Executive Summary

Within the United States, federal and state policies are encouraging or requiring the adoption of zero-tailpipe emissions vehicles (ZEVs) like battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles. President Biden issued an executive order setting a goal that by 2030 50% of all light-duty vehicles (LDVs) sold in the U.S. will be ZEVs. BEV sales are projected to increase significantly in the coming years, but it will take decades to turn over the current vehicle fleet.

S&P Global Mobility[1] reports that in July 2021 BEVs represented only 0.42% of vehicles in operation, which left 282 million internal combustion engine vehicles (ICEVs) on the roads in the U.S. By 2030, it is projected there will be 290 million ICEVs in operation. That same year, BEV sales were projected to total nearly 2.8 million units. If LDV sales maintain their historical level of about 16.5 million vehicles per year, this would mean that, even in 2030, consumers will purchase nearly 14 million new ICEVs, and those vehicles can be expected to be on the road in the U.S. for at least fifteen years. Accordingly, large numbers of ICEVs consuming liquid fuels will be on the road in the U.S. for decades to come.

Given the objective to reduce carbon emissions from the transportation sector, waiting for the market to transition to ZEVs without seeking solutions for the dominant powertrain on the roads is a strategy

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[1] https://www.transportationenergy.org/research/reports/ev-charger-deployment-optimization

which ignores the substantial reductions which can be achieved in current and future ICEVs. Embracing strategies to reduce carbon emissions from the nearly 300 million ICEVs that will continue to operate in the U.S. for the next several decades is imperative.

Fortunately, total lifecycle, as well as tailpipe, emissions reductions are already being achieved by increasing use of biofuels and reducing the carbon intensity of the fuel mixtures used in ICEVs. Additional near-term steps to reduce the carbon intensity of fuels will play a critical role in limiting the expected increase in cumulative mobile source greenhouse gas (GHG) emissions. ICEV technologies and the associated fuels can continue to be employed over broad and energy-intensive transportation applications while making substantial contributions to near- and long-term GHG emissions reductions. In fact, substantial reductions in GHG emissions from LDVs in the near term can only be achieved by reducing emissions from ICEVs.[2]

Stillwater Associates was engaged by the Transportation Energy Institute to identify and analyze the potential opportunities to expand on this critical GHG-reduction strategy. In this report, we examine the benefits achievable through the decarbonization of the existing on-road U.S. ICEV fleet given the extended timeframe which will be required to transition that fleet to ZEVs.

This study was executed in four stages:

1. **Prelude** – An overview of the current U.S. vehicle market composition, fleet turnover rates, GHG and criteria pollutant emissions, and the duration of various GHG emissions in the atmosphere;
2. **Life Cycle Analysis of Options** – Identify a slate of options which could materially contribute to a lower carbon ICEV market;
3. **Biofuels** – Demonstrate how bio- and renewable fuels present the most promising near-term option for lowering the carbon emissions of the existing ICEV fleet; and
4. **Market Transition** – Evaluate the practical implications and requirements for transitioning the existing ICEV fuel supply to the decarbonized fuel mix identified.

IN THIS REPORT, WE ASSESS THE VEHICLE FLEET AND GHG REDUCTIONS REALIZED FROM 2011 THROUGH 2021 AND DISCUSS GHG-REDUCTION POTENTIAL FROM 2022 THROUGH 2050.

IN THIS TIMEFRAME, BIOFUELED ICEVs ARE LIKELY TO REMAIN COMPETITIVE WITH ELECTRIC VEHICLE (EV) EMISSIONS REDUCTIONS. TAKEN TOGETHER, DECARBONIZING THE ICEV FLEET AND GROWING THE EV FLEET WILL MAXIMIZE CUMULATIVE GHG REDUCTIONS.

