Project ID # VAN023

Assessing Energy and Cost Impact of Advanced Vehicle Technologies

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2022 DOE Vehicle Technologies Office
Annual Merit Review

June 2022

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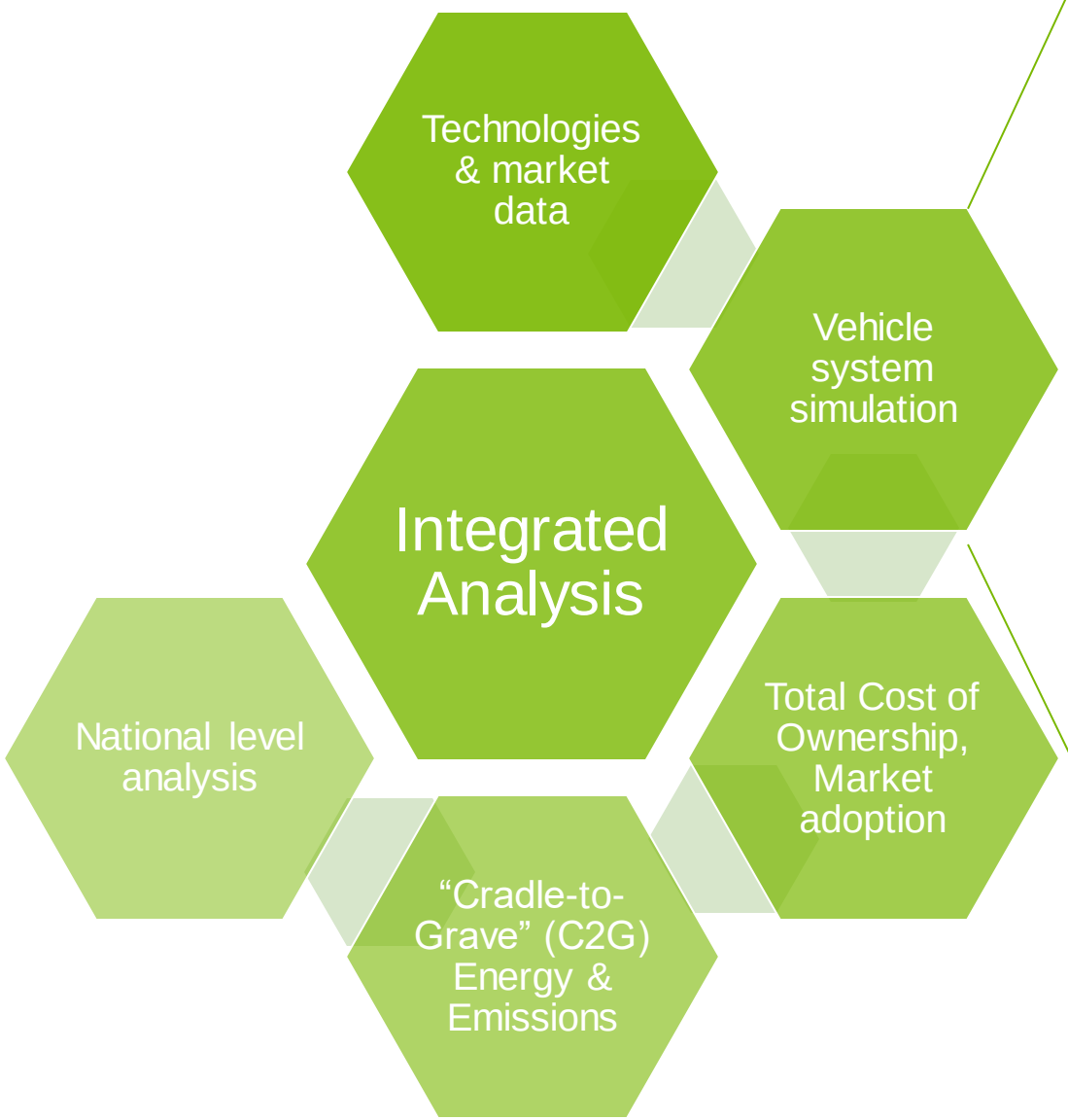
Project Overview

Timeline	Barriers* Addressed
• Project start date : October 2019 • Project end date : September 2022 • Percent complete : 95%	• Risk aversion • Constant advances in technology • Cost • Computational models, design, and simulation methodologies *from 2011-2015 VTP MYPP
Budget	**Partners**
• FY22 Funding : $300K • FY20-22 Planned Budget: $900K	• U.S. DRIVE Partners • 21 CTP Partners • U.S. DOT / NHTSA • NREL, ORNL (cycle and component info) • Outside companies (OEMs, suppliers, etc.)

Relevance

Quantify vehicle technologies impact on energy consumption, performance and cost



Directly answers	What is the contribution of individual technologies towards transportation decarbonization across timeframes, vehicle classes and powertrains?
	What is the impact of DOE Vehicle Technologies Office R&D?
	When/Under which assumptions will electrified powertrains (e.g., BEVs, FCHEVs, etc.) achieve cost parity?
	How will components' technology and cost uncertainties affect energy consumption, purchase price and total cost of ownership (TCO)?
	As vehicles and components evolve, how will component requirements (e.g., power, energy, etc.) change?
Supports answering	What would be the demand for critical battery materials on a national scale under different PEV adoption scenarios using BatPaC linkage?
	How do future fuel or energy costs affect advanced vehicles' TCO?
	How do advanced vehicles help reduce overall GHG emissions (e.g., GREET, C2G study)?
	How does DOE R&D impact vehicle technology market penetration (e.g., NREL TEMPO)?
	How do advanced vehicles impact the energy demand at the regional or national level (e.g., POLARIS under SMART Mobility Consortium)?
	How does the impact of connectivity, automation, and new modes affect vehicle technologies benefits (e.g., link with microsim)?

