WORKING PAPER

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Hybrid vehicle technology developments and opportunities in the 2025–2035 time frame

Aaron Isenstadt and Peter Slowik

SUMMARY

In the United States, greenhouse gas (GHG) emission standards have assisted in the proliferation of electric vehicles without requiring GHG emission reductions for each specific powertrain. Indeed, fleet-average emission standards can be met with greatly increased sales of zero-emission vehicles and little or no improvement in the combustion engine-based fleet. In its final rulemaking for model years 2027–2032, the U.S. Environmental Protection Agency projected that its rule could result in a 68% electric vehicle sales share (consisting of 56% battery electric and 13% plug-in hybrid electric) by 2032 and at the same time, the average emissions of the remaining non-electric-vehicle fleet would increase (U.S. Environmental Protection Agency, 2024b). This phenomenon is referred to as "backsliding."

At the state level, the California Air Resources Board has observed with its fleet averaging standards that increasing sales of zero-emission vehicles creates a risk of combustion engine vehicle backsliding. The increase in emissions may result from a variety of factors, including manufacturers discontinuing models with low carbon dioxide (CO_2) emissions, converting low-emitting combustion models to zero-emission vehicles, removing CO_2-reducing technologies on individual models, or neglecting to implement CO_2-reducing technologies while calibrating vehicles for improved performance only. Given the backsliding risk, the California Air Resources Board has proposed to promulgate standards that will ensure emissions from vehicles sold in the state with internal combustion engines (ICEs)—including plug-in hybrids—continue to improve (California Air Resources Board, 2024).

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www.theicct.org

communications@theicct.org

@theicct.org

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Of the readily available technologies automakers can implement cost-effectively beginning in 2025, strong hybrid electric vehicles represent the maximum level of GHG reductions achievable in non-plug-in vehicles demonstrated through 2024. This working paper therefore examines the extent to which strong hybridization technologies already in production and near production can reduce CO_2 emissions from new ICE vehicles. We also assess the cost-effectiveness of those technologies and how they could be used for compliance with a GHG standard for ICE vehicles. The analysis focuses on strong hybridization as a guidepost to estimate the potential for deep combustion vehicle CO_2 reductions based on already available and near future technologies. Supported by continued reductions in aerodynamic drag, mass, and rolling resistance (i.e., road loads), we show that improvements in engine and drivetrain efficiency through hybridization can enable automakers to significantly reduce the GHG emissions throughout their ICE-based fleets, including emissions from plug-in hybrid vehicles.

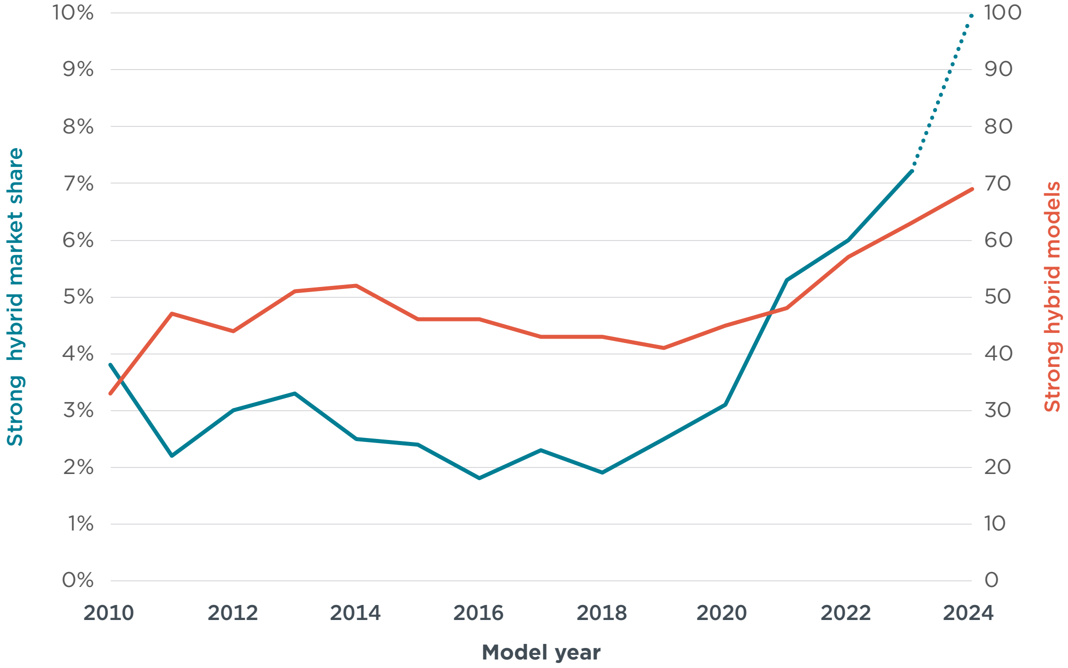
Results also show that a regulatory structure with more stringent standards that encourage hybridization of the remaining ICE fleet are achievable and cost-effective for automakers and consumers alike, and the benefits would carry on for years in the form of lower GHG emissions and thousands of dollars in fuel savings for buyers. Specifically, compared with an equivalent non-hybrid vehicle, strong hybrids in 2024 provide on average a 30% reduction in tailpipe GHG emissions at an average price premium of $2,000, with average 10-year fuel cost savings of $4,500. Future strong hybrids can provide an additional 15% reduction in GHG emissions at an average additional price premium of between $300 and $800.

THE U.S. HYBRID ELECTRIC VEHICLE MARKET

After the introduction of strong hybrid electric vehicles (HEVs) in the United States in 2001, their market share grew to 3.8% in model year (MY) 2010 and thereafter hovered between 1.8% and 3.1% through MY 2020. From MY 2010 to MY 2020, there were between 33 and 52 HEV models (including subconfigurations) available for purchase each year. These trends are illustrated in Figure 1, which also shows that after MY 2020, the HEV sales share nearly tripled, reaching 7.2% in MY 2023 and, based on preliminary data, is expected to be about 10% for MY 2024. During this time, the number of strong hybrid models available for sale in the United States increased from 33 in 2010 to 69 in 2024. The California new vehicle market also followed this upward trend: After hovering around 5% through calendar year 2020, strong HEVs occupied 13.8% of California's new fleet through September 2024 (Auto Outlook Inc., 2024b).

Figure 1

Hybrid electric vehicle market share and model availability in the United States, model years 2010–2024



Source: U.S. Environmental Protection Agency (2024); Hula et al. (2024)

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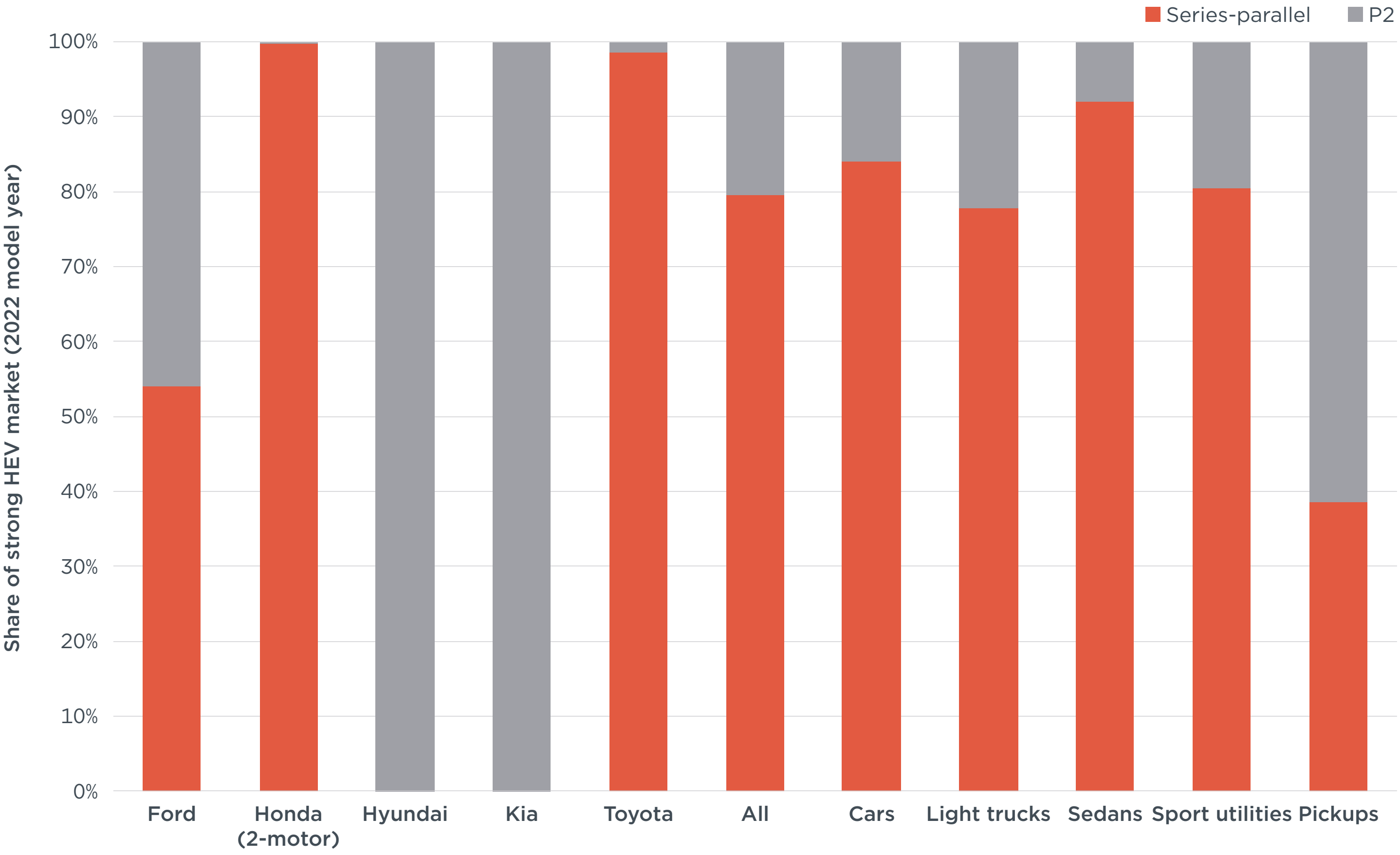
In MY 2022, just five manufacturers sold the 57 HEV models available in the United States: Ford, Honda, Hyundai, Kia, and Toyota. As of mid-2024, the number of MY 2024 HEV models available for sale increased to 69, and the small group of automakers producing these vehicles remained unchanged.