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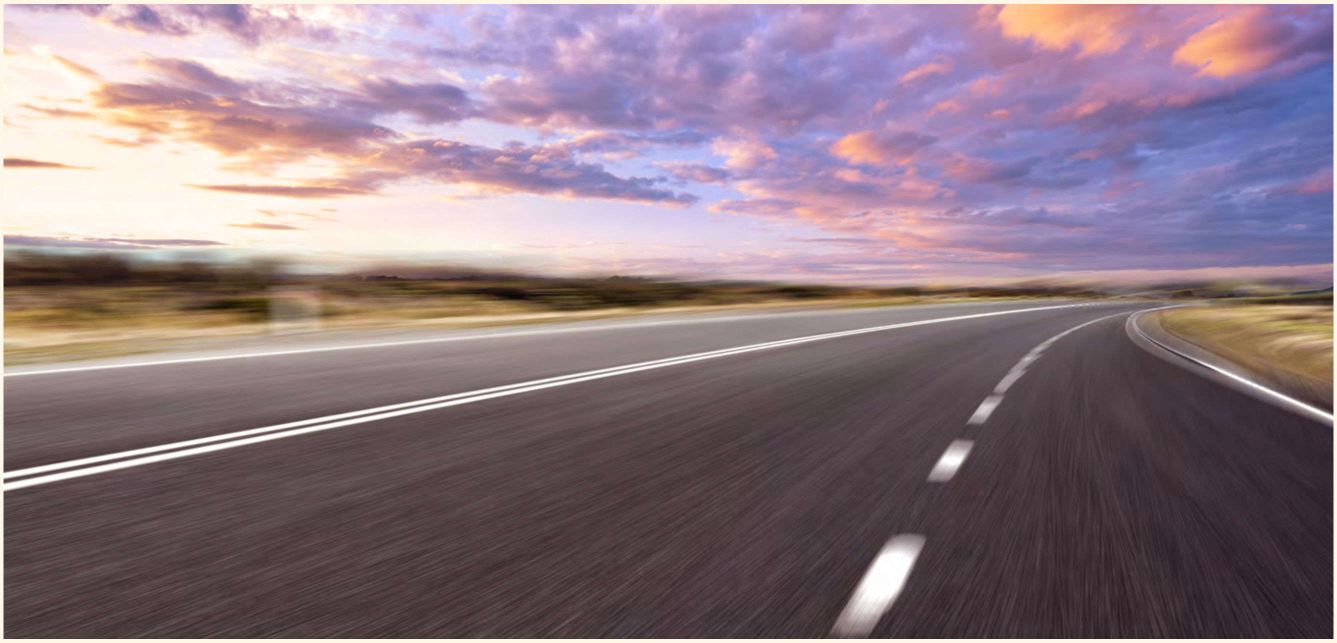
[2] U.S. Environmental Protection Agency (EPA) / Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Year 2022-2025.

The key findings of the prelude are:

1. **Biofueled ICEVs are reducing emissions now.** Since 2011, when California began tracking biofuel GHG reductions, biofueled ICEVs have reduced 76 million metric tons (MT) of GHG emissions while EVs have reduced 16 million MT. Biofueled ICEVs will continue generating more GHG reductions than EVs for at least the near term and likely into the longer term due to biofuels' low carbon intensities being used in the larger ICEV fleet.
2. **NOx and $PM_{2.5}$ emissions have been cut significantly from 2000 levels.** EPA estimates the national fleet of all vehicles (except motorcycles) reduced nitrogen oxide (NOx) emissions by 89% between 2000 and 2022. By 2030, the fleet's NOx emissions are projected to be reduced by up to 95% compared to the 2000 baseline. Today, diesel $PM_{2.5}$ emissions are 91% lower than 2000 levels, and by 2030 the fleet will be 97% lower than 2000 levels.
3. **New heavy-duty (HD) diesel vehicles provide substantial PM emissions reduction benefits.** The EPA emission inventories show new heavy-duty diesel vehicles' PM emissions in the laboratory are 99.86% lower than 1990 vehicles. When driven in air violation areas, the cleanest diesel ICEVs now operate 100.4% more cleanly than 1990s-era vehicles (i.e., modern ICEVs consume more air pollution than they emit).
4. **Fleet turnover to new technology vehicles will be slow due to higher vehicle costs and the required installation of new infrastructure.** This hinders progress towards replacing the oldest, dirtiest heavy-duty ICEVs and makes a single-track ZEV adoption approach a less economical and slower way to a cleaner vehicle fleet than reducing GHG emissions from ICEVs in the immediate term.
5. **GHG emissions reductions can be effected more immediately by incrementally reducing emissions with the current and future fleet of ICEVs than by waiting for the fleet to transition to ZEVs.** For example, if existing heavy-duty ICEVs were fueled with 100% renewable diesel (RD) starting in 2022, they would achieve GHG reductions four times greater than those achieved by EVs over the next decade. Heavy-duty ICEVs fueled with 20% biodiesel (BD) blended with 80% petroleum diesel (B20) would match expected heavy-duty EV GHG reductions over the decade. On the light- and medium-duty side, if gasoline with 15% ethanol (E15) replaced gasoline with 10% ethanol (E10), due to the significantly greater number of vehicles on the road that could use this fuel ethanol would provide twice the cumulative GHG reductions as the smaller market of EVs are expected to achieve over the decade.

