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August 17, 2026
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COMMENTS OF THE MANUFACTURERS OF EMISSION CONTROLS ASSOCIATION ON THE CALIFORNIA AIR RESOURCES BOARD SECOND LIGHT-DUTY DRIVE FORWARD WORKSHOP

The Manufacturers of Emission Controls Association (MECA) appreciates the opportunity to provide comments on the Drive Forward workshop held on June 22, 2026. MECA believes an important opportunity still exists for performance-based LEV and ZEV standards to continue to cost effectively reduce NOx, VOCs and PM from vehicles through the application of a diversity of cost-effective technologies on advanced internal combustion engines and electrified powertrain systems.

MECA appreciates the time and effort that CARB staff put into the Drive Forward regulatory process and workshop. We thank CARB staff for their dedication in receiving and incorporating feedback from a broad range of stakeholders. Below are our recommendations on specific provisions presented during the Light-Duty Drive Forward workshop. We look forward to continuing to discuss our suggestions with agency staff as you work to finalize this regulation.

Light-Duty Low Emission Vehicles (LEV) Program

- MECA supports an ICE-only NMOG+NOx fleet average of 20 mg/mile is readily attainable by vehicles with internal combustion engines by 2038. MECA believes that setting a more stringent ICE vehicle fleet average for criteria pollutants will incentivize further combustion powertrain emissions reductions regardless of the EV sales rate. Furthermore, as sales of EVs increase, an ICE vehicle fleet average will provide a backstop that ensures engine-equipped vehicles continue to meet stringent technology-enabled standards.

  MECA's industry assessment of the costs to reduce a Bin 30 vehicle to a Bin 15 vehicle by making upgrades to the three-way catalytic converter is approximately $50-$100. MECA members that specialize in exhaust emissions and engine controls continue to confirm that Bin 10 certification programs are currently being explored and will be attainable by the implementation dates.

Previous research has demonstrated that hybrid vehicles that employ electrically heated catalyst systems (EHCs) are one potential candidate for Bin 10.

Currently, many vehicles are emitting at levels with significant margins below the bins to which they are certified. For MY 2026 vehicles, 83 Vehicle Test Groups consisting of 212 vehicle models are certified to Bin 30 with NMOG+NOx certification levels ≤15 mg/mile. An even larger number have significant margins of 30-60% below the Bin 30 limit indicating these vehicles are excellent candidates for certification to bins 25, 20 and 15 with little or no further improvement. A variety of these MY2026 vehicles are shown in Figure 1 below. At least one automaker has already certified MY 2026 vehicles to Bin 25 without any additional technology.

Given that the LEV 4 extends to 2038, CARB should also include Bin 15 and Bin 10 compliance options in its Drive Forward proposal to incentivize future emissions reduction technology refinements and broader technology diversity. In addition, MECA believes that CARB should also include Bins at higher levels in increments of 5 mg/mile to align with the higher bins included in federal Tier 4 bin structure.

Besides upgrades to catalyst and substrate technologies that comprise a three-way catalytic converter, OEMs can reduce their NMOG+NOx emissions through improved calibration, thermal management and aftertreatment architecture design and canning.

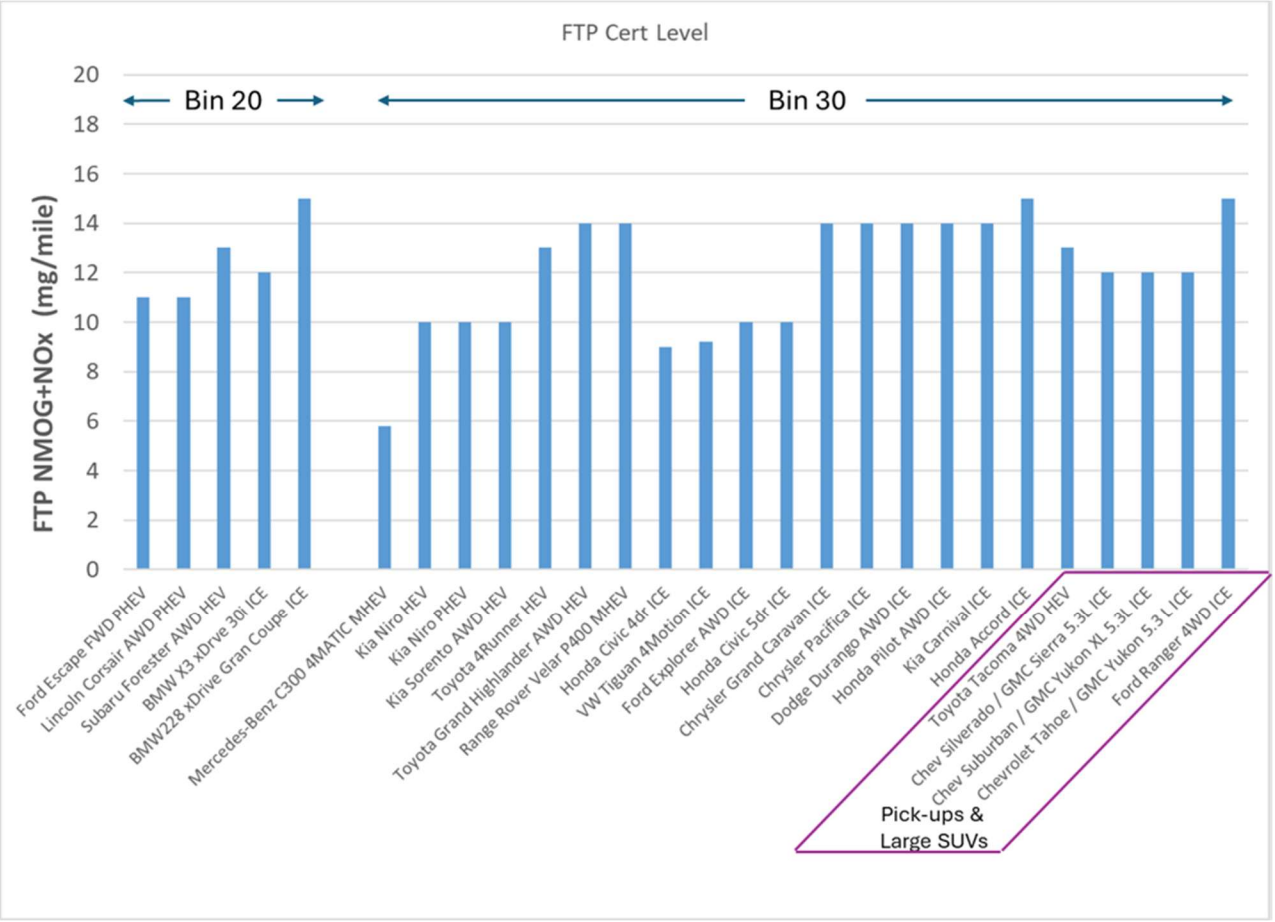


Figure 1. MY2026 LD Vehicles Meeting Ultra-Low NMOG+NOx Emission Limits

Additional information on emission control technologies and strategies is included in an appendix at the end of this comment.

