21st CENTURY TRUCK PARTNERSHIP℠

Internal Combustion Engine Technical Sector Team

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The 21st Century Truck Partnership would like to acknowledge the valuable inputs from all of our partners in creating this technical roadmap. We greatly appreciate the technical expertise of the subject matter experts at the U.S. Department of Energy's national laboratories in helping create the technical roadmap sections. Thanks also to the many industry and government partners who provided input through participation in group discussions about the roadmap.

NOTE: Achievement of the goals contained in this document is subject to a number of factors, including availability of funding to perform the research work. The Partnership will periodically review this document to ensure that it reflects current goals and funding availability.

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Executive Summary

The medium- and heavy-duty vehicle (MHDV) industry is at the start of an important transition. The U.S. economy is reliant on MHDVs, which move freight and passengers and play an essential role in infrastructure maintenance. However, most of today's MHDVs are powered by internal combustion engines (ICEs) and are significant contributors to greenhouse gas (GHG) emissions in the United States. Regulators, society, and even end users are challenging the industry to move toward a low-carbon future. Therefore, MHDVs must transition to low-carbon powertrains—and do so in a well-organized fashion so as not to disrupt the economy.

Electric vehicles, both battery electric (BEV) and fuel cell electric (FCEV), will be the final solution for many of the vocations within the MHDV market. However, the supportive clean infrastructure is not yet built out and matured, so there will be a need for interim solutions, i.e., clean and efficient technologies that operate fully or partially on ICEs.

As we look to decarbonize the MHDV market, we must consider GHG emissions across the life cycle, including those produced during vehicle manufacturing, fuel creation, vehicle use, and material recycling.

The Internal Combustion Engine Tech Sector Team (ICETST) within the 21st Century Truck Partnership (21CTP) has embraced the current industry perspective of a three-solution technology approach to a low-/zero-carbon future for MHDV and non-road powertrains. The new ICETST technology roadmap consists of system solutions for powertrain hybridization and net-/near-zero carbon fuels, along with the continued development of ICE to optimize each technology.

Figure ES-1. ICETST logo

The 21CTP ICETST aims to identify technical targets and solutions that need further research to optimize MHDV powertrains to get to the lowest-carbon footprint the fastest, considering the wide variety of end-user duty cycles.

The ICETST and associates also studied the state of technology and developed an understanding of the key challenges to be resolved for achieving rapid reduction of GHG emissions in this sector:

- Incomplete data and understanding of the diverse mission requirements that define architecture for the lowest-carbon MHDV powertrains and net-zero carbon fuel supply. The relevant applications include those found in non-road, hard-to-electrify sectors such as rail and marine.
- Technology gaps and high cost in the highest-efficiency MHDV powertrains, such as hybrid–electric systems.
- Inadequate understanding of the total market capability and needs of biofuel/e-fuel production volumes.
- Gaps in engine and emissions-control technology needed to enable the cleanest and most efficient use of affordable net-zero-carbon fuels.
  - Gaps in approaches to criteria pollutants at zero-impact levels.
- Gaps in key simulation, modeling, and virtual analysis tools needed to accelerate progress.

MHDVs have unique operational characteristics that may differ substantially from those of light-duty vehicles (LDVs) (e.g., MHDVs have more extreme duty cycles). Therefore, a BEV or FCEV may not always be an acceptable solution for many MHDVs or non-road vocations. In addition, the MHDV market differs from the LDV market in that MHDV fleets are run as businesses and make their purchasing decisions based on hard data, such as total cost of ownership (TCO). These attributes translate into requirements that challenge direct adoption of already developed (or-soon-to-be-developed) LDV electrification technology. To achieve a low-carbon industry, MHDVs require development of a specific set of dedicated technologies.

To this end, the ICETST developed this roadmap to identify research and development (R&D) strategies specific to MHDVs and off-highway vocations that can facilitate their widescale transition to de-carbonization. These strategies will inform 21CTP's R&D portfolio.

Top-priority R&D needs are summarized below.

- Research, analyze, and demonstrate hybrid driveline configurations to optimize performance, accelerate decarbonization, improve durability, and achieve a competitive TCO compared to conventional powertrains as applicable to specific duty cycles. Ideally, these duty cycles will be based on real-world data of freight movement that includes all mission requirement data.
- Conduct research and laboratory experiments of integrated engines intended specifically for hybrid drivetrains. The goal is to provide an optimum engine efficiency that is cost-competitive, with specific values targeted for Class 4/6, Class 8 regional-haul, and Class 8 long-haul (see Table D-1, Appendix D). Continued improvements in engine efficiency are synergistic to the development of hybrid powertrains.
- Determine the most essential renewable fuel properties required to achieve or exceed the engine goals stated above while also achieving a net-zero well-to-wheels (WTW) GHG at a future criteria emission level (i.e., post-2028 Phase 3 regulation). Low-/zero-carbon fuels that are economical and backward-compatible should be a focus. New engine efficiency targets will need to be established for renewable fuels, depending on fuel properties and degree of carbon reduction.
- Use experimental and modeling approaches to improve our understanding of net-zero-carbon fuels' effects on in-cylinder combustion and emissions formation processes in advanced engines. Conduct adequate research to ensure that renewable fuels are suitable in medium- and heavy-duty engines for petroleum displacement and customer TCO. This effort should be conducted in collaboration with fuel suppliers, while also including the non-road engine development workspace of construction, mining, rail, and agriculture equipment.
- Assemble a collection of technoeconomic reports/analysis that can provide direction on the TCO or levelized cost of driving for the various GHG-reducing engine and powertrain configurations listed in the recommendations above. Five distinct truck class applications will be queried: Class 8 long-haul, Class 8 regional-haul, Class 6 box truck, Class 4 step van, and Class 3 pick-up trucks.
- Compare WTW and cradle-to-grave carbon emissions for BEV, FCEV, and ICE hybrid vehicles to fully understand the short- and medium-term advantages of an ICE hybrid powertrain. Process costs, product costs, energy pathways, and market penetration are only a few of the many variables necessary for analysis.

- Develop full powertrain simulations that can model system-level hybrid components (e.g., engine, electric drive, and battery) and analyze total vehicle performance that may lead to overall lower costs.
- Leverage LDV volumes and technical solutions, whenever possible, as an approach to lowering the cost and diversity of hybrid powertrain components.
- Develop computational models and methods for combustion, computational fluid dynamics, and the interface between structural materials and the combustion chamber—specifically focused on net-zero-carbon fuels.
- Develop emissions control catalyst materials and modeling methods specifically focused on zero-carbon fuels.
- Develop materials for higher thermal and structural loads needed for higher power density and efficiency.
- Develop processes for manufacturing near-zero-carbon fuels at a lower cost. This is beneficial not only for new developed engines but also for legacy engines where retrofit kits might enable the use of zero-carbon fuels. The magnitude of the legacy fleet will challenge our GHG reduction goals, so we must also examine methods for reducing legacy fleet emissions.

Introduction

Roadmap Background and Scope

The 21st Century Truck Partnership (21CTP) Internal Combustion Engine Tech Sector Team (ICETST) developed this roadmap to support the decarbonization of medium- and heavy-duty vehicles (MHDVs). More specifically, the roadmap identifies research and development (R&D) strategies specific to MHDVs and off-highway vocations (e.g., tractors and bulldozers) that can facilitate their widescale transition to decarbonization.

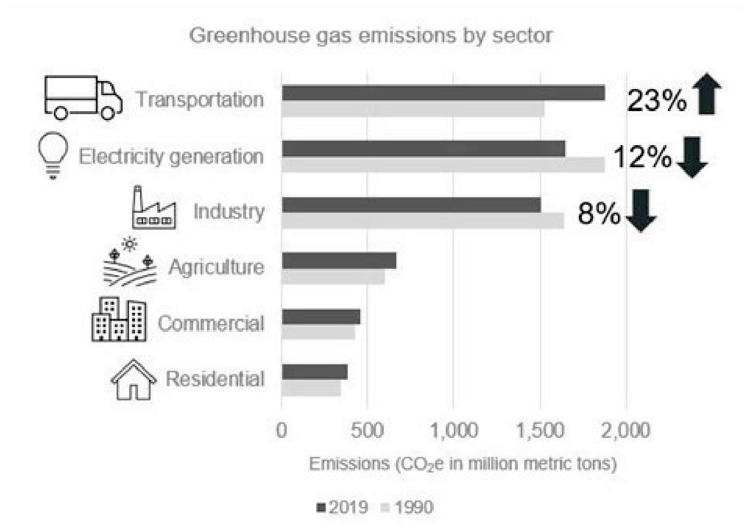

Figure 1. Of U.S. sectors, transportation has the highest GHG emissions. Source: Padmanabhan 2022

The MHDV industry is at the start of an important transition. The U.S. economy is reliant on MHDVs, which move freight and passengers and play an essential role in infrastructure maintenance. However, most of today's MHDVs are powered by internal combustion engines (ICEs), making transportation the U.S. sector with the highest greenhouse gas (GHG) emissions (see Figure 1). Regulators, society, and even end users are challenging the industry to move toward a low-carbon future. Therefore, MHDVs must transition to a low-carbon powertrain—and do so in a well-organized fashion so as not to disrupt the economy.

21CTP has a mission to address such challenges. The partnership has organized its initiatives into four technical areas, as shown in Figure 2; the ICETST focuses on IC [internal combustion] Engine Powertrains. The ICETST developed this roadmap to provide technical details in this focus area.

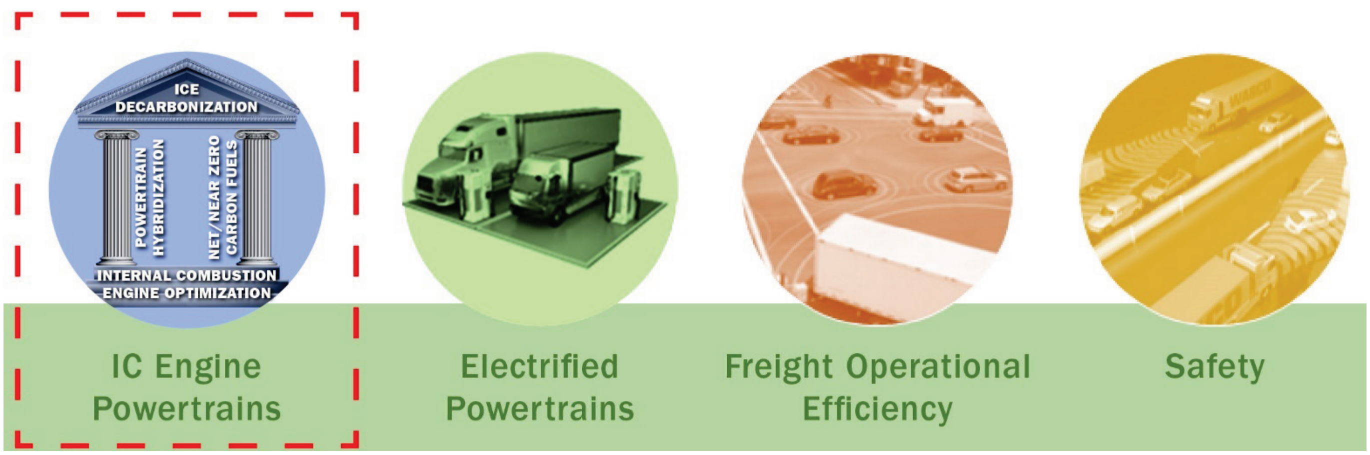

Figure 2. 21CTP has established four technical ("tech") teams.

The roadmap describes a portfolio of potential zero- and near-zero-carbon emission solutions for MHDV powertrains. The document examines the current technology status of these solutions, outlines recommended goals and targets, identifies major barriers to implementing these solutions, and suggests approaches to overcoming these barriers. The scope covers engine and system efficiency improvements at the vehicle powertrain level, along with analysis of potential low-carbon, renewable fuel options. The scope encompasses all classes, 3–8, and applications of trucks involved in hauling freight, as well as buses and powertrains for off-highway agricultural and marine applications that require an ICE for propulsion or auxiliary work.

Alignment with the National Blueprint for Transportation Decarbonization

The current Presidential Administration published the U.S National Blueprint for Transportation Decarbonization (hereafter "the Blueprint"), which calls for "net-zero GHG emissions economy-wide by the year 2050" to address the climate crisis (U.S. Departments of Energy, Transportation, Housing and Urban Development, and the Environmental Protection Agency 2023). The Blueprint notes that the transportation sector induces emissions throughout the life cycle, including fuel production and processing; vehicle manufacturing and disposal; and construction, maintenance, and disposal of transportation infrastructure. Furthermore, our future mobility system must be clean, safe, secure, accessible, affordable, and equitable, providing sustainable transportation options for people and goods.

Attaining these goals will require the use of all our technology options, with the transportation sector acting quickly to implement near-term partial approaches while working toward long-term, zero-carbon solutions. In addition, these solutions must encompass a life cycle approach. Significant contributions will be realized through widescale adoption of battery electric vehicle (BEV) and fuel cell electric vehicle (FCEV) trucks. However, certain vocations—specifically long-haul, heavy-haul, agriculture, and off-highway vehicles—are particularly hard to electrify, presenting technical and economic challenges that are not quickly resolved. Meeting our nation's goal will require all technology approaches: efficiency improvements of IC engines, fuel-agnostic powertrain platforms, and low- or zero-carbon fuel choices (Padmanabhan 2022).

The Blueprint recognizes the need for a multi-pronged approach, including near-term alternatives for legacy vehicles that rely on ICEs. The Blueprint notes that "there will likely be a suite of zero-emission technology solutions in the future to cover various use cases" and provides a high-level roadmap for understanding when battery electric, hydrogen, or sustainable liquid fuels make sense in a vehicle segment (see Figure 3). The Blueprint also recognizes that change may come slowly for the MHDV market, necessitating near-term technical solutions that can be applied to our existing MHDV fleet. This overall approach is consistent with international perspectives, which likewise emphasize the role of vehicle efficiency improvements and the need for low-/zero-carbon, cost-effective drop-in fuels to decarbonize the existing vehicle fleet. Only with the full suite of options can we achieve Blueprint's transportation sector goal of zero-carbon by 2050 (Kramer 2022).