The key findings of our lifecycle analysis of options are:

1. **GHG reduction options abound.** When considering the massive volume of ICEVs on the road for the decades to come, immediate solutions are necessary. There are at least 24 fuel sources for ICEVs that could provide equal or greater GHG reductions to the reduction seen in present US EVs charged using the average U.S. mix electricity (excluding coal). This demonstrates that, while the market for EVs expands, there is a diversity of biofuels sources to support significant GHG reductions from ICEVs into the future.
2. **ICEVs + biofuels is a winning immediate and long-term combo.** Conventional vehicles fueled with biofuels have the potential to provide at least 80% of total on-road transport GHG reductions through 2035 and 68% of GHG reductions through 2050.
3. **NOx emissions modeling falls short.** Applying laboratory testing results to real-world conditions results in an overestimation of realized NOx emissions from ICEVs as ambient NOx (i.e., the NOx concentration found in the air taken in by the ICEV engine) can be higher than the measured NOx in the exhaust. Thus, in real-world conditions, NOx emissions from the cleanest modern vehicles driven on the highway are a net negative. Put simply: ICEVs can clean NOx from the air.
4. **ICEVs' PM emissions have dramatically improved since 1980.** All vehicle options sold today reduce PM emissions within 3% of that logged by EVs charged using U.S. mix power. On the heavy-duty front, all properly operating (and non-coal-generated electricity charged) HD EV and HD diesel ICEVs provide equivalent PM reductions on a well-to-wheels or vehicle basis. However, high costs for newer and cleaner HD trucks often leaves older vehicles on the road for a prolonged period of time. Low carbon biofuels are necessary to improve overall emission reductions.



The key findings of the Biofuels analysis are:

1. **Biofuel benefits are not tapped out:** EIA projections indicate that the volume of biofuels used in ICEVs will hold steady through 2050 even as EVs displace ICEVs. With additional incentives for and approval of biofuels usage, these volumes and associated emissions reductions could grow.

2. **Easiest options:** Expanded usage of ethanol, RD, and BD is the lowest hanging fruit available to reduce the existing fleet's GHG emissions.

3. **Ethanol + carbon capture could provide significant benefits:** Demand for ethanol has been constrained by the absence of incentives under the current design of the federal Renewable Fuel Standard (RFS), biomass-based diesel blenders tax credit (BTC), and the cellulosic biofuel waiver credit, to price higher ethanol blends like E85 to be competitive with E10 at an energy equivalent level. The Inflation Reduction Act of 2022 (IRA)[3] expands the 45Q tax incentive for carbon capture, utilization, and storage (CCUS) and adds significant support for ethanol produced with CCUS.

4. **The food versus fuel debate is fading:** Ethanol and BD supply currently rely heavily on two feedstocks, corn and soybeans, respectively. The impact of using a growing share of corn for fuel instead of food has declined over time due to increasing crop yields, corn-to-biofuel conversion process efficiency, and improvements in the ability to extract coproducts like dried distillers grains with solubles and corn oil.

5. **Nonfood feedstocks show growth potential:** In addition to current and growing usage of inedible tallow, used cooking oil, and distillers corn oil, there is significant potential to use nonfood feedstocks, such as oilseeds from cover crops and dedicated energy crops, to produce biofuels with much less diversion of cropland to biofuel production and greater potential to reduce carbon intensity of transportation fuel. However, policy incentives that reward lower carbon fuels and improve their competitiveness and assured demand are critical to induce investment in these feedstocks. The transition from the BTC to the Clean Fuels Production Tax Credit (also referred to as 45Z) in 2025, as established by the IRA, provides increased incentive to utilize nonfood feedstocks for production of biofuels.

