Benefits Analysis of Multi-Fuel/Vehicle Platforms with a Focus on Hydrogen Fuel Cell Electric Vehicles

Principal investigator: **Tom Stephens**

Argonne National Laboratory

2017 Vehicle Technologies Annual Merit Review

June 6, 2017

Washington, DC

Project SA068

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

Ongoing project prior to FY 2016

Project start: 1 Oct 2015

Project end: 30 Sep 2018

Barriers

- Relating program technology goals to national-level benefits
- Integration with VTO Program benefits analysis

Budget

FY 2016: $100k

FY 2017: $50k

(100% DOE)

Partners

- Interactions / Collaborations
  - Oak Ridge National Laboratory
  - Sandia National Laboratories
  - Energetics, Inc.

Objective

Estimate potential future benefits attributable to the Hydrogen and Fuel Cells Technology Program (FCTO), including

- Petroleum use reduction
- GHG emission reduction
- Market acceptance of fuel cell vehicles
- Economic impacts

while considering synergies/interactions with the Vehicle Technologies Program (VTO)

Challenges

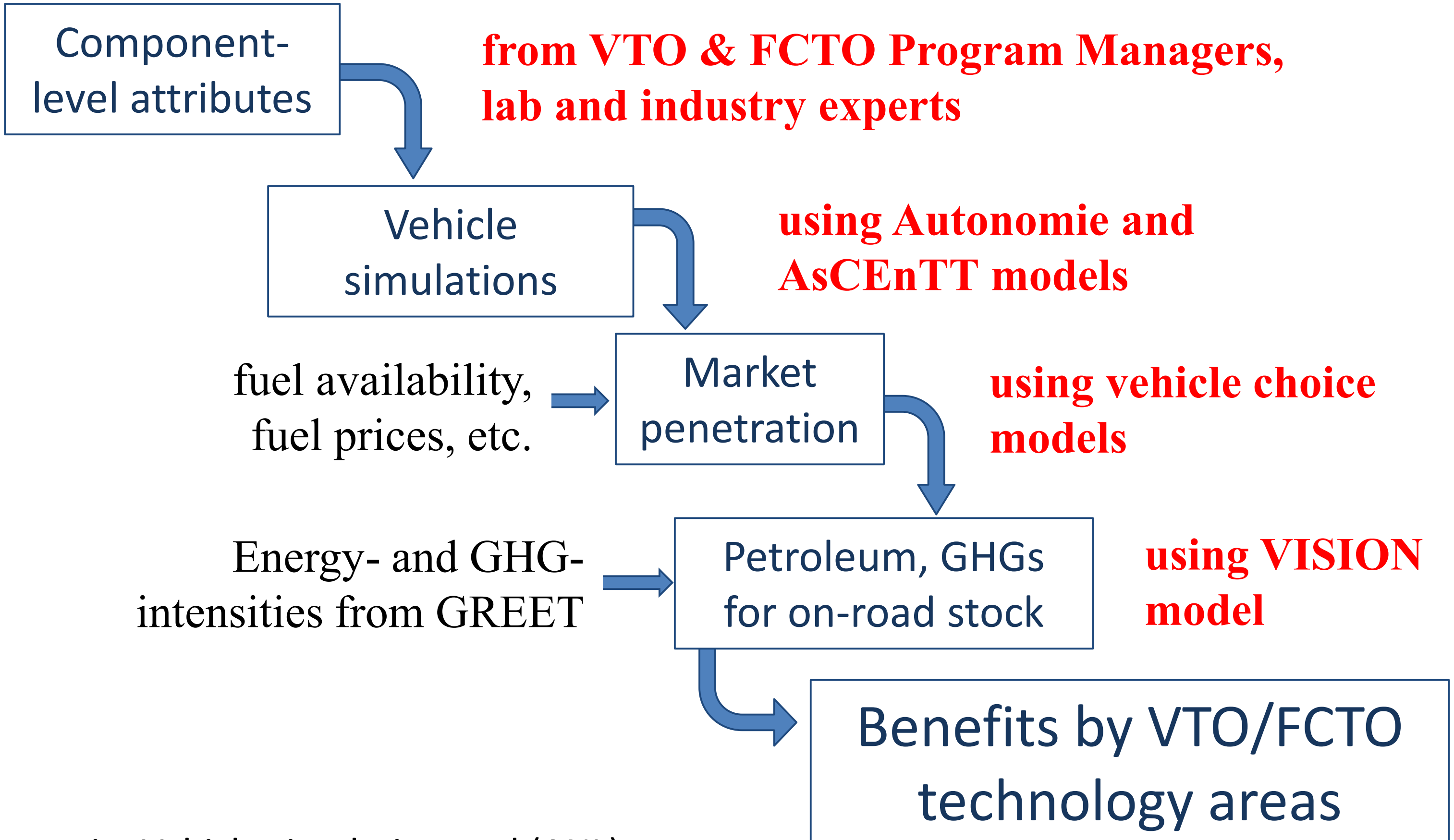
Establishing a transparent, well-founded link between FCTO (and VTO) program goals (performance and manufacturing cost, at the component level) and oil use, economic impacts, and GHG emissions at a national level

FCTO uses results of this analysis to communicate the benefits of the program to DOE management, other agencies, Congress and others.

