Paper ID APEN-MIT-2020_208
Applied Energy Symposium: MIT A+B
August 12-14, 2020 • Cambridge, USA

Biofuels with Tailored Properties (A) for Hybrid and Plug-in Electric Vehicles(B)

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Abstract— For the past five years, the Department of Energy's Co-Optima program has explored biomass-derived blendstocks with fuel properties that boost the efficiency of engines, seeking to enable technology for fuel-engine co-optimization. Past analysis quantified benefits of introducing co-optimized fuels and engines for light-duty vehicles with the core assumption that efficiency gains would be the same for vehicles with and without hybridized power trains. Vehicles with hybridized powertrains, however, could experience a different energy efficiency change than conventional vehicles, which could be a decrease, if the blended fuel is not tailored for their operation, or an increase, if the hybrid engine's operational conditions take better advantage of the blended fuel. Therefore, this study examines opportunities to reduce the environmental effects of light-duty transportation when fuel properties are tailored to the unique needs of hybrid electric and plug-in hybrid electric (HEV, PHEV) vehicles to improve their engine efficiency. The analysis tracks greenhouse gas emissions reductions on a well-to-wheels basis when co-designed fuels and engines for vehicles with hybridized power trains are introduced into the market. Engine efficiency gains and incremental vehicle cost are key parameters in the analysis as we seek fuel-engine technology that will significantly boost overall vehicle efficiency at a price point that is commercially viable. Twelve co-deployment scenarios were generated based on 3 different levels of engine efficiency improvement (8% ,10% and 12%) and 4 level incremental costs ($100, $250, $500 and $1000) and the corresponding environmental effects are tracked as the technologies gain market adoption. The preliminary results show that the effect of incremental cost and efficiency gain on vehicle sales indicates that adoption of co-optimized HEV, and PHEVs are relatively insensitive to incremental vehicle purchase costs up to $250. In addition, the results indicate higher adoption of co-optimized HEVs at $100 and $250 price increase and 12% efficiency gain while the adoption of HEVs and PHEVs across other scenarios remain consistent. From the best-case scenario ($100, vehicle price increase and 12% engine efficiency increase), the result shows that using biofuels with tailored properties and advanced engines to achieve an increase hybridized engine efficiency could translate to 17.5% reduction in greenhouse gas emissions from the light duty vehicle fleet including non-hybridized vehicles in 2050.

Keywords— Biofuels, PHEV, HEV

I. INTRODUCTION

A. *Role of Biofuel in Decarbonization*

Transportation emits about 20% of global greenhouse gas (GHG) emissions [1, 2]. As a result, researchers have explored many routes to cutting emissions from this sector [3,4,5,6,7,8,9, 10, 11]. These strategies rely on developing new technologies for liquid fuels and for advances in energy storage technology. Biofuels have been included in decarbonization strategies in several countries [3,5,6,12,13]. Indeed, there has been a notable increase in biofuel usage over the past years and currently biofuels represent 3% of the world's road transport fuel [14]. Biofuels offer the opportunity for exploitation of unique biomass composition and properties for improved engine efficiency in addition to their lower GHG emissions compared to conventional fuel [15]. As a result of the lower carbon intensity of biofuels [15], a reduction in transportation emissions can occur when biofuel is blended with conventional fuel. To this end, biofuels usage in the US has been supported through the national Renewable Fuel Standard with corn ethanol dominating the biofuel market. While biofuels offer many energy, environmental, and societal advantages, the role of liquid fuels in the light-duty fleet is changing as vehicles with hybridized powertrains and full electric vehicles gain market share. Although biofuel is playing a vital role in transportation sector decarbonization, improvements in combustion engine efficiency and advances in hybridized powertrains cannot be overlooked [16]. Certainly, PHEVs/HEVs play a critical role in transportation's decarbonization because they emit fewer GHG emissions per mile than comparable conventional vehicles [17]. However, most decarbonization plans target either fuels or advancing vehicles with hybridized powertrains as separate decarbonization strategies without considering the synergies between different decarbonization technologies. When the lower life cycle GHG emissions of biofuels are combined with the potential to tailor biofuel properties to boost fuel economy [15] in engines used in conventional internal combustion engine vehicles or in vehicles with hybridized powertrains, there is an opportunity to reduce GHG emissions beyond what could be achieved if fuel and vehicle technologies are separately pursued. With this benefit in mind, the Department of Energy's Bioenergy Technologies Office and Vehicle Technologies Office have worked with nine national laboratories in deploying the Co-Optima consortium to address fuel/engine co-design for internal combustion engine and hybrid powertrain vehicles [3].