6. **State-level low-carbon fuel standard (LCFS) programs are driving low-carbon fuel innovation:** LCFS-style programs, as currently exist in California, Oregon, and Washington (with potential to expand into additional states), have accelerated the use of renewable fuels beyond what is required by the federal RFS. In addition to supporting the replacement of ICEVs with ZEVs, LCFS programs provide unique incentives to producers of all low-carbon fuel options to continually reduce the CI (carbon intensity) of their production. As a result, existing LCFS programs have driven deeper decarbonization of ICEV fuels than would have been achieved with the RFS alone. In California, for example, the LCFS has led to the displacement of over one-third of petroleum diesel fuel demand with RD and BD.

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[3] 117th Congress / Public Law 117-169.

The key findings of the Market Transition Requirements analysis are:

1. **Immediate carbon reductions yield both short- and long-term benefits:** Many near-term options for reducing the carbon intensity of ICEV fuels will have near-term reductions in carbon emissions since those ICE fuels will be used in the current fleet of ICEVs and will continue into the future. Improvements to ICEVs' fuel economy amplify these carbon reductions.
2. **All options faces challenges:** There are varying degrees of viability and timing uncertainties in each of the options for further decarbonizing ICEVs.
3. **There is no silver bullet:** Given these uncertainties and the fact that some of these alternatives are highly aspirational, a portfolio approach to ICEV decarbonization is advisable.
4. **ICEV carbon reductions are a crucial near-term step toward net zero:** Since full ZEV deployment is not without significant challenges and is not viable as a short-term solution, deployment of lower carbon ICE vehicle and fuel options provides real near-term carbon emissions reductions and can be a hedge against slower ZEV deployment.
5. **ICEV improvements can complement ZEV deployment**: A portfolio approach will maximize the reductions in on-road transportation carbon emissions in both the near and long term and result in both ICEVs' (near-term) and ZEVs' (longer term) roles in minimizing transportation carbon emissions being realized.
6. **A portfolio approach:** Based on our analysis and comparison of the alternatives discussed in this report, we propose a list of prioritized options to optimize the carbon reduction of the ICEV fleet based on the parameters evaluated. These parameters include potential fleet carbon reductions, ease of economic and consumer acceptance, technical viability, costs, and timing. The ranked options are listed in the table below. The first-tier options are the lowest hanging fruit with reasonable feasibility and relatively low cost-to-benefit ratios. The second-tier options are opportunities that need more time to develop, and the third-tier options require a significant breakthrough to become practical alternatives. (Table ES 1)

