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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION
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Re: Comments on potential updates to the Advanced Clean Cars regulations

The International Council on Clean Transportation (ICCT) respectfully submits these comments on the California Air Resources Board's (CARB) potential updates to the Advanced Clean Cars regulations.

The ICCT was established in 2001 as an independent source to provide unbiased research and technical and policy expertise for motor vehicle regulators working to improve the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change. Our work supports the development and implementation of advanced vehicle regulations in the world's largest markets. In the United States, the ICCT has been highly engaged with federal and state-level vehicle regulations, participating in expert working groups, submitting public comments on regulations' technical designs, and regularly publishing research on vehicle regulations and standards.

The ICCT commends the California Air Resources Board (CARB) on its continuing effort to reduce passenger vehicle emissions and to support the state's growing zero-emission vehicle (ZEV) market. We welcome the opportunity to provide comments on CARB's potential updates to the Advanced Clean Cars regulations which sets increasingly stringent emissions standards for internal combustion engine (ICE) vehicles and requires an increasing number of ZEV sales to meet the state's goal of 100% ZEV sales by 2035. The comments below offer our support for the potential updates, provide international context for California's potential updates relative to global developments, and include some technical observations on plug-in hybrid electric vehicle utility factors and combustion vehicle technology costs and effectiveness.

We would be glad to clarify or elaborate on any points made in the comments. CARB staff can feel free to contact ICCT staff Pete Slowik (peter.slowik@theicct.org) or Dr. Stephanie Searle (stephanie.searle@theicct.org) with any questions.

Stephanie Searle, PhD
Chief Program Officer
International Council on Clean Transportation

## SUPPORT FOR THE POTENTIAL UPDATES

ICCT supports the potential updates to the Advanced Clean Cars regulations and recommends its development. This regulation is critical to achieving the pace and scale of needed transportation emission reductions in California. There is a clear and urgent need to rapidly transition the transportation sector to zero-emission vehicles while simultaneously limiting pollution from the remaining new combustion engine vehicles. Continued and strengthened standards are important to protect public health and deliver on the state's air quality and climate change obligations. We support the potential update to the Advanced Clean Cars regulations that would further limit criteria pollutant and greenhouse gas emissions from new vehicles, address large credit banks, and phase-out off-cycle credits.

As a member of the ZEV Transition Council and the International ZEV Alliance, California joins several of the world's major vehicle markets with the shared commitment to accelerate a global transition to ZEVs. This transition is crucial for decarbonizing road transport and meeting global climate goals. Specifically, ICCT's modeling shows that limiting global warming to below 2°C as targeted in the Paris Agreement will require that leading markets including California reach 100% zero-emission new light-duty vehicle sales no later than 2035.[1] Our modeling also shows that achieving Paris-compatible emissions reductions means that gasoline cars and light trucks also need to improve by 3.5% per year.[2] If new gasoline vehicle emissions backslide or remain stagnant, it would risk California falling off the path to meeting the Paris Climate Agreement goals while leaving consumer financial benefits on the table.

California is not alone in its commitment to 100% ZEVs while simultaneously reducing combustion engine vehicle emissions. There is precedent for regulating combustion-engine vehicles while requiring increasing ZEV sales in the UK's ZEV mandate for cars and vans, which entered into force in 2024. The core of this regulation is annual targets for the share of ZEVs for light-duty vehicles, rising to 80% of cars and 70% of vans by 2030. Recognizing the risk that backsliding on ICE vehicle emissions could jeopardize the carbon savings of the ZEV mandate, the UK's policy also requires that the fleetwide average $CO_2$ emissions of each manufacturer's new non-ZEV vehicles (including plug-in hybrids, which are not counted as ZEVs in the UK's scheme) do not rise over time, compared to each manufacturer's performance in 2022.[3] As with the ZEV sales requirements, trading among manufacturers is allowed in the non-ZEV $CO_2$ standard. The targets for each manufacturer do not change according to vehicle footprint or mass to ensure that a shift toward SUVs does not erode emissions savings.

Adopting the potential amendments to the Advanced Clean Cars regulations would further amplify the benefits to California and beyond. Many other jurisdictions follow California's leadership on automotive emissions regulations. As of July 23rd, 2024, 17 additional U.S. states

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[1] Sen, A., and Miller, J. Emissions reduction benefits of a faster, global transition to zero-emission vehicles. *International Council on Clean Transportation.* https://theicct.org/publication/zevs-global-transition-benefits-mar22/

[2] Slowik, P., and Miller, J. Aligning the U.S. greenhouse gas standard for cars and light trucks with the Paris Climate Agreement. *International Council on Clean Transportation. https://theicct.org/us-ghg-standard-paris-agreement-dec22/*

[3] Zero emission vehicle (ZEV) mandate consultation: summary of responses and joint government response. UK Government (2023, October 25). https://www.gov.uk/government/consultations/a-zero-emission-vehicle-zev-mandate-and-co2-emissions-regulation-for-new-cars-and-vans-in-the-uk/outcome/zero-emission-vehicle-zev-mandate-consultation-summary-of-responses-and-joint-government-response

plus Washington D.C. have adopted all or part of California's low-emission and zero-emission vehicle regulations, which together represent more than 40% of new U.S. light-duty vehicle registrations.[4] The ACC program has proven to be effective at reducing emissions in the transportation sector in California and beyond. It is likely that many other states will continue to follow California's leadership and adopt the ACC II Program to replicate the air and climate pollutant emission reductions in their own states.

## INTERNAL COMBUSTION ENGINE EMISSIONS REDUCTIONS POTENTIAL AND COST-EFFECTIVENESS

ICCT supports the implementation of an ICE-only fleet average standard and believes it is feasible, achievable, and cost-effective. While automakers are investing heavily in BEV development, the substantial progress that has been—and continues to be—made in ICE technology has yet to saturate the market. That is, many existing and recently announced ICEV technology improvements have ample room for increased application throughout the ICEV fleet. As many ICE vehicles are still to be sold in the MY2026-2034 timeframe, the proposed amendments are an opportunity to maximize their efficiency and minimize their tailpipe emissions, while providing substantial consumer fuel savings.

Research and analysis by the ICCT indicate that an ICE-only stringency that is at least comparable to strong hybrid-level emissions is achievable, feasible, and cost-effective. An ICE-only standard would ideally have a single footprint-based curve (i.e., cars and trucks combined) that achieves at least full hybridization by MY2034. Doing so would minimize tailpipe pollution and maximize cost-effectiveness and consumer fuel savings. ICCT also supports CARB's proposal to establish a PHEV-only fleet average standard for 2035+ so that PHEV emissions during charge sustaining mode continue to decline.

Further emission reduction improvements can be expected from advancements in strong hybrids from a variety of technologies such as battery and motor improvements, dedicated hybrid engines, and road load reductions (see Appendix). These types of improvements have been observed in successive generations of strong hybrid models popular in California today, achieving around 8%-10% improvement from each generation.[5]

Post-2034, once all vehicles that have combustion engines are plug-in hybrid electric vehicles, further efficiency improvements during charge-sustaining mode are possible. Because PHEVs have very similar combustion powertrains as strong hybrids, we would expect each new generation of PHEVs to benefit from the same types of improvements as strong hybrids, achieving an 8%-10% reduction in emissions during charge-sustaining mode. ICCT recommends the development and establishment of a PHEV-only fleet average standard for 2035+.

Our public comments on the EPA's "Multi-Pollutant Emissions Standard for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles" and on NHTSA's Corporate Average Fuel

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[4] States that have Adopted California's Vehicle Regulations. (Accessed July 23, 2024). *California Air Resources Board*. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/states-have-adopted-californias-vehicle-regulations

[5] Comment submitted by John Graham on EPA proposed Multi-Pollutant Emissions Standard for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles. (2023, July 6). https://www.regulations.gov/comment/EPA-HQ-OAR-2022-0829-0585

Economy Standards for Passenger Cars and Light Trucks for Model Years 2027-2032 and Fuel Efficiency Standards for Heavy-Duty Pickup Trucks and Vans for Model Years 2030-2035" are relevant to CARB's consideration of an ICE-only fleet standard and we have copied them below in an appendix for reference.[6]

## PLUG-IN HYBRID ELECTRIC VEHICLES

ICCT applauds CARB for proposing to update its analysis of PHEV real-world emissions and for its proposed ICE-only fleet average standard to not account for PHEV eVMT. This approach would most appropriately account for PHEVs' tailpipe emissions.