- The NMOG+NOx LEV fleet average under Drive Forward should remain focused on vehicles with tailpipe criteria pollutant emissions and refrain from the inclusion of zero emission vehicles.

  Recent actions to reconsider federal emissions standards and to revoke EPA waivers granted to California to enforce its regulations highlight the importance of enacting durable tailpipe criteria pollutant standards that provide a level playing field for multiple technology pathways toward air quality goals. MECA supports performance-based LEV standards limited to vehicles with internal combustion engines (ICE). This lays a durable regulatory foundation that provides greater market stability because it is not susceptible to unpredictable future EV sales. The unpredictability of the EV market was highlighted this year as federal policy shifts have resulted in reduced EV sales, even in California.

  Under ACC II, CARB set a ZEV sales requirement for OEMs and phased out ZEVs from the NMOG+NOx fleet average. Under the current Drive Forward proposal, staff have indicated that ZEVs will be averaged into an OEM's fleet at 0 g/mile for compliance. It is known that the EV fleet will have a non-zero impact on criteria pollutant emissions in real life due to upstream power generation emissions. Furthermore, California's Low Carbon Fuel Standard (LCFS) is limited to the consideration of upstream CO_2 emissions and there is no currently implemented accounting methodology for upstream criteria pollutants.

  Given the annual baseload and non-baseload (peak) NOx emissions reported in the 2025 eGrid Emissions Factor report[1] for the California (CAM-X) electrical grid, there are potentially significant non-zero NOx impacts from the generation of electricity used for recharging of BEVs which will likely impact those populations living near one of the hundreds of natural gas power plants that make up 40% of total in-state electricity generation[2].

  Developing a lifecycle methodology to incorporate the impacts of BEV and AI data center electricity demand on NOx and PM emissions would be highly complex. However, without such a methodology, assigning ZEVs to a Bin 0 category under Drive Forward LEV requirements does not adequately represent their real-world emissions impact and could potentially lead to backsliding of ICE vehicle emissions.

  For these stated reasons, we believe that the more expedient policy approach would be to adopt an ICE-only fleet average for NMOG+NOx at this time. This will encourage industry to continue to innovate and employ multiple combustion vehicle emissions reduction technologies, ensuring a higher probability of achieving much needed criteria pollutant emissions reductions. As we have detailed in our comments below, electric vehicles should

[1] https://www.epa.gov/egrid

[2] https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/california-electrical-energy-generation

continue to be counted toward compliance with GHG fleet averages, based on a life cycle accounting methodology that incorporates emissions from upstream power generation used for vehicle operation.

- With the exception of Bin 0, CARB should adopt the same bin structure as the US EPA Tier 4 finalized in 2023. A common bin structure provides a harmonized compliance path that supports cost reductions for manufacturers when they certify their vehicles federally and in California. The addition of a greater number of lower bins also encourages further advanced powertrain developments which supports a multi-pathway approach to lower vehicle emissions, improving outcomes from the LEV program.

- MECA supports CARB's phase-in period for NMOG+NOx fleet average standards. The current phase-in period of 2031 thru 2038 compares favorably with automaker advanced notice, product refresh and redesign cycles.

- MECA supports the elimination of Light-Duty Bin 125 and Bin 160.

- MECA supports the proposal for LDV and MDV particulate matter standard of 0.5 mg/mile and the proposed test cycle requirements, including the standard and cold (-7℃) FTP and US06. The 0.5 mg/mile PM standard is readily attainable by vehicles employing ICE powertrains with no reliance on sales of ZEVs.

  Gasoline and diesel particulate filters and advanced fuel injection systems provide known compliance pathways for LD and MD vehicle manufacturers. We believe that the cold temperature test represents a valid real-world test condition. There are several regions within California that reach -7℃ during a typical winter season, including high desert regions and high mountain areas like the Sierra Nevada mountain range. A GPF captures over 95% of the engine out PM at all temperatures and has even greater filtration efficiency under cold temperatures. CARB may consider offering certification testing flexibilities for manufacturers that install a GPF on their vehicles.

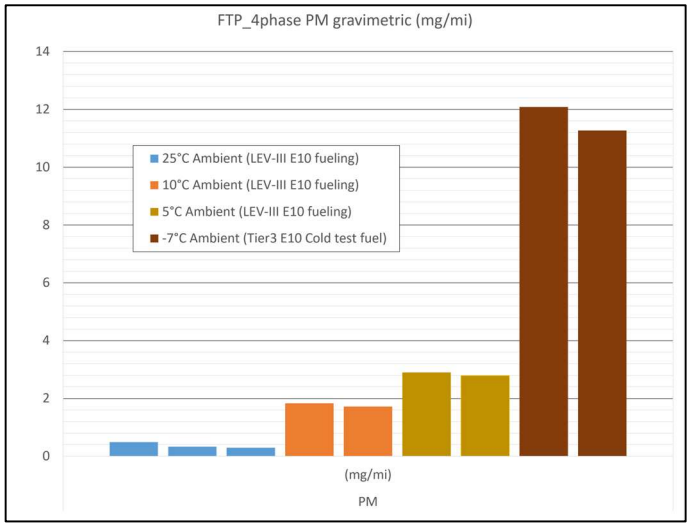


Figure 2. Engine out PM emissions as a function of test temperature

The test results in Figure 2 demonstrate the importance of understanding the PM emissions, especially at -7C because of the exponential increase in PM below 5C. A GPF would bring emissions to the same ultra-low level, regardless of varying ambient temperatures experienced throughout the state.

Table 1. Model Year 2026 Vehicle Models Certified with GPFs.