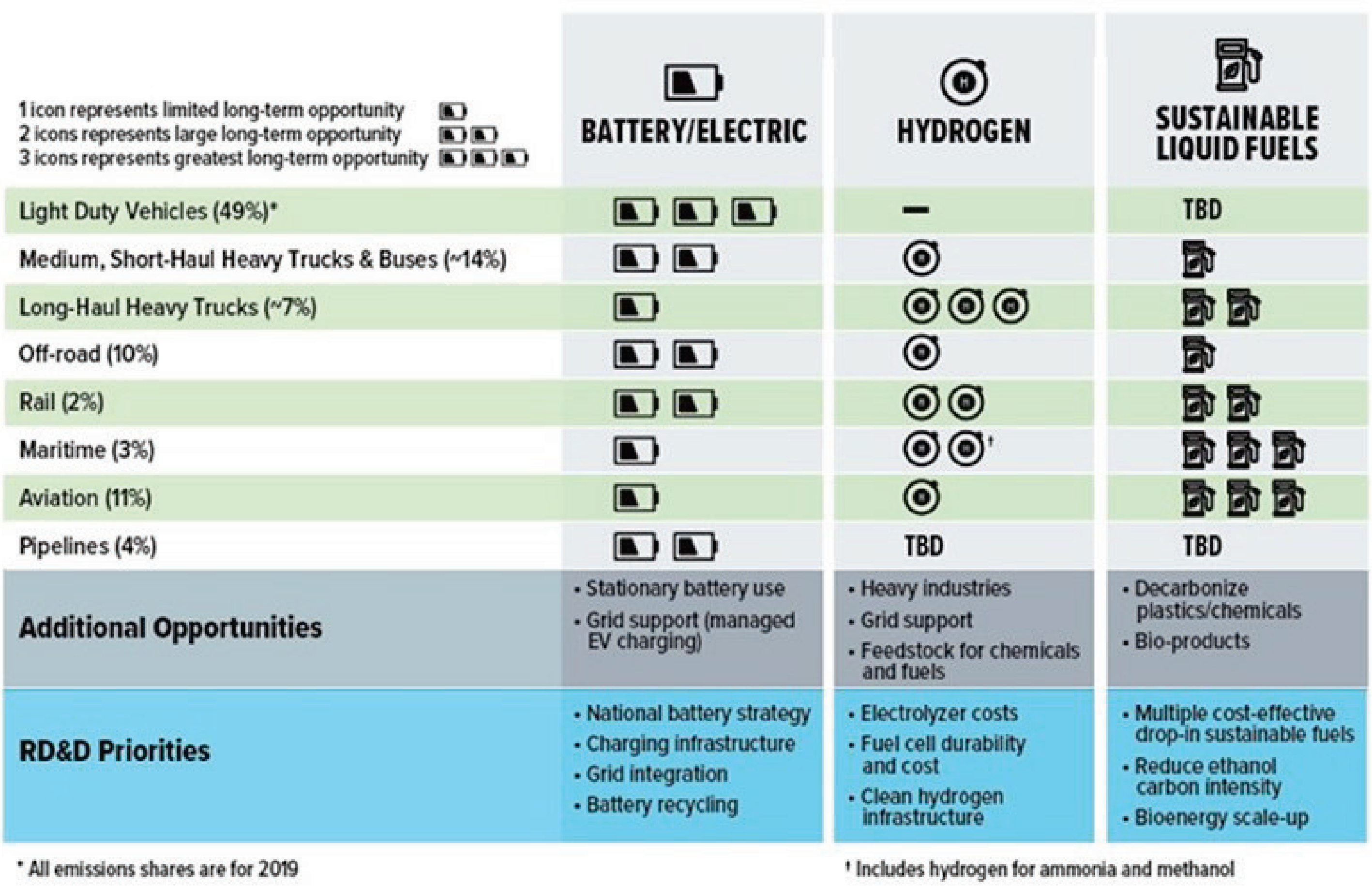

Figure 3. Achieving net-zero emissions requires a suite of technology solutions. Source: The Blueprint

Attaining this goal will also require research, development, and demonstration to identify the most promising near-term and long-term solutions that will likely have significant impacts on transportation sector emissions. To this end, this ICETST roadmap describes a portfolio of potential zero-/near-zero-carbon emissions solutions for ICEs and their associated powertrains.

Hard-to-Electrify Vehicle Segments

Many commercial transportation applications face major roadblocks to electrification. Challenges with economic viability, mission accomplishment, and infrastructure support make these applications hard to electrify. The challenges relate to high vehicle weight, high power demand, high mileage demands, and cost considerations.

In favorable ambient operating temperatures, BEVs are the best long-term solution for many lower-mileage and lower-weight MHDV applications. However, when considering the market breadth of current ICE usage (commercial vehicles, off-highway, agricultural, marine, etc.) a BEV powertrain is not always a favorable solution in terms of GHG-reducing potential—and in fact may not work at all. The transition from favorable to non-favorable occurs between regional and long-haul truck applications, as well as heavy Class 8 vocational applications.

Oak Ridge National Laboratory (ORNL) recently published a study looking at possible powertrain configurations for many hard-to-electrify MHDV applications. The study examines uses for engines within hybrid powertrains and identifies applications that would be difficult for BEVs to accomplish: Class 8 long- and regional-haul, Class 8 vocational, and Class 6 regional (see Figure 4). BEV technology is currently successful only for a range of up to ~250 miles. The analysis was based on operational cost, vehicle cost, mission fulfillment, and GHG-lowering potential.

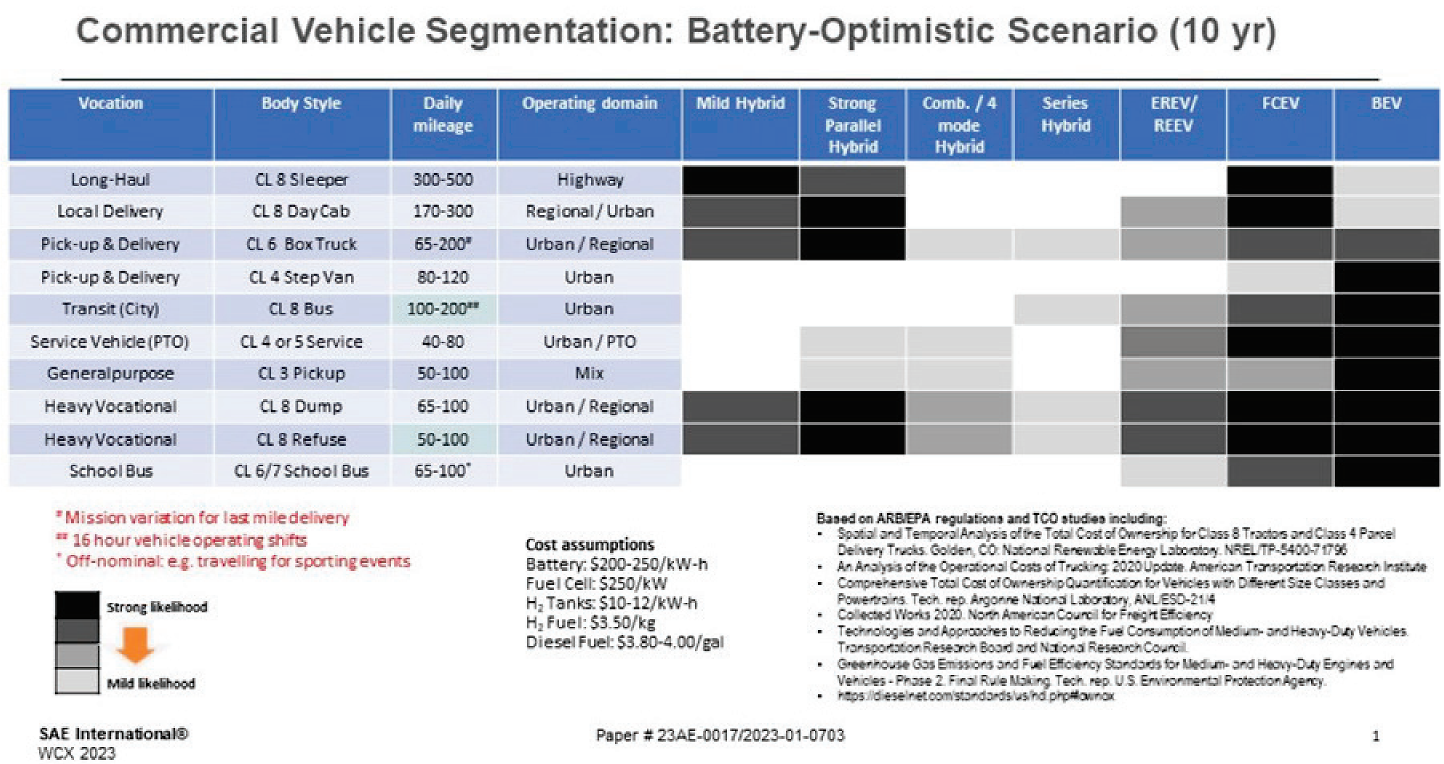

Figure 4. An ORNL study identifies several MHDV applications as hard-to-electrify. Source: Sujan et al. 2023

Until emerging technologies and supportive infrastructure (e.g., the hydrogen fuel marketplace) are mature and in place, a temporary solution is needed for these hard-to-electrify applications. A hybrid powertrain using near-/net-zero carbon fuels can fill this void for the near term and mid-term.

21CTP members have voiced similar findings. Looking at the portfolio of practical decarbonization technologies going out to 2050, 21CTP makes clear allowance for ICE technologies operating on carbon-neutral renewable fuels.

The ORNL study highlights the need for alternative powertrain choices for MHDVs in the future. There will not be a single powertrain solution that attains zero emissions while at the same time meeting the wide variety of vehicle applications and customer expectations regarding efficient and timely freight delivery or accomplishing the multitude of other application-specific missions. A thorough understanding of the many Classes 3–8 truck vocations will be necessary to understand which ones will benefit most from hybrid and net-zero fuel technology application to ICEs.

A Roadmap Strategy to Reduce Greenhouse Gas Emissions Faster

For aggressive CO_2 reduction in commercial on-highway vehicles there is high near-and mid-term potential in completing the development and deployment of advanced ICE MHDVs that utilize hybrid or extended-range electric vehicle (EREV) powertrains with zero-net-carbon fuels. Low net-carbon fuels are already having a billions-gallon petroleum reduction impact. This strategy can reduce GHG emissions while minimizing supply chain disruptions. For applications where BEVs and FCEVs are optimal long-term solutions, hybrid and plug-in hybrid vehicles provide a pathway to adoption by supporting powertrain component development, reducing costs through economies of scale, and scaling up manufacture of batteries and charging equipment.

Recent analytical forecasts of GHG reduction from the roll-out of electric and fuel cell MHDVs, using aggressive adoption scenarios, did not achieve zero carbon goals for 2050 in this sector due to ~20% vehicles on the road still being ICE, requiring 13 billion gallons of liquid fuel (Ledna et al, 2022). Measures for additional CO2 reduction could include more aggressive mpg achievements for ICE vehicles over the next decade, the deployment of greater quantities of life-cycle net-zero fuels (which were not yet analyzed), and better logistics efficiency. These are symbiotic approaches in that greater vehicle efficiency stretches the resources of net-zero fuels. During this near/mid term time period the combination of renewable fuels with hybrid powertrains can make a significant contribution to carbon reduction. For example, a new report from the Transportation Energy Institute, describes two scenarios. Although the supply of renewable diesel (RD) is currently limited, if ¼ of HD ICEVs used RD they would achieve GHG reductions similar to the expected HD EV market over the coming decade; and "HD ICEVs fueled with 20% biodiesel (BD) blended with 80% petroleum diesel (B20) would match expected heavy-duty EV GHG reductions over the decade." (Eichberger 2023)

Government-funded research for hybrid powertrains with associated engine improvements that utilize renewable fuels can accelerate the decarbonization of transportation resulting in significantly more cumulative carbon reductions by 2040. In Figure 5, Cummins 2021 analysis found about 1000 MMT (15%) fewer CO2 emissions are achievable by 2040 in this geography with a path that includes the use of renewable fuels with advanced ICE vehicles, along with the adoption of ZEV. *This finding is illustrative of the substantive potential benefits available by using hybridization and/or other low carbon fuels, along with ZEV.* Although using historical references of vehicle scrappage and new truck sales, the study is proprietary regarding the choice of future technological vehicle choices and the electrical grid make-up.

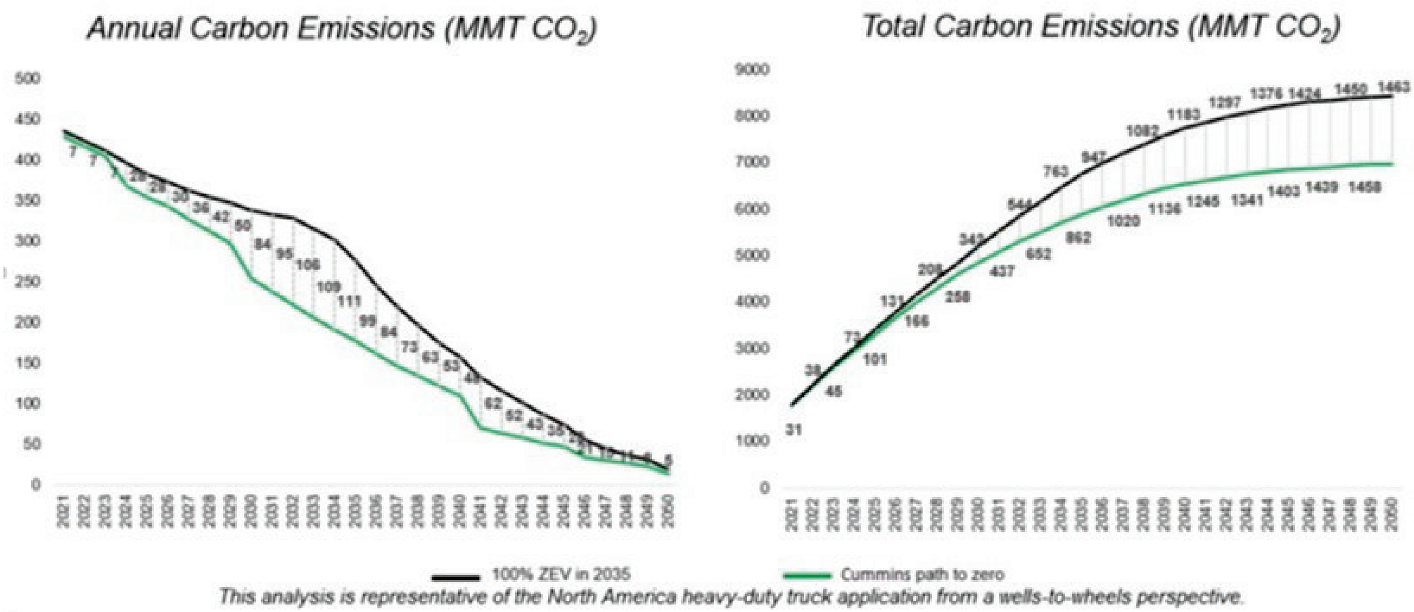

Figure 5. Two HD Vehicle Carbon Reduction Pathways (Based on W2W perspective).

Electric Infrastructure Considerations and Emissions Impact

Widescale medium- and heavy-duty BEV adoption will entail supportive charging infrastructure. In general, the charging solutions for plug-in hybrid electric vehicle (PHEV) and EREV hybrids will be less problematic than for full BEV solutions, as the battery is smaller, and the vehicle can operate on a secondary fuel. Nonetheless, MHDV PHEV and EREV users will require access to high-power chargers.

