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MECA Comments on the Progression of Net-Zero Emission Propulsion Technologies for the Off-Road Sector Request for Information (RFI)

June 07, 2024

MECA is pleased to provide comments regarding the U.S. DOE's request for information (RFI) on the Progression of Net-Zero Emission Propulsion Technologies for the Off-Road Sector.

We believe important opportunities exist to reduce near, mid and long-term GHG emissions from the off-road sector employing a variety of lower carbon, near-zero and net-zero carbon technologies which will provide greater clarity on the net-zero timeline. It is critically important for off-road equipment manufacturers, clean mobility suppliers and equipment users that a variety of strategies are developed which will provide more adequate lead times, flexibility and certainty during the decarbonization transition towards the net-zero goal.

MECA Background

MECA is a non-profit association of the world's leading manufacturers of technologies for clean mobility. Our members have over 50 years of experience and a proven track record in developing and manufacturing emission control, engine efficiency and electric propulsion technologies for a wide variety of on-road and off-road vehicles and equipment in all world markets.

Our industry has played an important role in the emissions success story associated with light- and heavy-duty vehicles and off-road equipment in the United States, and has continually supported efforts to develop innovative, technology advancing, emission reduction programs to deal with environmental problems.

MECA members represent over 70,000 of the nearly 300,000 North American jobs building the clean mobility technologies that improve the fuel economy, reduce emissions and transition on-road and non-road vehicles to net-zero tailpipe emissions. These jobs are in nearly every state in the United States – the top 10 states being Michigan, Texas, Illinois, Virginia, New York, Indiana, North Carolina, Ohio, Pennsylvania, and South Carolina. A diversified set of decarbonization strategies will provide greater certainty to technology suppliers and their OEM customers who continue to invest billions of dollars each year in developing the technologies toward decarbonization goals.

SUMMARY

- MECA strongly supports the need to reduce CO_2 emissions from the off-road sector by setting technology neutral, performance-based targets for cumulative near-, mid- and longer-term CO_2 reductions through the penetration of a variety of lower carbon, near-zero and net-zero carbon technologies to address the inherent diversity of the U.S. off-road sector.
- DOE should establish and fund technology development and demonstration programs equivalent to the SuperTruck program for key off-road sectors to better define more immediate lower carbon targets and the horizon to net-zero timelines for these sectors.
- Infrastructure planning, deployment and quality assurance are vital to off-road sector user acceptance.
- DOE should work with the U.S. EPA and other agencies towards an ambitious national off-road decarbonization program.

Current State of the Off-Road Fleet

The off-road equipment fleet is truly diverse with a vast number of equipment types, model variants, tool attachments and uses. Despite the diversity of equipment types and the significantly lower production volumes, the most common attribute is diesel engine powertrains which have the potential for further development and which can be combined with lower carbon, near-zero and net-zero carbon fuels. Technologies from advanced heavy-duty highway engines can be readily carried over and there is the potential for electrification of many equipment types and especially for site specific captive fleets located at ports, railyards, airports, etc.

The Challenge of High Utilization and Intermittent Use

Many off-road equipment types can face periods of high utilization, varied utilization or intermittent storage. These diverse utilization rates pose challenges for electric batteries which are longest lived in applications with continuous charge cycling.

Consideration is needed for either battery swapping or vehicle to grid (V2G) deployment for equipment with low intermittent use or storage periods. V2G applications can be used for local / on-site power management or grid stabilization.

Many off-road equipment types can experience continuous or periodic high utilization at a variety of sites. Line-haul locomotives are an example of continuous high use, whereas construction equipment is frequently moved from location to location and requires solutions for charging infrastructure which can be moved from site to site. Agricultural equipment used in field preparation, seeding, and harvesting can also experience high and periodic continuous usage at specific times of the year followed by periods of storage.

The Rebuilding of Off-Road Equipment

MECA would advise DOE to consider the long equipment lifespans and the prevalence of periodic off-road equipment rebuilds. The rebuilding process offers an opportunity to gain significant incremental GHG and other emissions reductions from high-use common equipment types such as cargo handling, construction, generator-sets and locomotives. Furthermore, rebuilding a powertrain to a lower carbon or net-zero carbon level removes a dirtier piece of equipment from the in-use fleet by upgrading it at a potentially lower cost than scrapping and replacement. It may also offer the opportunity for strategic incentivized equipment retirement and scrappage at these rebuild periods prior to significant rebuilding investment which would see the equipment life extended.

