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Evaluation of the Potential for Significant GHG Emission Reductions from ICEs Operated on Liquid Fuels

Final Report

July 2024

COORDINATING RESEARCH COUNCIL, INC.

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Evaluation of the potential for significant GHG emission reductions from ICEs operated on liquid fuels

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Acronyms and Abbreviations

BEV	Battery electric vehicle
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CM	Commissioning and ramp-up
CO	Construction
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
E10	Ethanol (10%)
E25	Ethanol (25%)
E85	Ethanol (85%)
E100	Ethanol (100%)
EAS	Exhaust aftertreatment system
eGRID	Emissions & generation resource integrated database
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
EJ	Exajoule
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FCV	Fuel cell vehicle
FFV	Flex fuel vehicle
FT	Fischer-Tropsch
GHG	Greenhouse gas (emissions)
GREET	Greenhouse gases, regulated emissions, and energy use in technologies
GWP_{100}	Global warming potential over a 100-year timeframe
GVWR	Gross vehicle weight rating
H_2	Hydrogen
HEV	Hybrid electric vehicle
HVO	Hydrotreated vegetable oil
HVO/HEFA	HVO/hydroprocessed esters and fatty acids
ICE	Internal combustion engine (vehicle-type)
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
ktons	Kilo-tons

LCFS	Low carbon fuel standard
LDV	Light-duty vehicle
LPG	Liquified petroleum gas
M17	Methanol (17%)
MJ	Megajoule
MOVES	Motor Vehicle Emission Simulator
MPG	Miles per gallon
MSW	Municipal solid waste
Mtons	Million tons
NG	Natural gas
PD	Project development and financing
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PTL	Power-to-liquid
RFS	Renewable fuel standard
RWGS	Reverse water-gas shift
SUV	Sport utility vehicle
TTW	Tank-to-wheel
UCO	Used cooking oil
VMT	Vehicle miles travelled
WTT	Well-to-tank
WTW	Well-to-wheel

EXECUTIVE SUMMARY

Objectives and Context

Given the uncertainty in the rate of uptake of BEVs and the speed of US grid decarbonization, this study aims to explore options available to ICE vehicles to accelerate the decarbonization of the US light duty vehicle fleet. The analysis considers ICE vehicles and BEVs as complementary rather than in competition with each other in how they can contribute to the decarbonization of the light duty vehicle fleet by 2030.

Approach

Two broad categories of fuel decarbonization options were evaluated: drop in fuels (compatible with existing vehicles with no modifications e.g. renewable gasoline) and non-drop in fuels (in vehicles designed specially to take these fuels e.g. flex fuel vehicles on E85).

The following analysis was conducted:

- Vehicle stock modelling was used to assess how the makeup of the fleet would change over time, and assess the potential penetration of vehicles able to use non-drop in fuels
- Fuel supply ramp up modelling was used to assess a realistic ramp up rate of both drop in and non-drop in fuels
- Well-to-wheel and lifecycle GHG analyses were then conducted to assess the potential contribution to decarbonization of drop in and non-drop in fuels

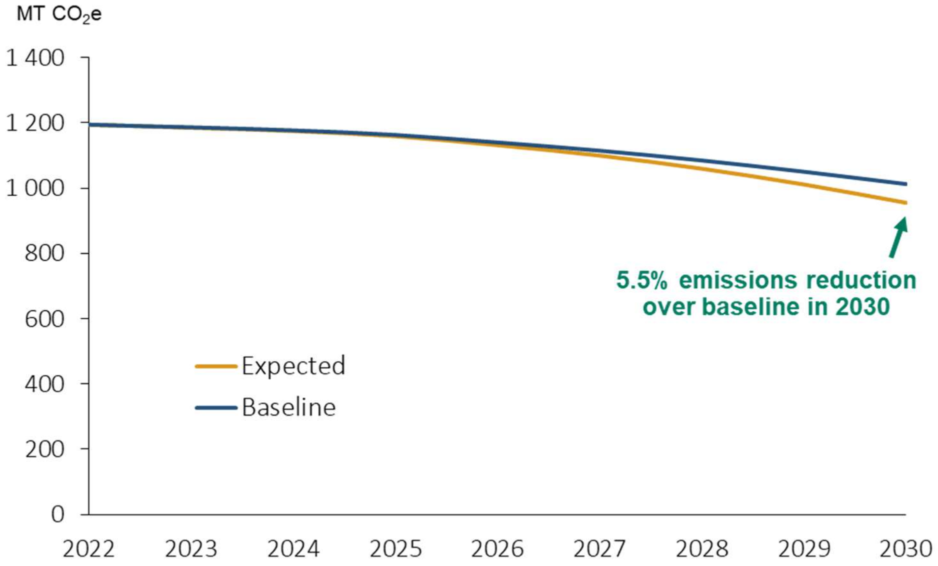
The study used 3 ‘cases’ to understand the potential decarbonization contribution of low carbon fuels:

- Baseline case = “**business as usual**”, which considers the fleet impact in 2030 of the use of a conventional gasoline blend (E10) in ICE vehicles and Section 177 weighted average grid mix for the BEVs. This aims to show the level of decarbonization **without the impact of drop in fuels and non-drop in fuels**.
- Expected case = **“what could be achieved?”**, which considers how current trends in low carbon fuels could lead to reductions in ICE vehicle emissions. This aims to show the **additional decarbonization that could be achieved with drop in and non-drop in fuels, based on a realistic rate of uptake of fuels and vehicles.** Note: BEV and PHEV uptake assumed to be the same in Baseline and Expected cases
- Aspirational case = **“what would need to be achieved?”**,which considers how an aspirational GHG emissions reduction target could be achieved through higher penetration of low carbon fuels and/or certain vehicle types.

Results and Discussion – Phase 1

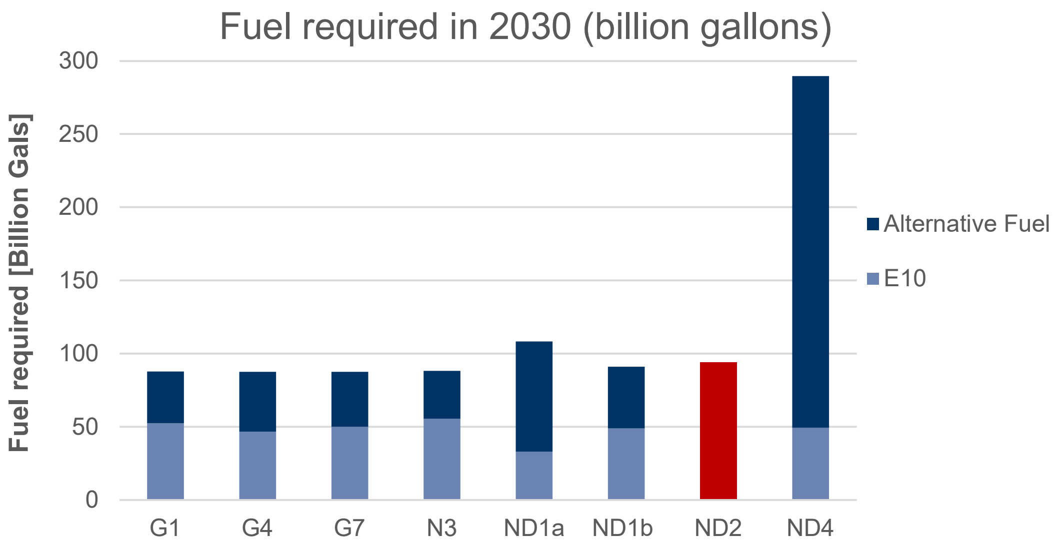
The aim of Phase 1 was to understand the role low carbon fuels in ICE vehicles might have in the decarbonization of the US light duty vehicle fleet between 2020 and 2030, on top of projected levels of electrification. The baseline scenario shows what the WTW GHG emissions of the fleet would look like based on a “business as usual” scenario, in which a reduction of 18% GHG emissions is achieved between 2020 and 2030 because of increasing penetration of PEVs (plug-in electric vehicles like PHEV and BEV) in addition to improved fuel economy and vehicle efficiency of new ICE vehicles. In the baseline, it was assumed that the ICE vehicle fleet is supplied with E10 (assuming corn-based ethanol).

The Expected scenario explored a realistic level of decarbonization achievable through the uptake of eight different drop in and non-drop in fuels (“alternative fuels”). The drop in fuels – those that require no ICE modifications – were considered alongside the E10 fuel mix for conventional ICE vehicles, whilst non-drop in fuels were considered alongside the introduction of modified ICE vehicles in the fleet. The Expected scenario showed further emissions reductions of 4.6% in 2030 relative to 2020 emissions, resulting in a 22,6% reduction, and a 5.5% reduction relative to the Baseline scenario in 2030. These reductions are fairly minor, due to the anticipated limited availability of alternative fuels (notably the drop in gasoline fuels) between 2022 and 2030 (~0.5 EJ). Fuel supply was projected based on current and planned projects, the number of developers and projections of plant deployments. In addition, there was limited deployment of non-drop in vehicles, only being introduced into the fleet from 2025 onwards. However, of the pathways explored, E85 showed the greatest contribution to GHG reductions compared to the baseline, largely due to future corn ethanol (with carbon capture and storage (CCS)) use being significantly higher than other pathways as a result of an already mature corn ethanol industry, the existence of FFV vehicles already in the fleet, and a higher share of FFV in new vehicle registrations beyond 2025.



Annual WTW GHG Emission Reductions – Baseline vs. Expected Scenarios

To better understand the scale of what would be required for alternative fuels to have a prominent role in the decarbonization of the LDV fleet by 2030, an Aspirational scenario was investigated. It considered a top-down approach, setting a GHG reduction target of 55% compared to 2005 levels, in line with the Paris Agreement. Such a target is equivalent to 702 Mt CO_{2e} emitted in 2030. Leaving PEV penetration at the same level as in Baseline and Expected, the cap on ICE WTW emissions was determined to be 634 Mt CO_{2e} in 2030. Approximately 4 EJ of alternative fuel would be required to achieve the emissions reduction target, a factor of 10 higher than what was estimated to be available under the Expected scenario. To supply this quantity of alternative fuel, 1000s of new plants would need to be built, and the majority of the US' biomass feedstock would need to be harnessed. In addition, for non-drop in routes, the fleet would need essentially all new registrations from 2022 to be non-drop in vehicles.



Annual WTW GHG Emission Reductions – Baseline vs. Expected Scenarios

ICE Fuel Pathways

Fuel Type	Pathway ID	All fuels produced by pathway Fuel focused on in this study (energy basis)	Fuel Process
Drop-in	G1	Bio-gasoline (92% of product slate), LPG	Waste gasification + Methanol-to-Gasoline
	G4	Bio-gasoline (58% of product slate), diesel, jet fuel, heavy fuel oil	Forestry & agricultural residues + pyrolysis + stabilization by Catalytic Hydrotreatment + upgrading
	G7	Diesel, jet fuel, bio-gasoline (24% of product slate), LPG, fuel gas	Oils/fats[1] co-processing in refinery units
	N3	Jet fuel, e-Naphtha (suitable for blending, 25% of product slate), diesel	CO_2 + green H_2 + RWGS + FT
Non-drop in	ND1a	E85 (bio-ethanol + fossil gasoline)	Corn ethanol + CCS (93% capture efficiency)
	ND1b	E25 (fully renewable, bio-ethanol + bio-naphtha), where the HVO process produces diesel, jet fuel, LPG, bio-naphtha (2% of process output)	Used cooking oil to HVO/HEFA Corn ethanol + CCS (93% capture efficiency)
	ND2	M17 (e-methanol + fossil gasoline)	CO_2 + Green H_2
	ND4	Gaseous Hydrogen	80% NG Steam reforming + CCS, 20% Green H_2 from Electrolysis & renewable power

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[1] Oils and fats comprise the maximum used cooking oil potential (UCO) in the US, with the remaining feedstock requirement met by soybean oil

The analysis does show that alternative fuels could significantly contribute to the decarbonisation of the LDV fleet, but with significant challenges associated with meeting the required demand.

By 2030, the analysis suggests PEV (PHEV and BEV) will represent 17% of the fleet. Even under an aggressive PEV deployment scenario, e.g., 100% new registrations from 2022 to 2030 (~17 million per year), there would still be approximately 114 million ICE vehicles on the road in 2030. Therefore, the amount of liquid fuel required even under the most aggressive EV deployment scenario is likely to still be substantial, with a continued need to consider low carbon fuels in LDV transport, and not just in the transport modes which are considered "hard-to-abate", like aviation.

For the supply of low carbon liquid fuels to be available, technologies need to be deployed rapidly, and the full spectrum of biomass, renewable electricity and CO_2 sources needs to be harnessed to achieve this. Investing in low carbon liquid fuels for the LDV sector need not shift focus from other sectors such as aviation, but could allow synergies and shared scale up to happen. Whilst significant amounts of feedstock and large numbers of plants would be required to meet the demand, other liquid fuels would also be produced in many of the pathways, suitable for the other transport modes like aviation. In addition, some of the pathways produce products which are intermediates for aviation fuel production (e.g., ethanol or methanol), therefore short-term investments into these technologies can be future proofed through additional conversion steps. Equally, fuels like ethanol or methanol could be sold into other sectors, such as chemicals.

Results and Discussion – Phase 2

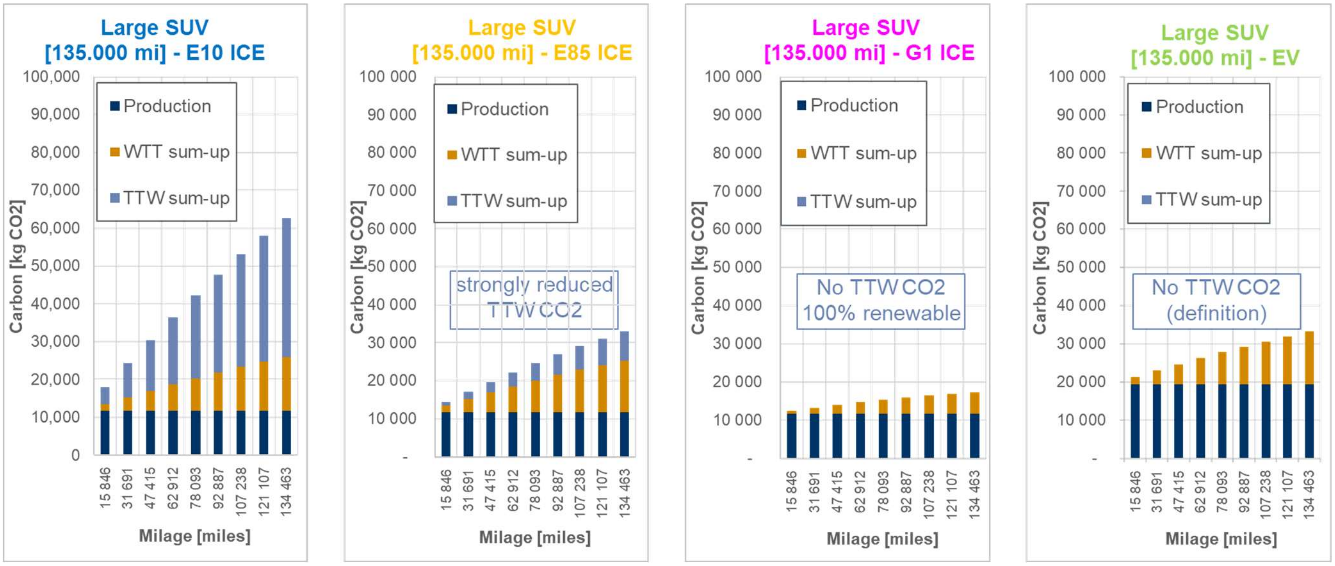
The aim of Phase 2 was to extend the GHG analysis beyond WTW to include the vehicle production to see how it affected the results of the study.

Comparing WTW and Lifecycle results on an individual vehicle basis

The figure below shows, on a per vehicle basis and for a fixed mileage, the full lifecycle emissions (broken down into WTT, TTW and vehicle production emissions) for E10 ICEs, E85 ICEs, ICEs running on fully renewable gasoline, and EVs. It can be observed that:

- E85 vehicles could have similar lifecycle emissions to EVs, based on the currently projected rate of grid decarbonization (which has a large impact on the EV's production and WTT emissions)
- Vehicles running on 100% renewable gasoline could have lower lifecycle emissions than EVs, based on the currently projected rate of grid decarbonization

However, this is a simplistic analysis which is intended to show the decarbonization **potential** of the E85 and 100% renewable gasoline options, **if deployed today.** As noted earlier in the study, the volumes of G1 (100% renewable gasoline) available today are small, and are not projected to increase significantly by 2030 under the Expected Scenario. Likewise, for E85, the fuel is not widely available and may only ramp up in appreciable amounts post-2025. Therefore, conclusions about the fleet-wide impact of E85 and 100% renewable gasoline options cannot be drawn directly from Figure 34, as they are not widely available today. In order to better understand the per-vehicle decarbonization potential of each option future analysis should extend beyond the 2030 timeframe, when the availability of E85 and 100% renewable gasoline options could be greater and the electricity grid intensity will also be lower.

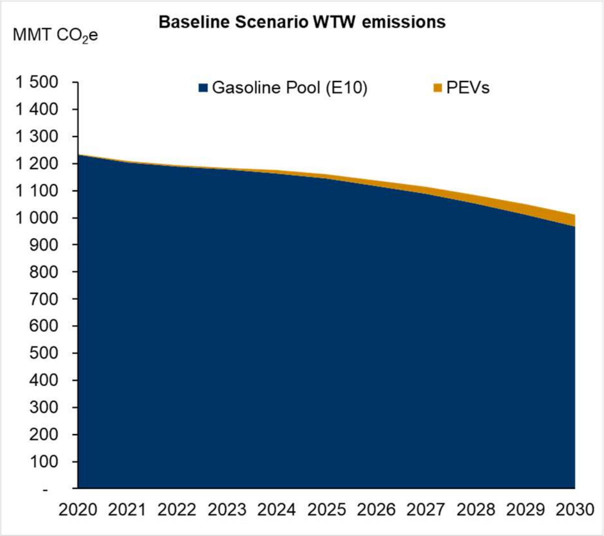


WTW and Lifecycle results on an individual vehicle basis

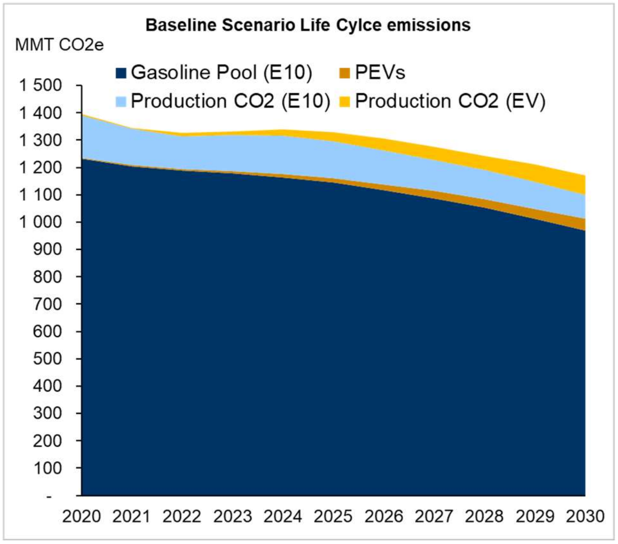
Comparing WTW and Lifecycle results on a fleet-wide basis

The figure below shows the evolution of emissions from a fleet-wide perspective for the Baseline scenario when considering WTW and Lifecycle emissions, based on the results of Phase 1 and 2. The light blue (E10 ICE vehicle) and light yellow (EV) shaded areas represent the emissions associated with vehicle production, which equate to around 160Mt CO_{2e} per year. For E10 ICE vehicles, the emissions decrease over time because fewer vehicles are being introduced to the market and the GHG intensity of the electricity used to produce the vehicles is decreasing. On the other hand, for EVs, as the total number of EVs being manufactured increases, this outweighs any benefit associated with grid intensity decreases, leading to an overall increase in production emissions associated with EVs.

WTW CO_2

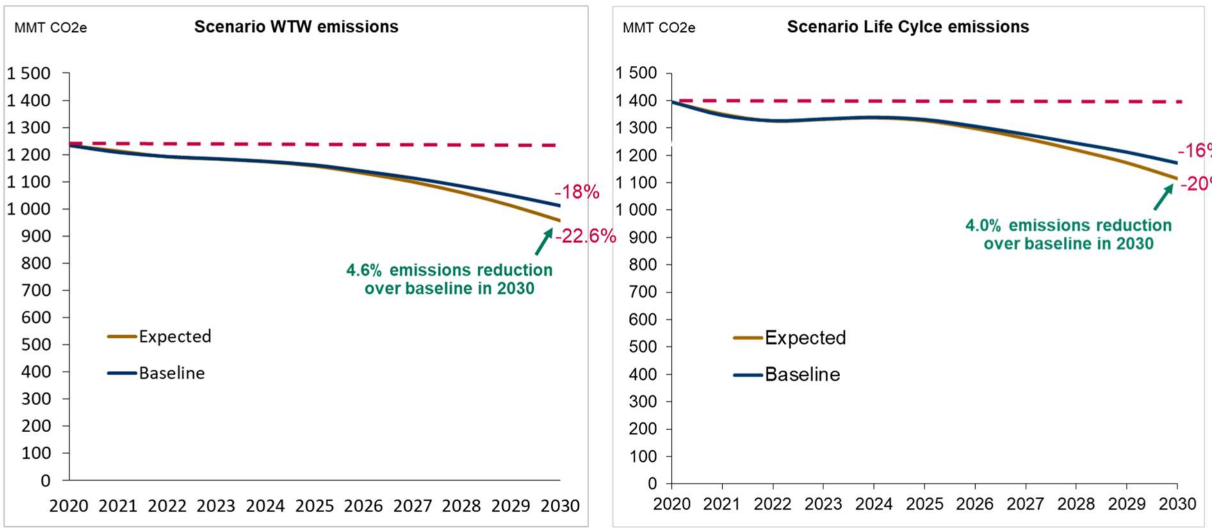


Life Cycle CO_2



WTW vs Lifecycle emissions for Baseline scenario

Lifecycle emissions in the Baseline (-16%) and Expected scenarios (-20%) decrease at a slightly slower rate than the WTW emissions (Baseline = -18%, Expected = -22.6%). The slower rate of GHG reduction on a lifecycle basis is a result of the increased number of EVs being produced (and their additional GHG burden of battery production), despite the decreasing GHG intensity of the grid. Overall, the higher lifecycle emissions compared to the WTW case and the slower rate of emissions reduction in the lifecycle case further emphasize the potential importance of low carbon fuels in reducing emissions in the short to medium term (besides the need to accelerate the decarbonization of vehicle production, especially EVs).


WTW CO_2

Life Cycle CO_2

WTW & Lifecycle emissions for Baseline and Expected Scenarios

Structure of report

This report has been developed to reflect the multi-phase structure of the project.

The first phase of the project considered the Well-to-Wheel (WTW) greenhouse gas (GHG[2]) analysis of the scenario-specific fuel decarbonization options for the US light duty vehicle fleet between 2022 and 2030.

An overall approach to Phase 1 of the study is included at the beginning of this report to summarize the main steps taken in this analysis. This is followed by a scenario-specific, detailed analysis of assumptions, data inputs, WTW GHG emissions calculations, and discussion of the main modelling results.

Phase 2 is a targeted look at a subset of the fuel/vehicle combinations investigated during Phase 1 and evaluates the ‘cradle-to-grave’ GHG footprint. Building upon the Phase 1 work, this effort considers vehicle manufacturing and disposal, and non-propulsion efficiency measures.

Additional information on data inputs and assumptions are included in the appendices at the end of the report.

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[2] Greenhouse gases include CO_2, CH_4 and N_2O for this study

1. INTRODUCTION

There is pressure to reduce GHG emissions from light duty vehicles, with U.S. regulators imposing increasingly stringent demands upon vehicle manufacturers and consumers. This could render further development and use of internal combustion engine (ICEs) vehicles uneconomic. The adoption of electric vehicles has become increasingly more popular in recent years. However, there are still uncertainties around mineral availability for battery manufacturing and availability of charging infrastructure. Plug-in electric vehicles (PEVs), to be effective at reducing emissions, require low carbon electricity generation plus a charging network that is widely accessible - both of which are not yet widely deployed in the U.S. Also, there is growing appreciation of the wider life cycle impacts of vehicles, with significant differences noted between PEVs and ICE vehicles, largely due to adverse impacts of battery manufacturing and disposal.

Liquid fossil fuels are widely established, and lower carbon fuel blends are gaining popularity, in part due to federal and state incentives, such as the Federal Renewable Fuel Standard (RFS) or California's Low Carbon Fuel Standard (LCFS). Some low carbon fuels can be utilized by the existing fleet of vehicles, blended to different levels, providing immediate GHG reductions. These liquid alternatives, called "drop-in fuels", can be employed in existing vehicles without any engine or fuel tank modification. Other alternative fuels will require different engine and vehicle technology – these fuels are described as "non-drop-in fuels".

1.1 Study Objectives

The aim of this study was to first understand whether there is a pathway to 2030 for significant WTW reductions by using low carbon fuels in internal combustion engines, in addition to the anticipated roll-out of PEVs. In Phase 1 of this study, specific steps included:

- Identify representative vehicle archetypes for the US light duty vehicle fleet
- Identify eight low carbon fuels pathways, including blends, compatible with existing or modified ICE vehicles
- Determine a representative electricity grid mix for PEV charging
- Determine the US LDV fleet makeup between 2022 and 2030 for (1) a baseline or business-as-usual scenario and (2) considering the realistic adoption of low carbon fuel pathways
- Evaluate the WTW GHG savings achieved through (2) in comparison to (1) and understand the implications of this
- Build upon (2), quantifying what level of low carbon fuel penetration would be necessary to achieve a specific carbon reduction goal

The second question, addressed in Phase 2 of the study, was then to understand the impact of considering GHGs over the whole vehicle life cycle, not just WTW.

2. PHASE 1: EVALUATION OF WELL-TO-WHEEL GHG EMISSIONS

2.1 Methodology

2.1.1 Overall approach

This analysis considered LDVs, including ICE vehicles and PEVs, with gross vehicle weight ratings (GVWR) less than 8,500 pounds, including passenger cars, small and large SUVs, as well as light-duty pickup trucks. The approach explores how a combination of PEVs and ICE vehicles would complement each other in the decarbonization of the passenger car fleet to 2030.

PEVs were considered in parallel to two broad categories of alternative fuels for the ICE fleet: drop-in fuels and non-drop in fuels.

To map the likely uptake of decarbonization options for the U.S. light duty vehicle fleet and estimate resulting GHG savings between 2022 and 2030, three scenarios were employed:

The **Baseline** scenario (“Business-as-Usual” scenario) aimed to show the level of decarbonization without the impact of drop-in and non-drop-in fuels. The U.S. fleet GHG emissions in 2030 were projected based on the use of a conventional gasoline blend with 10% ethanol (E10) in ICE vehicles, a small share of Flex Fuel Vehicles (FFV) using E10[3], and fuel cell electric vehicles (FCEV) using hydrogen. To calculate the grid emissions intensity for charging PEVs, a weighted-average electricity grid mix was calculated based on projected U.S. PEV population weighted in each electricity region through 2030.

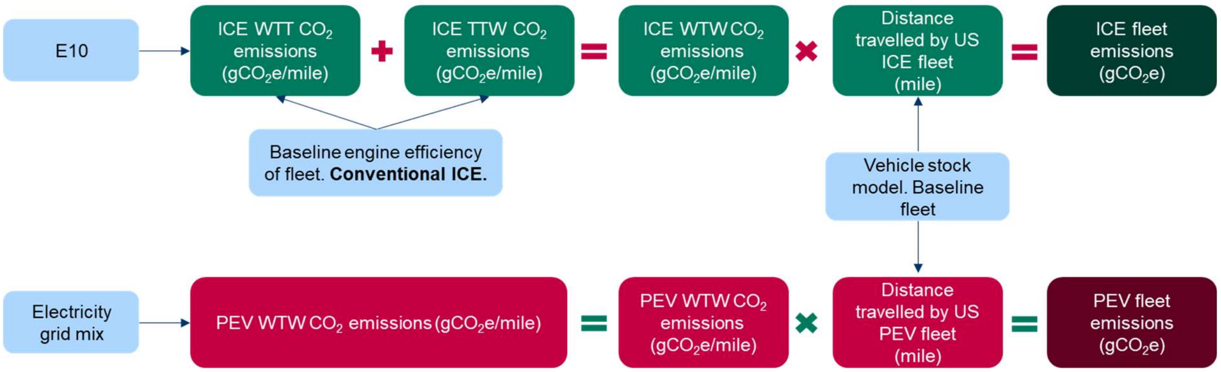

Figure 1. Baseline Scenario Overall Approach

The **Expected** scenario was designed to show an added level of decarbonization with drop-in and non-drop-in fuels, based on an estimated rate of uptake of these fuels and vehicles. This scenario used a “bottom up” approach to analyze the impact of low carbon fuels on ICE emissions. The calculated electricity grid mix used in the baseline scenario was also used for the Expected scenario.

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[3] FFV assumed to run on E10 rather than E85, as is currently the case in the US

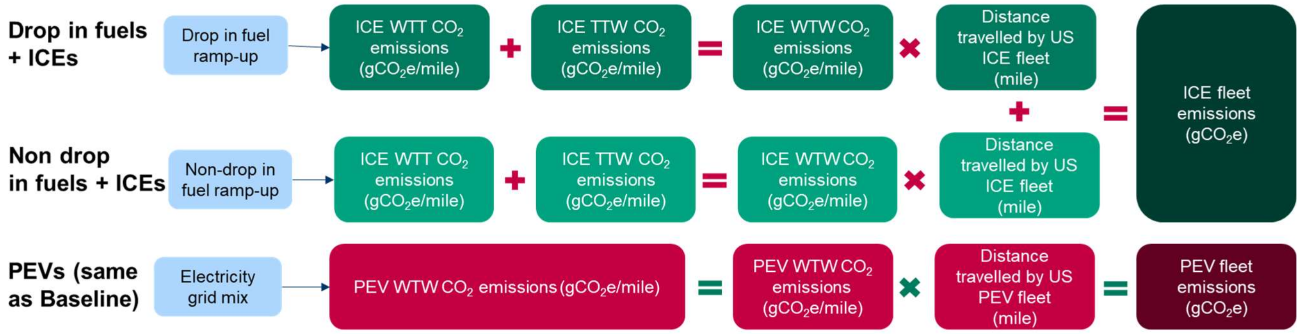

Figure 2. Expected Scenario Overall Approach

The **Aspirational** scenario looked at the decarbonization potential of drop-in and non-drop-in fuels as well as PEVs, going beyond the Expected case. The Aspirational case used a “top-down” approach, which set a decarbonization goal of 55% below 2005 emission levels by 2030. Then, considered each fuel pathway in turn and assessed what it would take to achieve the emissions reduction target. It should be noted that the Aspirational scenario does not contemplate improvements to the electric grid, which could provide additional savings when PEVs are charged.

Table 1. Summary of Scenarios’ Key Parameters

	Baseline	Expected Scenario	Aspirational Scenario
Vehicles in scope	ICE + PEV + FC (minor share)	ICE (conventional + modified to accept alternative fuel) + PEV + FC (minor share)	ICE (conventional+ modified to accept alternative fuel) + PEV + FC
Vehicle fleet composition	Based on data from IHS Markit	Building on the Baseline scenario as a function of fuel consumption & vehicle stock deployment (e.g., ramp-up scenarios for modified engines)	Top-down approach: 1. Set target (in terms of CO_2e) 2. Evaluate the potential for each pathway (drop-in and non-drop in) individually to meet this target, alongside a remaining E10 pool
Fuel in scope	E10, (small share of) E85	E10 + drop-in and non-drop-in fuels (bottom-up supply calculation)	
Grid mix for PEVs	Average grid used across all scenarios is based on U.S. projected PEV populations weighted in each electricity region (eGRID)		

2.1.2 WTW emissions calculation – GREET

Emissions from vehicles were broken down into two main categories – Well-to-Tank (WTT) and Tank-to-Wheel (TTW). WTT represents “upstream” emissions from the production, processing, transportation, and distribution of a fuel, while TTW represents “downstream” emissions, such as the combustion of a fuel within a vehicle’s engine. When the WTT and TTW emissions are combined, their total represents the WTW emissions associated with a specific fuel.

For this analysis, WTT emissions were calculated using “Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies” (GREET® 2021) model developed by Argonne National Laboratory. For fuel pathways not defined in GREET, the consulting team reviewed expert literature to estimate emissions. The GREET models' WTT results include energy use (by different energy sources), emissions of GHGs (in terms of CO_2 equivalent) and emissions of air pollutants. The GREET models' CO_2 equivalent values are in accordance with the Intergovernmental Panel on Climate Change (IPCC)'s fifth assessment report, the CO_2 global warming potential (over a 100-year period) for methane (CH_4) is 28 times higher than CO_2 and nitrous oxide (N_2O) is 265 times higher than CO_2.

TTW emissions were calculated using available information on vehicle type-specific efficiencies from US Department of Energy's 'www.fueleconomy.gov" website along with assumed carbon content of each fuel.

The WTW fleet wide GHG emissions for the Baseline and Expected Scenarios were calculated by determining:

- The US light-duty vehicle fleet from 2020 – 2030 using AVL's vehicle stock model and IHS Markit vehicle data.
    - *Outputs*: gallons of fuel demand, tank-to-wheel (TTW) combustion emissions from ICE vehicles; number of PEVs and their charging demand (kilowatt-hours, kWh)
- The U.S. weighted average grid mix for PEV vehicles based on projected in-use PEVs within individual states.
    - *Output*: Multiplied by their kWh's of charging demand, this provides the WTW emissions for PEVs
- The total ICE fuel availability differentiated by fuel type from 2020 – 2030 using E4tech's fuel supply model
    - *Output:* Fuel supplied to vehicle fleet
- The WTT emissions of individual fuel pathways on a grams of CO_2e per megajoule (gCO_2e/MJ) basis
    - Multiplied by the fuel supply, this provides the WTT emissions of the vehicle fleet. WTT and TTW emissions for the ICE fleet were then combined to obtain total WTW emissions.

Based on the above approach, WTW emissions were calculated for both the ICE and PEV fleet under the Baseline and Expected Scenarios. To determine the savings achieved under the Expected Scenario, the WTW emissions calculated were compared against the Baseline WTW emissions annually through 2030. These emission savings were summed together to provide an overall cumulative impact through 2030.

Unlike the Baseline and Expected Scenarios, a "top-down" approach was used for the Aspirational scenario, by setting a targeted GHG reduction of 55% compared to 2005 levels. The amount of alternative fuel required, and for the case of non-drop in fuels, the number of modified ICE vehicles (e.g., FFVs), was then evaluated against this GHG threshold.

2.1.3 ICE Fuel Pathways

2.1.3.1 Pathways in Baseline Scenario

In the Baseline Scenario, it is assumed that no alternative fuels are used, therefore only contains a single fuel pathway: conventional gasoline (E10) using ethanol produced from corn. This is the current fuel used by nearly all in-use LDVs in the U.S.

2.1.3.2 Pathways in the Expected and Aspirational Scenarios

The Expected and Aspirational Scenarios assume that portions of the conventional E10 gasoline pool will be displaced by both drop-in and non-drop-in fuels. For this analysis, eight alternative fuel pathways were considered, specifically four drop-in and four non-drop-in fuels (Table 2). Please refer to Appendix A for more details on how these fuel pathways were selected.

Table 2: ICE fuel pathways

Fuel Type	Pathway ID	All fuels produced by pathway Fuel focused on in this study (energy basis)	Fuel Process
Drop-in	G1	Bio-gasoline (92% of product slate), LPG	Waste gasification + Methanol-to-Gasoline
	G4	Bio-gasoline (58% of product slate), diesel, jet fuel, heavy fuel oil	Forestry & agricultural residues + pyrolysis + stabilization by Catalytic Hydrotreatment + upgrading
	G7	Diesel, jet fuel, bio-gasoline (24% of product slate), LPG, fuel gas	Oils/fats[4] co-processing in refinery units
	N3	Jet fuel, e-Naphtha (suitable for blending, 25% of product slate), diesel	CO_2 + green H_2 + RWGS + FT
Non-drop in	ND1a	E85 (bio-ethanol + fossil gasoline)	Corn ethanol + CCS (93% capture efficiency)
	ND1b	E25 (fully renewable, bio-ethanol + bio-naphtha), where the HVO process produces diesel, jet fuel, LPG, bio-naphtha (2% of process output)	Used cooking oil to HVO/HEFA Corn ethanol + CCS (93% capture efficiency)
	ND2	M17 (e-methanol + fossil gasoline)	CO_2 + Green H_2
	ND4	Gaseous Hydrogen	80% NG Steam reforming + CCS, 20% Green H_2 from Electrolysis & renewable power

2.1.3.3 WTW emissions for pathways

The WTW CO_2e emissions shown in Table 3 were determined using GREET – the only exception to this is for G1, which was not an option to consider in GREET, Hannula (2017) was instead used.[5] For pathways relying on oils and fats, used cooking oil (UCO) and soy oil were considered as feedstocks, and the WTT values below represent a weighted average depending on the supply estimated in the Expected Scenario where UCO is used to its full potential and soy oil is used for any remaining feedstock requirements.

Table 3. Fuel Pathways WTW Carbon Intensity

Fuel Type	Pathway ID	WTT Fuel Carbon Intensity (gCO_2/MJ) in 2020-2030
Drop-In	G1	8.99
	G4	21.61

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[4] Oils and fats comprise the maximum used cooking oil potential (UCO) in the US, with the remaining feedstock requirement met by soybean oil

[5] Hannula (2017).

	G7	14.87
	N3	0.41
Non Drop-In	ND1a	25.59
	ND1b	14.87
	ND2	23.89
	ND4	17.32

2.1.3.4 Determining fuel supply

Under the Expected scenario, estimating fuel supply through 2030 for the alternative fuel pathways required different approaches for each pathway, which depended on the feedstock and conversion technology used to produce the fuel.