Milestones

Month / Year	Description	Status
Dec 2016	Issue benefits report	Complete
Apr 2017	Presentation on benefits analysis results	Complete
Sep 2017	Report on side cases and sensitivities of program benefits	In progress

Integrated analysis workflow



Autonomie: Vehicle simulation tool (ANL)

AsCEnTT: Truck Energy model (Energetics, Inc.)

VISION: Stock/energy/Emissions accounting model (ANL)

GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (ANL)

Compare two scenarios, with and without successful deployment of FCTO and VTO Technologies

- Program Success: Vehicles meet FCTO and VTO performance, fuel economy and cost targets
  - Vehicle component cost and performance based on program targets, projected to 2050
  - Vehicle attributes estimated from component attributes
  - What's likely if VTO/FCTO hit all of the goals?
- Baseline (No Program): Without FCTO or VTO technology improvements
  - Vehicles simulated on the basis of FCTO & VTO inputs for "No Program"
  - What if DOE support for R&D stops immediately?

FCTO targets for:

- Fuel cell system
- H_2 storage

Assumptions about

- H_2 production (SMR, electrolysis)
- H_2 availability (# of stations)

Light-duty fuel cell electric vehicles (FCVs) only

Addressing technical barriers:

- **Relating program technology goals**
- **Integration with VTO Program benefits analysis**

Component-Level Inputs

Approach

Fuel cell system program targets from FCTO

	Units	2015	2020			2025			2030			2045		
		low	low	med	high	low	med	high	low	med	high	low	med	high
FC System-Specific Power	W/kg	659	659	670	680	659	665	710	659	680	740	670	760	870
Power Density	W/L	640	640	720	850	640	730	890	640	740	970	690	880	1150
Peak FC Efficiency at 25% Rated Power	%	59	63	65	66	64	66	67	65	67	68	68	69	70
Cost ($/kW)	$/kW	54	48	43	40	44	37	34	40	34	30	39	33	30

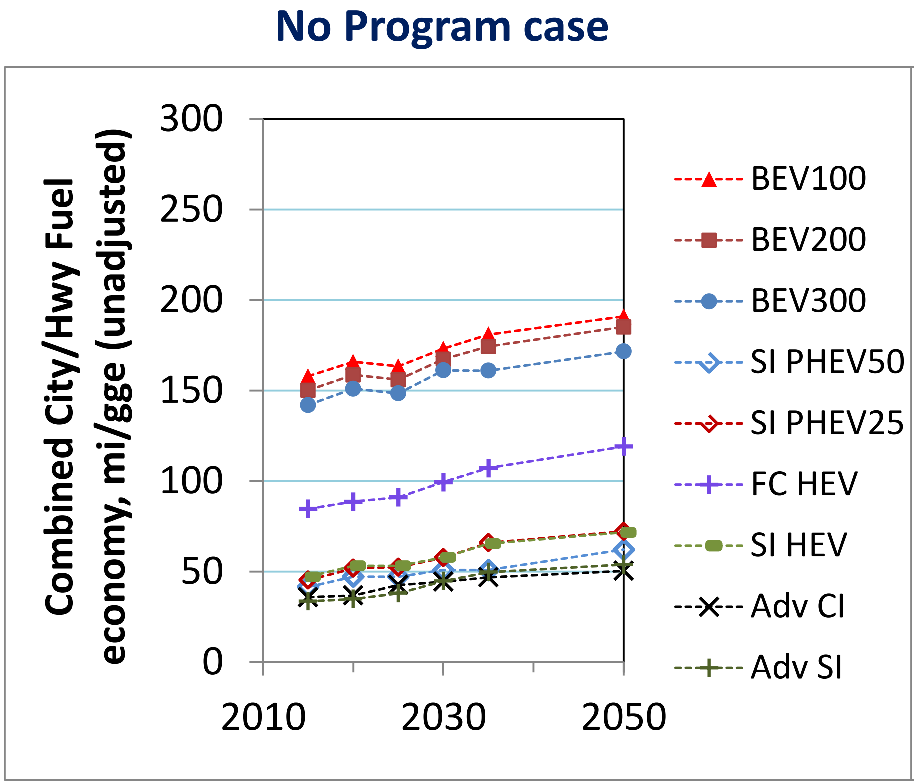
Hydrogen storage system program targets from FCTO