The roll-out of public charging infrastructure has so far focused mostly on serving electric LDVs. This early infrastructure deployment may serve as a guide for electrification of MHDVs. However, MHDVs require batteries with very high capacities, as MHDVs have heavy-duty work cycles and long-range operations that entail high-power charging. Today, most high-power chargers are designed for light-duty fleets that need on-route charging. These units are capable of depot and travel center MHDV charging at kilowatt-scale power but are not yet capable of megawatt-scale.

The Fuels Institute recently published a paper addressing EV and ICE life cycle carbon emissions (Eichberger 2021) and, more specifically, present and future grid carbon intensity scenarios in the United States. The paper emphasizes that finding optimal near- and mid-term solutions for efficient and effective carbon reduction will require evaluation of a complex market and energy systems, not a one-size-fits-all solution. Figure 6 below illustrates that, given our current grid situation (Extremely High-Carbon Grid), both ICE vehicles and hybrid electric vehicles (HEVs) outperform BEVs in terms of minimizing full life cycle or cradle-to-grave GHG emissions. Most analysts believe the electricity grid will become less carbon-intense over time, but for now, it makes sense to optimize vehicle technology to take advantage of energy market dynamics. BEVs do make sense in a low-carbon grid scenario when properly matched with appropriate drive cycle applications. However, a combination of ICE vehicles and HEVs with a lower-carbon-intensity fuel option, extended via battery hybrid systems, can be a valuable contributor to the MHDV market much sooner.

As we refine our understanding of the full life cycle carbon emissions associated with each technology choice, it will be important to consider both the geographic location and the time of day associated with vehicle changing. For example, in the absence of significant grid energy storage capacity, depot charging at night is unlikely to take advantage of low-carbon solar energy. Conversely, in regions with large amounts of wind power, nighttime charging is likely to be advantageous because of potentially higher, steadier wind energy production.

Non-Road Equipment Synergy

Historically, non-road vehicles and equipment (which tend to be lower-volume) have benefitted from the technology developed for higher-volume, on-highway vehicles. This statement is particularly true with regard to the ICE. Efficiency improvements and emission reduction technologies that have been developed for the on-highway market typically show up in the non-road market within a few years, and this trend will likely continue. However, several non-road applications deal with extreme demands—power required, daily hourly usage, infrastructure accessibility, and harsh ambient conditions—that may preclude BEV or FCEV solutions. These challenging applications will require innovative powertrain solutions if the industry is to meet carbon reduction goals.

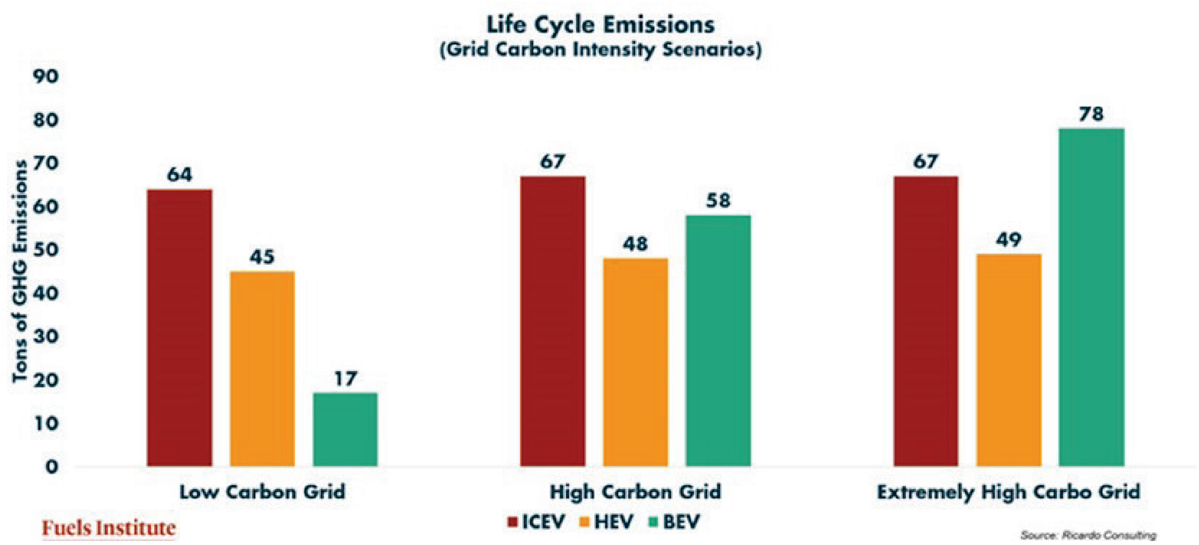

Figure 6. Reducing carbon efficiently and effectively requires complex evaluation of the markets. Source: Eichberger 2021

External Factors

In any analysis, the results are only as good as the assumptions placed into the model and are inherently not capable of dealing with global risk and uncertainty. This roadmap contains targets and goals for each technology considered. Having said that, external factors outside of our control can have significant impacts on the results. These factors include:

- Cost of energy carriers (e.g., hydrogen, electricity, biofuel, diesel fuel)
- Availability of critical materials

- New supply chain development
- New technology product adoption rate
- New technology infrastructure availability
- New technology reliability and its impacts on adoption rate
- Future global market factors
- Future government regulations

Regarding the final factor, the presently proposed U.S. Environmental Protection Agency (EPA) Phase 3 GHG regulations for MHDVs do not incentivize net-zero (life cycle) GHG fuels, even though their contribution to CO_2 reduction is accepted in science and state regulations. Proposed CO_2 standards for 2028 and beyond are performance-based and at vehicle level. For Class 8 trucks, for example, the 2032 averaged per-vehicle CO_2 standard is approximately 30% reduction, compared to a 2027 baseline. The EPA expects most of the reduction to come from strong market uptake of ZEVs (25%–34% in Class 8) by 2032. However, since existing ZEV technologies are not suitable for several MHDV applications, advanced ICE vehicles are needed to reduce emissions from these applications until usable ZEV technologies become available. Emissions performance of vehicles using ICE powertrains with efficiency exceeding 2027 expectations, averaged with emissions performance of ZEVs, would keep industry on track in terms of compliance. Therefore, advanced high-efficiency ICE powertrains, including hybrid electrics, may be necessary to achieve compliance with these emerging regulations for MHDVs.

Benefits of a Powertrain Decarbonization Strategy

Technology options exist for ICE powertrain solutions with net- or near-zero carbon emissions. These solutions, which include low-carbon fuels and engine efficiency improvements, offer significant promise to accelerate progress toward near- and mid-term carbon reduction goals. However, the technologies face challenges in terms of funding, market development, and policy gaps.

The powertrain decarbonization consists of the many choices available from the triangle of solutions: fuel-agnostic engines, hybrid electrification, and near- and net-zero-carbon fuels. There are sundry technological solutions within this triangle that can produce optimal solutions for customers and the environment.

For example, hybrid powertrains substantially increase efficiency and are compatible with renewable fuels that are in the market now (e.g., renewable natural gas, renewable diesel, and B100 diesel), providing a near-zero or zero-carbon solution today, while also meeting the requirements of commercial fleets and off-highway vehicle customers. In parallel, hybridized propulsion systems optimized for alternative low-carbon fuels, such as light alcohols or hydrogen, can be developed such that they are available when these fuels are available at scale.

Alternative fuels can offer significant benefits in terms of pollutant emissions as well, particularly in hybrid powertrain applications that may require many relatively cold engine restarts. Net-zero fuels show promise for ICE combustion solutions and hence for use in future large legacy fleets that operate MHDVs for 20 years or more.

Revisiting MHDV Hybrids for GHG Reduction

There was a “hybrid” initiative at the turn of the century. Several MHDV original equipment manufacturers (OEMs) placed small test fleets into various applications, looking for a good fit for a hybrid powertrain. Unfortunately, the technology was not yet mature, so most of these fleets were plagued with reliability issues. In addition, the components (in particular the Li-ion battery) were expensive, so the upcharge for a hybrid powertrain could not be justified through a total cost of ownership (TCO) analysis.

However, 20+ years of government and industry R&D have yielded hybrid components that are both significantly more reliable and less expensive. Although it is not the best solution for all applications (and hybrid retains the cost of some form of EATS), hybrid powertrains address range anxiety, allow for frequent electric power take-offs without depleting the battery, and can be used in many of the hard-to-electrify applications.

Use of Net-Zero-Carbon Fuels

With a net-zero-carbon fuel, the amount of CO_2 and other GHGs generated is equal to, or less than, the amount consumed (e.g., extracted from air and soil)—throughout the fuel’s life cycle of production, processing, use, and recycling or disposal. This balance of GHG generation and removal over the life cycle is sometimes called the “circular carbon economy.” Some net-zero-carbon fuels are backwards-compatible, that is, suitable for the enormous legacy fleet of combustion vehicles that will still be on the road in mid-century. The National Renewable Energy Laboratory calculates that, in 2050, 20%–25% of the legacy fleets of MHDVs on the road will continue to be ICE-powered. These vehicles will need net-zero combustion fuels, roughly 4 billion gallons/year, to ensure minimum CO_2 contribution (Ledna et al. 2022).

Life cycle analysis, and/or well-to-wheels analysis, is needed to determine how close a fuel is to net-zero. Fuels that contain zero carbon are not always net-zero over a life cycle. Some non-carbon fuels, such as ammonia, emit CO_2 during their production from natural gas. Such fuels are net-zero only if they are produced from carbon-free sources, such as solar–hydrogen or nuclear. Even carbon-free renewable power sources, such as solar and wind, have associated emissions: the components and facilities must be manufactured, built, and maintained; plants must eventually be retired or replaced; and components must be disposed of or recycled.

Vehicles, too, have full life cycles that must be analyzed. There is no such thing as a ZEV when considering transportation operational activities, infrastructure build-up, and vehicle manufacturing. When operated on low-carbon renewable fuels, ICE vehicles have life cycle GHG emissions like those from EVs using the current U.S. grid infrastructure mix (EPA 2021).

The measure of a fuel’s or technology’s life cycle emissions is called the carbon intensity, expressed as mass of CO_2 (equivalent global warming potential) released through the life cycle per energy generated (grams of CO_2-equivalent per megajoule). Analyses have been conducted on a range of fuels for their potential to significantly reduce net carbon; some are in use today. These fuels have net carbon reduction between 50% and 100%, depending on production details:

- Renewable diesel
  - Drop-in fuel

- Renewable natural gas
  - Negative carbon in some cases
  - In use in heavy-duty vehicles
- Renewable methanol
  - Certified for heavy-duty engines in the early 1990s
  - Conversion to gasoline is mature technology
- Ethanol
  - In use in LDVs
  - Can be converted to jet fuel blend
- Biodiesel
  - In widespread use
  - Mostly blends of 20% or less
  - 100% biodiesel with retrofit kit (Optimus Technologies 2021–2022)
- Renewable hydrogen/ammonia

As part of California State's Low Carbon Fuel Standard regulation, the California Air Resources Board maintains a database on fuel carbon intensities (California Air Resources Board 2023). Other estimates of carbon intensity have been published from recent work in the U.S. DRIVE Partnership from their Net-Zero Tech Team (U.S. DRIVE 2021) and recent analyses of biodiesel and renewable diesel (Xu et al. 2022).

The impact of low-carbon alternative fuels is already significant. Today's combined production of renewable natural gas and renewable diesel—approximately 2.4 billion gallons-equivalent per year (Coalition for Renewable Natural Gas 2021; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy n.d.a.)—is enough to displace the petroleum use of 100,000–115,000 ICE class 7/8 trucks compared to estimates of 250 BEV class 7/8 trucks on US roads in 2022. Renewable natural gas and renewable diesel are fungible in the existing, well-developed fuel distribution system. These fuels are primarily in use where incentives and regulations are favorable. Other low-carbon alternatives, such as methanol and hydrogen, require development, as their combustion and fuel dispensing systems differ from each other and from today's predominant fuels.

An existing regulatory incentive for low-carbon fuels is the aforementioned California Low Carbon Fuel Standard. Presently, no similar regulatory incentive exists at the federal level, but such policies have been studied and proposed in the past (U.S. Congress 2007; Yeh and Sperling 2012).

The Renewable Fuel Standard is a federal program that requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels (generally both conventional and advanced biofuels). The standard requires that renewable fuel be blended into transportation fuel in increasing amounts each year, escalating to 22.33 billion gallons per year in 2025 (approximately 70% of the annual total is corn based ethanol). Each renewable fuel category in the program must emit lower levels of GHGs than the petroleum fuel it replaces (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy n.d.b).

Whether green electricity or net-zero liquid fuels, a key question is whether the resources can provide a significant fraction of the necessary energy. The current bioenergy economy of 5 quads (1 quadrillion [1015] BTU, or the energy equivalent of 170 million barrels of petroleum) could grow three-fold to about 15 quads (500 million barrels of petroleum) without drastic land use changes and deforestation. For biofuels, the assessment of resources for ground transport and aviation fuels, well known as the Billion Ton Study, is periodically updated. The 2023 version is in preparation, but these insights can be found in the 2016 publication (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy 2016), reinforced in recent public presentations (Langholtz et al. 2023).

Engine Benefits, Challenges, and Opportunities

Efficiency Improvements for New System Solutions

Over the past several decades, the Vehicle Technologies Office has sponsored research (e.g., through SuperTruck II) to advance base engine efficiency improvements. Typical approaches to improve engine system efficiency include combustion recipe optimization (low-temperature combustion, piston bowl shape and compression ratio, improved spray targeting and atomization, higher pressure and flow injectors, air-handling improvements to reduce pumping losses, variable valve actuation strategies such as Miller Cycle and Cylinder Deactivation, etc.), friction and parasitic reduction, and waste heat recovery. Various research institutions and engine manufacturers have studied these approaches extensively and worked to develop them. Further, several manufacturers have developed innovative hardware and software (controls) solutions to co-optimize engine operation and aftertreatment thermal management, aiming to deliver optimal tradeoffs between nitrogen oxides (NOx), soot, and CO_2 in real-world applications.

Much of this work was based on diesel fuel and will therefore have to be revisited when incorporating net-zero-carbon liquid fuels, which are expected to have different physical and chemical properties from standard diesel, gasoline, and natural gas. Next steps will include ensuring robust engine and exhaust after-treatment system (EATS) performance. Further, there is little clarity as to which fuel or fuels will end up dominating the low-carbon fuel ecosystem, so engine systems need to design-protect for a range of potential candidate low-net-carbon fuels, which include a variety of biofuels and synthetic fuels, as well as liquid and gaseous fuels.