There are two primary architectures for strong hybridization used today in the United States: P2 and series-parallel. In P2 hybrids, the electric motor is located between the engine and the transmission. P2 hybrid architecture is commonly seen on all Hyundai and Kia HEVs, and on large pickups or sport utility vehicles (SUVs) that require towing capabilities. In 2024, series-parallel hybrids come in two varieties: input powersplit and 2-motor. Powersplit, used by Toyota and Ford, relies on a planetary gearset (the powersplit device) instead of a conventional transmission to divide and distribute power from the engine in series or in parallel with a motor/generator unit. Like powersplit HEVs, Honda's 2-motor hybrid systems also do away with a conventional transmission; unlike powersplits, Honda's 2-motor systems use a clutch to transmit power from the engine directly to the wheels during highway operation.

In MY 2022, series-parallel systems occupied 80% of the strong HEV market in the United States. Figure 2 shows the mix of hybrid system types that year by manufacturer and vehicle class. Toyota, with nearly three-fifths of the HEV market for MY 2022, used powersplit for all but a few high-power applications, namely the hybrid Tundra pickup truck. Ford and Honda each held around 14% of the HEV market. Ford sold roughly half powersplit and half P2 hybrids, whereas Honda only sold its 2-motor hybrids. Hyundai and Kia each sold exclusively P2 hybrids. Although the relative share of powersplit and P2 hybrids is fairly close between the regulatory classes of cars and light trucks, sedan HEVs are over 90% powersplit, while SUVs are 80% and pickups are around 40%.

Figure 2
Market share of HEV architectures by manufacturer in model year 2022



Source: National Highway Traffic Safety Administration (2024)

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CO_2 REDUCTIONS FROM HYBRID TECHNOLOGY

2023–2024 HYBRID ELECTRIC VEHICLE TECHNOLOGY

Some manufacturers offer both a non-hybrid and a hybrid variant of a vehicle model. These vehicle pairs allow for a direct comparison of the relative GHG emissions between the technologies. Using official fuel economy guides for MY 2023 and MY 2024, 86 HEV models were found to have a non-hybrid variant out of a total of 133 HEV models (U.S. Environmental Protection Agency [EPA], 2024a). These guides list the fuel economy of each vehicle over the city and highway drive cycles, as well as the combined “2-cycle” fuel economy of both cycles. Comparing the 2-cycle combined fuel consumption data for each pair revealed that HEVs reduce fuel consumption, and by extension CO_2 emissions, by as much as 40%. The average CO_2 reductions for P2 and series-parallel HEVs for each manufacturer are shown in Table 1. For Ford and Toyota, P2 applications are limited to large, high-power pickups and SUVs with relatively smaller electric motors compared with other P2 and powersplit hybrids. Engines on these vehicles may also be tuned for high-load applications, rather than for maximizing efficiency and minimizing CO_2 emissions, and that leads to much smaller efficiency gains. In contrast, the P2 hybrids of Hyundai and Kia demonstrate average CO_2 reductions equivalent to the series-parallel hybrids of Toyota, Ford, and Honda. The average CO_2 reduction in 2-cycle CO_2 emissions for these hybrid applications ranges from 30%–36%, depending on the segment.

Table 1

Average CO_2 reduction achieved by model years 2023 and 2024 hybrid electric vehicles compared with non-hybrid variant

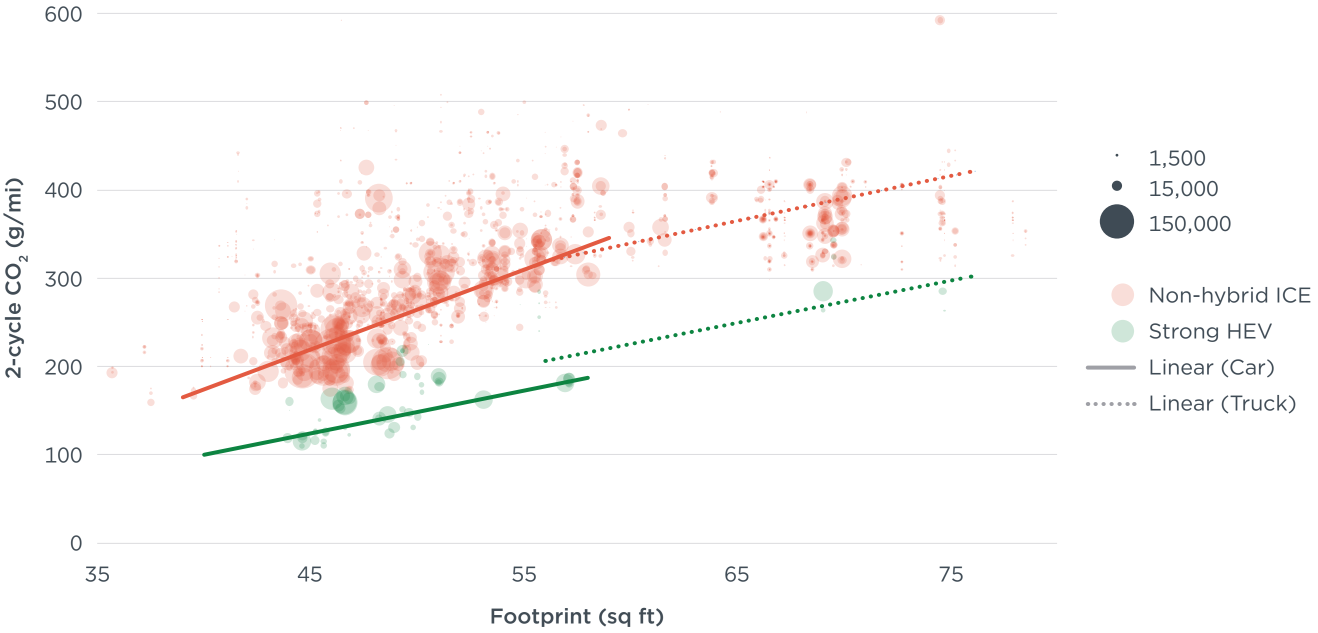
P2 hybrid			
	Pickup	**SUV**	**Car**
Toyota	-9%		
Ford	-17%	-15%	
Honda			
Hyundai		-32%	-35%
Kia		-32%	
All	-11%	-29%	-35%
Series-parallel hybrid			
	Pickup	**SUV**	**Car**
Toyota		-32%	-30%
Ford	-36%	-28%	
Honda		-27%	-32%
Hyundai			
Kia			
All	-36%	-31%	-30%

In addition to non-plug-in strong HEVs, plug-in hybrid electric vehicles (PHEVs) also rely on combustion and are expected to grow in market share in the United States over the next decade. While operating in charge-sustaining mode, when gasoline is the only source of motive energy, the reductions in GHG emissions from PHEVs when compared with non-hybrid ICE vehicles are similar to that of HEVs, but PHEVs tend to have slightly higher charge-sustaining GHG emissions than HEVs due to a combination of factors, including the higher mass of PHEVs because of their much larger batteries. Using MY 2024 fuel economy guides, five PHEV models were identified that have non-plug-in HEV variants, and 14 PHEV models were identified that have non-hybrid ICE variants (EPA, 2024a). Calculated from combined 2-cycle charge-sustaining fuel consumption, as reported in EPA's fuel economy guides, CO_2 emissions from PHEVs operating in charge-sustaining mode were found to be 1.4%–6.9% higher than corresponding HEV variants. When compared with non-hybrid ICE counterparts, the PHEV models exhibited 11%–32% lower CO_2 emissions. Thus, although PHEV emissions during charge-sustaining mode are slightly higher than non-plug-in HEVs, they still show emissions improvement versus non-hybrid ICE vehicles on par with non-plug-in HEVs. Additionally, as discussed later in this paper, virtually all future cost and CO_2 reduction opportunities for strong HEVs also apply to PHEVs.

In addition to the model-specific GHG reductions from the direct comparisons above, comparing the fleet-average GHG emissions of strong HEVs and non-hybrid vehicles also provides an approximation of the degree of emission reductions available. In plotting MY 2022 sales, footprint, and combined 2-cycle CO_2 emissions for every model (National Highway Traffic Safety Administration, 2024), Figure 3 compares the entire MY 2022 fleet of non-hybrid ICE vehicles with strong HEVs. Each bubble represents one model, and the size of the bubble indicates the relative sales for that model. The lines represent sales-weighted linear regressions of their respective fleet. Both the non-hybrid ICE fleet and the HEV fleet show some deviation from their linear regressions, as expected. Nevertheless, the trend is clear that hybridization provides a significant reduction in CO_2 emissions.

Figure 3

Two-cycle CO_2 emissions as a function of footprint of all model year 2022 non-hybrid ICE vehicles and strong HEVs



Note: Bubble size represents relative sales. Linear regressions shown for the regulatory car class (solid lines) and truck class (dashed).
Source: Derived from National Highway Traffic Safety Administration (2024)