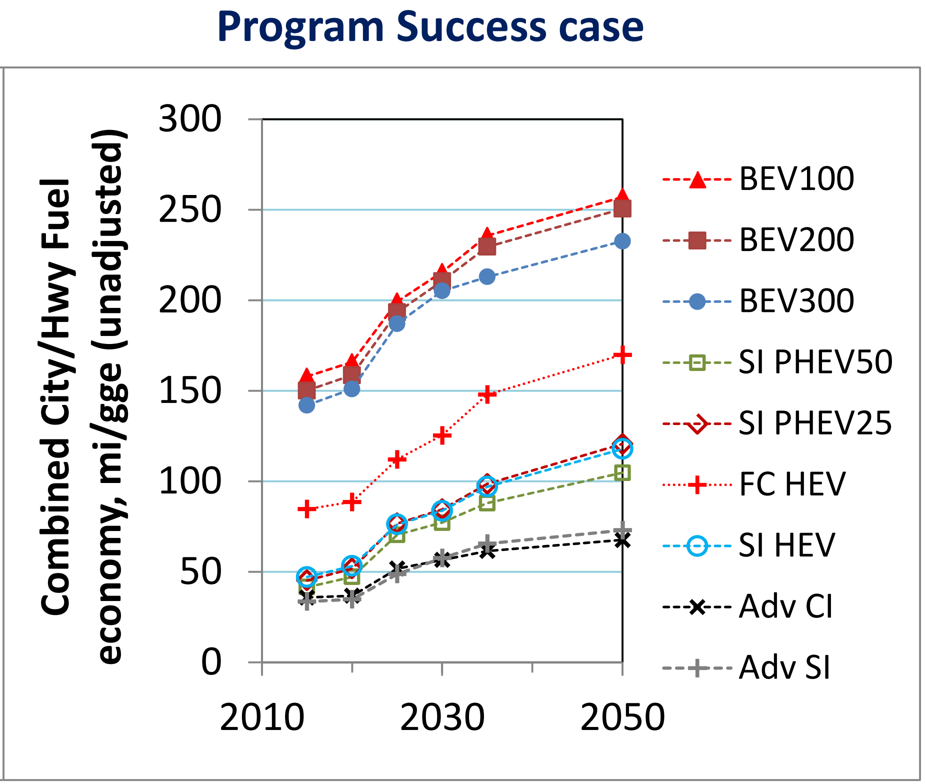
The cost is based on high production volumes (500,000 per year).

	Units	2015	2020			2025			2030			2045		
		low	low	med	high	low	med	high	low	med	high	low	med	high
System Capacity	Useable kWh/kg	1.5	1.5	1.6	1.8	1.6	1.7	2.0	1.6	1.8	2.3	1.7	2.0	2.5
	Useable kg H_2/kg of tank	0.045	0.045	0.048	0.054	0.048	0.051	0.060	0.048	0.054	0.069	0.051	0.060	0.075
Tank Cost	$/Useable kg H_2	576	450	391	335	430	375	310	391	317	274	380	311	267
	$/kWh	17.2	13.5	11.7	10.0	12.9	11.2	9.3	11.7	9.5	8.2	11.4	9.3	8.0
Usable H_2 in Tank	%	96	96	96	96	96	96	97	96	96	97	96	97	97

Future Vehicle Fuel Economy

- **Significant improvement in fuel economy across all powertrain types in the Program Success case**
- Vehicles simulated in UDDS and HWFET drive cycles
- Combined city/highway (43% city/57% highway), unadjusted values shown