Objectives

1. **Quantify energy consumption and cost impacts of VTO R&D.**
2. **Disseminate results to support DOE and non-DOE funded activities**

Component Specs

- EPA, GEM, SmartWay, A2MAC1, AuVID
- ORNL, IAV, SWRI, DOT, DOE

Classes & Vocations

- EPA regulation, VIUS
- DOE & Industry feedback

Sizing Criteria

- Acceleration time
  - 0-30mph, 0-60mph
- Cruising speed
- Daily driving Range
- 6% & highway grade speed
- Launch capability

Technology Status & Forecast

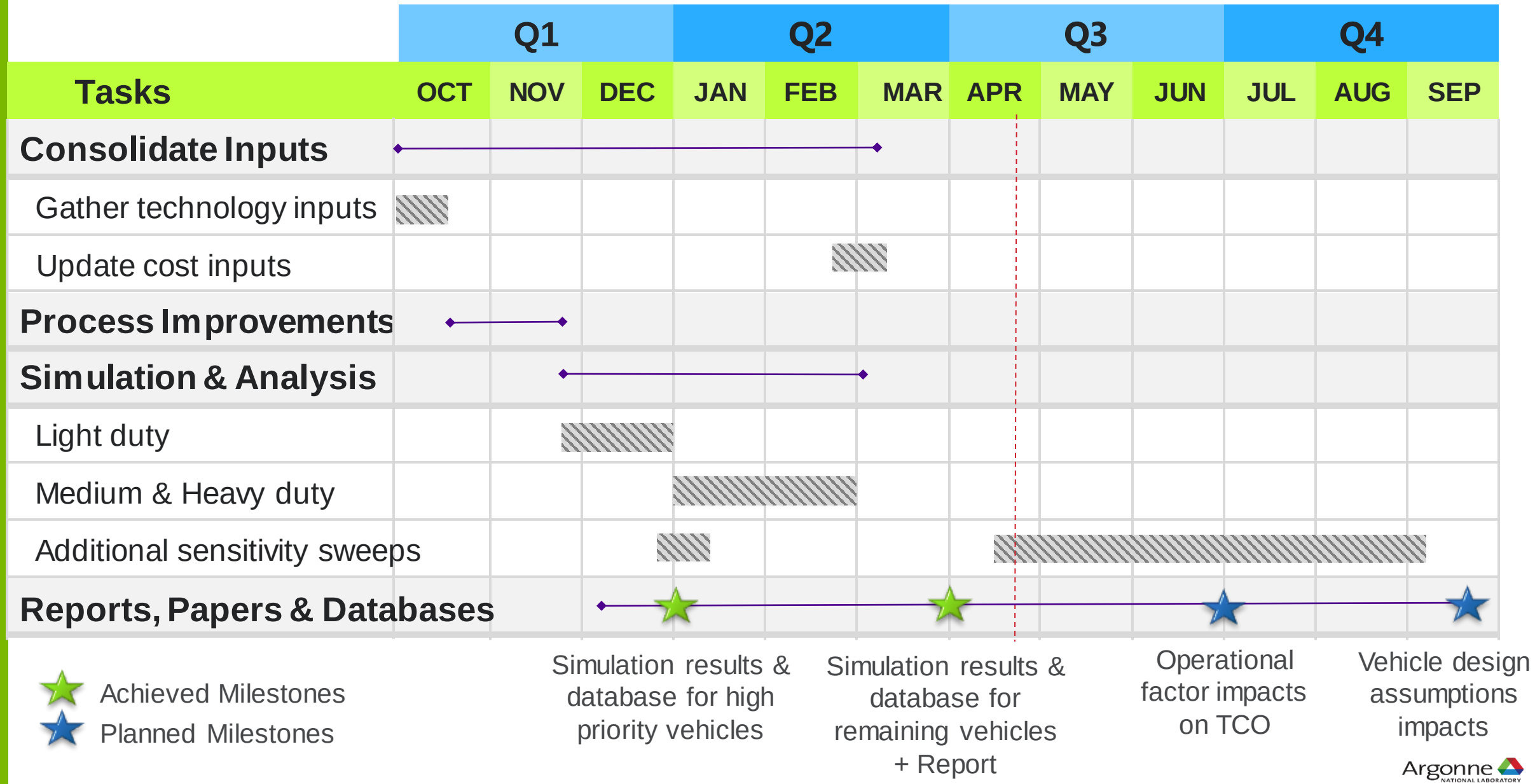
- National Labs
- Supertruck, Industry partners
- VTO, U.S.DRIVE, 21CTP

AUTONOMIE

BEAN
BEnefit ANalysis (techno-economic)

Vehicle models	SMART Mobility, EEMS [EEMS093, EEMS019], Transp system benefits [VAN035], Target setting [TA059], CoOptima, DOE-LPO activities.
Sizing Procedure	U.S.DRIVE, 21CTP Technology evaluation efforts
Component power & weight	GREET, C2G, LCA analysis [VAN017, SA178]
Energy Consumption	GREET, TCO, TEMPO, VTO Benefit analysis, Annual technology baseline (ATB) [SA176]
Vehicle cost	TCO analysis [VAN038], Target setting activities
Report & Databases	Annual technology baseline, VTO/HFTO Benefit, TEMPO, EPA, CARB, BNEF, IHS…
BEAN Analysis	U.S.DRIVE, 21CTP, OEMs (Ford, Cummins, etc.), Research Organizations…
Additional results	Ongoing work under DOE & 21CTP Impact of cargo, accessory, AER variations

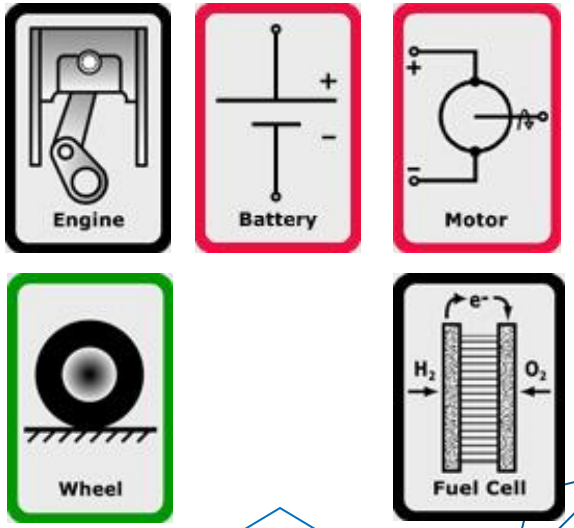
FY22 Milestones



Approach & Methodology:

Use performance based powertrain sizing to develop vehicle models across all classes. Quantify vehicle energy consumption, performance, cost and TCO.

Technology assumptions for performance and cost



Inputs
DOE tech teams, 21CTP, U.S.DRIVE, A2MAC1, etc.

Vehicle specifications

Component sizing requirements

AUTONOMIE

EPA Regulatory cycles, real world range & cargo inputs

Simulation results
Energy consumption, weight & cost

Component cost vs. production volume

BEAN

TCO assumptions (VTO multi-lab working group) [VAN038]

Outputs

Energy consumption, Component sizes, Manufacturing cost, TCO

The full set of assumptions from VTO/HFTO Analysis work is available from *https://vms.es.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/*

Technical Accomplishments

Improved Simulation and Analysis Process Focused on Accuracy, Speed, Scalability and Flexibility

- **More vehicles & powertrains added to analysis**
  - 2,600 vehicles in 2016 → 12,000 vehicles evaluated in 2021
  - 5 light duty classes to over 30 types of vehicles spanning light, medium and heavy duty applications.
  - Key enabler: Process automation and use of HPC

- **Large scale simulation capabilities**
  - Automated vehicle powertrain sizing algorithms developed and validated supports activities from other DOE offices (e.g., 21CTP Technical Targets) as well as DOT/NHTSA.