The Benefit of International Standards

Given the global nature of the off-road market, MECA supports international harmonization of standards wherever available and possible. An example of such standards are battery state-of-health (SOH) monitors and usable battery energy (UBE) measurement requirements as per UNECE GTR No. 22b that include vehicle miles traveled and power take-off (PTO) equivalent miles traveled. The UNECE is expected to finalize GTR No.22b for heavy-duty on-road trucks in 2025 and once completed DOE and EPA should consider an active role in the development of equivalent off-road battery durability standards. MECA also believes that mandated battery labeling requirements will facilitate in-use equipment service and end-of-life recycling.

The Challenge of Infrastructure Planning

The prioritization and building of forward-looking charging infrastructures is also critical to the penetration of net-zero emission technologies. For this reason, we believe that DOE should work with other agencies, like EPA and the Joint Office on Energy and Transportation, in funding charger and infrastructure technology development and demonstration and setting minimum charger efficiency standards to ensure that infrastructure funds are spent on chargers with the best utilization of electric power and capabilities that support off-road equipment operations.

While overnight charging at lower power may be appropriate for certain applications and fleets on a regimented schedule, we recommend the DOE prioritize the assessment of battery swapping and the planning and building of direct current fast chargers (DCFC). Both battery swapping and DCFCs are likely indispensable to allow in-service electric vehicles to address unforeseen day-to-day vehicle use variables which are common in the off-road sector. The development and demonstration of battery swapping and or portable DCFCs can address equipment becoming inoperable and stranded due to these changing in-use variables, allowing equipment to be rapidly charged and quickly returned to service to maximize equipment utilization.

Battery swapping and DCFCs should also allow for bidirectional charging strategies which futureproof infrastructure investment further by providing support for increasing electricity demand. Vehicle-to-Grid (“V2G”) technology can help address energy use and manage peak demand times and costs, as well as serve as backup power during an outage. V2G capabilities are also important as many equipment applications are periodic in nature, where equipment can sit for extended periods of time in storage. V2G addresses grid stabilization but also serves to cycle equipment batteries while unused or in storage maintaining their optimal long-term health.

MECA also recommends that DOE consider national certification, such as UL Certification, for infrastructure supply equipment to provide consistency, quality, safety, efficiency and compliance. A Certificate of Compliance will mean the product has passed a series of rigorous tests to demonstrate performance, safety, quality, and serviceability, while enhancing sustainability, strengthening security, and managing risk. National certification also supports local permitting efficiency, therefore, helps fast track deployment of charging stations.

For these reasons, MECA urges DOE to work with other government agencies and industry to develop national standards for minimum charger efficiency which will ensure the efficient energy utilization and lowest operating cost for electric equipment. With regards to technology, several suppliers of vehicle power electronics are applying similar electric efficiency technology innovation to the development of more efficient chargers to minimize switching losses and deliver maximum power to the battery. This is important to fleets as charging losses increase their operating cost and it is important to the environment because these loses represent electricity that is generated but never used. The difference in electric efficiency between the first generation of chargers, that are deployed in the field today, and the advanced second generation chargers can be as much as 10-20%. This becomes significant given the magnitude of battery energy in conventional vehicles.

Future BEV/FCEV Powertrain Efficiency Standards

Today, vehicle manufacturers are deploying the first generation of electric and fuel cell commercial vehicles. On the other hand, suppliers are already looking ahead and developing the next generation of advanced efficient batteries, power electronics, transmissions, e-motors and integrated drive units. Technology innovation has strived for greater efficiency and power for the past 50 years of combustion engines and similarly, electric component suppliers continue to innovate electric technology.

Some of these innovations will be revealed in the funded projects under the DOE's SuperTruck III program and can be carried over to the off-road sector. As such, it is important that DOE begins to consider the development of corresponding off-road specific technology development and demonstration programs which will spur accelerated development in the off-road sector.

Powertrain Technologies are the Most Promising for Off-Road Decarbonization

MECA supports the need to reduce near, mid and longer-term CO_2 emissions from the off-road sector through the development and implementation of technology neutral, performance-based strategies. These strategies should aim to progressively decarbonize existing and future off-road equipment, as well as meet the diverse needs of end users. It is our position that the developed strategies should be robust and incorporate a variety of fuel, engine and equipment powertrain technologies.