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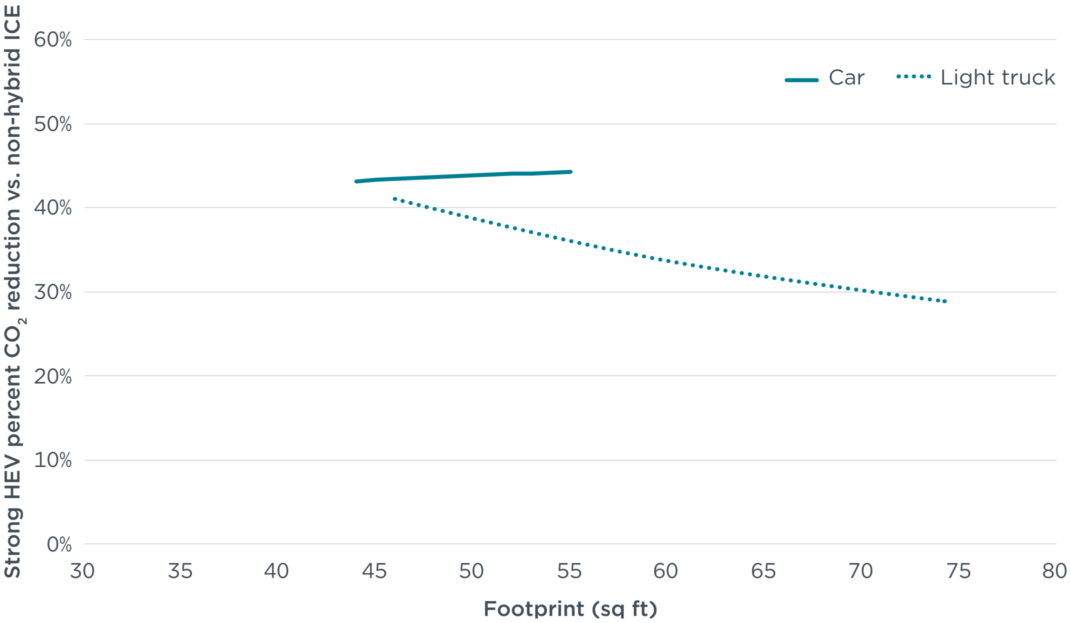
Taking the difference between the sales-weighted regression curves leads to the HEV improvement curves shown in Figure 4. These improvement curves are plotted over the range of footprints corresponding to actual HEV models sold in MY 2022. The percent reduction in average CO_2 emissions due to hybridization is 43%–44% for cars and 29%–41% for light trucks, which includes SUVs. The HEV percent improvement for cars is relatively flat across footprints, corresponding to the increased difference in absolute g CO_2/mile between HEV and non-HEV as footprint increases, as shown in Figure 3. Conversely, the HEV percent improvement for light trucks decreases with footprint. This decrease corresponds to a nearly constant difference between HEV and non-HEV absolute g CO_2/mile across footprint, visible in Figure 3. The decreasing efficacy of hybridization with increasing footprint of light trucks may be due to manufacturers calibrating larger trucks for high-load performance rather than efficiency and relying on smaller motors relative to vehicle size than cars and smaller light trucks. These levels of improvement are based on fleet-level average 2-cycle data and not the individual model-level improvement due to hybridization. If automakers prioritized truck hybridization for efficiency while still maintaining performance as they do for other vehicle types, the light truck curves in Figure 4 would be flatter. As discussed above, assessment of hybridization at the model-level tends to show lower average CO_2 improvement than assessment at the fleet-level. This is mainly due to the broad spread of non-hybrid ICE vehicle CO_2 emissions, which at the fleet scale results in higher relative CO_2 emissions compared with the HEV fleet average. Both the fleet-level and model-level comparisons clearly show that the climate benefits of HEV systems relative to non-hybrid ICEs in 2023–2024 are substantial.

Figure 4

Average reduction in fleet 2-cycle CO_2 emissions due to hybridization



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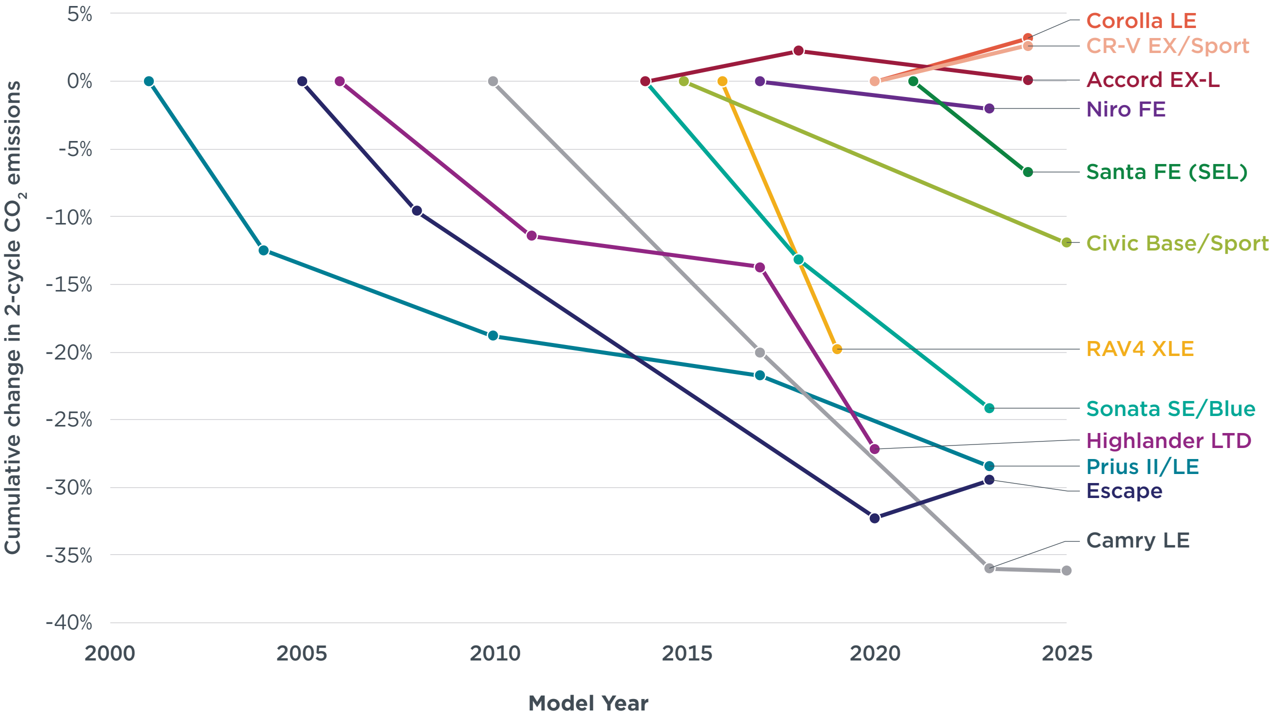
HISTORICAL IMPROVEMENT TRENDS – STRONG HYBRIDS

Examining the history of CO_2 emissions of strong HEVs shows how HEVs have consistently improved. To illustrate automaker capacity for reducing the CO_2 emissions of HEVs, we identified 12 HEV models available in 2024 with one or more previous generations. These vehicles are plotted in Figure 5. The Prius, first introduced in the early 2000s, has undergone several redesigns that have led to a nearly 30% cumulative reduction in 2-cycle CO_2 emissions since introduction. The Camry, RAV4, Highlander, Escape, and Sonata HEVs also exhibit similar patterns of efficiency improvement with each generation. The Kia Niro, Hyundai Santa Fe, and Honda Civic also show generational improvements, although to a lesser degree than the Toyota models.

Figure 5

Cumulative change in 2-cycle CO_2 emissions for several strong hybrid vehicle models since introduction



Source: U.S. Environmental Protection Agency (2024a)

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Improving HEV efficiency is neither required by regulation nor necessary for compliance with state or federal GHG standards as of 2024, and not all automakers have elected to improve specific HEV models. For example, the newest generations of the hybrid Toyota Corolla and Honda CR-V have slightly *higher* CO_2 ratings than their predecessors, albeit with much better performance and acceleration. However, all hybrid options remain significantly more efficient than their non-hybrid counterparts. Also, as discussed below, every generation of HEV—regardless of whether its efficiency increases or decreases—costs less to purchase in real dollars than its preceding generations.

FUTURE TECHNOLOGY – STRONG HYBRIDS

Although EPA's modeling supporting the final rulemaking for MYs 2027–2032 did not assume HEVs would undergo significant efficiency improvements (Graham & German, 2023), in-production and near-production technologies have demonstrated efficiency gains that could continue the historical trend of 10%–15% improvement in HEV efficiency with each generation (German, 2023; Graham & German, 2023; Hyundai Motor Company, 2024; Rogers et al., 2021).

The biggest opportunity for improving HEV efficiency is through the implementation of dedicated hybrid engines designed specifically for use in strong hybrid electric powertrains. By leveraging the ability of the relatively large electric motor to efficiently handle low-load and low-speed conditions, the engine can be tailored to operate in a narrow, more efficient operating window. Automakers including Nissan, Honda, Hyundai, and Toyota are already moving in this direction. Nissan's ePower engines, introduced in MY 2021 in the Qashqai, Note, and X-Trail models available outside the United States, achieve 43% peak brake thermal efficiency (BTE), which is the ratio of engine power output to the power available from fuel combustion. Honda and Toyota's most efficient current engines achieve 40% and 41% peak BTE, respectively, when applied in hybrid vehicles (American Honda Motor Company Inc., 2023; Hyundai Motor Company, 2024; Nissan Motor Co., n.d.; Toyota Motor Corporation, 2018). Honda recently announced that two new dedicated hybrid engines that have higher efficiency than the outgoing hybrid engines will be used in its next generation hybrid vehicles (Honda Motor Co Ltd., 2024).

Several changes to dedicated hybrid engines can lead to an additional average efficiency gain of four to five percentage points, or 10%–13%, reaching around 45% peak BTE (German, 2023; Rogers et al., 2021). These technology changes are relatively minor as they require minimal hardware changes and represent a continuation of trends already exhibited in highly efficient gasoline engines today. The changes include increasing cooled and low-pressure exhaust gas recirculation (EGR), increasing compression ratio, increasing stroke-to-bore ratio, reducing friction through downspeeding, increasing injection pressures up to and beyond 350 bar, and using high-energy or passive prechamber ignition (Kapus, 2020; National Academies of Sciences, Engineering, and Medicine 2021; Schoeffmann et al., 2020; Sens, 2023; Visnic, 2022; Zhang, 2020). Using a turbocharger on a dedicated hybrid engine sacrifices peak efficiency compared with a naturally aspirated engine, but broadens the range of engine loads and speeds at which the engine is at its highest efficiency, potentially leading to lower overall emissions (Sens, 2023). Such turbocharged dedicated hybrid engines have already been demonstrated (Greimel, 2024c; National Academies of Sciences, Engineering, and Medicine 2021; Nissan Motor Co., n.d.; Osborne & Sellers, 2019; Zhang, 2020).

Additional engine modifications could enable efficiencies that exceed 45% peak BTE. These modifications include friction reduction using engine oils currently in development, engine simplification, and even narrower operating range; further increases in injection pressures; reducing charge air cooling to near-ambient temperatures with electric supercharging and intercooling; increasing charge air turbulence; expanded use of cooled, low-pressure EGR; in-cylinder fuel reforming with pilot fuel injection during negative valve overlap; dedicated (electric) turbochargers optimized for a narrow-range engine; active pre-chamber ignition; variable compression ratios; waste heat recovery (through electric turbo, for example); even higher compression ratios; water injection; lean combustion; and electrically heated catalysts (Garrett Motion Inc., n.d.; Kapus, 2020; National Academies of Sciences, Engineering, and Medicine 2021; Nissan Motor Co., n.d.; Osborne & Sellers, 2019; Schoeffmann et al., 2020; Sens, 2023). The implementation of some of these technologies may require more research and development than others. However, many are available today, such as electric turbochargers, and others have been thoroughly simulated using advanced combustion modeling software (Garrett Motion Inc., n.d.; Kapus, 2020; Osborne & Sellers, 2019; Sens, 2023). Such computer simulations allow manufacturers and suppliers to rapidly assess many parameters before prototyping hardware, which reduces costs and development times (National Academies of Sciences, Engineering, and Medicine, 2021; Osborne & Sellers, 2019).