Supply estimates for the drop-in gasoline routes (G1, G4, N3) and ND2 came from E4tech's *Advanced Alternative Fuels Ramp-up Model*, based on current developer activity and technology readiness. The model is a bottom-up framework based on extensive information on companies currently developing alternative fuel production technology, and the plants they operate or have in development. The model was developed to reflect the technical ability of the industry to scale-up from its current state, based on the current number of active technology developers, the scale of existing and planned plants, and plausible build rates in this industry. The model has been used in previously published reports, including a 2018 JRC report on market development of advanced biofuels to 2030[6], and the Sustainable Aviation Fuels Roadmap[7]. Since the release of these studies, the model has been continually updated.

The supply of G7, ND1a, ND1b, and ND4 could not be estimated using the same methodology. In these cases, factors and constraints unique to each pathway were considered:

- Oils/fats HVO/HEFA (**ND1b**) and co-processing (G7) – HVO and HEFA is fully commercially mature, and therefore a ramp-up approach is not suitable. Instead, feedstock availability was determined to be the main constraint on future capacity.
- Corn ethanol + CCS (**ND1a, ND1b**) – corn ethanol is a fully mature industry, and therefore subject to market growth behavior, rather than influenced by the activity of individual developers. The constraints considered were the rate at which CCS technologies can be implemented (considering a realistic roll out rate of all steps of the CCS chain), and the expected growth rate of the corn ethanol supply.
- Gaseous hydrogen (**ND4**) – although a nascent industry, the manufacturing capacity required to produce electrolyzers is expected to be capable of ramping up extremely quickly.
    - Green hydrogen is assumed to be demand-driven whilst limited by electrolyzer manufacturing capacity and renewable energy availability.
    - Blue hydrogen is assumed to be limited by the growth rate of carbon capture technologies.

In the Aspirational scenario a top-down approach was taken to determine the required supply of alternative fuels to the ICE fleet given the emission target in 2030. Each pathway was considered individually to reflect the magnitude of fuel energy required to decarbonize the LDV sector to the targeted level.

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[6] JRC (2018) *Sustainable Advanced Biofuels* JRC Publications Repository - Sustainable Advanced Biofuels: Technology Market Report (europa.eu)

[7] Sustainable Aviation (2020) *Sustainable Aviation Fuels Road-map* SustainableAviation_FuelReport_20200231.pdf

2.1.4 *PEVs and grid mix*

Emissions from PEVs come from the generation of electricity to charge their onboard battery systems. The sources used to generate charging electricity can vary wildly between different regions of the US, resulting in vastly different emission rates for PEVs. Across all scenarios, this analysis conservatively used US Energy Information Administration's Annual Energy Outlook 2022 grid mix assumptions for the different electric regions in the US. Using 2020 to 2030 projected PEV population estimates[8] for each state, individual electricity regions were weighted to calculate one single grid mix for the US.

In 2021, the nation's grid mix is projected to be 53% fossil fuel-fired generation,14% nuclear powered generation, and 33% renewable generation sources. By 2030, renewable generation increases to 44%, while the nuclear portion remains constant, and fossil generation decreases to 42%. The assumed US weighted average grid mix between 2021 and 2030 is shown in Figure 3.

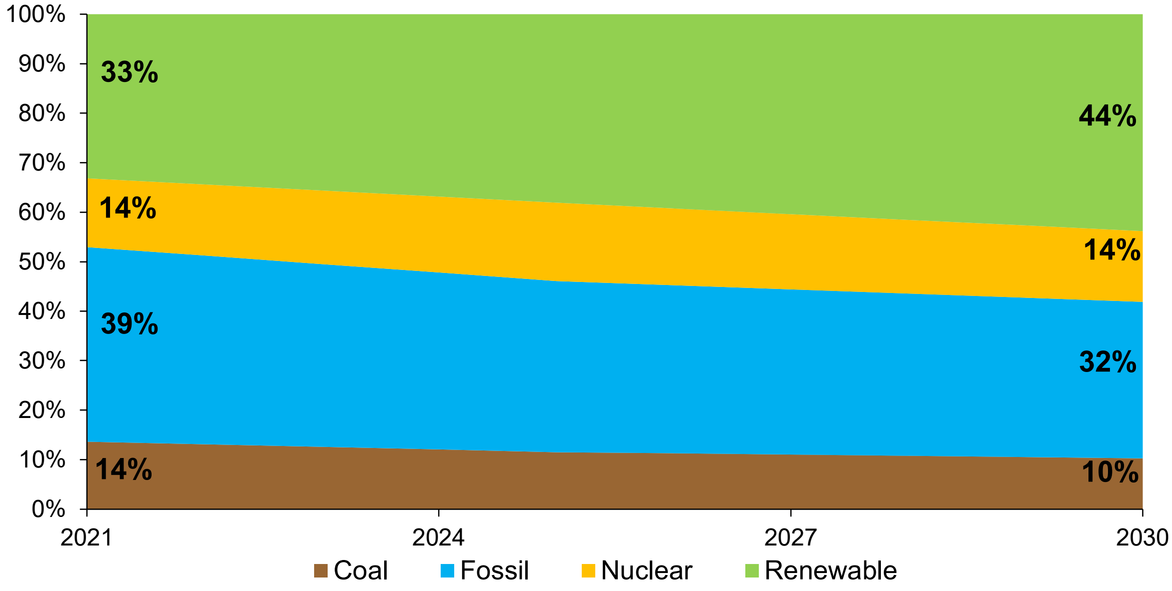

Figure 3. US Nationwide Electric Grid Mix

2.1.5 *Vehicle archetypes and efficiencies*

The focus of this study was the US light-duty vehicle (LDV) fleet. As such, LDVs categories typical within the US were used as representative archetypes. This section describes the sources and assumptions for on road vehicle population and activity as well as the associated adjustments made within AVL's *Light-Duty Fleet Model*. Projections of new registrations and fleet stock were done based on the latest version of the MOVES model reports [9] and EPA Automotive Trends Report data[10,11].

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[8] California's regulatory action, including the Advanced Clean Cars I and II programs, require manufacturers to sell increasing amounts of PEVs within the state. California's regulations have spurred other states to adopt (or plan to adopt) these mandated sales requirements within their own borders. The consulting team performed an assessment of state adoption of the Advanced Clean Cars rules to determine the realistic uptake of PEVs in individual states.

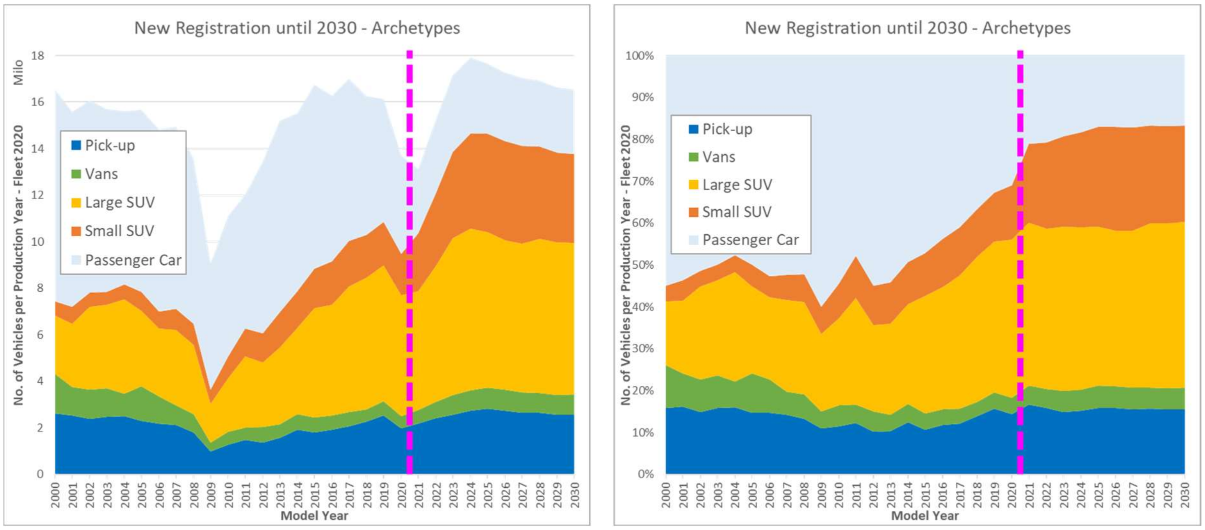
[9] 420R20023_Population and Activity of Onroad Vehicles in MOVES3_EPA-420-R-20-023_November 2020.pdf

[10] 420r21023_Light duty Automotive technology Carbon dioxide Emissions and Fuel economy trends_1975 through 2021.pdf

[11] ZyPDF_Light duty Automotive technology Carbon dioxide Emissions and Fuel economy trends_1975 through 2019.pdf
- 420r20006-report-tables.xlsx (data of Report for 2019)

It is important to note that uncertainties and variability in the default data contribute to the uncertainty in the resulting emission estimates. Therefore, the fleet model data was aligned with MOVES fleet model data for the year 2020 as a starting point – see Appendix B.

Within the modelling, four vehicle archetypes were considered, across two categories



- **LDV – Light-Duty Vehicles**: consisting of Passenger Cars and Small SUVs
- **LDT – Light-Duty Trucks**: Large SUVs and pick-up trucks (vans are shown in the figures for reference, but not used). Because vans are such a small percentage of the overall fleet, only trucks with 6,001-8,500 lbs. GVWR (EPA regulatory class 2a) were modeled.

The AVL Fleet model considered the following fuel types (or propulsion types) for the vehicles (Figure 4):

- Gasoline - includes conventional ICE, Stop/Start and Mild Hybrid burning E10 gasoline fuel.
- Flexible Fuel Vehicles (FFV) - includes vehicles that can run on standard E10 or higher amounts of ethanol such as E85 (fuels containing 70 to 85% ethanol by volume)
- Diesel - includes conventional and mild hybrid (Engine Stop/Start)
- Gasoline Hybrid (HEV) – includes gasoline hybrid-electric vehicles.
- Plug-In Hybrid (PHEV) – includes gasoline & diesel hybrid vehicles that can be recharged via electric vehicle supply equipment (EVSE), in conjunction with liquid fuels.
- Battery electric vehicle (BEV)
- Fuel Cell Electric Vehicle (FCV)

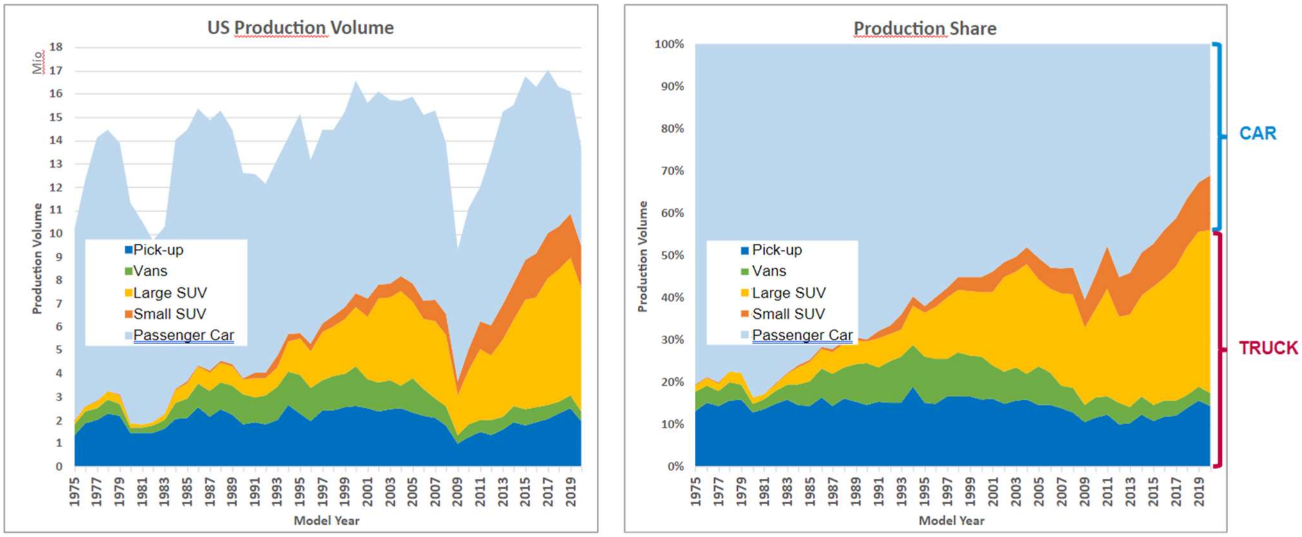


Figure 4. New Production by Archetypes – 1975 to 2020

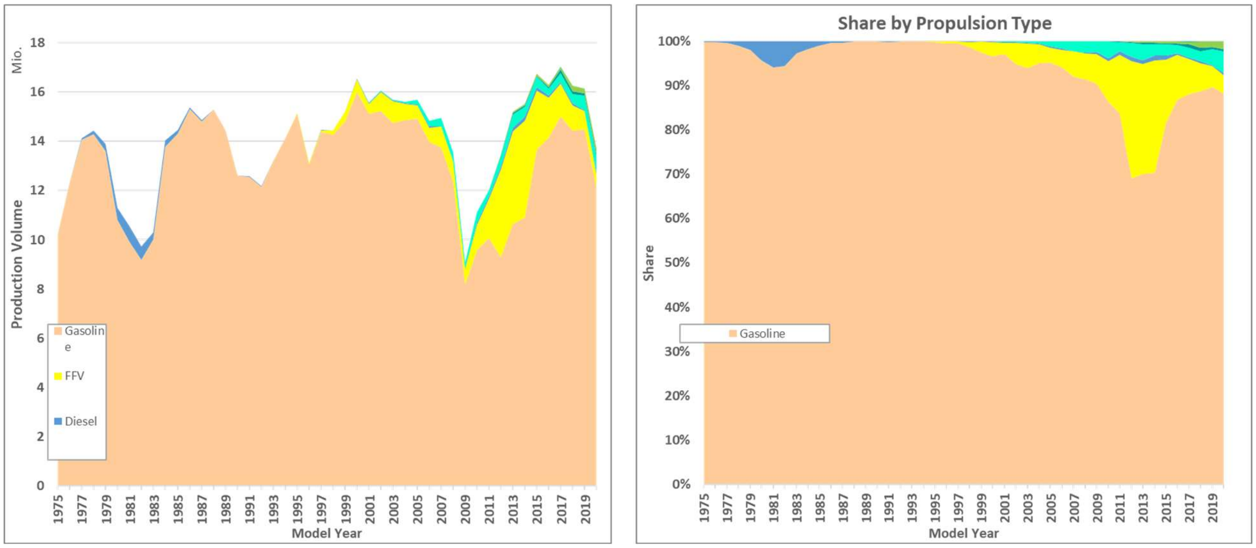


Figure 5. New Production by Fuel Type (acc. EPA – 1975 to 2020)

For the outlook beyond 2020, production forecast data from IHS[12] was used to predict the Baseline scenario for vehicle archetypes and fuel types of new registrations and the fleet (Figure 4 and Figure 5).

The projections through to 2030 showed that the new registrations (based on production numbers) had the following major changes:

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[12] IHS Automotive Light Vehicle Powertrain Forecast; forecast release: Sep. 2021 (AVL dataset)

- The share of cars (passenger car and small SUV) dropped from 43.9% in 2020 to 39.8% in 2030. This was mainly caused by the drop of passenger cars from 30.9%% in 2020 to 16.7% in 2030, whereas the share of small SUV grew.
- The share of trucks (large SUV and pick-up trucks) increased from 53.1% in 2020 to 55% in 2030. This was mainly caused by the slight increase of large SUVs and pick-up trucks by approx. 1% from 2020 to 2030 in this segment.
- The major shift of vehicle archetypes happened in the time frame 2020 to 2025.

New registrations based on fuel type (or propulsion type) through to 2030 saw the following major changes (mainly driven EPA CO2 standards and NHTSA CAFE standards):

- The share of ICE vehicles (Gasoline, FFV, Diesel and HEV and PHEV) dropped from 88.3% in 2020 to 42.1% in 2030
- The share of hybrid vehicles (PHEV and HEV) from 5.4% in 2020 to 18.3% in 2030.
- At the same time, the number of pure battery electric vehicles increased from 1.8% in 2020 to 38.1% in 2030.

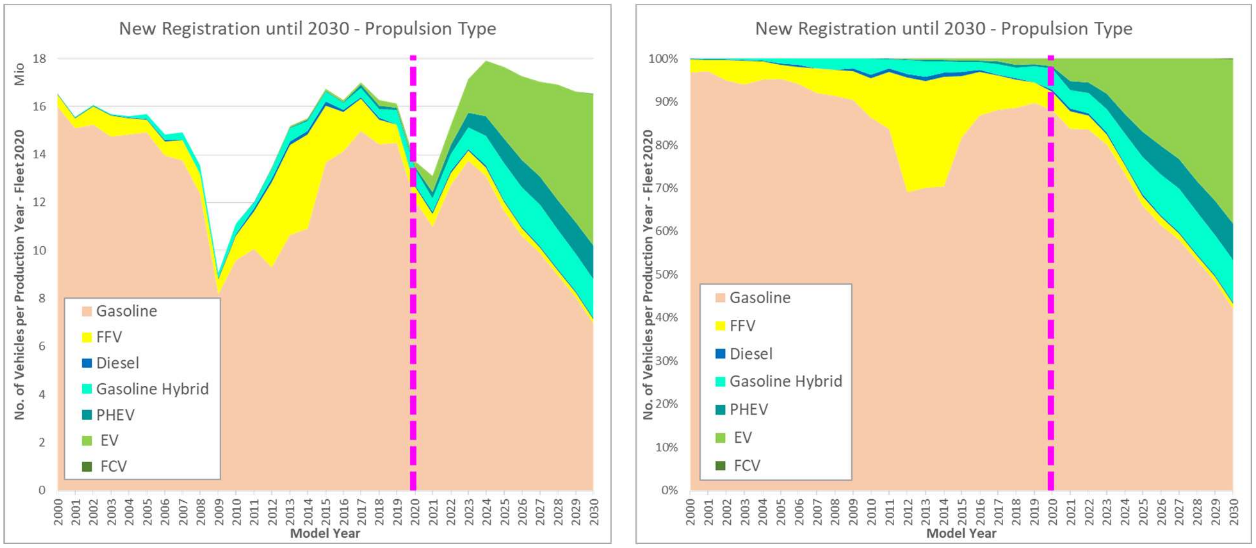

Figure 6. Forecast and Adoption by Propulsion Type 2021-2030

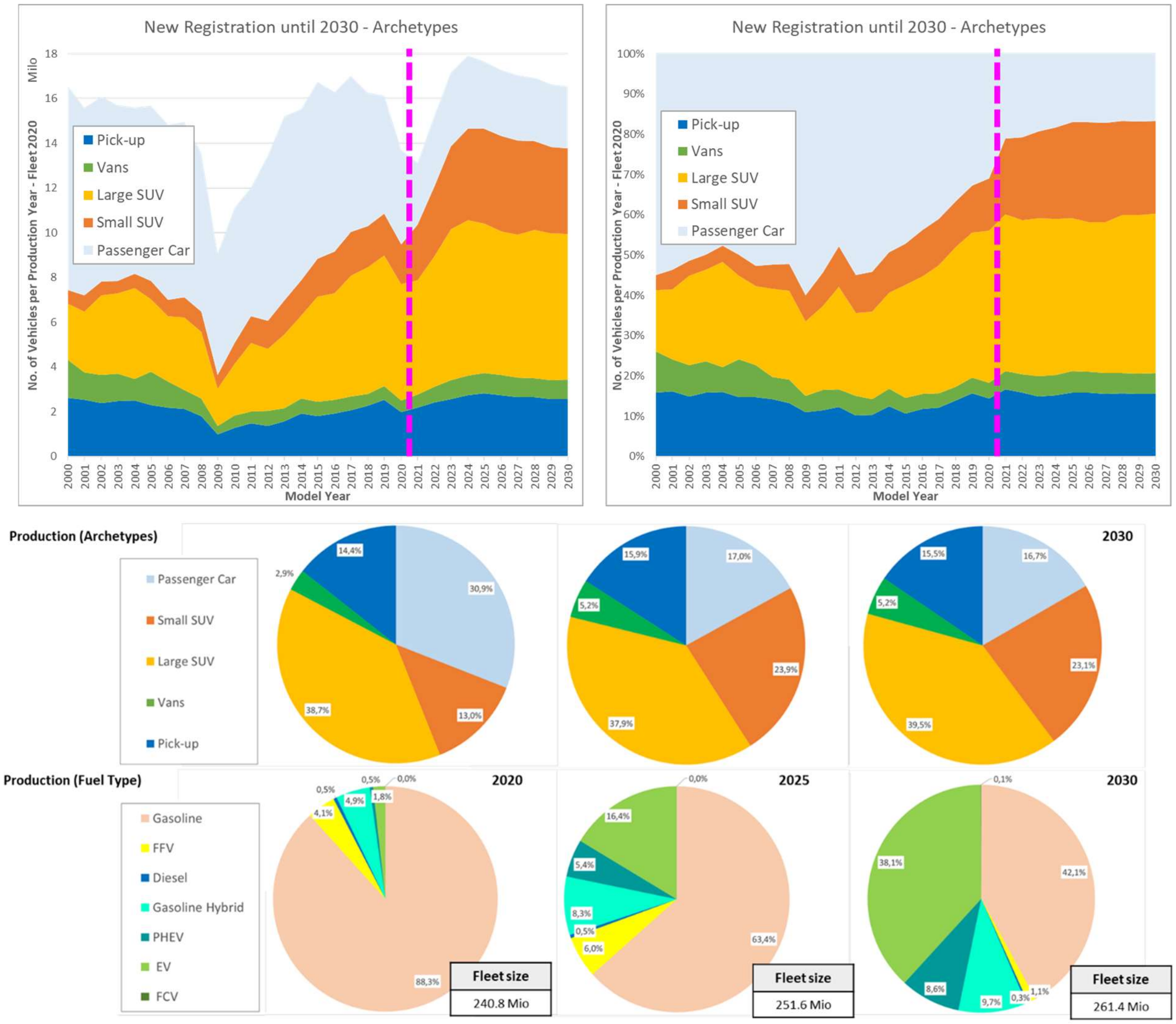

Figure 7. Vehicle Production by Archetype and Fuel Type: 2020 to 2030

The vehicle miles traveled (VMT) by vehicle type (see Figure 8) within AVL's Fleet model were implemented based on available data within the MOVES model.[13] VMT by vehicle type was kept constant for future fleet years (i.e., a brand new passenger car will drive 14,500 miles regardless of calendar year). The MOVES model was also used to obtain information on vehicle survival rates (e.g., how long a vehicle remains in-use). When vehicles retire, they are assumed to be replaced with a new vehicle, which can have increased fuel efficiency and thus reduced carbon emissions.[14]

Figure 8 shows that the fleet consists of vehicles ranging from newly bought vehicles to vehicles which are 30 years for cars and in some cases above 30 years for LD Trucks. For example, approximately 60% of cars & trucks in the 2020 fleet were 15 years old (registered in 2006). Furthermore, it can be seen in Figure 8, that newer vehicles have an average annual VMT of approximately 16,000 miles for trucks and 14,500 miles for cars. With increasing age of the vehicles, it is assumed that the average mileage those vehicles are driven is decreasing. For example, vehicles with an age of 16 years (registered in 2004)

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[13] 420R20023_Population and Activity of Onroad Vehicles in MOVES3_EPA-420-R-20-023_November 2020.pdf

[14] Liquid fuels such as Gasoline contain carbon and when combusted with oxygen-rich air, create carbon-dioxide (CO_2) which is released to the atmosphere. Reducing fuel use, in-turn, reduces CO_2 emissions

have an average mileage of about 9,000 miles per year. The AVL Fleet Model used VMT by vehicle type based on EPA MOVES 3 model (available through 2020).

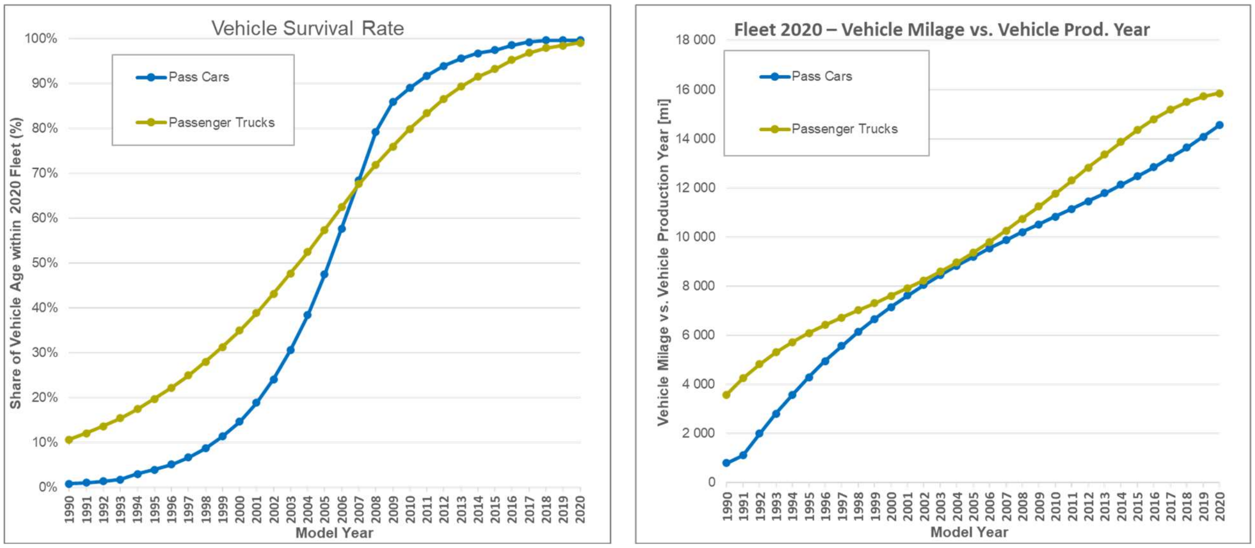

Figure 8. Summary of Survival Rates and VMT by Vehicle Class

2.2 Baseline Scenario

2.2.1 Baseline Fleet

Using the assumptions and approach discussed in the previous sections, a baseline fleet scenario without the addition of alternative fuels, but including realistic uptake of PEVs through to 2030, was calculated. Between 2020 and 2030, it was estimated that the fleet will grow by almost 10%, from 226 to 247 million vehicles (241 to 260 million vehicles incl. VANs), with much of the growth coming from small SUVs and large SUVs, as shown in Figure 9.

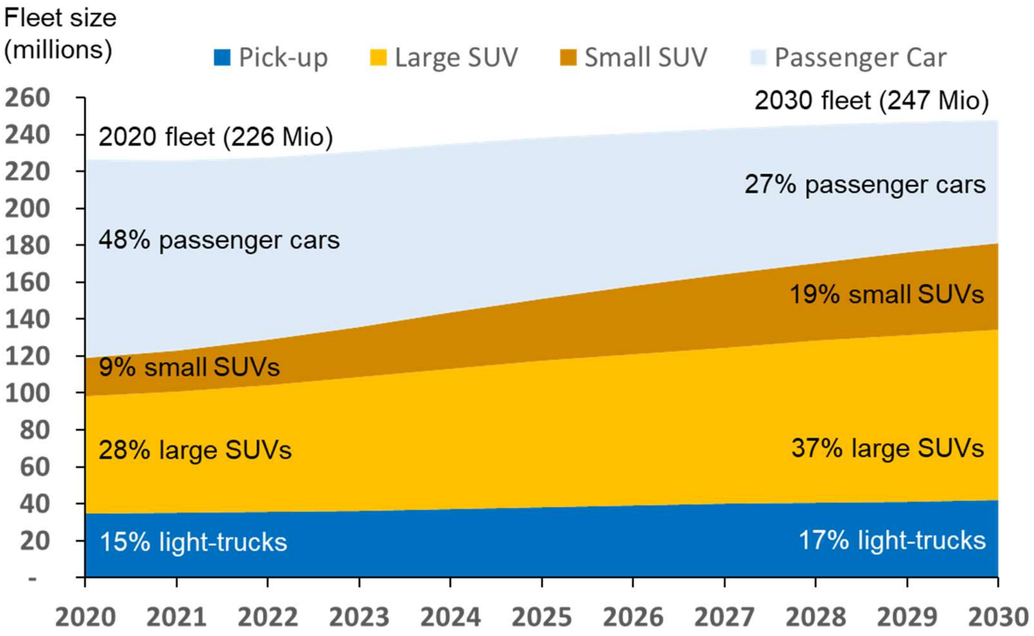

Figure 9. Baseline Fleet Size by Archetype

Figure 10 shows the fleet size split across different fuel types, including the uptake of PEVs to around 12% of the fleet in 2030. Despite an overall increase in vehicles on the road by 2030, the uptake of PEVs means the total demand for liquid fuels (i.e., E10) decreases as shown in Figure 11.

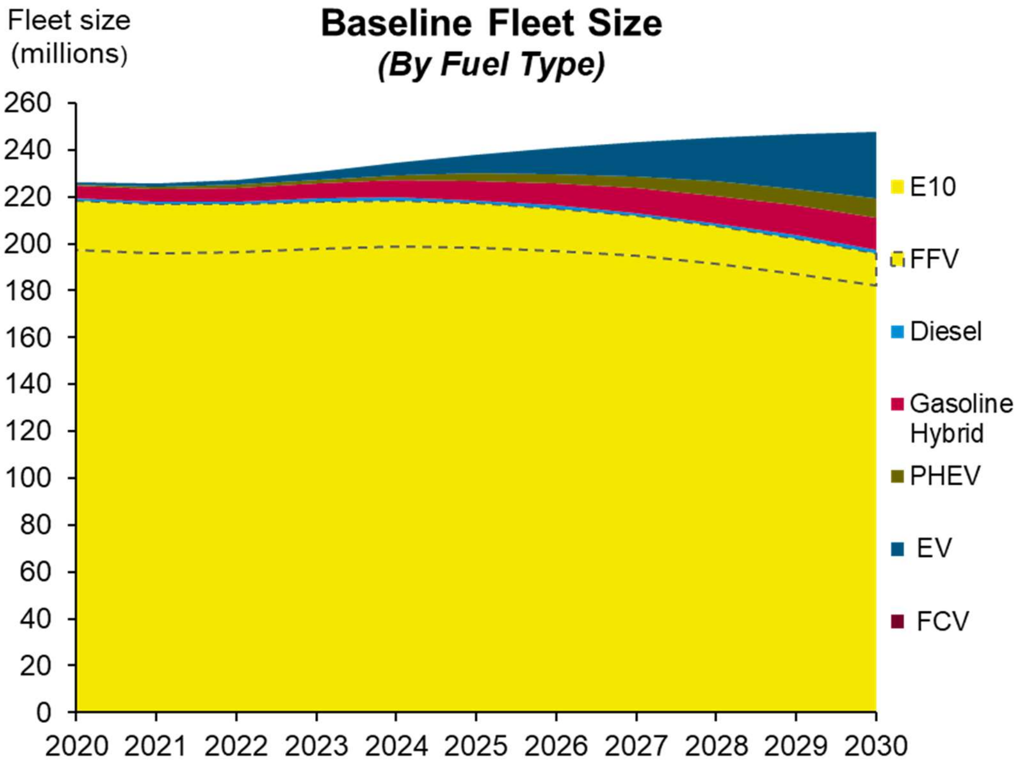

Figure 10. Baseline Fleet by Fuel Type

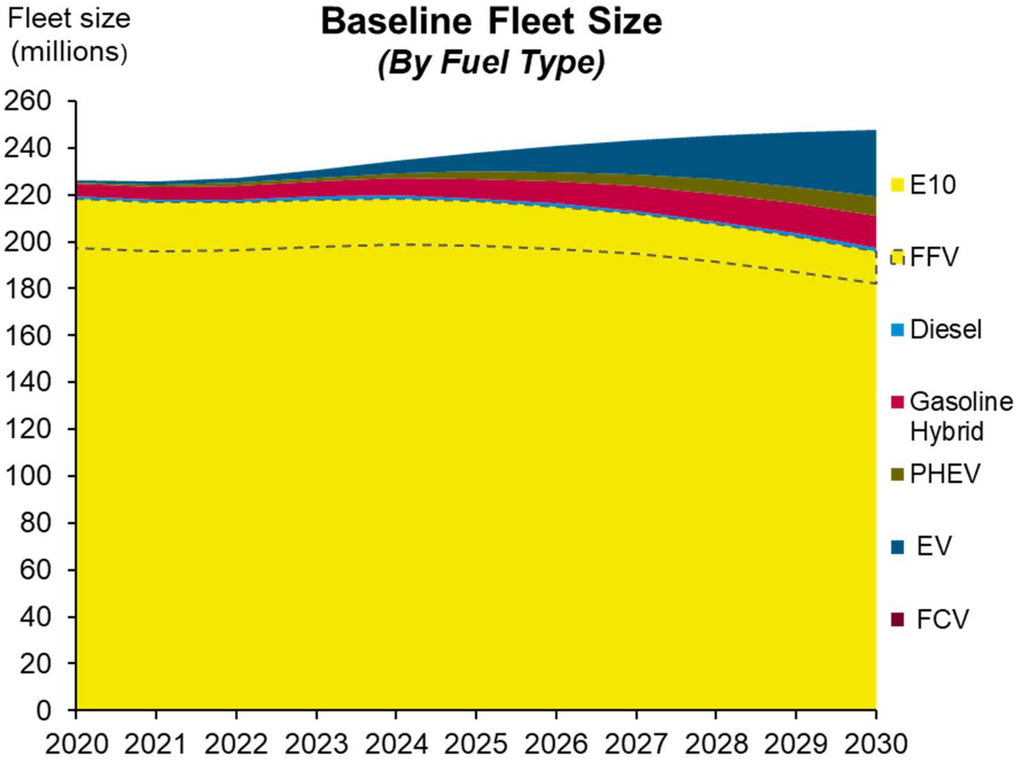

Figure 10. Baseline Fleet by Fuel Type

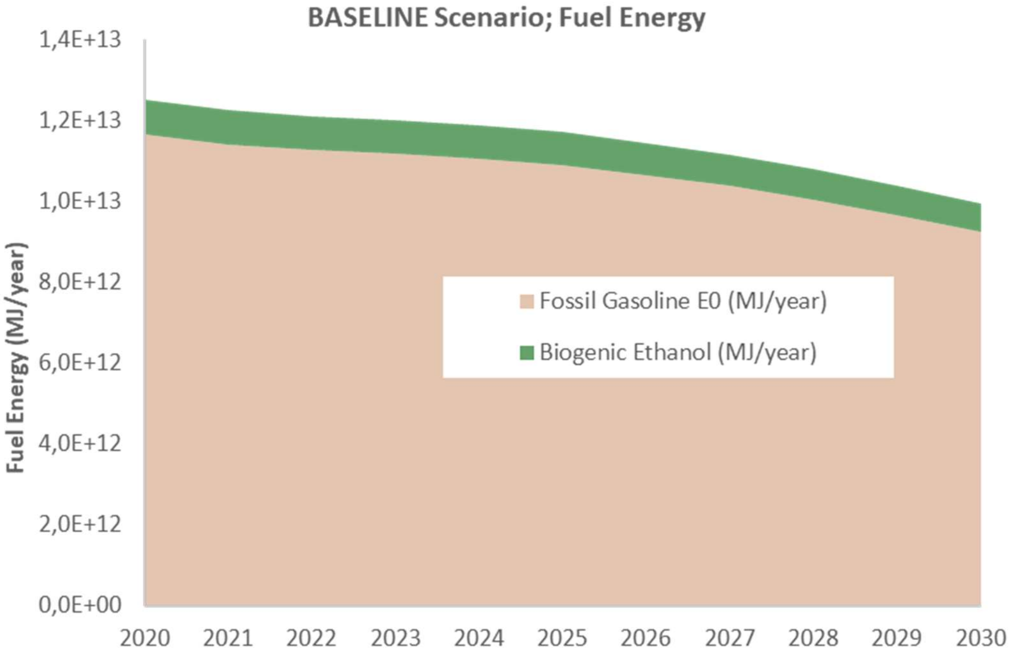

Figure 11. Fuel Energy Demand for the ICE Fleet 2020-2030

In addition to uptake of PEVs driving down total liquid fuel consumption, the model assumes annual improvements in fuel economy, across all archetypes and for all fuel types, which translate to improvements/ reduction in TTW (combustion) emissions, as shown in Table 5 (improvements shown relative to gasoline baseline). The fuel economy data was taken from EPA's Automotive trends report[15] on gasoline cars and trucks and manipulated for the other fuel types. For PEVs, the fuel economy was based on data from www.fuelecomony.gov.

Table 4. CO_2 and Fuel Economy Improvements for Fleet Simulation (Cars)

	Gasoline		Diesel		Flex Fuel		Gasoline HEV	PHEV	EV	FCV
	CO_2	**MPG**	**CO_2**	**MPG**	**CO_2**	**MPG**	**MPG**	**MPG**	**MPG**	**MPG**
2021	2.3%	2.3%	10%	12%	1%	-27%	26%	126%	215%	85%
2022	2.3%	2.3%	10%	12%	1%	-27%	26%	126%	215%	85%
2023	2.3%	2.3%	10%	12%	1%	-27%	26%	126%	215%	85%
2024	2.3%	2.3%	10%	12%	1%	-27%	26%	126%	215%	85%
2025	2.3%	2.3%	10%	12%	1%	-27%	26%	126%	215%	85%
2026	2.1%	2.1%	10%	12%	1%	-27%	26%	126%	215%	85%
2027	2.1%	2.1%	10%	12%	1%	-27%	26%	126%	215%	85%
2028	2.1%	2.1%	10%	12%	1%	-27%	26%	126%	215%	85%
2029	2.1%	2.1%	10%	12%	1%	-27%	26%	126%	215%	85%
2030	2.1%	2.1%	10%	12%	1%	-27%	26%	126%	215%	85%

Table 5. CO_2 and Fuel Economy Improvements for Fleet Simulation (SUV, Vans, Pick-up Trucks)

	Gasoline		Diesel		Flex Fuel		Gasoline HEV	PHEV	EV	FCV
	CO_2	**MPG**	**CO_2**	**MPG**	**CO_2**	**MPG**	**MPG**	**MPG**	**MPG**	**MPG**
2021	2.1%	2.1%	10%	30%	2%	-24%	26%	126%	215%	85%
2022	2.1%	2.1%	10%	30%	2%	-24%	26%	126%	215%	85%
2023	2.1%	2.1%	10%	30%	2%	-24%	26%	126%	215%	85%
2024	2.1%	2.1%	10%	30%	2%	-24%	26%	126%	215%	85%
2025	2.1%	2.1%	10%	30%	2%	-24%	26%	126%	215%	85%
2026	1.7%	1.7%	10%	30%	2%	-24%	26%	126%	215%	85%
2027	1.7%	1.7%	10%	30%	2%	-24%	26%	126%	215%	85%
2028	1.7%	1.7%	10%	30%	2%	-24%	26%	126%	215%	85%
2029	1.7%	1.7%	10%	30%	2%	-24%	26%	126%	215%	85%
2030	1.7%	1.7%	10%	30%	2%	-24%	26%	126%	215%	85%

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[15] EPA (2021) The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy and Technology since 1975.