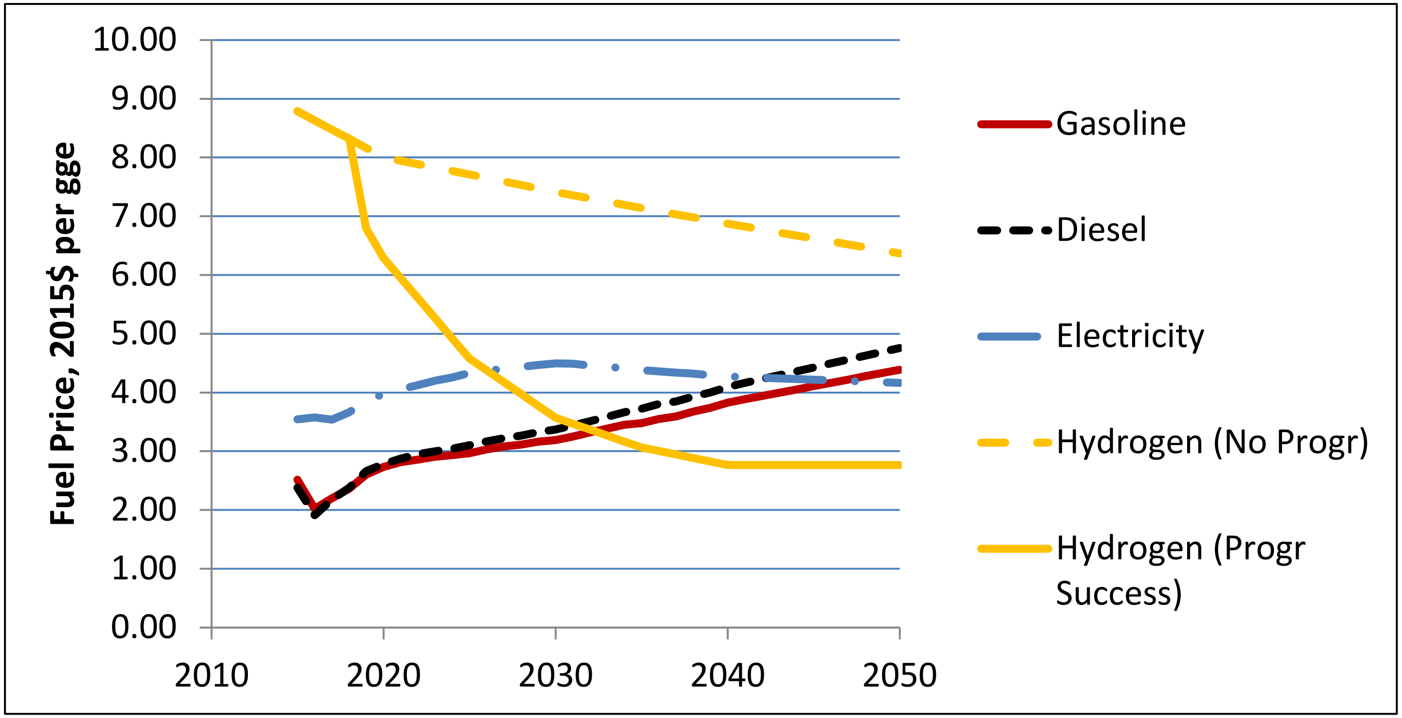




Light-duty vehicle simulations performed by ANL Autonomie Team (see presentation SA044 &poster VAN017)

Assumptions

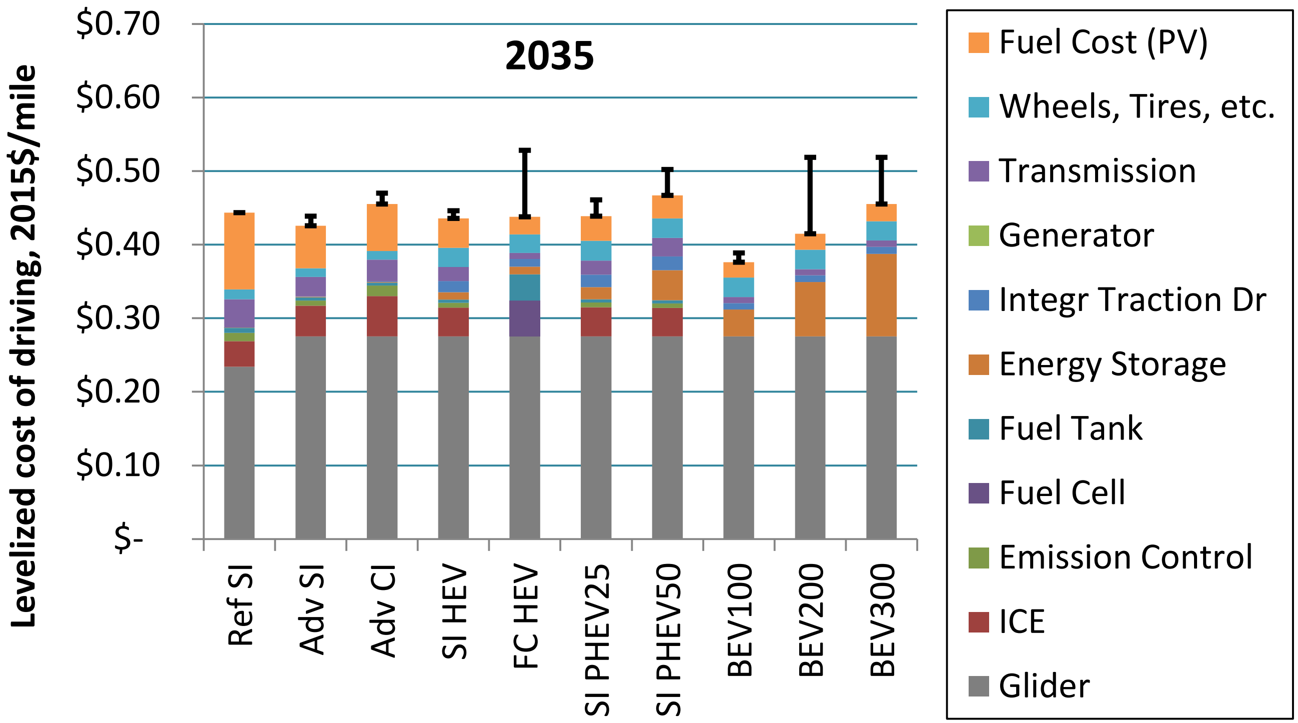
- H_2 prices from FCTO (other fuel prices from AEO2016 Reference case)
- Annual VMT per vehicle as projected in AEO, with slight elasticity of demand for LDVs
- GHG coefficients and upstream energy coefficients estimated from GREET™
  - No Program scenario: H_2 produced from steam methane reforming
  - Program Success scenario: H_2 produced from steam methane reforming & electrolysis



Ownership costs: Vehicles and fuel

- Levelized cost of driving (LCD), Midsize car, 2035

$$LCD = \frac{P_{Veh} + PV(C_{Fueli})}{\sum_i^N VMT/yr_i}$$



Fuel prices:
Gasoline: $3.32/gge
Diesel: $3.55/gge
Elec: $0.12/kWh
H_2: $3.03 - $7.05/gge