Manufacturer	Vehicle Classes	Powertrains	# Models	Models Include
BMW	PC, LDT2, LDT3	ICE, HEV, PHEV	30	X3 xDrive 30, X2, X1, 228, 330i, 340i, 430i, 440i, 550e, Mini Countryman ALL4,
FERRARI	PC	ICE, PHEV	8	12 Cilindri, Roma Spider, Daytona, 296 GTB
FORD	PC, LDT2, LDT4	ICE, HEV	17	F150 3.5L, Expedition 3.5L, Explorer 2.3L, Mustang 2.3L, Maverick 2L, Bronco Sport 2L
				Lincoln Nautilus, Navigator
HYUNDAI	PC	HEV	3	Palisade
JAGUAR LAND ROVER	LDT4	HEV	12	Defender, Range Rover
LOTUS	PC	ICE	1	Emira
MASERATI	PC	ICE	3	GT2 Stradale, MC20, MC20 Spyder
PORSCHE	PC	ICE, HEV	14	911 Carrera, 911 Carrera TARGA
VOLKSWAGEN	PC, LDT2	ICE	8	Tiguan, Taos, Audi Q5 Quattro and Sportback

Our members are already working with their OEM customers to integrate GPF technology onto vehicles. In fact, as shown in Table 1 above, there were 96 vehicle models certified by 9 vehicle manufacturers equipped with GPFs in model year 2026, with about 50 additional models expected by 2027 and another 18 models in 2028. Based on these projections, we believe OEMs are already well on the way to implementing technologies across their fleets to meet the 0.5 g/mile PM standard, with 100% coverage by MY 2031.

Numerous health studies and EPA in their PM NAAQS assessment have reported that there is no safe threshold dose for PM, particularly motor vehicle PM. This is particularly important given that university researchers at the University of Illinois and others in the U.S. have reported that light duty gasoline vehicle PM emissions remain prominent amongst the emission source sectors that cause the largest absolute exposure disparities experienced by historically marginalized communities[3]. Figure 3 shows that gasoline particle emissions from light-duty vehicles is a leading contributor to environmental injustice (dashed blue boxes). In several cases, the impact of light-duty gasoline vehicles has more impact on exposure than heavy-duty diesel vehicles.

[3] https://www.science.org/doi/10.1126/sciadv.abf4491

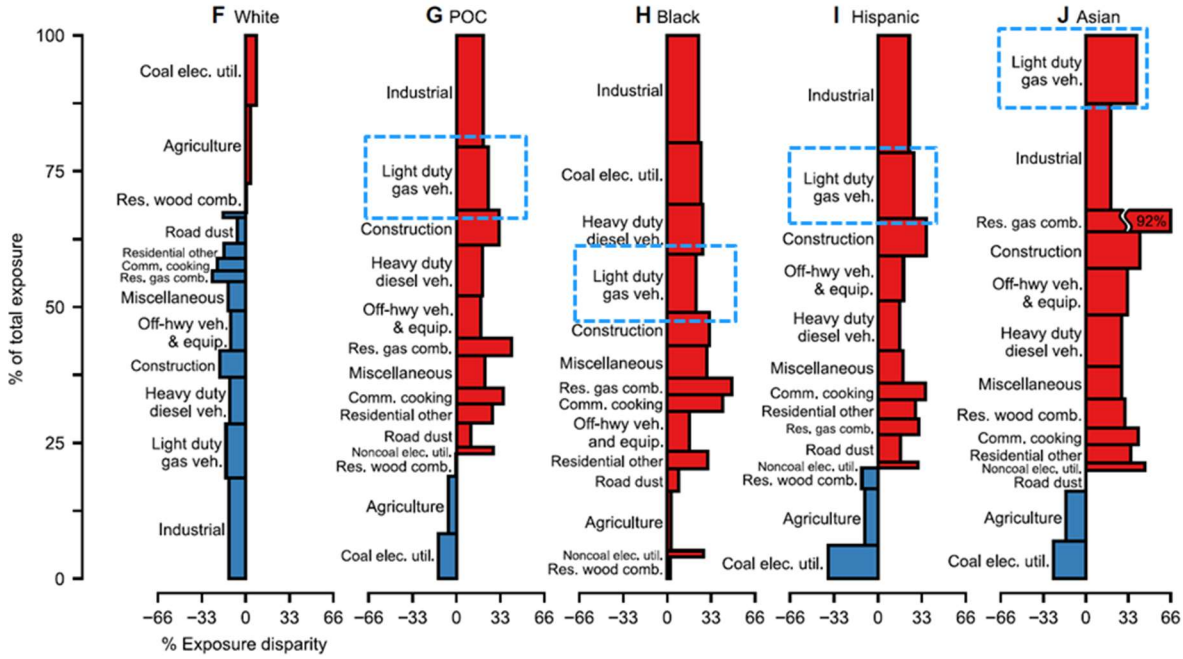


Figure 3. Source contributions to racial-ethnic disparity in PM2.5 exposure.

Another study funded by U.S. EPA and the National Institutes of Health concluded that the near-road exposure of PM in communities of color is greater than the white population, especially at distances less than 1000 meters from a roadway. [4] The modeled particulate matter exposures are shown in Figure 4.

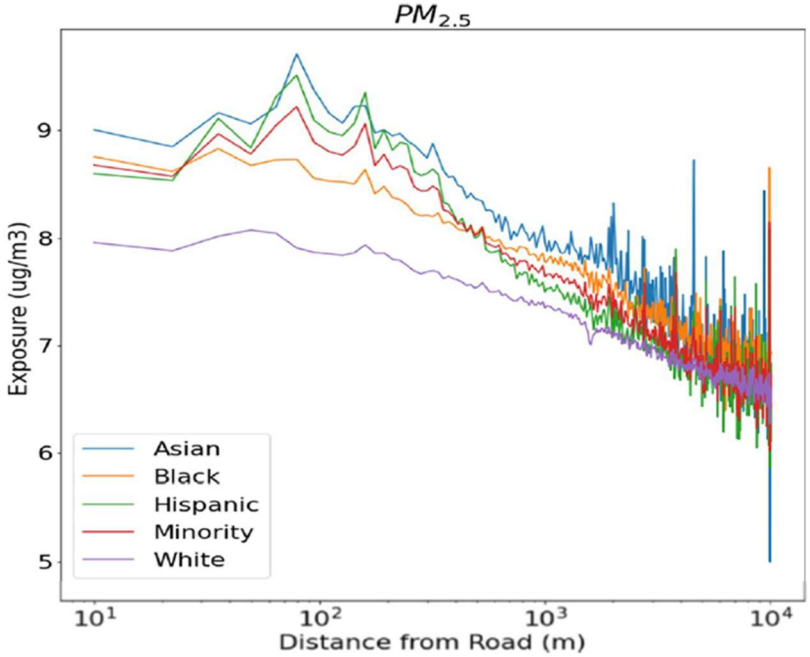


Figure 4. Modeled particulate matter exposure as a function of distance from roadway for various communities broken into predominant race of residents.