The AVL fleet model considers CO_2 equivalence of CH_4 and N_2O, in addition to the CO_2 emissions, using historic EPA data, carrying forward the factors from 2019 for the 2020-2030 period considered in this study.[16] More details can be found in the Appendix, but the overall contribution of CH_4 and N_2O to the TTW emissions is negligible (0.3 – 0.5%).

2.2.2 Baseline GHG emissions

Using the total projected fuel consumption of the baseline fleet, the baseline fleet well-to-wheels emissions through 2030 was calculated, as shown in Figure 12.

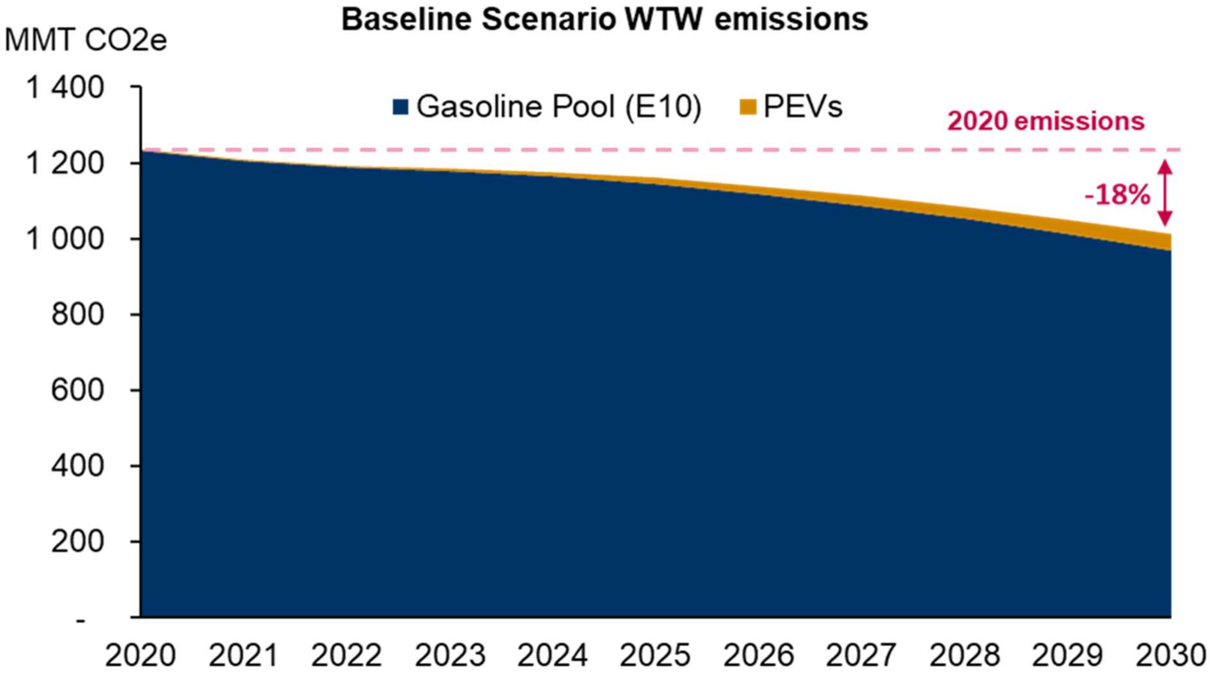

Figure 12. WTW GHG Emissions - Baseline Scenario

Despite the projected increase in fleet size to approximately 247 million vehicles in 2030, compared to 226 million in 2020, Figure 12 shows a baseline WTW CO_2e emissions reduction could be achieved. There are number of counteracting factors which influence this:

- The growing fleet size increases the fleet CO_2e emissions.
- The shift from passenger cars to light trucks and large SUVs also increases the fleet CO_2e emissions due to the increased vehicle size and weight.
- Alternatively, the increased deployment of PEVs (including hybrids) reduces fleet CO_2e emissions.
- In addition, the retirement of old ICE vehicles and the subsequent introduction of new, more efficient ICE vehicles further reduces fleet CO_2e emissions. Newer vehicles are required to meet increasingly stringent emission regulations and fuel economy standards and benefit from improvements related to aerodynamics, tires, friction losses, etc.

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[16] https://www.epa.gov/system/files/documents/2022-04/ghg_emission_factors_hub.pdf (2022-06-27)

The combination of the above factors results in an 18% reduction in WTW CO_2e emissions from the LDV fleet by 2030, compared to 2020 levels. In 2030, PEVs represent approximately 4% of WTW emissions, with the remainder attributable to ICE vehicles. The majority of the ICE vehicle emissions come from the combustion of fuels while they are used in operation (TTW emissions). See Figure 13, which shows the TTW CO_2e emissions from the baseline fleet separated between fossil and renewable emissions.

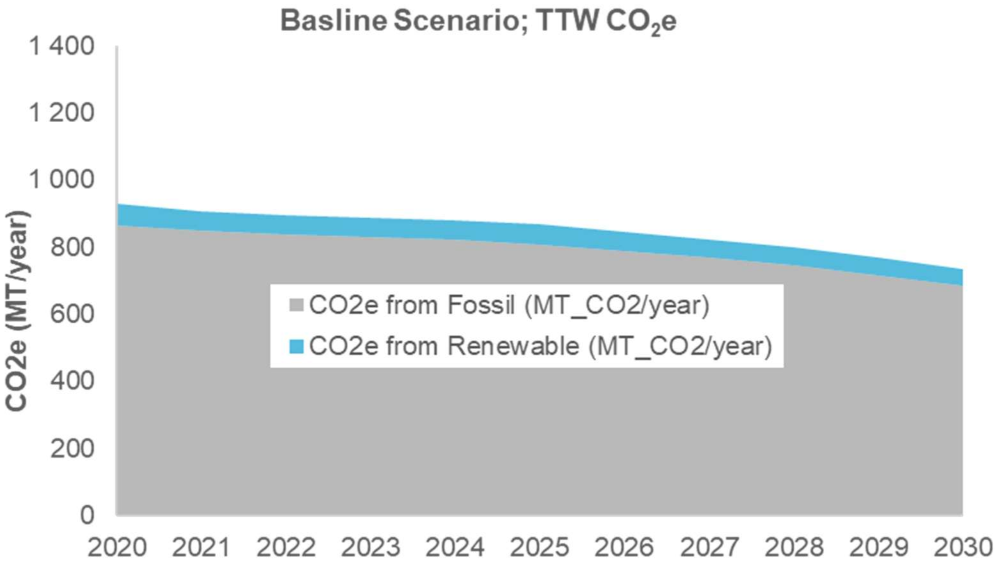

Figure 13. TTW GHG Emissions – Baseline Fuel Demand

2.3 Expected Scenario

Building on the ICE vehicle turnover and market share of PEVs in the Baseline scenario, the Expected scenario was developed to showcase a realistic level of decarbonization achievable using drop-in and non-drop-in fuels. The supply of drop-in and non-drop-in fuels was estimated using E4tech's *Advanced Alternative Fuels Ramp up Model* as well as expert literature to determine a representative uptake of these fuels through 2030. The following sections describe the modeling changes made to the vehicle fleet and fuel supply and resulting WTW emissions of the fleet.

2.3.1 Changes in Vehicle fleet

The Expected scenario saw the introduction of non-drop in fuels, which require modified ICE vehicles to accept these fuels. As such, the overall vehicle fleet changes in comparison to the baseline, as shown in Figure 14. The non-drop in fuel-vehicles (E85, E25, M17 and H_2) were introduced into to the fleet from 2025 (see Figure 15). By 2030, the model assumed that approximately 8.1 million vehicles would be operating with non-drop in fuels under the Expected scenario: E85 vehicles account for the majority of this (7.7 million). A distribution of vehicles by fuel type by year is shown in Tables 6 and 7.

The following considerations informed the Expected scenario's share of non-drop-in fuel vehicles:

- The increase of E85 FFVs after 2025 was modeled in a similar way to the FFV market growth during 2012 to 2014 where the US incentivized the use of flex fuels. For 2030, under the Expected scenario a share of approximately 18% of new registrations with E85 (2.9 million vehicles) was seen. For reference, the maximum share of new registrations of FFVs in 2012 was about 14% (approximately 3.5 million vehicles).

- For E25, the study estimated a possible share of 10% in 2030 based on maturity of ICE technology and the required modifications necessary to accept the fuel resulting in new registrations of approximately 1.6 million vehicles. In reality, E25 vehicle uptake is limited by the availability of E25 fuel and therefore only approximately 72,000 newly registered E25 vehicles. The fleet of E25 vehicles could grow to 0.36 million vehicles.
- M17 only has the potential to be a niche (e.g., due to toxicity of methanol and acceptance, infrastructure on petrol stations and required investments, etc.). Therefore, only a small number of new registrations until 2030 was considered, similar growth rate as happened at the start of FCEV for passenger cars within the last 10 years. Therefore, the Expected scenario included new registrations of approximately 16,000 vehicles with M17 and a possible fleet size of 47,000 M17 vehicles in 2030.
- Similarly for hydrogen, a minor market share is seen. The use of hydrogen in vehicles is mainly in FCEVs or in ICE vehicles for heavier on-road applications (e.g., for long haul trucks due to system costs) and other segments as ships and aviation. Estimated new registrations for the Expected scenario in 2030 are approximately 21,000 vehicles with H_2 and a possible fleet size of 50,000 H_2 vehicles.

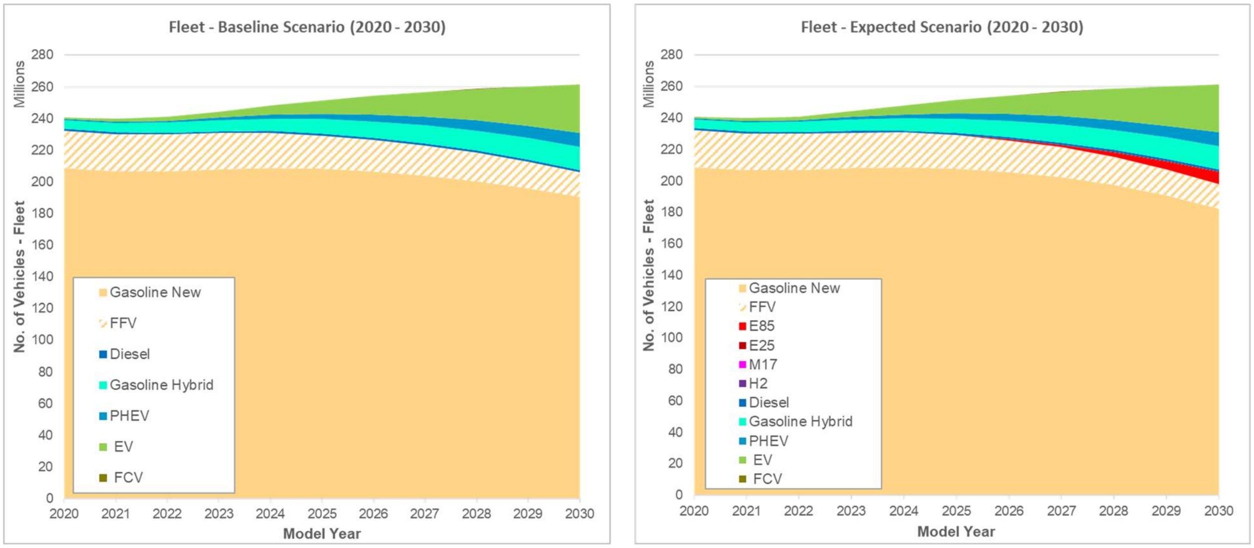

Figure 14. Vehicles by Fuel Type – Baseline vs. Expected Scenarios

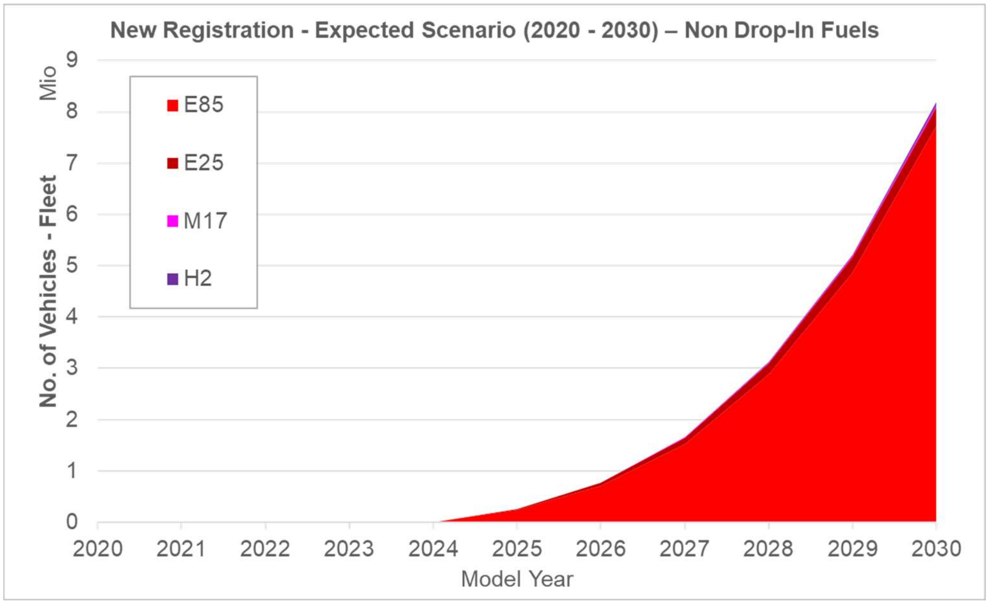

Figure 15. Vehicles Using Non Drop-In Fuels – Expected Scenario

Table 6. Number of Vehicles in fleet by Fuel Type – Expected Scenario

	Gasoline New	FFV	Diesel	Gasoline Hybrid	PHEV	EV	FCV	Non-Drop-In Fuel	Total
2020	208,758,017	23,717,294	1,117,698	5,564,499	645,777	1,025,138	9,570	-	240,837,993
2021	206,781,015	23,501,122	1,172,910	5,898,060	869,070	1,604,573	9,517	-	239,836,268
2022	206,789,716	23,169,407	1,221,480	6,340,928	1,187,600	2,322,336	9,442	-	241,040,911
2023	208,132,063	22,624,471	1,268,970	6,953,743	1,694,707	3,585,498	9,362	-	244,268,814
2024	208,915,971	21,923,459	1,303,377	7,848,105	2,394,754	5,778,708	9,253	-	248,173,627
2025	207,925,676	21,143,862	1,316,846	8,998,817	3,314,208	8,597,527	9,112	2,614,90	251,567,538
2026	205,698,393	20,181,064	1,315,901	10,218,681	4,290,300	11,859,026	10,157	7,764,74	254,349,996
2027	202,395,308	19,052,145	1,304,628	11,503,398	5,280,609	15,516,550	12,024	1,667,094	256,731,756
2028	197,455,712	17,859,148	1,287,499	12,701,597	6,304,305	19,937,107	16,668	3,124,856	258,686,892
2029	190,930,044	16,656,231	1,268,644	13,801,756	7,375,629	24,891,479	25,752	5,220,444	260,169,979
2030	182,464,910	15,474,577	1,250,137	14,923,755	8,519,152	30,555,446	37,831	8,185,926	261,411,735

Table 7. Number of Non Drop-In Fuel Vehicles by Fuel Type – Expected Scenario

	E85	E25	M17	H_2	Total
2025	241,248	17,528	1,578	1,136	261,490
2026	708,437	60,343	4,428	3,266	776,474
2027	1,527,475	122,918	9,344	7,357	1,667,094
2028	2,884,453	206,411	17,869	16,123	3,124,856
2029	4,868,221	292,073	30,246	29,904	5,220,444
2030	7,724,554	363,702	46,899	50,771	8,185,926

2.3.2 *Alternative Fuel Supply*

Table 8 outlines the key factors in the methodology for projecting the supply of each alternative fuel pathway to 2030. Half of the pathways utilize the *Advanced Fuels Ramp-up Model* which projects fuel volumes as a function of the schedule of the announced plants and the number of technology developers for each fuel pathway. Further details on the model can be found in Appendix C. The results are displayed in Figure 17 which illustrates the estimated availability of alternative fuels from each of the pathways explored in the Expected scenario.

Table 8. Methodology for fuel pathway projections

Pathway	Description	Method	Determining factors	Comments
G1	Methanol from Biomass	Ramp-up	Announced plants, number of developers, technology type	9 developers globally
G4	Pyrolysis/Catalytic Hydrotreatment/ upgrading	Ramp-up	Announced plants, number of developers, technology type	8 developers globally
G7	Oils/fats[17] co-processing	Market growth	Announced plants, expected growth rate	2 plants publicly announced in the US at present
N3	Waste CO_2 + green H_2 + Fischer Tropsch	Ramp-up	Announced plants, number of developers, technology type	10 developers globally
ND1a	Corn ethanol + CCS	Market growth	Current market size, market growth projections	Growth led by technology improvements. 20% CCS by 2030.
ND1b	HVO/HEFA[17] with Corn ethanol + CCS	Market growth	Current market size, market growth projections	Growth rate using historic fuel ethanol trends as a proxy
ND2	Green methanol	Ramp-up	Announced plants, number of developers, technology type	29 developers globally
ND4	Hydrogen (80% blue H_2, 20% green H_2)	Market growth	Current market size, growth targets by scenario	Blue H_2 growth led by technology improvements with 33% CAGR. Green H_2 CAGR of 35%.

Of the low carbon fuel pathways explored, ethanol with CCS (featuring in ND1a and ND1b) has the greatest potential to scale up by 2030, accounting for roughly 50% of the alternative fuel supply. This is largely a result of significant planned carbon capture and storage projects, which create the necessary CO_2 storage infrastructure to install CCS. For example, the Summit Carbon Solutions project is expected

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[17] Oils and fats comprise the maximum used cooking oil potential (UCO) in the US, with the remaining feedstock requirement met by soybean oil

to connect 31 ethanol plants to geologic storage via pipelines and is planned to be operational in 2024[18]. The rate of growth corresponds to the installation of CCS at 20% of the 198 currently operational ethanol facilities.

Green and blue hydrogen (ND4) account for a combined 40% of the alternative fuel supply. The U.S. Department of Energy indicated in June 2021 that it expected 13.5 GW of green hydrogen production to come online by 2030[19]: equivalent to ~1,490 ktons per year. The current trend of operational and planned projects listed by the IEA[20] points to ~1,200 ktons of blue hydrogen being produced in the U.S. by 2030.

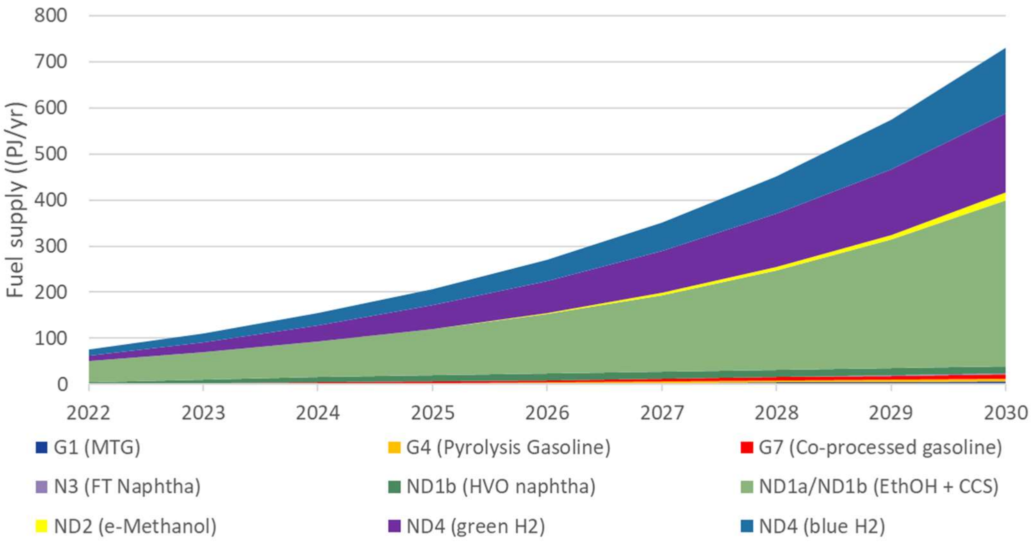

Figure 16. Alternative Fuel Supply Estimates – Expected Scenario

The total pool of fuels for the Expected Scenario includes E10 and all drop-in and non-drop-in fuels shown in Figure 16. Figure 17 shows the total fuel demand for the Expected scenario and lists the blend components of the drop-in and non-drop-in fuels as individual chemical species (such as ethanol, methanol, naphtha, etc.). In this way, the CO_2 production from all these individual compounds can be

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[18] https://www.summitag.com/news/summitcarbonsolutions

[19] IEA (2021), Global Hydrogen Review 2021, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2021

[20] https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

calculated. Furthermore, Figure 17 shows that all biogenic/renewable compounds are a small component compared to ethanol and fossil gasoline, so much so that they are not visible on the graph.

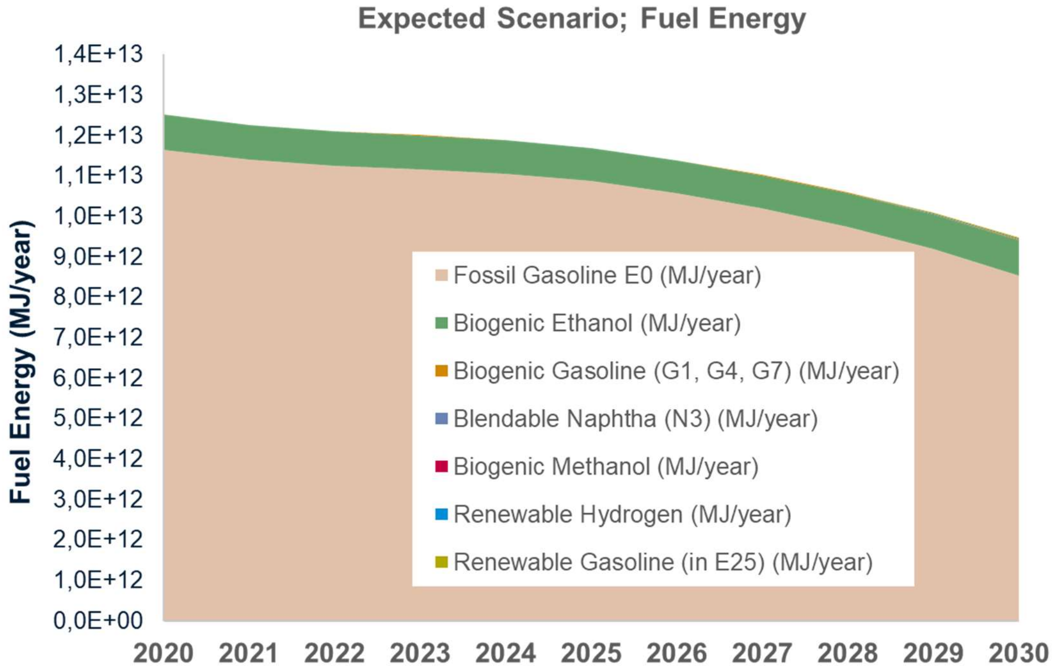

Figure 17. Fuel Demand – Expected Scenario

Figure 18 illustrates the combustion emissions (TTW) of the fuel energy shown in Figure 17, separated into two categories – a) fossil emissions and b) biogenic/renewable emissions. As mentioned previously, the biogenic portion of the fuel TTW emissions are treated as zero.

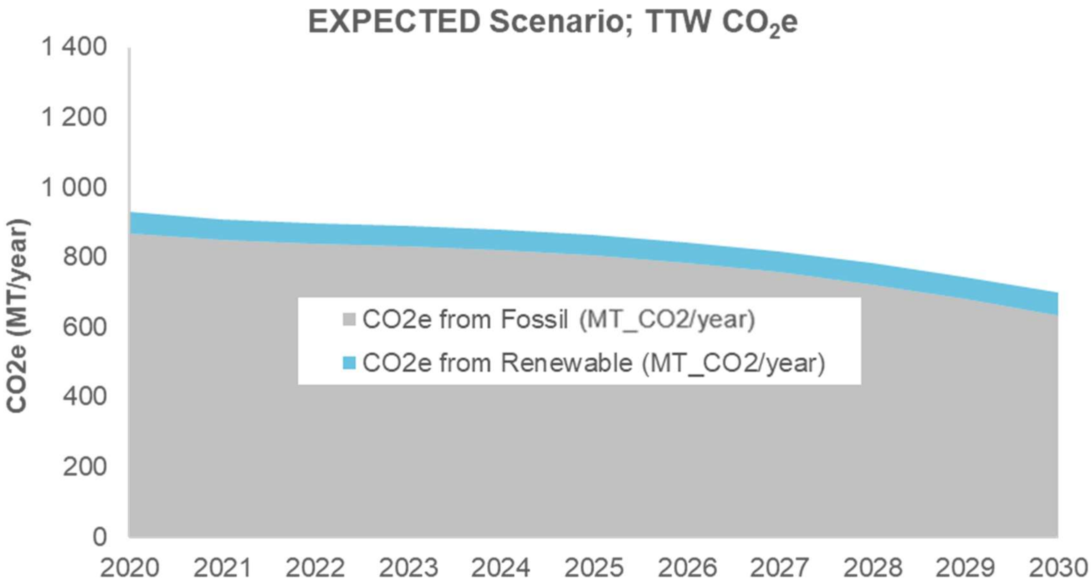

Figure 18. TTW GHG Emissions from Fuel Demand – Expected Scenario

Figure 19 compares the fossil TTW CO_2e emissions of Baseline versus Expected scenarios. According to the progressive ramp-up of alternative fuels, a visible gap appears only at the end of the decade and ends with 7.6% fossil CO_2e reduction in 2030, compared to the Baseline scenario. The main contribution for this comes from an increasing use of ethanol in E85 fuel, see also Appendix C.

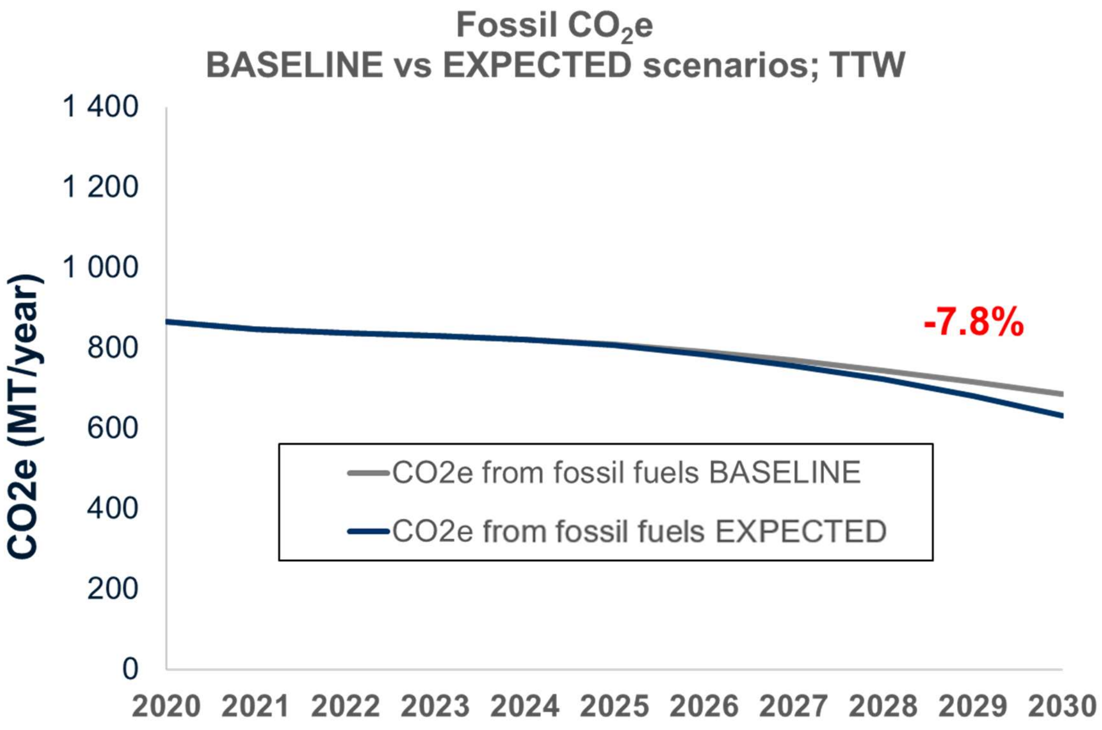

Figure 19. Fossil Fuel TTW GHG Emissions – Baseline vs. Expected Scenarios

Well-to-Wheel Results and Discussion

Combining the vehicle fleet and fuel supply estimates discussed above, the WTT (upstream) emissions and the TTW (combustion) emissions for each of the different drop-in and non-drop-in fuels and their impact to the overall light-duty vehicle fuel use were calculated. The alternative fuels displace standard E10 gasoline usage, thus creating reduced emissions compared to the Baseline scenario. The absolute contribution of WTW emissions from PEVs remains the same under both the Baseline and Expected scenarios as the level of penetration of PEVs into the fleet was fixed at the same level across both scenarios. Due to relatively minor emissions improvements from the uptake of alternative fuels the relative contribution of PEVs remains similar in both scenarios, accounting for about 4.5% of total WTW emissions by 2030 – see Figure 20 for the total WTW emission under the Expected scenario in million tonnes CO_2e (MT CO_2e).

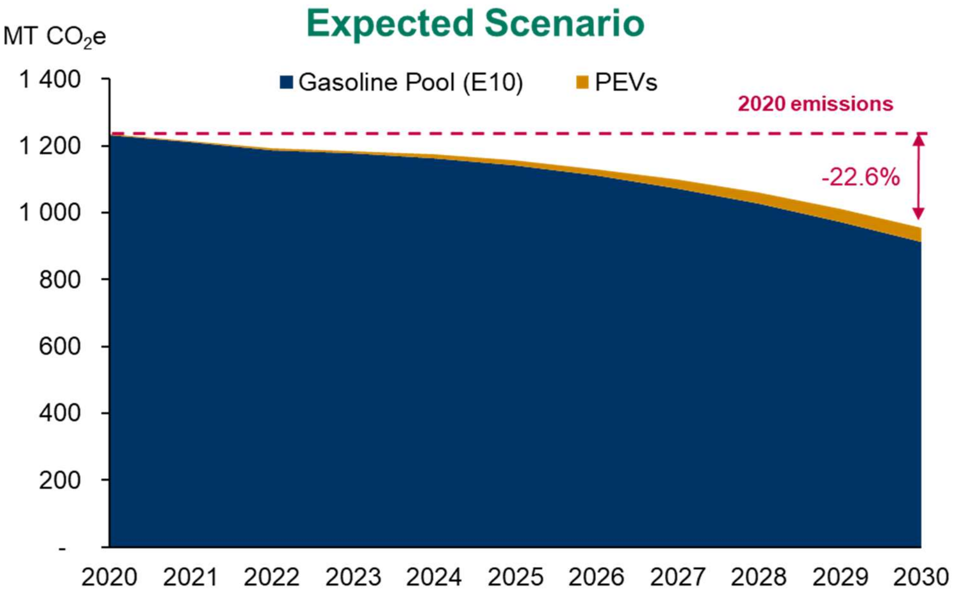

Figure 20. WTW GHG Emissions – Expected Scenario

Due to the addition of alternative fuel blends, the Expected scenario WTW emissions are projected to decrease by 22.6% in 2030 compared with 2020 levels. See Figure 21 for a comparison of WTW emissions under the Expected and Baseline scenarios through 2030, and Figure 22, which illustrates the emissions reductions achieved under the Expected scenario on an annual basis.

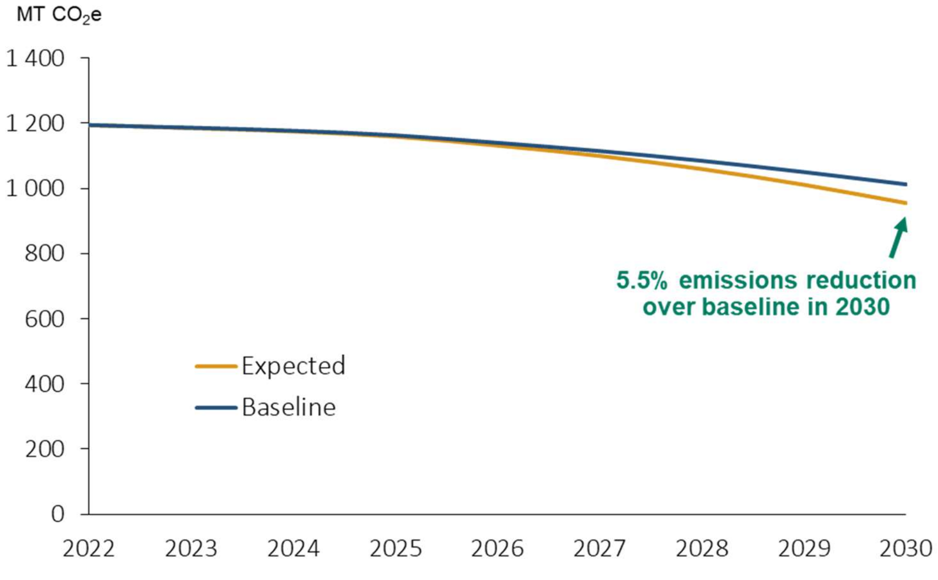

Figure 21. Annual WTW GHG Emission Reductions – Baseline vs. Expected Scenarios

As shown in Figure 22, the Expected scenario results in an incremental 5.5% reduction in emissions over the Baseline scenario by 2030 due to the inclusion of drop-in and non-drop-in fuels. These reductions can be further broken down into upstream (WTT) and combustion (TTW) emissions as seen in Figure 22. Illustrated in the chart is that most of the reductions are attributable to the combustion of these alternative fuels due to their biogenic nature (i.e., their emissions are renewable and therefore excluded from fossil combustion emissions). It should also be noted that most of the Expected Scenario reductions happen in the later years (2028 to 2030) due to the increased availability of renewable ethanol-based fuels (e.g., E85 and E25) and the assumption that FFV sales would increase to meet this supply. In 2030, the contribution of drop-in and non-drop-in fuels results in a projected 55 MT CO_2e.

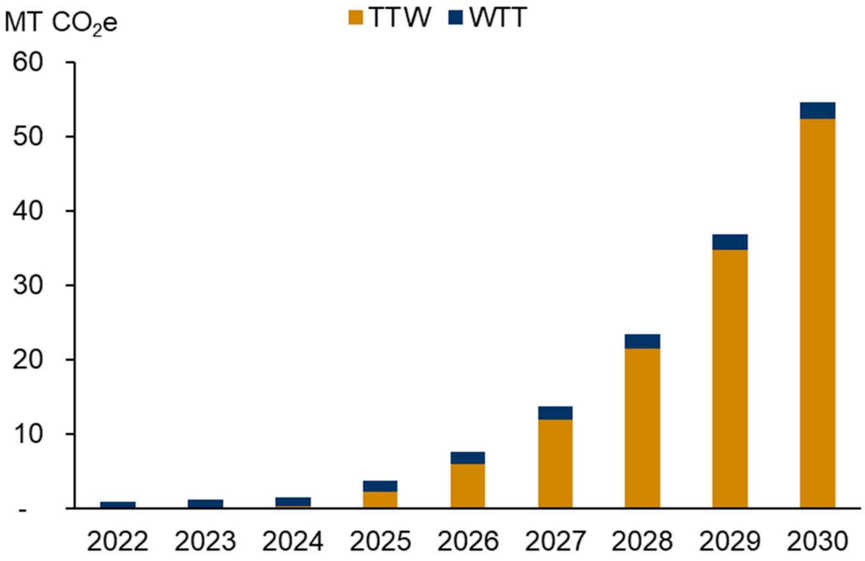

Figure 22. Annual WTW GHG Emission Reductions – Expected Scenario

Drop-in and non-drop-in fuels have varying contributions to emissions reductions over the time period due to their supply and introduction constraints (e.g., limited production or feedstock supply, require the purchase of new vehicle technology, etc.). Figure 23 is presented to help illustrate the ramp up of fuels and the emissions impact of specific drop-in and non-drop-in fuels over the timeframe of this analysis.