Several engine, powertrain, propulsion and fuel technologies continue to evolve and should be considered in DOE's analyses for the off-road sector. These include a wide-array of internal combustion engine technologies, such as cylinder deactivation, advanced driven turbochargers, hybrid powertrains, vehicle electrification and hydrogen internal combustion engines.

MECA members have been engaged in developing a large portfolio of technology options that can be employed to optimize the lowest GHG emissions. However, technology commercialization has a long development cycle, including design, testing, integration and real-world deployment across the many off-road applications in the field to make sure systems are reliable and durable. This long cycle time is why consistent long-term policies and funding are a critical signal to industry to make investments and to foster the increased collaboration between equipment manufacturers and technology suppliers that will be needed in the future.

The penetration of fuel-saving technologies into the heavy-duty highway fleet has been spurred by U.S. EPA's Heavy-Duty Greenhouse Gas Phase 1 through 3 Standards. At the same time, research undertaken by multiple teams as part of the Department of Energy's SuperTruck programs has demonstrated how technologies can be combined to achieve further boosts in efficiency. Participants in the SuperTruck II program have demonstrated even greater gains in fuel and freight efficiency, with engines achieving 55% brake thermal efficiency using technologies like waste heat recovery. Last year DOE awarded five OEMs funding to develop electric powertrains in SuperTruck III. DOE should initiate equivalent technology development and demonstration programs targeting prioritized off-road equipment markets.

Available GHG Reducing Technologies

The portfolio of technology options available to reduce GHG emissions from heavy-duty trucks and engines is continually growing in response to effective regulation. A review of U.S. EPA heavy-duty engine certifications from 2002 to 2023 shows that once targets are finalized, industry will respond with the deployment of new technologies. Several HD highway truck engines certified since 2010 have shown the ability to meet future Phase 2 GHG regulation limits for vocational engines that go into effect in 2021, 2024 and 2027 as well as achieve 0.1 g/bhp-hr or lower NOx emissions over the composite FTP certification cycle, which is 50% below the current standard. This example highlights that setting stringent targets for CO_2 emissions has resulted in engineers expanding their toolbox from the engine to the powertrain to enable further engine efficiency improvements.

It is our position that many of these developments can be readily carried over to the off-road sector. Engine efficiency technologies – such as cylinder deactivation, advanced driven turbochargers, and hybridization – have also been demonstrated in combination with advanced aftertreatment technologies on heavy-duty diesel engines. Testing has shown that available aftertreatment systems allow these engine technologies to be optimized to reduce GHG emissions while still meeting the future NOx and PM limits finalized by EPA and CARB.

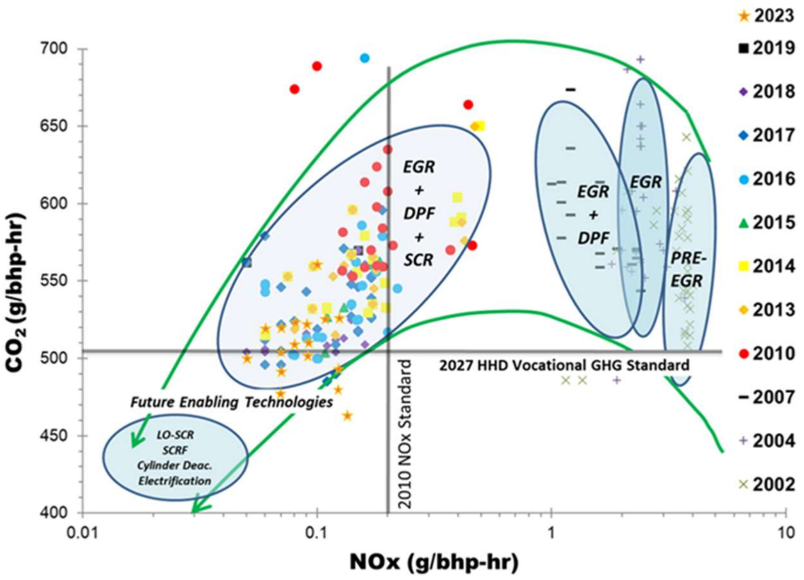

Figure 1. Model Year 2002-2023 Heavy-Duty Engine Certification Test Data for NOx and CO_2.