A relatively new development is that of the hydrogen-fueled internal combustion engine (H_2-ICE). Burning hydrogen in a spark-ignited, ICE-powered vehicle reduce carbon emissions to zero, assuming the hydrogen is produced through green processes using energy from renewable sources. H_2-ICE also produces very low NOx, although engine efficiency is currently lower than the traditional compression-ignition engine. The NOx characteristics are similar to those of natural gas engines that have been certified to 0.02 g/hp-hr (Roeth et al. 2023).

H_2-ICE EATS would not include diesel oxidation catalyst or diesel particulate filter components. However, NOx emissions are still formed during the H_2-ICE combustion process and a selective catalytic reduction system would still be required, though it may be smaller than one in a comparable diesel-fueled ICE. The use of lean air–fuel ratios, and not exhaust gas recirculation, is the most effective way to control NOx in an H_2-ICE, as exhaust gas recirculation is less effective with hydrogen because of the absence of CO_2 in the exhaust gas. H_2-ICE technology can be implemented rapidly, using an OEM's existing tooling, manufacturing processes, and engine design expertise (EPA 2023a).

In concept, H_2-ICE engines are very similar to existing ICEs and can leverage the extensive technical expertise manufacturers have developed with existing products. Similarly, H_2-ICE products can be built on the same assembly lines as traditional ICE vehicles, by the same workers and with many of the same component suppliers. H_2-ICE could be a viable solution for Class 8 long-haul applications and duty cycles, such as heavy haul, for which BEVs are not a good match.

Efficiency Opportunities as a Result of Electrification

There is significant room for improvement in ICE efficiency and power density when the ICE is combined with a hybrid electric powertrain. Modern ICEs have been optimized for a century to deliver power, efficiency, and low emissions over a range of operating conditions, e.g., low speed torque and full power. This optimization has compromised peak operating point performance, such as efficiency and power density. Heavy hybridization enables the engine to be re-optimized over a narrower operating range, potentially even a single operating point.

Optimization over a narrower range affects selection of components such as turbochargers, fuel systems, and EATS, thus allowing components to operate at higher efficiency. The narrow operating range also allows for increased efficiency and power while maintaining low criteria pollutant emissions at optimal operating conditions. Emissions during transient events, as encountered with today's powertrain solutions, often compromises engine performance (e.g., lower efficiency and power density). Engine re-optimization can be integrated with overall hybrid powertrain designs to reduce the negative impacts of cold transient operation. For example, whether a single operating point or a narrow range is preferred depends upon a complete system optimization with electrified components. *This optimization should be done with the primary goal of minimizing* CO_2 *emissions* and account for likely future states of battery technology and lower-carbon electricity grids.

Engine size can be reduced by integration into hybrid power trains, which lowers parasitic loads during transport operation. Since the electric power train would manage transient events, including high torque requests, the engine can be sized to average load instead of peak load, enabling many engine-related component efficiencies. Also, as a narrower operating range allows for greater optimization, it is reasonable to expect power density to increase, enabling a smaller engine to deliver more power. With full global electric transportation resources used in the optimization, the engine may be further reduced to the size required to extend the vehicle range (rather than to service average energy consumption) since green electricity via battery charging will provide a significant part of the overall energy.

With the clear move toward powertrain electrification, there is an opportunity for new systems solutions that leverage the potential availability of higher on-board kilowatt-hours of stored electric energy, as well as higher-voltage systems (48 V to 700 V). Several of these new system advantages are listed below:

- Electrification of air-handling components
- EATS electric thermal management
- Ability to reduce negative impact of transient operation

- Hybrid powertrain controls look-ahead to optimize engine operation (leveraging connectivity, data, automation, on-the-fly calibration optimization specific to customer/route versus one-size-fits-all)
- Engine customization for electrified applications that could be simpler and more cost-effective than engines in conventional powertrains
- Improved battery durability using the engine to reduce negative battery discharge rate conditions
- Research into impacts of a downsized engine operating at higher load factors, along with the concomitant impact on EATS, including durability and warranty effects

Beyond engine efficiency, a total system re-optimization that reduces CO_2 emissions would improve the global resource use of transportation-related materials. For example, battery utilization in the relevant applications can be improved. Since battery material supplies are limited worldwide, maximizing utilization would enable quicker large-scale fleet electrification. The battery can be sized to enable full electric operation and maximize green electricity charging for most operations. This type of optimization may lead the engine to be used only in less frequent longer drive cycles (as necessitated by the application), reducing the use of scarce low-carbon fuel resources as well.

ICE Summary

Benefits

- Co-optimizing engines to use future zero-carbon fuels provides an opportunity for significant reduction of carbon emissions in the legacy fleet with existing infrastructure.
- Pairing hybrid electric powertrains with renewable and zero-carbon fuels, whose adoption is currently limited, can expand use of such fuels considerably.
- ICEs using hydrogen fuel (and other low-carbon fuels) can take advantage of the manufacturing, labor, service, and supply chains currently employed by today's large engine business.
- ICE optimization can improve battery utilization, enabling more efficient and sustainable use of limited battery material resources.

Challenges

- Criteria pollutant regulations must still be achieved with new ICE solutions.
- High costs are associated with new engine development, new EATS solutions, and additional hybrid electric components (including batteries).

R&D Opportunities

- Innovations in engine systems can enable opportunities for efficiency in the hybrid powertrain operation.
- Projects can identify and evaluate ways to reduce EATS component sizes and costs and to provide heaters for EATS operation (necessary for both electrification and new fuels).

- There is a need for in-use methods to detect fuel properties and modify engine calibration and controls, especially in the case of biofuels.
- Innovations are needed to reconfigure engines using advanced components and controls to enable compatibility with various fuels.
- Systems using low-net-carbon fuels (e.g., hydrogen or B100) must be developed to provide diesel-like efficiency, power-density, durability, and ultra-low NOx.

Hybrid Powertrain Benefits, Challenges, and Opportunities

Defining Relevant Hybrid Powertrain Topologies

As defined by the National Academy of Sciences, Engineering, and Medicine (2020), the goal of a hybrid propulsion system is to manage energy flows most efficiently throughout the drivetrain system, thereby reducing fuel consumption and GHG emissions, by:

- Allowing the engine to be turned off during inefficient operating conditions, such as idling, and to be restarted very quickly when necessary (stop–start).
- Running the engine near the curve of highest efficiency as much as practicable.
- Following functional control strategies that supplement the engine power during periods of acceleration (launch assist), which can reduce enrichment or transient control approaches that increase fuel consumption, owing to the excellent low-speed torque characteristics of electric motors.
- Providing supplemental power and launch assist, which also offers the possibility to down-size the ICE while maintaining equal performance, so long as operational strategy maintains sufficient state of charge in the battery.
- Operating the vehicle accessories (such as air conditioning compressors or power steering pumps) independent of engine speed, which allows both vehicle operation while the engine is not running and the potential to operate the accessories at closer to peak efficiency points.
- Using batteries and drive motors to support the use of electric energy transfer, such as waste heat recovery systems or fuel cell adaptation (EPA and U.S. Department of Transportation 2016).
- Allowing a mechanism to store energy that is normally lost to heat during braking, allowing that energy to be recovered and applied during subsequent vehicle acceleration (regenerative braking).[1]

[1] The significance of regeneration becomes apparent when one considers that approximately 60% of the total energy spent in the Federal Urban Driving Schedule is used to overcome the effect of inertia and that, theoretically, up to 50% of this energy could be recovered.

As depicted below in Figure 7, hybrid powertrain configurations have various strengths and weaknesses, depending on the truck application. Opportunities and benefits for hybrid strategies vary with the architecture. For a parallel HEV, transient torque requirements are reduced, thus potentially reducing both CO_2 and criteria emissions, and additional electrified auxiliaries are enabled, which can reduce power demands and assist with emission controls. In addition, a ZEV mode is possible, and using a PHEV can greatly extend ZEV mode operation time and/or distance. A series HEV provides these benefits and others.

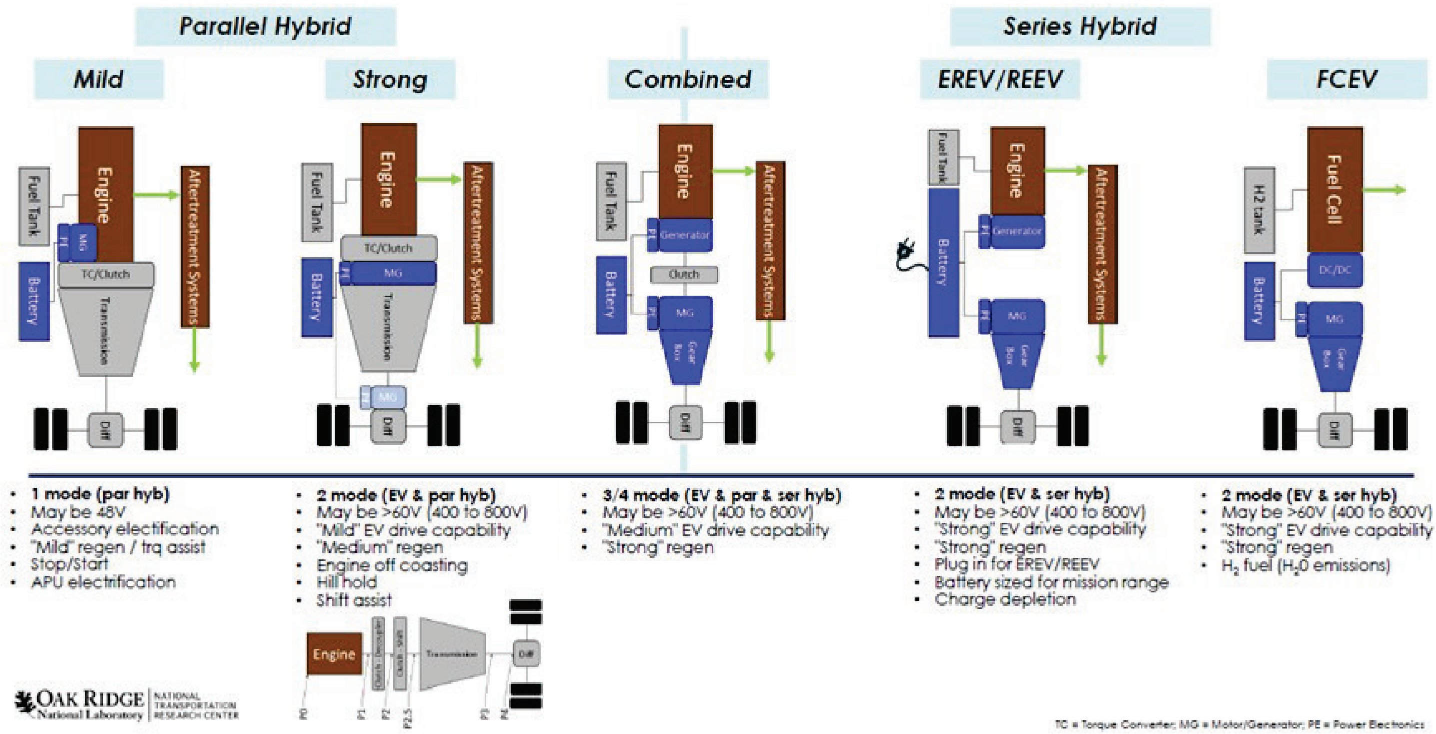

Figure 7. Hybrid Electric Architecture Categories

In addition to the topology of the hybrid system, an HEV can offer a plug-in feature (PHEV). PHEVs are an extension of HEVs with the potential to charge the battery system from the electric power grid. PHEVs were developed to allowing the vehicle to operate in electric mode without the ICE engine (at least for a time), thereby reducing local criteria pollutants (smog and health effects pollution). PHEVs also offer the potential to replace liquid fuel consumption with grid electric power, thereby reducing CO_2 and other GHG emissions.

PHEVs gain extended all-electric range with increased battery size, as determined by goals for electric operation and cost, but the technology faces challenges. The stored energy must propel vehicles that can range from 10,000 pounds (Class 2b) to 80,000 pounds (Class 8), resulting in enormous and expensive battery packs. As with all hybrid vehicles, the duty cycle has a significant impact on energy efficiency and, in the case of PHEVs, the potential all-electric range. During charge-depleting operation, the high power required to accelerate heavy vehicles can quickly deplete the battery, which then requires an extended time to recharge. Significant R&D is needed to address these challenges, and vehicle manufacturers must undertake trade-off studies to determine the optimum battery size and its associated cost when developing PHEVs (National Academy of Sciences, Engineering, and Medicine 2020).

Regardless of the hybrid powertrain configuration chosen, R&D is needed in three main technology areas to broaden and augment the potential for CO_2 reduction: ICE development, electric machines and power electronics, and zero-carbon fuel use. These areas are interdependent with respect to their use and benefits for hybrid operation.

Necessary Research

Current heavy-duty hybrid systems tend to integrate engines designed and optimized for transient performance over a broad range of speeds and loads. Research must move beyond isolated engine optimization to include total system optimization (including changes to the engine), focusing on maximizing performance and minimizing GHGs for the integrated hybrid powertrain. Research is also needed to incorporate low-net-carbon fuels (e.g., bio-derived fuels and green hydrogen) into the future engines that are optimized for the hybrid powertrain. Finally, we must develop and introduce new electric and battery components into the hybrid powertrain, which may need to be optimized differently from a full BEV.

Hybrid Powertrain Summary

Benefits

- Pairing hybrid electric powertrains with renewable and zero-carbon fuels, whose adoption is currently limited, can expand use of such fuels by 20% to 40% (as noted in the ICE Summary).
- Adoption of hybrid powertrains will reduce GHG emissions in the MHDV sector in the coming two decades.

Challenges

- Hybrid powertrains increase powertrain and electronic complexity.
- Additional components increase vehicle mass, increase costs, and can affect overall system reliability.
- Benefits may not be fully realized if the drivetrain is not optimized for the appropriate drive cycle.
- Widescale adoption is contingent on charging infrastructure deployment.

R&D Opportunities

- Battery-powered auxiliary power units must be reliable.
- On-board diagnostics and certification are needed for hybrid MHDVs.
- There is a need for optimal calibration of power management that is adaptive to hybrid and electric systems.
- Research is needed to categorize the relative advantages of PHEV and HEV trucks.

Net- and Near-Zero-Carbon Fuel Benefits, Challenges, and Opportunities

Identifying the Possibilities

Examples of fuels with near-net-zero-carbon potential include:

- Renewable diesel (drop-in fuel, in use)
- Renewable natural gas (negative carbon in some cases, in use)
- Renewable methanol (certified for heavy-duty engines in the early 1990s)
- Ethanol (in use in LDVs)
- Biodiesel (in use)
- Renewable hydrogen/ammonia
- Dimethyl ether (DME) (can be synthesized with renewables)

Some degree of engine optimization (either spark ignition or compression ignition) is warranted for best use of these fuels, but many are already in use or certified for use. Although best suited for urban driving/delivery missions, hybridization is generally a highly effective approach for GHG reduction across most MHDV classes, without the need for a new fuel infrastructure. The present certification process for GHG and fuel consumption includes features to accommodate (account for the benefits of) hybrid powertrains.