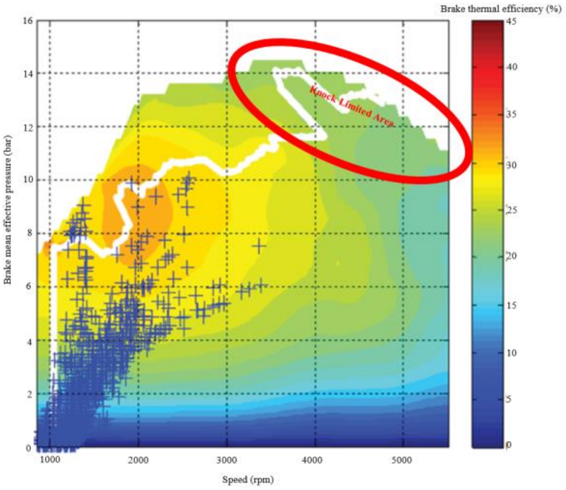
B. Co-Optima: Fuel and Engine Co-design

Today's engines were designed specifically for fuels that could be produced profitably from petroleum. Revisiting the potential co-design of fuels and engines to target desirable outcomes that can be achieved with biofuel blends including improved engine efficiency and lower engine-out emissions has been of interest to Co-Optima [3]. In the case of light-duty vehicles, this consortium has investigated the relationship between fuel properties and engine efficiency. One fuel property that benefits engine efficiency and can be tailored to improve engine efficiency is research octane number (RON) [18, 19, 20]. Co-Optima has explored in particular how unique fuel properties may be obtained when leveraging biomass-derived blendstocks [21,22,23]. Motivations for deriving blendstocks from biomass include performance-advantaged molecules that are in biomass but not in fossil fuels (e.g., oxygenated compounds), societal benefits such as increased employment in rural areas, and environmental benefits including lower GHG emissions from biofuels as compared to fossil fuels [4].

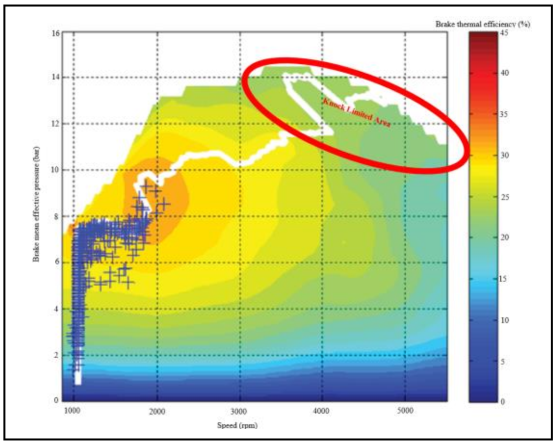
C. How Fuel Properties Enable Higer Efficiency in Boosted Spark Ignition Engines (BSI) when coupled with Hybridized Powertrains

Compared to vehicles with conventional powertrains, engines in vehicles with hybridized powertrains have a narrower operating range requirement, which offers opportunities to tailor the fuel properties with the engine design that can provide increased vehicle fuel economy. For example, BSI engines experience increased efficiency when operating at high loads using fuels with high research octane number (RON). At low loads, however, fuels with high RON do not provide any efficiency benefit unless the engine is re-optimized, or co-optimized with the improved fuel properties. In the case of a hybrid powertrain, the operating range of the engine can be shifted so it operates in a region that takes better advantage of the high octane, but that is dependent on the vehicle drive cycle.