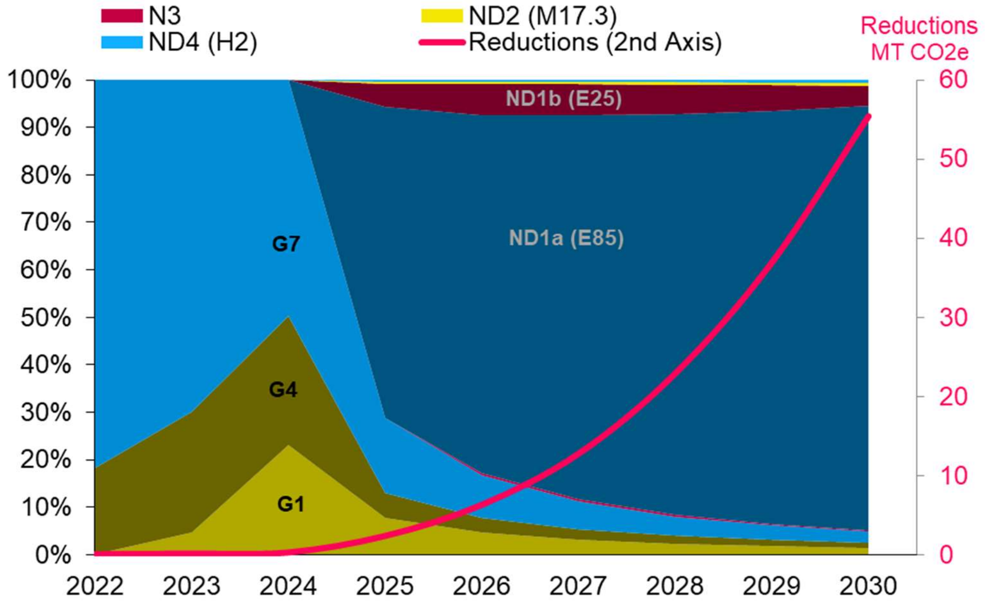

Figure 23. Annual WTW GHG Emission Reductions by Fuel Type for Expected Scenario

From Figure 23, you can see that the contribution of emissions reductions come from renewable gasoline sources (G1, G4 and G7) in the early years, but the impact to emissions reductions is constrained due to their limited production potential. Due to this, reductions only reach an estimated 330,000 metric tons of CO_2e by 2024 (secondary axis). After 2025, anticipated production capacity for E85 (ND1a) and E25 (ND1b) are expected to ramp up and displace a portion of light duty E10 fuel use, driving emission reductions to nearly 60 million tonnes by 2030. All told, E85 and E25 represent nearly 92% of emissions reductions attributable under the Expected scenario compared to the Baseline scenario.

Key Takeaways

The Expected scenario envisioned a realistic uptake of drop-in and non-drop in fuels based on the consultant team's current view of feedstock availability, production capabilities and constraints faced by these alternative fuels, while also maintaining the same level of PEVs as in the Baseline scenario. Below are a few key takeaways from this scenario:

- The reductions are modest compared to the Baseline scenario, representing 5.5% due to the limited deployment of drop-in and non-drop-in fuels.
- Renewable gasoline production has the capability to ramp up quickly, but due to supply constraints, provides only limited reductions.
- Expansion of renewable ethanol fuels after 2025, such as E85 and E25, could provide significant emissions savings, but require the purchase of FFVs to achieve reductions. Total ethanol production with CCS by 2030 would need to be eight times current production levels. This is equivalent to an additional 81 ethanol plants with CCS facilities by 2030, bringing the total to 86.

2.4 Aspirational Scenario

Building on the results of the Expected scenario, the Aspirational scenario looks to quantify, at a high-level, “what would it take” to achieve more ambitious levels of decarbonization than shown in the Expected scenario. In order to determine an appropriate level of ambition for this scenario, U.S. decarbonization and fuel-based policies were first reviewed.

Following this, a top-down approach was adopted to determine what the ICE fuel pool and vehicle fleet composition would need to look like to achieve a certain percentage savings in terms of volumes of alternative fuels required. One of the main objectives of the Aspirational scenario was to understand the magnitude of alternative fuel volumes, each of their feedstocks and number of vehicles required to meet significant reductions in GHG emissions. To accomplish this, each of the 8 alternative pathways was analyzed individually. For the Aspirational scenario, the study maintained the same level of PEVs as the Baseline and Expected scenarios to highlight the opportunities for low carbon drop-in and non-drop in fuels.

2.4.1 Review of U.S. Policies

With the Aspirational scenario being a top-down approach, a goal (or reduction level) needed to be first determined. As an initial step, a literature review was performed of U.S Federal and State-Level Policies as well as any fuel-based policies available. These policies include:

- Federal Policies:
    - Paris Climate Agreement, Renewable Fuel Standard (RFS), Proposed New and Revised Standards for Passenger Cars and Light-Duty Vehicles for Model Years 2023 to 2026, Inflation Reduction Act
- State Level Policies:
    - California’s Low-Carbon Fuel Standards (LCFS), Oregon’s LCFS program, and other State GHG reduction (non-LCFS) programs

Informed by the review of state and federal policies, a 55 percent emissions reduction target for 2030 was chosen based on the Paris Climate Agreement trajectory. As described in the Paris Climate Agreement, this reduction trajectory is compared to 2005 levels.

2.4.2 Aspirational Scenario results and discussion

Based on the policy review and input from CRC Steering Committee, the agreed target reduction of 55% in 2030 compared to 2005 levels was translated to a GHG threshold of 702 $MtCO_2e$ in 2030 as shown in Figure 24. As there was no change assumed for the uptake of PEVs compared to the Baseline and Expected scenarios, the WTW contribution of PEVs (43 $MtCO_2e$) was subtracted from the threshold, leaving a maximum allowable emission of 659 $MtCO_2e$ for the ICE vehicles in the fleet.

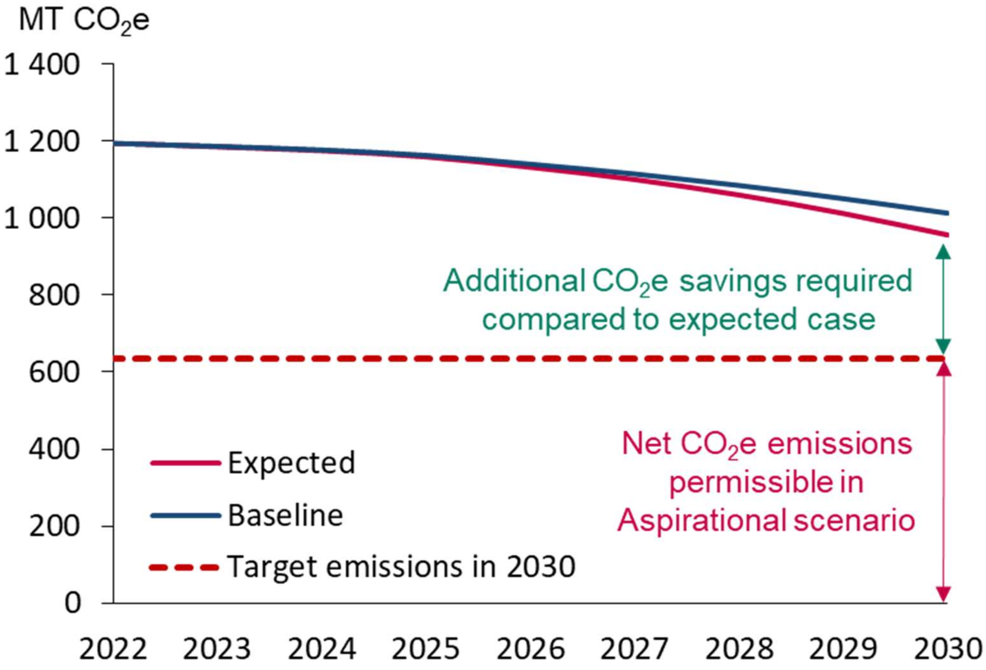

Figure 24. Aspirational Scenario Target GHG Reduction Threshold Compared to the Baseline and Expected Scenarios

Taking each pathway in turn, a series of calculations and iterations were performed to determine first whether it would be theoretically possible for the pathway in question to achieve the target in 2030, and then secondly evaluate what that would look like in terms of fuel supply (and remaining E10 supply) and vehicles (for non-drop in fuels).

Assuming the total energy consumption of the ICE vehicle fleet remains the same as the expected and baseline scenario in 2030 [~10.3 exajoules (EJ)], the first step was to calculate the required quantities of alternative fuel required that would both **meet the demand** and **the GHG emissions savings required.** The minimum amount of alternative fuel that would satisfy both criteria was determined, with the remaining fuel demand met by E10. To simplify the analysis in this scenario, an average fuel consumption per vehicle of 387 gallons/vehicle was used, based on the baseline case which had 230 million ICE vehicles consuming 89 billion gallons of E10 in 2030.

Figure 25 shows the calculated WTT and TTW emissions of the alternative fuels and E10. The only pathway where the emissions target was not possible was ND2 (M17). Even when assuming 100% uptake of M17 in the ICE vehicle fleet, the GHG emissions savings threshold is not met. This is primarily due to the high fossil content in M17, resulting in high TTW emissions (~67gCO_2e/MJ), which is very similar to E10 (~69 gCO_2e/MJ). For all other pathways, the target was achievable and required volumes of the alternative fuel and E10 are shown in Figure 26.

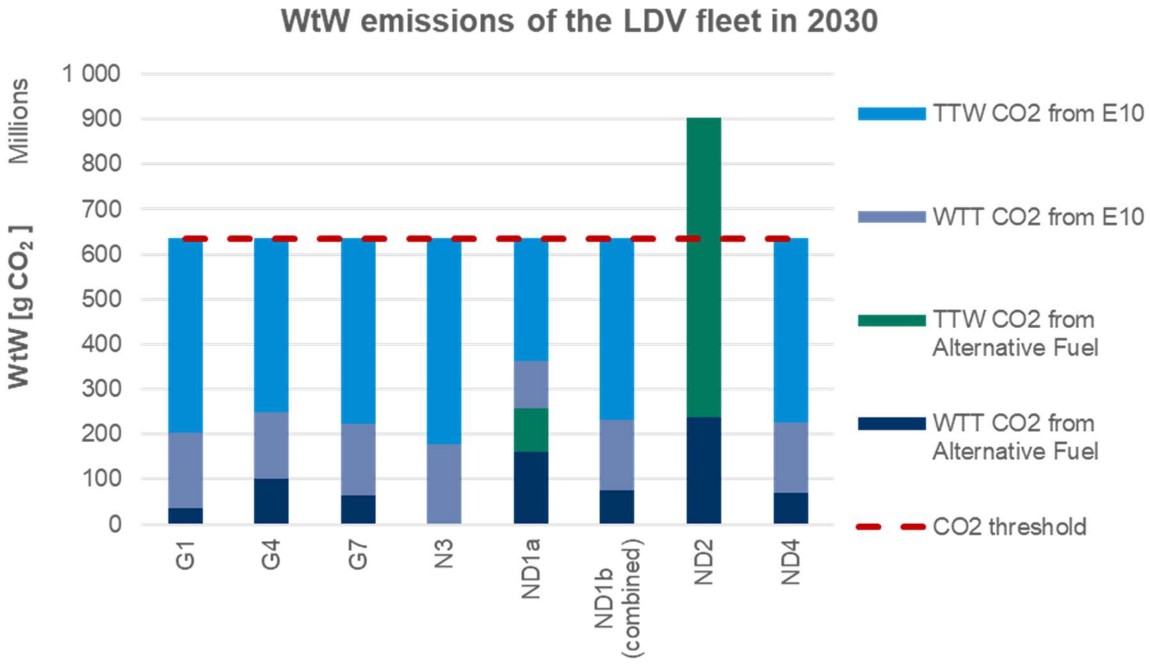

Figure 25. WTW Fleet Impact of Alternative Fuels and E10

Figures 26 and 27 show that for the drop-in routes (G1, G4, G7, and N3), approximately 55 – 65% of the ICE vehicle fleet could still operate on E10, whilst meeting the threshold. However, this would represent a significant increase in drop-in fuel supply compared to what is currently expected: it would require ~4 EJ in 2030, compared to the ~0.02 EJ projected to be supplied in the Expected Scenario. Compared to the wholly renewable drop-in pathways, ND1b (E25) and hydrogen (no carbon), noticeably more ND1a (E85) is needed to hit the target because with every MJ of E85 approximately half as many GHG emissions are being saved, due to E85's higher WTW value. For all pathways, the fuel supply requirements are two orders of magnitude larger than in the Expected Scenario and would require significant deployment of conversion plants and feedstocks to be available, this is further summarized in Appendix C.

For completeness, ND2 is included in Figures 26 and 27; however, it is highlighted in red to demonstrate that it is not possible to achieve the emissions reductions using this pathway.

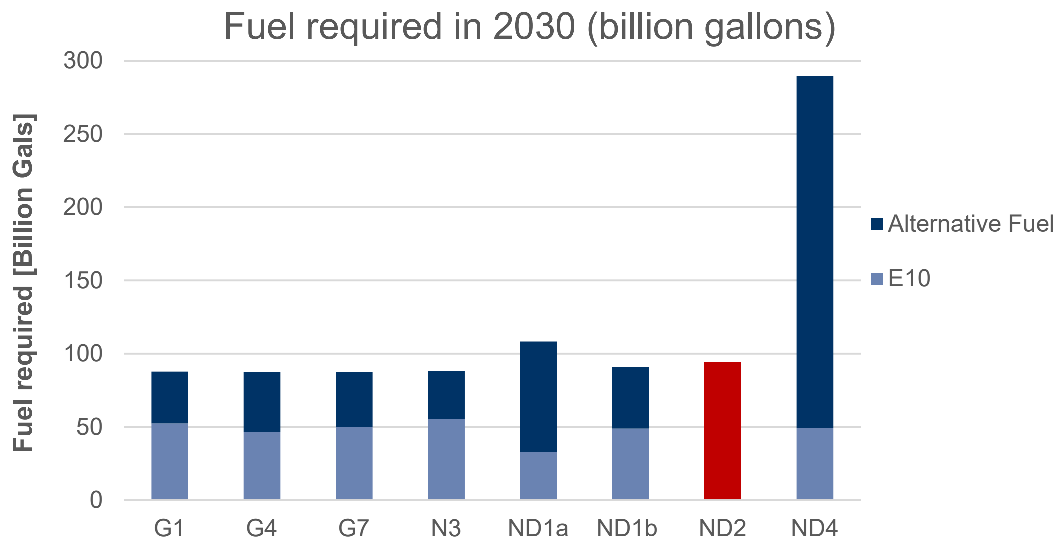

Figure 26. Drop-In, Non Drop-In and E10 Fuels Required to Meet the 55% Reduction Target – Volume Basis

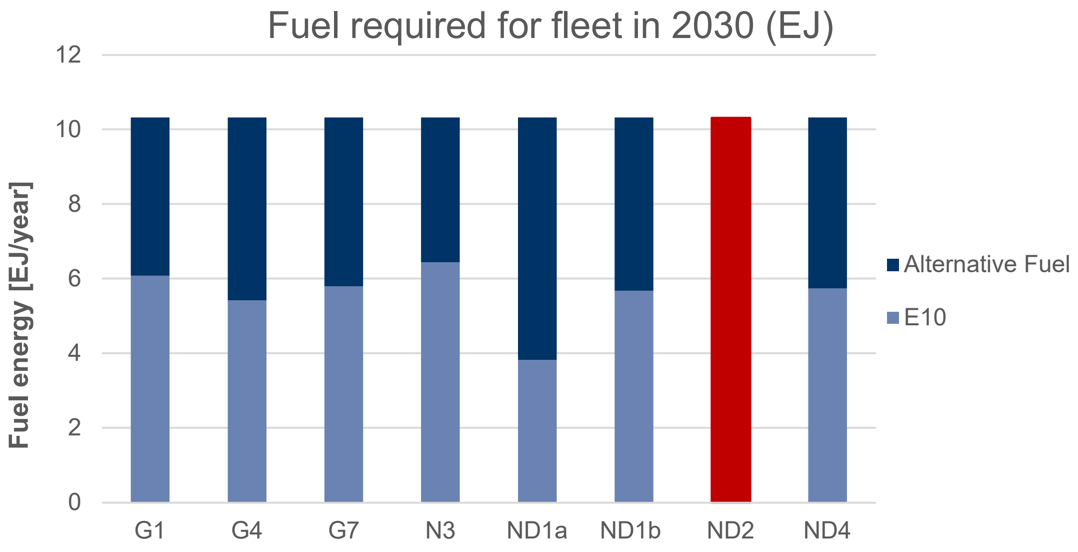

Figure 27. Drop-In, Non Drop-In and E10 Fuels Required to Meet the 55% Reduction Target – Energy Basis

For the drop-in pathways, the total number of ICE vehicles remains constant, at approximate 230 million – in reality the drop-in fuel and E10 would be treated as one fuel pool and vehicles would refill on a combination. However, for the non-drop in pathways to be realized, new, modified ICE vehicles would need to be deployed to facilitate uptake of the non-drop in fuels – see 9. Depending on the fuel pathway, the number of new non-drop in vehicles required by 2030 is in the range of 100 to 145 million.

Table 9. Summary of Key Parameters for the Aspirational Scenario – 2030 Snapshot

	WTW Emissions (gCO_2e/MJ)	Alt. Fuel Required (kt)	E10 Required (kt)	Number of Non Drop-In Vehicles on Road (million)	Number of Fuel Production Plants	Required CAGR	Feedstock Required (Mt) For all production plants, including co-product production
G1 (MTG)	8.99	98,952	147,772	-	Methanol plants: 1,094 MTG plants: 743 The number of methanol plants is noticeably more than MTG plants due to the efficiency of the MTG process requiring larger volumes of methanol		Waste: 528 Mt
G4 (pyrolysis)	21.61	114,454	131,62	-	Pyrolysis plants: 2,971		Biomass Residues: 718 Mt
G7 (co-processing)	14.87	105,614	140,832	-	Co-Processing plants: 5,440. Based on average co-processing capacities of existing and planned plants. Potentially fewer plants if % co-processing could increase, but typically limited to 5-10% of mineral oil capacity. Gasoline-like fuels represent 24% of the product slate.		Waste/Veg Oil: 554 Mt
N3 (e-FT)	0.41	91,760	156,468	-	FT synthesis plants: 3,235 (naphtha 25% of the product slate)		H2: 209 Mt
ND1a (E85)	41.36	224,000	92,870	145	Corn ethanol + CCS plants: 569	74 % for CCS	Corn: 503 Mt
ND1b (E25)	17.00	120,171	138,068	103	HVO plants: 11,811 (naphtha only 2% of the product slate) Corn ethanol + CCS plants: 80	40 % for CCS	Waste/Veg Oil: 5,499 Mt Corn: 88 Mt
ND2 (M17)	90.93				Even w/ 100% of the fleet running on M17, it is not possible to meet the target.		
ND4 (H2)	15.94	38,186	139,463	102		61% for green H2 99% for blue H2	Electricity: 1.37 EJ Natural gas: 113 Mt

Plants and infrastructure

To produce alternative liquid fuels at the scale required, several EJs, significant deployment of fuel production facilities will be necessary. Table 9 shows an indicative number of plants that would be required to meet the demand of the aspirational scenario. The number of plants varies between pathways, not just because of the different volumes of fuel required but also as a result of:

- **Nameplate capacities** for different technologies (e.g., 93 ML nameplate capacity for a fast pyrolysis plant or 203 ML for a methanol to gasoline plant).
- **Conversion efficiencies**: For example, in G1 there are two conversion plants, methanol synthesis and methanol-to-gasoline. The number of primary conversion plants (methanol synthesis) is greater because (a) efficiency losses in the secondary conversion and (b) secondary conversion plants not constrained by biomass / waste feedstock in the same way as the primary conversion and are therefore easier to scale up.
- **Technology product slates:** For ND1b (E25), ~11,800 HVO plants would be required to supply the naphtha (~92,000 ktonnes), this is significantly higher than any of the other pathways largely because naphtha represents only 2% of the HVO plant's product slate. In comparison, N3 which requires approximately ~84,000 ktonnes naphtha (0.9 times ND1b) would need ~3,200 plants – almost 4 times less. This is because in the FT process, naphtha could correspond to 25% of the product slate compared to the 2% it represents in the HVO process.

Biomass supply chains remain immature and significant infrastructure investment will be required to deploy sufficient infrastructure. This is likewise the case for CCS; operational pipeline transport networks and storage facilities for the captured CO_2 remain limited in number and capacity which in turn inhibits potential production of blue hydrogen.

Feedstock

The quantity of biomass feedstock that would be required to achieve the targeted level of decarbonisation depends on the pathways considered but is huge in all cases. The 2016 Billion-Ton Report[21] by the US Department of Energy remains the most complete assessment of biomass feedstock potential in the US. The report estimates the potential of a range of feedstocks including forestry and agricultural residues, municipal solid waste (MSW) and energy crops, assuming different feedstock cost points (higher feedstock cost increases feedstock potential). For forestry and agricultural residues, the potential is ~270 million tonnes and 45 million tonnes for MSW. If the US LDV was supplied solely by E10 and G1, it would require 528 million tonnes of MSW feedstock – an order of magnitude higher than the MSW that might be available. This is similarly the case when considering the residues required for G4.

Feedstock limitations will also be encountered with increased production via fuel pathways G7 and ND1b. Both pathways involve the hydroprocessing of oils and fats. In the aspirational scenario, the combined US capacity of the two pathways increases by a factor of 78 by 2030. From a sustainability perspective, the feedstock requirements would ideally be met with oils and fats from waste sources such as used cooking oil (UCO) and tallow. However, the potential to ramp up collection of waste fats and oils for fuel production is limited, with nearly all that is recoverable economically already being collected and used for fuel production or other processes[22]. As a result, this large increase in hydroprocessing capacity will likely be met with more readily available feedstocks such as soy oil, canola oil or distiller's corn oil. This could result in a tightening of the vegetable oil market with knock-on cost implications for other vegetable oil consumers.

However, as the values for feedstock required quoted in Table 9 takes into account the product slate, there would also be significant volumes of other fuels, such as jet fuel produced too. For example, the

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[21] DOE. 2016. 2016 Billion-Ton Report.

[22] C. Malins and C. Sanford. 2021, *Animal, vegetable or mineral (oil)?*, ICCT

HVO contribution to fuel pathway ND1b is estimated to also produce just over 4 billion gallons of jet fuel in 2030 in the aspirational scenario.

In any case, this analysis suggests that the full range of biomass feedstocks will need to be considered when pursuing alternative liquid fuels and meeting ambitious targets may require importing feedstocks into the US.

Vehicle types

For non-drop in pathways, there is not just fuel supply to consider. By 2030 almost half of all ICE vehicles would need to be non-drop in vehicles. The average new registration in the baseline is approximately 17 million vehicles per year (avg. 2025 to 2030), of which approximately 5.4 million are PEVs (PHEV and BEV). Assuming the remainder of new vehicle registrations is therefore the non-drop in ICE based vehicles, the results of the Aspirational scenario can be sense checked. With an introduction of approximately 12 to 13 million non-drop in ICE based vehicles (avg. 2025 to 2030 of Gasoline ICE + FFV + HEV + PHEV):

- Starting from 2025 (as in the Expected scenario), approximately 74 million ICE based vehicles would be capable of running on a non-drop in fuel in 2030 (Figure 25)
- Assuming instead the non-drop in vehicles are introduced from 2022, approximately 103 million ICE based vehicles would be capable of running on a non-drop in fuel in 2030 (Figure 25).

Considering this the theoretical maximum for the introduction of non-drop in ICE vehicles, it would be possible for the pathways ND1b (E25) and ND4 to reach the GHG emissions reduction target by 2030, if essentially all new ICE vehicle registrations between 2022 and 2030 are for that pathway, as shown in Figure 28. For ND1a (E85), 145 million vehicles on the road in 2030 would be required, therefore the renewal rate would not allow this to be achieved, unless vehicles start retiring earlier, allowing for an increased renewal rate (16-18 million per year from 2022). To achieve the level of retirement discussed would require active influence from policymakers to incentivize vehicle uptake through tax credits, rebates, or other means of reducing vehicle costs, as well as regulations to enforce vehicle manufacturers to sell these vehicles.

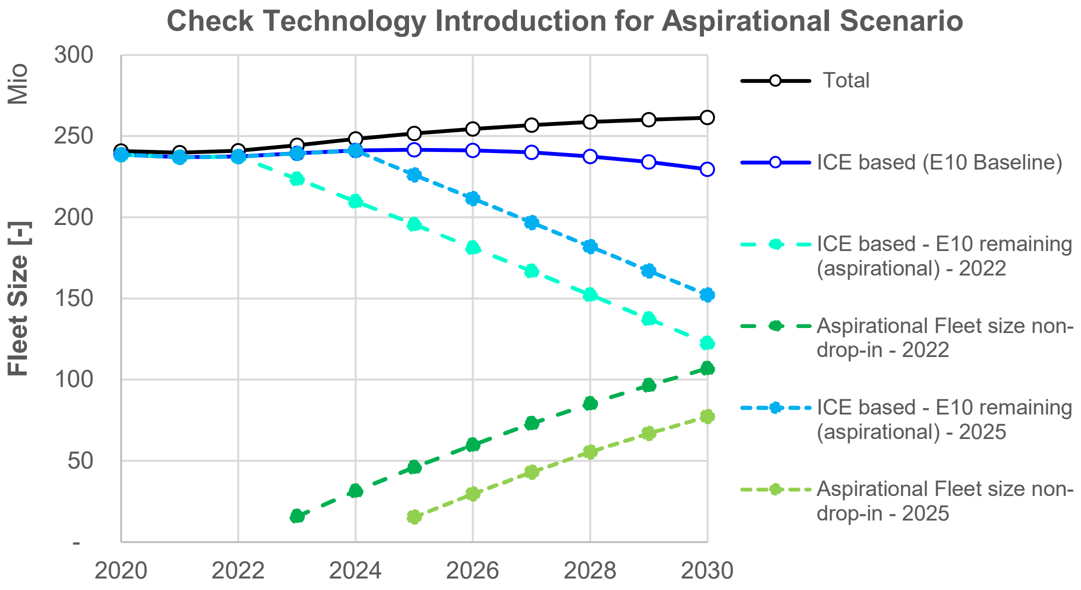


Figure 28. Maximum Achievable New Registrations of Non Drop-In Vehicle Types (Starting in 2022 or 2025) based on the Theoretical Maximum Renewal Rate of ICE Vehicles

2.5 Phase 1 Conclusions

The aim of Phase 1 was to understand what role low carbon fuels in ICE vehicles might have in the US light duty vehicle fleet between 2020 and 2030, on top of projected levels of electrification. The baseline scenario shows what the WTW GHG emissions of the fleet would look like based on a “business as usual” scenario, in which a reduction of 18% GHG emissions is achieved between 2020 and 2030 because of increasing penetration of PEVs in addition to improved fuel economy and vehicle efficiency of new ICE vehicles. In the baseline, it was assumed that the ICE vehicle fleet was supplied with E10 (assuming corn-based ethanol).

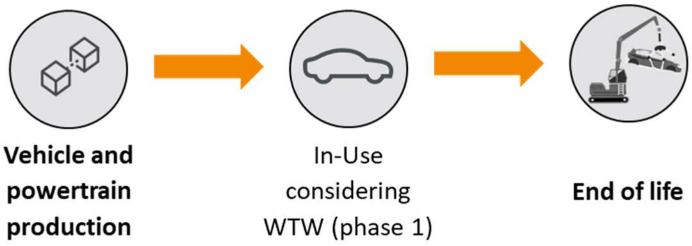
Under the Expected scenario, a realistic level of decarbonization achievable through the uptake of eight different drop-in and non-drop in fuels (“alternative fuels”) was explored. The drop-in fuels – those that require no ICE modifications – were considered alongside the E10 fuel mix for conventional ICE, whilst non-drop in fuels were considered alongside the introduction of modified ICE vehicles in the fleet. The Expected scenario showed further emissions reductions of 4.5% in 2030 compared to the Baseline scenario, contributing to a 22,6% reduction compared to 2020. These reductions are fairly minor, due to the limited availability of alternative fuels (notably the drop in gasoline fuels) anticipated to be available between 2022 and 2030 (~0.5 EJ). Fuel supply was projected based on current and planned projects, the number of developers and projections of plant deployments. In addition, there was limited deployment of non-drop in vehicles, only being introduced into the fleet from 2025. However, of the pathways explored, ND1a (E85) showed the greatest potential for GHG reductions compared to the baseline, largely due to the future corn ethanol (with CCS) fuel supply being significantly higher than other pathways, due to an already mature corn ethanol industry, the existence of FFV vehicles already in the fleet, and a higher share of FFV in new vehicle registrations beyond 2025. The Expected scenario shows that the rate of deployment of PEVs, alongside potentially available alternative fuels, could reduce GHG emissions by 36% compared to 2005 levels, but only a 4.5% reduction compared to the 2030 Baseline scenario.

To better understand the scale of what would be required for alternative fuels to have a prominent role in the decarbonisation of the LDV fleet by 2030, an Aspirational scenario was investigated. It considered a top-down approach, setting a GHG reduction target of 55% compared to 2005 levels, in line with the Paris Agreement. Such target is equivalent to 702 Mt CO_{2e} emitted in 2030. Leaving PEV penetration at the same level as in Baseline and Expected, the cap on ICE WTW emissions was determined to be 634 Mt CO_{2e} in 2030. Approximately 4 EJ of alternative fuel would be required to achieve the emissions reduction target, a factor of 10 higher than what was estimated to be available under the Expected scenario. In order to supply this quantity of alternative fuel, 1000s of new plants would need to be built, and the majority of the US' biomass feedstock would need to be harnessed. In addition, for non-drop in routes, the fleet would need essentially all new registrations from 2022 to be non-drop in vehicles.

Despite the challenges associated with meeting the required demand for alternative fuels, the analysis does show that such fuels could add to decarbonisation of the LDV fleet. By 2030, the analysis suggests PEV (PHEV and BEV) will represent 17% of the fleet. Even under an aggressive PEV deployment scenario, e.g., 100% new registrations from 2022 to 2030 (~17 million per year), there would still be approximately 114 million ICE vehicles on the road in 2030, therefore there is likely still a need to decarbonize the liquid fuel pool. The amount of liquid fuel still required even under the most aggressive EV deployment scenario is likely to still be substantial, therefore there is a need to consider low carbon fuels in the LDV transport modes, not just in the transport modes which are considered "hard-to-abate", like aviation. The analysis showed that whilst significant amounts of feedstock and large numbers of plants would be required to meet the demand, other liquid fuels would also be produced in many of the pathways, these fuels could be suitable for the other transport modes, like aviation, which is likely to rely on liquid fuels far beyond 2030. In addition, some of the pathways produce products which are intermediates for aviation fuel production (e.g., ethanol or methanol), therefore short-term investments into these technologies can be future proofed through additional conversion steps. Equally, fuels like ethanol or methanol could be sold into other sectors, such as chemicals. For the supply of low carbon liquid fuels to be available, technologies need to be deployed rapidly, and the full spectrum of biomass, renewable electricity and CO_2 sources needs to be harnessed to achieve this. Investing in low carbon liquid fuels for the LDV sector will not shift focus from other in need sectors such as aviation, but could allow synergies and shared scale up to happen, for example using technologies which have a mixed product slate serving both sectors, or boosting ethanol supply which can then be converted into jet fuel when demand in road drops.

3. PHASE 2: EVALUATION OF LIFECYCLE GHG EMISSIONS

Phase 1 demonstrated that the Well-to-Wheel (WTW) emissions of Plug-In Electric Vehicles (PEVs) are significantly lower compared to Internal Combustion Engine (ICE) vehicles. However, WTW emissions represent only a portion of the total emissions. Therefore, in Phase 2 the system boundaries of the analysis are expanded to include GHG emissions arising during the vehicle production and end of life stages.



3.1 Pathways and vehicle archetype selection

This analysis is conducted on two alternative fuel pathways assessed in Phase 1 in comparison to one electric pathway. It was decided to select one drop-in and one non-drop in pathway to allow a comparison of drop-in ICE, non-drop-in modified ICE and plug-in battery electric (PEV) vehicle variants.

Table 10: Pathways selected

Pathway	Fuel produced & proportion of product slate given on an energy basis	Fuel process
DI Fuel Pathway	G1 – Bio-gasoline (92% of product slate), LPG	Waste gasification + Methanol-to-Gasoline
NDI Fuel Pathway	E85 (bio-ethanol + fossil gasoline)	Corn ethanol _ CCS (93% capture efficiency)
PEV	Plug-in battery electric vehicle comparator	

The life cycle analysis on the three pathways is conducted for one vehicle archetype, chosen to be a D/E-segment SUV. The example of the Jeep Grand Cherokee is to provide the reader a representation of the vehicle type of a large SUV. The data is not meant to represent current or future Jeep Grand Cherokee archetypes or specifications unless otherwise noted. This vehicle archetype has a share of 28% in the fleet (see Figure 9), builds a sound basis to scale for smaller and larger vehicles. The following table shows the main technical specifications for the three vehicle variants. For the ICEs, it was agreed that for the purpose of this project, the differences in main technical specifications are negligible for the chosen drop-in and non-drop-in pathways. The example of the BMW iX was chosen to provide the reader a representation for the PEV comparator in a similar segment and sizing. The nominal system voltage level of the PEV is 400V.

Table 11: Vehicle archetype specifications

Mid-size crossover SUV (D/E-segment)	ICE (DI & NDI)	PEV
Considered Vehicle Mass [kg]	2,368	2,624
Vehicle Dimensions (l w h) [mm]	4,822 x 2,154 x 1,781	4,953 x 1,967 x 1,695
Fuel Tank [L]	93	-
Battery Size [kWh]	-	111.5
Battery Chemistry	-	NMC 631
Power [kW]	~300 (V8)	385 (front + rear EM)
Voltage level [V]	12V for vehicle electrics and electronics	400V for powertrain system and 12V for vehicle electrics and electronics

3.2 Carbon footprint assessment methodology and boundary conditions

To evaluate the vehicle and powertrain production emissions of the chosen pathways, AVL performed a bottom-up CO_2e assessment considering material and manufacturing carbon footprints. Figure 29 provides a high-level visualization of the approach and displays the main tools supporting the assessment. For the material portion, GREET and ecoinvent were used to compile material usage into CO_2e values. For modelling manufacturing footprints, Siemens Teamcenter, i-Point as well as ecoinvent were used as supportive tools.
More details will be shown in the production carbon footprint allocation chapter.

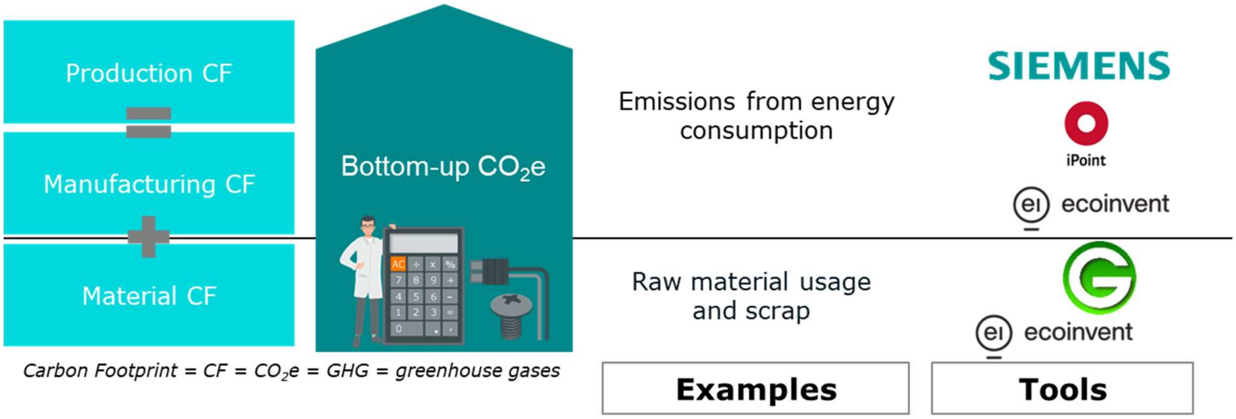


Figure 29: Carbon footprint assessment methodology

The key boundary conditions that influence the assessment, such as production localization, annual volume and the energy mix used for vehicle production are shown in the next tables.

Table 12: Boundary conditions

Boundary conditions for the carbon footprint assessment	
Annual volume	**100,000 cars/year**
Final vehicle assembly location	**US**
Raw material origin (primary)	**North America**
Supplier structure	**North America, Mexico**
Lifetime of production	6-8 years
Number of manufacturing lots	12 lots/year
Shift model	3 shifts / 8 hours / 5 days / 48 weeks
Production hours	5,760 hours/year
Efficiency factor Production & Assembly	85 %

Primary boundary conditions in bold letters

Table 13: Electricity mix in vehicle production

Electricity Source	Share	Intensity
	Share in % for year 2021	*Carbon intensity g/kWh*
Oil	1	886
Gas	37	460
Coal	23	997
Nuclear	19	4
Biomass	1	25
Hydro	6	2
Other renewable	13	28
Others	0	650
USA Electricity Mix 2021	411 g/kWh	

3.3 Bill of materials

The high-level bill of materials shows the differences between the three pathways. Parts and subassemblies are clustered into twelve assembly groups which are assigned to vehicle or powertrain subsystem. The differences among the pathways are shown with:

x … as baseline for the ICE drop-in variant
y … to show potential differences for the non-drop-in variant and
z … to distinguish the components for the BEV.

Table 14: High level bill of materials showing differences between pathways

	Mid-size crossover SUV (D/E-segment)	ICE drop-in	ICE non-drop-in	PEV
Vehicle	Body in White & Doors & Closures	x	x	x
	Chassis	x	x	z
	Non-Powertrain E/E	x	x	x
	Exterior	x	x	x
	Interior	x	x	x
	Cooling and HVAC System HVAC… Heating, Ventilation & Air Conditioning	x	x	z
Powertrain	Electric Motor (front+rear)	-	-	z
	ICE incl. EAS (Internal Combustion Engine incl. Exhaust Gas Aftertreatment System)	x	x/y*	-
	Transmission (Automatic 8-speed, cardan shaft, transfer case, differentials vs. single-speed, differentials)	x	x	z
	Battery (Traction)	-	-	z
	Fuel Storage and Exhaust (Fuel tank, pump and distribution, exhaust muffler and pipe)	x	x/y*	-
	E/E Powertrain (On-Board-Charger, DC/DC, Inverters, high voltage wiring system and power distribution)	x	x	z

* Differences in terms of CO_2e are negligible. Aligned at status meeting on 2nd of August based on AVL flex fuel application slides.

In terms of the vehicle subsystem, the two ICE pathways are identical, with differences to the PEV comparator identified only for the Chassis and Cooling and HVAC.

