Advanced Vehicle Technology Competition: Challenge-X 2008 DOE Merit Review

Building on 19 successful years of advanced vehicle technology competitions

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This presentation does not contain any proprietary or confidential information

Outline

- Current Competition Program Introduction/Overview
- Goals and Objectives
- Approach
- Collaborations/Interactions
- Performance Measures and Accomplishments
- Next Competition Program Introduction/Overview
- Summary

Competition Introduction

- DOE has had a successful 19-year history of Advanced Vehicle Technology Competitions (AVTCs):

  - ✓ *Methanol Marathon and Methanol Challenge (GM)*
  - ✓ *Natural Gas (GM), Ethanol (GM), and Propane Vehicle Challenges (DaimlerChrysler)*
  - ✓ *Sunrayce 1990*
  - ✓ *HEV Challenge and FutureCar (with PNGV-GM/Ford/DaimlerChrysler)*
  - ✓ *FutureTruck (GM/Ford/DaimlerChrysler)*
  - ✓ *Challenge X (final year-GM)*
  - ⇒ *EcoCAR (the next AVTC challenge)*

- AVTCs integrate key DOE vehicle technologies

Goals and Objectives

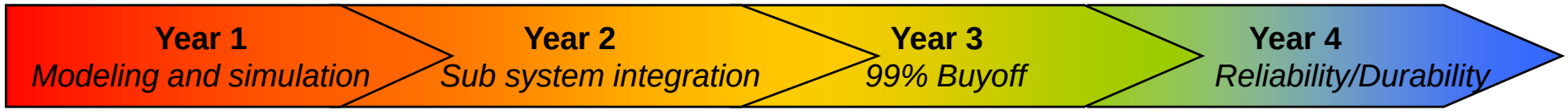
- Investigate, develop, and demonstrate a broad spectrum of advanced vehicle technologies aligned with DOE's objectives: *renewable fuels, energy diversity, advanced combustion, energy storage technology, electric machines, high power electronics, fuel cells, vehicle simulation modeling, and other critical technologies*
- Explore technical solutions that minimize petroleum consumption and reduce well-to-wheel greenhouse gas emissions relative to current production counterparts
- Train the next generation of engineers to bring advanced technology vehicles into production while grooming future industry leaders
- Increase public awareness through the Challenge X outreach program of the state of development and capabilities of advanced vehicle technology

Approach to Achieving Goals/Objectives

- Establish an AVTC series in partnership with vehicle manufacturers, fuel and component suppliers for colleges and universities in North America
- Select universities with core capabilities and a high potential for success (out of 105 university applicants, only 17 were selected for Challenge X)
- Ensure a broad technology spectrum across teams selected that covers critical technologies and fuels of interest to the DOE
- Develop a rigorous competition framework based on safety and progressive development and testing of a multitude of advanced vehicle and fuel technologies

Challenge X Overview

- Four year engineering competition to develop advanced powertrain and fuel technologies with General Motors (GM)
- Based on GM's Global Vehicle Development Process utilizing math-based design tools and simulation
- 17 North American schools re-engineer a 2005 Chevrolet Equinox with hybrid powertrains of their design
  - ✓ Increase energy efficiency and reduce fossil energy consumption based on a well-to-wheels analysis
  - ✓ Reduce criteria tailpipe emissions and greenhouse gases
  - ✓ Maintain or exceed consumer acceptability in performance, utility, and safety



Diverse Industry Base Supplies the Students with Cutting Edge Technologies

HEADLINE SPONSORS
U.S. Department of Energy
General Motors

PLATINUM SPONSORS
Natural Resources Canada
The MathWorks
National Instruments
Freescale Semiconductor
AVL Powertrain Engineering, Inc.
U.S. Environmental Protection Agency
U.S. Department of Transportation

GOLD SPONSORS
National Science Foundation
BP
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SILVER SPONSORS
Cobasys
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Ballard Power Systems, Inc.
Michelin North America
Renewable Fuels Association

BRONZE SPONSORS
Caterpillar, Inc.
Vector CANtech, Inc.
Intrepid Control Systems, Inc.
Hydrogenics Corporation
MotoTron Corporation
UGS
XM Radio
On Star