## OFF-CYCLE CREDITS

ICCT strongly supports CARB's proposal to sunset or eliminate air-conditioning (AC) and off-cycle credits (OC). ICCT recommends full elimination of off-cycle credits and AC credits starting in MY2030.

ICCT recently submit public comments to EPA based on the agency's consideration of off-cycle credits in its Proposed Multi-Pollutant rule in July 2023 that are relevant to CARB.[7] These are copied below:

"Eliminating the AC leakage credit is reasonable, since at least 95% of new LD vehicles now use HFO-1234yf,[8] which is a low-GWP refrigerant. Since virtually all vehicles have this low-GWP refrigerant, this low-GWP status is now the baseline and there is no need to grant further AC leakage credits. Regarding AC efficiency credits, ICCT supports EPA limiting these credits to ICEVs, as the credits are based on ICE tailpipe emissions reductions for AC-system improvements. While BEVs also benefit from improved AC system efficiency, BEVs do not require the additional incentive provided by AC credits. BEVs already are granted compliance emissions values of 0 g/mi, and advances in AC efficiency are inherent to BEV development, as passenger and battery heating/cooling loads can significantly impact BEV range and battery size requirements.

ICCT supports the proposal to phaseout OC credits by MY2031, to eliminate the off-menu OC credit option starting MY2027, and to limit OC credits to ICE vehicles. As with AC credits, a large portion of the fleet already incorporates the technologies that are granted OC credits. According to the 2022 Automotive Trends Report data, MY2021 cars averaged 5.1 g/mi in OC credits (51% of the 10 g/mi cap) and trucks averaged 10.2

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[6] ICCT comments on EPA proposed Multi-Pollutant Emissions Standards for MY 2027 and Later Light-Duty and Medium-Duty Vehicles. https://theicct.org/pc-epa-multi-pollutant-es-jul23/; ICCT comments on NHTSA's Proposed Fuel Efficiency Standards for 2027-2035 Vehicles. https://theicct.org/icct-comments-nhtsa-proposed-fuel-efficiency-standards-2027-2035-vehicles-oct23/

[7] ICCT comments on EPA proposed Multi-Pollutant Emissions Standards for MY 2027 and Later Light-Duty and Medium-Duty Vehicles. https://theicct.org/pc-epa-multi-pollutant-es-jul23/

[8] EPA. (2022). Automotive Trends Report. https://www.epa.gov/automotive-trends/download-automotive-trends-report#Full%20Report

g/mi in OC credits (102% of the 10 g/mi cap).[9] With these averages as a proxy for the share of the car and truck fleets with OC technology, this technology is already widespread in the baseline and requires no further incentivization. Evidence suggests that the menu OC credit values (such as solar and thermal load control) overestimate the real-world impact of OC technologies.[10] Moreover, the menu credits are defined in terms of absolute g/mi reductions, rather than relative or percentage-based reductions, as virtually all on-cycle technologies are defined. Because of this inappropriate definition, as vehicles become increasingly efficient, these absolute credit values represent unrealistically large shares of vehicles' overall emissions improvement. Additionally, as OC credits are based on reduced tailpipe emissions from ICE vehicles, they are not applicable to BEVs. As with AC efficiency improvements, any innovation that reduces real world energy consumption in BEVs is inherently incentivized by the reduced battery capacity requirements of incorporating such innovations. Relatedly, ICCT supports the proposal to scale PHEV OC credits by the (newly proposed) utility factor.

ICCT recommends EPA adjust its modeling of OC credits to more accurately reflect the trend of the car and truck fleets taking full advantage of the OC credit cap. As currently modeled, both the car and truck fleets use the full value of their respective AC efficiency credit cap.[11] The OC credits, however, are not modeled as reaching their cap for either car or truck fleet in any model year. As evidenced in the 2022 Automotive Trends Report data discussed above, the car fleet is currently receiving at least 50% of the full OC credit cap, while the truck fleet is receiving at least 100% of the full OC credit cap. ICCT suggests EPA modify its inputs to OMEGA to capture the real-world trend of manufacturers taking full advantage of the off-cycle credit cap. (The AC efficiency credits are appropriately modeled at the full value of the cap, which accurately represents the trend of the fleet receiving nearly 90% of the AC credit cap in MY2021.) If EPA incorporates the maximal use of OC credits during years that the OC cap is nonzero, then the standards could be made more stringent to offset this higher OC credit usage and maintain the same GHG emissions impacts."

## ADDRESSING CREDIT BANKS

ICCT strongly supports CARB's proposal to address credit banks and expire a subset of credits generated between California's ACC I fleet target and EPA's final rule.

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[9] EPA. (2022). Automotive Trends Report [data]. https://www.epa.gov/automotive-trends/explore-automotive-trends-data

[10] Lutsey, N., Isenstadt, A. (2018). How will off-cycle credits impact U.S. 2025 efficiency standards? *International Council on Clean Transportation.* https://theicct.org/publication/how-will-off-cycle-credits-impact-u-s-2025-efficiency-standards/

[11] Based on analysis of column BV of output file 2023_03_14_22_42_30_central_3alts_20230314_Proposal_vehicles.csv as well as inspection of input file offcycle_credits_20230206.csv

# APPENDIX

**From our public comments to EPA:**

ICEV technology has been consistently improving for decades. While automakers are investing heavily in BEV development, the substantial progress that has been—and continues to be—made in ICE technology has yet to saturate the market. That is, many existing and recently announced ICEV technology improvements have ample room for increased application throughout the ICEV fleet. As many ICE vehicles are still to be sold in the MY2027-2032 timeframe, the proposed rule is an opportunity to maximize their efficiency and minimize their tailpipe emissions, while providing substantial consumer fuel savings.

ICCT commented extensively on recent ICEV technology improvements in its 2018 comments on the SAFE NPRM for 2021-26 cars and light trucks (ICCT 2018 comments)[12], its study of LPM and OMEGA modeling of the 2018 Camry (ICCT 2018 Camry)[13], its supplemental comments responding to Toyota comments on ICCT's study of LPM and OMEGA modeling of the 2018 Camry (ICCT 2019 comments)[14], and its 2021 comments on the Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (ICCT 2021 comments).[15] Much of the content of these prior comments are reiterated or summarized in the following subsections, as appropriate and relevant for this proposed rule. Moreover, recent reports demonstrate that further technology improvements are coming that can boost ICE vehicle efficiency levels well beyond that of even the highly-efficient Atkinson cycle engine efficiency

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[12] ICCT Comments on the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Truck. (2018, October 26). https://theicct.org/news/comments-safe-regulation-2021-2026 (ICCT 2018 comments)

[13] German J. (2018, February 21). How things work: OMEGA modeling case study based on the 2018 Toyota Camry. https://theicct.org/publications/how-things-work-omega-modeling-case-study-based-2018-toyota-camry (ICCT 2018 Camry)

[14] Supplemental Comment from the International Council on Clean Transportation. (2019, April 28). Docket #NHTSA-2018-0067-12387. https://www.regulations.gov/comment/NHTSA-2018-0067-12387, #NHTSA-2018-0067-12388 https://www.regulations.gov/comment/NHTSA-2018-0067-12388 (ICCT 2019 comments)

[15] ICCT comments on the Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards. (2021, September 29). Docket ID EPA-HQ-OAR-2021-0208, https://www.regulations.gov/docket/EPA-HQ-OAR-2021-0208, Comment ID EPA-HQ-OAR-2021-0208-0522, https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0522 (ICCT 2021 comments)

levels assumed in this proposal,[16,17] as well as show the declining costs of 48-volt mild hybrid systems.[18,19]

As documented in the following subsections, the efficiency potential of ICE technology has continued to improve, while costs have remained lower than previously estimated. Thus, if technology costs and benefits were updated with the latest information, it would show that the proposed standards are even more feasible and lower-cost than EPA's analysis indicates. The following subsections discuss various ICE technologies and compare the assumptions about cost and efficiency potential within EPA's OMEGA analysis with independent research by the ICCT and other experts.