The North American Council for Freight Efficiency (NACFE) has produced several real-world studies and reports on the use of alternative fuels by fleets (2023). NACFE suggests that fleets must begin taking a comprehensive look at all the available information upon which to base adoption decisions for their future truck technology. The Council provides a technology readiness chart for powertrain alternatives (see Figure 8), which is intended to reflect the conditions for 2025 and project where each powertrain will be at that time. The chart illustrates some of the major attributes and trade-offs of various solutions. As there always are special circumstances for each option, the ranking is intended to illustrate typical or average features. Of course, as these product offerings evolve, the scaling will change. The NACFE ranking suggests that, at least in the short term, zero-carbon fuels such as renewable diesel, renewable natural gas, and green hydrogen present the most mature technology readiness options.

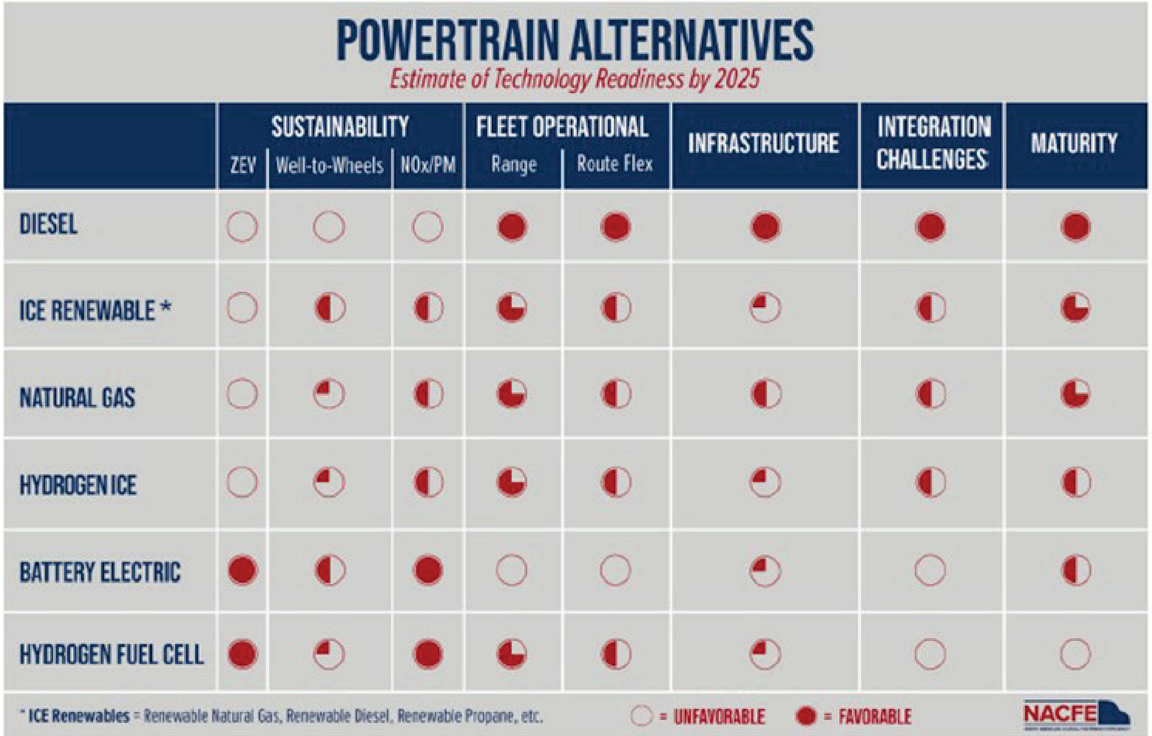

Figure 8. NACFE compares the different types of powertrains being offered and the key factors for fleets to consider when selecting power options. Source: NACFE 2023

Electrification and ICEs will co-exist in the transportation sector for a long time, requiring a new holistic approach beyond today's regulations that mandate reduced carbon intensity values for transportation fuels. A new type of vehicle/fuel carbon footprint assessment model may be required to correctly assess the GHG impacts of future fuel/vehicle systems on a new basis, such as LCA based on per mile driven, to account for contributions from both low-carbon fuels and vehicle efficiency.

E-fuels (electrofuels and similar names) have been the subject of much study, conceptualization, and experiments, but examples of production at scale are limited (so far). Although there are multiple configurations and architectures, e-fuels are all typically synthesized from a CO_2 source, a hydrogen source (usually water electrolysis), and renewable electricity. The CO_2 can be sourced from biomass or fossil products, from the atmosphere, or from any processing operation that produces CO_2. Products of e-fuel reactors are typically simple molecules such as methanol or formate that are then converted to traditional fuels by known processes. The literature on e-fuels is extensive (see Figure 9).

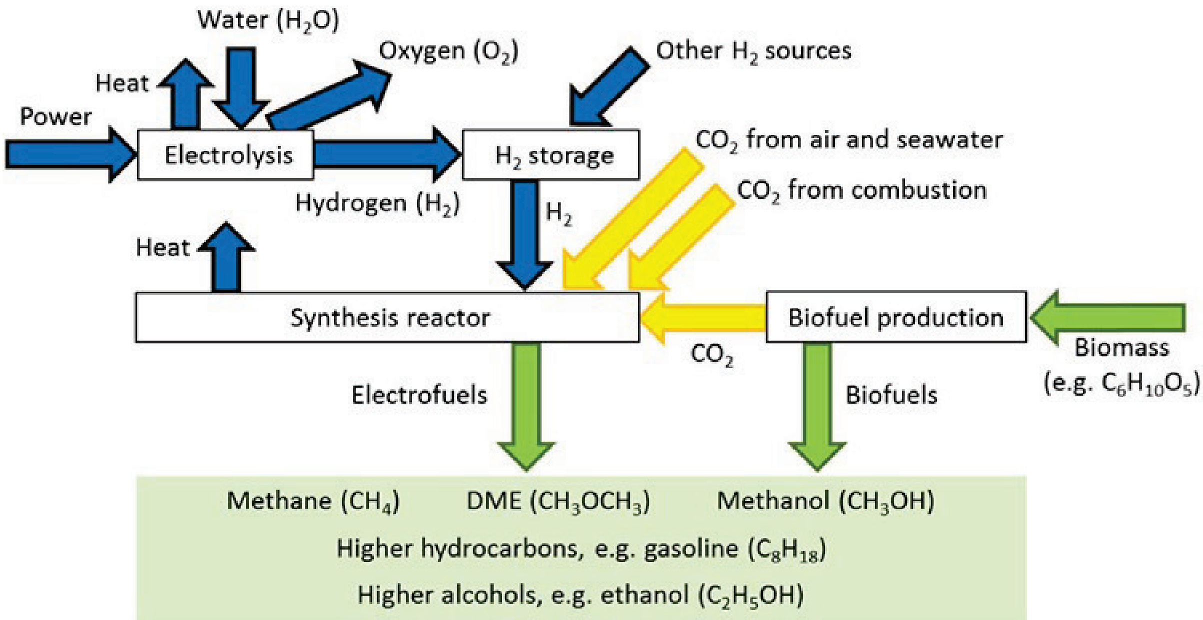

Figure 9. This graphic provides a summary illustration of e-fuels process paths with biofuels in parallel. Source: Brynolf et al. 2018

A different category of e-fuel synthesis is via electrochemical or electrocatalytic cells, also powered by renewable electricity. As simply defined, water and CO_2 are reacted in a catalytic cell with an electric charge to produce simple hydrocarbon products and fuel building blocks. A separate hydrogen input stream is typically not used. E-fuel synthesis is a thriving research area, but scale-up is in early stages (Ferrell 2021; Pei et al. 2021; Zhang et al. 2017).

Large-scale and pilot facilities for producing e-fuels are modest in numbers. Audi was largely responsible for the first e-fuels (e-methane) production plant in 2013 in Werlte, Germany (Audi n.d.), which still exists today but is reported as economically unfavorable at present (IEA Bioenergy 2021). Singh et al. listed approximately eight commercial e-fuel/chemical commercial facilities in an overview paper (2022). *The Future of Mobility*, an EPA report, also reviews e-fuels in some detail (2021). Studies have shown that e-fuels and combustion vehicles require 2–4 times the electric power per mile needed for a BEV, but the refueling infrastructure for liquid fuels is robust and fully adequate. If liquid, e-fuels can be produced in solar-rich or nuclear regions and transported globally by ocean vessels.

Recently, Porsche and partner HIF Global have started pilot operations of an e-fuel production plant in Chile and plan additional facilities in Australia and Texas (Soni 2023). The pilot process generates synthetic methanol as an intermediate that can then be converted to gasoline with well-established methods. The cost of these fuels is very high but expected to decline to less than $8/gallon by 2026 scale-up. E-fuels have combustion properties similar to fossil fuels and so do not offer an elimination of tailpipe criteria emissions.

The principal barrier to widespread deployment of e-fuels is their cost. Numerous studies are consistent on the key cost factors (Brynolf et al. 2018; Concawe and Aramco 2022): 1) the cost of the renewable electricity (by far the dominant component), 2) the capital cost of the electrolyzers, and 3) the cost of the CO_2. Overall, the studies agree that, although the costs will decline substantially over time, policy to incentivize these fuels may be necessary for economic viability. Estimates for the 2050 e-fuel cost are diverse, ranging from 0.9–1.7 Euro/liter diesel equivalent, with e-fuels expected to be slightly more costly than biofuels. The costs for e-fuels with relatively simple molecular structures—such as hydrogen, methane, methanol, and DME—are lower than for fuels with more complicated molecular structures, such as e-kerosene. Nevertheless, there are commitments to incorporate e-kerosene production for sustainable aviation fuel in Europe.

A comprehensive analysis of decarbonization strategies for Europe and the United Kingdom, recently published by FVV, incorporates e-fuels (including hydrogen) as a necessary component of achieving near-net-zero-carbon fleets by 2050 (Kramer 2022). Among the key insights is the following: "…the speed of deploying GHG-neutral mobility solutions (complete GHG-neutral technology pathways on a WTW [well-to-wheels] basis) is much more important than the choice of technologies."

Net-Zero-Carbon Fuels Summary

Benefits

- Net-zero-carbon fuels provide an opportunity for large reduction of carbon emissions in legacy fleets, using existing infrastructure. These fuels are already having GHG impacts of >100,000 BEV trucks.
- There is potential to co-optimize fuel formulation and the engine for efficiency and emissions.

Challenges

- Non-highway fuel users compete for resources (biomass and renewable electricity).
- Costs are high, especially for e-fuels.
- E-fuels must be made with renewable electricity to have overall low carbon intensity, and the grid still relies mostly on traditional sources.
- Net-zero-carbon fuels do not represent a complete solution for criteria emissions.

R&D Opportunities

- End-use (vehicle) efficiency must be improved to extend fuel supply.
- Innovations that reduce costs are needed in processing and renewable hydrogen.

Regulatory and Well-to-Wheels Emission Impacts

Regulatory Considerations

Regulations supporting clean, decarbonized transportation have historically covered three distinct areas: GHGs, criteria air pollutants (CAPs), and renewable fuel standards. GHG and CAP emissions standards are expected to be combined under the Clean Trucks Plan as the final rulemaking processes proceed. Additionally, ZEV programs combine GHG and CAP requirements by defining ZEVs as vehicles that produce zero exhaust emissions of any criteria pollutant (or precursor pollutant) under any and all possible operational modes and conditions (California Code of Regulations 2023a).

Greenhouse Gas Regulations

The first-ever regulations for GHG and fuel consumption in MHDVs were enacted in 2011, jointly by the EPA and the National Highway Traffic Safety Administration. The initial requirements to meet standards began in 2014, with separate but complementary standards for engines and whole vehicles. In this first phase of regulations, CO_2 emissions from heavy-duty long-haul tractors were reduced by 9%–23% over 2010 baselines, depending on cab style and roof height, while vocational vehicle CO_2 emissions were reduced from 6%–9%. The regulatory timeline shown below notes that, in 2016, a second phase of regulations was passed that covered vehicles out to 2027. During the Phase 2 standards beginning in model year (MY) 2021, a 15%–27% reduction in CO_2 emissions will be achieved by MY 2027 over the 2017 baseline (DieselNet n.d.). A third phase of GHG rules is currently being developed as a NPRM.

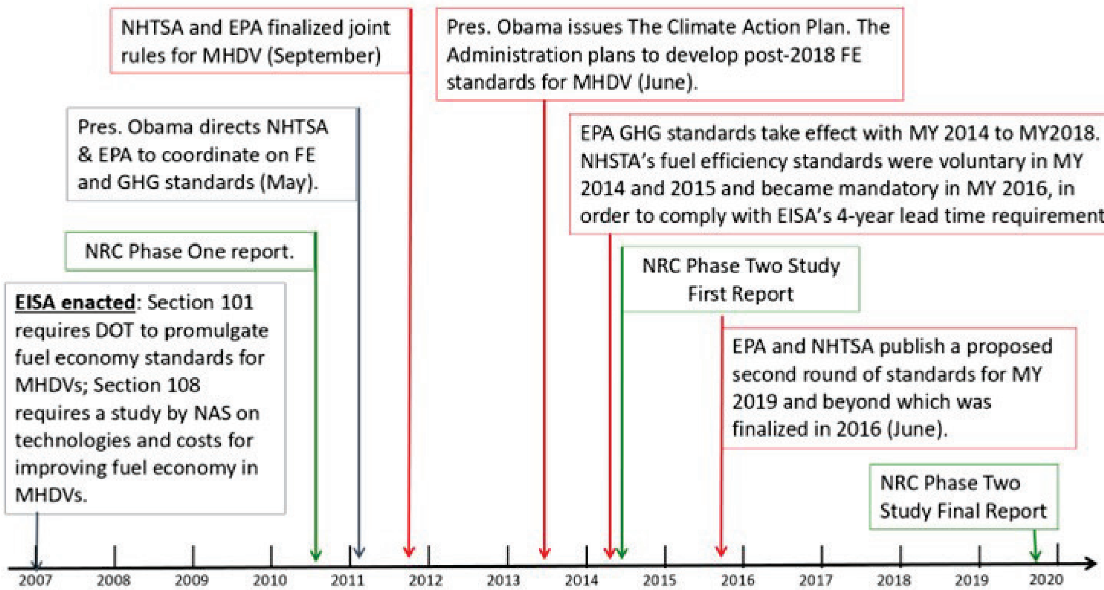

Figure 10. The regulatory timeline shows major actions from 2007 to 2020. Source: National Academy of Sciences 2020

Criteria Emissions

Regulated Tailpipe Emissions

Although reducing life cycle GHG emissions is a central focus of the national Blueprint, reducing or eliminating other pollutant emissions is of equal importance. As the Blueprint states, "...no one should be exposed to air pollution in their community or on their ride to school or work…" The Partnership has included strong objectives for environmental stewardship since its inception. Given the high percentage use of diesel engines for freight trucks, the CAPs of primary concern remain NOx and particular matter (PM). Historically, 21CTP has adopted goals for CAPs that are the same as the prevailing regulatory levels. Given that the EPA regulations have been only for tailpipe (or tank-to-wheel) emissions instead of life cycle or WTW emissions, 21CTP had similarly focused on engine tailpipe emissions up until recently. However, most technologies and fuels choices have considerable upstream, or well-to-tank, contributions with impacts on GHG and CAP emissions. This realization has drawn attention to life cycle emissions and motivated life cycle analyses. In addition to the well-to-tank emissions associated with the fuel cycle, significant emissions associated with vehicle manufacturing must be considered.