To optimize engine operation and take advantage of increased BTE, the hybrid system relies on the electrified powertrain to handle or assist in driving loads and conditions that would force the engine to operate at points on its map outside the region of peak engine efficiency. These include low-load and low-torque conditions, which the electric motor may handle entirely on its own, and high-load at high-speed or high-torque conditions, which the motor may handle or assist, depending on system architecture and component capabilities (National Academies of Sciences, Engineering, and Medicine, 2021). Additional improvements to batteries and motors will also lead to greater electric capabilities that enable further engine optimization.

Battery costs for lithium-ion chemistries are expected to fall due to increased global production volumes, learning, and shifts in chemistry. Automakers could take advantage of these cost reductions by increasing battery pack capacity in HEVs without increasing manufacturing cost. Increasing pack capacity enables longer duration of electric-only or electric-assist operation and allows more energy to be recouped from braking. This greater electric operation equates to reduced engine operation and thus lower CO_2 emissions. In addition to learning, innovation may bring additional battery improvements. For example, Toyota has developed bipolar battery structures that increase power density and reduce pack size for the same capacity (Greimel, 2021; Tomita et al., 2024). This structure is used for both HEV (NiMH and Li-ion chemistries) and battery electric vehicle batteries. Eventually, solid-state batteries, which have higher power densities than conventional Li-ion batteries today, may be implemented in HEVs (Toyota Motor Corporation, 2023). Improvements in motors and inverters are also expected to increase efficiency and power density while reducing size and cost (German, 2023; Mair, 2024; National Academies of Sciences, Engineering, and Medicine, 2021; Tomita et al., 2024).

Although city and highway drive cycle engine efficiency heat maps are not widely available for many current vehicles, Bhattacharjya et al. (2024) compared the drive cycle performance of a MY 2021 Ford F-150 non-hybrid with a simulated dedicated hybrid engine F-150 PHEV. (Note that the 3.5 L engine in the MY 2021 F-150 is virtually identical to the engine on the MY 2024 F-150 HEV.) The authors found that the MY 2021 F-150 spent most of its time between 26% and 34% BTE (peak BTE of 34.2%), although significant portions of both cycles were spent under 26% BTE. The dedicated hybrid F-150 spent more time in its efficient region, with no time spent below 33% BTE, and operated at 34%–41% BTE over both cycles. Sens (2023) and Osborne and Sellers (2019) showed similar results of increased time spent near peak efficiency with advanced dedicated hybrid engines.

PLUG-IN HYBRID ELECTRIC VEHICLES

As PHEVs today tend to have larger battery packs and more powerful motors than non-plug-in HEVs, they represent a clear opportunity to optimize engine efficiency and severely limit engine operation to only when it is able to operate in regions near peak engine efficiency. By relying on the electric powertrain for effectively all transient loads, the engine can be used essentially as a range-extending battery charger that operates independently of vehicle speed and load. In this way, manufacturers can use the engine as an energy management tool to improve overall efficiency by increasing the amount of time the engine spends at high efficiency when it is operating and reduce engine energy consumption overall through increased electric driving (Rogers et al., 2021; Sens, 2023). Controlling the engine in this way would require at least a series hybrid configuration, as the engine would primarily charge the battery and the motor would primarily drive the wheels, with the possibility of parallel operation under conditions in which the engine would contribute to driving the wheels if it can remain operating at or near peak efficiency. Thus, several of the engine technologies discussed above can also be adopted in PHEVs, which would result in engine efficiency improvements as well as CO_2 reductions. These improvements could exceed those of HEVs, as the engine in a PHEV can spend more time operating near peak efficiency. Although overall charge-sustaining CO_2 emissions can decrease due to the above powertrain improvements, the maximum benefits of these improvements for PHEVs will only be realized when consumers regularly plug in to recharge (Isenstadt et al., 2022).

Overall, four to five percentage points of improvement in peak BTE (with assumed similar improvement in efficiency surrounding the peak) coupled with more time spent near peak efficiency due to modest improvements and increases in capabilities of the electric powertrain (mainly motor and battery) would easily enable the 10%–15% efficiency improvement and CO_2 emissions reduction seen with successive generations of HEVs to date. Additional reductions in aerodynamic drag, tire rolling resistance, vehicle mass, and accessory loads, which are applicable to all powertrain types, could lead to improvements of more than 15% for both HEVs and PHEVs (National Academies of Sciences, Engineering, and Medicine, 2021).

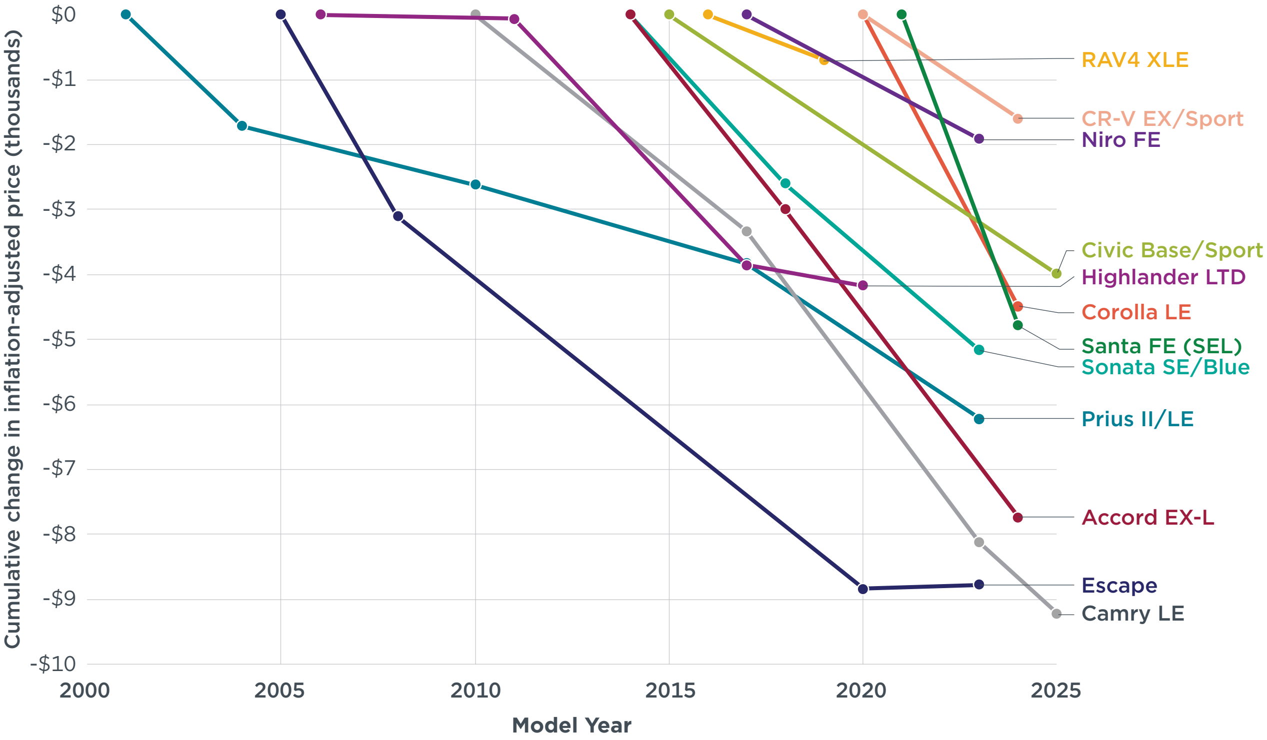
HYBRID ELECTRIC VEHICLE SYSTEM COST

COSTS THROUGH 2024

Recall that many of the HEV models offered in 2024 which had been through at least one redesign since being introduced exhibited improved efficiency with each generation. As of their most recent redesign, *all* of these models have lower inflation-adjusted manufacturer suggested retail price (MSRP) than their initial generation. In addition, nearly all have lower prices for each successive generation. In other words, adjusting for inflation, HEV models tend to decrease in price while reducing, or at least maintaining, CO_2 emissions. Figure 6 depicts this trend with the same HEV models as in Figure 5. In all but one case, each generation of HEV model costs less to purchase than the previous generation. For most of these vehicles, this reduced upfront cost is also accompanied by reduced operating cost in the form of additional fuel savings compared with prior generations.

Figure 6

Cumulative change in inflation-adjusted price for several hybrid vehicles since introduction



Source: Annual inflation data from Consumer Price Index (U.S. Bureau of Labor Statistics, n.d.) and manufacturer suggested retail price taken from https://www.motortrend.com/cars/ and individual manufacturer websites.

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The 2023 version of the Camry is $8,000 cheaper than when it was first introduced in MY 2010. For MY 2025, Toyota will only offer the Camry as an HEV; this suggests that the incremental cost of the hybrid system is so low that it is expected to be acceptable to all customers, including those who may not value fuel economy. The MY 2025 Camry HEV is nearly $1,000 cheaper (inflation-adjusted) than the MY 2023 version. In 2024 dollars, the MY 2025 HEV Camry MSRP is about $1,400 more than the MY 2023 non-HEV Camry MSRP.[1] As the Camry was the top-selling ICE car in the United States and in California in 2023 (Auto Outlook Inc., 2024a; Capparella, 2024), Toyota's decision to offer strong hybrid technology as standard suggests that the HEV model is as profitable as the ICE-only version and highly cost-effective to manufacture.

Determining precise strong hybrid system cost estimates and HEV profit margins is a complicated undertaking. Automakers frequently adjust prices and cross-subsidize among vehicles for many reasons. Nevertheless, comparing the MSRP of HEV and non-HEV models offers a reasonable method for estimating the total cost of hybridization, inclusive of profit margins.