## Gasoline Direct Injection (GDI)

### Cost

Based on the DRIA Table 2-30, GDI direct manufacturing costs in EPA's OMEGA modeling are between $55-$81 per cylinder. ICCT submitted direct injection cost data in our 2018 comments based on a 2016 FEV teardown cost study (FEV 2016)[20], which found per-cylinder costs to be about $40 per cylinder. For additional information see:

- ICCT 2021 comments page 6
- ICCT 2018 comments pages I-69–I-70
- FEV 2016

## Cylinder deactivation (DEAC)

### Application in OMEGA

Based on the response surface equations (RSE) input file (simulated_vehicles_rse_ice_20221021_debug_noP2.csv), there are no technology packages/cost curve classes with DEAC on a turbocharged engine in EPA's OMEGA modeling. While adding DEAC to a turbocharged engine has smaller pumping loss reductions than for naturally aspirated engines, DEAC still has significant pumping loss reductions and has the additional benefit of enabling the engine to operate in a more thermal efficient region of the engine fuel map. As described in the National Academies

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[16] AVL Webinar on Passenger Car powertrain 4.x – Fuel Consumption, Emissions, and Cost. (2020, June 2). https://www.avl.com/-/passenger-car-powertrain-4.x-fuel-consumption-emissions-and-cost (Slides available at https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0522) (AVL 2020)

[17] Roush report on Gasoline Engine Technologies for Improved Efficiency (Roush 2021 LDV) https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0210

[18] Roush report on 48V and BEV costs (Roush 2021 48V) https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0210

[19] Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction. https://theicct.org/publication/mild-hybrid-emissions-jul22/ (ICCT 2022 MHEV)

[20] David Blanco-Rodriguez, 2025 Passenger car and light commercial vehicle powertrain technology analysis. FEV GmbH. (2016, November 21). https://www.theicct.org/publications/2025-passenger-car-and-light-commercial-vehicle-powertrain-technology-analysis (FEV 2016)

of Sciences' 2021 report on light-duty vehicle fuel economy (NAS 2021)[21], turbocharged engines with DEAC are already in production (NAS 2021, section 4.1.3). EPA could consider adding DEAC option to turbocharged cost curve classes.

## Cooled Exhaust Gas Recirculation (CEGR)

### Application in OMEGA

Similar to the application of DEAC, based on the RSE input file, there are no cost curve classes with CEGR on a base turbo engine in EPA's OMEGA modeling (i.e. "TDS" within the input file). As reported in NAS 2021 (section 4.1.3) turbocharged engines with CEGR are already in production. NAS 2021 also provides estimates for the efficiency benefit of including CEGR on a base turbo engine. EPA could consider adding CEGR option to turbocharged cost curve classes.

## Atkinson cycle engine (ATK)

### Application in OMEGA

EPA appears to have excluded the modeling and application of ATK from pickups and other body-on-frame vehicles (DRIA page 1-10 and RSE input file). However, as detailed in ICCT 2021 comments (pages 14-16), this exclusion could be lifted, allowing all vehicle classes to adopt ATK in the OMEGA model.

To briefly summarize those ICCT 2021 comments, engines in pickup trucks and high-performance vehicles are sized and powered to handle higher peak loads. This means larger engines that operate at lower loads relative to their maximum capacity on the 2-cycle test – and during most real-world driving. This, in turn, means that pickup trucks and high-performance vehicles will spend more time in Atkinson Cycle operation than lower performance vehicles on both the test cycles and in the real world. This includes time spent towing, which represents a very small fraction of light-duty pickup usage.[22,23] Altogether, the large majority of pickup trucks spend the vast majority of driving at low loads relative to the engine's capability, where Atkinson Cycle engines are very effective. In other words, ATK is likely a highly cost-effective technology for pickup trucks, which may be the most challenging to electrify, as evidenced by the low BEV share of pickups in the 2027-2031 time frame compared to other body styles in EPA's modeling (Preamble Table 80). Furthermore, the claim that an Atkinson Cycle engine that switches to Otto cycle on demand cannot provide the additional torque reserve is not accurate (a claim previously used to justify blocking ATK on pickups in prior rulemakings, see ICCT 2021 comments).

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[21] National Academies of Sciences, Engineering, and Medicine. (2021). Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy—2025-2035. *The National Academies Press*. https://doi.org/10.17226/26092

[22] Berk, B. (2019, March 13). You Don't Need a Full-Size Pickup Truck, You Need a Cowboy Costume. *Thedrive.com.* https://www.thedrive.com/news/26907/you-dont-need-a-full-size-pickup-truck-you-need-a-cowboy-costume

[23] Chase, W., Whalen, J., Muller, J. (2023, January 23). Pickup Trucks: from workhorse to joyride. *Axios*. https://www.axios.com/ford-pickup-trucks-history

Moreover, Atkinson Cycle engines have been used on the Toyota Tacoma pickup V6 engine since 2017, illustrating that Atkinson Cycle engines are cost-effective for use on pickups.

For additional information see:

- ICCT 2021 comments pages 14-16
- ICCT 2018 comments pages I-2–I-12
- ICCT 2018 Camry study

## Miller cycle engine (MIL)

### Cost

It is unclear from the DRIA how MIL costs were developed and how OMEGA calculates MIL costs. Nevertheless, based on analysis of output file engine costs, MIL costs appear too high, especially as compared to base turbo costs (TDS).

Table 1 below is an excerpt from the central analysis of the proposed standards (2023_03_14_22_42_30_central_3alts_20230314_Proposal_vehicles.csv). It highlights 9 ICE vehicles which changed from being equipped with MIL to being equipped with TDS only. Note that the change from a more advanced engine (MIL) to a less advanced engine (TDS) is an artefact of the modeling and is unlikely to occur in the real world as such a change may come at the expense of reduced performance, fuel economy, or other consumer-valued function. Comparing solely the engine costs associated with a specific vehicle model (assigned to a base year vehicle ID in the table), the cost of MIL appears to be $600-$2400 more expensive than TDS. As MIL costs very little compared to a turbocharged, downsized engine such as that used in the proposal analysis to represent TDS (2016 Honda 1.5L L15B7) (see NAS 2021), the incremental costs shown in the table suggest the MIL costs are far too high. ICCT 2021 comments, ICCT 2018 comments, and NAS 2021 explain that incremental MIL costs range from $0–$250.

*Table 1. Comparison of Miller (MIL) and Turbo-downsized (TDS) engine costs*

| Base year veh ID | Model year | No. of cylinders | Displacement (L) | Cost curve class | engine cost | Cost of MIL over TDS |
|---|---|---|---|---|---|---|
| 696 | 2026 | 2 | 0.6 | MIL_TRX22_SS0 | $4,657 | $608 |
| | 2032 | 2 | 0.6 | TDS_TRX21_SS0 | $4,049 | |
| 393 | 2025 | 4 | 1.6 | MIL_TRX12_SS1 | $9,200 | $1,854 |
| | 2031 | 4 | 1.6 | TDS_TRX22_SS0 | $7,346 | |
| 10 | 2025 | 4 | 1.6 | MIL_TRX22_SS1 | $9,160 | $1,849 |
| | 2031 | 4 | 1.6 | TDS_TRX10_SS0 | $7,311 | |
| 540 | 2024 | 4 | 1.97 | MIL_TRX12_SS1 | $9,358 | $2,057 |
| | 2030 | 4 | 1.97 | TDS_TRX22_SS0 | $7,301 | |
| 9 | 2022 | 4 | 2 | MIL_TRX22_SS1 | $11,808 | $1,513 |
| | 2023 | 4 | 2 | TDS_TRX10_SS0 | $10,295 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | 2022 | 4 | 2 | MIL_TRX22_SS1 | $11,787 | $1,519 |
| | 2023 | 4 | 2 | TDS_TRX10_SS0 | $10,267 | |
| 539 | 2024 | 4 | 1.6 | MIL_TRX12_SS1 | $9,338 | $1,943 |
| | 2025 | 4 | 1.6 | TDS_TRX22_SS0 | $7,395 | |
| 610 | 2023 | 4 | 2.8 | MIL_TRX12_SS0 | $11,948 | $2,408 |
| | 2024 | 4 | 2.8 | TDS_TRX21_SS0 | $9,540 | |
| 611 | 2023 | 4 | 2.8 | MIL_TRX12_SS0 | $11,949 | $2,395 |
| | 2024 | 4 | 2.8 | TDS_TRX21_SS0 | $9,555 | |
| Column AF | Column F | Column DV | Column DT | Column AV | Column DH | Calculation |

*Note. The data in each column above was taken from the following columns in 2023_03_14_22_42_30_central_3alts_20230314_Proposal_vehicles.csv*

In prior rulemakings, EPA included the cost of ATK in the cost of MIL which led to unnecessarily high MIL costs. While it is unclear if ATK costs are included in MIL in the current proposal analysis, such an inclusion would contribute to high MIL costs.