Challenge X 2007 Team Technologies and Configurations

TEAM	HEV ARCHITECTURE	ENGINE	FUEL	TRANSMISSION	ENERGY STORAGE	MOTOR
Michigan Technological University	Through-the-road Parallel	2.0-L 4 Cylinder Spark Ignition	Reformulated	4-speed Automatic	COBASYS, Nickel Metal Hydride - 336V	50 kW Solectria AC Induction Transaxle
Mississippi State University	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20)	GM F40 6-speed Manual	Johnson Controls, Nickel Metal Hydride - 330V	45 kW Ballard Integrated Power Transaxle
The Ohio State University	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20)	Aisin-Warner AF40 6-speed automatic transaxle	Panasonic, Nickel Metal Hydride - 300V	67 kW Ballard AC Induction Transaxle / 10.6 kW Brushless DC Generator
Pennsylvania State University	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rose-Hulman Institute of Technology	Power Split	2.5-L 4 Cylinder Direct Injection Turbo	Bio Diesel (B20)	Custom Rose Hybrid 1-Mode Trans-	COBASYS, Nickel Metal Hydride - 336V	(2) 60 kW Custom AC Induction Motors
San Diego State University	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20)	GM F40 6-speed Manual	Panasonic, Nickel Metal Hydride - 400V	150 kW AC Propulsion AC Induction
Texas Tech University	Parallel Hybrid	2.4 L GM Ecotec VVT	Ethanol (E85) & Hydrogen	GM 4T45E, 4-speed Automatic	COBASYS, Nickel Metal Hydride - 36V	4 kW GM Belt-Alternator-Starter
University of Akron	Series Parallel 2 by 2	1.9-L 4 Cylinder Diesel Turbo Direct Injection	Bio Diesel (B20)	Direct Shift Gear Box (DSG) 6-Speed Manumatic	Nesscap, Ultracapacitor Bank - 370V	67 kW Ballard Integrated Power Transaxle / 36 kW Siemens Perma-nent Magnet Generator
University of California -- Davis	Pre-Transmission Parallel Plug-In Hybrid Capable	1.5-L Atkinson Spark Ignition	Ethanol (E85)	UC-Davis Custom Continuously [illegible]	GIA Lithium Technology, Lithium Ion-346 V	75 kW UQM Permanent Magnet - Front /60 kW ENOVA AC Induction - Rear
University of Michigan	Series Hydraulic	1.9-L GM Direct Injection Turbo [illegible]	[illegible]	[illegible]	Hydraulic Accumulators	Hydraulic 80 cc/rev & 55cc/rev Bent Axis Variable Displacement
University of Tennessee	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20)	GM F40 6 Speed Manual	COBASYS, Nickel Metal Hydride - 288V	67 kW Ballard AC Induction
University of Texas at Austin	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20)	GM F40 6-speed Manual	Johnson Controls, Nickel Metal Hydride - 42V	5 kW Hitachi AC Induction Belt-Driven Alternator/Starter
University of Tulsa	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20) & Hydrogen	GM F40 6-speed Manual	COBASYS, Nickel Metal Hydride - 288V	67 kW Ballard AC Induction Transaxle
University of Waterloo	Series Fuel Cell Electric	65 kW Hydrogenics HyPM Fuel Cell	[illegible]	[illegible]	COBASYS, Nickel Metal Hydride - 288V	(2) 67 kW Ballard AC Induction Transaxles
University of Wisconsin -- Madison	Through-the-road [illegible]	1.9-L GM Direct [illegible]	Bio Diesel (B20)	GM F40 6-speed [illegible]	Johnson Controls, Nickel Metal [illegible]	45 kW Ballard Integrated Power Transaxle
Virginia Tech	Split Parallel	2.3-L Saab Turbo Spark [illegible]	Ethanol (E85)	GM 5-speed Manual	COBASYS, Nickel Metal Hydride	52 kW Ballard AC Induction Transaxle / 8kW MES AC Induction Belt-Alternator/Starter
West Virginia University	Through-the-road Parallel	1.9-L GM Direct Injection Turbo Diesel	Bio Diesel (B20)	Aisin-Warner AF40 6-speed automatic transaxle	Maxwell, Ultra-cap - 750 kJ	(2) PML Wheel Hub Motors / 18 hp AC Induction Generator