[4] https://doi.org/10.1371/journal.pone.0286406

These latest developments highlight that ambient PM concentrations measured at centralized monitoring stations do not reveal an accurate picture of the exposure next to roadways, primarily experienced by under-resourced communities, and therefore should not be the sole criteria for assessing the health benefits of reduced PM emissions driven by tighter tailpipe standards. The benefits of continued tightening of the PM2.5 standards should be analyzed at the near-road and community level to better understand the exposure impacts of the remaining light-duty gasoline fueled vehicles on underserved communities.

Medium Duty Vehicles

- MECA supports the MD Vehicle NMOG+NOx fleet average of 100 mg/mile (excluding Bin 0), the proposed Bin values, as well as the proposed Moving Average Windows in-use standard for chassis-certified gasoline and diesel MDVs.

Evaporative Emissions

- MECA Supports CARB's proposed 0.001-inch diameter in-use leak threshold for NIRCO (sealed tank) systems. Small leaks in sealed, pressurized systems can create large uncontrolled evaporative emissions. Evaporative emissions test data found in EPA IUVP data suggests current OBD systems often do not identify leaks under current requirements, resulting in vehicles failing the hot soak + 48 hour evaporative emission standard without a signal from the OBD system. It is critical that those leaks, and those significantly smaller, be identified.

  To improve leak detection, OBD and in-use checks for sealed fuel tank systems should be strengthened. The on-vehicle computer and OBD software should be modified in such a way that the system evaluates if tank pressure changes are commensurate with fuel temperature increases, and using appropriate criteria, sets a code in the OBD memory if the pressure change does not occur over a given period of time. This code could be checked in IUVP and during I/M as is now done for the 0.020" evaporative leak monitoring requirement.

- MECA would prefer that a test procedure for puff loss control be implemented to ensure puff losses are controlled under relevant conditions. Should CARB retain a design equation, the equation should ensure adequate canister capacity under high tank temperature and pressure conditions. CARB and EPA have "harmonized" evaporative and refueling emission control test procedures and emission standards for over 25 years. Since EPA has adopted a puff loss control regulation and it is now in effect, it would be helpful if CARB would work with EPA to consider harmonized requirements for puff loss control.

- MECA supports ORVR for incomplete vehicles. ORVR is a proven technology and should apply to incomplete medium-duty and heavy-duty spark-ignition vehicles, as is required from model year 2030 by EPA.

- MECA requests clarification on the 0.01 g/mile running loss proposal. CARB asserts that vehicles are already meeting a 0.01 g/mile level and it would be helpful to know which fuel system/vehicle technologies were used on those vehicles. Furthermore, CARB should more clearly explain the fuel system technology changes CARB expects manufacturers to adopt in response to the proposed running loss emission standard and the incremental costs of control, including whether the proposal would encourage broader use of sealed fuel tank systems as a compliance strategy. Since small leaks in sealed tank systems can create a potential pathway for uncontrolled evaporative emissions, CARB should evaluate whether the proposed change would, in practice, achieve meaningful emission reductions. Additionally, it is important to note that the current running loss standard is not enforceable in either IUVP or in-use surveillance testing. Should CARB proceed with revising the running loss standard, consideration should be given to how to incorporate in-use enforcement and ensure compliance, especially if sealed tank systems are a technology pathway for compliance.

MECA offers the following additional comments regarding evaporative emissions.

Leak Detection for NIRCO Fuel Systems

CARB has identified non-integrated refueling canister-only (NIRCO) fuel systems, commonly used in plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs), as an area requiring additional attention. MECA supports CARB's proposal to tighten the in-use leak standard from 0.02 inch to 0.001 inch for these systems.

NIRCO systems rely on a sealed fuel tank to contain vapors as temperature and pressure increase. That design can be effective, but the fuel tank, the fuel cap, and the fuel tank isolation valve (FTIV) together become the primary emissions control device for the vehicle. This makes system integrity critical. Prior MECA data submitted to EPA[5] showed that a leak larger than 0.002 inch in a sealed system can produce emissions greater than a conventional system with a 0.02-inch leak. As more HEVs and PHEVs enter the fleet, CARB should ensure that small leaks do not become a significant uncontrolled emission source.

MECA has reviewed EPA In-Use Verification Program (IUVP) data for all available PHEVs certified under Tier 3 / LEV III evaporative standards. Of 51 vehicles evaluated, 42 passed and 9 failed the hot soak plus 48-hour diurnal test, a failure rate of approximately 17 percent. The failing vehicles averaged about 925 percent of their applicable standard, while passing vehicles averaged about 46 percent of their standard. At the same time, HEVs and PHEVs passed the ORVR IUVP test at a rate of 100%, indicating that refueling emission controls (based on sufficient canister capacity and purge) are functioning effectively. These results suggest that fuel system leakage, rather than basic evaporative control design, may be the primary driver of the observed failures.

To address the issue of higher leak prevalence and higher leak rates from NIRCO systems, MECA recommends that CARB:

[5] EPA-HQ-OAR-2011-0135-0437

- Adopt the proposed 0.001-inch in-use leak threshold for NIRCO systems.
- Update OBD requirements so sealed tank systems continuously evaluate pressure and temperature behavior. For example, a temperature increase (ΔT) without a corresponding pressure increase (ΔP) should indicate potential leakage and trigger a specific diagnostic response. This response could be achieved through setting a new specific P code on the OBD computer, which could be identified at inspection at IUVP or I/M through specific query of this new code to aid in determining if a vehicle is a leaker and subject it to the leak test and/or a full diurnal to confirm a failure of the emission standard.
- Consider expanding in-use leak checks beyond IUVP and include Inspection and Maintenance (I/M) programs where commercially available leak detection equipment is also available to identify and support repair of leaks.
- Develop a standardized pressure-based fuel system integrity test that reflects real-world sealed tank operating conditions.
- Require reporting of peak fuel tank pressure during the certification running loss drive and the 2- and 3- day diurnal for all vehicles, regardless of fuel system designs.
- Require the manufacturer to measure and report purge volumes as measured during the canister preconditioning steps in the evaporative and refueling emission test procedures and running loss drives. This is a very inexpensive way to assess evaporative and refueling system performance without the need to perform full SHED tests.