For additional information see:

- ICCT 2021 comments page 7

## Mild hybrid (MHEV)

### Cost

The costs for position 0 (P0) MHEV are determined according to the equations in DRIA Table 2-36. In Table 2 below, by comparing these MHEV costs to those found by ICCT in 2016[24] and more recently in 2022[25], ICCT finds the EPA MHEV costs to be 2x-3x more expensive. Consequently, ICCT recommends EPA reassess and adjust its MHEV costs to better reflect the most recent data, which are summarized below. One possible source of added cost in the proposal is the identical calculation of MHEV and HEV costs (scaled by motor power). This approach may lead to an overestimate of MHEV costs because the 48V electrical systems of MHEVs do not require the same safety and electrical hardware as higher voltage HEVs. ICCT recommends adjusting MHEV cost calculations according to the table below.

*Table 2. Comparison of EPA and ICCT P0 mild hybrid (MHEV) direct manufacturing costs*

| P0 MHEV cost component | EPA Table 2-36 (2019 USD) | ICCT 2022 (2020 USD) | ICCT 2016 (2019 USD) |
|---|---|---|---|

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[24] Isenstadt, A., German, J. (ICCT), Dorobantu, M. (Eaton), Boggs, D. (Ricardo), Watson, T. (JCI). (2016). Downsized, boosted gasoline engines. https://theicct.org/publication/downsized-boosted-gasoline-engines-2/

[25] Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction. https://theicct.org/publication/mild-hybrid-emissions-jul22/ (ICCT 2022 MHEV)

| | | | |
|---|---|---|---|
| battery (kWh) | 0.53 | 0.53 | 0.53 |
| power (kW) | 15 | 15 | 15 |
| Non-battery component | | | |
| Motor + Inverter | $362 | component costs not estimated | $300 |
| Alternator ** | -- | | -$65 |
| DC-DC converter | $139 | | $150 |
| HV cables | $190 | | $0 |
| brakes & actuators | $200 | | $78 |
| Non-battery subtotal | $891 | $323 | $462 |
| Battery subtotal | $880 | $314 | $449 |
| Total | $1,771 | $637 | $911 |
| | | | |

** Alternator removal costs represented by negative cost (cost savings)

For further information, see Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). *Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction*. https://theicct.org/publication/mild-hybrid-emissions-jul22/ and

Isenstadt, A., German, J. (ICCT), Dorobantu, M. (Eaton), Boggs, D. (Ricardo), Watson, T. (JCI). (2016). *Downsized, boosted gasoline engines*. https://theicct.org/publication/downsized-boosted-gasoline-engines-2/

Beyond P0 MHEV architectures, there are substantial $CO_2$ reduction benefits achievable by implementing P1-P4 architectures, representing placement of the motor/generator in positions of increasing distance from the engine along the driveline. While such systems cost more than P0, they are more cost-effective in that they have lower cost per percent reduction in $CO_2$. Thus, ICCT recommends EPA consider including in its modeling more advanced MHEV architectures beyond P0. Additional discussion on MHEV effectiveness is in the following section. Table 3 below replicates Table 18 in ICCT 2022 MHEV. As shown in the table, P1-P4 MHEV architectures with specifications similar to P0 MHEV can increase cost by at most 53% (P4+P0 for FWD) with P4+P0 for AWD *decreasing* costs vs P0. At the same time, P2-P4 architectures can more than double P0 effectiveness. Combining the "Total" cost scaling shown in the below table with the ICCT P0 cost in the table above, all architectures have lower cost than the P0 MHEV cost used in the proposal.

*Table 3. Mild hybrid architecture cost in 2020 (ICCT 2022 MHEV, Table 18)*

| **Architecture** | **System specifications** | | **Cost normalized to P0** | | | **Effectiveness** | |
|---|---|---|---|---|---|---|---|
| | Motor | Battery | Battery | Non-battery | Total | WLTP $CO_2$ reduction | Cost per % $CO_2$ reduction normalized to P0 |
| P0 | 16 kW | 800 Wh | 1.00 | 1.00 | 1.00 | 6.6% | 1.00 |
| P1 | 15 kW | 800 Wh | 1.00 | 1.29 | 1.15 | 8.5% | 0.89 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| P2 side mounted | 16 kW | 800 Wh | 1.00 | 1.51 | 1.27 | 11.9% | 0.70 |
| P2 coaxial | 15 kW | 800 Wh | 1.00 | 1.62 | 1.32 | 14.8% | 0.59 |
| P3 | 16 kW | 800 Wh | 1.00 | 1.65 | 1.34 | 15.3% | 0.58 |
| P4+P0 vs. FWD | 15 kW+4kW | 800 Wh | 1.00 | 2.01 | 1.53 | 15.5% | 0.65 |
| P4+P0 vs. AWD | 15 kW+4kW | 800 Wh | 1.00 | 0.82 | 0.91 | 23.9% | 0.25 |

For further information, see Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction. https://theicct.org/publication/mild-hybrid-emissions-jul22/

**Effectiveness**

Outlined in the table above, MHEV architectures beyond P0 can have substantial $CO_2$-reduction benefits. However, the benefits of more advanced MHEV architectures are expected to exceed those illustrated in the table, through the implementation of higher power systems (20kW-30kW). Roush 2021 LDV[26] describes the additional benefits offered by higher power MHEV systems, including advancements in electric boosting, high energy ignition systems (see section below), accessory electrification, and electrically heated catalysts. Enabling electrically heated catalysts in particular permits further fuel economy optimization through, for example, aggressive stop-start strategies.

For additional information, see:

- Roush 2021 LDV page 11 and pages 38-40
- Roush 2021 48V[27] pages 11-23
- AVL 2020 slide 62[28]

Roush 2021 LDV provides specific example applications of high power MHEV systems and the associated fuel efficiency improvements on pickups and SUVs. These examples, which have not previously been considered by either EPA or ICCT, are excerpted below:

*Pickup/full-size SUV GHG reduction*: As ICCT previously commented, Roush 2021 states “Two powertrain configurations are recommended for study and could support future rulemaking. The first option synergistically combines available technologies (without a major redesign of the underlying engine architecture) to give maximum fuel economy benefit for a relatively low cost, hence high effectiveness. It combines a naturally aspirated DI engine with advanced cylinder deactivation and a 30kW 48V P2 mild hybrid system. The 48V hybrid system is used to actively smooth out crankshaft torque pulsations to enable aggressive cylinder deactivation strategies (advanced deac

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[26] Roush report on Gasoline Engine Technologies for Improved Efficiency (Roush 2021 LDV) https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0210

[27] Roush report on 48V and BEV costs (Roush 2021 48V) https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0210

[28] AVL Webinar on Passenger Car powertrain 4.x – Fuel Consumption, Emissions, and Cost. (2020, June 2). https://www.avl.com/-/passenger-car-powertrain-4.x-fuel-consumption-emissions-and-cost (Slides available at https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0522) (AVL 2020)

– like the Tula Skipfire System). Such a system will also enable start-stop, electric creep, regen braking, slow-speed electric driving, and a heated catalyst. Depending on system integration factors Roush estimates a reduction in GHG emissions of 20% or more, compared to a baseline naturally aspirated direct-injection V8." (Roush 2021 LDV page 13).