Fig. 1 shows the engine operating points of a common Urban Dynamometer Driving Schedule (UDDS) cycle overplotted with the engine efficiency. The use of a hybrid powertrain can keep the engine operating at its most efficient speed and load range a greater amount of time. If a fuel property is improved (RON in this example), the engine will be more efficient in the range of operation that is knock limited at high speeds and loads (circled in red on the graphs). However, on this particular drive cycle, the engine never operates in the area of improved efficiency, regardless of which powertrain is in the vehicle. To take advantage of this improved efficiency, the engine must be re-optimized with a higher compression ratio, which will provide efficiency improvement across the entire operating map. Further benefits of hybridizing the powertrain can also be realized when the size of the engine can be reduced. A hybrid powertrain allows this to be done without performance penalty because the battery/electric motor of the hybrid powertrain can make up the additional power needed during heavy acceleration [24].



a)



b)

Fig. 1. Engine operating points during the Urban Dynamometer Driving Schedule: (a) with a BSI engine in a conventional power train, (b) with a BSI engine in a hybrid powertrain. Adapted from [24]

D. Benefits of co-optimizing fuels and engines for vehicles with hybridized power trains

To evaluate how co-design of fuels and engines for both conventional and hybridized powertrains could contribute to decarbonization strategies, analysis is required. The Co-Optima program has evaluated the environmental benefits from deployment of biofuels co-optimized with solely BSI engines [4]. The results from the study showed that the adoption of co-optimized fuels and engines resulted in reduced petroleum consumption, GHG emissions, water consumption, and criteria air pollutant with about 7% reduction in GHG emission in 2050. In that analysis, BSI engines in HEVs and PHEVs were assumed to have the same engine efficiency gains as vehicles with conventional powertrains when using a fuel blend containing petroleum- and bio-derived blendstocks with properties tailored for BSI engines. The role of HEVs and PHEVs in these analyses, however, deserves a closer look because the engine efficiency change they experience could be different from that exhibited in a conventional powertrain. HEV or PHEV engines could, for example, experience a greater engine efficiency gain, no efficiency gain, or a decrease in engine efficiency compared to BSI engines. In a new analysis, we therefore investigate strategic routes to developing biomass-derived blendstocks (technology A) with properties that boost the unique engines in HEVs and PHEVs (technology B) that could guide research within Co-Optima and other programs and illuminate how this technology combination could reduce transportation sector GHG emissions. Critical to this strategy development is analyses that directs research towards fuel-engine technology that will significantly boost overall vehicle efficiency at a price point that is viable commercially. To this end, we explored the parameter space for fuel economy gains and incremental vehicle cost that would influence adoption of co-optimized vehicles with hybridized power trains. The overall goal is to track the environmental effects of deploying co-optimized fuels and engines in the light-duty fleet with fuel properties tailored for HEV and PHEV to understand what we can expect in terms of GHG reductions over time as the technology is introduced.

II. MODELING TECHNIQUES FOR SCENARIO ANALYSIS

The modeling suite we use is described in Fig. 2. The Automotive Deployment Options Projection (ADOPT) model projects the changes in light-duty fleet composition over time as new vehicle technology enters the market. In determining the best-selling vehicles, the ADOPT model integrates market and regulatory data forecasts with main model assumption based on fuel prices, GHG emission rates for each fuel type and CAFE & GHG standards for light-duty cars and trucks. 12 scenarios were run in ADOPT to cover the range of cost increases and hybrid engine efficiency improvements. The average peak engine efficiency input in ADOPT for conventional engines in 2019 was 36% [25]. This figure was set to increase to 38% in 2027 as co-optimized vehicles had a simulated market introduction in 2027. During the period of analysis (2027-2050), the conventional Co-Optima vehicle experienced 8% engine efficiency gain relative to baseline petroleum ICEVs while the hybridized Co-Optima vehicles experienced three potential engine efficiency gains of 8–12% relative to baseline petroleum ICEVs as shown in Table 1 at 4 potential price points. The average cost of an ICE engine is about \$4,000. The incremental cost increases range from \$100 - \$1000 (2.5% to 25% of total average ICE engine cost) in our cost scenarios.