Cylinder Deactivation

Cylinder deactivation (CDA) is an established technology on light-duty vehicles, with the primary objective of reducing fuel consumption and CO_2 emissions. This technology combines hardware and software computing power to, in effect, "shut down" some of an engine's cylinders, based on the power demand, and keep the effective cylinder load in the more efficient portions of the engine map reducing fuel consumption. Based on decades of experience with CDA on passenger cars and trucks, CDA is now being adapted to heavy-duty diesel engines. On a diesel engine, CDA is programmed to operate differently than on gasoline engines, with the goal of the diesel engine running hotter in low load situations by having the pistons that are firing do more work. This programming is particularly important for vehicles that spend a lot of time in creep and idle operation modes. During low load operation, the use of CDA results in exhaust temperatures increasing by 50°C to 100°C to maintain effective conversion of NOx in the SCR [1] while reducing CO2 emissions. In some demonstrations, CDA has been combined with a 48V mild hybrid motor with launch and sailing capability to extend the range of CDA operation over the engine, and this may deliver multiplicative CO_2 reductions from these synergistic technologies [2,3]. In another study, CDA combined with an electric heater or fuel burner has been shown to reduce NOx as well as CO_2 to levels below the capabilities of each technology individually [4]. CDA has also been synergistically combined with high efficiency turbochargers, and an electrically driven EGR pump to yield an additional 1.7 to 3.6% reduction in CO_2 [5].

Advanced Turbochargers

Advances in turbochargers are providing a variety of available design options enabling lower CO_2 emissions by improving thermal management capability, such as: i) state of the art aerodynamics, ii) electrically actuated wastegates that allow exhaust gases to by-pass the turbocharger to increase the temperature in the aftertreatment, and iii) advanced ball bearings to improve transient boost response. More advanced turbochargers are designed with a variable nozzle that adjusts with exhaust flow to provide more control of intake pressure and optimization of the air-to-fuel ratio for improved performance (e.g., improved torque at lower speeds) and fuel economy. These variable geometry turbochargers (VGT), also known as variable nozzle turbines (VNT) and variable turbine geometry (VTG), also enable lower CO_2 emissions through improved thermal management capability to enhance aftertreatment light-off. Finally, modern turbochargers have enabled engine and vehicle manufacturers the ability to downsize engines, resulting in fuel savings without sacrificing power and/or performance.

Turbo-compounding

Turbo-compounding is a variant of turbocharger technology that allows for the energy from the exhaust gas to be extracted and mechanically added to the engine crankshaft. Alternatively, waste exhaust energy can also be extracted by using an electric turbine to recover the waste exhaust energy electrically (see *Driven Turbochargers*) and used to increase primary turbocharger response and efficiency or to power other electric vehicle systems.

Mechanical turbo-compounding has been employed on some commercial diesel engines to reduce fuel consumption, and EPA estimated penetration to reach 10% in the U.S. by the time the Phase 2 GHG Regulation is fully implemented in 2027 [6]. An early 2014 version of a turbo-compound-equipped engine was used during the first stage of testing at SwRI under the CARB HD Low NOx Test Program, and the results from this engine with advanced aftertreatment have been summarized in several SAE technical papers [7, 8, 9].

Driven turbochargers

Driven turbochargers can be used to control the speed of the turbomachinery independently of the engine’s exhaust flow and vary the relative ratio between engine speed and turbo speed. Driven turbochargers may be utilized for several reasons, including performance, efficiency, and emissions. Considered an ‘on-demand’ air device, a driven turbocharger also receives transient power from its turbine. During transient operation, a driven turbocharger will behave like a supercharger and consume mechanical or electrical energy to accelerate the turbomachinery for improved engine response. At high-speed operation, the driven turbocharger will return mechanical or electrical power to the engine in the form of turbo-compounding, which recovers excess exhaust power to improve efficiency [10]. This cumulative effect lets a driven turbocharger perform all the functions of a supercharger, turbocharger, and turbo-compounder.

Electrification: Mild Hybridization

In the near future, 48-volt mild hybrid electrical systems and components are expected to make their way onto medium and heavy-duty vehicles and off-road equipment. These 48-volt systems can be found today on many light- duty vehicle models primarily in Europe. In the U.S., FCA is offering a 48-volt system on the RAM 1500 pick-up and the Jeep Wrangler under the eTorque trademark. Because the safe voltage threshold is 60 volts, which is especially important when technicians perform maintenance on the electrical system, 48-volt systems are advantageous from an implementation standpoint. From a cost perspective, 48-volt systems include smaller starter and wire gauge requirements, offering cost savings from a high voltage architecture of a full hybrid. The U.S. Department of Energy's SuperTruck II program teams employed 48-volt technologies on their vehicles to demonstrate trucks with greater than 55% brake thermal efficiency.