Additional information can be found at:

- Roush 2021 LDV Section 13.1 page 65

*Compact SUV GHG Reduction*: Relatedly, as ICCT previously commented, Roush 2021 states, "A 30kW 48-volt P2 system mated to a low bore-to-stroke ratio Miller cycle engine with electrified boosting, advanced cylinder deactivation, cooled EGR and a heated catalyst can provide a fuel economy benefit close to a full high voltage hybrid powertrain at a much lower cost. The 48V electric motor can supplement the engine torque under low- speed high load conditions, thereby avoiding this knock-prone area of the engine map. Also, the use of an advanced boosting system, combining a turbocharger and a 48V electric supercharger, will reduce engine backpressure (larger turbine) and improve scavenging, reduce combustion residuals, and reduce the propensity for knock. This combination enables the use of a higher compression ratio, thereby increasing engine efficiency. A combination of a high-energy ignition system (high energy spark plug/plasma ignition) and fuel reforming by pilot fuel injection during NVO can be used to increase cEGR tolerance at low loads. The initial part of such a project would include engine and combustion modeling, followed by prototype engine testing. The overall GHG reduction potential will require modeling and optimization of engine design, calibration parameters, and boosting system sizing and control. Roush estimates a reduction in GHG emissions exceeding 30% is possible compared to a level 1 (NHTSA) turbocharged engine." (Roush 2021 LDV page 14).

Additional information can be found at:

- Roush 2021 LDV Section 2.3 pages 23-25 on higher compression ratios and higher Miller/Atkinson ratios.
- Roush 2021 LDV Sections 2.4 and 2.5 pages 26-28 on low bore-to-stroke ratio benefits
- Roush 2021 LDV Section 13.2 page 66

## Strong hybrid (HEV)

### Cost

EPA's estimated HEV costs also appear to be overestimated. Due to the challenge of disentangling the costs and effects of both electrified and conventional powertrain component changes from one redesign to the next, ICCT examined total powertrain costs from the central analysis output file (2023_03_14_22_42_30_central_3alts_20230314_Proposal_vehicles.csv). Total powertrain costs are calculated as the sum of battery cost, electrified driveline cost, e-machine cost, driveline cost, and engine cost. For redesigns that occur between MY2023-2027, the difference in cost between the HEV powertrain and non-HEV powertrain ranges from approximately $3,400 to over $9,000. For redesigns that occur after MY2027, the HEV powertrain cost difference ranges between approximately $2,700 to over $10,000. Cost changes due to learning notwithstanding, as analyzed in ICCT's 2015 report on hybrids,[29] these levels of cost premiums are not plausible.

As with MIL costs, it is not clear precisely how HEV engine (MIL, DHE, and DHE2) costs are calculated. Regardless, as HEV engines are modeled as either Atkinson or Miller cycle engines, their costs ought to be very similar to the same types of engines on non-HEV models. As ATK and MIL are fairly inexpensive as compared to a sufficiently advanced engine (NAS 2021), modeled HEV engine costs ought not to be significantly more expensive than their non-HEV counterparts. In fact, due to the capacity of HEV motor to take up low-speed, high torque demand and transient response, HEV engines can be optimized to a narrower operating range than non-HEV engines. This can enable higher compression ratios, increase EGR dilution, and potentially decrease costs. Especially in the case of a serial hybrid or range extended PHEV, the engine is effectively decoupled from the drivetrain, permitting deep optimization, with up to 40% engine cost reduction depending on electrification.[30]

### Effectiveness

ICCT commends EPA's incorporation of advanced Atkinson and Miller cycle engines. However, the notion of a dedicated hybrid engine (DHE) extends beyond the engine maps used during ALPHA HEV simulation. ICCT recommends EPA consider even further optimized/efficient dedicated hybrid engines, both for HEV applications and for PHEVs. As described in ICCT's 2021 comments and in SAE (2021),[31] "EPA should focus on the expanded application of energy management capabilities in full hybrid powertrains to also minimize operation under the low-speed high torque areas of the engine which are prone to knocking by torque augmentation with the electric motor. The instantaneous torque capability of the electric motor can effectively support transient torque demand. This will allow both naturally aspirated and turbocharged engines that are part of a hybrid powertrain to be optimized for a narrow operating range incorporating higher compression ratios and increased EGR dilution (maintaining stoichiometric operation), thereby prioritizing efficiency over peak torque at low engine speeds and transient response." (Roush 2021 LDV page 12)

For additional information, see:

- Roush 2021 LDV Section 7.0 pages 41-44
- AVL 2020 slide 24: BSFC for Lambda=1
- AVL 2020 slides 25-26: Dedicated Hybrid Engine Efficiency Roadmaps (45% Lambda=1, 51% ideal)
- AVL 2020 slides 35-42: WLTP CO2 reduction potential of various hybrid configurations

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[29] German, J. (2015). Hybrid vehicles: Trends in technology development and cost reduction. *International Council on Clean Transportation.* https://www.theicct.org/hybrid-vehicles-trends-technology-development-and-cost-reduction

[30] SAE 2021. (2021). Optimizing hybrids for cost and efficiency. *SAE Automotive Engineering*. Page 18. https://www.nxtbook.com/smg/sae/21AE04/index.php#/p/18

[31] Ibid.

- AVL 2020 slide 43: Relative comparison of attributes for three powertrain architectures
- AVL 2020 slide 62: WLTP % CO2 reduction and slide 63: cost per % FC reduction

Such dedicated hybrid engines can achieve 45% brake thermal efficiency (BTE) at stoichiometric air-fuel ratio using known technologies,[32] or 50% BTE in a serial/range-extender with pre-chamber ignition, ultra-high pressure injection, and reduced intake air temperatures (SAE 2021).

## Negative valve overlap in-cylinder fuel reforming (NVO)

### Effectiveness

As ICCT previously commented, Roush states, “In-cylinder fuel reforming by using pilot fuel injection during NVO has shown to significantly improve cooled EGR (cEGR) tolerance, combustion stability, and engine efficiency. Such a system can have wide application in turbocharged and NA engines across different vehicle segments with minimal hardware requirements. Depending on the base engine, Roush estimates an efficiency improvement, and the corresponding reduction in GHG emissions, in the range of 5 to 10% is possible and low cost, therefore correspondingly high effectiveness.” (Roush 2021 LDV page 14).
Additional information can be found at:

- Roush 2021 LDV Section 10.0 pages 50-52
- Roush 2021 LDV Section 13.3 page 66

## Passive prechamber combustion (PPC)

### Effectiveness

As ICCT previously commented, Roush states, “Prechamber combustion systems are one of the most promising technologies for improving the dilution limit of engines, thereby improving system efficiency. It can also enable extremely fast burn rates increasing the knock tolerance of turbocharged engines, allowing higher compression ratios and the associated efficiency improvements. The Maserati Nettuno engine in the 2021 Maserati MC20 will be the first application of a passive prechamber engine in production. However, the primary objective in the MC20 is high performance. It would be very valuable to study the effect of the system on knock tolerance, burn rates, dilution tolerance (EGR and air), and emissions. The effort should focus on quantifying possible efficiency gains in a non-performance application.” (Roush 2021 LDV pages 14-15). In a dedicated hybrid engine developed by Mahle, pre-chamber combustion enabled a $CO_2$ emissions reduction of over 5%.[33]
Additional information can be found at:

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[32] Visnic, B. (2022, April). Keeping combustion in the conversation. *SAE Automotive Engineering*. Page 18. https://www.nxtbook.com/smg/sae/22AE04/index.php#/p/18

[33] Birch, S. (2019, November). Mahle reveals modular, scalable integrated hybrid powertrain. *SAE Automotive Engineering*. Page 14. https://www.nxtbook.com/nxtbooks/sae/19AUTP11/index.php#/p/14

- Roush 2021 LDV Section 13.4 page 67
- AVL 2020 slides 28, 31, and 33

## High energy ignition (HEI)

### Effectiveness

As ICCT previously commented, Roush states, “High energy volume ignition systems can enable combustion of dilute (cEGR or air diluted) in-cylinder mixtures resulting in a step-change in engine efficiency compared to conventional spark plugs. Such systems can be a drop-in replacement for a spark plug, thereby representing a cost-effective GHG improvement option. Such systems should be evaluated for maximum efficiency potential, in conventional, 48V mild hybrid, and full HV hybrid applications. Roush estimates that systems such as plasma ignition can support good combustion stability with high amounts of cooled EGR, thereby achieving engine efficiency improvements in the range of 5-10% over a baseline turbocharged DI, dual VVT engine. Microwave ignition systems, on the other hand, have the potential to achieve levels consistent with prechamber ignition systems. This would enable lean-burn engines with low engine-out NOx emissions which can achieve brake thermal efficiency which exceeds 45% in light-duty vehicle applications, compared to a level of 36-38% for a baseline turbocharged DI, dual VVT engine.” (Roush 2021 LDV page 15). Additional information can be found at:

- Roush 2021 LDV Section 11.0 pages 53-62
- Roush 2021 LDV Section 13.5 page 67

## Transmissions

### Application in OMEGA

In this proposal, EPA did not consider the application of automatic transmissions with 9 or more gear ratios. This is unrealistic, as nearly 40% of pickups were equipped with such transmissions in 2021, and EPA expects more than a quarter of all vehicles to have such transmissions in MY2022.[34] Without including the costs and benefits of transmissions with additional gears, EPA is missing important fuel-savings technology. Consequently, ICCT recommends EPA incorporate in its analysis transmissions with 9 or more gears.