The corresponding fuel demand based on the output from ADOPT is communicated to the Biomass Scenario Model (BSM). BSM evaluates the cost of biofuels, and their availability based on feedstock and biorefinery availability and growth. There is a yearly time step interconnection between BSM and ADOPT models [26]. The output from BSM consists of annual fuel consumption, total vehicle miles travelled by vehicle technology, and average fuel economy by vehicle technology. Finally, the BSM communicates the energy/fuel consumption by vehicle technology to the Bioeconomy Air and Greenhouse Gas Emissions (Bioeconomy AGE) model. Based on the life-cycle energy and water consumption and GHG and air pollutant factors from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model, Bioeconomy AGE calculates key energy and environmental effects over time and compares them to a business as usual case (BAU).

TABLE I. POWERTRAIN EFFICIENCY ASSUMPTIONS

Powertrain	Engine Efficiency (2027-2050)
Conventional	38.0%
Co-Optima Conventional	41.0%
Co-Optima HEV and PHEV	41.0%, 41.8%, 42.6%
Co-Optima Conservative	38% *(100% + 8%) = 41.0%
Co-Optima Mid	38% *(100% + 10%) = 41.8%
Co-Optima Optimistic	38% *(100% + 12%) = 42.6%

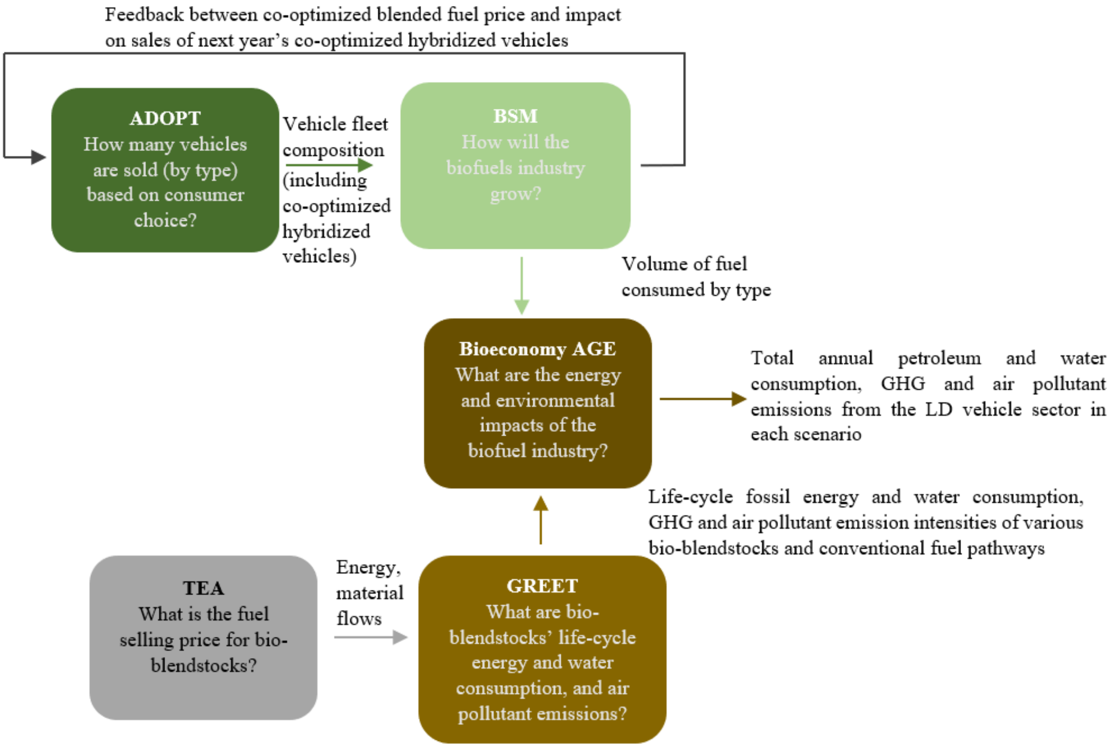


Fig. 2. Modelling techniques for scenario analysis. ADOPT: Automotive Deployment Options Projection Tool. BSM: Biomass Scenario Model TEA: Techno-economic Analysis. GREET®: Greenhouse gases, Regulated Emissions, and Energy use in Transportation. Bioeconomy AGE: Bioeconomy Air and Greenhouse Gas Emissions

To promote comparison between the BAU case and the co-optimized case, a set of assumptions and conditions were defined for the baseline model in ADOPT/BSM. These were used in generating the BAU and the co-optimized scenarios and the major difference lies in the absence of Co-Optima fuel and vehicles in the BAU case. The baseline for oil price and overall vehicle sales projection followed the 2020 Annual Energy Outlook (AEO) reference case [27].