Since 21CTP was established, NOx and PM tailpipe emissions have been reduced by over 90% in commercial engine products. These accomplishments required strong cooperation and collaboration between industry and government, as well as key technical achievements in combustion, fuels, and emission controls (catalytic aftertreatment). Continued environmental and societal needs have recently led the EPA to revise the emission standards for engines in 2027 and beyond to produce 82.5% lower NOx with longer lifetime and improved low-temperature performance (EPA 2023a). For specific reference, we note the current NOx standard of 200 mg/hp-h and the new 2027 standard of 35 mg/hp-h for diesel-fueled engines (measured over a specified test cycle). Another key feature of the new 2027 regulations is the extension of the full-useful-life requirement from 435,000 miles to 650,000 miles in most applications.

With respect to ultimate low-NOx feasibility, the Cummins heavy-duty natural gas engine is certified at 20 mg/hp-h, and experimental systems have achieved even lower in laboratory configurations (Singh et al. 2021). Drop-in low-carbon diesel fuels (e.g., renewable diesel) are expected to have emissions potential similar to petroleum diesel, but the lower sulfur may extend the EATS lifetime. Low-carbon spark-ignition fuels other than renewable natural gas include methanol, hydrogen, and synthetic gasolines. Their NOx-reduction potentials are similar to those of renewable natural gas.

Hybrid powertrains are discussed elsewhere in this roadmap, but we note here that hybridization enables part-time zero tailpipe emissions for combustion-powered vehicles.

Well-to-Wheels Criteria Emissions

Progress in electric vehicle batteries in the last ten years has suggested strong economic viability for electric vehicle freight movement in some MHDV classes (NACFE 2022). As noted above, electric vehicles have no tailpipe emissions, but there are considerable upstream emissions for generating electricity and in the manufacturing and disposal of key components such as batteries. Hence, it is appropriate to use WTW analysis when comparing ICE vehicles to electric vehicles as complementary paths to reduce GHG emissions. However, such analyses for MHDV vehicles are sparse, and here we rely for guidance on a paper from Argonne National Laboratory, in which Lui et al. use a suite of analysis and simulation tools to examine both CAP and GHG emissions from ICE and electric trucks on a WTW basis for the fuel cycle (2021). The study does not include GHG emissions associated with manufacturing, and the use of regional grid-averaged CAP and GHG emissions likely underestimates the real-world emissions significantly, but the results do provide directional guidance—particularly with respect to the emissions rates across vehicle classes. Figure 5 of this reference (and Figure 11 below) summarizes the key findings for CAPs:

- NOx, carbon monoxide, and volatile organic compound emissions from long-haul trucks are considerably higher than vocational or short-haul applications. BEVs can be expected to produce lower WTW emissions, although the amount will depend strongly on the power mix in use at the time of charging.

- Across vehicle classes, PM emissions from BEVs were generally higher by 9%–109% because the grid remains heavily fossil-fueled.
- For similar reasons, sulfur oxides from BEVs were found to be substantially higher.

In this study, the NOx production by ICE trucks was taken from the MOVES model and data and hence represents a broad spectrum of vehicles (EPA n.d.b). The new regulations will require ~82.5% NOx reduction compared to regulations that have been in place for the last decade. The distinct NOx advantage for BEVs does depend on the progress made reducing fossil fuels in the grid.

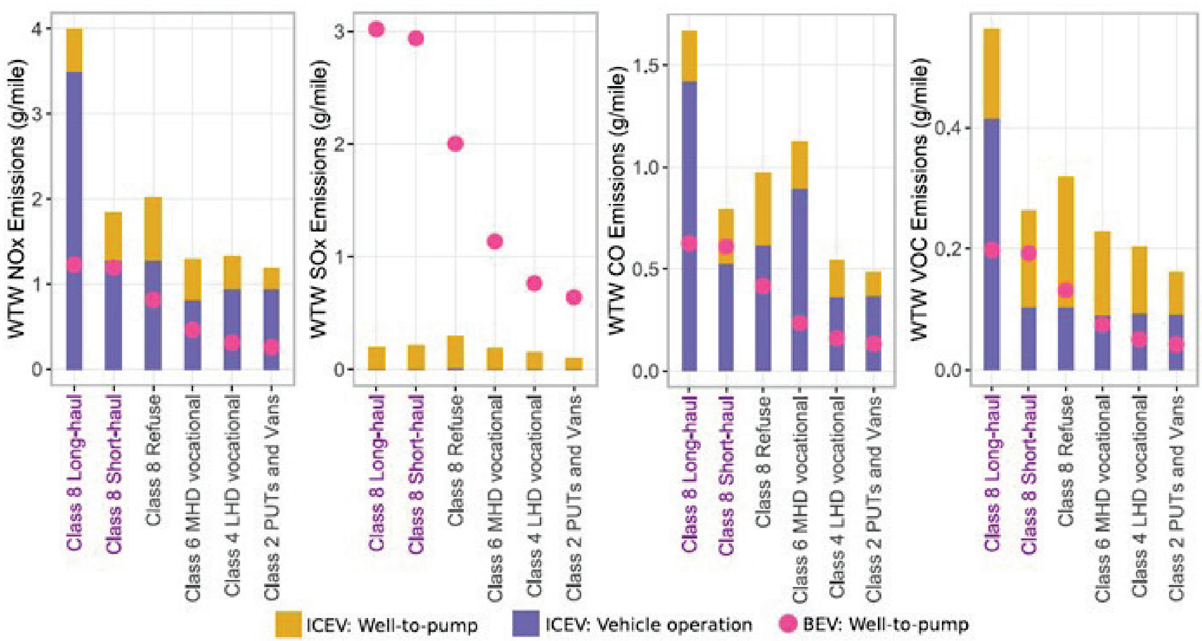

Figure 11. Figure 5 of the Liu et al. 2021 study (above) shows WTW CAP emissions using the 2019 U.S. electricity generation grid mix (g/mile). For each panel, the purple-colored labels represent nonvocational vehicles, while the black-colored labels represent vocational vehicles.

ZEV Mandates

In addition to the GHG and CAP regulations summarized above, in 2020 California adopted ZEV sales requirements for truck manufacturers as a part of the Advanced Clean Truck (ACT) Regulation. Under the ACT Regulation, ZEV sales requirements are phased in such that, by 2045, 100% of new truck sales in California will be ZEVs. From 2030 to 2035, there is an allowance for plug-in hybrid vehicles with a minimum electric range of 75 miles, considered “near-ZEVs.” Governments of Massachusetts, New Jersey, New York, Oregon, and Washington have adopted this regulation. There is currently a Advanced Clean Fleets proposal for drayage truck operations that requires all manufacturers to exclusively sell zero emission MHDV’s beginning in 2036, and California Executive Order N-79-20 requires that strategies be developed for 100% of non-road vehicles and equipment sales be ZEV by 2035 (Executive Department of the State of California 2020).

Notably, there is no allowance in the MHDV ZEV mandates for credits for H_2-ICE-powered vehicles such as in California's initial Advanced Clean Cars regulation (California Code of Regulations 2023b). The Advanced Clean Cars II regulation, applicable to LDVs from model year 2026 onward, likewise omits credits for H_2-ICEs (California Code of Regulations 2022). In contrast, current European regulations define ZEVs to "include battery electric vehicles, fuel-cell and other hydrogen powered vehicles"—presumably refering to vehicles with H_2-ICE powerplants (Council of the European Parliament 2023).

Renewable Fuels Incentives

The U.S. Renewable Fuel Standard (RFS) was established by the Energy Policy Act of 2005 and was modified to RFS2 under the Energy Independence and Security Act of 2007. To qualify as a renewable fuel under the RFS program, fuels must be produced from renewable biomass and meet statutory GHG emissions reduction threshold requirements in four fuel groups, as compared to a 2005 baseline (i.e., GHG reduction thresholds). The threshold requirements are 20% lower carbon intensity for fuels categorized as "Renewable Fuel," 50% lower for "Advanced Biofuels" and "Biomass-Based Diesel Fuel," and 60% lower for "Cellulosic Fuels." The required GHG reductions are assessed on a life cycle basis, "including direct emissions and significant indirect emissions such as emissions from land use changes" (EPA 2021).

The EPA Mobile Sources Technical Review Committee produced a figure titled "Life Cycle Greenhouse Gas Emissions by Feedstock and Fuel Type" (see Appendix C of this document), which shows that several renewable fuels have the potential for a 50% reduction in life cycle GHG emissions as compared to baseline diesel. Ethanol, cellulosic diesel, and bio-diesel all possess this potential, but the market volume required for Class 8 vehicles cannot match today's diesel consumption. This is one of the benefits of hybrid vehicle electrification within hard-to-electrify applications: the ability to extend the use of near-/net-zero liquid fuels that have a limited supply compared to the needs of the entire market.

The 21CTP Perspective

The 21CTP has never set targets for GHG emissions; instead, the Partnership selects targets for engine efficiency that can be easily expressed as g-CO_2 per hp-h, as current regulations are written. Recent certification data for engines, along with GHG standards, were converted to efficiency to enable comparison with historical trends and previous targets for peak efficiency adopted in 21CTP (Appendix B). Even with continuous progress in engine efficiency, shifting to alternative fuels with reduced carbon and with net-zero WTW carbon is clearly essential for the necessary large reductions in GHG at the engine. Net-zero fuel use is being accomplished already, with annual use of approximately 3 billion diesel-gallons-equivalent of renewable diesel and renewable natural gas. Incentives for real CO_2 reduction via net-zero fuels are hindered by federal regulatory practices that remain focused only on tailpipe emissions. In contrast, California's Low Carbon Fuel Standard is based on life cycle emissions. Studies by the National Academies and others have recommended adoption of regulations based on WTW emissions (National Academy of Sciences, Engineering, and Medicine 2020).

Technoeconomic Studies

Compare Hybrid ICE Powertrains to Other Future Solutions

In Figure 12 below, the capital cost of the technology is compared to the value of the fuel savings. Along with TCO, one of the most used economic measures in the industry is the simple payback period. This is the capital cost divided by annual fuel savings, at an assumed fuel price. Truck manufacturers and purchasers use the payback period as a heuristic for the value of new technology. The payback period captures, in a rough approximation, the cost of capital and the uncertainty associated with the adoption of new technologies. These uncertainties include the benefits of the new technology under real-world duty cycles, volatility in fuel prices, unanticipated maintenance costs, etc. Fleets generally look for 1.5- to 2-year paybacks on baseline diesel equipment or, in other cases, for a payback period that is half the expected ownership period of the vehicle's first owner. For Class 2b pickups, the payback periods are calculated using the gasoline price projected for 2027 ($2.88 per gallon) by the U.S. Department of Energy in its 2017 Annual Energy Outlook (U.S. Energy Information Administration 2017). For the other vehicle classes, the payback periods are calculated using the forecast for the diesel fuel price of $3.52 per gallon.

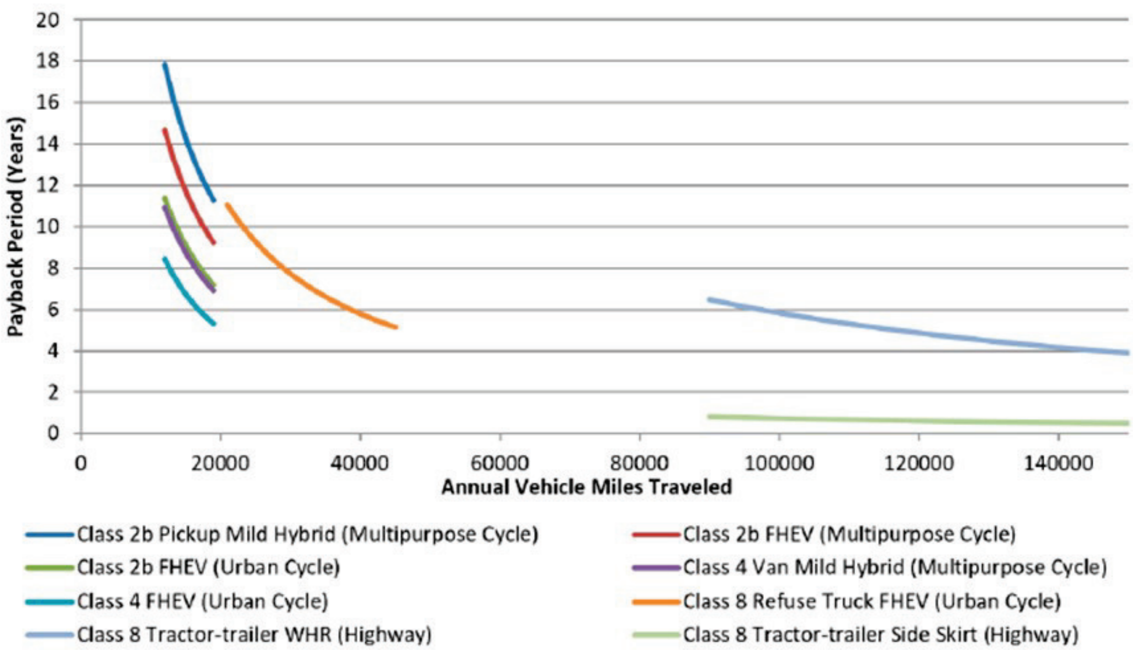

Figure 12. Payback Period is sensitive to vehicle miles traveled for hybrid technology. Source: National Academy of Sciences, Engineering, and Medicine 2020

It becomes apparent from the calculation that several full hybrid applications provide a beneficial payback period: Class 8 tractor using side skirts, Class 8 refuse, and Class 4 urban delivery trucks. In fact, the National Academy of Sciences recommends that since hybrid technologies could play an increasing role in achieving reductions in fuel consumption in the post-2027 period, developments in the cost and efficiency of these technologies should be monitored and be included in a formal interim review of fuel consumption standards (2020).