RFG + light weighting

H2 combustion assist, B20 powered diesel parallel hybrid

Power split series hybrid

Plug-in hybrid

Series hydraulic hybrid

Dedicated fuel cell

B20 powered diesel through-the-road hybrid

E85 powered split parallel hybrid

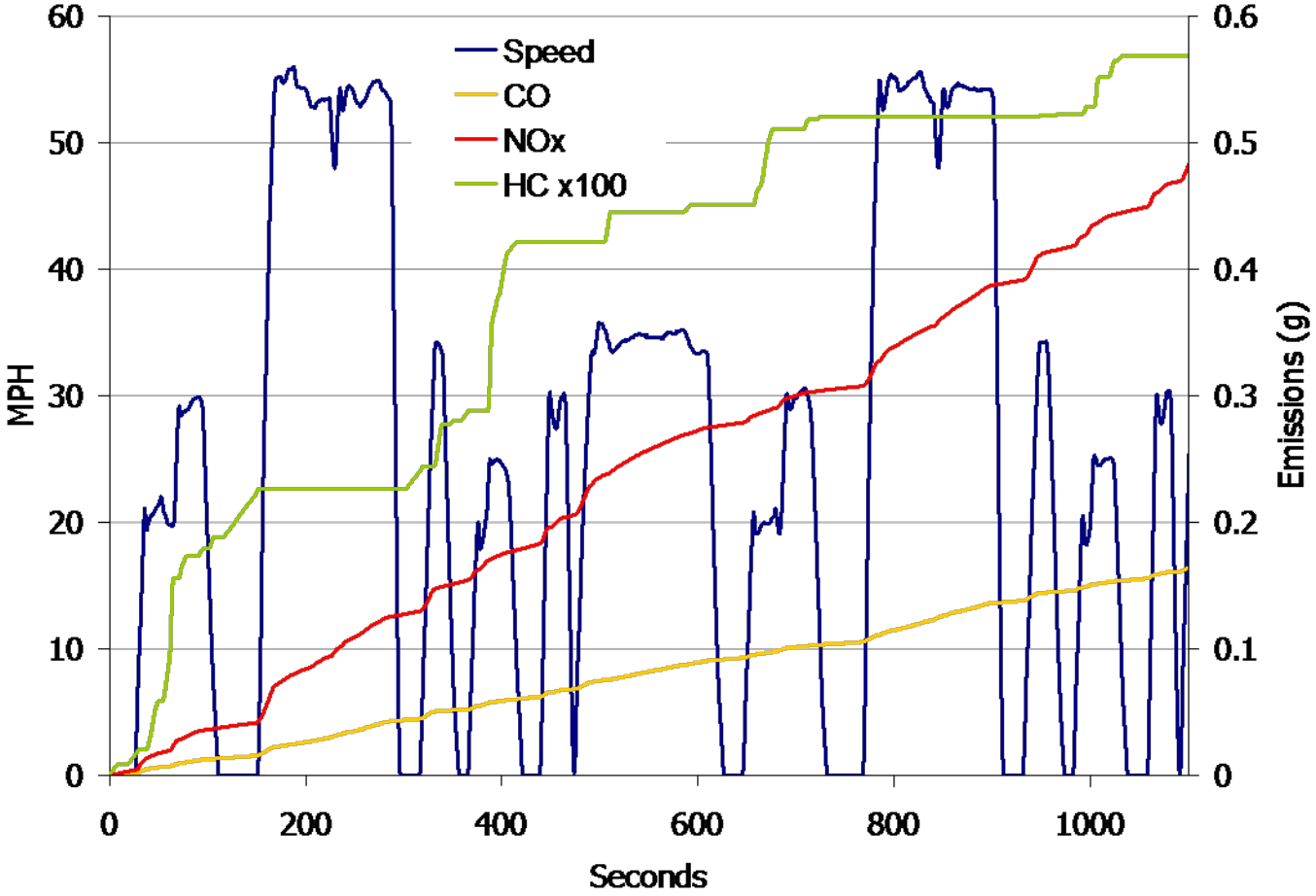
Performance Measures: Technical Accomplishments