Similar to the passenger car fleet, truck OEMs are considering converting mechanically driven components with electrically driven versions to gain efficiency. Converting electrical accessories from 12-volts to 48-volts reduces electrical losses and this is particularly advantageous for components that draw more power, such as pumps and fans. The types of components that may be electrified include electric turbos, electronic EGR pumps, AC compressors, electrically heated catalysts, electric cooling fans, oil pumps and coolant pumps, among others. Another technology that 48-volt systems could enable is electric power take-offs rather than using an engine powered auxiliary power unit or idling the main engine during hoteling while drivers rest. MECA members supplying commercial 48V components for commercial vehicles believe that the technology may be feasible to apply to a limited number of engine families by 2024, and it is likely to see greater penetration by 2027, especially on Class 8 line-haul where full hybridization is less practical.

Stop/start deployment also reduces fuel consumption and provides a thermal management benefit to diesel aftertreatment by preventing cooling airflow during idle conditions. In this way, 48-volt mild hybridization is complementary technology to CDA and start-stop capability, allowing the combination of multiple technologies on a vehicle to yield synergistic benefits to reduce CO_2 while recovering the energy for these systems [11, 12].

In lighter medium-duty applications, advanced start-stop systems have been developed that use an induction motor in a 48-volt belt-driven starter-generator (BSG). When the engine is running, the motor, acting as a generator, will charge a separate battery. When the engine needs to be started, the motor then applies its torque via the accessory belt and cranks the engine instead of using the starter motor. The separate battery can also be recharged via a regenerative braking or other energy recovery systems. In addition to the start-stop function, a BSG system can enhance fuel economy by delivering a short power boost to the drivetrain. This boost is typically 10 to 20 kW and is limited by the capacity of the 48V battery and accessory belt linking the motor to the crankshaft. New designs are linking the BSG directly to the crankshaft and allowing additional power boost of up to 30kW to be delivered, giving greater benefits [2].

Electrification: Full hybridization and electric vehicles

Full hybrid configurations are currently found on a growing number of models of light-duty passenger cars and light trucks in the U.S. and a limited number of medium-duty trucks and urban buses. These include models that can also be plugged-in (PHEVs) to enable electric operation for a determined "all- electric" range (AER). A full hybrid (HEV) can enable enhanced electrification of many of the components described above for mild hybrid vehicles as the higher voltages allow for more parts to be electrified and to a larger degree. Full hybrids also employ larger electric motors and batteries, which support greater acceleration capability and regenerative braking power. Full hybrid and plug-in hybrid vehicles have made the highest penetration into vocational applications such as parcel delivery, beverage delivery and food distribution vehicles because they can take advantage of regenerative braking in urban driving [13] and operate from a central location. Model predictions of HD HEV 600-800V technology recently verified at Oak Ridge National Laboratory [14] have shown that GHG emissions reductions of 9% on tractor certification cycles and 13%-19% on the vocational cycles, while enabling both anti-idle and hoteling function.

We expect to see the increasing application of strong / parallel and serial hybrids to reduce CO_2 emissions in several off-road applications. Integrated electric drivetrain systems, consisting of a fully qualified transmission, motor and power electronics controller, are now commercially available. With power levels of over 160kW and the ability to meet high torque requirements, these systems enable electrification. There is also an increasing number of electric drivetrain solutions up to and over 300kW that are suitable for Class 8 vehicles that can be used with either hybrid [15], battery or fuel cell power sources [2] and could be readily carried over to off-road equipment.

MECA members are commercializing components for electric and hydrogen fuel cell vehicles. This includes battery materials for the manufacture of both cathode and anodes utilizing unique macrostructure and composite formulations to improve efficiency and energy density. Electric component manufacturers are using state of the art transistor materials in their motors and power electronics that operate at higher voltages and require simpler cooling strategies to again reduce switching losses and improve electric efficiency of the system architecture in electric powertrains. To facilitate integration, component suppliers are integrating the motor, inverter and transmission into electric drive units to simplify the thermal management of the electric components and ease design into vehicles.