Minimum Canister Capacity and Puff Loss Control

MECA supports CARB's objective of ensuring that puff losses before refueling are adequately controlled over the full useful life of the vehicle. This issue is particularly important for PHEV and NIRCO systems and other gasoline-fueled vehicles that operate at higher in-use tank pressures and temperatures.

MECA continues to believe the most effective approach is a test procedure that directly evaluates puff loss control for vehicles covered by the requirement. A test-based requirement would ensure in-use emission reductions than a design equation that applies only to certification.

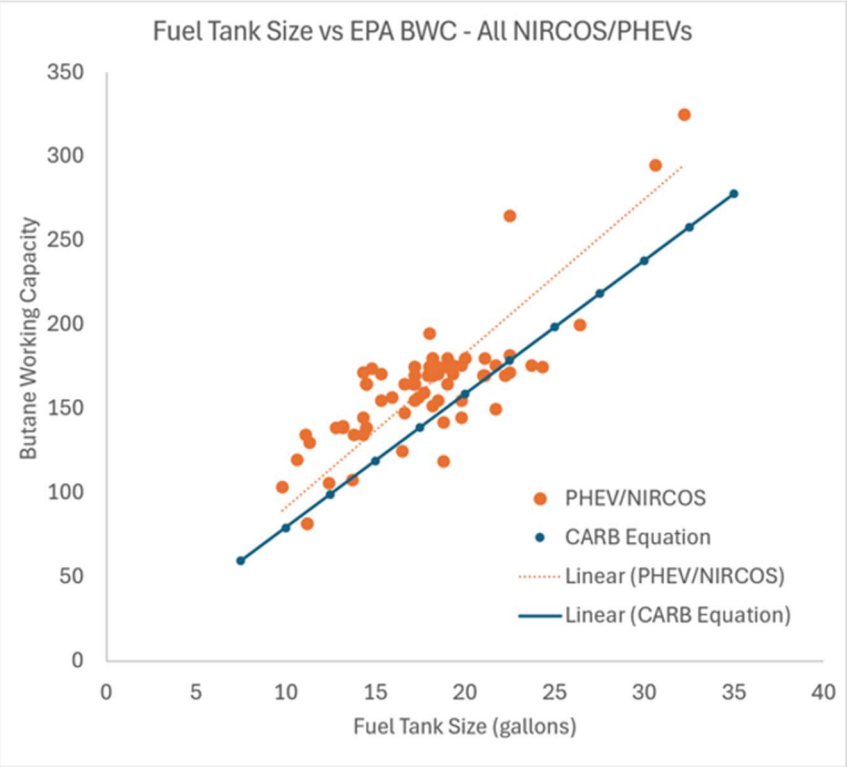


Figure 5. EPA certification data for MY 2023-2026 NIRCO systems compared to the proposed CARB equation which generally bounds the lower range of reported canister capacity

If CARB chooses to retain a minimum canister sizing equation instead of establishing a puff loss test procedure, MECA recommends that CARB ensures the equation provides sufficient minimum capacity for the full canister system to function under real-world conditions, including elevated tank temperature and pressure before refueling. MECA's review of EPA certification data for MY 2023-2026 NIRCO systems indicates that the proposed equation generally bounds the lower range of reported canister capacity, but some models fall below the calculated minimum (See Figure 5 above). CARB should therefore ensure the final approach is robust enough to protect against excess in-use puff loss and refueling emissions.

ORVR for Incomplete Vehicles

MECA supports CARB's proposal to extend refueling requirements to all incomplete medium and heavy-duty spark-ignition vehicles (i.e., >8,500 lb GVWR), including the proposed 0.20 grams hydrocarbon per gallon refueling standard for a useful life of 15 years or 150,000 miles. CARB has proposed implementing this requirement starting in 2031 model year, whereas EPA implements by 2030 for both medium-duty and heavy-duty incompletes, inclusive of any alternative phase-in schedules. While CARB has proposed to allow for early certifications prior to the proposed 2031 California implementation, MECA's position is the EPA national program should take precedence. ORVR is a proven technology that reduces refueling VOC emissions, secondary particulate matter precursors, and hazardous air pollutants. The refueling emission controls already used on similar weight complete vehicles should be equally applicable to corresponding incomplete vehicles in the same weight categories.

Running Loss Standard

MECA understands CARB's goal of eliminating high emitters and encouraging robust system designs through a proposed 0.01 g/mile running loss standard. However, running losses are not tested in-use, and the expected technology response to this lower standard is not clear. CARB should provide additional information on the technologies expected to achieve the proposed level and whether the proposal would encourage broader use of sealed fuel tank (NIRCO) systems as a compliance strategy.

If the proposed running loss standard is expected to drive greater adoption of NIRCO sealed tank systems, CARB should also strengthen certification leak detection requirements and in-use enforcement for those systems. In the absence of a lower leak threshold and effective OBD monitoring, small leaks in pressurized sealed tanks could become an uncontrolled emissions pathway and erode the expected benefits of the more stringent running loss standard. CARB should explicitly assess the likely prevalence of these leaks and quantify any potential emission offsets in its impact analysis.

Other Evaporative Provisions

MECA supports CARB's additional proposals for fuel tank temperature profile attestation/data requirements for PHEV running loss testing, and the other proposed regulatory alignments with existing EPA requirements.

ZEV Requirements

- MECA supports the durability, warranty, convenience cord, data standardization, labeling and service information requirements for electric vehicles. These requirements help to maintain a level playing field amongst vehicles with different powertrains and sustain U.S. technology leadership and competitiveness. The new ZEV label format should help to better inform consumers about what to expect from their vehicles as they get accustomed to the technology under different operating conditions.

  MECA supports CARB's warranty requirements for light-duty BEV and PHEV batteries and associated electric powertrain components, such as electric machines, power electronics, and similar key electric powertrain components. We agree with the concept of building on high value component warranty provisions, similar to those already existing for emission controls. We support designating the high-voltage battery and associated electric powertrain components for light-duty electric vehicles as high value components subject to a warranty period of 8 years or 100,000 miles. In addition, we support the same warranty periods for components in medium-duty BEVs and PHEVs.