Table 2 shows that of the five automakers offering HEV models in MY 2024 (Ford, Honda, Hyundai, Kia, and Toyota), over a dozen non-luxury models were found to

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[1] The 2023 MSRP was converted to 2024 dollars using a factor of 1.03. This inflation adjustment factor is based on the Consumer Price Index for All Urban Consumers data from U.S. Bureau of Labor Statistics (n.d.).

have both HEV and non-hybrid ICE variants. The MSRP for the HEV and non-hybrid ICE variants with comparable trim levels were found on the respective manufacturer websites. The difference between the HEV MSRP and non-hybrid ICE MSRP ranges from $500 to $3,720, with an average of $2,079 and median of $1,800. Following EPA's assumption in its recent final rulemaking of a retail price equivalent factor of 1.5, direct costs for hybridization range from approximately $330 to $2,500, with an average of $1,400 and median of $1,200 (German, 2023). Recent announcements from automakers of their intentions to quickly offer hybrid variants of many of their models indicates that hybridization adds relatively little to a vehicle's sticker price (less than $2,000 in the case of Toyota; Shirouzu, 2024). There are equivalent or greater profits from selling HEVs than from non-hybrid ICE vehicles, HEVs can be developed in a short time frame, and their production costs are falling (Greimel, 2024a, 2024b, 2024d; Hyundai Motor Company, 2024; Leussink, 2024; Martinez, 2024; Shirouzu, 2024).

Table 2

Difference in hybrid versus non-hybrid internal combustion engine vehicle price

Model	Price difference
2024 Camry LE	$2,435
2024 Corolla LE	$1,400
2024 Highlander LE AWD	$1,700
2024 RAV4 LE AWD	$1,600
2024 Toyota Tundra Limited AWD	$3,720
2024 Toyota Tacoma (TRD Sport 4WD)	$3,700
2024 Ford Escape	$3,000
2024 Ford Maverick	$1,500
2024 F150	$1,900
2025 Honda Civic Sport	$2,500
2024 Honda Accord	$2,635
2024 Honda CR-V	$1,690
2024 Hyundai Elantra	$2,385
2024 Hyundai Sonata	$3,300
2024 Hyundai Tucson	$1,455
2024 Hyundai Santa Fe	$500
2024 Kia Sportage	$1,400
2024 Kia Sorento	$600
Average	$2,079

Source: Prices obtained from manufacturer websites.

ENVIRONMENTAL PROTECTION AGENCY ESTIMATED BASELINE COSTS

In the Regulatory Impact Analysis of its final rulemaking for MY 2027–2032, EPA presented equations for determining the direct and total cost of various hybrid and non-hybrid system components, engines, and transmissions (EPA, 2024b). The sum of these and other component costs is an initial price estimate before adjustments such as cross-subsidization. Several of these cost equations were derived from or developed by work performed by FEV Consulting Inc. (2023). Through teardowns, FEV estimated that, on average, 16% of total HEV manufacturing costs come from the powertrain, which is nearly identical to the powertrain cost share of non-strong (mild) hybrid ICE vehicles; meanwhile, the powertrain cost share for PHEVs is 40%, on average. Compared with MSRPs for the Toyota Prius, Honda CR-V, and mild hybrid Ram 1500 eTorque, FEV's equations result in total costs that are 17% higher for a hybrid car, 9% for a hybrid SUV, and 2% for a hybrid pickup.

The FEV cost equations are used within the Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) to estimate total costs for each vehicle (EPA, 2024c). To assess the impact of hybridization within EPA's simulation modeling, the equations were applied to both the non-hybrid ICE and HEV variants of the vehicles in Table 2. Engine, transmission, and hybrid system specifications were found on manufacturer websites and in EPA's fuel economy guides (EPA, 2024a). These specifications were put into the OMEGA cost equations to estimate powertrain costs, and then the difference between HEV and non-hybrid ICE variants' powertrain costs were calculated. After adjusting the 2022 dollar values used in OMEGA to 2024 dollars, these differences were tabulated in the second numerical column in Table 3.

Table 3

Difference in hybrid electric versus non-hybrid combustion engine vehicle price and OMEGA model estimated hybrid system price

Model	MSRP delta	OMEGA delta	OMEGA minus MSRP	% of MSRP delta
2024 Camry LE	$2,435	$3,575	$1,140	47%
2024 Corolla LE	$1,400	$3,352	$1,952	139%
2024 Highlander LE AWD	$1,700	$4,452	$2,752	162%
2024 RAV4 LE AWD	$1,600	$4,238	$2,638	165%
2024 Toyota Tundra Limited AWD	$3,720	$4,827	$1,127	30%
2024 Toyota Tacoma (TRD Sport 4WD)	$3,700	$4,506	$786	21%
2024 Ford Escape	$3,000	$2,904	-$96	-3%
2024 Ford Maverick	$1,500	$2,677	$1,177	78%
2024 F150	$1,900	$4,350	$2,450	129%
2025 Honda Civic Sport	$2,500	$3,361	$861	34%
2024 Honda Accord	$2,635	$3,063	$428	16%
2024 Honda CR-V	$1,690	$3,208	$1,518	90%
2024 Hyundai Elantra	$2,385	$3,322	$937	39%
2024 Hyundai Sonata	$3,300	$3,018	-$282	-9%
2024 Hyundai Tucson	$1,455	$3,617	$2,162	149%
2024 Hyundai Santa Fe	$500	$2,382	$1,882	376%
2024 Kia Sportage	$1,400	$3,072	$1,672	119%
2024 Kia Sorento	$600	$2,372	$1,772	295%
Average	$2,079	$3,461	$1,382	66%

Source: MSRPs are from manufacturer websites and the OMEGA prices were calculated using engine, transmission, and HEV system specifications from EPA and automaker websites.

Taking the difference between the OMEGA results and the MSRP results generated the third and fourth columns of the table, and we see that OMEGA tends to vastly overestimate the cost of HEVs as compared with equivalent non-hybrid ICEs. With three exceptions, the excess cost is over 20%, and for eight of the 18 vehicles, excess cost is at least 100%. Similarly, for most of the nameplates in the top 20 of sales in the United States and in California in 2023, OMEGA overestimates the total cost of hybridization by more than $1,000. Although modeling was not conducted to confirm this, overestimation of HEV costs within OMEGA, combined with likely large underestimation of benefits (Graham & German, 2023), may lead to EPA's regulatory analysis results projecting lower penetration of HEVs in future model years, higher emissions from HEVs that are projected in the future, and higher costs for these future vehicles.

FUTURE COSTS

The historical HEV cost trends shown in Figure 6 suggest that the cost of future HEVs will be much lower than in 2024. The reductions in HEV CO_2 emissions and costs through 2024, combined with analyses of potential future HEV improvements, point to a continued decrease in the cost of hybridization.

Incremental changes to battery assembly, construction, and chemistry, motor design changes, and economies of scale can drive vehicle costs down. Examples of existing HEV battery and motor improvements that reduce cost include smaller and lighter motors operating at higher revolutions per minute (German, 2023) and bipolar battery cell structure that increase cell power density by 80% and pack energy density by 50% (Sasaki et al., 2023; Tomita et al., 2024). Continued battery and motor cost reductions through economies of scale can be expected as manufacturers offer more HEV models and develop supply chains and production capabilities for PHEVs and battery electric vehicles. These savings can offset some potential increase in cost that may occur due to developing HEVs with electrified powertrains that are more capable.

It is counterintuitive, but in the case of highly efficient HEVs with engines dedicated to hybrid operation, research suggests engine costs can be as much as 25%–40% lower than modern non-hybrid ICE engines (Birch, 2019; Schoeffmann et al., 2020; Schöffmann et al., 2019). Fine tuning the engine within a hybrid system to run in a very limited, but efficient operating range allows for significant simplification (Osborne & Sellers, 2019) because many components that today enable a high degree of control over the engine are no longer needed. Examples of such "de-contenting" include replacing the variable geometry turbo with a larger, non-variable turbocharger, removal of variable valve lift and timing, replacing direct and port injection with only port injection, reducing the number of valves to two per cylinder, switching to single camshaft instead of dual, and removing the front-end accessory drive by switching to fully electrified accessories. Due to these engine-simplification measures, components for dedicated HEV engines could be shared across entire engine families, furthering cost reductions through economies of scale (Schoeffmann et al., 2020). With a simplified engine in a dedicated hybrid powertrain, automakers can use the engine as an energy management tool and tune the system to charge the battery from the engine when it is most efficient.

Researchers at AVL estimated in 2020 that future HEV system cost would be €60–€75 per percent reduction in fuel consumption with respect to a modern turbocharged gasoline engine baseline (Kapus, 2020). Thus, a 45% reduction in fuel consumption of a future HEV versus a baseline non-hybrid ICE vehicle might cost

€2,700–€3,400. Assuming conventional HEVs achieve a 30%–35% reduction in fuel consumption versus non-hybrid ICE, AVL's estimated cost premium for advanced HEV systems is about €600–€1,100. Using the 2020 average exchange rate of 1.141 dollars per euro (Federal Reserve Board, 2025) and a 2020 to 2024 inflation adjustment of 1.212 (Bureau of Labor Statistics, n.d.), this AVL estimated cost is approximately $830–$1,500.

As mentioned above, EPA used cost equations developed by FEV to estimate various non-battery costs for hybrid vehicles. In particular, FEV assessed the individual components of multiple electric motors and inverters from different classes of vehicles to develop its cost curves. Additionally, EPA analyzed motor and inverter information from other teardowns. Thus, although EPA's OMEGA cost model tends to overestimate strong HEV costs overall, the equations for motor and inverter costs are based on the best available information as of this writing. Future HEV costs can thus be estimated by combining this with the OMEGA model battery cost equation.

Table 4 lists the specifications for a typical strong hybrid car, SUV, and pickup in 2024. Engine size and componentry are based on descriptions in EPA's *Model Year 2024 Fuel Economy Guide*, as well as HEV engine specifications described in the Regulatory Impact Analysis of EPA's final rule (EPA, 2024a, 2024b). It is assumed that through engine simplification as described above, engine costs can be reduced by 20% for future HEVs relative to 2024 HEVs.

The *Model Year 2024 Fuel Economy Guide* also provides information on motor power and battery capacity on a model-by-model basis. Motor power was averaged for HEV car, SUV, and pickup models. For SUVs and pickups with all-wheel drive, secondary motor power for a motor located at the rear axle (P4 motor) was also averaged. Additionally, motor power was averaged according to application on powersplit (Toyota and Ford models), series-parallel (Honda models), and P2 (Toyota, Ford, Hyundai, Kia models) architectures. For cases where no HEV configuration existed in 2024, such as series-parallel pickups, motor power was assumed based on the specific application. These hypothetical configurations are indicated in the table. Similar to motor power averaging, battery capacity was averaged according to class and HEV configuration using *2024 Fuel Economy Guide* data.