## Lightweighting

### Cost

In the proposal, the only lightweighting option is the switch to an aluminum body. This is certainly a viable lightweighting option, but it is not the only one. Manufacturers have many avenues for lightweighting with various degrees of mass reduction and associated cost (NAS 2021 and ICCT 2018 comments).

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[34] EPA. (2022). Automotive Trends Report [detailed automotive trends data]. https://www.epa.gov/automotive-trends/explore-automotive-trends-data

EPA should consider adjusting its lightweighting options in its analysis to incorporate varying levels of mass reduction at vary levels of cost per unit mass saved. This methodology has been used in prior rulemakings and can fit into EPA's existing mass and cost calculations. Alternatively, EPA can add a single, discrete, intermediate lightweighting option (between the base steel body and lightweighted aluminum body) that mimics the same format as the two existing options. This intermediate option would be composed of primarily ultra-, advanced- and high strength steels (as opposed to conventional or mild steel). Such steels with optimized design can offer mass reductions on the order of 10%-15% (higher for specific parts), at costs comparable to existing steel costs.[35] More recent steel developments indicate further mass reductions are possible with both steel and better design optimization, with high strength steel costs similar to mild steel costs up to half the cost of lightweighting with Aluminum.[36]"
**From our public comments to NHTSA**:

**Outdated engine maps**
Although NHTSA scales its MY2010 hybrid Atkinson engine map to match the thermal efficiency of the MY2017 Toyota Prius, this appears to have been the only update made to the several engine maps that underpin all base and advanced engine technologies. The remaining engine maps are still primarily based on outdated engines (e.g., from MY2011, 2013 and 2014 vehicles). Even with the updated hybrid engine, the newest Toyota Prius demonstrates an additional 10% improvement over the outgoing variant,

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[35] Isenstadt, A. and German, J. (ICCT); Piyush Bubna and Marc Wiseman (Ricardo Strategic Consulting); Umamaheswaran Venkatakrishnan and Lenar Abbasov (SABIC); Pedro Guillen and Nick Moroz (Detroit Materials); Doug Richman (Aluminum Association), Greg Kolwich (FEV). Lightweighting technology development and trends in U.S. passenger vehicles, (2016, December 19). http://www.theicct.org/lightweighting-technology-development-and-trends-us-passenger-vehicles

[36] Brooke, L. (2019, May). The economics of materials selection. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Gehm, R. (2019, September). Latest mass-reducing innovations honored by Altair. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Visnic, B., Brooke, L. (2019, September). Stuck on structural adhesives. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Weissler, P. (2019, October). Cutting weight seen as less vital for automated and shared vehicles. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Gehm, R. (2020, September). Altair honors lightweight advances. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Macek. B. (FCA), Lutz, J. (US Steel). (2020, September). Virtual and physical testing of Third-generation High Strength Steel. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Vartanov, G. (2021, June). Lightweight steel on a (cold) roll. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Gehm, R. (2021, September). Altair honors weight-saving innovations. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Brooke, L. (2022, September). A materials lesson in Civics. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Gehm, R. (2022, September). Altair honors innovations in sustainability and lightweighting. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues; Brooke, L. (2023, March). Battle for the box. *SAE Automotive Engineering*. https://www.sae.org/publications/magazines/automotive-engineering/past-issues

due in part to improvements in engine efficiency.[37] For additional information, see ICCT 2021 comments page 3-4.

**Turbocharging effectiveness**

EPA added a 2nd generation turbocharged downsized engine package based on EPA benchmark testing of the Honda L15B7 1.5L turbocharged, direct-injection engine to its 2018 mid-term evaluation, which was not used in NHTSA's proposed rule.[38]

**HCR engine effectiveness**

EPA added an engine map in its 2018 mid-term evaluation for Atkinson (ATK2+CEGR) technology based on EPA benchmark testing of the MY2018 Camry 2.5L A25A FKS engine. However, NHTSA's proposed rule appears to continue to use developmental engine test data and GT-POWER engine modeling.[39]

**Cylinder Deactivation on Turbocharged Vehicles and HCR engines**

The modeled benefit of adding cylinder deactivation (DEAC) to turbocharged and HCR engines appears to be only about 25% of the benefit of adding DEAC to the base engine.[40] While DEAC added to turbo or HCR engines will have lower pumping loss reductions than when added to base naturally aspirated engines, DEAC can still be expected to provide significant pumping loss reductions while enabling the engine to operate in a more thermally efficient region of the engine map. For additional information, see ICCT 2021 comments page 5.

**Engine downsizing and secondary mass reduction restrictions**

For this proposal, NHTSA continues to only downsize engines for large changes in tractive load. As commented previously, this artificially increases the overall performance of the fleet, the consumer benefits of which the proposed rule does not address. ICCT recommends to always model the appropriate amount of engine downsizing to maintain performance. For additional information, see ICCT 2021 comments page 5.

**Strong hybrid**

As mentioned earlier, NHTSA relies on hybrid engine effectiveness that may already be outdated compared to what is currently available on the market. Moreover, NHTSA assumes no additional hybrid powertrain improvements. This is unrealistic, as, for example, every subsequent generation of Toyota's hybrid system significantly improves

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[37] COMMENTS BY JOHN GERMAN AND JOHN D. GRAHAM ON EPA'S NPRM CONTAINING NEW CO2 STANDARDS FOR LIGHT-DUTY AND MEDIUM-DUTY VEHICLES, MODEL YEARS 2027-2032 (2023, July 5). Docket ID No. EPA–HQ– OAR–2022–0829. Comment ID EPA-HQ-OAR-2022-0829-0585. https://www.regulations.gov/comment/EPA-HQ-OAR-2022-0829-0585

[38] Stuhldreher, M., Kargul, J., Barba, D., McDonald, J., Bohac, S., Dekraker, P., & Moskalik, A. (2018). Benchmarking a 2016 Honda Civic 1.5-liter L15B7 turbocharged engine and evaluating the future efficiency potential of turbocharged engines. SAE International journal of engines, 11(6), 1273.

[39] Kargul, J., Stuhldreher, M., Barba, D., Schenk, C., Bohac, S., McDonald, J., & Dekraker, P. (2019). Benchmarking a 2018 Toyota Camry 2.5-liter Atkinson Cycle Engine with Cooled-EGR. SAE International Journal of Advances and Current Practices in Mobility, 1(2), 601.

[40] Draft Technical Support Document Figure 3-10

upon the prior generation’s efficiency.[41] ICCT recommends NHTSA include at least one future hybrid system improvement beyond that which is already modeled. ICCT also recommends NHTSA allow hybridization on all vehicle types, as well as carefully consider updated costs. Additional information on hybrid system costs, effectiveness, and applicability can be found in ICCT 2021 comments, pages 21-25.

## New technology studies

As mentioned previously, several new studies describe promising technology trends that have yet to be incorporated into NHTSA’s modeling of the proposed standards (footnoted above: AVL 2020, Roush 2021 LDV, Roush 2021 48V, ICCT 2022 MHEV).

### 48V Mild Hybrids (MHEV)

ICCT estimated the cost of position 0 (P0) MHEV systems in 2016[42] and more recently in 2022[43], finding substantial reductions in cost. These costs are presented in **Error! Reference source not found.**. Alongside ICCT’s estimates are those from NHTSA used in this proposal.[44] As the table clearly shows, proposed MHEV costs are higher than ICCT’s current estimates. These higher costs appear to be due to higher component cost per kW or cost per kWh. If NHTSA P0 MHEV costs were scaled up to match the specifications of ICCT’s P0 system, the NHTSA costs would be even higher. ICCT believes that NHTSA could reduce its P0 MHEV costs accordingly.