  As experience with battery durability and warranty develops, MECA requests the requirements be revisited and extended to better represent the useful life of light- and medium-duty vehicles. Most consumers expect the battery to last the life of the vehicle, and alignment of the durability period with the vehicle useful life will facilitate consumer acceptance and drive innovation in battery technology. Aligning EV durability and warranty requirements with those for ICE will also provide a

level playing field for all vehicles whether EV or ICE and give consumers confidence in the reliability of any powertrain they choose.

Greenhouse Gases

- MECA agrees that a variety of powertrain technologies exist and will continue to be developed in response to performance based GHG targets.

- MECA supports that a GHG fleet average can and should consider EVs in the average as upstream GHG emissions are incorporated under California's Low Carbon Fuel Standard (LCFS).

- California has prioritized decarbonizing both the state grid and liquid fuel streams. MECA agrees that programs like LCFS are addressing the upstream GHG emissions. However, the lack of a compliance/crediting link between vehicles and their fuels results in a skewed playing field. From a GHG perspective, both ICE vehicles and EVs could have very similar operational footprints if the LCFS results in decarbonized gasoline being sold in the state. If, during certification and compliance, vehicle manufacturers could account for GHG emission benefits resulting from actual use of low carbon fuels, then we would anticipate a growth in the market for diverse low- and zero-carbon vehicle and complementary fuel technologies.

- The proposal for car and truck footprint curves presents an abrupt change between 2030 and 2031. Staff should better articulate the rationale and state air quality need for this abrupt change and the modeled uptake of technology pathways expected to be necessary for compliance. MECA encourages CARB to make manufacturer credit balances known to facilitate the assessment of credit impact on compliance.

MECA looks forward to continuing discussions with CARB staff to better inform and support California's Drive Forward Program.

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Appendix. Technology Strategies to Meet LEV 4 Criteria Pollutant Standards

Engine Mapping and Calibration

One of the most cost-effective strategies to optimize tailpipe emissions is engine calibration. OEMs work with their emission control technology suppliers to calibrate the engine for the best operation that takes advantage of the catalyst and filter designed for the engine. MECA members work with the OEM calibration engineers to design aftertreatment systems for each engine family. This can be a time-consuming process that if not needed to meet lower fleet average targets, is often short cut or overlooked. This explains why similar vehicle types made by different manufacturers can have vastly different certification levels, by a factor of two or three.

To comply with lower NMOG+NOx and PM emissions standards over certification cycles such as the FTP, US06, SC03, and LA92, manufacturers will employ improved engine maps and calibration strategies of existing engines and emission control related systems. Other design changes to system architecture, such as placement or insulation can be used to manage engine-out emissions and exhaust flows, reduce catalyst light-off times, increase exhaust temperatures during periods of low-load or idle and reduce hot running temperatures to protect engine and emission control components.

Advanced Ceramic Honeycomb Substrates

Several emission control choices can be made to improve and optimize emission control performance. For gasoline engines, the technology base of advanced three-way catalysts deposited on high cell density (as high as 1200 cells/in^2), thin-walled substrates (approaching 0.05mm) have evolved dramatically for light- and medium-duty chassis certified vehicles to comply with Tier 3/LEV 3 standards. Recent advances have yielded high porosity, low thermal mass substrates with narrow pore size distributions, which enable high emission reduction efficiency with less precious metal loading[6,7]. Catalyst manufacturers have optimized catalyst coating techniques based on layered or zoned architectures to strategically deposit precious metals on these substrates in ways that optimize their performance and cost. These advanced catalysts are then packaged using specially designed matting materials and passive thermal management strategies which can be used to meet lowest Bin emissions.

In support of the Tier 3 light-duty regulation[8], EPA tested a 2011 LDT4 pick-up truck with a 5.3L V8 engine that included a MECA supplied aftertreatment system. The aftertreatment package consisted of advanced catalyst coating on 900 cpsi substrates in the close-coupled location as well as underfloor catalysts and was aged to 150,000 miles. The system was combined with cylinder deactivation and achieved an FTP NMHC+NOx level of 18 mg/mile. A 2026 MY version of that same

[6] T. Asako, D. Saito, T. Hirao and E. Popp, "Achieving SULEV30 Regulation Requirement with Three-Way Catalyst on High-Porosity Substrate while Reducing Platinum Group Metal Loading (SAE 2022-01-0543)," in SAE WCX, Detroit, MI, 2022.

[7] J. Warkins, T. Tao, M. Shen and S. Lyu, "Application of Low-Mass Corning FLORA Substrates for Cold-Start Emissions Reduction to Meet Upcoming LEV III SULEV30 Regulation Requirement (SAE 2020-01-0652)," in SAE WCX, Detroit, MI, 2020.

[8] U.S. EPA, "EPA," March 2013. [Online]. Available: https://www.epa.gov/regulations-emissions-vehicles-and-engines/proposed-rule-and-related-materials-control-air-pollution.

pick-up truck is reporting certification levels of 12 mg/mile deploying only 750 cpsi substrates and is a testament to the innovation at suppliers and OEMs to meet standards without increasing costs.

Gasoline Particulate Filter Technologies to Meet LEV 4 PM Standards

Gasoline particulate filters (GPFs) are exhaust aftertreatment devices designed to reduce fine particulate matter emitted by gasoline engines, particularly those using gasoline direct injection (GDI). Like their diesel counterparts (DPFs), GPFs employ a ceramic wall-flow honeycomb structure—typically made of cordierite—forcing exhaust gases through porous channel walls where particles are trapped and stored. These systems are optimized to capture very small particles (PM2.5 and below), which are prevalent in the exhaust of gasoline-fueled engines and in particular, engines utilizing direct fuel injection (GDI) exhaust due to incomplete fuel atomization and combustion.

In real-world operation, modern GPF-equipped vehicles demonstrate very high control of particulate emissions, often reducing PM to well below regulatory limits across a wide range of driving conditions. Filtration efficiencies exceeding 90–95% are typical, and efficiency can even increase over time as an ash layer develops in the filter. For gasoline engines, GPFs typically operate under passive regeneration due to their characteristically higher exhaust temperatures compared to diesel engines with only very occasional active measures initiated via engine control when necessary.

The current state of the art in GPF technology focuses on improving filtration efficiency, durability, and system integration while minimizing backpressure and fuel consumption penalties. Advanced designs incorporate higher-porosity ceramic substrates, optimized microstructures, and catalyzed coatings that combine particulate filtration with additional emissions control functions. Emerging "next-generation" filters use hierarchical pore architectures and proprietary processing methods to capture smaller particles (down to ~10 nm) while maintaining low pressure drop, being driven by future regulations such as Euro 7[9, 10]. Overall GPFs are now considered a mature and essential technology for meeting current and near-term gasoline particulate emissions standards.