14,000 mi/yr

5 year ownership period

7% discount rate

No resale value assumed

EVSE cost not included

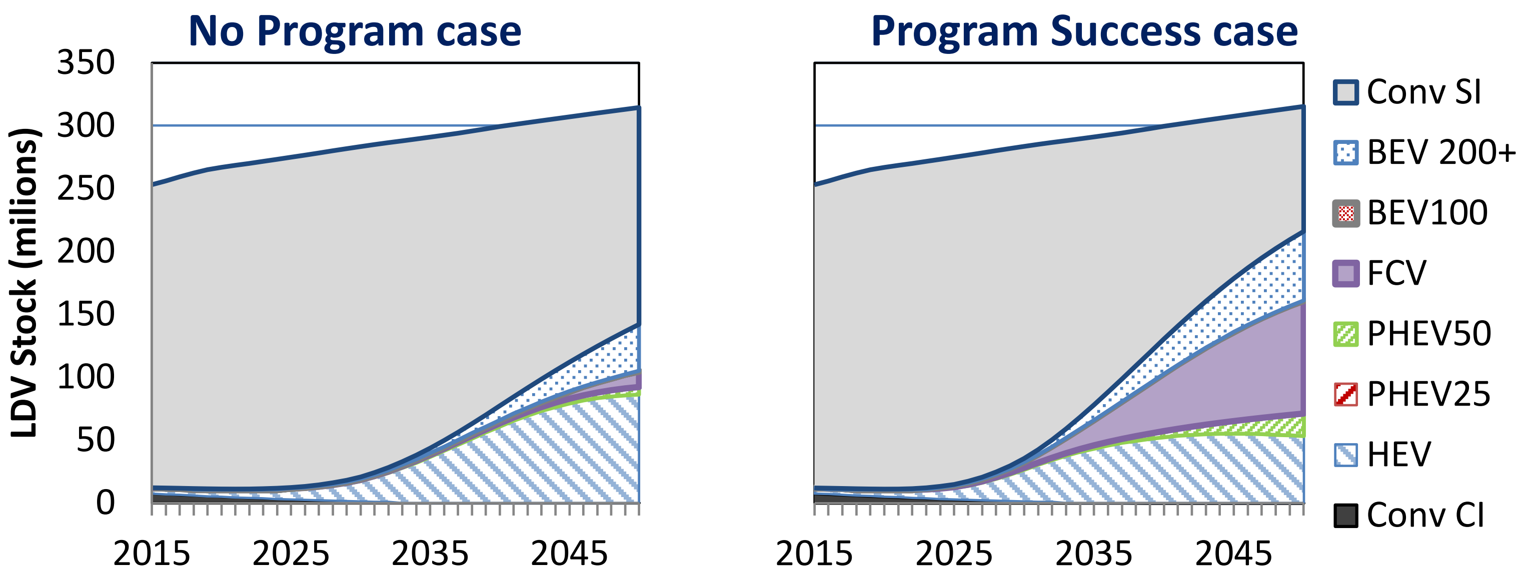
- Colored bars show LCD for Program Success
- Tops of error bars show LCD for No Program

FCVs become competitive due to reduction in vehicle and fuel costs

Projected on-road vehicle stock by powertrain

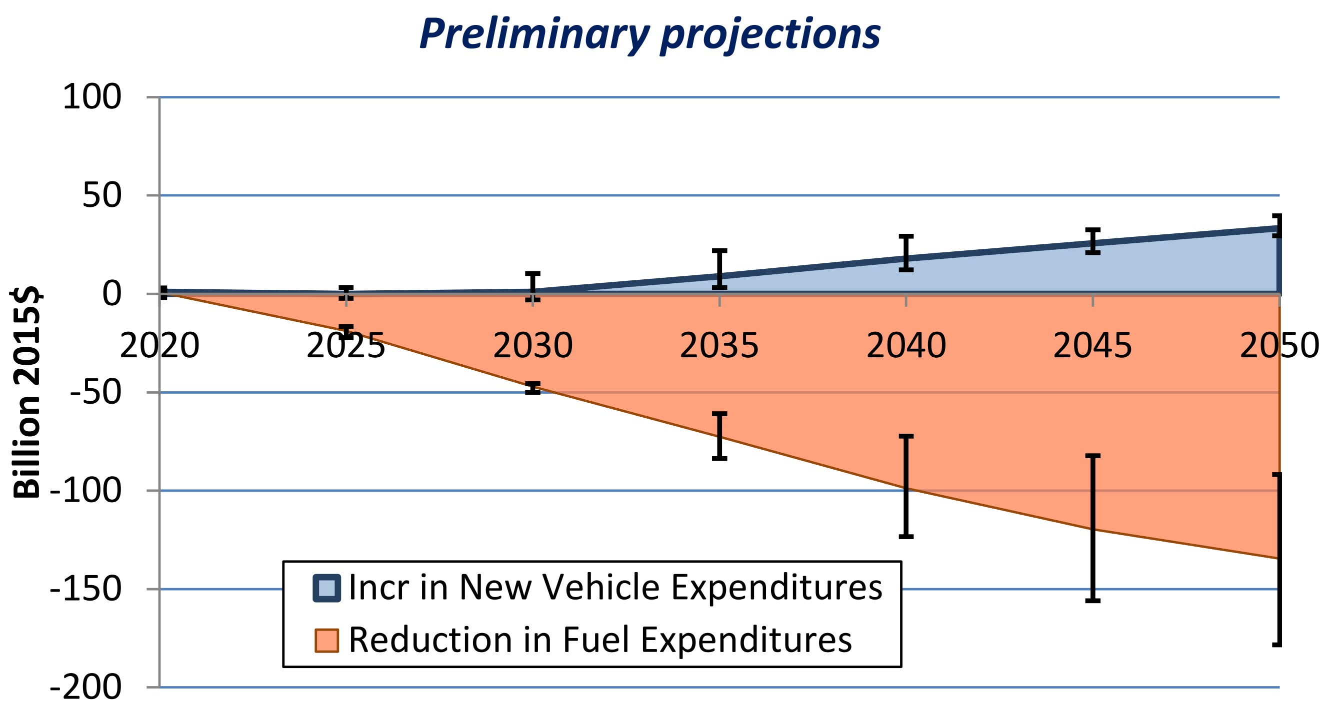
- One of four sets of projections shown (LAVE-Trans model, ORNL)