- **What is new in this year's work ?**
  - Combined report for 10 LD vehicle classes and 23 MD & HD vehicle classes.
  - Deployment of BEAN (excel based tool shared with report and result data)
    - TCO, GHG estimates (assumptions are from GREET & multi lab TCO report)
    - Supports scenario cost analysis to answer 'what-if' questions.
  - New architecture with multi-speed transmissions for heavy electric vehicles.
  - One source for current and previous reports and data
    https://vms.es.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

Increased Fleet Coverage Supports Additional Projects and Analysis.

Based on DOE guidance, the analysis was completed for all vehicles by FY22 Q2 to align with project deadlines

- Light duty vehicle classification is coordinated across studies for multiple agencies of US Government (DOE LPO, NHTSA).
- Over 20 class/vocation combinations are currently available, covering a majority of trucks in US
  - **59%** of the trucks by numbers
  - **82%** of the miles driven by trucks
  - **85%** of the fuel used by trucks

How?

- Improvements in AMBER/Autonomie
- Most of the improvements are due to BEAN and the updated cost calculation methods

Light Duty
Compact
Midsize
Small SUV
Midsize SUV
Pickup

2 categories

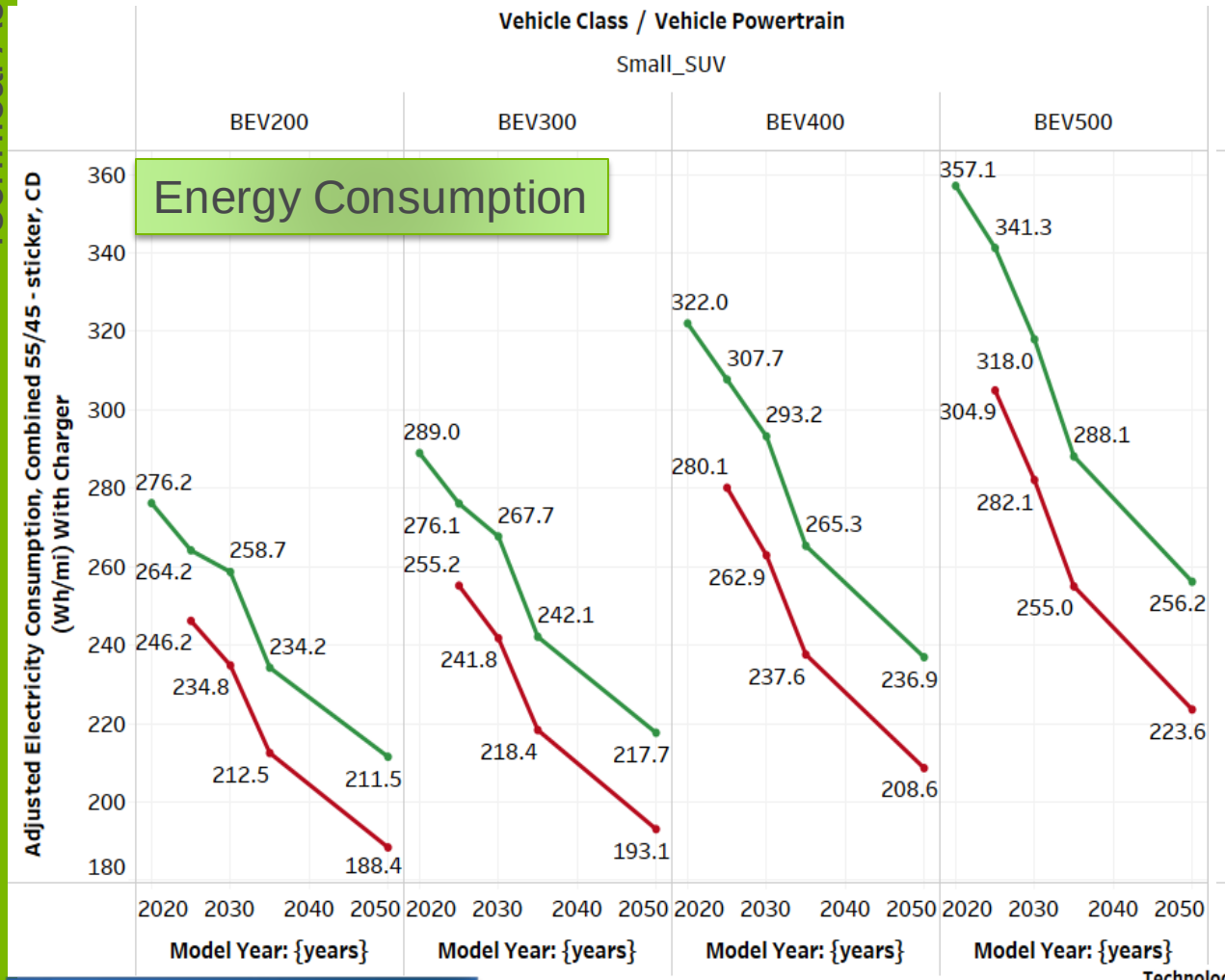
- Premium/ Performance
- Base/ Economy

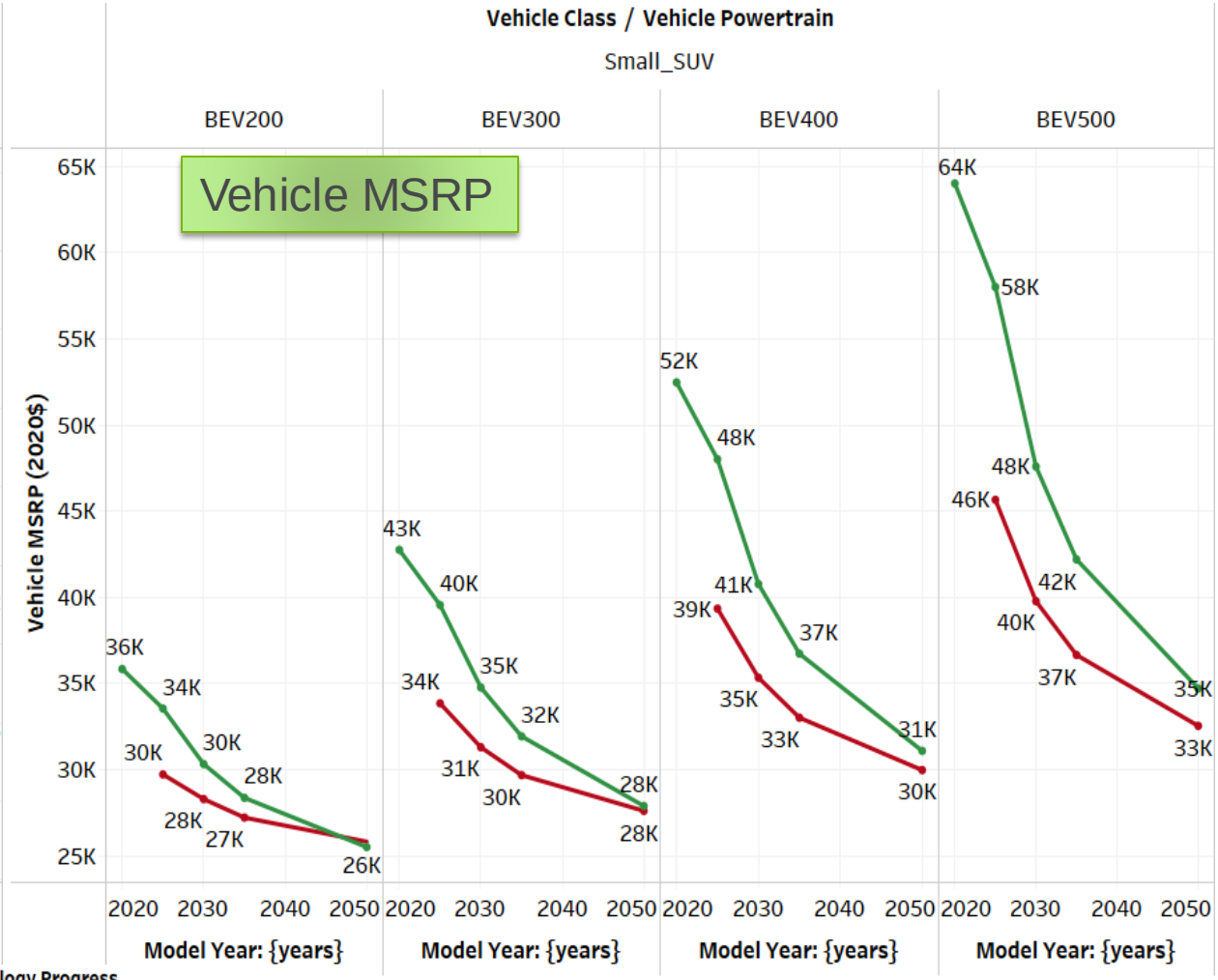
Medium Duty	
Class	**Purpose**
2	Van
3	Box
3	Van
3	School
3	Pickup
4	Box
4	StepVan
4	Service
5	Utility
6	StepVan
6	Box
6	Construction

Heavy Duty	
Class	**Purpose**
7	Tractor
7	Vocational
7	Box
7	School
8	Longhaul
8	Beverage
8	Drayage
8	Vocational
8	Transit
8	Refuse
8	Regional

VTO-Funded Research Helps Achieve Significant Energy Consumption & Vehicle Cost Reductions

By 2050, battery electric vehicles (BEVs) will consume ~30% less energy and be ~40% cheaper compared to present day BEVs

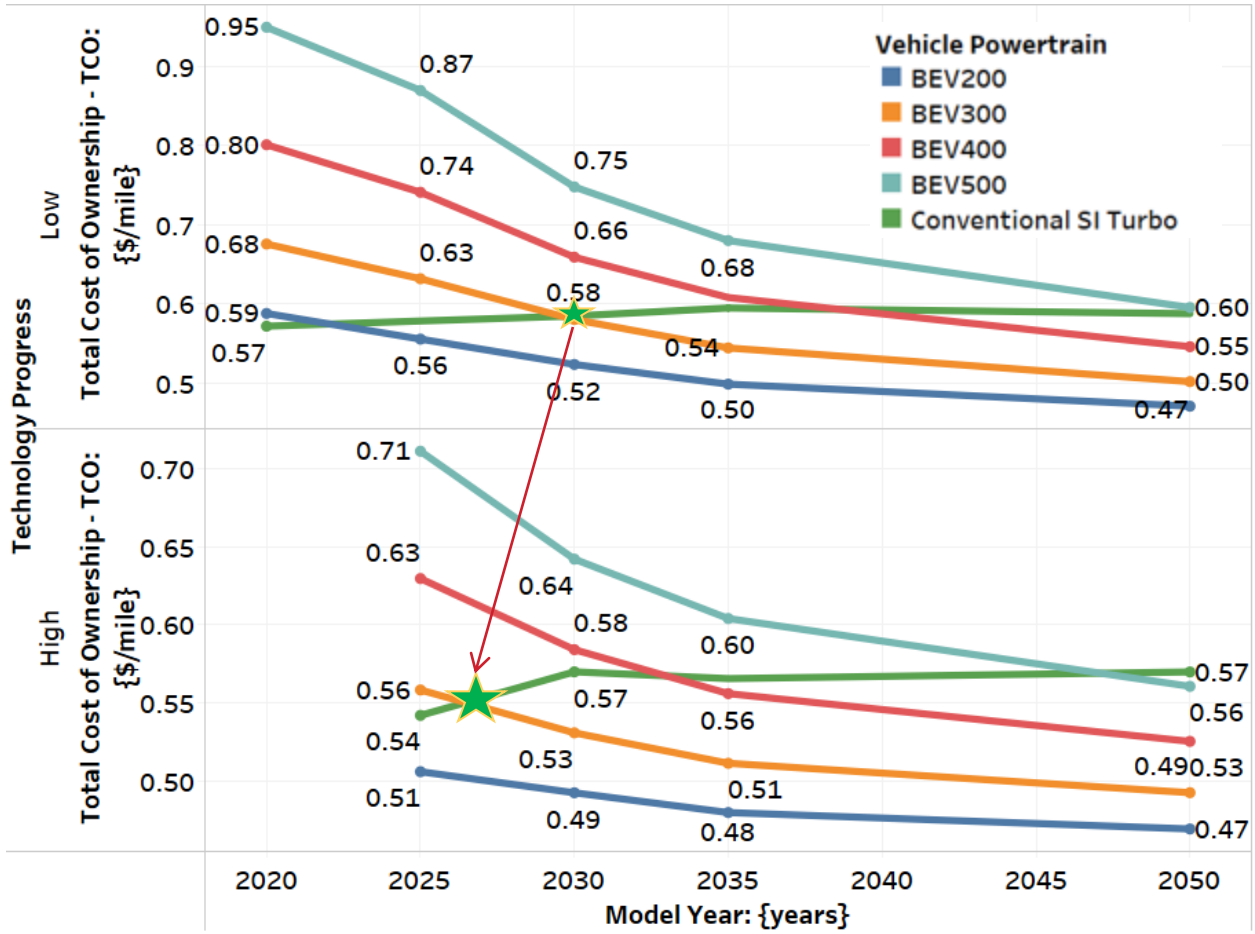




Technology Progress
Low
High

Example: Small SUV

VTO-Funded Research Accelerates Passenger Car BEVs' Cost Parity with Conventional Vehicles by 5 Years Compared with the Business-as-usual (Low) Scenario