Table 4

Specifications for 2024 and future (2030+) more-efficient hybrid electric vehicles

		2024 HEV specs			2030+ HEV specs		
		Car	**SUV**	**Pickup**	**Car**	**SUV**	**Pickup**
Drivetrain type		FWD	AWD	AWD	FWD	AWD	AWD
Engine		2 L, I4 DI, EGR, VVT, ATK	2.5 L, I4 DI, EGR, VVT, ATK	3.5 L, V6 DI, EGR, VVT, Miller	-20% cost reduction through DI deletion, switch to SOHC, switch to fixed geometry turbo, reduced number of valves, etc.		
Primary drive motor	**Powersplit**	80 kW	103 kW	94 kW	135 kW	150 kW	175 kW
	Series-parallel (2-motor)	135 kW	135 kW	150 kW[a]	135 kW	150 kW	175 kW
	P2	34 kW	42 kW	42 kW	135 kW	150 kW	175 kW
Secondary drive motor (P4)		None	42 kW	42 kW	None	80 kW	150 kW
Inverters		Same power as respective motor			Same power as respective motor		
Thermal (motor & battery cooling)		Default direct costs from OMEGA model			20% higher costs due to more powerful motors and larger batteries		
Battery		1.10 kWh	1.27 kWh	1.75 kWh	4.40 kWh	5.08 kWh	7.00 kWh

Notes: FWD = front wheel drive; AWD = All- or four-wheel drive; DI = direct injection; EGR = exhaust gas recirculation; VVT = Variable valve timing; ATK = Atkinson (over-expansion combustion cycle on naturally aspirated engines); Miller = over-expansion combustion cycle on forced induction engines; SOHC = single overhead camshaft

[a] Assumed specification because no 2024 model data was available

Future HEV motors were sized assuming they would handle most of the driving load, while the engine is used mainly as a generator and to drive the wheels at low load/high speed when efficiency is maximized (e.g., highway speeds). This assumption is consistent with existing Honda HEVs and simulations of future HEVs in Bhattacharjya et al. (2024). Thus, primary drive motor power for future HEVs is constant across HEV configurations within a given class and increases for SUV and pickup classes compared with 2024 HEVs. Batteries for all classes are assumed to be four times larger capacity for future HEVs than 2024 HEVs. This capacity increase likely overestimates the energy needed for future HEVs to operate in all-electric mode for longer in both real-world conditions and over regulatory test cycles (Sens, 2023; Bhattacharjya et al., 2024). However, a conservative estimate for battery capacity would enable maintaining engine operation at peak efficiency and securing a reduction in CO_2 emissions of at least 15% compared with 2024 HEVs. These future pack sizes would remain significantly smaller than packs on PHEVs, which could be as much as 5.5 times larger than those depicted in Table 4 (Bhattacharjya et al., 2024).

Only one other cost component—motor and battery thermal control—is assumed to change due to improvements in future 2030 HEVs. Greater motor and battery utilization generates more heat, which is assumed to require 20% higher costs to maintain desired operating temperatures. Though there are many additional cost components that are assumed to be shared between 2024 and 2030+ HEVs, such as generator motors, gearbox or transmission, and fuel system, among others, these components are assumed to remain largely identical and are excluded from the cost comparison.

Inserting the specifications in Table 4 into the relevant OMEGA model cost equations for engine, motor, thermal control, and battery leads to the results in Table 5. These results are depicted in 2024 dollars and represent costs as they would be in 2030 due to manufacturer learning, rounded to two significant figures. As the table shows, future HEV engine costs are 20% lower than 2024 engine costs; this is due to engine simplification. Motor and inverter costs are 15%–40% higher for powersplit and P2 HEV configurations due to the application of motors with higher power. Series-parallel HEVs already use comparatively high-power drive motors, so do not require as much power increase as powersplit and P2 HEVs. Thermal costs are 20% higher due to higher heat generation in the motor and increased control of battery temperature. Battery costs are approximately 80%–90% higher for future HEVs. Overall, powertrain costs in 2030 for future HEVs are projected to be at most 5%–11% ($340–$730) higher than powertrain costs in 2030 for typical 2024 HEVs. Compared with 2024 HEVs, future HEVs deliver better performance in the form of lower CO_2 emissions, reduced consumer spending on fuel, and increased electric propulsion.

For reference, the cost equations that generate the values in Table 5 are from Tables 2-35, 2-38, and 2-40 in EPA, (2024b). These equations are as follows:

*Total cost = (direct cost) * (retail price equivalent) * (learning) * (inflation)*

Direct costs:

- Engine:
    - I: (324.71*LITERS + 632.34) + (212) + (100) + (100) + (4.907 * 4^2 - 29.957 * 4 + 130.18)
    - V: (246.87*LITERS + 1125.2) + (319) + (100) + (100) + (4.907 * 6^2 - 29.957 * 6 + 130.18) + (756)
    - The elements in the above equations correspond to the following components: (engine block) + (direct injection) + (exhaust gas recirculation) + (variable valve timing) + (Atkinson/Miller) [+ turbo]
- Motor: (1.1097*kW + 323.22)
- Inverter: (1.26*kW+559)
- Thermal: $493.78 (car, SUV), $559.63 (pickup)
- Battery: (122.9 + 509.6 / (kWh^0.7649) - 4.443 * (year - 2023) * EXP(0.01018 * (year - 2023))) * kWh

Retail price equivalent = 1.5

Learning factor (2030 vs. 2022) = 0.61 (non-engine), 0.97 (engine)

Inflation adjustment (2022$ to 2024$) = 1.07 (U.S. Bureau of Labor Statistics, n.d.)

Table 5

Estimated total cost of typical 2024 HEVs and potential future HEVs

		2024 HEV cost in 2030			2030+ HEV cost in 2030			Difference		
		Car	**SUV**	**Pickup**	**Car**	**SUV**	**Pickup**	**Car**	**SUV**	**Pickup**
Drivetrain type		FWD	AWD	AWD	FWD	AWD	AWD	FWD	AWD	AWD
Engine		$2,800	$3,000	$5,300	$2,200	$2,400	$4,200	-$560	-$610	-$1,100
Motor	**Primary drive motor (powersplit)**	$400	$430	$420	$460	$480	$510	$60	$51	$88
	Primary drive motor (series-parallel)	$460	$460	$480	$460	$480	$510	$0	$16	$27
	Primary drive motor (P2)	$350	$360	$360	$460	$480	$510	$110	$120	$140
	Secondary (P4) motor power	$0	$360	$360	$0	$400	$480	$0	$41	$120
Inverter	**Primary motor inverter (PS)**	$650	$680	$660	$720	$730	$760	$68	$58	$100
	Primary motor inverter (S-P)	$720	$720	$730	$720	$730	$760	$0	$19	$31
	Primary motor inverter (P2)	$590	$600	$600	$720	$730	$760	$120	$130	$160
	Secondary motor inverter	$0	$600	$600	$0	$650	$730	$0	$47	$130
Thermal		$480	$480	$550	$580	$580	$660	$97	$97	$110
Battery		$1,000	$1,000	$1,200	$1,800	$1,900	$2,300	$800	$880	$1,100
Total, powersplit		$5,300	$6,600	$9,100	$5,800	$7,200	$9,700	$470	$570	$610
Total, series-parallel		$5,400	$6,700	$9,200	$5,800	$7,200	$9,700	$340	$500	$480
Total, P2		$5,200	$6,500	$9,000	$5,800	$7,200	$9,700	$570	$710	$730

Note: Costs are in 2024 U.S. dollars and represent hypothetical cost in MY 2030, rounded to two significant figures.

COST-EFFECTIVENESS AND CONSUMER BENEFITS

Historically, automakers have reduced HEV emissions and reduced the cost of the vehicle at the same time. This combination of cost and efficiency improvements has occurred while HEVs achieve profits similar to those of non-HEVs. As virtually every automaker in the United States has offered or is offering mild, strong, or plug-in hybrids, the entire industry is familiar with HEV development and production. Thus, today's pace of hybridized vehicle development, along with motor and battery research, supports continued reduction in HEV costs and likely relatively low or little cost for improved HEV efficiency.

Based on the above analysis, a 15% reduction in HEV emissions compared with 2022–2024 HEVs is likely through improved vehicle electrification and optimized engines. Though not analyzed here, non-powertrain technologies can complement powertrain improvements and achieve 15% or greater reductions in CO_2 emissions. The prices of 2024 and future HEVs were estimated to be around $1,500–$3,000 more than non-hybrid ICE vehicles, but costs are expected to fall. Further, as discussed above, there are other cost reductions associated with future HEVs, such as through dedicated-HEV engines, resulting in savings that will likely offset much of the potential cost increases due to developing more-efficient HEVs with more-capable electrified powertrains.

Although the profit for automakers from selling HEVs and non-hybrid ICE vehicles is similar, consumers benefit from driving a hybrid. A simple comparison of fuel savings and MSRP illustrates this. Using MY 2024 fuel economy data (EPA, 2024a), all non-plug-in vehicles offered in both a non-hybrid ICE and HEV variant were compared. Prices for each nameplate were obtained from the manufacturer's website for at least one trim level that had both HEV and non-hybrid options. The resulting list of vehicles is longer than that shown in Table 2 due to additional trim levels and all-/four-wheel drive options. The average annual mileage for 5-year and 10-year old vehicles was taken from the vehicle miles traveled schedule in EPA's OMEGA model (EPA, 2024c). The most recent 5-year average of gasoline price ($3.123/gallon) was applied as the average cost of gasoline for both 5-year and 10-year ownership periods (Bureau of Labor Statistics, 2024).

Combining price, mileage, fuel efficiency, and fuel cost resulted in Figure 7, which illustrates that the vast majority of strong HEV options result in both 5- and 10-year savings for consumers. Of the variants, 28 out of 37 deliver net savings from lower fuel costs within 5 years, with 18 of these variants offering more than $1,000 in savings (undiscounted). In addition, 34 of 37 variants deliver net 10-year savings, and 28 of these offer more than $2,000 in savings. Net savings of $3,700–$7,000 over 10 years was achieved for 17 of the variants. Taking the simple average of these savings by class, the average HEV car saves drivers over $200 in the first 5 years of ownership compared with a non-hybrid car, and over $2,500 in the first 10 years. The average hybrid SUV saves $1,500 over 5 years, and more than $3,900 over 10 years. The average pickup HEV costs consumers about $1,200 more on average but shows net savings over 10 years. As these consumer cost calculations are based solely on MSRP and fuel consumption, they exclude other costs such as maintenance, insurance, and depreciation. HEVs generally have lower maintenance costs than non-hybrid ICEs, so the savings of HEVs compared with the non-hybrid ICE counterparts could be even greater than shown in the figure (Burnham et al., 2021). According to *Consumer Reports* reliability survey data, owners of hybrid vehicles reported problems 26% less often than owners of non-hybrid ICE vehicles (Linkov & Bergmann, 2023).