Preliminary projections



- Projections based on LDV sales shares developed using four consumer choice models:
  - LVCFlex (Energetics, Inc.)
  - LAVE-Trans (Oak Ridge National Laboratory)
  - MA^{3}T (Oak Ridge National Laboratory)
  - ParaChoice (Sandia National Laboratories)
- **Although future consumer behavior is uncertain, VTO petroleum and GHG reductions are significant**

Changes in national expenditures for new vehicles and fuel



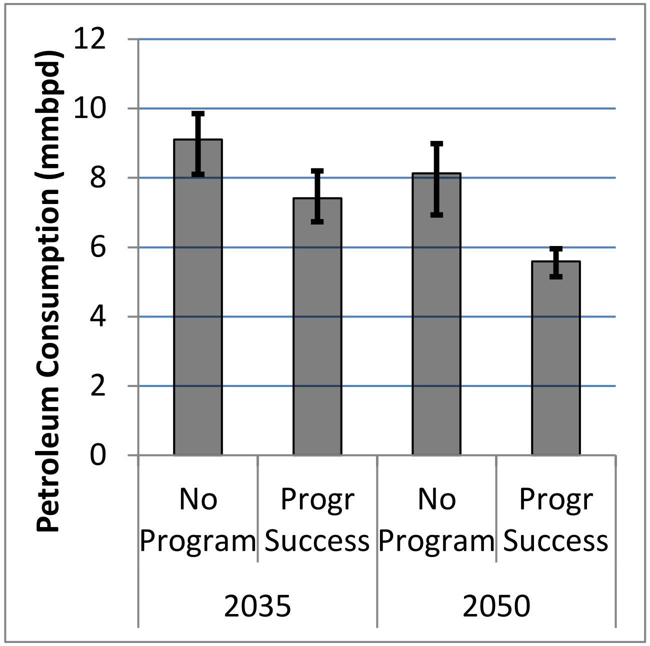
- Changes due to both FCTO and VTO Programs
- Error bars show ranges for each scenario due to different market projections

Advanced vehicle technology increases vehicle expenditures somewhat, but decreases fuel expenditures more

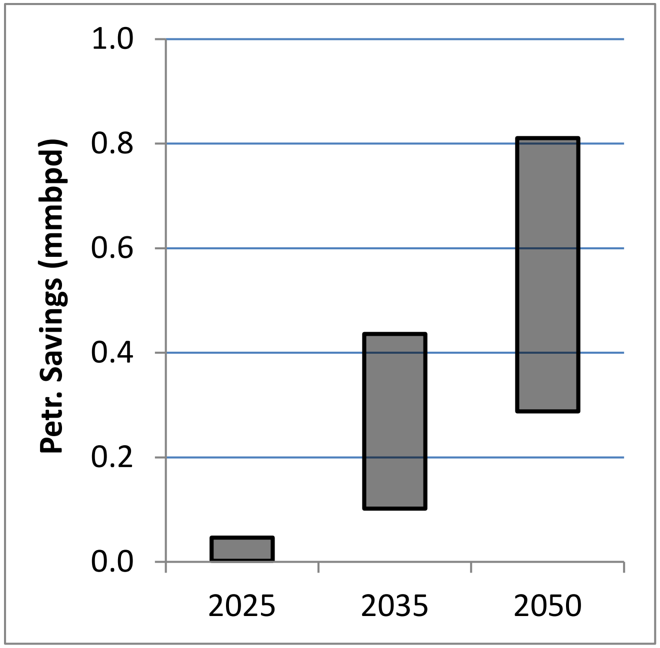
Projected petroleum use and savings *by FCTO and by FCTO & VTO*