*Table 4. Comparison of NHTSA, ICCT 2016 and 2022 P0 mild hybrid (MHEV) direct manufacturing costs*

| P0 MHEV cost component | Proposal (MY2022) | ICCT 2022 (2021 USD) | ICCT 2016 (2019 USD) |
|---|---|---|---|
| battery (kWh) | 0.403 | 0.53 | 0.53 |
| power (kW) | 10 | 15 | 15 |
| Non-battery component | | | |
| Motor + Inverter | component costs not estimated | component costs not estimated | $300 |
| Alternator ** | | | -$65 |
| DC-DC converter | | | $150 |
| HV cables | | | $0 |
| brakes & actuators | | | $78 |

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[41] COMMENTS BY JOHN GERMAN AND JOHN D. GRAHAM ON EPA’S NPRM CONTAINING NEW CO2 STANDARDS FOR LIGHT-DUTY AND MEDIUM-DUTY VEHICLES, MODEL YEARS 2027-2032 (2023, July 5). Docket ID No. EPA–HQ– OAR–2022–0829. Comment ID EPA-HQ-OAR-2022-0829-0585. https://www.regulations.gov/comment/EPA-HQ-OAR-2022-0829-0585

[42] Isenstadt, A., German, J. (ICCT), Dorobantu, M. (Eaton), Boggs, D. (Ricardo), Watson, T. (JCI). (2016). Downsized, boosted gasoline engines. https://theicct.org/publication/downsized-boosted-gasoline-engines-2/

[43] Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction. https://theicct.org/publication/mild-hybrid-emissions-jul22/ (ICCT 2022 MHEV)

[44] Draft TSD Table 3-88, total costs in Table 3-88 have been divided by the RPE (1.5) to compare with ICCT’s direct costs.

| | | | |
|---|---|---|---|
| Non-battery subtotal | $418 | $340 | $462 |
| Battery subtotal | $283 | $331 | $449 |
| Total | $701 | $671 | $911 |
| ** Alternator removal costs represented by negative cost (cost savings) | | | |

For further information, see Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). *Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction*. https://theicct.org/publication/mild-hybrid-emissions-jul22/ and

Isenstadt, A., German, J. (ICCT), Dorobantu, M. (Eaton), Boggs, D. (Ricardo), Watson, T. (JCI). (2016). *Downsized, boosted gasoline engines*. https://theicct.org/publication/downsized-boosted-gasoline-engines-2/

Beyond P0 MHEV architectures, there are substantial fuel savings benefits achievable by implementing P1-P4 architectures, representing placement of the motor/generator in positions of increasing distance from the engine along the driveline. While such systems cost more than P0, they are more cost-effective in that they have lower cost per percent reduction in fuel consumption. Thus, ICCT finds that NHTSA could consider including in its modeling more advanced MHEV architectures beyond P0.

**Error! Reference source not found.** below replicates Table 18 in ICCT 2022 MHEV. As shown in the table, P1-P4 MHEV architectures with specifications similar to P0 MHEV can increase cost by at most 53% (P4+P0 for FWD) with P4+P0 for AWD *decreasing* costs vs P0. At the same time, P2-P4 architectures can more than double P0 effectiveness.

*Table 5. Mild hybrid architecture cost in 2020 (ICCT 2022 MHEV, Table 18)*

| **Architecture** | **System specifications** | | **Cost normalized to P0** | | | **Effectiveness** | |
|---|---|---|---|---|---|---|---|
| | Motor | Battery | Battery | Non-battery | Total | WLTP $CO_2$ reduction | Cost per % $CO_2$ reduction normalized to P0 |
| P0 | 16 kW | 800 Wh | 1.00 | 1.00 | 1.00 | 6.6% | 1.00 |
| P1 | 15 kW | 800 Wh | 1.00 | 1.29 | 1.15 | 8.5% | 0.89 |
| P2 side mounted | 16 kW | 800 Wh | 1.00 | 1.51 | 1.27 | 11.9% | 0.70 |
| P2 coaxial | 15 kW | 800 Wh | 1.00 | 1.62 | 1.32 | 14.8% | 0.59 |
| P3 | 16 kW | 800 Wh | 1.00 | 1.65 | 1.34 | 15.3% | 0.58 |
| P4+P0 vs. FWD | 15 kW+4kW | 800 Wh | 1.00 | 2.01 | 1.53 | 15.5% | 0.65 |
| P4+P0 vs. AWD | 15 kW+4kW | 800 Wh | 1.00 | 0.82 | 0.91 | 23.9% | 0.25 |

For further information, see Dornoff, J., German, J., Deo, A. (ICCT), Dimaratos, A. (DITENCO). (2022). Mild-hybrid vehicles: a near term technology trend for $CO_2$ emissions reduction. https://theicct.org/publication/mild-hybrid-emissions-jul22/

Outlined in the table above, MHEV architectures beyond P0 can have substantial fuel savings benefits. However, the benefits of more advanced MHEV architectures are expected to exceed those illustrated in the table, through the implementation of higher power systems (20kW-30kW). Roush 2021 LDV[45] describes the additional benefits offered by higher power MHEV systems, including advancements in electric boosting, high energy ignition systems (see section below), accessory electrification, and electrically heated catalysts. Enabling electrically heated catalysts in particular permits further fuel economy optimization through, for example, aggressive stop-start strategies.

For additional information, see:

- Roush 2021 LDV page 11 and pages 38-40
- Roush 2021 48V[46] pages 11-23
- AVL 2020 slide 62[47]

Roush 2021 LDV provides specific example applications of high power MHEV systems and the associated fuel efficiency improvements on pickups and SUVs. These examples, which have not previously been considered by either NHTSA or ICCT, are excerpted below:

*Pickup/full-size SUV GHG reduction*: As ICCT previously commented, Roush 2021 states "Two powertrain configurations are recommended for study and could support future rulemaking. The first option synergistically combines available technologies (without a major redesign of the underlying engine architecture) to give maximum fuel economy benefit for a relatively low cost, hence high effectiveness. It combines a naturally aspirated DI engine with advanced cylinder deactivation and a 30kW 48V P2 mild hybrid system. The 48V hybrid system is used to actively smooth out crankshaft torque pulsations to enable aggressive cylinder deactivation strategies (advanced deac – like the Tula Skipfire System). Such a system will also enable start-stop, electric creep, regen braking, slow-speed electric driving, and a heated catalyst. Depending on system integration factors Roush estimates a reduction in GHG emissions of 20% or more, compared to a baseline naturally aspirated direct-injection V8." (Roush 2021 LDV page 13).
Additional information can be found at:

- Roush 2021 LDV Section 13.1 page 65

*Compact SUV GHG Reduction*: Relatedly, as ICCT previously commented, Roush 2021 states, "A 30kW 48-volt P2 system mated to a low bore-to-stroke ratio Miller cycle engine with electrified boosting, advanced cylinder deactivation, cooled EGR and a heated catalyst can provide a fuel economy benefit close to a full high voltage hybrid powertrain at a much lower cost. The 48V electric motor can supplement the engine torque under low- speed high load conditions, thereby avoiding this knock-prone area of the engine map. Also, the use of an advanced boosting system, combining a

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[45] Roush report on Gasoline Engine Technologies for Improved Efficiency (Roush 2021 LDV) https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0210

[46] Roush report on 48V and BEV costs (Roush 2021 48V) https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0210

[47] AVL Webinar on Passenger Car powertrain 4.x – Fuel Consumption, Emissions, and Cost. (2020, June 2). https://www.avl.com/-/passenger-car-powertrain-4.x-fuel-consumption-emissions-and-cost (Slides available at https://www.regulations.gov/comment/EPA-HQ-OAR-2021-0208-0522) (AVL 2020)

turbocharger and a 48V electric supercharger, will reduce engine backpressure (larger turbine) and improve scavenging, reduce combustion residuals, and reduce the propensity for knock. This combination enables the use of a higher compression ratio, thereby increasing engine efficiency. A combination of a high-energy ignition system (high energy spark plug/plasma ignition) and fuel reforming by pilot fuel injection during NVO can be used to increase cEGR tolerance at low loads. The initial part of such a project would include engine and combustion modeling, followed by prototype engine testing. The overall GHG reduction potential will require modeling and optimization of engine design, calibration parameters, and boosting system sizing and control. Roush estimates a reduction in GHG emissions exceeding 30% is possible compared to a level 1 (NHTSA) turbocharged engine." (Roush 2021 LDV page 14).
Additional information can be found at:

- Roush 2021 LDV Section 2.3 pages 23-25 on higher compression ratios and higher
  Miller/Atkinson ratios.
- Roush 2021 LDV Sections 2.4 and 2.5 pages 26-28 on low bore-to-stroke ratio benefits
- Roush 2021 LDV Section 13.2 page 66

**Dedicated hybrid engines**
In addition to ICCT's recommendation for improved future hybrid system efficiency, ICCT finds that NHTSA could consider even further optimized/efficient *dedicated* hybrid engines, both for HEV applications and for PHEVs. Due to the capacity of hybrid vehicles' (HEV) electric motor to take up low-speed, high torque demand and transient response, HEV engines can be optimized to a narrower operating range than non-HEV engines. This can enable higher compression ratios, increase EGR dilution, and potentially decrease costs. Especially in the case of a serial hybrid or range-extended PHEV, the engine is effectively decoupled from the drivetrain, permitting deep optimization, with up to 40% engine cost reduction depending on electrification.[48]

As described in ICCT's 2021 comments and in SAE (2021),[49] NHTSA should consider "the expanded application of energy management capabilities in full hybrid powertrains to also minimize operation under the low-speed high torque areas of the engine which are prone to knocking by torque augmentation with the electric motor. The instantaneous torque capability of the electric motor can effectively support transient torque demand. This will allow both naturally aspirated and turbocharged engines that are part of a hybrid powertrain to be optimized for a narrow operating range incorporating higher compression ratios and increased EGR dilution (maintaining stoichiometric operation), thereby prioritizing efficiency over peak torque at low engine speeds and transient response." (Roush 2021 LDV page 12)
For additional information, see:

- Roush 2021 LDV Section 7.0 pages 41-44
- AVL 2020 slide 24: BSFC for Lambda=1

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[48] SAE 2021. (2021). Optimizing hybrids for cost and efficiency. *SAE Automotive Engineering*. Page 18. https://www.nxtbook.com/smg/sae/21AE04/index.php#/p/18

[49] Ibid.

- AVL 2020 slides 25-26: Dedicated Hybrid Engine Efficiency Roadmaps (45% Lambda=1, 51% ideal)
- AVL 2020 slides 35-42: WLTP CO2 reduction potential of various hybrid configurations
- AVL 2020 slide 43: Relative comparison of attributes for three powertrain architectures
- AVL 2020 slide 62: WLTP % CO2 reduction and slide 63: cost per % FC reduction

Such dedicated hybrid engines can achieve 45% brake thermal efficiency (BTE) at stoichiometric air-fuel ratio using known technologies,[50] or 50% BTE in a serial/range-extender with pre-chamber ignition, ultra-high pressure injection, and reduced intake air temperatures (SAE 2021).

**Negative valve overlap in-cylinder fuel reforming (NVO)**

As ICCT previously commented, Roush states, “In-cylinder fuel reforming by using pilot fuel injection during NVO has shown to significantly improve cooled EGR (cEGR) tolerance, combustion stability, and engine efficiency. Such a system can have wide application in turbocharged and NA engines across different vehicle segments with minimal hardware requirements. Depending on the base engine, Roush estimates an efficiency improvement…in the range of 5 to 10% is possible and low cost, therefore correspondingly high effectiveness.” (Roush 2021 LDV page 14).
Additional information can be found at:

- Roush 2021 LDV Section 10.0 pages 50-52
- Roush 2021 LDV Section 13.3 page 66

**Passive prechamber combustion (PPC)**

As ICCT previously commented, Roush states, “Prechamber combustion systems are one of the most promising technologies for improving the dilution limit of engines, thereby improving system efficiency. It can also enable extremely fast burn rates increasing the knock tolerance of turbocharged engines, allowing higher compression ratios and the associated efficiency improvements. The Maserati Nettuno engine in the 2021 Maserati MC20 will be the first application of a passive prechamber engine in production. However, the primary objective in the MC20 is high performance. It would be very valuable to study the effect of the system on knock tolerance, burn rates, dilution tolerance (EGR and air), and emissions. The effort should focus on quantifying possible efficiency gains in a non-performance application.” (Roush 2021 LDV pages 14-15). In a dedicated hybrid engine developed by Mahle, pre-chamber combustion enabled an efficiency improvement of over 5%.[51]
Additional information can be found at:

- Roush 2021 LDV Section 13.4 page 67
- AVL 2020 slides 28, 31, and 33

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[50] Visnic, B. (2022, April). Keeping combustion in the conversation. *SAE Automotive Engineering*. Page 18. https://www.nxtbook.com/smg/sae/22AE04/index.php#/p/18

[51] Birch, S. (2019, November). Mahle reveals modular, scalable integrated hybrid powertrain. *SAE Automotive Engineering*. Page 14. https://www.nxtbook.com/nxtbooks/sae/19AUTP11/index.php#/p/14

### High energy ignition (HEI)

As ICCT previously commented, Roush states, "High energy volume ignition systems can enable combustion of dilute (cEGR or air diluted) in-cylinder mixtures resulting in a step-change in engine efficiency compared to conventional spark plugs. Such systems can be a drop-in replacement for a spark plug, thereby representing a cost-effective GHG improvement option. Such systems should be evaluated for maximum efficiency potential, in conventional, 48V mild hybrid, and full HV hybrid applications. Roush estimates that systems such as plasma ignition can support good combustion stability with high amounts of cooled EGR, thereby achieving engine efficiency improvements in the range of 5-10% over a baseline turbocharged DI, dual VVT engine. Microwave ignition systems, on the other hand, have the potential to achieve levels consistent with prechamber ignition systems. This would enable lean-burn engines with low engine-out NOx emissions which can achieve brake thermal efficiency which exceeds 45% in light-duty vehicle applications, compared to a level of 36-38% for a baseline turbocharged DI, dual VVT engine." (Roush 2021 LDV page 15). Additional information can be found at:

- Roush 2021 LDV Section 11.0 pages 53-62
- Roush 2021 LDV Section 13.5 page 67

### Atkinson cycle engine restrictions (HCR, HCRE, HCRD)

NHTSA inappropriately prevents the application of HCR engines on engines with more than 405 horsepower, pickup trucks and vehicles that share engines with pickup trucks, or performance-focused manufacturers.[52]

As discussed in ICCT 2021 comments, engines in pickup trucks and high-performance vehicles are sized and powered to handle higher peak loads. This means larger engines operate at lower loads relative to their maximum capacity on the 2-cycle test – and during most real-world driving. This, in turn, means that pickup trucks and high-performance vehicles will spend more time in Atkinson Cycle operation than lower performance vehicles on both the test cycles and in the real world. This includes time spent towing, which represents a very small fraction of light-duty pickup usage.[53,54] Altogether, most light-duty pickup trucks spend the vast majority of driving at low loads relative to the engine's capability, where Atkinson Cycle engines are very effective. In other words, HCR is likely a highly cost-effective technology for pickup trucks. Furthermore, the claim that an Atkinson Cycle engine that switches to Otto cycle on demand cannot provide the additional torque reserve is not accurate (a claim previously used to justify blocking HCR on pickups in prior rulemakings, see ICCT 2021 comments).

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[52] Draft TSD, Section 3.1.3.3, page 3-26

[53] Berk, B. (2019, March 13). You Don't Need a Full-Size Pickup Truck, You Need a Cowboy Costume. *Thedrive.com.* https://www.thedrive.com/news/26907/you-dont-need-a-full-size-pickup-truck-you-need-a-cowboy-costume

[54] Chase, W., Whalen, J., Muller, J. (2023, January 23). Pickup Trucks: from workhorse to joyride. *Axios*. https://www.axios.com/ford-pickup-trucks-history

Moreover, Atkinson Cycle engines have been used on the Toyota Tacoma pickup V6 engine since 2017, illustrating that Atkinson Cycle engines are cost-effective for use on pickups.

For additional information see:

- ICCT 2021 comments pages 25-28
- ICCT 2018 comments pages I-2–I-12
- ICCT 2018 Camry study