In their latest roadmap document, the 21CTP Electrification Technical Team has chosen levelized cost of driving (LCOD) as the metric to compare the various powertrains (21CTP 2023). LCOD is a simpler approach than TCO but still works well to compare powertrain technologies. LCOD is made up of two main components, one representing the vehicle cost and one representing the energy cost. Other costs, such as maintenance cost, driver cost, insurance cost, financing cost, and other operating costs, are not considered. The calculation discounts future costs over the ownership period of the vehicle and calculates a resale value at the end of the ownership period. LCOD is expressed in dollars per mile and is based on:

- Vehicle purchase price
- Vehicle resale value
- Yearly mileage
- Ownership period
- Price of energy used

For both the 2030 and 2040 timeframes, the LCODs for the hybrid electric Class 8 regional-haul tractor and the BEV are equivalent (see Figure 13). For the Class 6 box truck, the HEV LCOD compares well with the BEV in 2030 and is only slightly more expensive than the BEV in 2040.

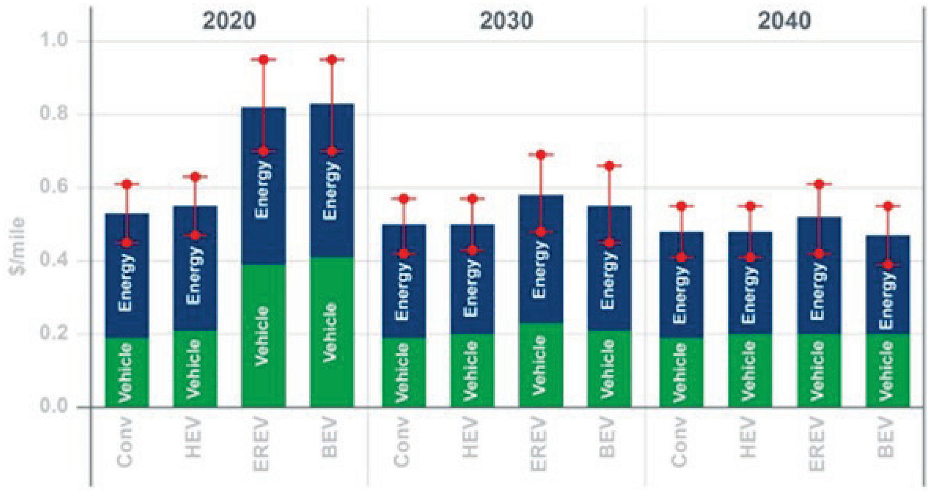

Figure LCOD values for Class 8 regional haul tractor

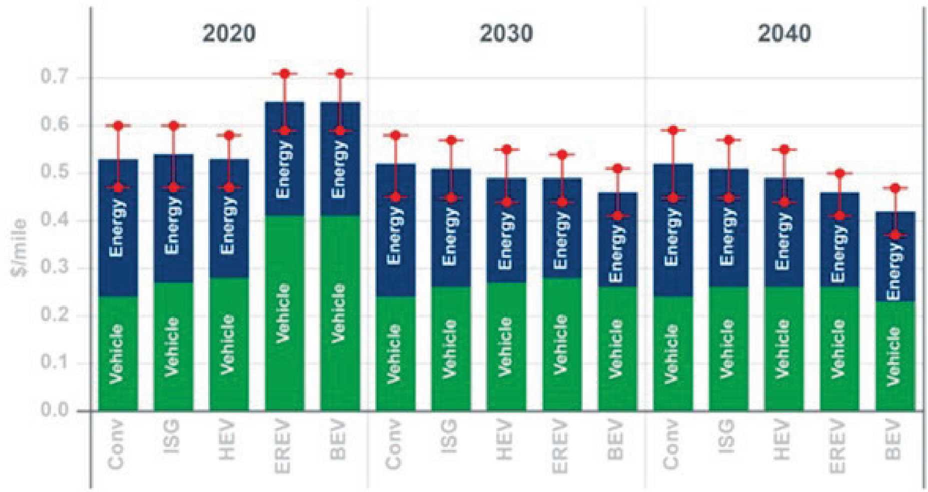

Figure LCOD values for Class 6 box truck

Figure 13. LCOD values for Class 8 and Class 6 vehicles. Source: 21CTP 2023.

The figures above use the following abbreviations/acronyms:

- CONV – Conventional
- ISG – Integrated starter generator (or mild hybrid)
- HEV – Hybrid electric vehicle (not a plug-in)
- EREV – Extended-range electric vehicle
- BEV – Battery electric vehicle

The takeaway from these technoeconomic studies is that, for some vocations, an HEV can be a cost-effective powertrain solution that contributes to decarbonization—delivering a faster and greater impact than waiting for the electric and/or hydrogen infrastructure to be completed (while eliminating range anxiety).

It should be noted that in neither analysis have the ICE or the electric hybrid components been optimized for any vocation. During the 2022 Vehicle Technologies Office Annual Merit Review presentation on the SuperTruck II project, PACCAR Inc. listed a 13% improvement in powertrain efficiency by hybridizing and electrifying some of the components (Meijer 2022). Additional research could reduce the LCOD for fleets using HEVs, thereby improving the adoption rate for this technology and delivering further GHG reductions.

Lastly, HEVs can be operated on net-/near-zero carbon fuels. Therefore, when a vocation is hard-to-electrify or located in a remote area without electric grid infrastructure for ZEVs, HEVs offer a powertrain solution that can have a significant impact on decarbonizing both the transportation system and non-road vocations, assuming that fuel supply tanks are provided.

Conclusion

Government-funded research is needed to develop advanced ICEs that work in hybrid powertrains and with net-zero carbon fuels.

Today, there is no national infrastructure to support medium- or heavy-duty BEVs or FCEVs. A renewable fuel/hybrid strategy will accelerate GHG emissions reduction while the national infrastructure for MHDVs is being developed and deployed. This approach is the most promising short- and mid-term solution to decarbonizing the transportation sector. Hybrid vehicles can also facilitate the long-term solutions by supplying a bridge for automotive suppliers to deliver a secure and robust supply chain of electric vehicle components during the transition to ZEVs. In other words, hybridization accelerates CO_2 emission reductions with reduced reliance on infrastructure buildout while ensuring stable supply chains.

The hybrid strategy could also maximize decarbonization impacts for many non-road vocations (construction, agriculture, and mining). A secondary benefit will be mutual development opportunities for hybrid powertrains between on-road trucks and certain segments of non-road vehicles. When beneficial, these opportunities should be recognized and promoted.

In addition, a government-supported, robust hybrid strategy for MHDV applications will result in a competitive hybrid powertrain payback period. Without a change in emissions regulation, most fleets will not change powertrain technologies until the payback period for the new technology is equal to or better than the current powertrain technology. For many vocations, BEVs and FCEVs have high TCOs that are not expected to match the conventional powertrain TCO until 2035. Hybrid powertrains could provide these vocations with cost-effective solutions through 2035, with impacts on decarbonization that would not otherwise be realized in that time.

In addition, adapting ICEs to net-zero-carbon fuels would optimize their use. An HEV with good fuel economy will reduce the consumption of these fuels, which are in limited supply, extending their benefits.

The U.S. DRIVE Net-Zero Fuels Tech Team is focusing on renewable diesel production through carbon atom efficiency at the process level. The ICETST should help by defining what duty cycles/truck segments can use renewable diesel in the most efficient way. This work will create efficiencies for both fuel stock and battery material consumption. (For example, a truck that runs 100 miles per day for 8 days but 500 miles per day on Days 9 and 10 could be an EREV, so it could use a smaller battery than a typical long-haul truck.) Rapid CO_2 reductions will require an initial focus on diesel-like drop-in fuels (renewable and biodiesel), but research into adapting engines to accommodate new fuels (e.g., hydrogen) will help ensure future compatibility. Perhaps the U.S. Department of Energy could consider launching a SuperTruck IV, focused on the use of net-zero carbon fuels and their compatibility with ICEs combined with electric MHDVs.

Driven by GHG emissions regulations, medium- and heavy-duty vehicles have become increasingly fuel-efficient over the last decade. A recent analysis, conducted by the International Council on Clean Transportation, identified the potential for further efficiency improvements beyond 2027, the last model year of the Phase 2 emission standards, and out to 2035 (Buysse, Sharpe, and Delgado 2021). The analysis focused on two representative vehicle segments, a Class 8 high-roof sleeper cab and a Class 6–7 multipurpose vocational vehicle. Two relevant conclusions regarding ICE improvements and hybrid powertrain inclusion were the following:

- Engine efficiency improvements deliver the largest efficiency benefits for both vehicle segments (12% CO_2 reduction—see Appendix D).
- The full potential of tractor–trailer technologies could further reduce ton-per-mile CO_2 emissions to 34% below the Phase 2 standard. The technologies include a mild hybrid powertrain that delivers a CO_2 reduction of 9%.

> *We have impressive technologies at our disposal, yet there are still many commercial transportation applications that face major roadblocks to electrification. Economic viability, mission accomplishment, and infrastructure support are the key factors behind these hard-to-electrify applications. One school of thought is to wait for battery–electric or fuel cell electric technologies to catch up to these applications, but we simply cannot afford to release more carbon emissions every day that we cannot take back. Every gram of carbon emitted will contribute to climate change. In the U.S. alone, medium- and heavy-duty trucks emit over one million metric tons of CO_2 every single day. For these hard-to-electrify commercial transportation applications, there are options available today to significantly reduce or fully eliminate carbon emissions: low- to zero-carbon fuels.*
>
> – Skrikanth Padmanabhan, Vice President and President, Engine Segment, Cummins

If we can assume that a form of electric hybridization is to be included with ICE development operating on a net-zero-carbon fuel, then a wide variety of potential solutions exist. Noting the three components of the technology roadmap (ICE, electric, and zero-carbon fuel), hybrid vehicles are possible with a variety of combinations for BEV/hydrogen electrification, low- to zero-carbon fuels, and fuel-agnostic engines. Any improvement in engine/vehicle efficiency may help offset the cost and limited current availability of net-zero fuels.

Below are the significant benefits that could be realized through ICE R&D of optimized hybrid powertrains and net-zero fuels for decarbonization and future criteria emissions:

- Realize greater near-term benefits through the use of net-zero carbon fuels for CO_2 reductions
- Reduce lifecycle CO_2 emissions for extended-range operation
- Provide geographical flexibility as ZEV infrastructure develops
- Transition smoothly to a supplier base in electrified component technologies
- Accelerate improvements in non-road, agriculture, marine, and rail engines

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Appendix A. Terminology and Acronyms

21CTP	21st Century Truck Partnership
ACT	Advanced Clean Truck (Regulation)
BEV	Battery Electric Vehicle
CAP	Criteria Air Pollutant
CO2	Carbon Dioxide
EATS	Exhaust After-Treatment System
EPA	U.S. Environmental Protection Agency
EREV	Extended-Range Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
g	Gram(s)
GHG	Greenhouse Gas
H2-ICE	Hydrogen-Fueled Internal Combustion Engine
HEV	Hybrid Electric Vehicle
hp	Horsepower
hr	Hour
IC	Internal Combustion
ICE	Internal Combustion Engine
ICETST	Internal Combustion Engine Tech Sector Team
LCOD	Levelized Cost of Driving
LDV	Light-Duty Vehicle
MHDV	Medium- and Heavy-Duty Vehicle
MY	Model Year
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
R&D	Research and Development
RFS	Renewable Fuel Standard
TCO	Total Cost of Ownership
V	Volt(s)
WTW	Well-to-Wheels
ZEV	Zero-Emissions Vehicle

Appendix B. Criteria Emission Regulations

The latest federal criteria air pollutant regulation for heavy-duty engines and vehicles went into effect in March 2023 and reduces NOx emissions to 35 mg/hp-h, effective in 2027. Particulate emissions are also halved from current regulations to 5 mg/hp-h. The NOx standards are less stringent than those developed in California under the Heavy-Duty Omnibus Regulation, which sets NOx emission limits to 50 mg/hp-h, effective in 2024, and 20 mg/hp-h, effective in 2027. Particulate emissions standards match the federal regulation. The California regulation also has a more stringent accelerated durability test requirement of 800,000 miles.

Current federal regulations are much less restrictive for heavy-duty non-road vehicles than for on-road vehicles, with NOx emissions for engines between 75–750 hp capped at 300 mg/hp-h and particulate emissions at 15 mg/hp-h. Discussions are underway to define a new California "Tier 5" standard, but this would be of limited imapct unless matched by the federal regulations, since California non-road regulatory authority is limited to engines over 175 hp.

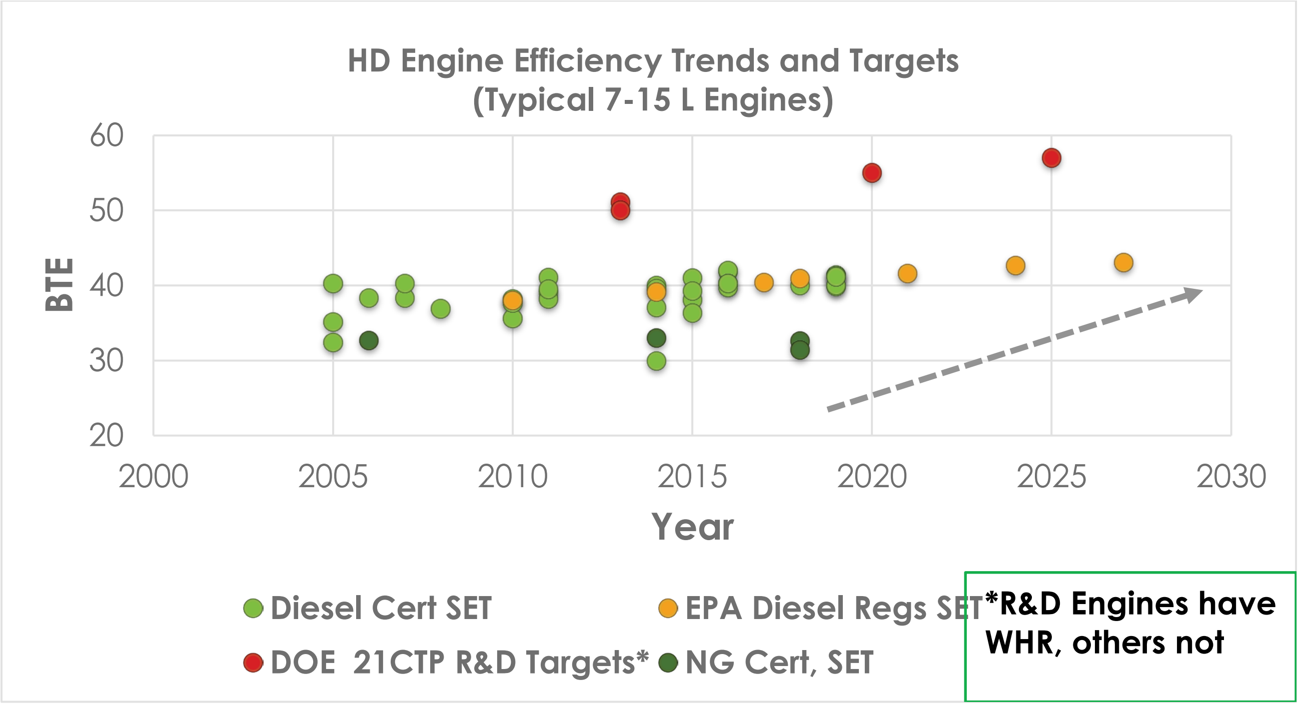

Figure B-1. HD Engine Efficiency Trends and Targets. Source: Graves 2021

Appendix C. Life Cycle Greenhouse Gas Emissions by Feedstock and Fuel Type

The graphic below shows carbon intensity values for various fuel pathways.