Preliminary projections

VTO (LDV + HDV) and FCTO



Savings attributed to FCTO



- Differences in the bars on the left show the petroleum savings due to both VTO and FCTO programs
- Error bars on the left show the range of projections from four consumer choice models

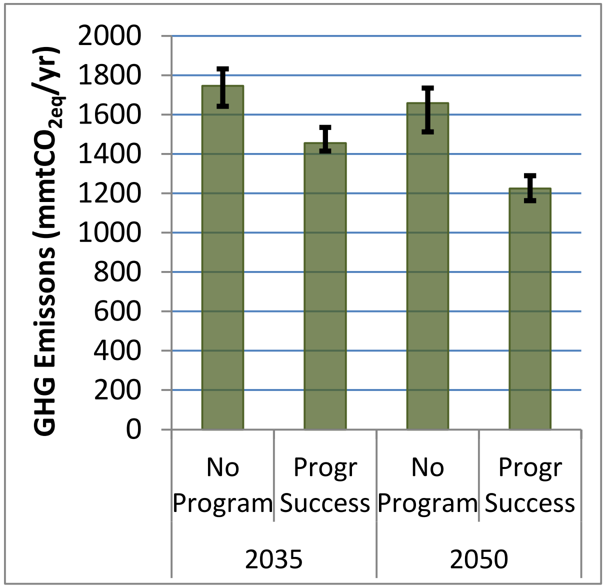
- Ranges of savings due to FCTO programs are shown on the right

Although future consumer behavior is uncertain, projected petroleum savings are significant

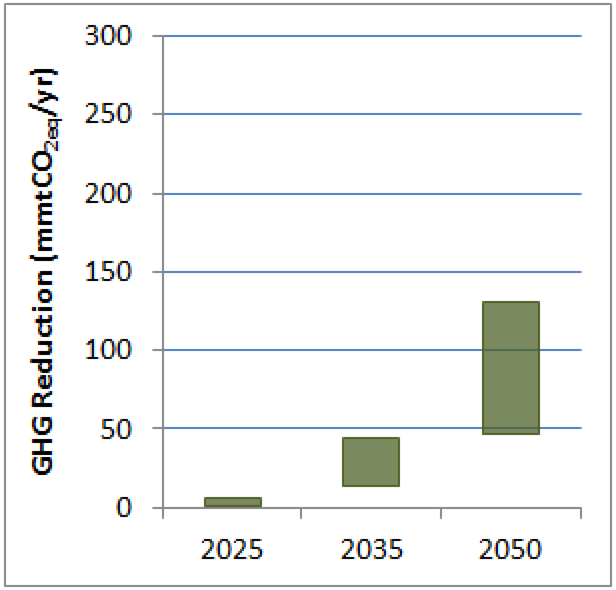
Projected GHG emissions and reductions *by FCTO and by FCTO & VTO*

Preliminary projections

VTO (LDV + HDV) and FCTO



Reduction attributed to FCTO



- Differences in the bars on the left show the GHG reduction due to both VTO and FCTO programs
- Error bars on the left show the range of projections from four consumer choice models

- Ranges of GHG reduction due to FCTO programs are shown on the right
- Reductions attributed to FCTO are a significant fraction of the total reduction by 2050

Although future consumer behavior is uncertain, projected GHG reductions are significant

Responses to Previous Reviewers' Comments

- New start in FY16

Collaborating with other laboratories

- Teaming with multiple labs to develop market share projections
  - LVCFlex (Energetics)
  - LAVE-Trans, MA^3T (Oak Ridge National Laboratory)
  - ParaChoice (Sandia National Laboratories)
  - TRUCK (Energetics, Inc. for medium- and heavy-duty vehicles)

ENERGETICS
A Subsidiary of VSE Corporation

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Sandia National Laboratories

Remaining Challenges and Barriers

- Make results more robust
  - Examine uncertainty to other variables (fuel prices, hydrogen availability)
  - Improved relationship between vehicle manufacturing costs and retail prices

- Assess competitiveness of fuel cell vehicles
  - More comprehensive assessment of ownership costs, e.g., include all relevant ownership cost, by powertrain type
  - Maintenance, repair (including battery packs), depreciation, taxes & fees, etc.