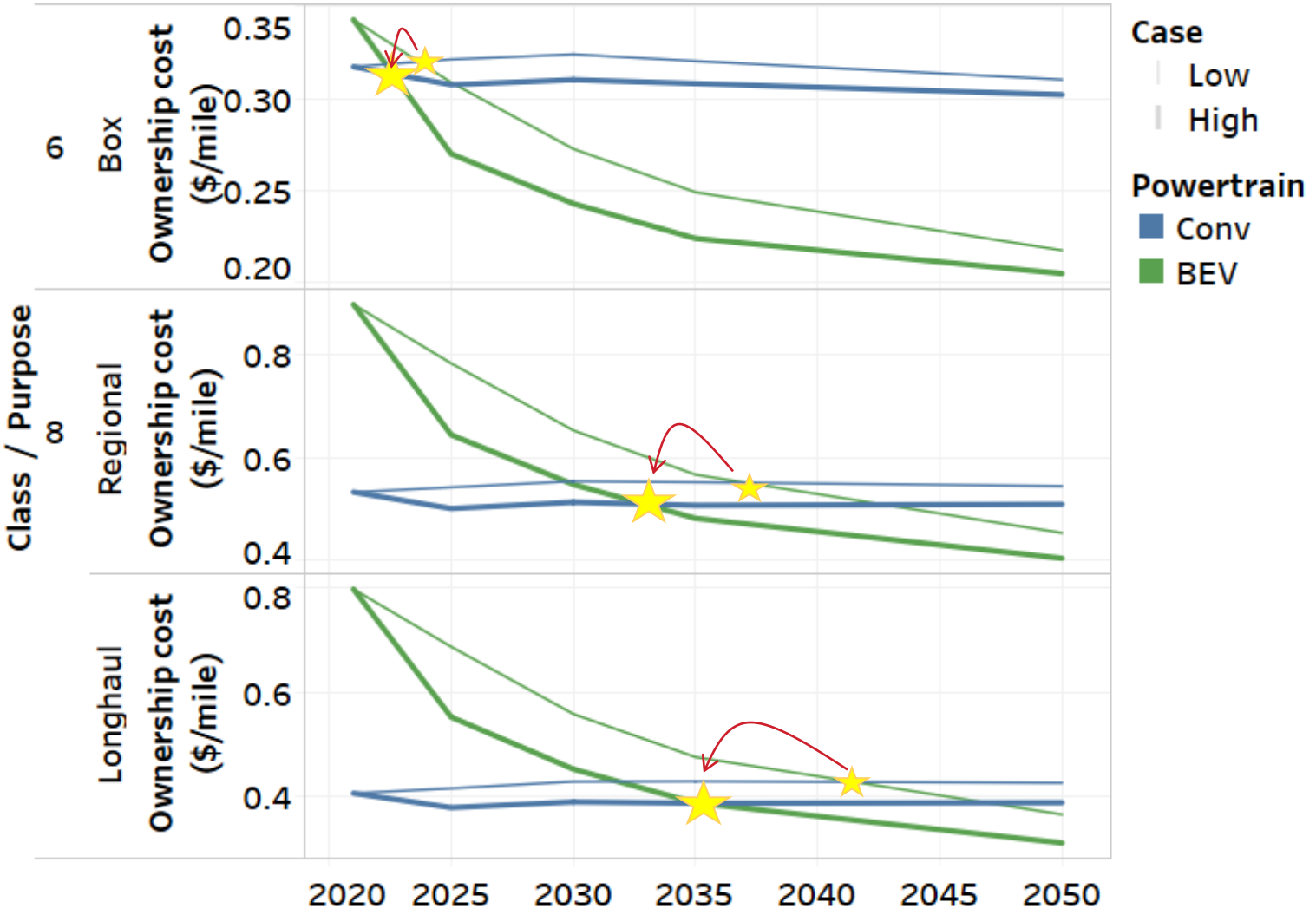
For Small SUVs, under the business as usual scenario, battery electric vehicles (BEVs) would become cost competitive with conventional powertrains between 2022 (BEV 200 miles) and 2050 (BEV 500 miles).

Under a higher technology progress scenario with VTO funding, BEVs can be cost competitive an average of 5 years earlier, thus significantly accelerating their market adoption.

Similar TCO estimates are available for all vehicle & powertrain combinations.

Example: Small SUV

VTO-Funded Research Accelerates HD Truck BEVs Cost Parity by 3-7 Years, Compared to the BAU Scenario



Example: Medium & Heavy trucks

- Introduction of medium duty trucks (150 miles range) will be accelerated by 2-3 years due to VTO-funded research.
- In addition to ownership cost parity, other metrics are also considered, including energy savings, purchase price, cargo carrying capacity...

Newly Released Free Techno-economic Analysis and Data Visualization Tool for Vehicle Technology Evaluation

BEAN

User Interface	Autonomie Link	GREET Link	TCO Link	Component & Fuel costs	Calculations	Predefined plots
Excel based. User friendly	Results for over 5000 vehicle choices	WTP GHG impact for fuel pathways (US average mix)	Based on multi lab TCO report	Default values are provided. Users can easily update	Open, documented	Purchase Price, TCO, LCOD, CCM, GHG

BEAN combines outputs from multiple high-fidelity tools and VTO Analysis projects

- Autonomie for vehicle and component characteristics, including energy consumption
- "VTO multi-lab consortium" for total cost of ownership
- GREET for LCA, GHG
- Over 300 downloads in last 3 months

"Argonne's BEAN tool is an invaluable resource in visualizing and making accessing the wealth of data on vehicle costs and performance from the Autonomie Model in a digestible and accessible format." [Tim Wallington, Senior Technical Leader, Environmental Science & Sustainability, Ford Motor Company]

https://vms.es.anl.gov/tools/bean/

Remaining Challenges and Barriers

- Q3-Q4 deliverables: Quantify the impact of powertrain design and operational assumptions on truck energy consumption and cost to support 21CTP and VTO Analysis stakeholders questions
  - Operational: Impact of cargo weight & accessory loads on energy consumption for different types of trucks
    - Parametric sweeps with vehicles developed in Q1 & Q2.
  - Design: Impact of the BEV desired range on purchase price & TCO parity
    - Are BEVs viable for the 500+ mile range long haul applications? At what range requirement do FCHEVs become more attractive? How do uncertainties (e.g., electricity cost) impact results?
    - Can BEVs be economically even more attractive if we design for 50th or 75th percentile requirements?
  - Previous studies have shown the usefulness of having multi-speed transmission for HD BEVs. Can we use transmissions to lower electric machine torque requirement and improve vehicle cost and efficiency?