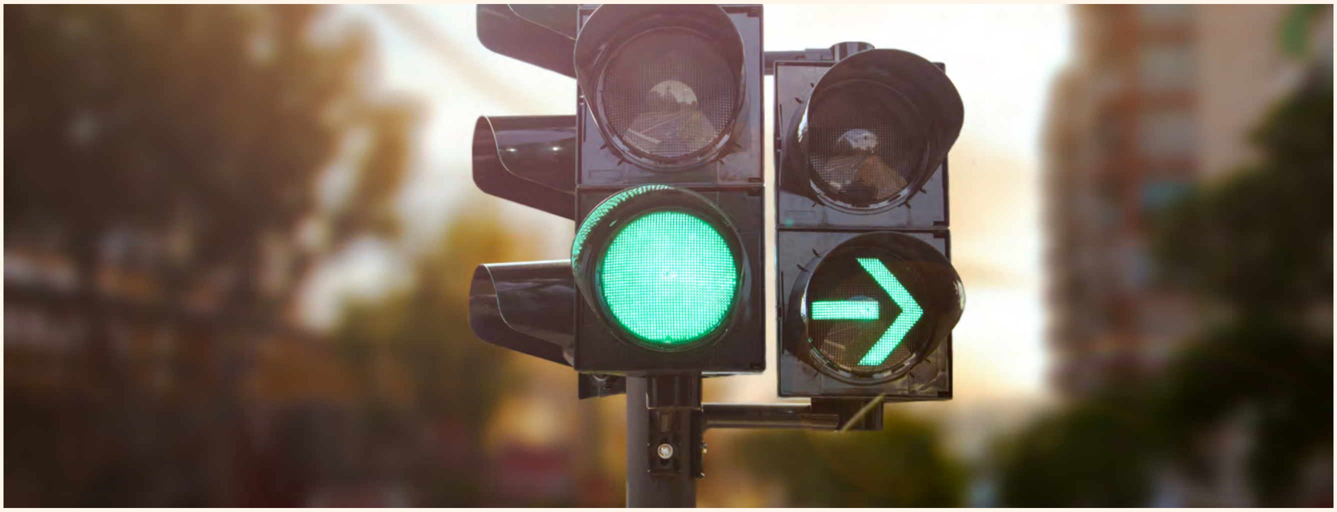

TABLE ES-1. TIERED ICEV CARBON-REDUCTION POTENTIAL OF ALTERNATIVE OPTIONS*

TIER	OPTION	PAIRED VEHICLE TECHNOLOGY	CARBON REDUCTION VS. CURRENT FLEET & FUELS	POTENTIAL IMPACT	INITIATIVES REQUIRED	
					REGULATORY	MARKETPLACE
0	Current ULSD & E10 Gasoline	Current Gas ICEV	base	N/A	N/A	N/A
1	Biodiesel (B5)	Current Diesel ICEV	<5%	small	N/A	Increased feedstock generation
1	Ethanol (E15)	Current Gas ICEV	3%	small	Wider EPA approval	Infrastructure build-out
1	Renewable Gasoline (RG)	Current Gas ICEV	50-70%	small	Continuation/expansion of existing regulatory incentives	Scalability of production
1	Renewable Natural Gas (RNG)	NGV	100+%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Renewable Propane (RP)	LPG ICEV	60-70%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Reduced CI Gasoline & Diesel	Current ICEVs	5-15%	small to medium	Strengthened regulations on upstream flaring and methane emissions; continued move to renewable marine fuels; continued regulatory incentives for CCUS and use of renewable energy at refineries	Refinery investment in CCUS and usage of renewable energy
1	Ethanol (E15)	Hybrids (HEV & PHEV)	20%	small to medium	E15 approval and increased incentives for hybrid expanded vehicle purchases	Conversion to hybrid vehicle fleet and expansion of E15 infrastructure
1	Biodiesel (B20)	Current Diesel ICEV	5-15%	small to medium	N/A	Increased feedstock generation
1	Ethanol (E85)	FFV	15-25%	small to medium	Increased incentives for FFV production and purchase (adjustments to CAFE) and potential aftermarket equipment certification program for FFV conversions	Fueling infrastructure expansion and increased vehicle and fuel availability
1	Renewable Diesel (R99)[3]	Current Diesel ICEV	50-70%	medium	Continuation/expansion of existing regulatory incentives	Increased feedstock generation
1	Renewable Diesel (R99)	Hybrids (HEV & PHEV)	55-85%	medium	Increased incentives for hybrid vehicles	Conversion to hybrid vehicle fleet and increased feedstock generation
2	Ethanol (Intermediate Blends)	Dedicated Vehicle	5-15%	small	New incentives for development of dedicated intermediate-ethanol-blend vehicle production	Expanded compatible fuel infrastructure
2	Biodiesel (B20+)	Current Diesel ICEV	40-60%	small	Establish ASTM standards	OEM warranty, expanded fueling infrastructure, and increased feedstock generation
2	ICEV Improvements	NA (current fuels)	20-50%	medium	Technology-neutral testing and CAFE standards	Broad OEM roll-out
2/3	Hydrogen (H_2)	H_2 ICEV	60-100%+	small	Substantial financial incentives	Build-out of hydrogen production hubs, expansion of dedicated fueling infrastructure, conversion of vehicle fleet to H_2
3	Cellulosic Ethanol (E10)	Current Gas ICEVs	5-10%	small	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Cellulosic Diesel	Current Diesel ICEVs	60-90%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	FT Diesel (BTL)	Current Diesel ICEVs	20-100+%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Pyrolysis Fuels	Current Gas & Diesel ICEVs	0-60%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	E-Fuels	Current Gas & Diesel ICEVs	40-100%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost

*For an explanation of the assigned tiers presented in this table, please refer to page 175.

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[4] Renewable Diesel (RD) at 100% by volume (R100) can be placed into a vehicle without issue, but the Biomass-Based Diesel Blenders Tax Credit (BTC) requires blending of RD with petroleum diesel in order to generate the credit. As such, essentially all RD in the market is blended with at least a small amount of petroleum diesel.