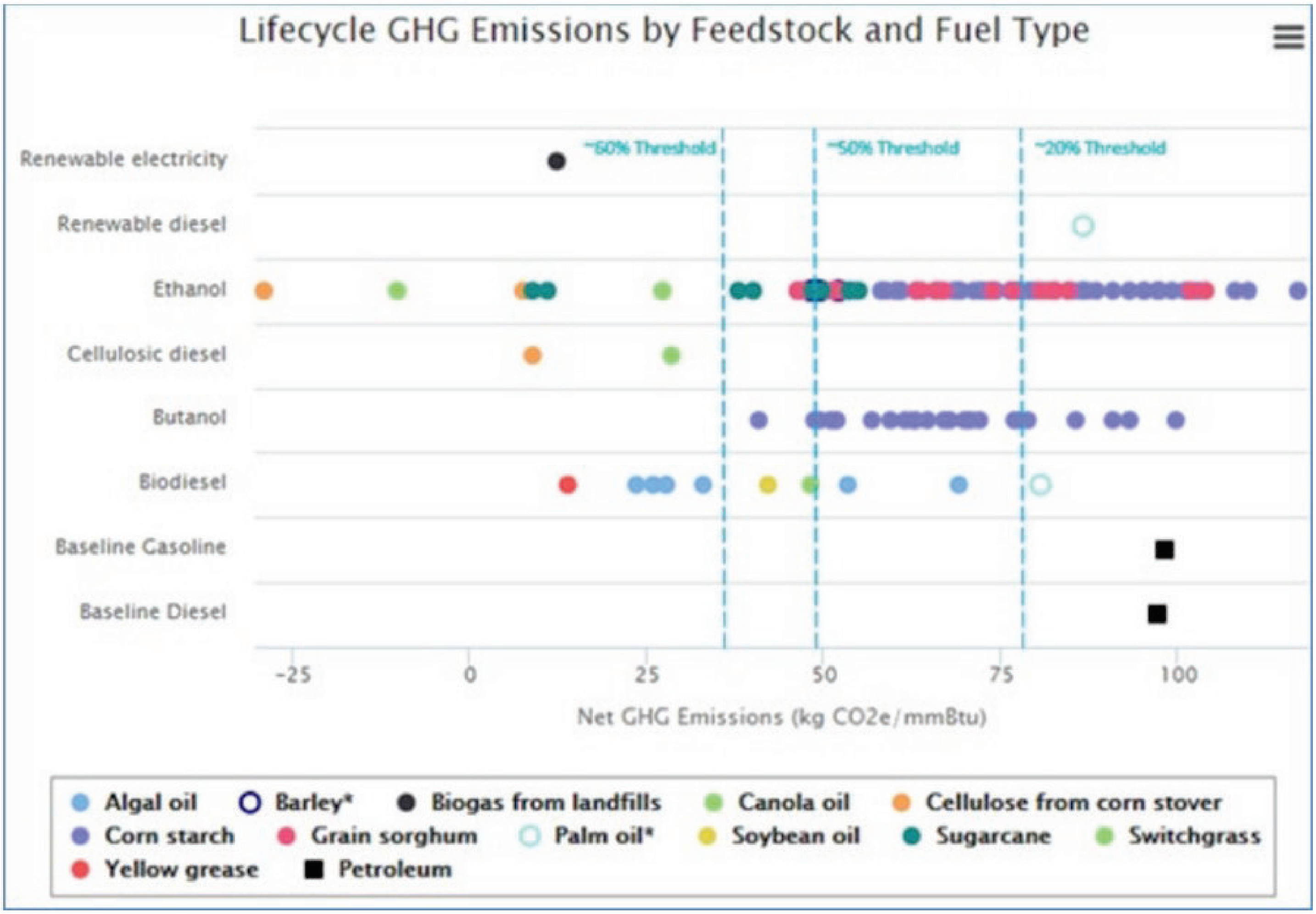

Figure C-1. Lifecycle GHG Emissions by Feedstock and Fuel Type. Source: Hoekman 2020 (citing Aaron Levy of the EPA, October 2019)

Appendix D. Vehicle and Component Assumptions used to Model MHDVs

Table D-1. Key Engine and Vehicle Characteristics

	Long/Regional Haul			Class 6 Truck			Class 4 Step Van		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
Engine peak efficiency (%)				44	48	50	44	48	50
Engine peak efficiency (%) – long haul	48.6	55	57						
Engine peak efficiency (%) – regional haul	48.6	51	53.4						
Motor peak efficiency (%)	94	96	96	94	96	96	94	96	96
Inverter peak efficiency (%)	97	98	98	97	98	98	97	98	98
Usable pack energy density (Wh/kg)	158	273	350	158	273	350	158	273	350
Coefficient of drag				0.63	0.55	0.55	0.7	0.65	0.65
Coefficient of drag – conv, ISG, HEV, EREV long haul*	0.52	0.42	0.39						
Coefficient of drag – regional haul	0.58	0.50	0.50						
Tire rolling resistance (ton/kg)	5.37	4.9	4.7	5.85	5.58	5.4	5.85	5.58	5.4
Auxiliary load (kW)	3.4	2.6	2	2.5	2.5	2.5	1.5	1.5	1.5
Cargo weight (lbs)	38,000	38,000	38,000	11,200	11,200	11,200	5,700	5,700	5,700
Ownership period (years)	5 / 15	5 / 15	5 / 15	15	15	15	15	15	15
Annual mileage	100,000/ 50,000	100,000/ 50,000	100,000/ 50,000	22,000	22,000	22,000	22,000	22,000	22,000

Vehicle Requirements

Vehicle-level requirements for a Class 8 long-haul tractor, Class 8 regional-haul tractor, Class 6 box truck, and Class 4 step van are listed in Table D-2.

Table D-2. High-Level Requirements for Several Vocations

Vehicle level requirements	Class 8 Long Haul	Class 8 Regional Haul	Class 6 Box Truck	Class 4 Step van
Speed at 6% grade	> 30 mph	> 30 mph	> 45 mph	> 40 mph
Grade at 65 mph	1.25%	1.25%		
Grade at 60 mph			1.50%	1.50%
0-60 mph acceleration	80 sec	80 sec	40 sec	35 sec
0-30 mph acceleration	20 sec	20 sec	14 sec	9 sec
Startability	15%	15%	20%	20%

Representative cycles for each of these four vocations, based on Fleet DNA real-world data, were used to model energy consumption and conduct battery sizing studies (National Renewable Energy Laboratory n.d.).

The tables above are from the draft 21CTP Electrification Technical Team roadmap, due to be published in 2023.

Appendix E. Hybrid Truck Fuel Economy Potential Per Class

A variety of hybrid vehicle potential fuel consumption reductions relative to technology, collected by Oak Ridge National Laboratory via literature search (Kaul 2022).

Table E-1. Hybrid Truck Fuel Economy Potential Per Class

Vehicle Class	Hybrid Type	Vehicle Use	Duty Cycle	Approx. FC Reduction (%)
Class 2B-3	12V Start/Stop Belt-Starter-Generator (BSG)	Heavy-duty pickup and van	Urban + Highway	3.5%
Class 2B-3	Integrated S/S with regen/launch assist (48V)	Heavy-duty pickup and van	Urban + Highway	10%
Class 2B-3	Parallel Strong Hybrid	Heavy-duty pickup and van	Urban + Highway	20%
Class 4-5	12V Start/Stop Belt-Starter-Generator (BSG)	Vocational Vehicles	Urban + Highway	3.5%
Class 4-5	Integrated S/S with regen/launch assist	Vocational Vehicles	Urban + Highway	16%
Class 4-5	Parallel Strong Hybrid	Vocational Vehicles	Urban + Highway	20%
Class 4-5	12V Start/Stop Belt-Starter-Generator (BSG)	Delivery Trucks	Urban Delivery	3.5%
Class 4-5	Integrated S/S with regen/launch assist	Delivery Trucks	Urban Delivery	20%
Class 4-5	Parallel Strong Hybrid	Delivery Trucks	Urban Delivery	25%
Class 6-7	12V Start/Stop Belt-Starter-Generator (BSG)	Vocational Vehicles	Urban + Highway	3.5%
Class 6-7	Integrated S/S with regen/launch assist	Vocational Vehicles	Urban + Highway	16%
Class 6-7	Parallel Strong Hybrid	Vocational Vehicles	Urban + Highway	20%
Class 6-7	12V Start/Stop Belt-Starter-Generator (BSG)	Delivery Trucks	Urban Delivery	3.5%
Class 6-7	Integrated S/S with regen/launch assist	Delivery Trucks	Urban Delivery	20%
Class 6-7	Parallel Strong Hybrid	Delivery Trucks	Urban Delivery	25%
Class 8	12V Start/Stop Belt-Starter-Generator (BSG)	Vocational Refuse Truck	Urban Accel/Brake	3.5%
Class 8	Integrated S/S with regen/launch assist	Vocational Refuse Truck	Urban Accel/Brake	22%
Class 8	Parallel Strong Hybrid	Vocational Refuse Truck	Urban Accel/Brake	30%

Appendix F. Truck Emissions Summary Chart

	LHDD / MHDD / HHDD* CARB 24-26MY Requirement	LHDD / MHDD / HHDD* CARB 27MY- 30MY Requirement	LHDD / MHDD / HHDD* CARB 31MY Requirement
Criteria Emissions			
HDFTP and SET NOx (g/hp-hr)	0.050	0.020 / 0.035 at 600k FUL	0.035 at 800k FUL
HDFTP and SET NMHC (g/hp-hr)	0.14	0.14	No change
HDFTP and SET CO (g/hp-hr)	15.5	15.5	No change
LLC NOx (g/hp-hr)	0.20	0.050 / 0.090 at 600k FUL	0.090 at 800k FUL
LLC NMHC (g/hp-hr)	0.14	0.14	No change
LLC CO (g/hp-hr)	15.5	15.5	No change
Idling NOx (g/hr)	10 / 30	5	No change
HDFTP and SET PM (mg/hp-hr)	5	5	No change
FULL USEFUL LIFE (miles/years/hrs.)			
LHDD (Class 2b-5)	110k / 10	190k / 12 / n/a	270k / 15 / n/a
MHDD (Class 6-7)	185k / 10	270k / 11 / n/a	350k / 12 / n/a
HHDD (Class 8)	435k / 10 / 22000	600k / 11 / 30000	800k / 12 / 40000
HEAVY DUTY IN USE TESTING and Conformity Factor	CF = 2.0 No cold start, No avg pwr < 10% 3 Bins - Idle, Low load and Med/Hi load	CF = 2.0 (2029 MY); CF = 1.5 (2030 MY); Cold start incl., No avg pwr clips 3 Bins - Idle, Low load and Med/Hi load	CF = 1.5 Cold start incl., No avg pwr clips 3 Bins - Idle, Low load and Med/Hi load

	EPA Pre-MY 2027	EPA 27MY and Later
Criteria Emissions		
HDFTP and SET NOx (g/hp-hr)	0.20	0.035
HDFTP and SET NMHC (g/hp-hr)	0.14	0.060
HDFTP and SET CO (g/hp-hr)	15.5	6.0
LLC NOx (g/hp-hr)	N/A	0.050
LLC NMHC (g/hp-hr)	N/A	0.140
LLC CO (g/hp-hr)	N/A	6.0
Idling NOx (g/hr)	30	10
HDFTP and SET PM (mg/hp-hr)	10	5
FULL USEFUL LIFE (miles/years/hrs.)		
Light HDE	110k / 10 / n/a	270k / 15 / 13,000
Medium HDE	185k / 10 / n/a	350k / 12 / 17,000
Heavy HDE	435k / 10 / 22000	650k / 11 / 32000
HEAVY DUTY IN USE TESTING and Conformity Factor	NTE = 1.5	Bin 1 (Idle): CF = 1.0 Bin 2 (Low/medium/high); CF = 1.5 Bin 1 adjustment: 0.25 * (25 - Tamb) Bin 2 adjustment: 2.2 * (25 - Tamb)

	EPA 2024-2026	EPA 2027 and Later
HDFTP ENGINE LEVEL CO2 Emissions (g/hp-hr)		
LHDD (Class 2b-5)	555	552
MHDD (Class 6-7)	538	535
HHDD (Class 8)	506	503
SET ENGINE LEVEL CO2 Emissions (g/hp-hr)		
LHDD (Class 2b-5)	n/a	n/a
MHDD (Class 6-7)	461	457
HHDD (Class 8)	436	432
GEM VEHICLE LEVEL CO2 Emissions Class 2b-5 (g/ton-mile)	**2024-2026**	**2027 Phase 2 GHG**
Multi-purpose	344	330
Regional	296	291
Urban	385	367
GEM VEHICLE LEVEL CO2 Emissions Class 6-7 (g/ton-mile)		
Multi-purpose	246	235
Regional	221	218
Urban	271	258
GEM VEHICLE LEVEL CO2 Emissions Class 8 (g/ton-mile)		
Multi-purpose	242	230
Regional	194	189
Urban	283	269

Appendix G. ICETST Issues for Roadmap 2.0

Renewable Liquid Fuels

"Investigate possible volumes of zero carbon liquid fuel production."

The work to date is based on the Billion Ton study of bio-feedstock done some time ago. But that study was based on a particular biomass cost per ton threshold. I'm not aware that this threshold was ever revisited. I suspect the volume versus cost is extremely nonlinear. There is likely much more biomass available at incrementally higher cost. I think this could be useful to understand considering much of the push back on liquid fuels for highway applications in based on available feedstock. I think the feedstock availability is not nearly as well understood as it should be.

On the forecasts of biofuel availability, a recent summary of the studies under "Billion Ton" analyses was presented at SAE Gov-Industry in Jan 23. Author says ok to cite. Estimates show total 62 billion gallons biofuel possible. Enough for "hard to electrify sectors" but not coverage of all MHDV (improved efficiency may not have been fully accounted for.

Should Canada and Mexico renewable markets also be added to availability?

Phase 3 Emission Impact

Determine the impact of the phase 3 emission standard (expected to be passed by end of 2023).

Figure 5 Analysis

Perform a more complete analysis of figure 5 in this current roadmap. Define assumptions and determine the potential of renewable fuel and hybrid technology solutions on carbon reduction through 2040.

Highlight W2W analysis

Discuss the impacts and develop a thorough understanding of W2W analysis on technology and fuel choices.