Advanced Fuel Injection Systems for Particulate Control

Turbocharging is a key enabler for the implementation of higher-pressure fuel injection systems employing direct fuel injection (DFI). Combinations of DFI and port fuel injection (PFI) also support higher compression ratios providing improved efficiency, engine power and reduced emissions under both warm and cold ambient conditions. The combination of DFI and PFI offers optimized fueling under the full range of engine operation.

In North America, most fuel injection systems still operate under 200 or 250 bar pressures with a transition to 350 bar underway. However, in Asian and European markets 500 bar direct injection systems are receiving growing interest from OEMs. The implementation of 500 bar direct fuel injection has been found to reduce particulate matter (PM) and particle number (PN) levels being driven by tighter Euro 7 PN standards. In the US market, the availability of 500 bar DFI systems offers another

[9] https://www.corning.com/worldwide/en/products/environmental-technologies/products/ceramic-particulate-filters/corning-dura-trap-gc-filters.html

[10] https://saemobilus.sae.org/papers/next-generations-gasoline-particulate-filters-catalyzed-applications-2024-01-2384

technology pathway for meeting the 0.5 g/mile PM standard with minimal incremental costs to account for improved materials of construction.[11]

Evolution in Exhaust Architectures

Close-coupled catalyst exhaust architectures (with or without a secondary underfloor converter) have been used on light-duty vehicles starting with Tier 2 LDV standards and are an effective strategy for reducing catalyst light-off times during cold-start or low-load operation. Early close-coupled architecture, still being used on many vehicles today, consisted of a first converter just outside the engine compartment in the firewall position. Larger displacement engines would use a second converter in the underfloor position to capture the last remaining pollutants that may have slipped by the close-coupled converters. MECA's survey of architectures on the cleanest Bin 30 and all Bin 20 certified vehicles shows some clear changes in how OEMs manage the catalyst temperature for cold start that encompasses over 80% of the cycle emissions. The cleanest vehicles being sold today find the first converter positioned inside the engine compartment and mounted on the side of the engine block to transfer engine heat to the light-off catalyst. This is often mounted directly to the turbo exit on boosted engines. On larger engines, the second converter is often positioned just outside the firewall where the close-coupled catalyst used to be in older designs.

Cylinder Deactivation and Variable Valve Actuation

Cylinder deactivation (CDA) is an established technology on light-duty gasoline cars and trucks, with the primary objective of reducing fuel consumption. This technology combines hardware and software computing power to seamlessly, in effect, "shut down" some of an engine's cylinders, based on the power demand, and keep the effective cylinder load in an efficient portion of the engine map without burning more fuel. Based on decades of experience with CDA on gasoline passenger cars and trucks, CDA is now being adapted for 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, CDA has resulted in exhaust temperatures increasing by 50°C to 100°C when it is most needed to maintain peak engine efficiency and effective diesel engine exhaust emissions control. In some demonstrations, CDA has been combined with a 48-V mild hybrid motor with launch and sailing capability to extend the range of CDA operation over the engine map, and this may deliver multiplicative fuel savings from these synergistic technologies.[12].

Modern Turbochargers

Modern turbochargers enable engines to be downsized, resulting in fuel savings without sacrificing power and/or performance. Today's turbochargers have a variety of available design options enabling improved fuel economy 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

[11] Gomot at al., "500 BAR Gasoline Direct Injection (GDI) System From Development to Serial Production", Aachen Colloquim – Sustainable Mobility 2024, October 8th, 2024.

[12] https://www.meca.org/wp-content/uploads/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf

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 fuel efficiency through improved thermal management capability to enhance aftertreatment light-off. Continuous improvement in turbocharger technology is making it possible to run leaner combustion (high air/fuel ratios), which increases efficiency. This improvement allows for very low particulate generation and even lower engine-out NOx.

Mild Hybridization (MHEVs) and 48 Volt System Technologies

48-volt systems can be found on many light-duty vehicle models (primarily from Europe) from Mercedes, Audi, VW, Renault and PSA. In the U.S., Stellantis is offering a 48-volt system on the RAM 1500 pick-up and the Jeep Wrangler under the eTorque™ trademark. 48-volt mild hybrid electrical systems and components are making their way onto an increasing number of vehicles including commercial diesel vehicles as they reduce starter size and wire gauge requirements, offering cost and weight savings which increase with increasing vehicle size.

Like the passenger car fleet, OEMs are considering replacing traditionally mechanically-driven components with electric versions to gain efficiency on an increasing range of light- and medium-duty vehicles. Running accessories off 48-volt electricity rather than 12-volts is more efficient due to reduced electrical losses and because components that draw more power, such as pumps and fans, have increased efficiency when operating at higher voltages. 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.

Mild hybridization covers a range of configurations, but a promising one includes an electric motor/generator, regenerative braking, electric boost and advanced batteries. In this way, 48-volt mild hybridization is complementary technology to cylinder deactivation and start-stop capability, allowing the combination of multiple technologies on a vehicle to yield synergistic benefits.

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 it acts as a generator charging 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 system. In addition to the start-stop function, a BSG system can enhance fuel economy even during highway driving by cutting off the fuel supply when cruising or decelerating. Such systems can also be designed to deliver a short power boost to the drivetrain. This boost is typically 10 to 20 kW and is limited by the capacity of the 48-V 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 30 kW to be delivered, giving greater benefits to light and medium commercial vehicles[13].

[13] https://www.meca.org/wp-content/uploads/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf

Full / Strong Hybridization (HEVs)

A full hybrid can enable electrification of many of the components described above for mild hybrid vehicles, but the higher voltages allow for more parts to be electrified and to a higher degree of efficiency. Full hybrids which implement larger electric motors and batteries also support greater acceleration capability, regenerative braking power recovery and fully electric operation over short distances. Full hybrid vehicles offer the greatest benefit over urban driving conditions where they can take advantage of efficiency gains due to variable lower vehicle speeds and regenerative braking[14].

The Honda Insight and Toyota Prius were the first full hybrid vehicles offered for sale in the U.S. in MY1999 and MY2000 respectively. After 25 years, full hybrids are now a common product offering on small and larger light-duty cars, crossovers, SUVs and pick-ups from manufacturers such as Toyota, Honda, Ford, Hyundai, Kia, Mazda and Subaru. In 2025, full hybrid vehicle sales industry wide represented 16% of all new U.S. vehicle sales with Toyota sales approaching 50%[15]. With respect to pick-ups, the hybrid versions of the Toyota Tacoma, Tundra, Ford F150 and Maverick represented 11.1%, 20.7%, 10.8% and 52% of sales respectively[16, 17].