Figure 7

Cost (positive) or savings (negative) of HEV ownership compared with comparable non-HEV

Notes: Fuel consumption and purchase price only were considered. Fuel price is assumed to be the average of the past 5 years of gasoline prices, $3.123/gallon of gasoline (U.S. Bureau of Labor Statistics, 2024). Average annual mileage for the first 5 years is 14,892 miles for cars, 15,389 mi for SUVs, and 17,141 for pickups. Average annual mileage for the first 10 years is 13,794 for cars, 14,381 for SUVs, and 15,319 for pickups (U.S. Environmental Protection Agency, 2024c).

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A 2018 analysis by Vincentric considered several factors in addition to price and fuel consumption, including depreciation, insurance, maintenance, and repairs (Vincentric, 2018). The analysis also incorporated HEVs that do not have an exact non-HEV counterpart but have a close comparison (e.g., Toyota's Prius C and Yaris). The authors found that more than half of HEVs (42 of 79) had a lower 5-year total cost of ownership than their non-hybrid counterparts. In its more recent analysis of ownership costs, Vincentric found that HEVs provide consumers with thousands of dollars in savings on average for each segment, both in California and in the United States as a whole (Vincentric, 2024).

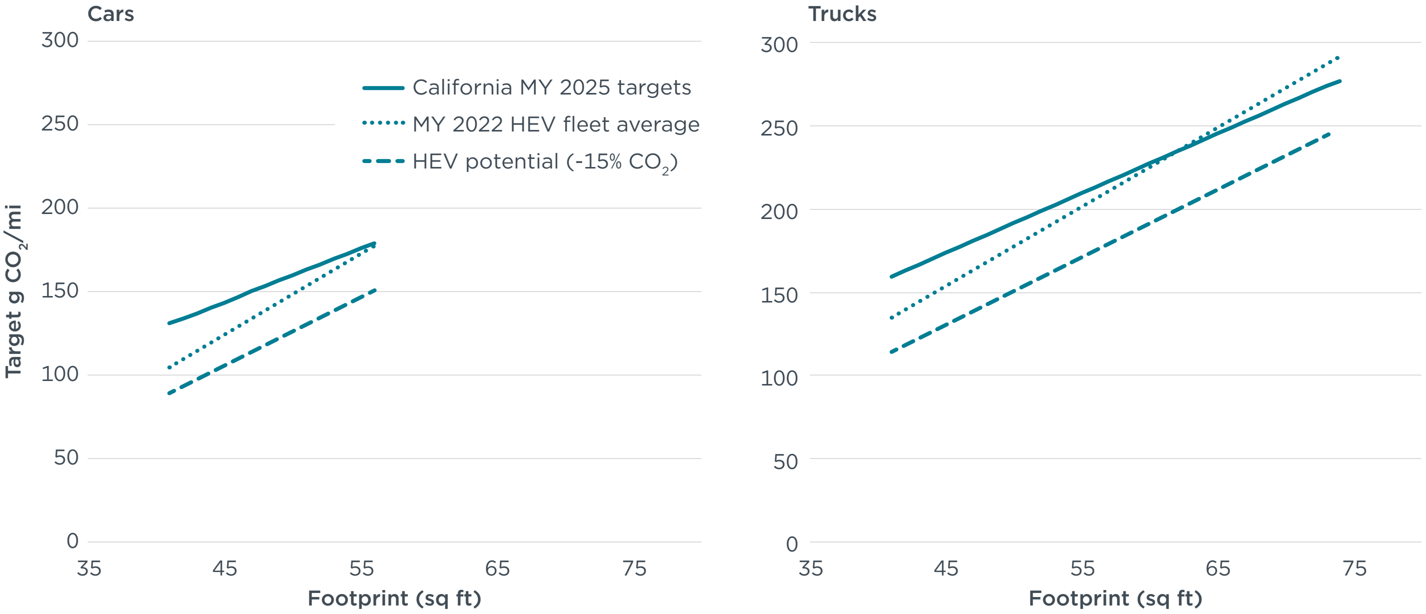
STRINGENCY IN FUTURE GHG STANDARDS

California has proposed introducing a new GHG standard for new ICE-equipped vehicles, including PHEVs, for MYs 2030–2034, and a PHEV-only GHG standard for 2035 and beyond (California Air Resources Board, 2024). The state has a zero-emission vehicle sales requirement that reaches 100% in 2035, but without a standard that is stringent enough to require CO_2 reductions from all ICE-equipped vehicles, including PHEVs, there is a risk that tailpipe CO_2 emissions from these vehicles could stagnate or backslide. Thus, California's proposal provides an opportunity to ensure that remaining ICE-equipped vehicles minimize GHG emissions.

The final year of increasingly stringent standards in California is MY 2025, and model years after that are subject to the same requirements. The MY 2025 target will be used as a reference point for future standards and the car and light truck fleet targets are shown in Figure 8 (solid lines). The MY 2025 standards are constructed so that manufacturers can use hybrids and non-hybrids, as well as PHEVs and battery electric vehicles, to meet the target.

Figure 8

California MY 2025 targets and potential ICE-only fleet-average standards based on MY 2022 HEV fleet average CO_2 and 15% lower CO_2 from MY 2022 HEV average



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To minimize GHG emissions from the ICE fleet, the targets illustrated in Figure 8 could be applied in a standard that targets GHG emissions from only vehicles with combustion engines (non-hybrid ICE, mild and strong HEV, and PHEV). Precedent for ICE-only standards already exist through California's LEV IV regulation, and ICE-only standards for nonmethane organic gas, nitrogen oxides, and particulate matter are currently enforced (California Air Resources Board, 2024).

The dotted lines in Figure 8 represent the fleet-average 2-cycle performance of MY 2022 strong HEVs, which are the same as in Figure 3. To achieve a fleet-average GHG emissions level on par with MY 2022 strong HEVs, a potential ICE-only target would need to be at least as stringent as the fleet-average performance of HEVs in MY 2022. Comparing the dotted and solid lines in Figure 8 shows that for cars, MY 2022 HEVs over-comply with the existing 2025 target, even before considering off-cycle and air conditioning technology credits, and MY 2022 HEV trucks very nearly overlap the existing 2025 target.

To capture the potential improvement of HEVs and charge-sustaining PHEVs beyond MY 2022, the dashed lines in Figure 8 also illustrate a 15% reduction in 2-cycle CO_2 emissions—corresponding to a 15% improvement in HEV efficiency—as compared with the MY 2022 HEV fleet. As discussed previously, this level of improvement is feasible and cost-effective with known technologies. Since typical automotive redesign schedules are around 5–7 years, within the 10 years between 2024 and 2034, automakers likely have ample time to redesign and re-engineer their HEVs to be more efficient. Thus, the dashed lines shown in the figure represent a potential fleet-average curve for a fleet with efficiency and CO_2 emission levels on par with future HEV technology.

The curves in Figure 8 represent targets that manufacturers would have to comply with on average. To meet the standards, automakers have many flexibilities, including off-cycle and air conditioning credits that reduce 2-cycle emissions by their sum. To illustrate the effect of these credits, example GHG emissions were calculated for HEV variants of five of the top 10 highest-selling nameplates in 2023. These nameplates were selected as they already have strong hybrid variants available. Table 6 shows the CARB 2025 target and the -15% HEV CO_2 target for each vehicle, corresponding to their respective locations on the solid and dashed curves in Figure 8. The table also shows the actual 2-cycle CO_2 emissions for these vehicles in MY 2024. Their 2-cycle CO_2 emissions in MY 2024 show that three of the five models meet their California 2025 target without considering the effect of credits. Assuming each vehicle is awarded maximum technology credits in 2030—this reflects the reality that automakers were already nearly maximizing credit usage in MY 2023 (Hula et al., 2024)—each model gets significantly closer to complying with a potential future HEV target. If automakers apply maximum credits and reduce CO_2 by 15% (from 2024 values), all but one model meets or exceeds its -15% HEV CO_2 target. From this comparison, to set a future standard when considering credit flexibilities, the curves based solely on 2-cycle emissions could be lowered by the maximum amount of credits available. Increasing stringency to account for credits also reduces some of the risk that use of many credits leads to little real-world GHG benefits (Lutsey & Isenstadt, 2018).

Table 6

Impact of potential HEV standard and off-cycle and air conditioning credit flexibilities on HEV versions of top nameplates in 2023

2023 Hybrid nameplate	California 2025 target	-15% HEV CO_2 target	2024 2-cycle CO_2	2024 CO_2 with 2030 credits	2024 CO_2 -15% with 2030 credits
F150 (AWD)	259	227	292	271	227
RAV4 (AWD)	179	137	164	143	119
CR-V (AWD)	180	138	168	147	122
Camry	154	119	124	106	87
Grand Cherokee (4xe)[a]	202	163	268	248	207

Note: Maximum 2030 credits are based on Table 20 of EPA's final rule for MY 2027–2032: 17.8 g/mi for cars, 20.6 g/mi for trucks (Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles, 2024).

[a] The Grand Cherokee is a PHEV. Its gasoline-only operation is shown here.