In the powertrain subsystem, some material adaptations for fuel storage, ICE and EAS are necessary for a change from DI to NDI fuel in the two ICE pathways. Despite the need to partly use other materials, the impact on the carbon footprint is very small. This is due to two reasons: changes in alloys cause no or only a very small change in the carbon footprint of a material, and compared to the overall vehicle, only a few parts and thus only a very small mass is affected. Therefore, the already small difference in the CO_2e factor is furthermore reduced and the overall impact considered as negligible.
Regarding the PEV comparator pathway, major changes, implying entirely different powertrain sub-assemblies and technologies, need to be considered:

- Electric motors on front and rear axles for vehicle propulsion instead of the internal combustion engine including the exhaust aftertreatment system.
- Single speed transmissions and differentials on front and rear axles for torque and power distribution of the e-machines, also realizing all-wheel drive capability for the PEV. For the ICE variants automatic 8-speed transmissions, differentials, a transfer case and a cardan shaft for mechanically realizing all-wheel drive capability are needed.
- A Lithium-Ion traction battery in the PEV with a nominal voltage of 400V and a capacity of ~110kWh using a NMC631 chemistry.
  The 12V batteries for the ICE variants (typically referred to as starter battery) but also for the PEV variant to supply low voltage vehicle electrics and electronics is considered in E/E Powertrain and not assumed to be a differentiator for this analysis.

- Conventional fuel storage and exhaust systems including fuel tank, pump and distribution, exhaust muffler and pipe are only considered for the ICE variants, whereas differences between drop-in and non-drop in are negligible.
- The E/E powertrain position for the PEV considers 400V on-board charger, 12V/400V DC/DC converter, 400V inverters for the e-motors and the 400V wiring harness and power distribution. The 12V battery and low voltage wiring harness for vehicle electrics and electronics is considered to be similar for the ICE and PEV variants.

3.4 Weight and material definition

To detail the high level bill of materials of Table 14 the vehicle database of A2MAC1[23] was used. A2MAC1 provides vehicle benchmarks and assesses the vehicles down to individual parts. With this teardown information, material detail. weight shares are gathered The Jeep Grand Cherokee is one potential reference vehicle for the two ICE pathways and the BMW iX one for the PEV comparator. For the PEV, A2MAC1 does not offer detailed enough information for EDU and traction battery. In this case, AVL data from benchmarking projects and neutralized development projects was used.

Table 15: Weights

SYSTEM	ICE (Drop-in and non-drop-in)	PEV
	System Weight in kg	
Body in White & Doors & Closures	815	
Chassis	638	571
Non-Powertrain E/E	52	
Exterior	42	
Interior	225	
Cooling and HVAC System	34	66
Electric Motor	-	95
ICE incl. EAS	236	-
Transmission	235	79
Battery (Traction)	-	643
Fuel Storage and Exhaust	77	-
E/E Powertrain	14	37
SUM	**2,368**	**2,624**

Based on these material shares, CO_2e emission values for materials and pre-processed products were taken from databases like ecoinvent and the GREET model.

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[23] https://ibp.a2mac1.com/

Table 16: Materials used

MATERIAL	Usage ICE	Usage PEV	CF Factor	MATERIAL	Usage ICE	Usage PEV	CF Factor
	Used material in kg		*kg CO_2e/kg*		*Used material in kg*		*kg CO_2e/kg*
Cardboard	1.66		1.00	**PUR**	7.01	6.18	6.33
Carpet	24.00		2.74	**PMMA**	4.5		8.71
Carpets + Sound Dampening	3.27	2.64	2.74	**PP**	62.78	76.11	2.29
Glass	38.98		1.74	**TPV; TPE**	29.35	29.40	2.79
Leather	15.14		66.88	**Synthetic fibers**	20.53	16.53	2.29
Electric motor	9.61	11.08	3.63	**Aluminum**	217.20	252.73	10.90
Electronic Components	78.68	52.58	25.03	**Lead Acid Battery**	26.79		0.78
Metal + Elastomers	68.85	7.80	2.68	**Airbag**	10.53		5.35
Metal + Plastic	33.02	19.33	2.95	**Compressor**	5.92	-	7.87
Other Elastomers	5.21	3.40	3.70	**Steel**	1506.98	1221.06	2.24
Other Plastics	37.66	36.19	4.61	**Steel + Alloy**	54.25	-	6.57
ABS	21.56	22.16	4.65	**Cast iron**	31.95	-	1.81
ABS-PC	4.22	4.17	6.07	**Wire harness**	3.08	16.58	6.10
ASA; SMA	8.04	8.04	4.65	**Copper**	-	15.79	6.74
EPDM	1.45	20.59	2.79	**Inverter**	-	16.84	43.30
PA; PC; PE; PBT; PET	18.05	11.04	8.25	**Magnets**	-	5.09	33.40
PPO; PPE; PPS	3.69		4.61	**Battery**	-	643.30	-

3.5 Production carbon footprint allocation (material and manufacturing)

The production carbon footprint assessment is based on an activity-based costing tool, wherein the ‘currency’ used for the tool is CO_2 equivalent emissions instead of $. This approach considers all production-related CO_2 emissions including emissions of raw materials, manufacturing, assembly processes and applicable overhead. This tool was also used to generate CO_2 emissions for the disposal/ recycling phase.

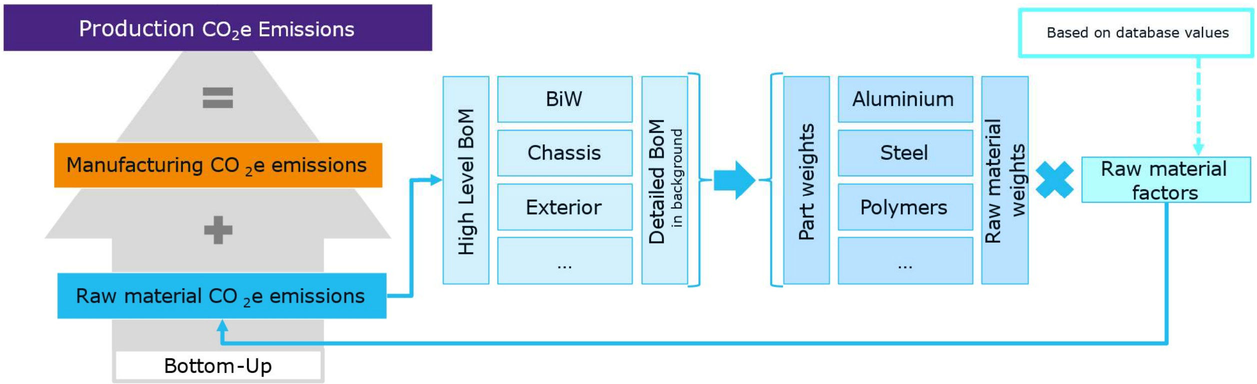

Figure 30: Material carbon footprint allocation

Emissions from raw materials are calculated using database values for kg of CO_2e per kg of raw material. The quantity of raw material used is derived from the detailed BoM available from A2Mac1. A raw material is assigned to the corresponding part in the BoM and then multiplied with the database value to gain results on rough BoM and vehicle level.

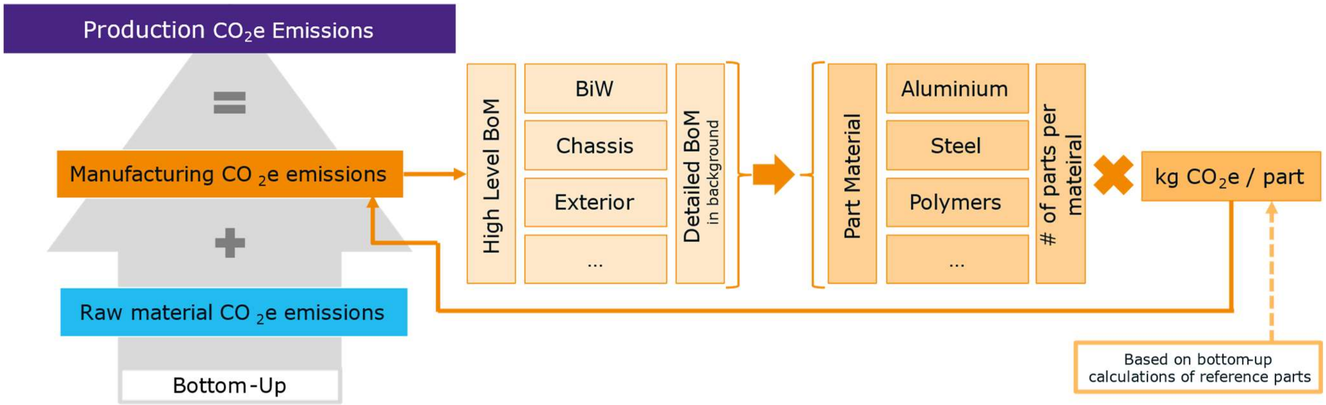

Figure 31: Manufacturing carbon footprint calculation

The CO_2e values for manufacturing are derived based on a rough modelling of major manufacturing processes in Siemens TcPCM: e.g., die casting, injection molding, extrusion, and deep drawing. From these reference calculations, a general factor for the material groups in focus are derived and applied. The material allocation of the detailed BoM is used to link kg CO_2e per part values to the line items.

By applying those two approaches, the following values in Table 17 for the ICEs and the PEV were derived:

Table 17: Carbon footprint

SYSTEM	ICE (Drop-in and non-drop-in)	PEV
	System total carbon footprint in kg CO_2e	
Body in White & Doors & Closures	2,876	
Chassis	2,703	3,376
Non-Powertrain E/E	225	
Exterior	205	
Interior	2,152	
Cooling and HVAC System	255	608
Electric Motor	-	466
ICE incl. EAS	1,457	-
Transmission	1,245	294
Battery (Traction)	-	8,324
Fuel Storage and Exhaust	287	-
E/E Powertrain	288	922
SUM	**11,700**	**19,400**

3.6 Scaling for different vehicle types and sizes

Based on the detailed assessment of the large SUV a scaling to other vehicle segments – passenger car, small SUV and light pick-up truck – was done.

SEGMENT	ICE (drop-in)	ICE (non-drop-in)	PEV	
Passenger Car	~ 7,000		~ 13,200	~60kWh
Small SUV	~ 7,800		~ 14,200	
Large SUV	~ 11,700		~ 19,400	~110kWh
Light Truck	~ 13,300		~ 21,200	
	Carbon footprint in kg CO2e			*Battery capacity*

For the large SUV and the light truck the same powertrain specifications and components were considered. Differences were considered in the vehicle glider and thus in the carbon footprint. In the lower segments all systems were scaled with significantly smaller battery sizing as well ICE and e-machine powers (~200kW).

3.7 End-of-life carbon footprint

The end-of-life phase of the vehicle is evaluated using factors for the raw materials. The underlying assumption is that the vehicle is properly disassembled properly on a wrecking yard and segregated into its raw materials as far as possible. Dismantling and purifying is included in this category. A benefit for recycling is not considered in this scope and highly depends on the overall market situation and the assumed boundary conditions.

Table 18: End-of-life carbon footprint

SYSTEM	ICE (Drop-in and non-drop-in)	PEV
	carbon footprint in kg CO_2e	
Production	11700	19400
End of life	880	1700
TOTAL	12582	21000

3.8 Reduction potentials

Generally, the reduction potentials described in this chapter primarily aim at the production phase with improvements of the material footprints as well as efficiency gains in production technologies and the associated energy mixes. On the other hand, in-use optimization potentials on vehicle level should be pointed out as well.

In the production of ICE and PEV, aluminum and steel are some of the main materials used. Taking those materials as a starting point for reduction efforts, the material carbon footprint can be reduced. For steel, new technologies to produce near carbon neutral primary steel are developed using green hydrogen. For aluminum, low GHG intense electricity by using renewable energy is the main potential of reducing emissions during primary production.

Considering the production of green hydrogen and applying a direct reduction process, the emissions for producing high quality steel can be lowered to 0.05 kg CO_{2e}/kg of steel according to Global Energy Solutions e.V. For aluminum, a switch to renewable electricity in the whole production chain leads to a reduction of 90%. Applying purely these measures to the vehicle glider would lead to a reduction of circa 50% for both ICE and PEV.

The same reduction potential also applies to the powertrain components. As the share of metals is higher in these components, the reduction in material emissions is also higher. Potentially, exhaust emission standards will become stricter in the future. These higher standards are included in the powertrain components with a higher factor for precious metals. Compared to the rest of the vehicle, the share of metals in the powertrain components is higher and therefore the potential reduction due to more environmentally friendly production of aluminum and steel. Three fourths of the emissions can be saved in this manner.

Separate reduction potential was considered for the battery cell raw materials and the battery cell manufacturing. For comparability, cell chemistry and energy densities are considered unchanged. Due to higher recycling content and cleaner raw material production routes, a reduction of 30% for battery cell raw material emissions was considered. Due to the use of green energy in the manufacturing steps of the battery cell, a reduction of 50% is considered. This leads to a reduction of one third in the battery production.

Applying several solutions in the manufacturing processes in the electronics industry have the potential to reduce the electronic components' carbon footprint in vehicle and powertrain by up to 25% without compromising functionality. This optimization also generates cost savings.

The above-mentioned reduction potential refers to the production (raw material and manufacturing) of the ICE and PEV vehicles.

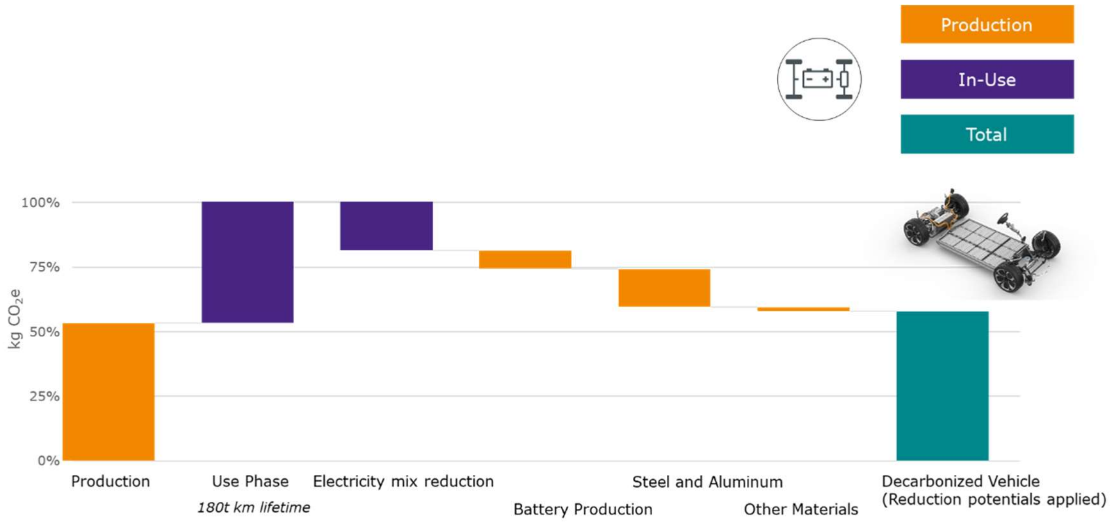

Figure 32: PEV production emissions reduction potential

Compared to the PEVs, ICE reductions in production of the vehicle only account for a small share of the total lifetime emissions due to the different proportion of production and in-use emissions. Production improvements lead to a stronger lever in PEV due to higher masses while in-use reductions show a higher potential for ICE.

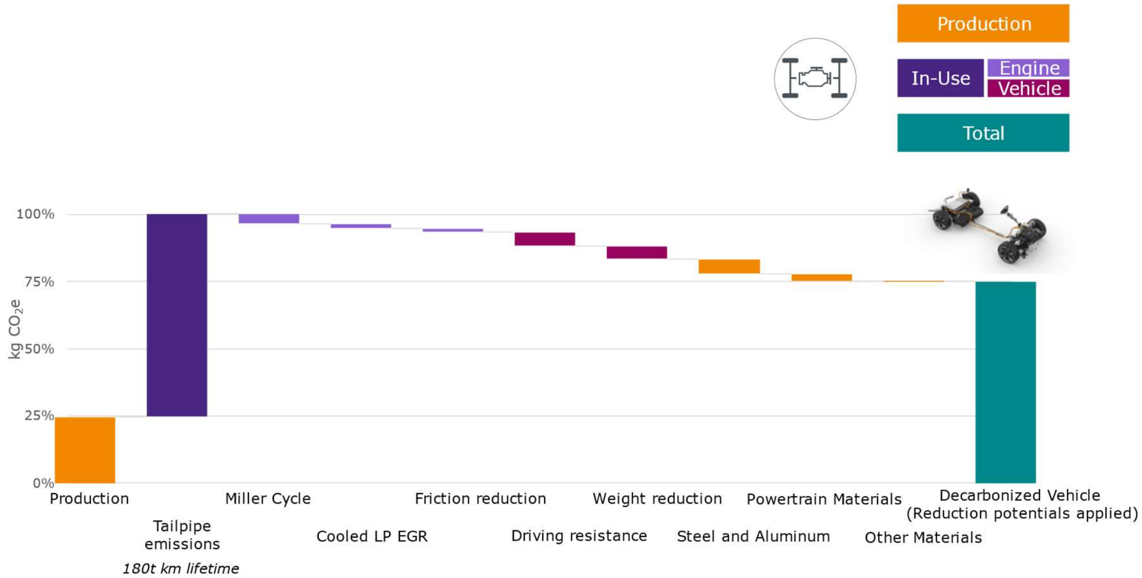

Figure 33: ICE production emissions reduction potential

Combining all measures show that the total decrease for ICEs might be lower than for PEV. Relatively the decrease of overall vehicle production carbon footprint is higher for ICEs, -57% for the ICE (drop-in and non-drop-in) and up to -44% for the PEV.

3.9 Phase 2 Conclusions

Phase 2 carbon footprint evaluation of production and end-of-life phase are built upon bill of materials and weight shares of two reference vehicles, representing the ICE and PEV pathways. Regarding drop-in and non-drop-in pathways of the ICE base version, no major differences in the carbon footprint can be identified, as the material differences were assessed to be negligible.

The evaluation incorporates emissions from raw material as well as those originating from manufacturing and assembly processes. By structuring the BOMs into two primary categories, namely vehicle and powertrain subsystems, synergies as well as differentiating positions could be identified in an efficient way. The results indicate a production carbon footprint for the PEV which is nearly 70% higher compared to its ICE comparator (19.4 vs. 11.6 tons). Generally, this is an order of magnitude which has been expected by the authors, especially considering the large battery used in the D/E SUV segment with the associated energy mixes currently in place. Based on this detailed assessment a scaling to smaller and larger vehicle segments was done. Furthermore, optimization potentials for production and in-use phase were shown. However, from production point of view, these potentials do not result in an inversion of the results, still being the PEV the variant resulting in a higher production footprint.

Overall conclusions comprising phase 1 and 2 results on fleet and life cycle, will be described in the following chapter.

4. COMBINED CONCLUSIONS FROM PHASE 1 & 2

4.1 Comparing WTW and Lifecycle results on an individual vehicle basis

To understand the decarbonisation potential of some of the most promising options examined in this study, Figure 34 was created, which shows, on a per vehicle basis, for a fixed mileage, the full lifecycle emissions (broken down into WTT, TTW and production emissions) for E10 ICEs, E85 ICEs, ICEs running on fully renewable gasoline, and EVs.

At face value, it can be observed that:

- E85 vehicles could have similar lifecycle emissions to EVs, based on the currently projected rate of grid decarbonisation (which has a large impact on the EV's production and WTT emissions)
- Vehicles running on 100% renewable gasoline could have lower lifecycle emissions than EVs, based on the currently projected rate of grid decarbonisation

However, this is a simplistic analysis which is intended to show the decarbonisation **potential** of the E85 and 100% renewable gasoline options, if **deployed today.** As noted earlier in the study, the volumes of G1 (100% renewable gasoline) available today are small, and are not projected to increase significantly by 2030 under the Expected Scenario. Likewise, for E85, the fuel is not widely available and may only ramp up in appreciable amounts post-2025. Therefore, conclusions about the fleet-wide impact of E85 and 100% renewable gasoline options cannot be drawn directly from Figure 34, as they are not widely available today.

It is recommended that, in order to better understand the per-vehicle decarbonisation potential of each option, that in future work the analysis is extended into the 2030+ timeframe, wherein the availability of E85 and 100% renewable gasoline options could potentially be greater than now, but where the electricity grid intensity is also expected to be lower.

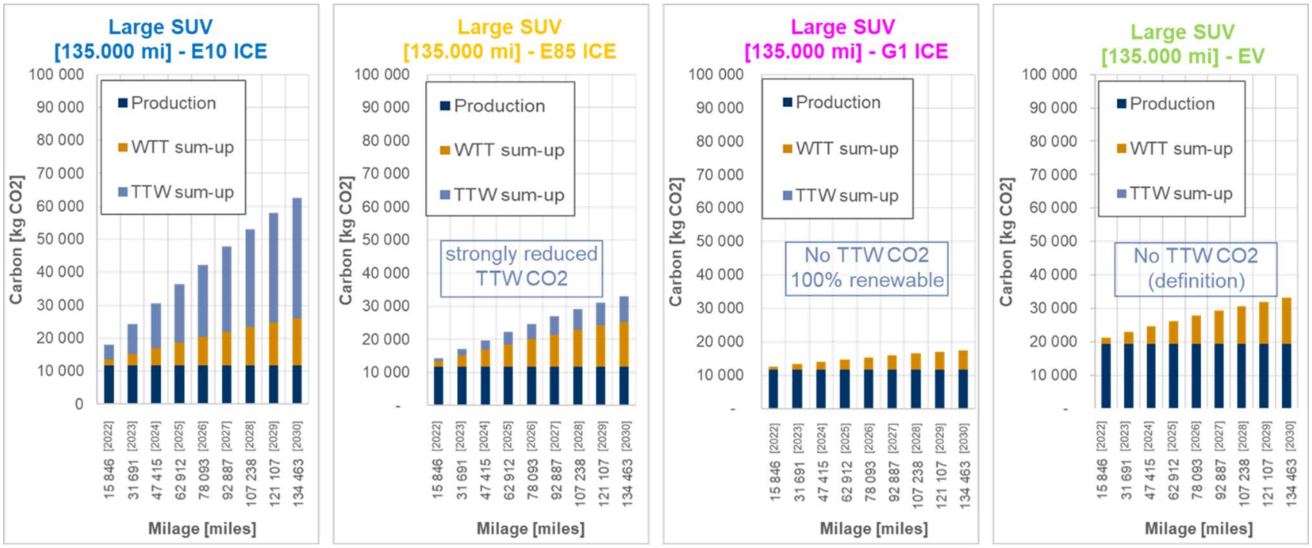

Figure 34: WTW and lifecycle results on an individual vehicle basis (2022 to 2030)

4.2 Comparing WTW and Lifecycle results on a fleet-wide basis

In order to better understand decarbonization benefits from a fleet-wide perspective, the results of Phase 1 and 2 were compared as per the discussion below.

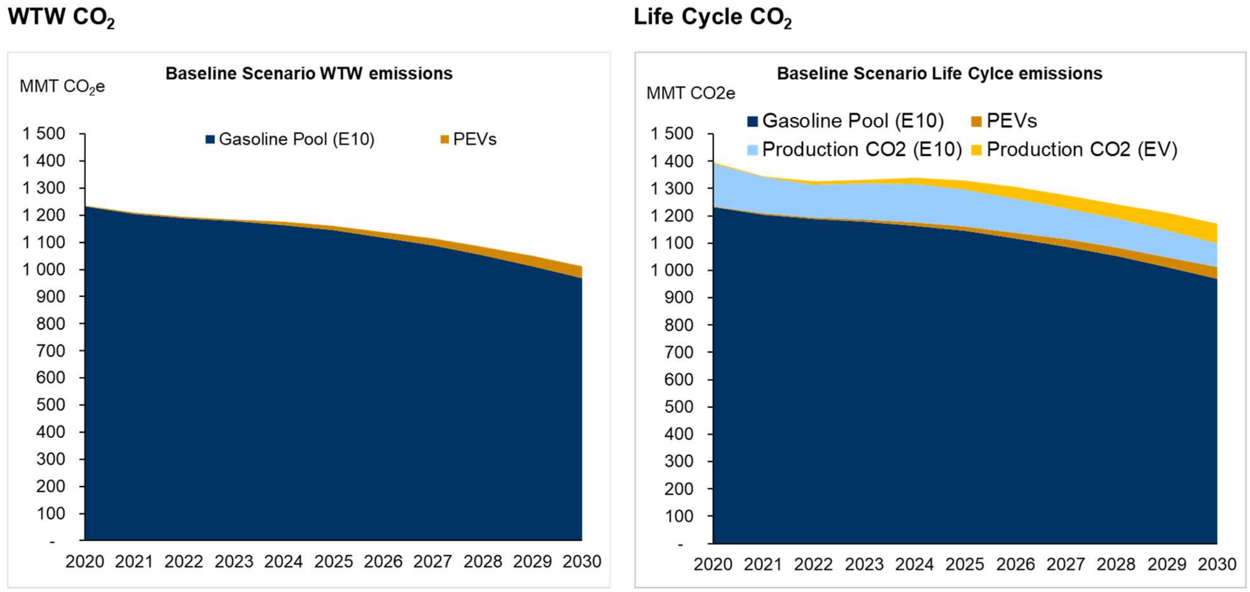

Figure 35: WTW vs Lifecycle emissions for baseline scenario

As evidenced in Figure 35, the lifecycle emissions are higher than the well to wheel emissions, as expected, but also follow a similar decreasing trend. The light blue (E10 ICE vehicle) and light yellow (EV) shaded areas represent the difference in emissions (from vehicle production) between the life cycle and well to wheel emissions, which equates to around 160Mt CO_{2e} per year. For E10 ICE vehicles, the emissions decrease over time because fewer vehicles are being produced and also due to the fact that the GHG intensity of the electricity used to produce the vehicles is decreasing, in line with the grid intensity assumptions taken elsewhere in the study. On the other hand, for EVs, as the total number of EVs being manufactured increases, this outweighs any benefit associated with grid intensity decreases, leading to an overall increase in production emissions from EVs.

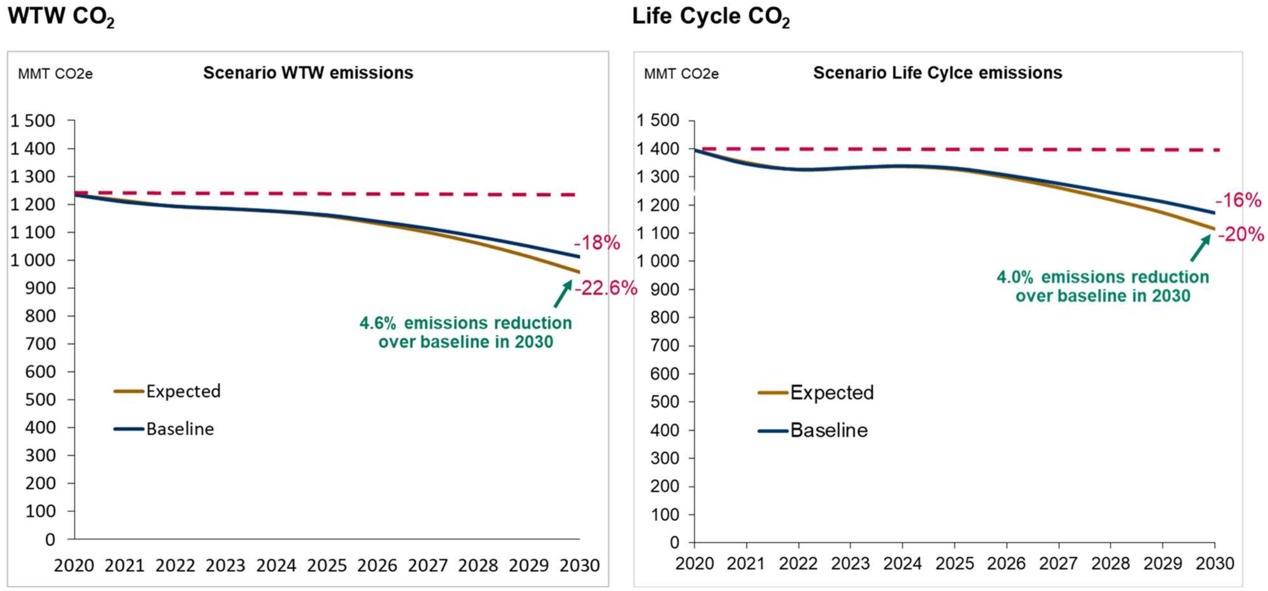

Figure 36: WTW & Lifecycle emissions for Baseline and Expected Scenarios

In Figure 36, it can be seen that the lifecycle emissions in the Baseline (-16%) and Expected scenarios (-20%) decrease at a slightly slower rate than the well to wheel emissions (Baseline = -18%, Expected = -22.6%). The slower rate of GHG reduction on a lifecycle basis is a result of the increased number of EVs being produced (and their additional GHG burden of battery production), despite the GHG intensity reduction of the grid decreasing. Overall, the higher lifecycle emissions compared to the WTW case and the slower rate of emissions reduction in the lifecycle case further emphasize the potential importance of low carbon fuels in reducing emissions in the short to medium term (besides the need to accelerate the decarbonization of vehicle production, especially EVs).

APPENDIX A ICE FUEL PATHWAYS AND ELECTRICAL GRID MIX ASSUMED FOR BEVS

Eleven (11) drop-in and 6 non-drop in fuel pathway-engines were initially scored in a high-level traffic light assessment against a set of criteria, in order to identify the eight most relevant options to include in the study, considering the timeframe 2022 – 2030. The fuel pathways were categorized as drop-in if the product slate included gasoline or naphtha and thus could be used in conventional ICE vehicles and non-drop-in for all other options, which would require new or modified engines.

The criteria included in the qualitative assessment were:

- Drop-in fuel criteria:
    - Route TRL: technology readiness level of the fuel production pathway.
    - Relative Well-to-Tank Carbon Intensity (WTT CI)[24]: routes which have avoided methane emissions result in lower (or even negative) CI compared to lignocellulosic and waste oil feedstocks.
    - Relative cost: driven mostly by feedstock used and/or dependence on renewable electricity.
    - Status: current activity/projects for the route.
    - Barriers: factors that may inhibit the routes potential to penetrate the market between now and 2030.
- Non-drop in fuel vehicles criteria (Focus on vehicle rather than fuel):
    - TRL: technology readiness level in view of “engine technology”.
    - Price impact: price impact in view of vehicle sales price.
    - GHG reduction potential Tank-to-Wheel & Well-to-Tank: GHG reduction potential with respect to baseline gasoline option.
    - Barriers: factors that may inhibit the routes potential to penetrate the market between now and 2030.

The criteria and scoring were considered alongside CRC’s interest and appetite to explore a range of technologies.

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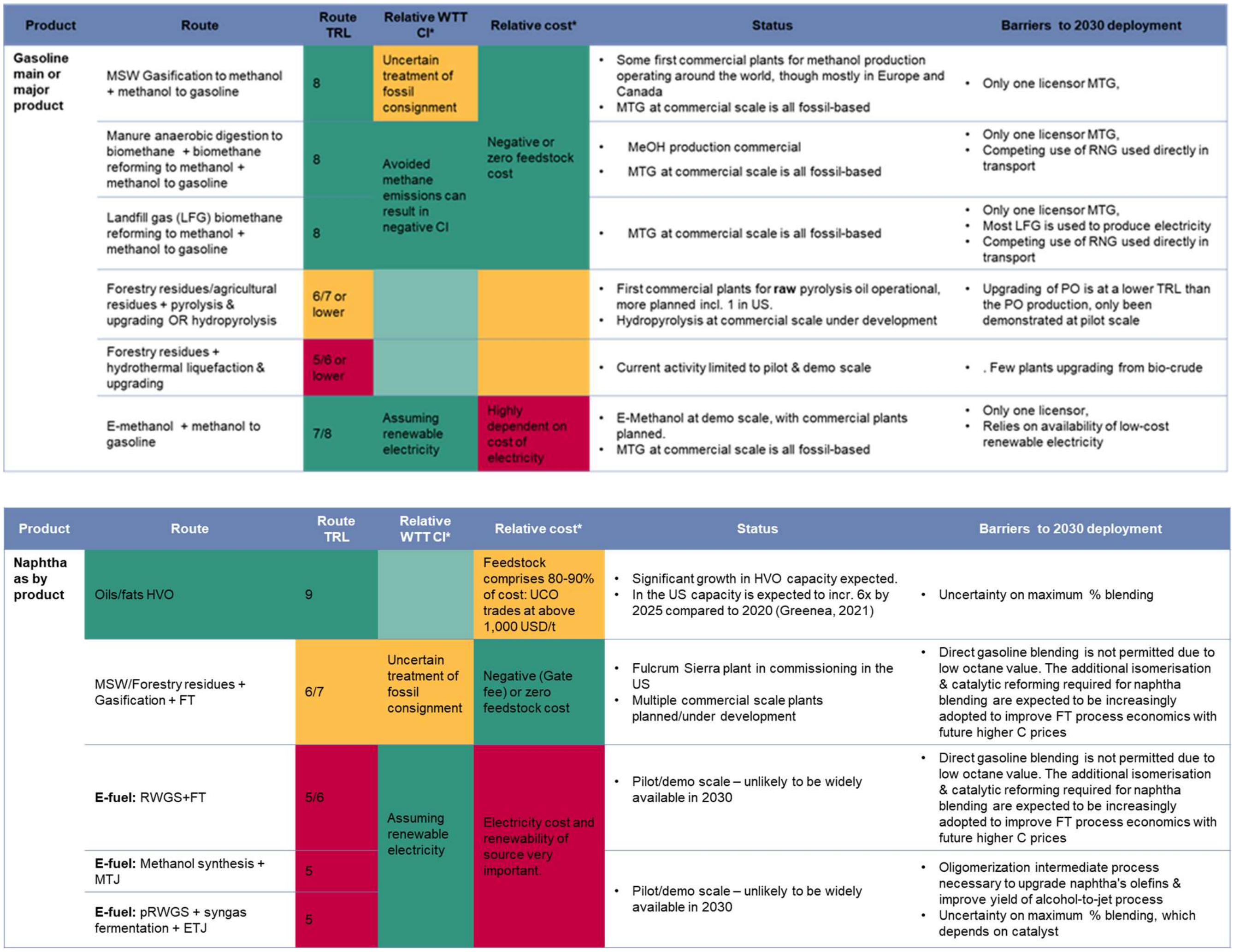
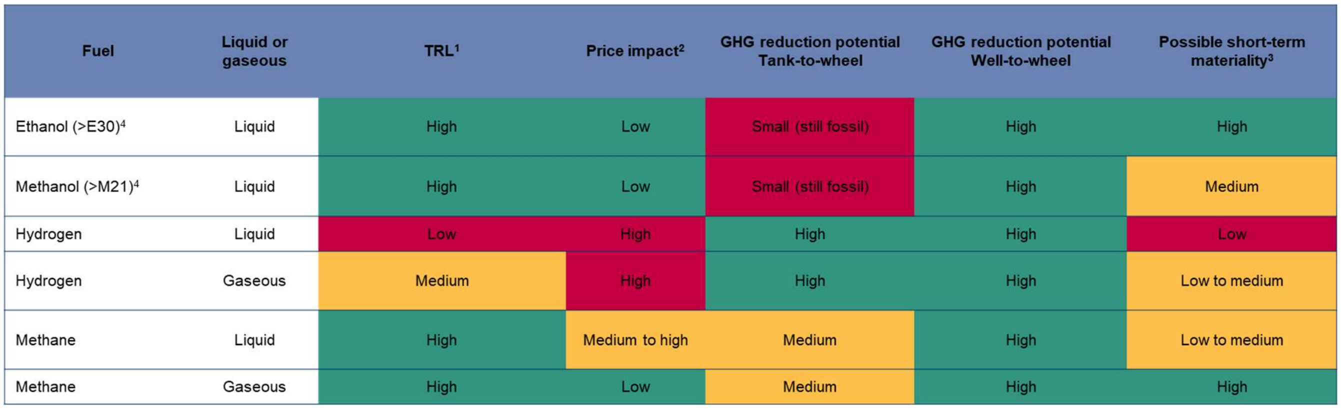
[24] Note, the WTW CI reduction potential for all these routes will be high as biogenic or renewable CO2 have “zero” combustion emissions during the TTW stage. The exception is routes using MSW, where the treatment of the fossil consignment is unclear.