Proposed Future Work

- Examine selected side cases and assess sensitivities
  - Fuel prices, other market uncertainties, timing and availability of new models
  - Improve realism of vehicle attributes: include low-volume manufacturing costs, etc.
  - Consider a wider range of fuel cell vehicles, e.g., medium and heavy duty

Summary: Successful development and deployment of FCTO technologies (along with VTO technologies) can reduce petroleum use & GHG emissions, with significant economic benefits to consumers

- **Relevance:** Estimating FCTO's potential reductions petroleum use, GHG emissions, and other metrics
- **Approach:** Scenarios link specific program targets and on-road future benefits
  - Integrated with VTO analysis efforts to address key technical barrier
- **Accomplishments:** Significant benefits from FCTO programs
  - Elucidates the contribution of FCTO (by technology) to EERE mission
  - Provide quantitative projections to communicate the impacts of FCTO technologies

	2035	2050
Oil savings (million bpd)	**1.4-2.0**	**1.8-3.4**
Oil savings (million bpd) attributed to FCTO	**0.1-0.4**	**0.3-0.8**
GHG emission reduction (million mt CO_2eq/yr)	**256–322**	**350-520**
GHG emission reduction (million mt CO_2eq/yr), FCTO	**13-44**	**47-131**

- **Proposed future work:**
  - Examine side cases and assess sensitivities
  - Update benefits analysis for Budget Year 2020

Technical Back-up Slides

Acronyms

AEO	Annual Energy Outlook (US DOE Energy Information Agency)
AsCEnTT	Assessment of cycle energy of truck technologies (model)
BEV	Battery electric vehicle
EVSE	Electric vehicle service equipment
FCTO	Fuel Cell Technology Office
FCV	Fuel cell vehicle
GGE	Gallon of gasoline equivalent
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (model)
HDV	Heavy duty vehicle
HEV	Hybrid electric vehicle
HWFET	Highway fuel economy test
LCD	Levelized cost of driving
LDV	Light duty vehicle
PHEV	Plug-on hybrid electric vehicle
UDDS	Urban dynamometer test schedule
VMT	Vehicle-miles-traveled
VTO	Vehicle Technologies Office

Modeling the On-Road Stock

- Energy used by the on-road stock of vehicles of each powertrain type was calculated using the Argonne VISION model
- Given the following, VISION provides the consumption of all fuel types in on-road vehicles of each powertrain type
  - Fuel economy (from vehicle simulations),
  - Sales shares by powertrain type (from vehicle choice models)
  - Annual vehicle-miles-traveled and survival functions (based on FHWA & NHTS data, taken from the AEO input file, modified for LDVs using a elasticity of travel demand)
- Additional analysis is done to disaggregate heavy vehicles by fuel and size class and to disaggregate fuel savings by vehicle technology
- Use of GREET coefficients gives fuel-fuel cycle energy and GHG emissions
- Reductions in fuel use attributable to each VTO subprogram and to Fuel Cell Technologies Office program are then disaggregated for each powertrain type

Methods for Petroleum Savings Attribution (LDVs)

- Petroleum is saved by
  - More efficient conventional and hybrid electric vehicles (drivetrain improvement)
  - Replacement of vehicles that use petroleum by vehicles that use less or no petroleum
- For VTO, technologies, these two components are estimated for Conv, HEVs and PHEVs
- Fuel saved by BEVs and FCVs by replacement of vehicles that use petroleum by vehicles that use less or no petroleum
- FCVs are assumed to replace the average non-FCV
- Petroleum reduction is attributed to subprograms:
  - Battery and electric drive – Fuel cell technologies (FC system, storage, and H_2 infrastructure
  - Adv Combustion Engines
  - Materials
  - Fuels and lubricants

FCVs, Petroleum Saved by FCVs replacing other vehicles

How much VMT by FCVs is replaced VMT by non-FCVs?

How much petroleum is saved due to this replacement, $\Delta P_{FC\ Cars}$?

$$\Delta P_{FC\ Cars} = \left(\frac{Petroleum\ used}{VMT\ of\ nonFC\ cars}\right)\left(VMT_{FC\ Cars}^{PrgSucc} - VMT_{FC\ Cars}^{NoPrg}\right)$$

$$\Delta P_{FC\ Cars} = \left(\frac{P_{Tot\ Cars}^{PrgSucc}}{VMT_{Tot\ Cars}^{PrgSucc} - VMT_{FC\ Cars}^{PrgSucc}}\right)\left(VMT_{FC\ Cars}^{PrgSucc} - VMT_{FC\ Cars}^{NoPrg}\right)$$

$P_{Tot\ Cars}^{PrgSucc} =$ Total petroleum consumed by all cars in Program Success

Petroleum saved by FC light trucks calculated analogously

$$\Delta P_{FCVs} = \Delta P_{FC\ Cars} + \Delta P_{FC\ LTs}$$

GHG Reduction Attributed to FCVs

Reduction = GHG emission in *No Program* – GHG emissions in *Program Success*

From VISION, we know the electricity and hydrogen used

$$\Delta GHG_{FCVs} = \Delta P_{FCVs}\left(\frac{GHG}{quad\ petroleum}\right) -$$

$$(H_2use)^{PrgSucc}\left(\frac{GHG}{quad\ H_2}\right)^{PrgSucc} + (H_2use)^{NoPrg}\left(\frac{GHG}{quad\ H_2}\right)^{NoPrg} -$$

$$\begin{cases} \Delta Elec\left(\frac{GHG}{quad\ elec}\right) & , \Delta Elec < 0 \\ 0 & , \Delta Elec \geq 0 \end{cases}$$

$$\Delta Elec = (Elec\ use)^{PrgSucc} - (Elec\ use)^{NoPrg}$$

This gives approximate values that are then adjusted to match the total GHG reduction