Comments from Previous Reviews

Reviewer Comments	Answers
The reviewer would potentially include a plan for retiring technologies if the industry is moving away from certain technology options, and would create documentation around criteria for retiring technologies that are no longer in use	Autonomie Vehicle Information Database (AuVID) is an Argonne effort to collect vehicle technology information on production vehicles. The database includes representative technologies for present and past model years (e.g., EPA test, sales…). AuVID helps identify individual technology penetrations over time, which supports vehicle design assumptions.
Data driven simulations can be accelerated through machine learning (ML) so that the computational process can be faster and reproducible by others	A parallel effort on ML-based energy consumption prediction, based on vehicles developed in this project, is underway [EEMS013]. The new tool called "Autonomie ML" is expected to be released in FY23.
One potential issue is dissemination of the data and results. Autonomie is proprietary, and it is not clear how much of the input assumptions and outputs will be publicly available to a wider research audience	All vehicles from this work are shared through Autonomie & two **free** versions of Autonomie that do not require expensive 3rd party toolboxes [EEMS013] • Autonomie Lite (fast tunable compiled models) • Autonomie Express (faster non-tunable compiled models for evaluating large number of cycles) All assumptions, results and reports are shared on Argonne website and integrated into BEAN, which is freely downloadable.
Reviewers had appreciated the collaboration with industry partners	We have continued to participate in USDRIVE & 21CTP working groups. Several discussions in Powertrain & System Analysis as well as Hydrogen and Fuel cell working groups, as well as interactions with OEMs have informed this project.

Collaborations

Inputs

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

21st CENTURY TRUCK PARTNERSHIP

NHTSA

National Labs

Other stakeholders

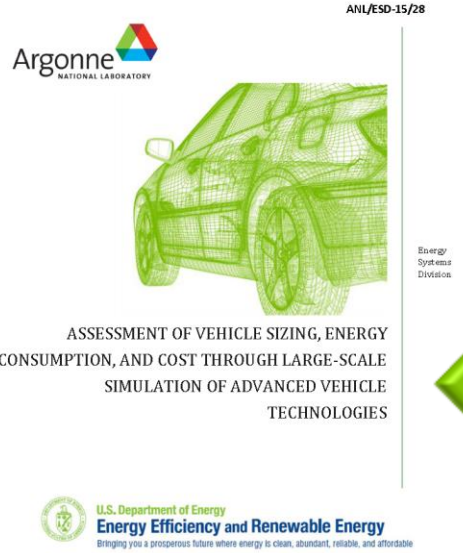
…

Review of vehicle performance, component sizing & cost assumptions

Component details

Vehicles & parameters of interest

Analysis & Reports



Techno-Economic

BEAN

Stakeholders

EEMS/SMART mobility consortium [EEMS083,093,109,110,…]
- Vehicles used to support SMART workflow are from this work

ATB [SA176]
- Provides vehicle related inputs for Annual Technology Baseline (https://atb.nrel.gov/)

TEMPO
- Provides vehicle related inputs for TEMPO (https://www.nrel.gov/transportation/tempo-model.html)

GREET [VAN017]
- GREET uses the energy consumption estimates from this work as input

Technology benefits [VAN035] [EEMS093]
- Benefit analysis work for VTO, HFTO, SMART, CoOptima, uses vehicles developed in this work as baseline

TCO [VAN038]
- Vehicle cost and fuel economy values form the input for TCO analysis

C2G [VAN017] [SA178]
- Supports ISATT work.
- Mass estimates for components
- Critical battery materials requirements

External users
- A lot of interest from EPA, CARB, Ford, BNEF, IHS, Cummins, WRI and more. 300+ downloads of BEAN in last 3 months alone.

Future Research

- Electrified powertrains are in an early stage for trucks. Setting the right technology targets will accelerate the introduction of efficient technologies. This work is already being used to support target setting activities across various DOE offices.
  - Vehicle models have to be periodically updated to model new technologies in production as well as predicted technology evolution.
- Continue to improve BEAN to serve as one common tool to evaluate the impact of technologies on transportation decarbonization, including energy consumption, TCO & GHG emission.
- Include more vehicles and use cases in future evaluations, and carry out sensitivity analysis for more design and operational parameters.
  - Eg. Gasoline (MD), Natural gas (HD) and H2 ICE variants
  - Explore fuel and technologies identified by CoOptima and architectures identified by Supertruck teams
  - Continue to support 21CTP & U.S.DRIVE in technical evaluations
- Expand analysis to additional modes (e.g., off-road, rail, air, marine, etc.)

Any proposed future work is subject to change based on funding levels

Summary

Quantified energy saving benefits and economic impacts of VTO funded technologies. Provided data and tools to a large number of diverse stakeholders

Component Specs

- EPA, GEM, SmartWay
- ORNL,IAV, SWRI, DOT, DOE

Classes & Vocations

- EPA regulation, VIUS
- DOE & Industry feedback

Sizing Criteria

- Acceleration time
  - 0-30mph, 0-60mph
- Cruising speed
- Daily driving Range
- 6% grade speed
- Launch capability

Technology Status & Forecast

- National Labs
- Supertruck, Industry partners
- VTO, U.S.DRIVE, 21CTP

AUTONOMIE

BEAN

✓ Developed vehicle models, spanning over 30 classes & 8 powertrains	SMART Mobility Target setting activities CoOptima, LPO (ATVM)
✓ Sizing Procedure is updated to include launch, highway grade etc	U.S.DRIVE, 21CTP Technology evaluation efforts
✓ Quantified component power & mass estimates for present and future vehicles	C2G, LCA analysis
✓ Quantified Energy Consumption	LCA, TCO, TEMPO, VTO Benefit analysis, Annual technology baseline (ATB)
✓ Quantified vehicle cost for advanced powertrain choices	TCO analysis, target setting activities
✓ Published Report & Databases to share data	Annual technology baseline, VTO Benefit analysis, TEMPO
✓ Published BEAN as a free techno-economic tool	For technology evaluation work, involving energy, TCO and GHG
✓ Continues to provide additional results	Support ongoing work under DOE & 21CTP Impact of cargo, accessory, AER variations

https://vms.es.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

TECHNICAL BACKUP SLIDES

APPROACH

Quantify the impact of VTO funded technologies on energy consumption, performance and cost of advanced vehicles.