Product	Route	Route TRL	Relative WTT CI*	Relative cost*	Status	Barriers to 2030 deployment
Gasoline main or major product	MSW Gasification to methanol + methanol to gasoline	8	Uncertain treatment of fossil consignment	Negative or zero feedstock cost	Some first commercial plants for methanol production operating around the world, though mostly in Europe and Canada MTG at commercial scale is all fossil-based	Only one licensor MTG,
	Manure anaerobic digestion to biomethane + biomethane reforming to methanol + methanol to gasoline	8	Avoided methane emissions can result in negative CI		MeOH production commercial MTG at commercial scale is all fossil-based	Only one licensor MTG, Competing use of RNG used directly in transport
	Landfill gas (LFG) biomethane reforming to methanol + methanol to gasoline	8			MTG at commercial scale is all fossil-based	Only one licensor MTG, Most LFG is used to produce electricity Competing use of RNG used directly in transport
	Forestry residues/agricultural residues + pyrolysis & upgrading OR hydropyrolysis	6/7 or lower			First commercial plants for **raw** pyrolysis oil operational, more planned incl. 1 in US. Hydropyrolysis at commercial scale under development	Upgrading of PO is at a lower TRL than the PO production, only been demonstrated at pilot scale
	Forestry residues + hydrothermal liquefaction & upgrading	5/6 or lower			Current activity limited to pilot & demo scale	. Few plants upgrading from bio-crude
	E-methanol + methanol to gasoline	7/8	Assuming renewable electricity	Highly dependent on cost of electricity	E-Methanol at demo scale, with commercial plants planned. MTG at commercial scale is all fossil-based	Only one licensor, Relies on availability of low-cost renewable electricity

Product	Route	Route TRL	Relative WTT CI*	Relative cost*	Status	Barriers to 2030 deployment
Naphtha as by product	Oils/fats HVO	9		Feedstock comprises 80-90% of cost: UCO trades at above 1,000 USD/t	Significant growth in HVO capacity expected. In the US capacity is expected to incr. 6x by 2025 compared to 2020 (Greenea, 2021)	Uncertainty on maximum % blending
	MSW/Forestry residues + Gasification + FT	6/7	Uncertain treatment of fossil consignment	Negative (Gate fee) or zero feedstock cost	Fulcrum Sierra plant in commissioning in the US Multiple commercial scale plants planned/under development	Direct gasoline blending is not permitted due to low octane value. The additional isomerisation & catalytic reforming required for naphtha blending are expected to be increasingly adopted to improve FT process economics with future higher C prices
	E-fuel: RWGS+FT	5/6	Assuming renewable electricity	Electricity cost and renewability of source very important.	Pilot/demo scale – unlikely to be widely available in 2030	Direct gasoline blending is not permitted due to low octane value. The additional isomerisation & catalytic reforming required for naphtha blending are expected to be increasingly adopted to improve FT process economics with future higher C prices
	E-fuel: Methanol synthesis + MTJ	5			Pilot/demo scale – unlikely to be widely available in 2030	Oligomerization intermediate process necessary to upgrade naphtha's olefins & improve yield of alcohol-to-jet process Uncertainty on maximum % blending, which depends on catalyst
	E-fuel: pRWGS + syngas fermentation + ETJ	5				

Figure 37. Drop-In Pathways Initially Considered



Fuel	Liquid or gaseous	TRL[1]	Price impact[2]	GHG reduction potential Tank-to-wheel	GHG reduction potential Well-to-wheel	Possible short-term materiality[3]
Ethanol (>E30)[4]	Liquid	High	Low	Small (still fossil)	High	High
Methanol (>M21)[4]	Liquid	High	Low	Small (still fossil)	High	Medium
Hydrogen	Liquid	Low	High	High	High	Low
Hydrogen	Gaseous	Medium	High	High	High	Low to medium
Methane	Liquid	High	Medium to high	Medium	High	Low to medium
Methane	Gaseous	High	Low	Medium	High	High

Figure 38. Non Drop-In Pathways Initially Considered

APPENDIX B VEHICLE ARCHETYPES AND EFFICIENCIES

Introduction

This report describes the sources and derivation for on road vehicle population and activity information, and associated adjustments were used for the AVL fleet modeling. The modelling for the new registrations and for the fleet was done based on available versions of MOVES model reports[25] and EPA Automotive Trends Report data[26,27].

It is important to note that uncertainties and variability in the default data contribute to the uncertainty in the resulting emission estimates. Therefore, the fleet model data was aligned with MOVES fleet model data for the year 2020 as a starting point.

For the outlook into the years after 2020 until 2030 production, forecast data from IHS[28] was used as a supplement to predict the baseline model for vehicles archetypes and fuel types of new registration and the fleet.

Regulatory Classes

Vehicle groups included in the modeling:

- LDV – Light-Duty Vehicles (“Pass Cars”): Consisting of passenger cars and small SUVs
- LDT – Light-Duty Trucks (“Trucks”): Large SUVs and pick-up trucks (vans are shown for reference but are not used in the analysis). LDT was further defined for this exercise to be those that are Class 2a (GVWR of 6,001-8,500 lbs.) using the EPA regulatory distinction between light-duty (LD) and heavy-duty (HD) as a benchmark.

Fuel Types (Propulsion Types)

The AVL Fleet model considers the following fuel types (propulsion types) for the vehicles:

- Gasoline (includes conventional, Stop/Start, Mild Hybrid, CNG, LNG)
- FFV Flexible Fuel Vehicles (includes vehicles that can run on either gasoline or E85/E100 where E85 - fuels contain 70-85 percent ethanol by volume. In the AVL fleet model the fuel type refers to the capability of the vehicle rather than the fuel in the tank.
- Diesel (includes conventional, Stop/Start, Mild Hybrid)
- Gasoline Hybrid – HEV
- Plug-In Hybrid – PHEV (Plug-in Hybrid Gasoline & Diesel)
- Battery electric vehicle – BEV
- Fuel Cell Electric Vehicle – FCV

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[25] Population and Activity of Onroad Vehicles in MOVES3 (EPA-420-20-023)

[26] The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, Executive Summary (EPA-420-S-21-002, November 2021)

[27] 2019 Automotive Trends Report Appendix Tables (EPA-420-R-20-006

[28] IHS Automotive Light Vehicle Powertrain Forecast; forecast release: Sep. 2021 (AVL dataset)

VMT – Vehicle Miles Traveled by Calendar Year & Vehicle Type

The AVL Fleet Model used VMT by vehicle type based on MOVES model[29]. The MOVES model data was available through 2020; to estimate annual mileage accumulation for future years, historical trends of annual VMT by vehicle age were applied (e.g., a 10-year old vehicle in 2030 would travel the same VMT as a 10-year old vehicle in 2020.

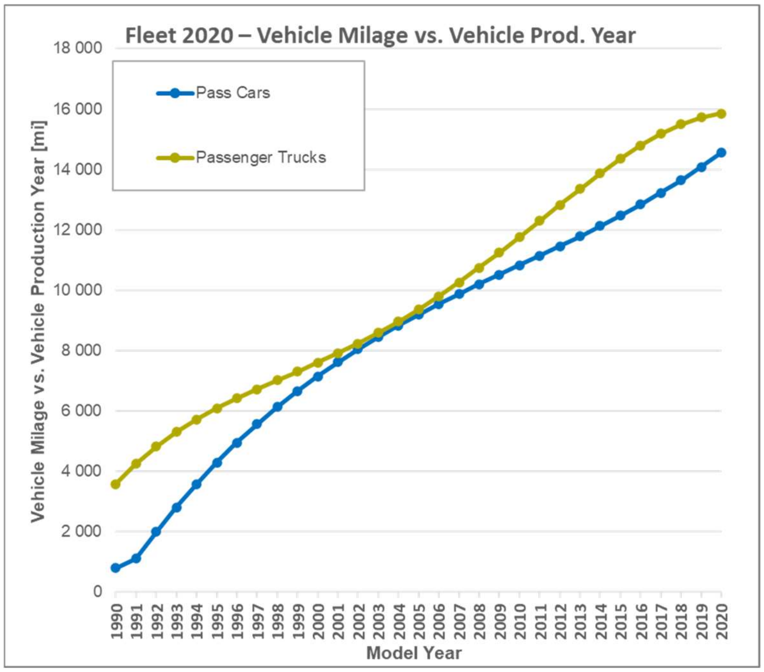

Figure 39. VMT by Vehicle Class

Table 19. VMT by Vehicle Type and Age

Vehicle Age (Years)	Passenger Cars	Trucks
32		2,799
31	800	3,585
30	1,120	4,252
29	2,000	4,818
28	2,819	5,302
27	3,581	5,720
26	4,290	6,088
25	4,950	6,419
24	5,562	6,725
23	6,132	7,019
22	6,662	7,309
21	7,155	7,604
20	7,616	7,912

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[29] Population and Activity of Onroad Vehicles in MOVES3 (EPA-420-20-023)

19	8,046	8,239
18	8,451	8,588
17	8,832	8,963
16	9,194	9,365
15	9,540	9,796
14	9,872	10,254
13	10,196	10,737
12	10,513	11,242
11	10,827	11,763
10	11,142	12,295
9	11,461	12,829
8	11,787	13,357
7	12,124	13,868
6	12,474	14,352
5	12,843	14,794
4	13,232	15,181
3	13,645	15,497
2	14,085	15,724
1	14,557	15,846

Vehicle Population by Calendar Year and Vehicle Type

Survival rates (e.g., how long a vehicle remains in the overall fleet) were incorporated into the AVL Fleet model. The Survival rates were established using EPA’s MOVES model and data available from the Bureau of Transportation Statistics[30,31].

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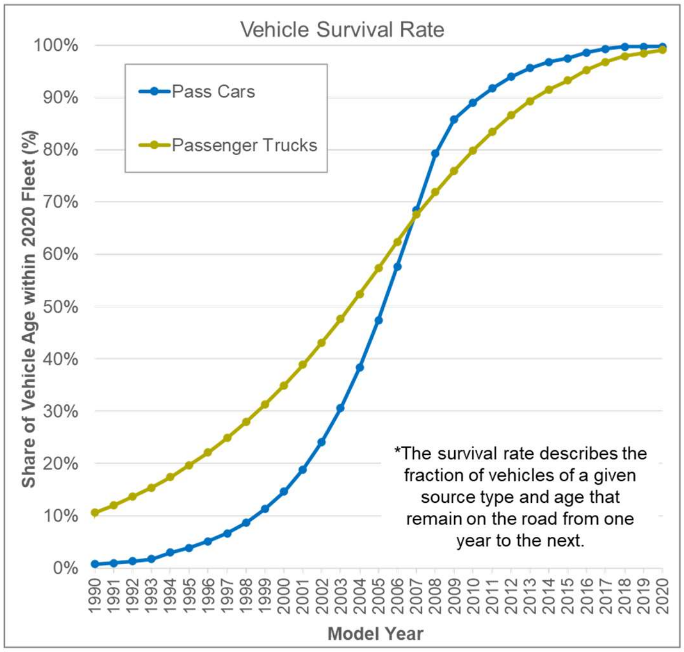
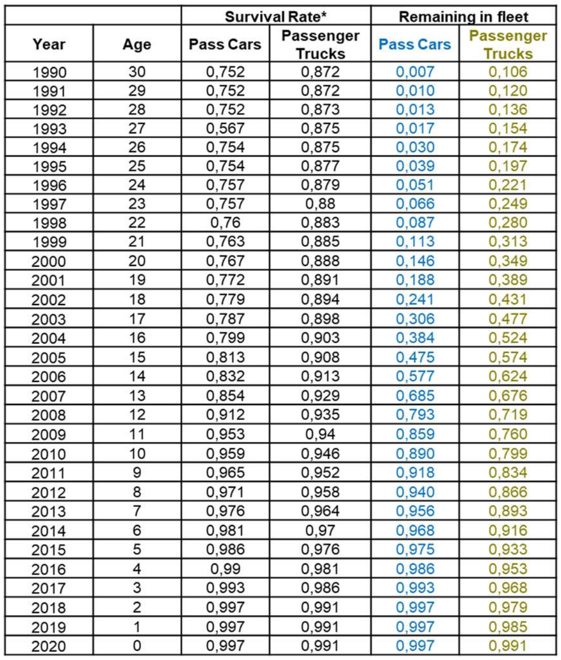
[30] Population and Activity of Onroad Vehicles in MOVES3 (EPA-420-20-023)

[31] https://www.bts.gov/content/average-age-automobiles-and-trucks-operation-united-states (2022-05-23)



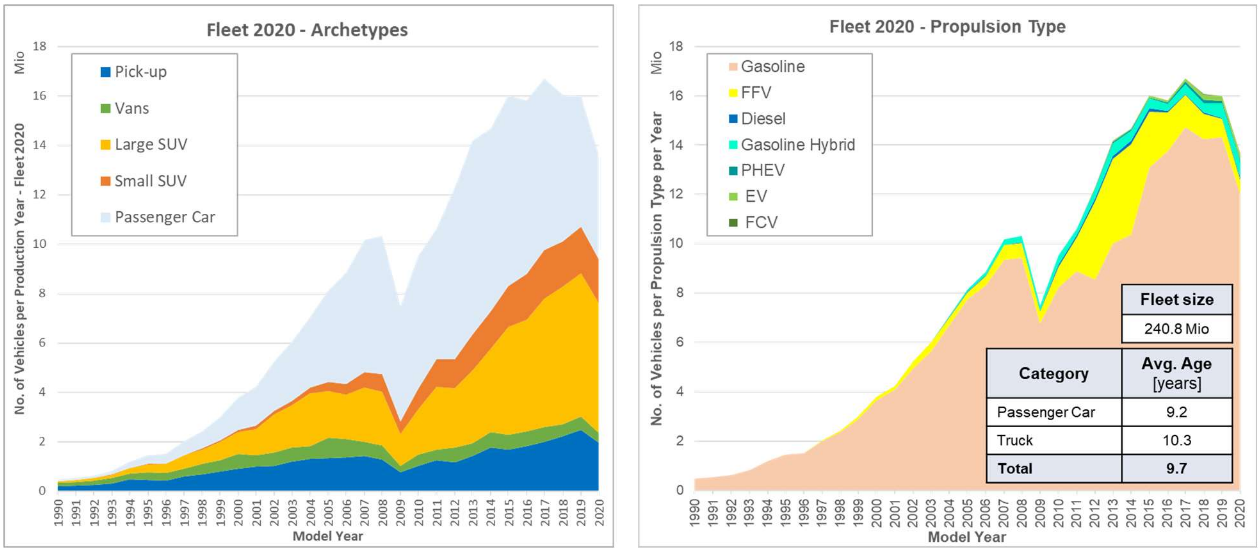
*The survival rate describes the fraction of vehicles of a given source type and age that remain on the road from one year to the next.



		Survival Rate*		Remaining in fleet	
Year	Age	Pass Cars	Passenger Trucks	Pass Cars	Passenger Trucks
1990	30	0,752	0,872	0,007	0,106
1991	29	0,752	0,872	0,010	0,120
1992	28	0,752	0,873	0,013	0,136
1993	27	0,567	0,875	0,017	0,154
1994	26	0,754	0,875	0,030	0,174
1995	25	0,754	0,877	0,039	0,197
1996	24	0,757	0,879	0,051	0,221
1997	23	0,757	0,88	0,066	0,249
1998	22	0,76	0,883	0,087	0,280
1999	21	0,763	0,885	0,113	0,313
2000	20	0,767	0,888	0,146	0,349
2001	19	0,772	0,891	0,188	0,389
2002	18	0,779	0,894	0,241	0,431
2003	17	0,787	0,898	0,306	0,477
2004	16	0,799	0,903	0,384	0,524
2005	15	0,813	0,908	0,475	0,574
2006	14	0,832	0,913	0,577	0,624
2007	13	0,854	0,929	0,685	0,676
2008	12	0,912	0,935	0,793	0,719
2009	11	0,953	0,94	0,859	0,760
2010	10	0,959	0,946	0,890	0,799
2011	9	0,965	0,952	0,918	0,834
2012	8	0,971	0,958	0,940	0,866
2013	7	0,976	0,964	0,956	0,893
2014	6	0,981	0,97	0,968	0,916
2015	5	0,986	0,976	0,975	0,933
2016	4	0,99	0,981	0,986	0,953
2017	3	0,993	0,986	0,993	0,968
2018	2	0,997	0,991	0,997	0,979
2019	1	0,997	0,991	0,997	0,985
2020	0	0,997	0,991	0,997	0,991

Figure 40. Vehicle Survival Rates by Vehicle Type

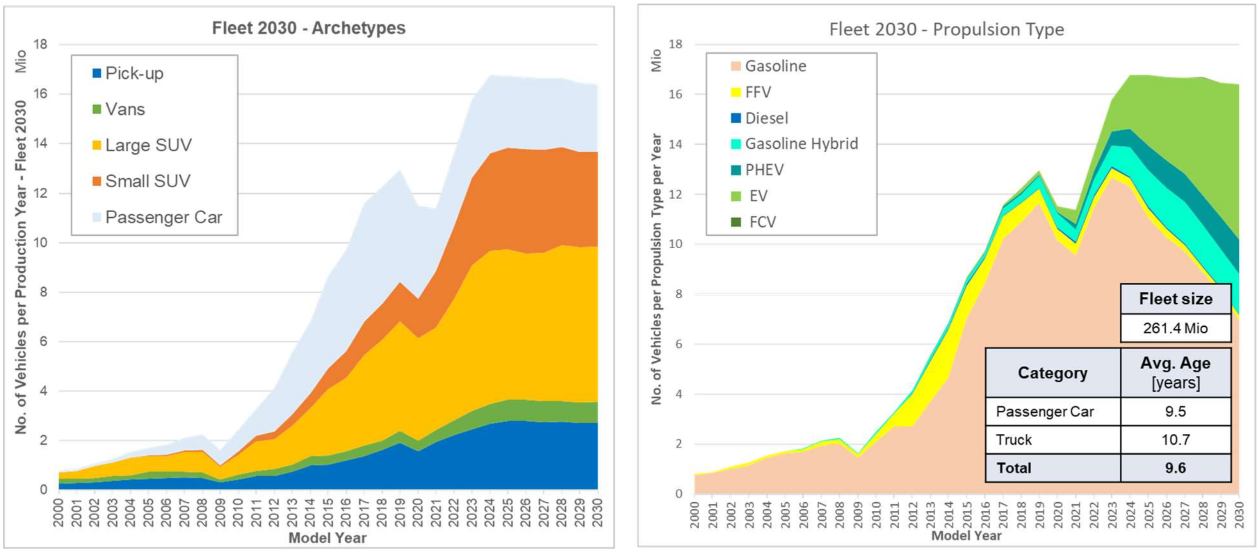
The following Figures show examples of the applied survival rates to calculate the base age distribution of vehicles.



Fleet size
240.8 Mio

Category	Avg. Age [years]
Passenger Car	9.2
Truck	10.3
Total	**9.7**

Figure 41. Vehicle Survival Rates by Archetype (left) and Propulsion Type (right) in 2020



Fleet size
261.4 Mio

Category	Avg. Age [years]
Passenger Car	9.5
Truck	10.7
Total	**9.6**

Figure 42. Vehicle Survival Rates by Archetype (left) and Propulsion Type (right) in 2030

New Vehicle Registration by Fuel Type and Archetype

The following Figures show New Registration (i.e., annual vehicle production) data by Fuel Type and Archetype:

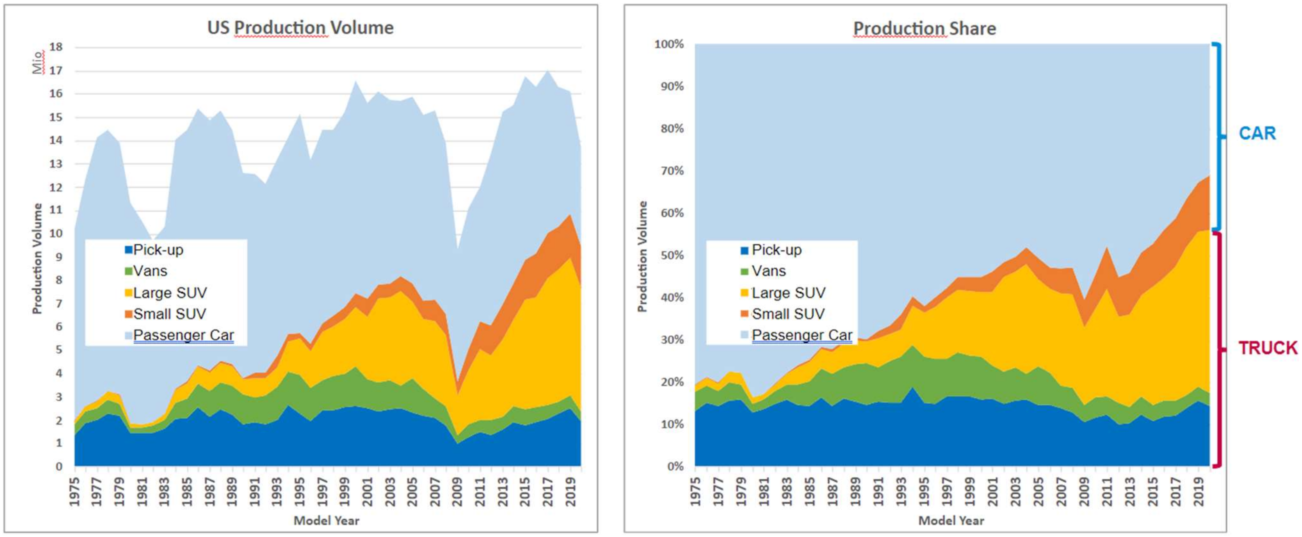


Figure 43. New Vehicle Production Volume and Share by Archetype 1975 to 2020

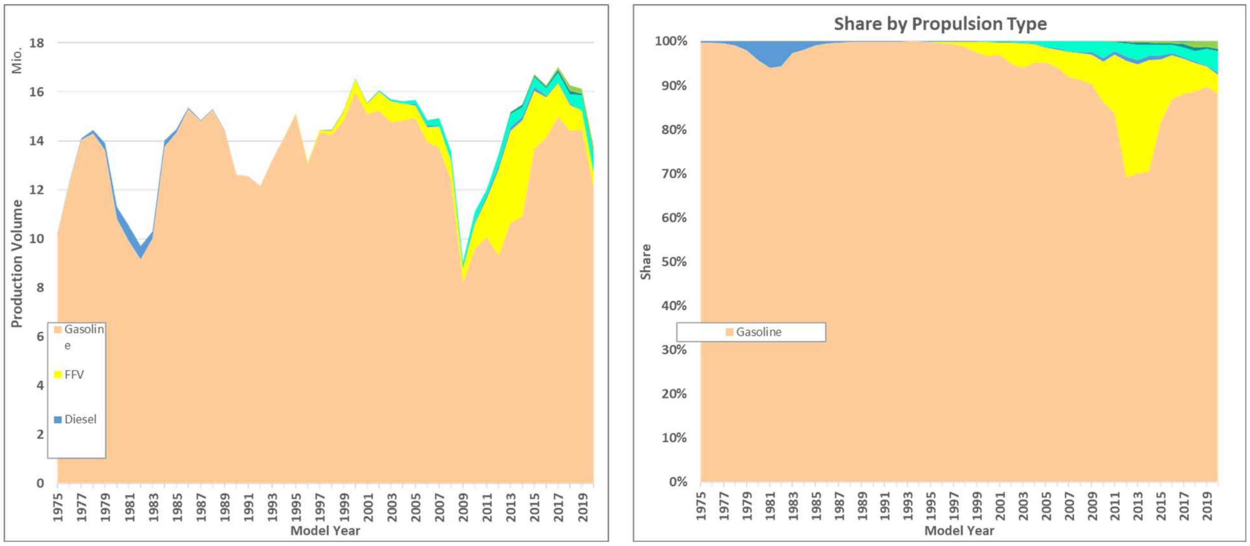
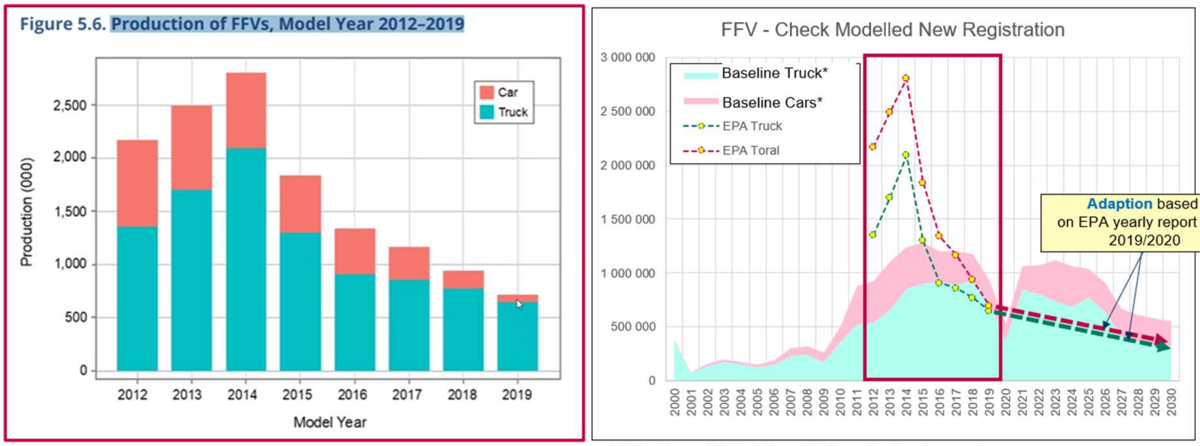


Figure 44. New Vehicle Production by Propulsion Type (Volume and Share) 1975 to 2020

Figure 38 shows how FFV production was adapted from the baseline IHS prediction by applying an initial plausibility check and alignment according the 2020 data available from EPA. As a means to equitably distribute the reduction of FFV in future years, the reductions were equally distributed to other propulsion types using a population share method (see Figures 42-44).



* EPA Moves03 Model and IHS production forecast

Figure 45. FFV Production Data Comparison EPA (MOVES3) vs. IHS FFV Production Forecast

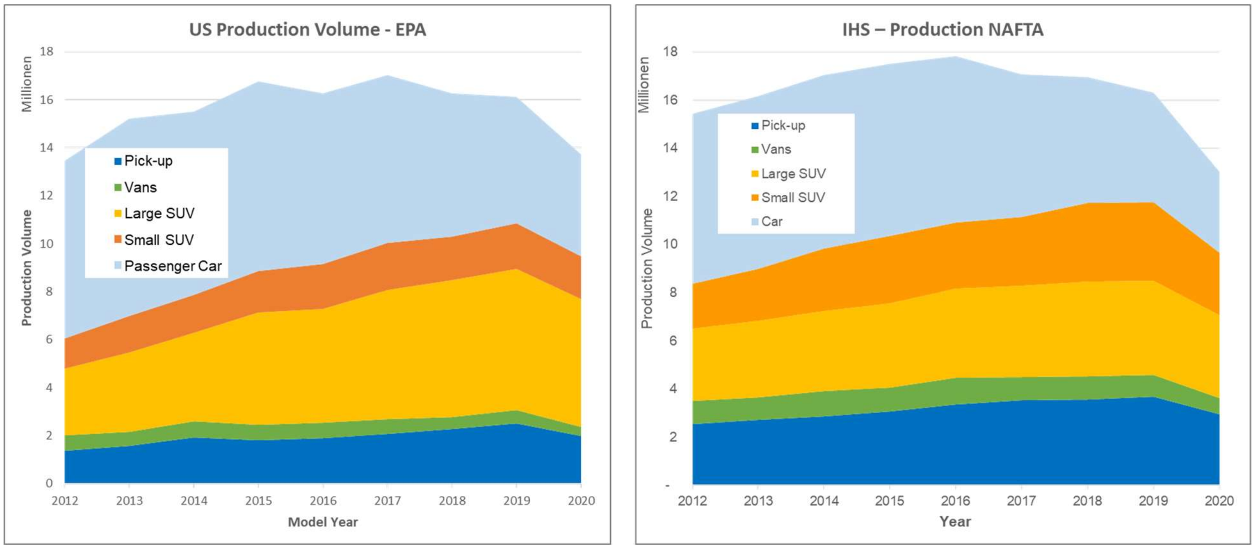


Figure 46. Vehicle Production Volume Estimates by Archetype – EPA (MOVES3) vs. IHS

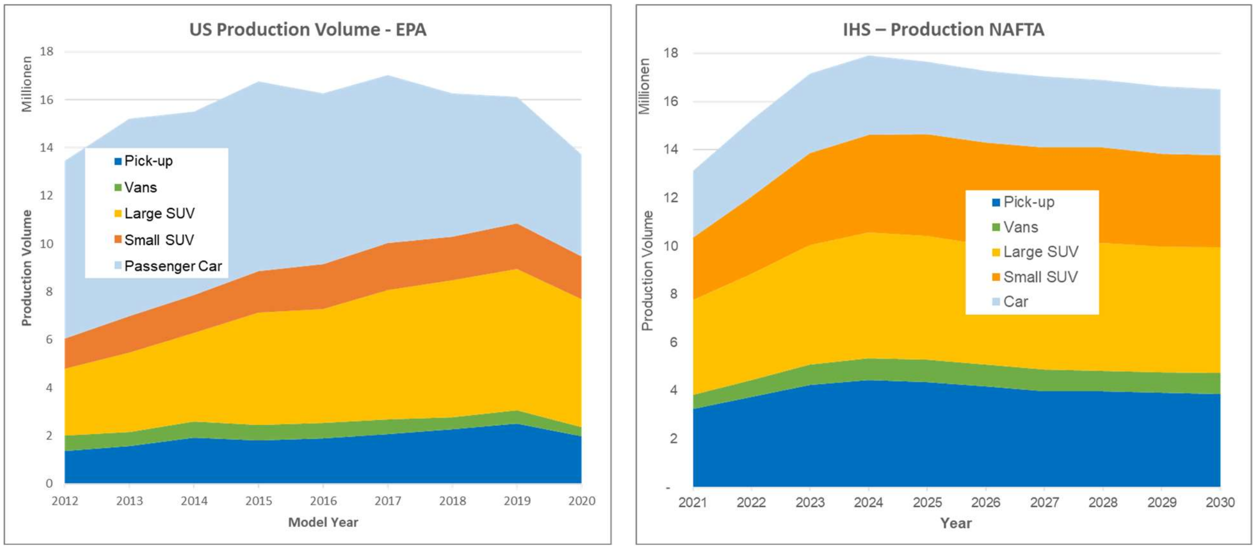
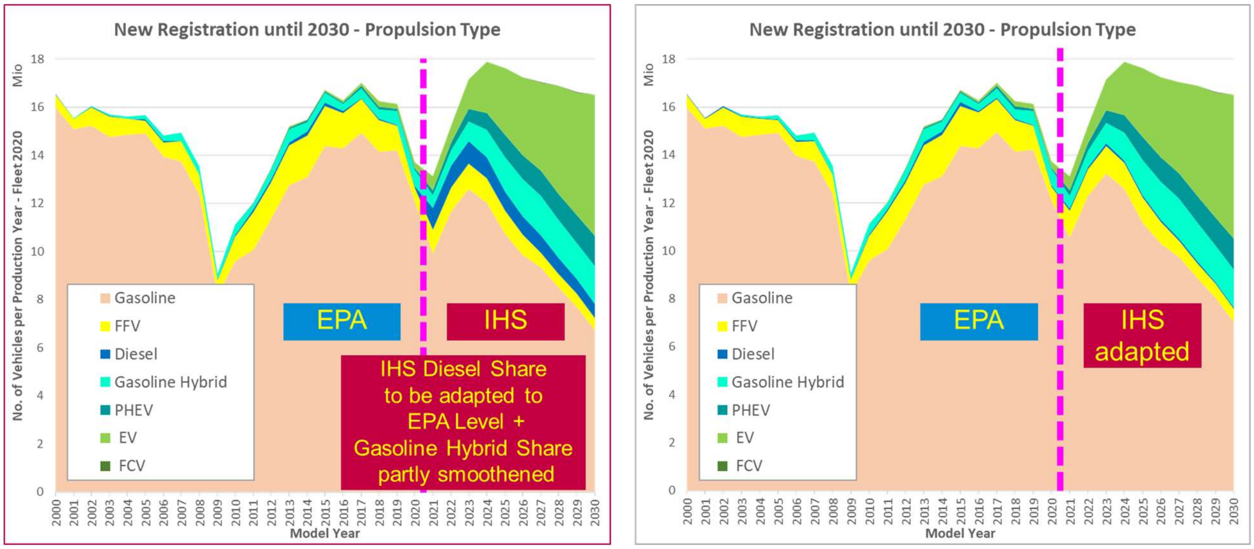


Figure 47. New Vehicle Registrations by Archetype – EPA (MOVES3) vs. IHS

Figure 41 shows how diesel production was adapted from the baseline IHS prediction by applying an initial plausibility check and alignment according to the 2020 data available from EPA. Similar to FFV, the diesel share (increases through 2024 and decreases afterwards) were equally distributed to other propulsion types using a population share method (see Figures 42-44).



IHS Diesel Share to be adapted to EPA Level + Gasoline Hybrid Share partly smoothened

Figure 48. New Registrations Forecast

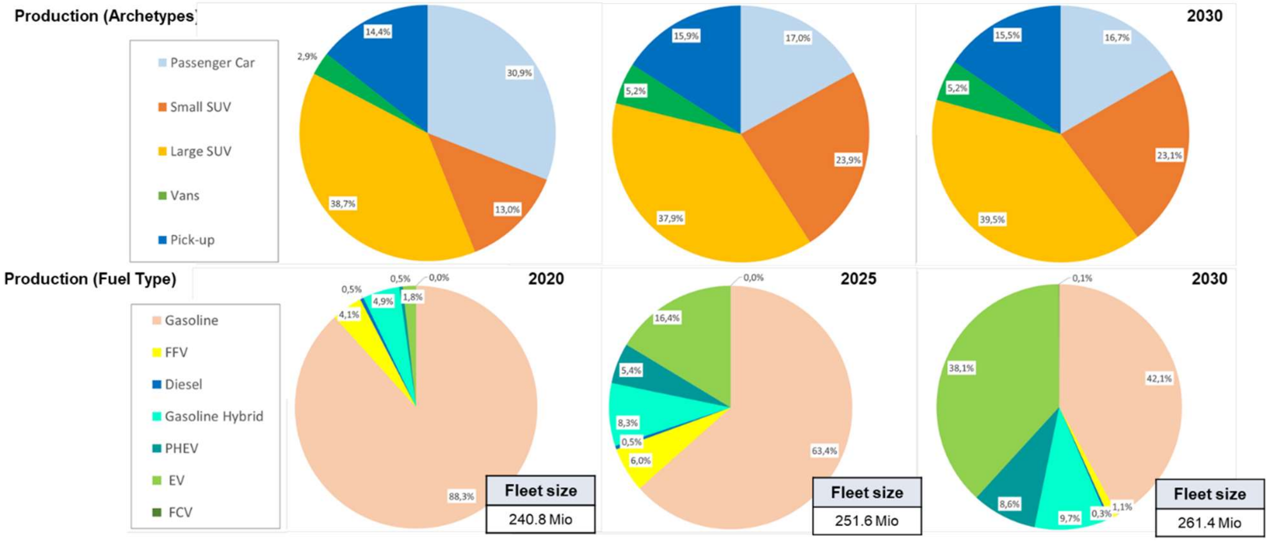


Figure 49. New Vehicle Production by Archetype: 2020/2025/2030

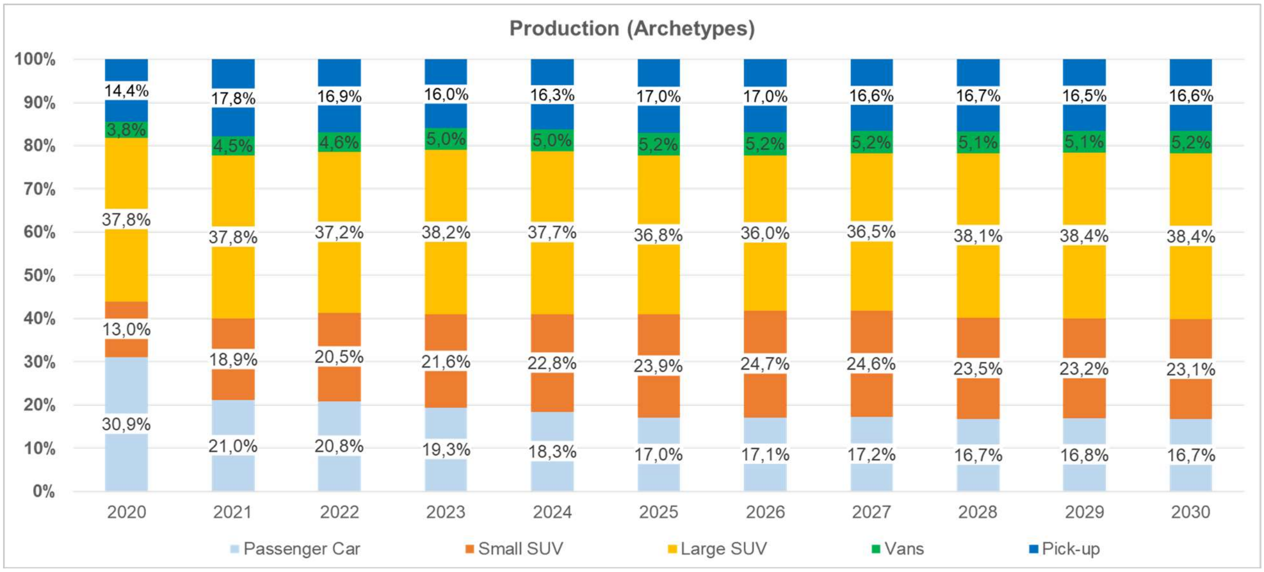


Figure 50. New Vehicle Production by Archetype 2020-2030

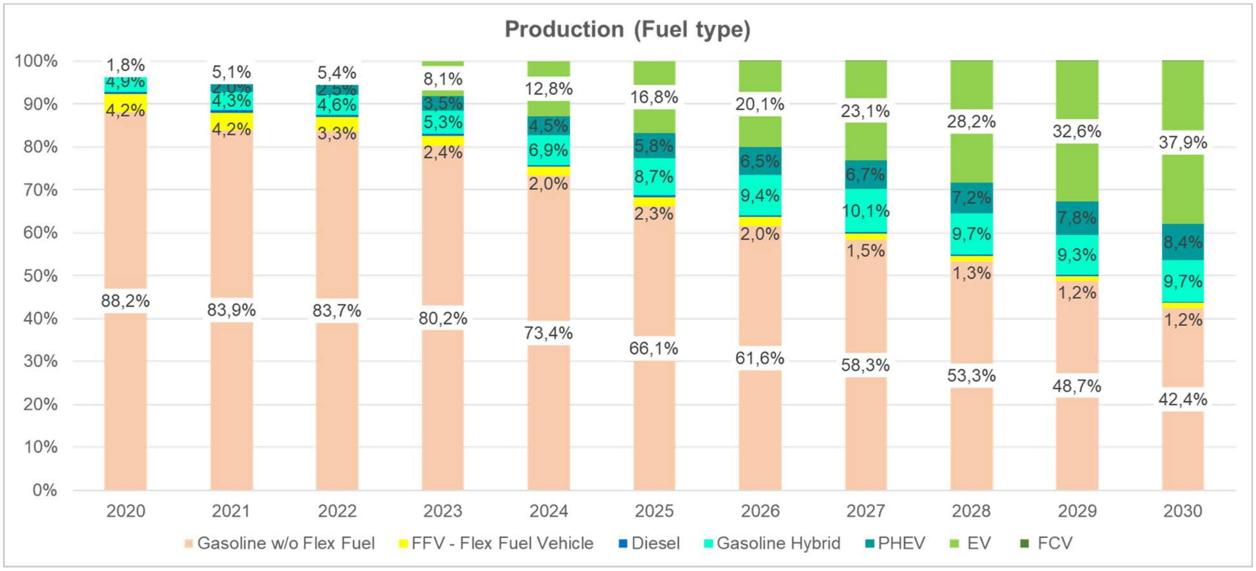
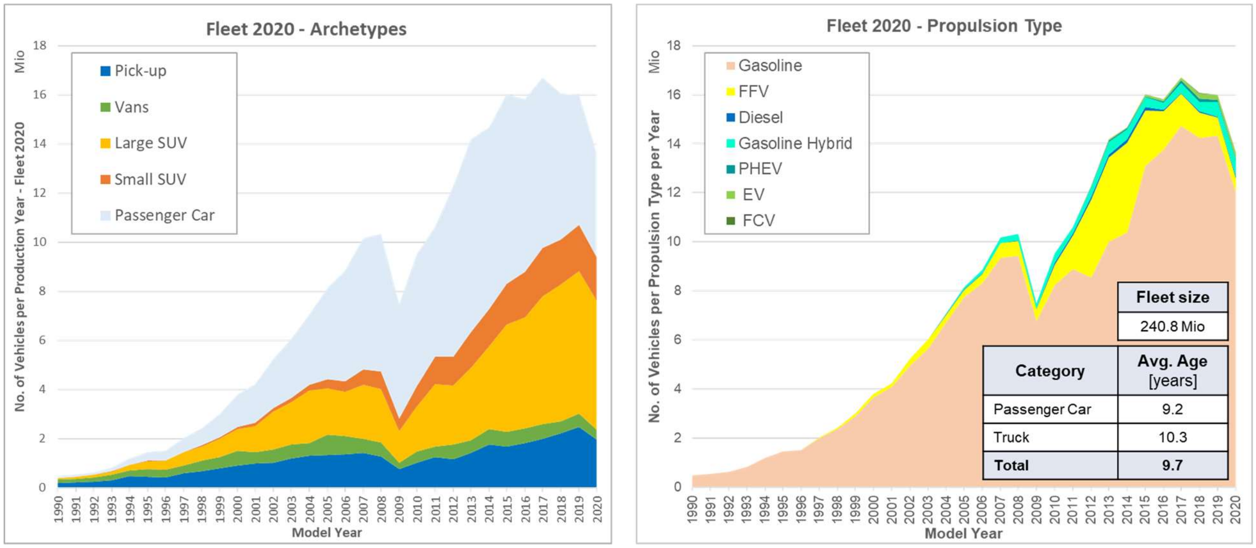


Figure 51. New Vehicle Production by Fuel Type 2020-2030

Vehicle Fleet Data by Fuel Type and Archetype

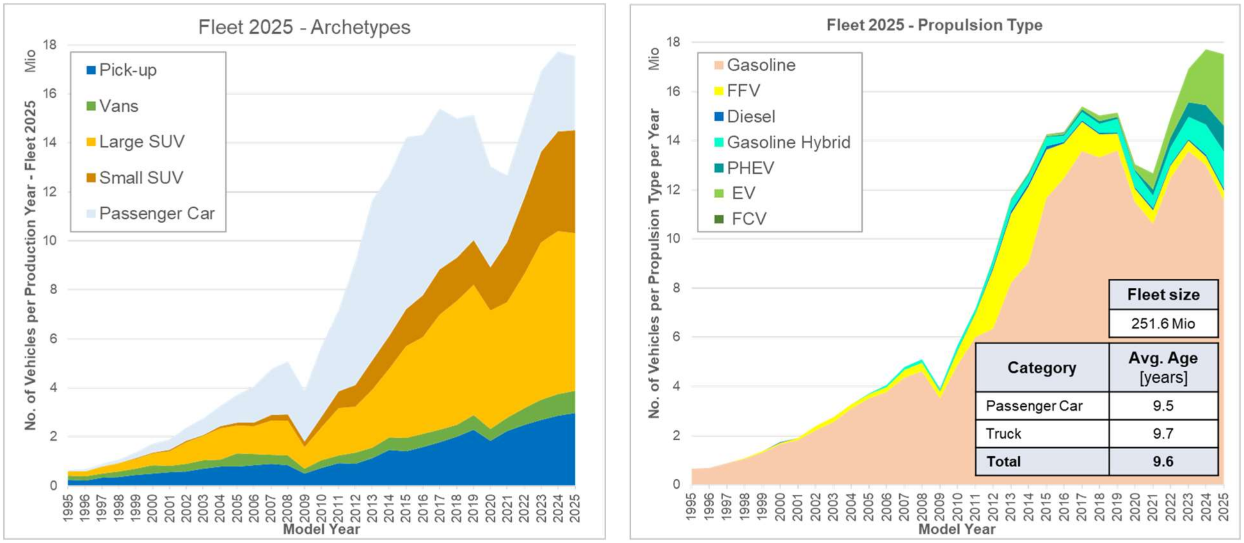
Figures 45-50 demonstrate the number of vehicles in the overall fleet between 2020 and 2030 by vehicle archetype. These were developed using the IHS baseline data, applying survival rate data that was informed by the EPA MOVES model supporting data. Additionally, the AVL fleet model estimated vehicle populations from 1990-2030 and because of the predictive nature of the 2020-2030 values, the 1990-2017 data was benchmarked against the IHS Markit data and EPA MOVES3 model to ensure reasonable consistency between the AVL fleet model and prior studies. Figure 51 demonstrates that the AVL Fleet Model predicts the fleet population consistently with these other historical data sources.