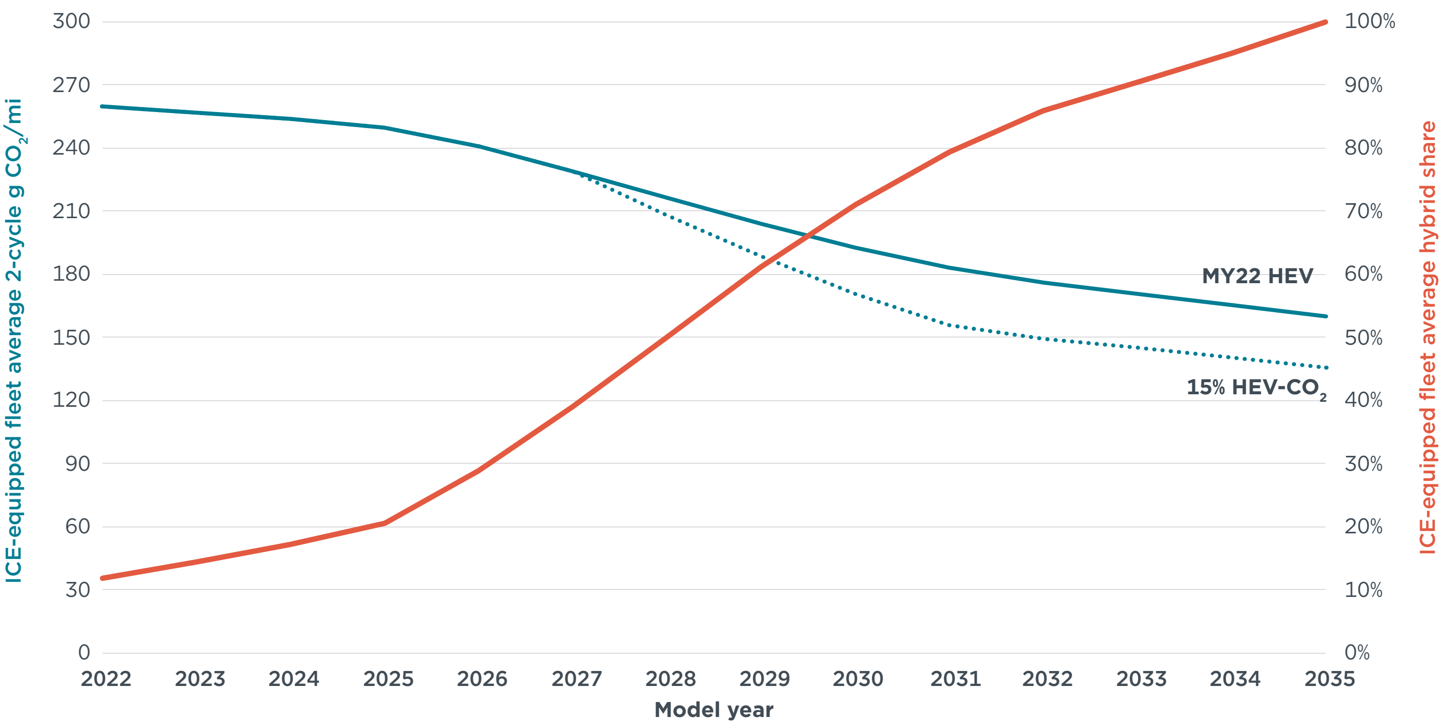
The market share of HEVs and PHEVs in sales of new vehicles in California in 2024 was 17.2% through September 2024 (Auto Outlook Inc., 2024b). The state's annual requirements for zero-emission vehicle sales (battery electric, PHEVs, and hydrogen fuel-cell electric vehicles), which increase to 100% in 2035, ensure that all new ICE-equipped vehicles in MY 2035 are PHEVs. Between 2024 and 2035, the share and efficiency of ICE-equipped vehicles remains uncertain.

Figure 9 illustrates the possible CO_2 impact of a standard requiring the ICE fleet to meet the future GHG target corresponding to 15% reductions in GHG emissions from hybrids (dashed curve in Figure 8). Starting with actual shares of strong HEVs and PHEVs in California in MY 2022 through MY 2024, the orange curve illustrates the historic (2022–2024) and projected share of strong hybrid and plug-in hybrid vehicles within the ICE-equipped fleet. Recall that California requires that 100% of ICE-equipped vehicles in MY 2035 be PHEVs. The shares in model years between 2024 and 2035 are assumed to follow a logistic function with 50% share in 2028.

The fleet-average CO_2 emissions of the ICE-equipped fleet are projected according to the share of strong hybrids plus PHEVs as outlined above, and the average emissions of HEVs. The solid curve shows the estimated fleet-average CO_2 emissions of ICE-equipped vehicles if all hybrids (both plug-in and non-plug-in) maintain MY 2022 levels of CO_2 emissions on average. The dotted curve shows the estimated ICE-equipped fleet-average CO_2 emissions if all hybrids (both plug-in and non-plug-in) eventually reach 15% lower 2-cycle CO_2 emissions (15% greater efficiency) than MY 2022 HEVs. For the dotted curve over MY 2028–2032, it is assumed that automakers increase sales of 15% lower emitting vehicles by 25 percentage points each year. Note that the PHEV CO_2 emissions rate corresponds to charge-sustaining mode. Both the solid and dotted curves rely on the same market share of HEVs and PHEVs depicted by the orange curve.

Figure 9

Estimated average tailpipe CO_2 emissions for new internal combustion engine vehicles in California, 2022–2035



Note: Fleet-average emission levels assume a new vehicle sales share of 47.5% for the car regulatory class (Auto Outlook Inc., 2024b; class market shares updated to reflect class definitions used by EPA). Non-HEV and HEV CO_2 emissions averages are from U.S. MY 2022 data (National Highway Traffic Safety Administration, 2024).

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Several additional points provide context to the findings shown in Figure 9. The solid curve—an ICE-equipped fleet based on the CO_2 emissions of MY 2022 HEVs—reaches California's estimated MY 2025 target of 179 g CO_2/mi on average by MY 2032. Based on the sales-weighted average car and light truck footprints in the United States in MY 2022, and California's market split of cars and trucks (47.5% cars / 52.5% light trucks), the average California MY 2025 target is estimated to be 179 g CO_2/mi (Auto Outlook Inc., 2024b; National Highway Traffic Safety Administration, 2024). This MY 2025 target is reached, in part, through hybridization following the orange hybrid market share curve and the average CO_2 of MY 2022 HEVs. Note that MY 2022 HEV 2-cycle CO_2 emissions are on average lower than MY 2025 targets (see Figure 8).

The dotted CO_2/mi trajectory follows the same orange hybrid sales share curve as the orange trajectory. However, the dotted curve models automaker response to a tighter standard by phasing in vehicles with 15% lower 2-cycle CO_2 emissions over the period 2028–2032. The modeling thus assumes that automakers will respond to more-stringent standards by slowly beginning to sell lower-emitting vehicles before the future standards go into effect, thereby making future compliance and consumer acceptance easier.

The 2035 average ICE fleet emissions are about 24 g/mi lower for the HEV technology potential trajectory, and the cumulative lifetime CO_2 emissions difference for vehicles sold in the years 2028–2035 is around 23 million metric tons. The cumulative emissions difference is estimated assuming survival weighted vehicle miles travelled of 195,264 for cars and 225,865 for trucks, and 1.8 million new sales annually, scaled down according to the maximum allowable share of ICE-equipped vehicles (Auto Outlook Inc., 2024b; Greenhouse Gas Exhaust Emission Standards and Test Procedures--2017 and Subsequent Model Passenger Cars, Light-Duty Trucks, and Medium-Duty Passenger Vehicles, 2022; Zero-Emission Vehicle Requirements for 2026 and Subsequent Model Year Passenger Cars and Light-Duty Trucks, 2022). The gap between the two curves, which determines cumulative emissions difference, would likely continue for years.

As this shows, current light-duty GHG standards are not stringent enough to compel automakers to minimize GHG emissions from ICE vehicles through strong hybridization or other methods. On the contrary, as expressed by the California Air Resources Board and EPA, the remaining future fleet of new ICE vehicles could backslide. Data from EPA already show that the CO_2 emissions of the ICE-based fleet are stagnating. As our analysis shows, more stringent standards that encourage hybridization of the remaining ICE fleet are achievable and cost-effective for automakers and consumers alike. The benefits would carry on for years in the form of lower GHG emissions and thousands in fuel savings for each buyer of these improved vehicles. In markets experiencing high zero-emission vehicle sales growth that offsets the need for continued and cost-effective ICE improvements to maintain compliance with CO_2 regulations, regulators could consider implementing an ICE-only emissions standard.

CONCLUSIONS

This paper analyzed HEV technology and potential CO_2 emission reductions, the historic and future costs of this technology, and how future regulations could be designed to minimize emissions from ICE-equipped vehicles. From this we draw the following conclusions:

Strong hybrids are cost-effective for consumers and automakers. The automotive industry has a long history of offering strong hybrid vehicles. In 2024, hybrids are generally as profitable as or more profitable than non-hybrid ICE vehicles. Most hybrids provide consumers with fuel savings that offset any higher upfront price. In MY 2024, 29 of 39 HEV models provide consumers with \$2,000–\$7,000 in net fuel savings over a 10-year ownership period. This does not consider further savings due to lower maintenance costs, longer brake life, and greater reliability. Alongside these fuel savings, hybrid vehicles in 2024 offer the largest CO_2 reductions amongst non-plug-in combustion vehicle technologies, and their emissions reductions could further improve by at least 15% based on existing or very near-future electrification and engine technologies.

Hybrid vehicles cost less than previously assumed in regulatory documents and their cost will likely decrease further in the future. Based on MSRP data, new hybrid vehicles in 2024 typically had price premiums over their gasoline-only counterparts ranging from under \$500 to \$3,700, with an average of about \$2,000. From these price levels we estimate direct manufacturing costs of \$1,400 on average, using RPE of 1.5. The cost model used to support EPA's recent rulemaking for MYs 2027–2032 overstates total hybridization costs by an average of \$1,382 compared with MY 2024 hybrid real-world price premiums. Moreover, each generation or redesign of a hybrid model has tended to decrease in inflation-adjusted price. Given that automakers will likely redesign existing hybrid models and engineer new offerings at least once in the decade between 2024 and 2034, it is likely that the cost of hybridization will further decrease, and potentially fall below $1,000 versus a comparable non-hybrid ICE on average. Additionally, future dedicated hybrid systems can narrow the range of engine operation, and this comes with engine simplification and decreased engine cost. Alongside increasing economies of scale for hybrid batteries and motors, the net cost for future improved hybridization could be between $340 and $730 by 2030 versus a comparable HEV with typical 2024 specifications and CO_2 emissions.

The efficiency of hybrids can continue to improve through application of known, cost-effective technologies. Powertrain improvements can increase hybrid vehicle efficiency and decrease CO_2 emissions by at least 15%. Specifically, engines and control algorithms can be designed for dedicated application within a hybrid powertrain. Dedicated hybrid engines have improved peak efficiency and/or wider regions of high efficiency compared with engines on both hybrids and non-hybrids today. Enabled by more-capable motors and batteries, engine operation can be limited to these regions of highest efficiency for longer durations across a broader range of driving conditions than today’s hybrids. These improvements are possible with existing technologies and trends in engine, battery, and motor development. Additionally, road-load improvements that apply regardless of powertrain type are continuously being developed. While not explored in this paper, such improvements could make a 15% HEV improvement easier to achieve because less powertrain improvement is needed, or they could lead to total improvements beyond 15% when coupled with road-load improvements.

The combination of increased hybrid sales and reduced hybrid emissions would lead to greater CO_2 reductions. Future regulations can continue to drive advanced hybrid technology to market to deliver not only these emissions reductions but also consumer savings from reduced fuel use.

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www.theicct.org

communications@theicct.org

@theicct.org

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