III. RESULTS AND DISCUSSIONS

A. ADOPT Modelling

Exploring the effect of incremental cost and efficiency gain on vehicle sales in ADOPT modelling, the preliminary results indicated that adoption of co-optimized HEVs and PHEVs were relatively insensitive to incremental vehicle purchase costs up to $250. Once the incremental cost exceeds $500, there is a notable drop in vehicle sales despite expected fuel cost savings. The results from the three notable scenarios scenarios in ADOPT is summarized in Fig. 3. These Figures represent cases with $100, vehicle price increase and 12% engine efficiency increase categorized as the best case scenario, $500, vehicle price increase and 10% engine efficiency increase categorized as mid case scenario and $1000, vehicle price increase and 8% engine efficiency increase categorized as the conservative case scenario. In all scenarios with incremental costs below $500 with Fig. 3a as an example, co-optimized PHEVs constituted the main share of the new co-optimized vehicle sales over the analysis period. In all cases across the scenarios, the effects of engine efficiency gains (8-12%) was less pronounced, but the share of co-optimized HEVs increased as efficiency gains increased.

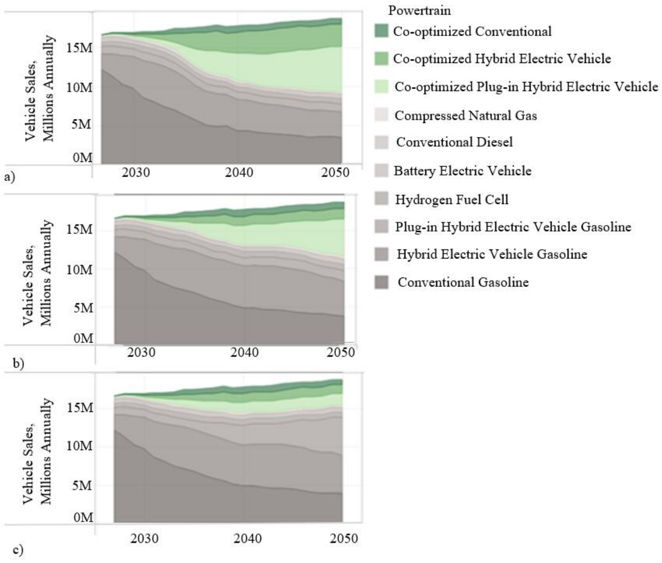


Fig. 3. Summary of ADOPT modelling results: (a) $100 incremental cost, 12% Efficiency Gain (b) $500 incremental cost, 10% Efficiency Gain and (c) $1000 incremental cost, 8% Efficiency Gain

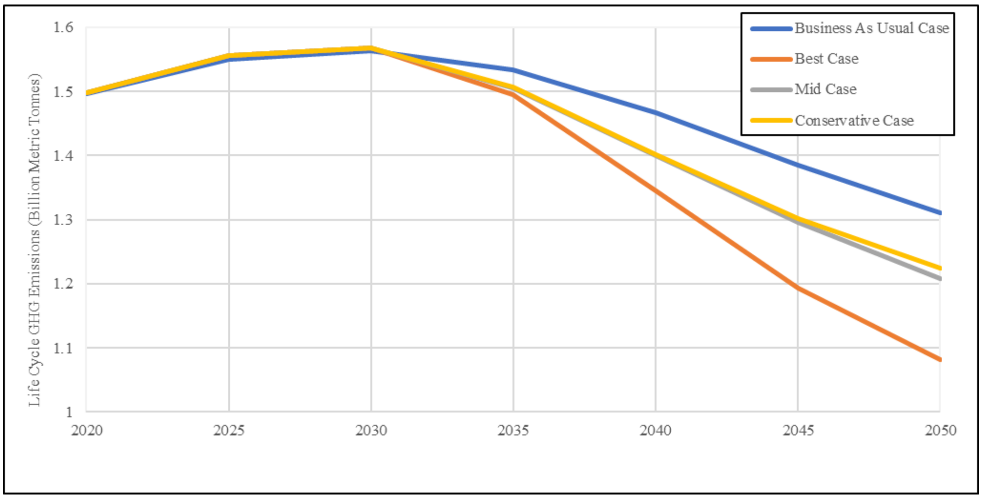


Fig. 4. Life cycle GHG emissions results for the three cases compared to Business as usual case