Fleet size
240.8 Mio

Category	Avg. Age [years]
Passenger Car	9.2
Truck	10.3
Total	**9.7**

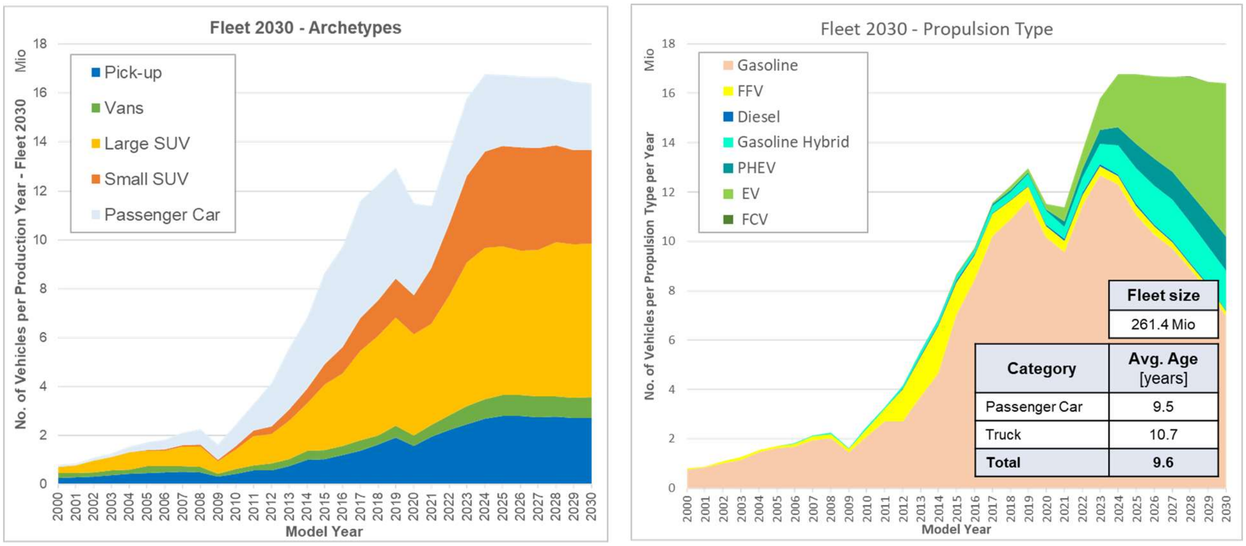
Figure 52. Example Fleet Population by Archetype and Propulsion Type – 2020



Fleet size
251.6 Mio

Category	Avg. Age [years]
Passenger Car	9.5
Truck	9.7
Total	**9.6**

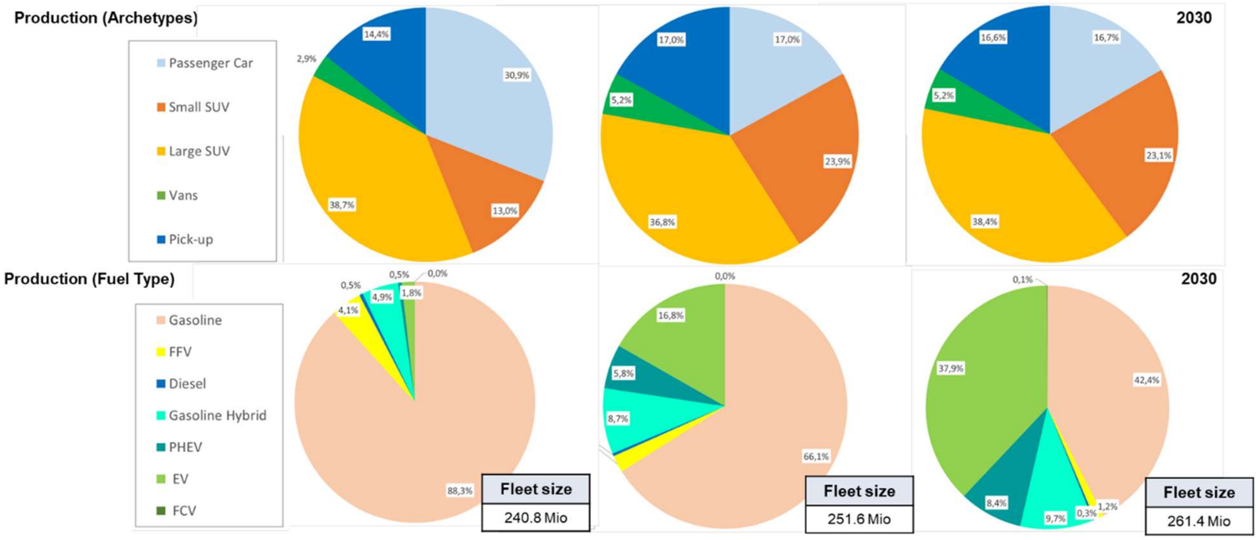
Figure 53. Example Fleet Population by Archetype and Propulsion Type – 2025



Fleet size
261.4 Mio

Category	Avg. Age [years]
Passenger Car	9.5
Truck	10.7
Total	**9.6**

Figure 54. Example Fleet Population by Archetype and Propulsion Type – 2030



Fleet size
240.8 Mio

Fleet size
251.6 Mio

Fleet size
261.4 Mio

Figure 55. Vehicles by Archetype and Fuel Type: 2020/2025/2030

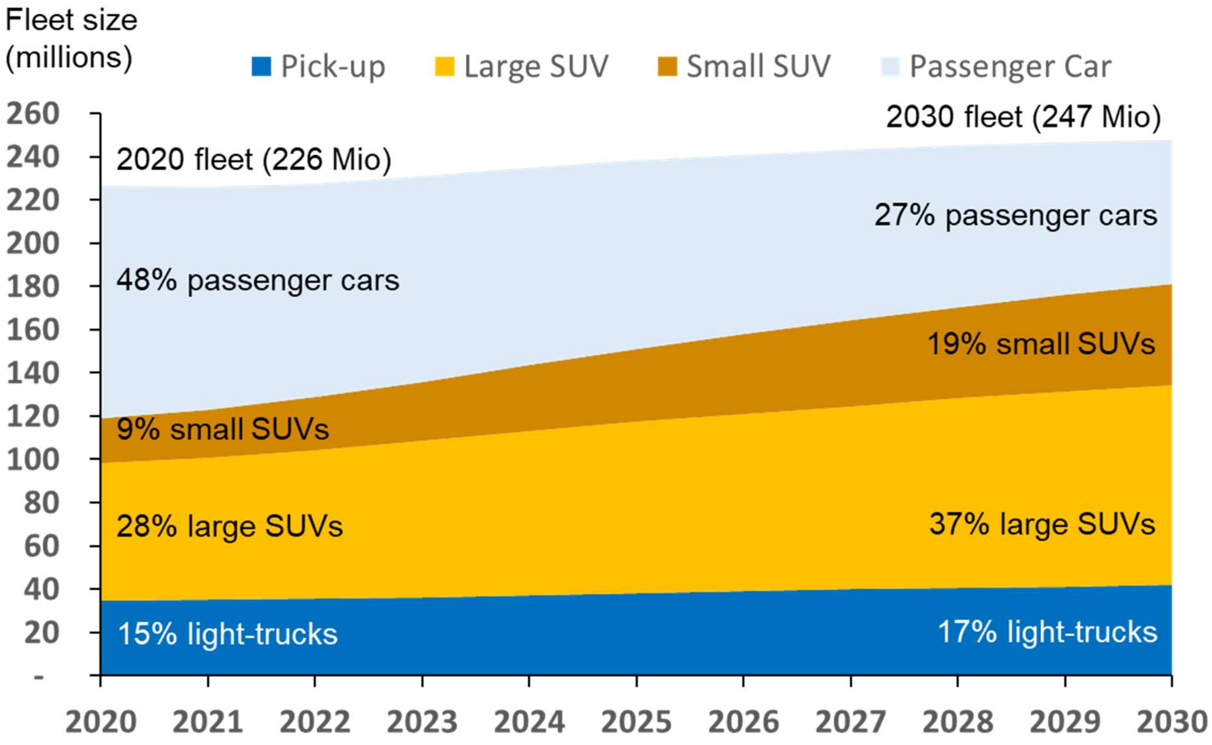


Figure 56. Fleet Composition by Archetype 2020-2030

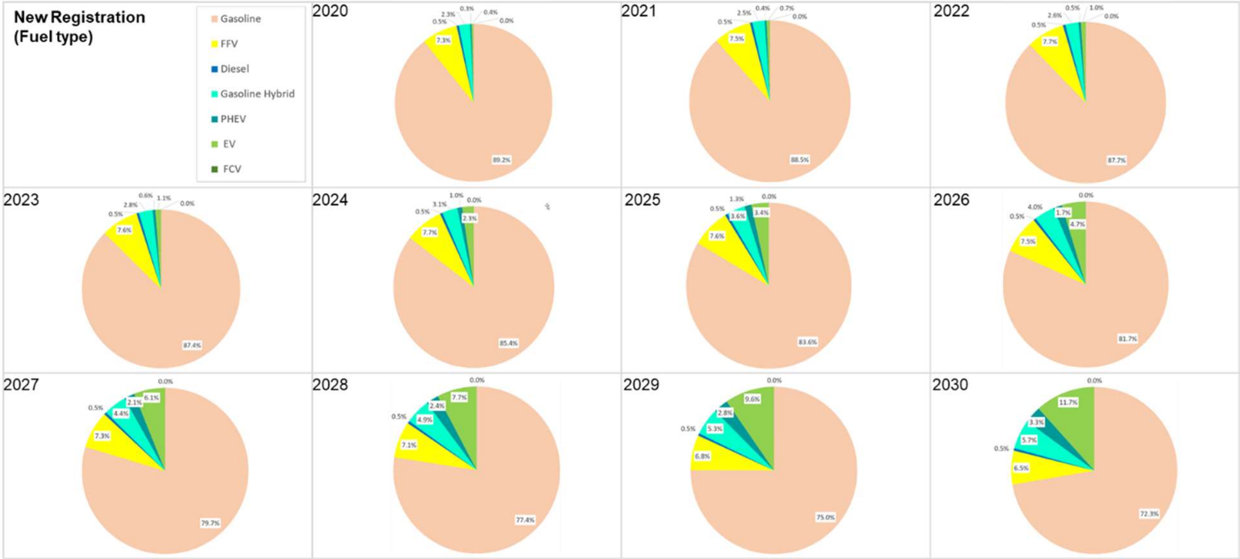
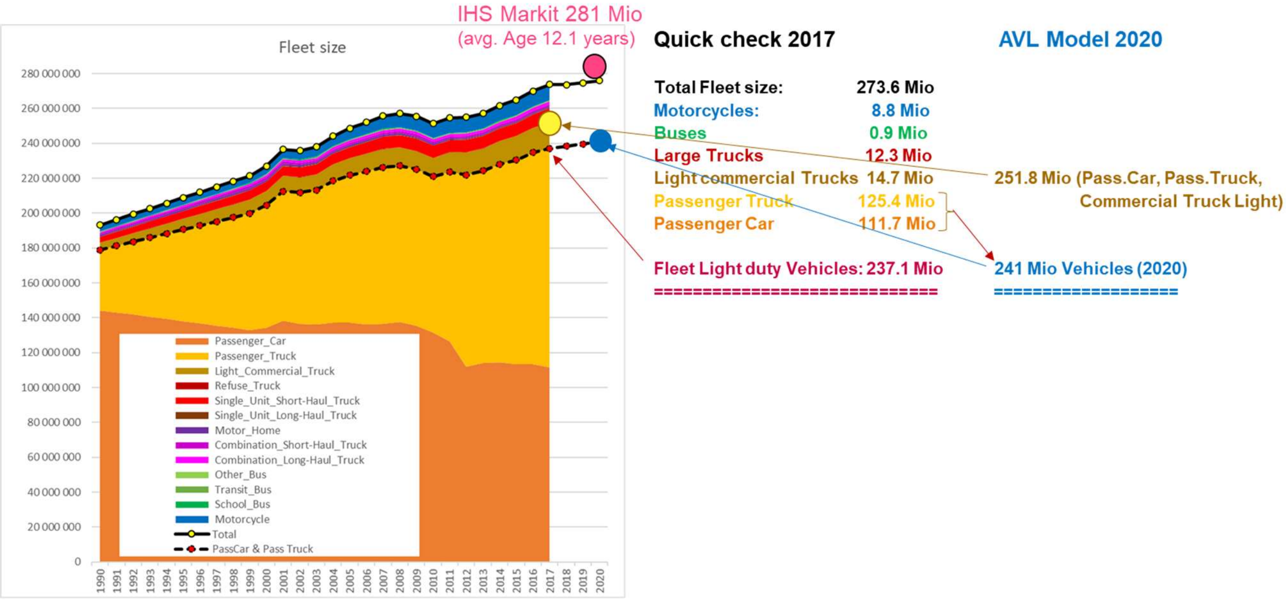


Figure 57. Overview - Year 2020 to 2030 Fleet by Fuel Type



Quick check 2017

AVL Model 2020

Total Fleet size: 273.6 Mio
Motorcycles: 8.8 Mio
Buses 0.9 Mio
Large Trucks 12.3 Mio
Light commercial Trucks 14.7 Mio
Passenger Truck 125.4 Mio
Passenger Car 111.7 Mio

251.8 Mio (Pass.Car, Pass.Truck, Commercial Truck Light)

Fleet Light duty Vehicles: 237.1 Mio
==============================

241 Mio Vehicles (2020)
====================

Figure 58. Data Calibration of the AVL Model vs. EPA MOVES3

Real-World Fuel Economy and CO_2 emissions

The AVL Fleet model was also benchmarked against several additional data sources. For conventional powertrains, both real-world fuel economy and CO_2 emissions were compared to the EPA Automotive Trends Report[32,33]. Data from fueleconomy.gov[34] was used as a comparator for electric vehicles.

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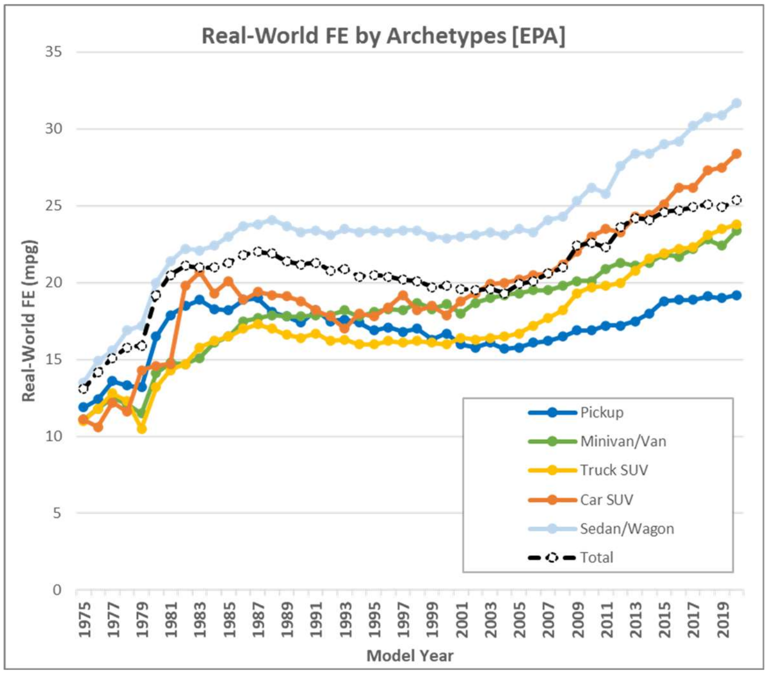
[32] The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, Executive Summary (EPA-420-S-21-002, November 2021)

[33] 2019 Automotive Trends Report Appendix Tables (EPA-420-R-20-006

[34] https://www.fueleconomy.gov/feg/SmartWay.do (2022-06-27)



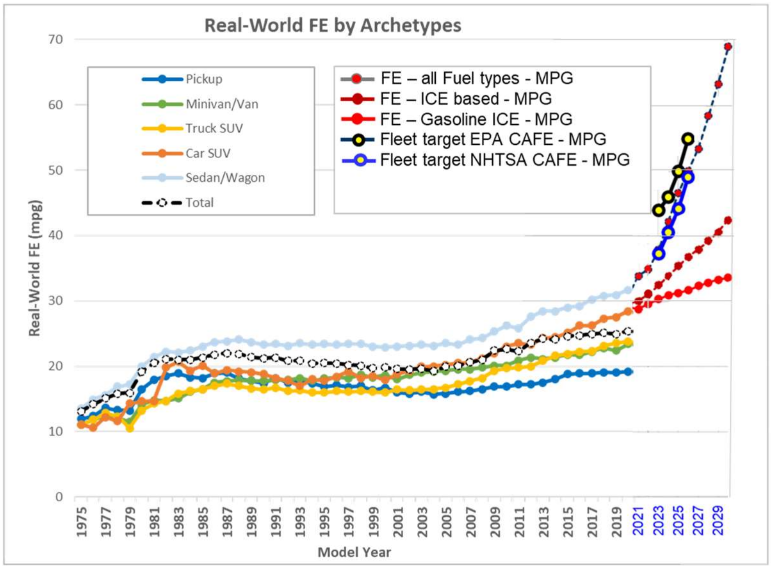


Figure 59. Real-World Fuel Economy of New Vehicles by Archetype 1975-2020 (top) and avg. modelled FE based on EPA and NHSTA CAFE targets

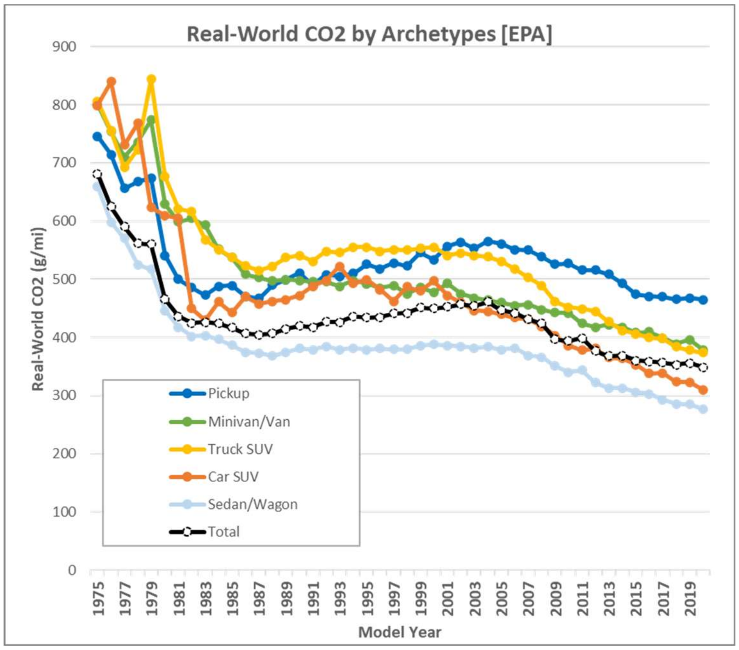
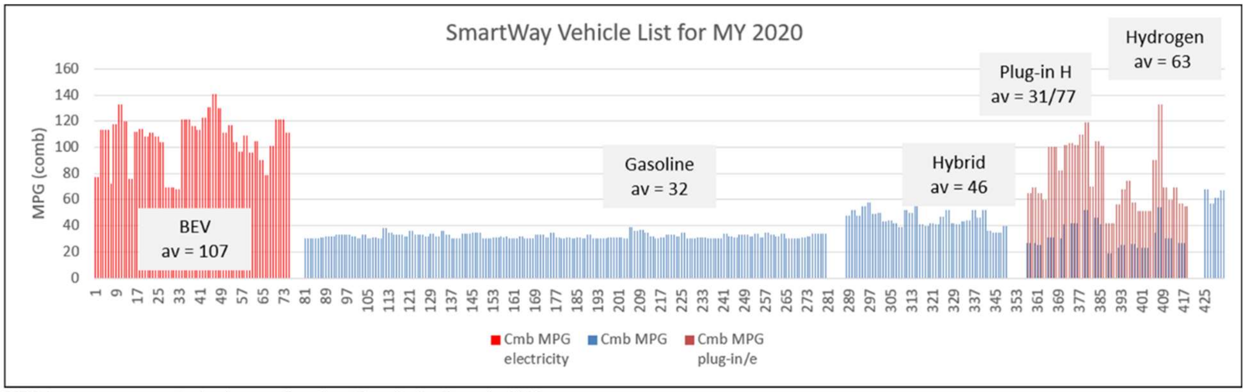


Figure 60. Real-World CO_2 Emissions by Archetype 1975-2020

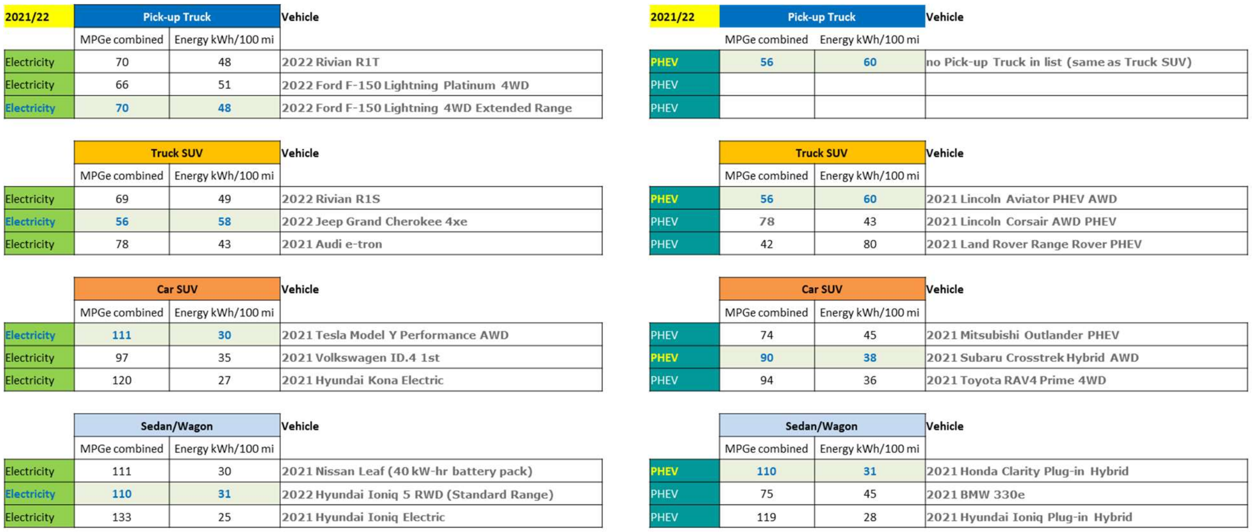


MPG improvement per technology vs. Baseline (Gasoline) – Example 2020:

- FlexFuel -27%
- Diesel +12%
- Gasoline Hybrid +26%
- PHEV +126% (MPGe)
- EV +215% (MPGe)
- FCV +85% (MPGe)

Figure 61. Fuel Economy Improvements by Technology (MY 2020)

Table 62. Fuel Economy Improvement by Technology for Different Archetypes (BEV and PHEV)



2021/22	Pick-up Truck		Vehicle
	MPGe combined	Energy kWh/100 mi	
Electricity	70	48	2022 Rivian R1T
Electricity	66	51	2022 Ford F-150 Lightning Platinum 4WD
Electricity	70	48	2022 Ford F-150 Lightning 4WD Extended Range

	Truck SUV		Vehicle
	MPGe combined	Energy kWh/100 mi	
Electricity	69	49	2022 Rivian R1S
Electricity	56	58	2022 Jeep Grand Cherokee 4xe
Electricity	78	43	2021 Audi e-tron

	Car SUV		Vehicle
	MPGe combined	Energy kWh/100 mi	
Electricity	111	30	2021 Tesla Model Y Performance AWD
Electricity	97	35	2021 Volkswagen ID.4 1st
Electricity	120	27	2021 Hyundai Kona Electric

	Sedan/Wagon		Vehicle
	MPGe combined	Energy kWh/100 mi	
Electricity	111	30	2021 Nissan Leaf (40 kW-hr battery pack)
Electricity	110	31	2022 Hyundai Ioniq 5 RWD (Standard Range)
Electricity	133	25	2021 Hyundai Ioniq Electric

2021/22	Pick-up Truck		Vehicle
	MPGe combined	Energy kWh/100 mi	
PHEV	56	60	no Pick-up Truck in list (same as Truck SUV)
PHEV			
PHEV			

	Truck SUV		Vehicle
	MPGe combined	Energy kWh/100 mi	
PHEV	56	60	2021 Lincoln Aviator PHEV AWD
PHEV	78	43	2021 Lincoln Corsair AWD PHEV
PHEV	42	80	2021 Land Rover Range Rover PHEV

	Car SUV		Vehicle
	MPGe combined	Energy kWh/100 mi	
PHEV	74	45	2021 Mitsubishi Outlander PHEV
PHEV	90	38	2021 Subaru Crosstrek Hybrid AWD
PHEV	94	36	2021 Toyota RAV4 Prime 4WD

	Sedan/Wagon		Vehicle
	MPGe combined	Energy kWh/100 mi	
PHEV	110	31	2021 Honda Clarity Plug-in Hybrid
PHEV	75	45	2021 BMW 330e
PHEV	119	28	2021 Hyundai Ioniq Plug-in Hybrid

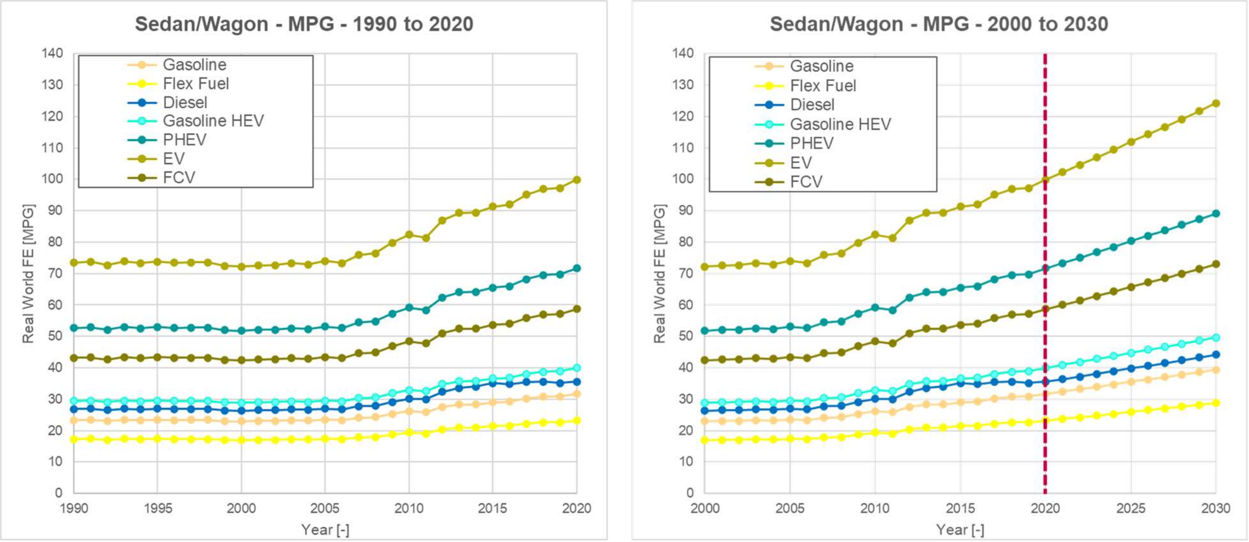


Figure 63. Real-World Fuel Economy by Fuel Type (Sedan/Wagon Subset of Passenger Cars) Used in the AVL Fleet Model

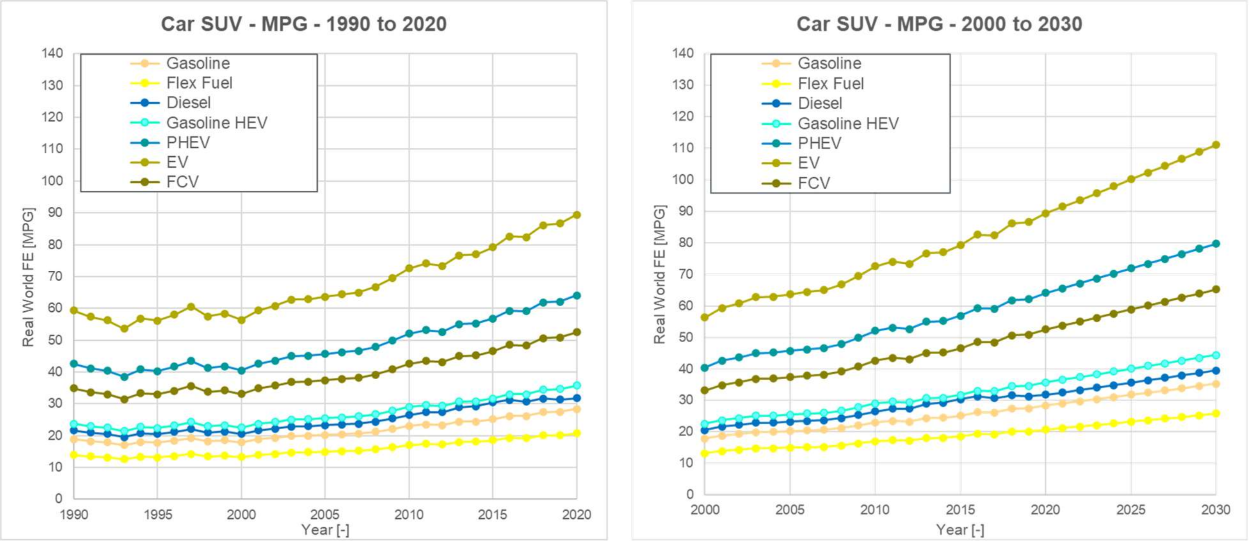


Figure 64. Real-World Fuel Economy by Fuel Type for Passenger Car (Small SUV Subset) Used in the AVL Fleet Model

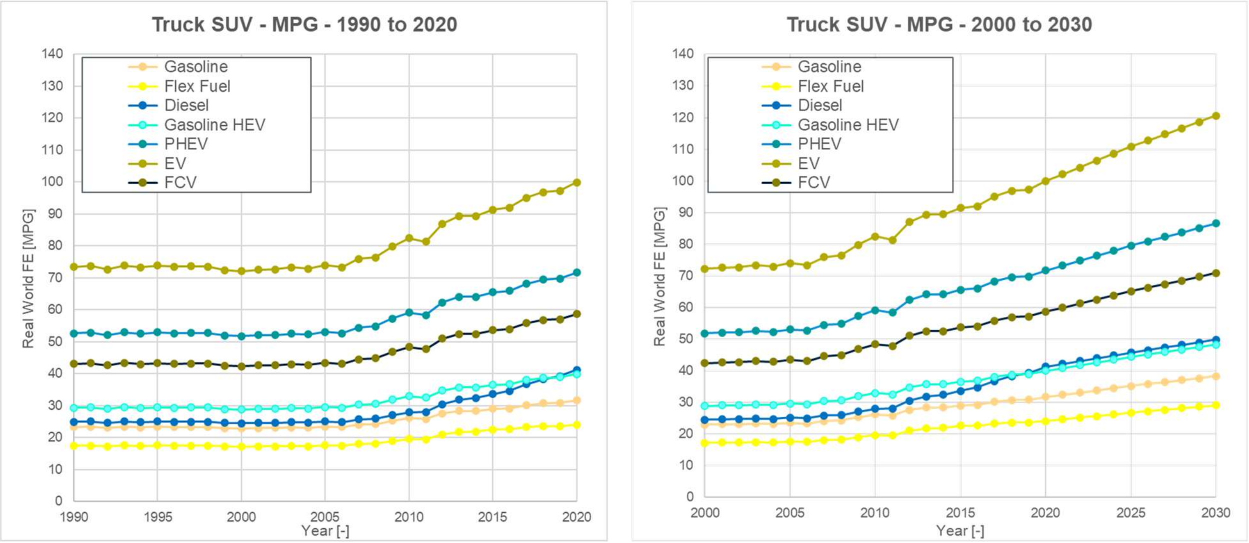


Figure 65. Real-World Fuel Economy by Fuel Type for Large SUVs Used in the AVL Fleet Model