To drive future U.S. technology leadership, DOE should recognize the need to include life cycle analysis as part of their net-zero strategy development. This is particularly relevant to heavy-duty vehicles and off-road equipment because of the magnitude of their power demand, battery size and charging time. Efficiency regulations have historically driven manufacturers and technology suppliers to continue to innovate and develop better materials, components, and vehicle systems to reduce energy demand, operating costs and related emissions of vehicles. By assigning realistic "non-zero" emission values to electric and fuel cell power off-road equipment types, DOE will provide a regulatory incentive to further improve the electric efficiency of components and powertrain technologies that will further reduce vehicle related environmental impacts.

Hydrogen-Fueled Internal Combustion Engines

Another promising technology that is being commercialized to reduce the carbon footprint of heavy-duty engines is the hydrogen internal combustion engine (H_2ICE). These engines, when coupled with advanced NOx aftertreatment, have demonstrated their ability to attain near-zero carbon tailpipe emissions as well as meet the MY 2027 HD highway low NOx limits when operated on renewable green hydrogen. There is broad industry support for internal combustion engines fueled with clean hydrogen and most engine manufacturers and component suppliers are conducting significant development work and testing with ongoing on-road and off-road demonstrations in Europe and North America. H_2ICEs are attractive options for equipment applications where challenges exist in applying current electric or hydrogen fuel cell technology.

One of the main benefits of H_2ICE is their lower upfront capital costs due to the leveraging of existing investments in manufacturing capacity in engines, emission controls and powertrain as well as vehicle servicing. H_2ICE vehicles share many components with today's diesel and natural gas-powered vehicle fleet, including the base engine, installation parts, powertrain components and aftertreatment system architectures. Furthermore, H_2ICE can borrow technology from currently available natural gas engines, such as cylinder heads, ignition systems, fuel injection, turbochargers, cooled exhaust gas recirculation (EGR), and engine control unit/software, among others. Nearly all on-road and off-road engine OEMs, along with their suppliers, are developing H_2ICE for commercial introduction in the MY 2026-2027 timeframe.

H2ICE engines are also well suited to dusty and high vibration conditions typical of many off-road equipment uses and which presently represent a serious challenge to the deployment of fuel cells. H2ICE engines can also tolerate hydrogen impurities that also pose challenge to fuel cells.

Suppliers of on-vehicle hydrogen storage tanks are looking at this H_2ICE transition technology to grow the manufacturing capacity for 350 bar and 700 bar high pressure hydrogen tanks and bring down their costs. This will accelerate the introduction of fuel cell systems that will rely on the same high pressure fuel tanks and hydrogen infrastructure that they will share with H_2ICE powered engines. Manufacturers are targeting the introduction of H_2ICE trucks at least 10 years before fuel cells will become cost competitive. The early introduction of H_2ICE will help to accelerate the build-out of the hydrogen infrastructure and allow fleets to seamlessly transition from H_2ICE to fuel cells in the future. These benefits apply to both on and off-road sectors.

These technologies represent only a few of the potential pathways available to OEMs to reduce CO_2 from commercial engines and equipment types. It is MECA's recommendation that DOE include analyses of potential net-zero pathways beyond only battery electric or fuel cell powertrains, to include improvements in engine and powertrain efficiency and incorporate them into a robust decarbonization program.

Off-Road Sector Transition to Net-Zero Emission GHG Technologies

An accurate prediction of the penetration of net-zero carbon technologies in the off-road sector remains difficult at this time. There are many factors that will impact net-zero technology uptake, including infrastructure readiness, grid resiliency and critical material availability for batteries and transformers and the broad range of equipment types, uses and user needs.

MECA strongly believes that DOE should rather set targets for cumulative GHG reductions and that a range of lower carbon, near-zero and net-zero carbon fuels and powertrain strategies should be assessed to support this goal while defining a pathway to a net-zero horizon.

MECA strongly advises that DOE's immediate action should be the development of off-road specific equivalents to the SuperTruck program for various off-road sectors such as transportation logistics, construction, rail, etc. It is also imperative that such demonstrations be technology neutral and performance-based which will promote the penetration of a variety of lower carbon, near-zero and net- zero carbon technologies to address the inherent diversity of the U.S. off-road sector.

MECA believes that such demonstrations are paramount to support DOE's longer-term net-zero goal.

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