B. Bioeconomy AGE Modelling

From the 12 scenarios output from ADOPT modelling, Bioeconomy AGE focused on three major scenarios, the best case scenario ($100, vehicle price increase and 12% engine efficiency increase), the mid case scenario ($500, vehicle price increase and 10% engine efficiency increase), and the conservative case scenario ($1000, vehicle price increase and 8% engine efficiency increase). We analyzed the environmental effects of co-deploying biofuels with hybridized powertrains focusing on greenhouse gas (GHG) emissions (Fig. 4). In the BAU case, GHG emissions start to decline in 2029 after a period of emissions increase due to increased travel demand then continues to decline until 2050. With co-optimized vehicles introduced in 2027, the emission benefit begins to accumulate after 2030 in the three cases compared to the BAU case. The best case scenario offers a cumulative emission reduction benefit of 5% between the period of 2027-2050 and 17.5% reduction in 2050 representing 229 million metric tonnes in 2050 relative to the BAU case. For the mid and conservative case scenarios, the cumulative emission reduction benefit is capped at 2.4% and 2.3% respectively relative to the BAU case. The lower emission benefit observed in these two cases are a result of lower co-optimized vehicles adoption due to higher vehicle incremental cost compared to the best case scenario.

We broke down the emission benefit by vehicle type (Fig. 5). The major driver behind the emission reduction is the replacement of other vehicle types such as conventional ICEVs and conventional hybrid including EVs with co-optimized vehicles. We see a major contribution from gasoline ICEVs and HEVs as co-optimized vehicles gain market penetration and displace the conventional vehicles. For the purpose of clarity, it is worth noting that the categories of gasoline vehicles below include the Co-Optima versions of each vehicle type. Another driver for the emissions benefit is the reduced life cycle carbon intensity of co-optimized fuels and increased efficiency of co-optimized hybridized engines.

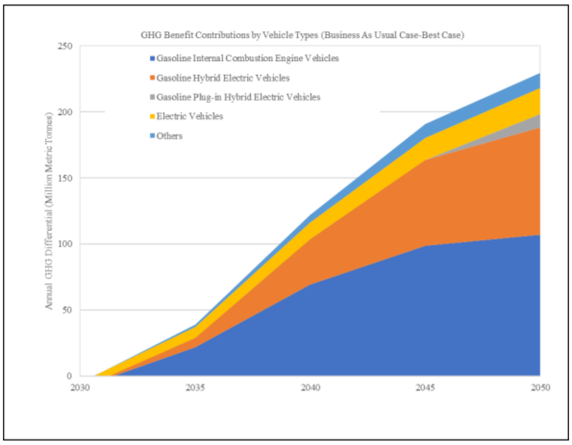


Fig. 5. Emission benefits contribution by vehicle types

IV. CONCLUSIONS

We have explored the effect of incremental cost and efficiency gain on vehicle sales and tracked the environmental impact of co-deploying co-optimized fuels and engines in the light-duty fleet with fuel properties tailored for HEV and PHEV. The results have shown that for incremental vehicle prices between $100-500, sales of co-optimized vehicles are significant for the range of efficiency improvements (8-12%) considered. Overall, our current results indicate that although there is an increase in vehicle price, using biofuels with properties tailored to the unique need of hybridized powertrains to improve their engine efficiency could translate to a 17.5% reduction in GHG emissions from the light duty vehicle fleet in 2050. Co-optimized engines and biofuels in HEVs contributed more to reduction in environmental impacts compared to PHEVs. We continue to explore this space, estimating GHG emissions reductions, energy and water consumption, and air pollutant emissions effects of co-deploying biofuels and vehicles with hybridized powertrains towards improved fuel economy. These analyses will in turn help guide the development of new fuel and engine technologies within the Co-Optima program and broader research community.

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