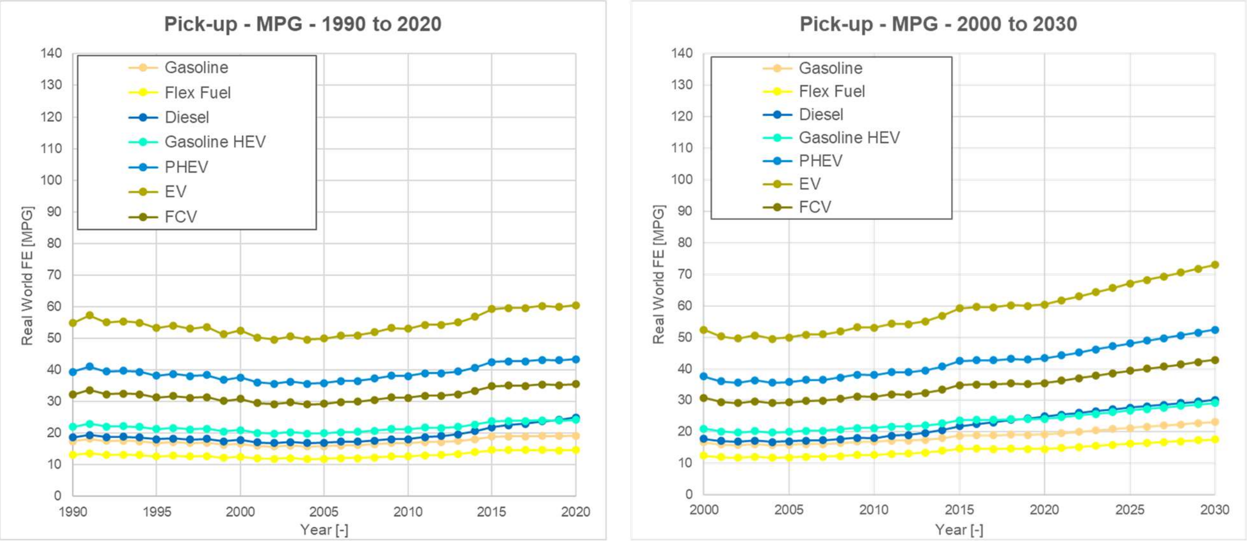
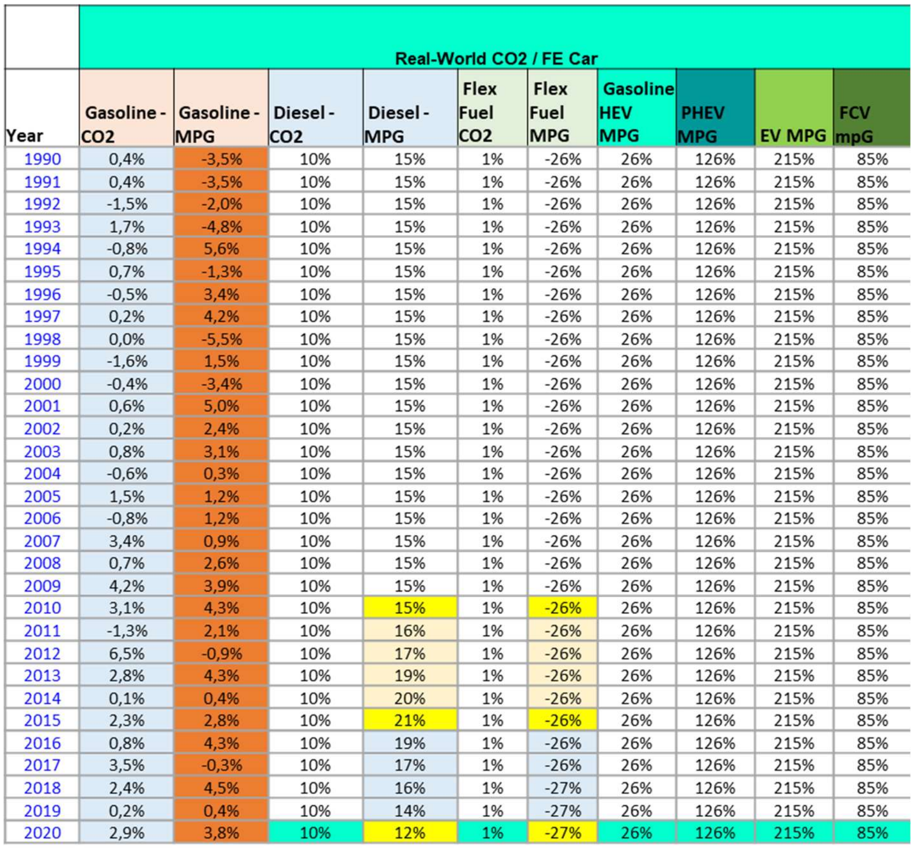
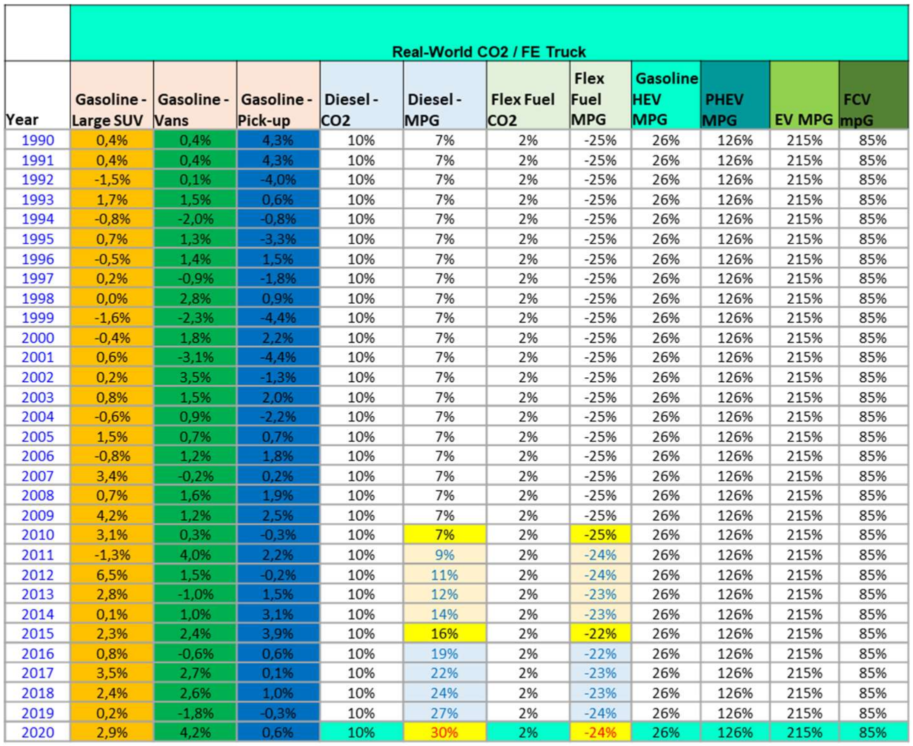


Figure 66. Real-World Fuel Economy by Fuel Type for Pickup Trucks Used in the AVL Fleet Model

Table 20. CO_2 improvement by Technology for fleet simulation – 1990 to 2020



	Real-World CO2 / FE Car									
Year	Gasoline - CO2	Gasoline - MPG	Diesel - CO2	Diesel - MPG	Flex Fuel CO2	Flex Fuel MPG	Gasoline HEV MPG	PHEV MPG	EV MPG	FCV mpG
1990	0,4%	-3,5%	10%	15%	1%	-26%	26%	126%	215%	85%
1991	0,4%	-3,5%	10%	15%	1%	-26%	26%	126%	215%	85%
1992	-1,5%	-2,0%	10%	15%	1%	-26%	26%	126%	215%	85%
1993	1,7%	-4,8%	10%	15%	1%	-26%	26%	126%	215%	85%
1994	-0,8%	5,6%	10%	15%	1%	-26%	26%	126%	215%	85%
1995	0,7%	-1,3%	10%	15%	1%	-26%	26%	126%	215%	85%
1996	-0,5%	3,4%	10%	15%	1%	-26%	26%	126%	215%	85%
1997	0,2%	4,2%	10%	15%	1%	-26%	26%	126%	215%	85%
1998	0,0%	-5,5%	10%	15%	1%	-26%	26%	126%	215%	85%
1999	-1,6%	1,5%	10%	15%	1%	-26%	26%	126%	215%	85%
2000	-0,4%	-3,4%	10%	15%	1%	-26%	26%	126%	215%	85%
2001	0,6%	5,0%	10%	15%	1%	-26%	26%	126%	215%	85%
2002	0,2%	2,4%	10%	15%	1%	-26%	26%	126%	215%	85%
2003	0,8%	3,1%	10%	15%	1%	-26%	26%	126%	215%	85%
2004	-0,6%	0,3%	10%	15%	1%	-26%	26%	126%	215%	85%
2005	1,5%	1,2%	10%	15%	1%	-26%	26%	126%	215%	85%
2006	-0,8%	1,2%	10%	15%	1%	-26%	26%	126%	215%	85%
2007	3,4%	0,9%	10%	15%	1%	-26%	26%	126%	215%	85%
2008	0,7%	2,6%	10%	15%	1%	-26%	26%	126%	215%	85%
2009	4,2%	3,9%	10%	15%	1%	-26%	26%	126%	215%	85%
2010	3,1%	4,3%	10%	15%	1%	-26%	26%	126%	215%	85%
2011	-1,3%	2,1%	10%	16%	1%	-26%	26%	126%	215%	85%
2012	6,5%	-0,9%	10%	17%	1%	-26%	26%	126%	215%	85%
2013	2,8%	4,3%	10%	19%	1%	-26%	26%	126%	215%	85%
2014	0,1%	0,4%	10%	20%	1%	-26%	26%	126%	215%	85%
2015	2,3%	2,8%	10%	21%	1%	-26%	26%	126%	215%	85%
2016	0,8%	4,3%	10%	19%	1%	-26%	26%	126%	215%	85%
2017	3,5%	-0,3%	10%	17%	1%	-26%	26%	126%	215%	85%
2018	2,4%	4,5%	10%	16%	1%	-27%	26%	126%	215%	85%
2019	0,2%	0,4%	10%	14%	1%	-27%	26%	126%	215%	85%
2020	2,9%	3,8%	10%	12%	1%	-27%	26%	126%	215%	85%



	Real-World CO2 / FE Truck										
Year	Gasoline - Large SUV	Gasoline - Vans	Gasoline - Pick-up	Diesel - CO2	Diesel - MPG	Flex Fuel CO2	Flex Fuel MPG	Gasoline HEV MPG	PHEV MPG	EV MPG	FCV mpG
1990	0,4%	0,4%	4,3%	10%	7%	2%	-25%	26%	126%	215%	85%
1991	0,4%	0,4%	4,3%	10%	7%	2%	-25%	26%	126%	215%	85%
1992	-1,5%	0,1%	-4,0%	10%	7%	2%	-25%	26%	126%	215%	85%
1993	1,7%	1,5%	0,6%	10%	7%	2%	-25%	26%	126%	215%	85%
1994	-0,8%	-2,0%	-0,8%	10%	7%	2%	-25%	26%	126%	215%	85%
1995	0,7%	1,3%	-3,3%	10%	7%	2%	-25%	26%	126%	215%	85%
1996	-0,5%	1,4%	1,5%	10%	7%	2%	-25%	26%	126%	215%	85%
1997	0,2%	-0,9%	-1,8%	10%	7%	2%	-25%	26%	126%	215%	85%
1998	0,0%	2,8%	0,9%	10%	7%	2%	-25%	26%	126%	215%	85%
1999	-1,6%	-2,3%	-4,4%	10%	7%	2%	-25%	26%	126%	215%	85%
2000	-0,4%	1,8%	2,2%	10%	7%	2%	-25%	26%	126%	215%	85%
2001	0,6%	-3,1%	-4,4%	10%	7%	2%	-25%	26%	126%	215%	85%
2002	0,2%	3,5%	-1,3%	10%	7%	2%	-25%	26%	126%	215%	85%
2003	0,8%	1,5%	2,0%	10%	7%	2%	-25%	26%	126%	215%	85%
2004	-0,6%	0,9%	-2,2%	10%	7%	2%	-25%	26%	126%	215%	85%
2005	1,5%	0,7%	0,7%	10%	7%	2%	-25%	26%	126%	215%	85%
2006	-0,8%	1,2%	1,8%	10%	7%	2%	-25%	26%	126%	215%	85%
2007	3,4%	-0,2%	0,2%	10%	7%	2%	-25%	26%	126%	215%	85%
2008	0,7%	1,6%	1,9%	10%	7%	2%	-25%	26%	126%	215%	85%
2009	4,2%	1,2%	2,5%	10%	7%	2%	-25%	26%	126%	215%	85%
2010	3,1%	0,3%	-0,3%	10%	7%	2%	-25%	26%	126%	215%	85%
2011	-1,3%	4,0%	2,2%	10%	9%	2%	-24%	26%	126%	215%	85%
2012	6,5%	1,5%	-0,2%	10%	11%	2%	-24%	26%	126%	215%	85%
2013	2,8%	-1,0%	1,5%	10%	12%	2%	-23%	26%	126%	215%	85%
2014	0,1%	1,0%	3,1%	10%	14%	2%	-23%	26%	126%	215%	85%
2015	2,3%	2,4%	3,9%	10%	16%	2%	-22%	26%	126%	215%	85%
2016	0,8%	-0,6%	0,6%	10%	19%	2%	-22%	26%	126%	215%	85%
2017	3,5%	2,7%	0,1%	10%	22%	2%	-23%	26%	126%	215%	85%
2018	2,4%	2,6%	1,0%	10%	24%	2%	-23%	26%	126%	215%	85%
2019	0,2%	-1,8%	-0,3%	10%	27%	2%	-24%	26%	126%	215%	85%
2020	2,9%	4,2%	0,6%	10%	30%	2%	-24%	26%	126%	215%	85%

Calculation of CO_2 equivalent of CH_4 and N_2O

To determine GHG CO_2e emissions, both CH_4 and N_20 were included. Emissions of these pollutants were estimated based on published data from EPA[35]; however, this data was only available through 2019. As a conservative measure, future emission rates of CH4 and N2O were made equivalent to the 2019 EPA predictions.

Conversion to CO_2e was accomplished using published global warming potential over a 100-year timeframe (GWP_{100}) equivalency factors from the IPCC[36]:

CH4 is 28 times higher than CO2 and

N2O is 265 times higher than CO2.

An example calculation of CO_2e (for a 2020 MY Gasoline Car) is shown below:

CH_4 CO_2e [g/yr] = Emission Factor (g/mile) x CH_4 GWP_{100} Multiplier x VMT

CH_4: 0.0051 g/mile x 28 x 15,845 miles = 2.263 g

N_2O CO_2e [g/yr] = Emission Factor (g/mile) x N_2O GWP_{100} Multiplier x VMT

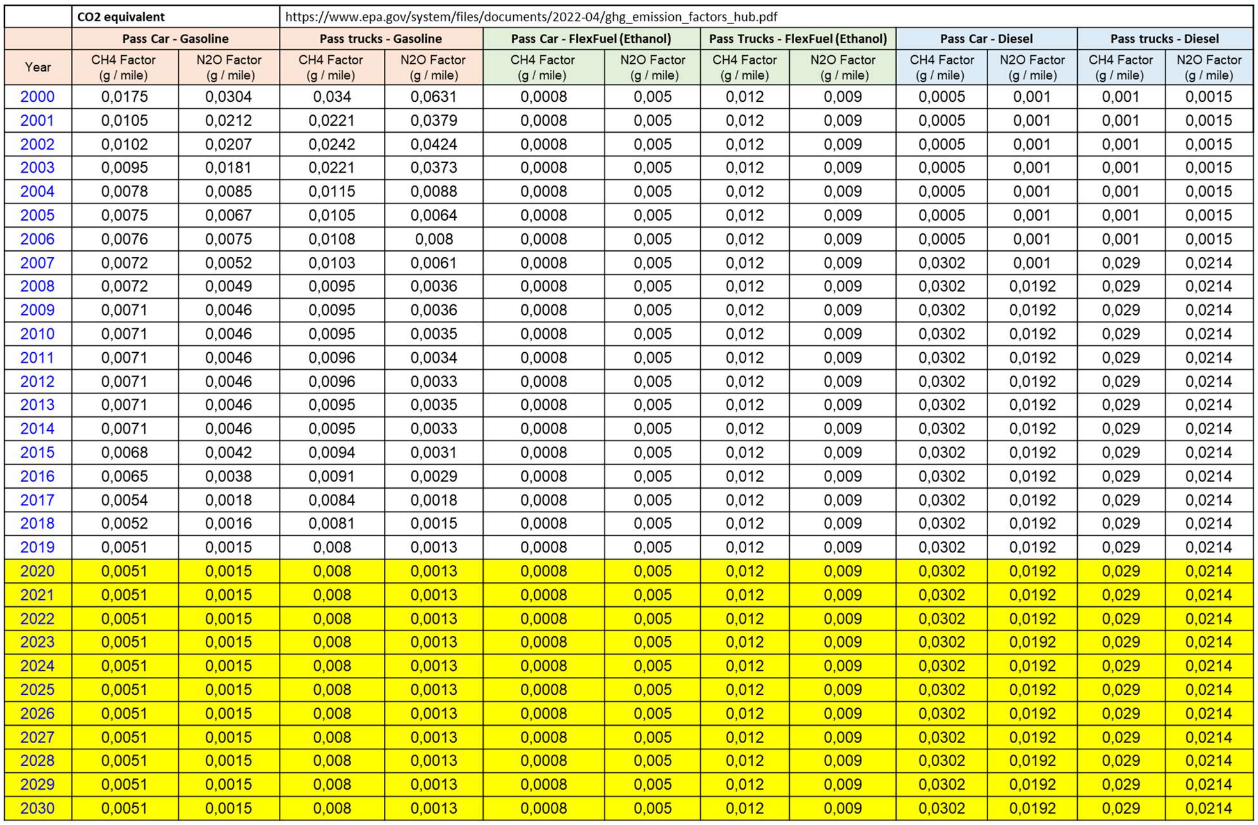
---

[35] https://www.epa.gov/system/files/documents/2022-04/ghg_emission_factors_hub.pdf (2022-06-27)

[36] IPCC Fifth Assessment Report

N_2O: 0.0015 g/mile x 265 x 15,845 miles = 6.298 g

Table 21. CO_2 equivalent for CH_4 and N_2O by Fuel Type and Vehicle Type



	CO2 equivalent		https://www.epa.gov/system/files/documents/2022-04/ghg_emission_factors_hub.pdf									
	Pass Car - Gasoline		**Pass trucks - Gasoline**		**Pass Car - FlexFuel (Ethanol)**		**Pass Trucks - FlexFuel (Ethanol)**		**Pass Car - Diesel**		**Pass trucks - Diesel**	
Year	CH4 Factor (g / mile)	N2O Factor (g / mile)	CH4 Factor (g / mile)	N2O Factor (g / mile)	CH4 Factor (g / mile)	N2O Factor (g / mile)	CH4 Factor (g / mile)	N2O Factor (g / mile)	CH4 Factor (g / mile)	N2O Factor (g / mile)	CH4 Factor (g / mile)	N2O Factor (g / mile)
2000	0,0175	0,0304	0,034	0,0631	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2001	0,0105	0,0212	0,0221	0,0379	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2002	0,0102	0,0207	0,0242	0,0424	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2003	0,0095	0,0181	0,0221	0,0373	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2004	0,0078	0,0085	0,0115	0,0088	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2005	0,0075	0,0067	0,0105	0,0064	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2006	0,0076	0,0075	0,0108	0,008	0,0008	0,005	0,012	0,009	0,0005	0,001	0,001	0,0015
2007	0,0072	0,0052	0,0103	0,0061	0,0008	0,005	0,012	0,009	0,0302	0,001	0,029	0,0214
2008	0,0072	0,0049	0,0095	0,0036	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2009	0,0071	0,0046	0,0095	0,0036	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2010	0,0071	0,0046	0,0095	0,0035	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2011	0,0071	0,0046	0,0096	0,0034	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2012	0,0071	0,0046	0,0096	0,0033	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2013	0,0071	0,0046	0,0095	0,0035	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2014	0,0071	0,0046	0,0095	0,0033	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2015	0,0068	0,0042	0,0094	0,0031	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2016	0,0065	0,0038	0,0091	0,0029	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2017	0,0054	0,0018	0,0084	0,0018	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2018	0,0052	0,0016	0,0081	0,0015	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2019	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2020	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2021	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2022	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2023	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2024	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2025	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2026	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2027	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2028	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2029	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214
2030	0,0051	0,0015	0,008	0,0013	0,0008	0,005	0,012	0,009	0,0302	0,0192	0,029	0,0214

The following Figures show the calculated CO_2 equivalent of the Fleet in 2020 and 2030 and the contribution of single model years (on the left side the CO_2 equivalent related to total Fleet CO_2 and on the right side in comparison to the diesel wedge of the left hand figure – already minor contribution).

CH_4 and N_20 increase the Fleet CO_2 (based on TTW) by approx. 0.3% to 0.5%, depending on fleet year and vehicle category.

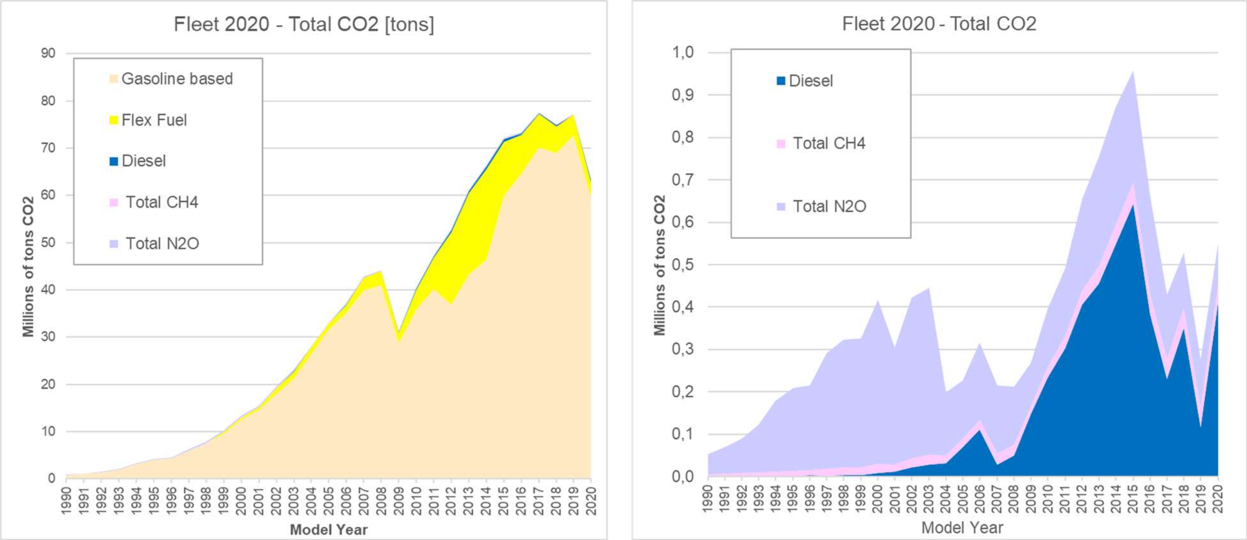


Figure 67. CO$_2$e of CH$_4$ and N$_2$0 – 2020 Fleet Population Example

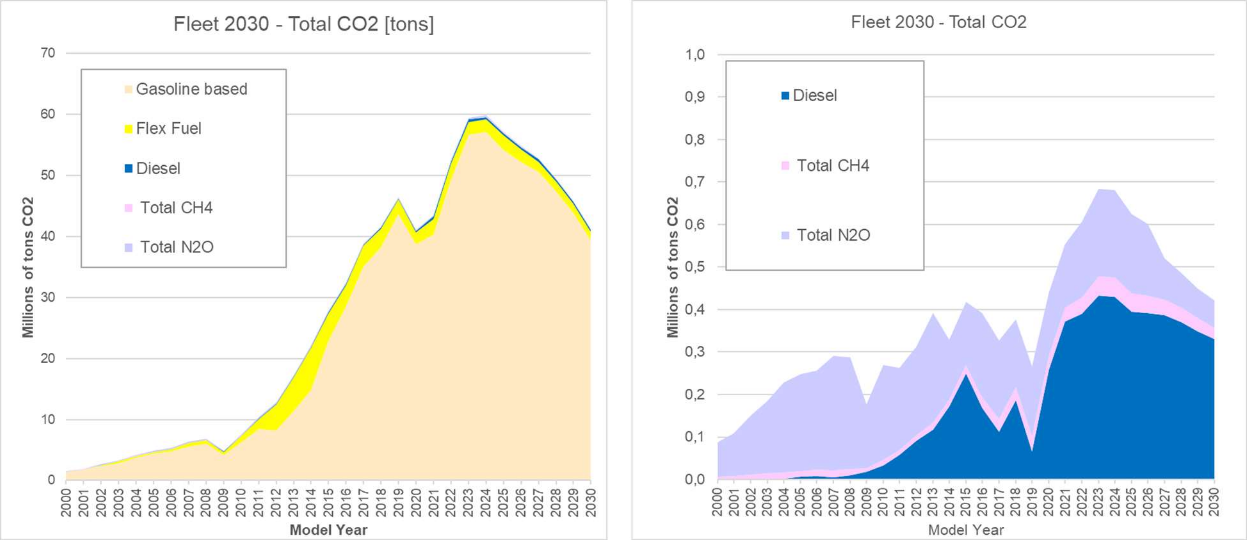


Figure 68. CO2e of CH4 and N20 – 2030 Fleet Population Example

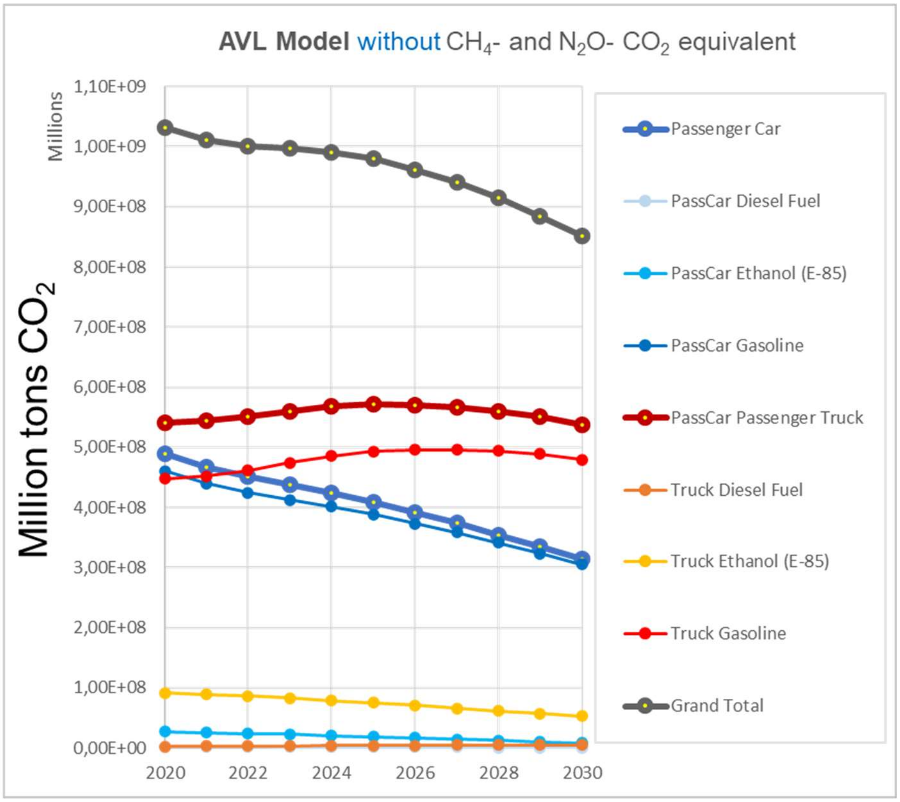


Figure 69. Fleet CO_2e (Not Including CH_4 and N_2O)

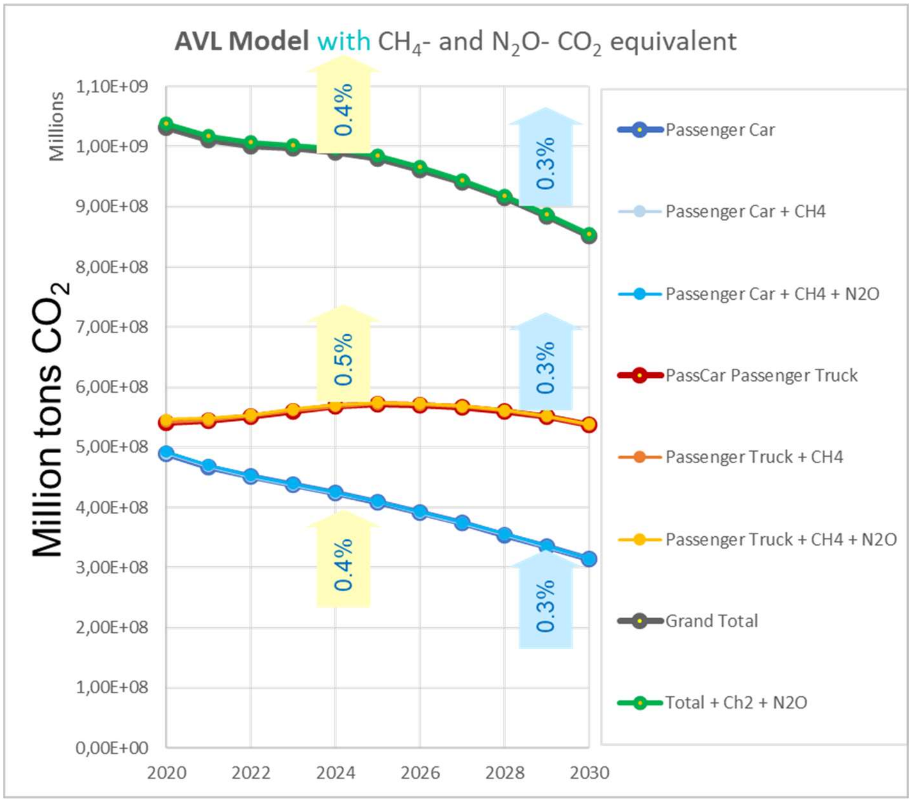


Figure 70. Fleet CO_{2e} (Including CH4 and N2O)

APPENDIX C ALTERNATIVE FUEL SUPPLY

Methodology

The *Alternative Fuels Ramp-up Model* is built upon the current and planned global deployment of plants using the selected pathway technologies. Importantly, the framework of the model does not consider competition between the individual developers or conversion routes, but instead considers how fast each developer and route could expand given demand to do so. The model operates with two distinct growth phases: a ramp-up phase and a growth phase.

The ramp-up phase, or introductory phase, acts as the foundation of the model, and determines near-term growth based on potential new facility build rates. Each known project is added to the model to provide a baseline of current and planned alternative fuel production capacity over time, which is dependent on the starting date of each project, the reported scale of the plant and expected plant lifetime. Developers are assumed to build additional plants over time, corresponding to the stage of technology development (Demonstration, 1st commercial, 2nd commercial, nth commercial), with the rate of capacity growth determined by a range of factors.

Beyond 2030, the model introduces a growth phase, where the growth rate is determined by overall market expansion, rather than individual developer growth. However, this analysis considered only the timeframe up to 2030 and hence this phase was not utilized.

This methodology is followed for all pathways, with the exception of HEFA. The rate at which HVO plants can be built is unlikely to be a limiting factor in the short-to-medium-term, since there are several technology and plant developers already operating at commercial scales, with further plans to expand in response to growing demand. Instead, the main limiting factor will be the availability of advanced feedstocks, such as waste oils and fats. Although novel energy crops such as Camelina and Carinata are being explored, their use at scale, particularly when cultivated on degraded land or as a cover crop, is yet to be proven and subject to high uncertainty. Establishing energy crops on degraded land requires a sustained effort over a period of years, and degraded sites often have alternative uses[37]. Cover crops are traditionally tilled into the soil to provide additional nutrients and organic matter, and to protect the soil from erosion and crusting: the harvesting of cover crops could therefore produce unwanted side-effects, including reducing crop yields and soil quality. Hence, sustainability remains a major challenge, while crop yields in literature can be significantly reduced if sustainable farming practices are followed[38].

As a result, only feedstocks from waste oils were considered in this study. The technical UCO potential in the US is estimated to be approximately 1.2 Mtons per annum[39]. The analysis showed that operating US HVO capacity far exceeds UCO potential at present and is expected to continue to dwarf UCO potential in the future. Hence, the remaining HVO feedstock was assumed to be vegetable oils. HVO supply was projected using an S-curve derived from historic fuel ethanol trends, starting at the current capacity from operational and planned plants, and approaching a plateau by 2030.

Ramp-up phase assumptions

The number of developers is an important factor in determining future deployment of a technology, as each developer is expected to progress their technology to commercial scale and begin initiating new

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[37] IRENA, 2017. Bioenergy from degraded land in Africa. https://www.irena.org/publications/2017/Dec/Bioenergy-from-degraded-land-in-Africa

[38] Matteo, Roberto, et al. "Camelina (Camelina sativa L. Crantz) under low-input management systems in northern Italy: Yields, chemical characterization and environmental sustainability." Italian Journal of Agronomy 15.2 (2020): 132-143.

[39] Greenea, 2021. https://www.greenea.com/wp-content/uploads/2021/01/Greenea-Horizon-2030-Which-investments-will-see-the-light-in-the-biofuel-industry-1.pdf

commercial projects (accounting for failure rates) either under an owner-operator or a licensing model. Projects are only included that have reached pilot scale or beyond: lab-scale facilities, research institutes, and developers without proven technologies at this scale, are excluded. Once these developers and plants are added to the model, future deployment is then projected based on several key factors, which are summarized below:

Technology type

Each pathway was assigned a technology archetype, either chemical, thermochemical, or biological, based on the type of processes involved and equipment required. For each archetype, a different set of assumptions were used regarding project development timelines. In this analysis, G1 and G4 formed the thermochemical group whilst N3 and ND2 formed the chemical group.

Project timelines

The development timeline defines how long it would take from project inception to a fully operational plant. This includes project development & financing (PD), construction (CO), commissioning & ramp-up (CM) phases. For each technology type (biological, thermochemical and chemical) and for each stage of plant scale-up (pilot, demonstration, 1st commercial, 2nd commercial and Nth commercial) an average development timeline is applied, as illustrated in Figure 71: Project timelines for each technology archetype

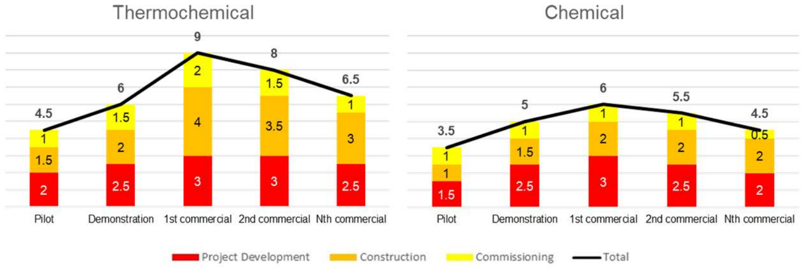

Figure 71: Project timelines for each technology archetype

The project development timelines for each archetype were based on discussions with industrial partners and stakeholders. Pilot and demonstration plants are generally quick to design, and build compared to 1st commercial facilities, where technologies are being rigorously tested at larger scales, proven over an extended period, and where there are additional supply chain complexities. 2nd and subsequent (Nth) commercial plants are assumed to have shorter development timelines, as a result of learning and replication.

Launch point

The launch points define when the next project is most likely to start, assuming that the next project represents the next stage of commercialization for the technology. Launch points are not relevant for operational or planned projects: in these cases, the reported year of construction/operation is input into the model. The launch point for projected projects was assumed to be similar for each technology type, reflecting the fact that investors are likely to require a similar number of years of operational evidence before taking larger investment decisions, independent of the specific technology. However, the launch points vary depending upon the technology stage, as seen in Table 11. There is no launch point for pilot plants, as developers at lab scale are excluded from the model.

Table 22. Launch Point Assumptions at Each Technology Stage

Technology stage	Launch point
Demonstration	PD begins 0.5 years from the point at which the pilot plant is fully operational
1st Commercial	PD begins 2 years from the beginning of the commissioning period of the demonstration plant
2nd Commercial	PD begins 2 years from the beginning of the commissioning period of the 1st commercial plant
Nth Commercial	PD begins 1.5 years after the previous plant begins development

Plant lifetime

Table 23 shows the assumed plant lifetimes used in modeling. With this approach, pilot and demonstration-scale plants built during the early period do not contribute to the total production capacities towards the end of the ramp-up period. The short lifetime of pilot and demonstration plants reflects the fact that they are often loss-making facilities, and generally, developers choose to operate these plants for only long enough to gain valuable test data and experience, to finance future plants.

Table 23. Plant Lifetime at Each Technology Stage

Technology Stage	Plan Lifetime (years)
Pilot	3
Demonstration	5
Commercial	28

Generic plant output

The assumed capacity of projected Nth commercial plants is shown for each pathway in Table 24 based on planned facilities. It was assumed that each technology pathway would converge towards an average fuel output capacity per year. These are not assumed to vary by scenario, given that economically viable plant scales are not particularly dependent on the wider industry development – rather they depend on capital costs, operating costs, and efficiencies, trading off against feedstock prices and local availability near plants (or imports).

Table 24. Nth Plant Capacity for Each Fuel Pathway

Pathway	Nth plant capacity (ML/year)
G1	270
G4	83
N3	140
ND2	195

Biofuel production facilities using lignocellulosic residues are limited in their scale by relatively low conversion efficiencies. An optimized collection distance, or “sourcing radius” is often a key consideration in bioenergy projects, which typically is a matter of optimizing the trade-off between decreasing levelized capital costs of the conversion plant and increasing biomass feedstock costs as the required collection radius increases. This is highly dependent upon the feedstock: for instance, woodchips from logging residues have a significantly smaller economical collection radius than woodchips from energy crops[40]. However, factors such as the availability of infrastructure (e.g., forest roads, railways, canals), capital expenditure limits, biomass price volatility, and local regulations also play a role. There are also geographical constraints that must be considered.

For this reason, facilities receiving primary biomass residues, such as wood or agricultural residues, are assumed to be smaller in scale on average than plants receiving secondary products (e.g., ethanol or concentrated sugars).

Availability of plants

All plants across all pathways were assumed to run at 90% utilization once successfully constructed and commissioned. Therefore, actual annual fuel production is slightly below the nameplate capacities.

Product slate

The technology pathways considered in the model can produce several different fuel types. A product slate is applied to the pathway output to determine the proportion of the output which is the desired fuel type. Where this proportion is not 100%, the proportion is denoted in Table 2.

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[40] Moskalik, T.; Gendek, A. Production of Chips from Logging Residues and Their Quality for Energy: A Review of European Literature. Forests 2019, 10, 262. https://doi.org/10.3390/f10030262

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