Vehicles

Light Duty
Compact
Midsize
Small SUV
Midsize SUV
Pickup

Performance Category
Base
Premium

Class	Purpose	Class	Purpose
2	Van	7	Tractor
3	Box	7	Vocational
3	Van	7	Box
3	School	7	School
3	Pickup	8	Longhaul
4	Box	8	Beverage
4	StepVan	8	Drayage
4	Service	8	Vocational
5	Utility	8	Transit
6	StepVan	8	Refuse
6	Box	8	Regional
6	Construction		

⊗

Timeframes

Current

…

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2050

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Powertrain Configurations

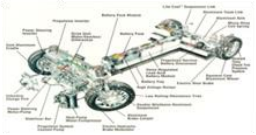
Conventional

ICE HEV

PHEV

Fuel Cell

Electric



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Fuels

Gasoline

Diesel

Ethanol

H_2

CNG

⊗

Technology Progress

Risk Analysis

Low (business-as-usual)

High (VTO advancements)

mpgge
Wh/mile

Energy storage requirement

Purchase price parity

TCO parity

GHG impact
CO_2 g/mile

~ 5000 vehicle combinations

Technology Forecast Assumptions

Inputs from SuperTruck (ST), EPA, Smartway, 21CTP Roadmap & DOE Targets

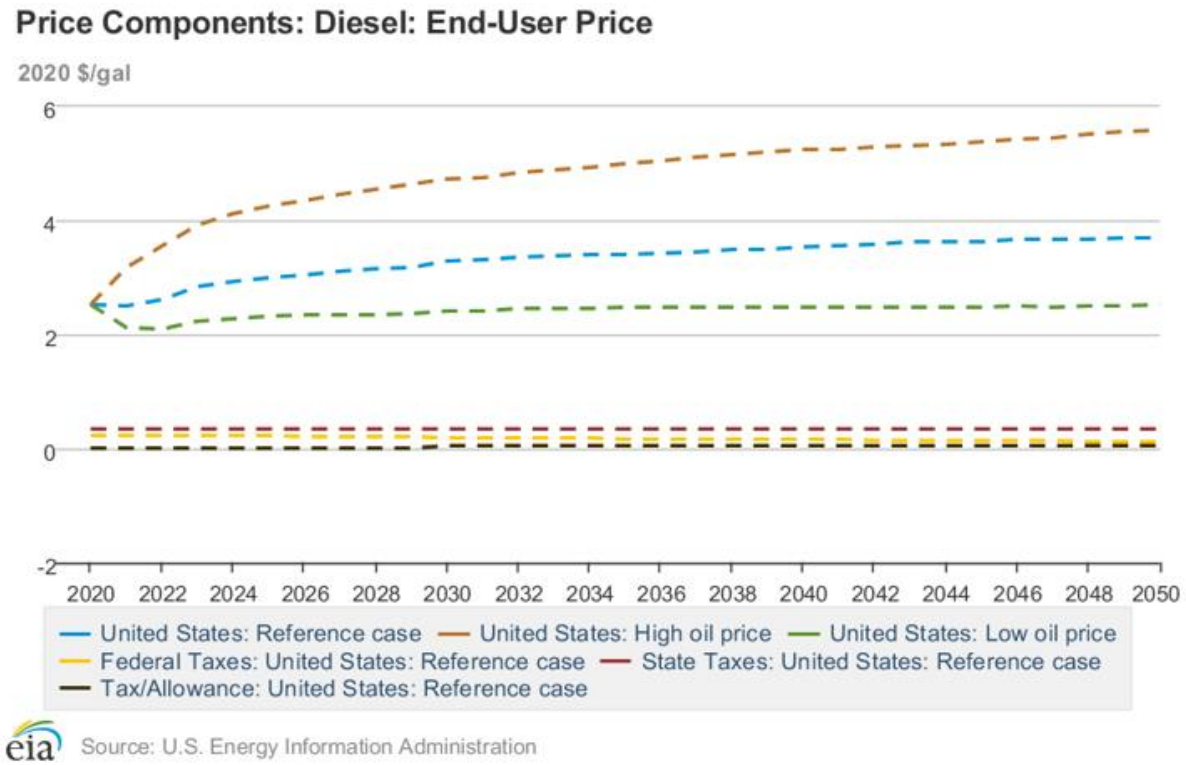
- Technology adoption in class 8 fleets from NACFE 2016 fleet study used to identify technologies in current trucks
- Similar data for other classes of vehicles will be valuable.

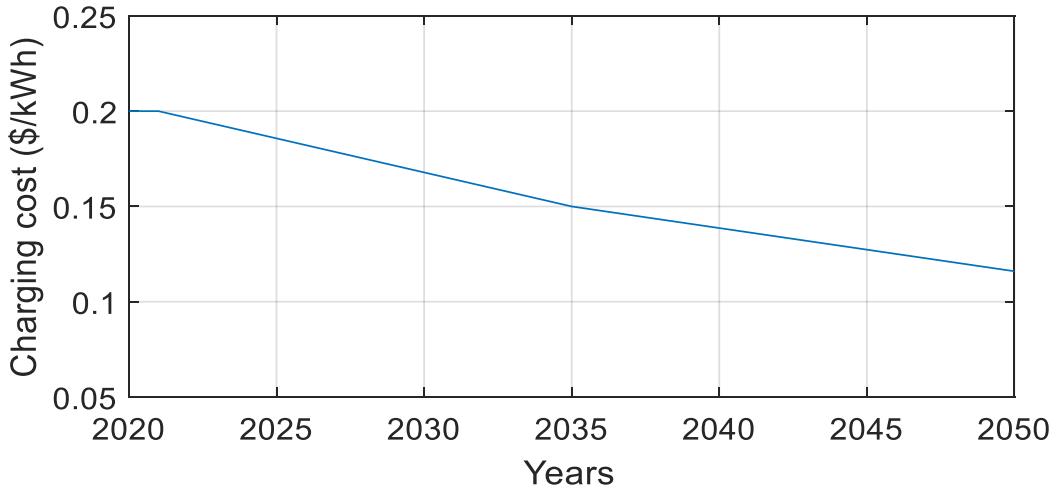
Parameter	Current Reference	Future References
Cd, Frontal Area	Truck data index, 21CTP inputs, EPA[1]	ST1[2] results & 21CTP
Rolling resistance	SmartWay	ST1 results
Auxiliary loads	EPA[1]	ST1 results
Light Weighting	Reports from DOE Tech Teams[3]	
Engine efficiency	EPA test data, GEM	ACEC, ST1 results, ST2 target, 21CTP + DOE inputs
Electric machines & Battery	From DOE Battery Tech Team	

