Aggregate/analyze large amounts of data to generalize across use cases/duty cycles
  - Understand impacts of layering multiple fuel types and technologies across applications/duty cycles
  - More high-fidelity simulations to improve sub-models or create surrogate models
  - Enable/accelerate efficient and optimal design studies for complex systems
  - Adaptive digital twins for vehicle and powertrain to maximize technology benefits
  - Aid operation and decision making for multi-vehicle control algorithms like CACC
  - Develop OBD strategies with AI/ML and redirect OEM time and resources into vehicle efficiency increases
  - Learning driver habits for driver feedback and coaching: maximizes technology benefit/limits effects of negative driver habits

5. Other Considerations

- **Additional input (not associated with a particular question)**
  - The tractor-trailer combination is a vehicle system and these components can interact beneficially. Need to clarify from a regulatory standpoint that the tractor-trailer combination is a system to incentivize manufacturers to take responsibility for both parts of the system. There are currently two different marketplaces for each, constraining innovation.

Wrap-Up

- Our team continues to review the detailed responses.
- Responses will inform/guide EERE's medium and heavy-duty R&D portfolio including multi-year program plans, technology roadmaps.

- A recording of today's webinar and PowerPoint will be posted at: *https://www.energy.gov/eere/vehicles/events/webinar-discuss-key-findings-does-request-information-support-medium-and-heavy*

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- Learn more at https://www.energy.gov/eere/articles/eere-launches-new-portal-applying-funding-opportunities
- Note: Must use Google Chrome to access the Portal

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