Hybridized vehicles can be calibrated to take advantage of the electric motor drive during periods of high acceleration to reduce the transient load on the gasoline engine and reduce NOx emissions. Figure A1 shows that the relative NOx emissions from a full hybrid has been reported to be reduced by about 10-30% compared to a pure ICE vehicle.

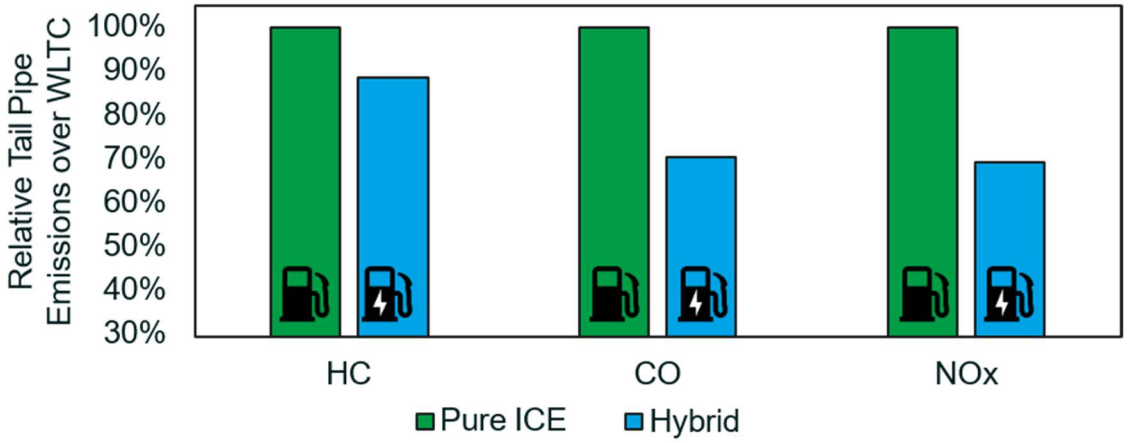


Figure A1. Relative Tailpipe Emissions of a Pure ICE Vehicle and Hybrid Electric Vehicle Tested Over the WLTC.[18]

[14] CARB, "Draft Technology Assessment: Heavy-Duty Hybrid Vehicles," 2015.
[15] https://www.nada.org/nada/market-beat.
[16] https://www.fromtheroad.ford.com/us/en/articles/2026/ford-2025-full-year-us-sales-results
[17] https://s3.amazonaws.com/toyota-cms-media/toyota-pdfs/US%20December%202025%20FINAL.pdf
[18] 2025 Emission Control Technology Conference in New Delhi, India

Full hybrids (commonly parallel hybrids) offer several opportunities to reduce NMOG+NOx as well as PM emissions as described by Toyota engineers[19]. During engine start, the high voltage electric motor allows the engine to be spun up to target speed, with valve actuation pumping air within the cylinder to generate heat. This can be followed by the start of ignition followed finally by the injection of fuel to initiate combustion. Such a motored engine start reduces NMOG+NOx and PM emissions.

Upon cold-start, parallel hybrids can employ a rapid heat-up strategy, operating in a lower emissions generator mode, where the engine is decoupled from the transient drive cycle. During this warm-up period, aggressive cold-start strategies such as aggressive use of Atkinson cycle combustion, retarded ignition, richer air-fuel ratio, exhaust throttling or secondary air injection can be used for active thermal management. Transient operation is blended in as catalyst light-off temperature is attained. Once the catalyst and coolant reach target operating temperatures and battery state of charge is replenished, engine control can transition to normal hybrid cycling.

In addition, due to the presence of a high voltage system architecture, hybrids are well-suited to the addition of electric heating elements to further reduce the time to catalyst light-off. In addition, hybrids can employ advanced predictive model-based control of engine-electric motor coordination to reduce the magnitude of engine transient operation, engine-only operation and maximize electric only drive operation. By employing such techniques, Toyota engineers were able to demonstrate FTP NMOG+NOx emissions of 3 mg/mile.

Advanced Extended Range Electric Vehicles (EREVs)

With respect to passenger and larger "non-passenger vehicles", there is renewed interest in serial hybrid technologies with no engine-to-wheel connection – a hybrid powertrain more commonly known as extended range electric vehicles (EREVs). Of special note, the 2027 Nissan Rogue will offer an EREV variant[20] (known as e-Power™) and EREV technologies are anticipated to be utilized on larger passenger as well as light and medium pick-up duty trucks[21, 22] where they can offer greater towing capacities.

Integrated hybrid electric drivetrain systems, consisting of a fully qualified transmission, motor and power electronics controller, are now also commercially available for medium-duty vehicles[23]. With the ability to meet high torque requirements, these systems will enable hybridization of a broad range of medium duty vehicles.

[19] SAE 2019-01-2217, "ICE Vehicle Challenge Toward Zero Emissions: Future Technology Harmonization in Electrified Powertrain System".
[20] https://www.caranddriver.com/news/a69635288/2027-nissan-rogue-e-power-hybrid-preview/
[21] https://www.stellantisfleet.com/news-and-events/stellantis-news/range-extended-ram-1500-ramcharger-to-lead-brands-electrification-push.html
[22] https://fordauthority.com/2025/02/ford-lineup-including-super-duty-to-get-erev-variants-report/
[23] https://harbingermotors.com/newsroom/harbinger-unveils-first-of-its-kind-plug-in-hybrid-vehicle-for-medium-duty-fleets/

Plug-in Hybrids (PHEVs)

Plug-in hybrids (PHEVs) can be practical for light and medium- duty vehicles that do not travel long distances or operate for long periods of time without returning to the owner's home or to a central fleet location for overnight recharging. PHEVs can also provide a usable daily driving range for many owners charging from conventional 110V wall outlets when the vehicles are not in use.

An increasing number of PHEVs now offer all-electric ranges in excess of 40 miles including the BMW X5, Mercedes GLC350e, GLE450e, S580e, and AMG E53, Toyota Prius and RAV4, and Volvo S60 and T60.

It is worth highlighting that both HEVs and PHEVs can deliver significant emission reductions and fuel economy benefits compared to their conventional vehicle counterparts by employing relatively low-capacity batteries.