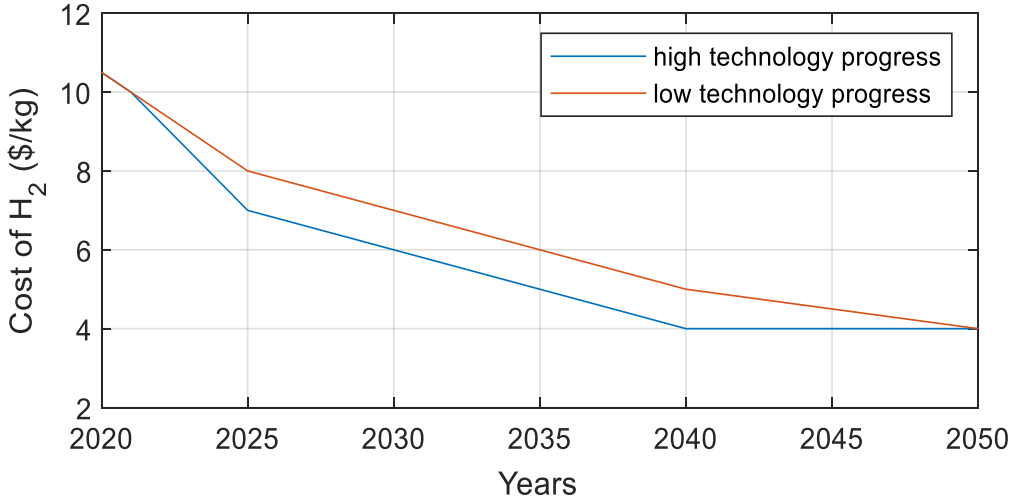
All assumptions are shared from https://vms.es.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

[1] EPA – assumptions used by EPA & NHTSA in the medium & heavy duty rule making
[2] Average values achieved by participants in Super Truck 1 program
[3] WORKSHOP REPORT: Trucks and Heavy-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, February 2013

Fuel & Energy costs





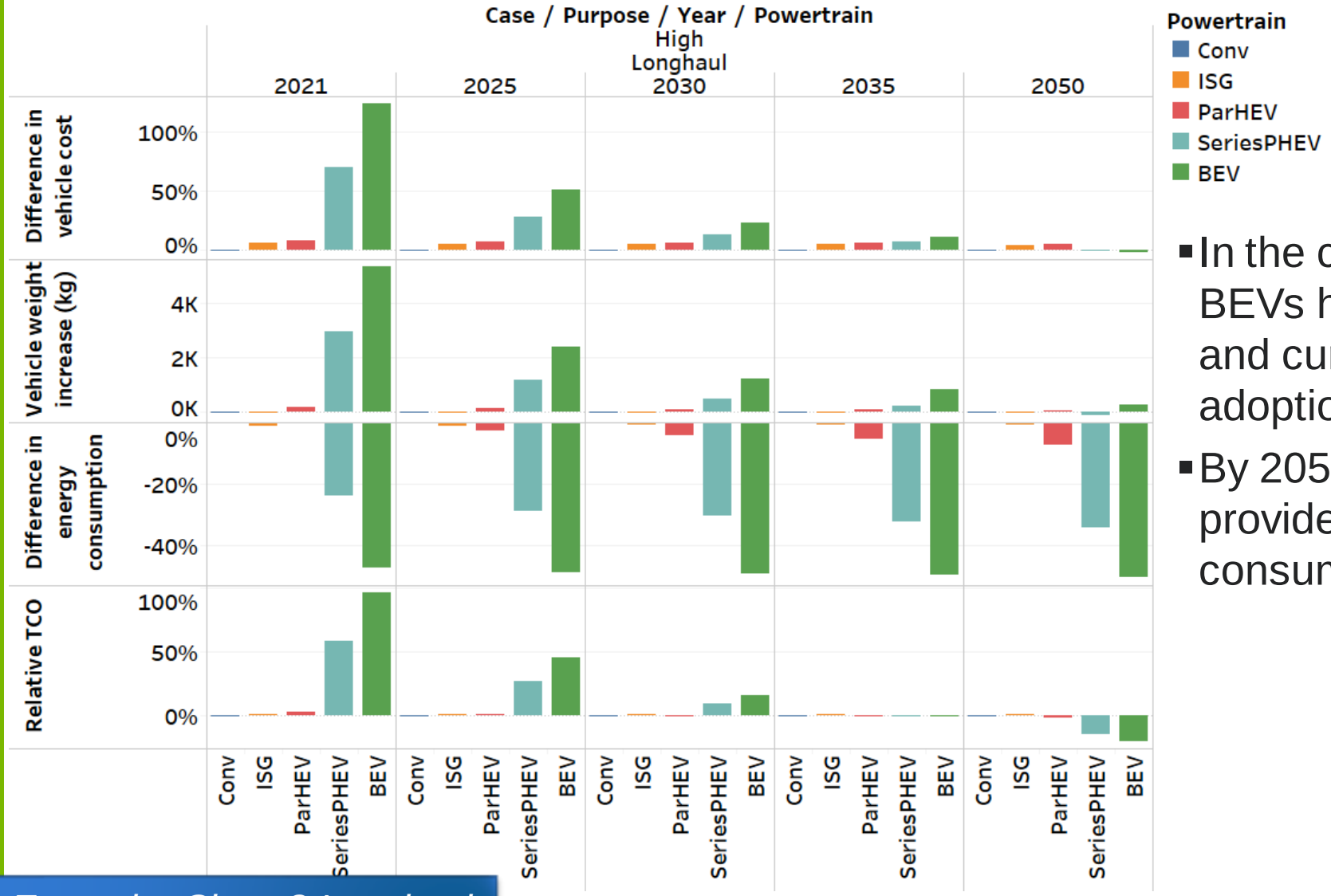


Autonomie Vehicles are Regularly Compared With Existing Vehicles

Conventional Turbocharged Engine Vehicles (Midsize)

Make	Model	2019-2020 Sales (thousands)*	Engine Disp. (L)	Rated HP	# of Cylinders	Transmission Type	# of Gears	Equivalent Test Weight (lbs.)	Adj UDDS (mpg)	Adj HWFET (mpg)	Adj. Combined (mpg)	MSRP** $	Accel time 0-60mph (s)
HONDA	ACCORD	376	2	252	4	Automatic	10	3625	23	34	27	31060	7.6
Kia	Optima	204	1.6	178	4	Automatic	7	3625	27	37	31	27190	6.9
Ford	Fusion	183	1.5	169	4	Automatic	6	3750	23	34	27	28690	8.9
Hyundai	Sonata	135	1.6	180	4	Automatic	8	3625	27	36	31	33500	7.3
CHEVROLET	MALIBU	102	2	260	4	Automatic	9	3627	29	36	32	33320	8.2
Mazda	Mazda 6	33	2.5	227	4	Automatic	6	3876	23	31	26	29800	7.9
VW	Passat	30	2	174	4	Automatic	6	3748	23	34	27	28645	7.8
MY20 Average	**Midsize**	**220**	**2**	**206**	**4**	**Automatic**	**6**	**3696**	**25**	**35**	**29**	**30315**	**8**
Autonomie	**Midsize**		**2**	**194**	**4**	**Automatic**	**6**	**3468**	**28.3**	**34.1**	**30.7**	**28630**	**7.9**

Analysis shows that VTO funded research is important in achieving TCO & functional parity



- In the case of long haul trucks, PHEVs & BEVs have higher manufacturing cost and curb weight, which could limit their adoption in the near future
- By 2050, technology improvements provide ~40% reduction in energy consumption

Example: Class 8 Longhaul