- **Mississippi State achieved 30.1 mpg gasoline equivalent (37 mpg), 48% improvement** over production baseline for on road energy event
- **At the same time, Mississippi State demonstrated a 23% faster 0-60 mph** acceleration time relative to production vehicle (0-60 in 7.6 sec)
- **University of Waterloo emitted zero tailpipe emissions** for on road emissions event
- **University of Waterloo competed successfully in every event** as a dedicated fuel cell powered vehicle
- **Penn State achieved 0.06 g/mi NOx** emissions utilizing a downsized B20 powered diesel engine and a urea injection system (< production vehicle)
- **Virginia Tech demonstrated an impressive 77% reduction in petroleum use** with their E85 – Ethanol powered split parallel hybrid
- Utilizing Argonne National Laboratory's GREET model, **University of Wisconsin-Madison team demonstrated a 52% reduction in GHG emissions** relative to production counterpart




Technical Accomplishments: On Road Emissions Measured Real Time

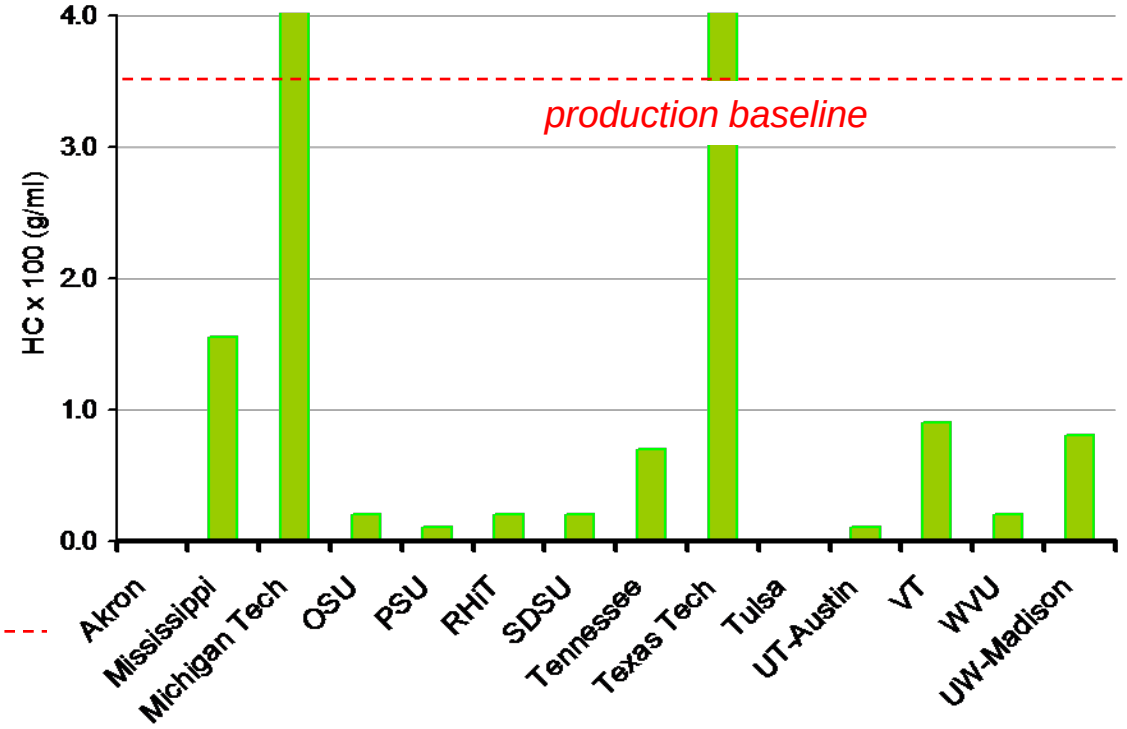
Actual WVU 2007 on road emission results

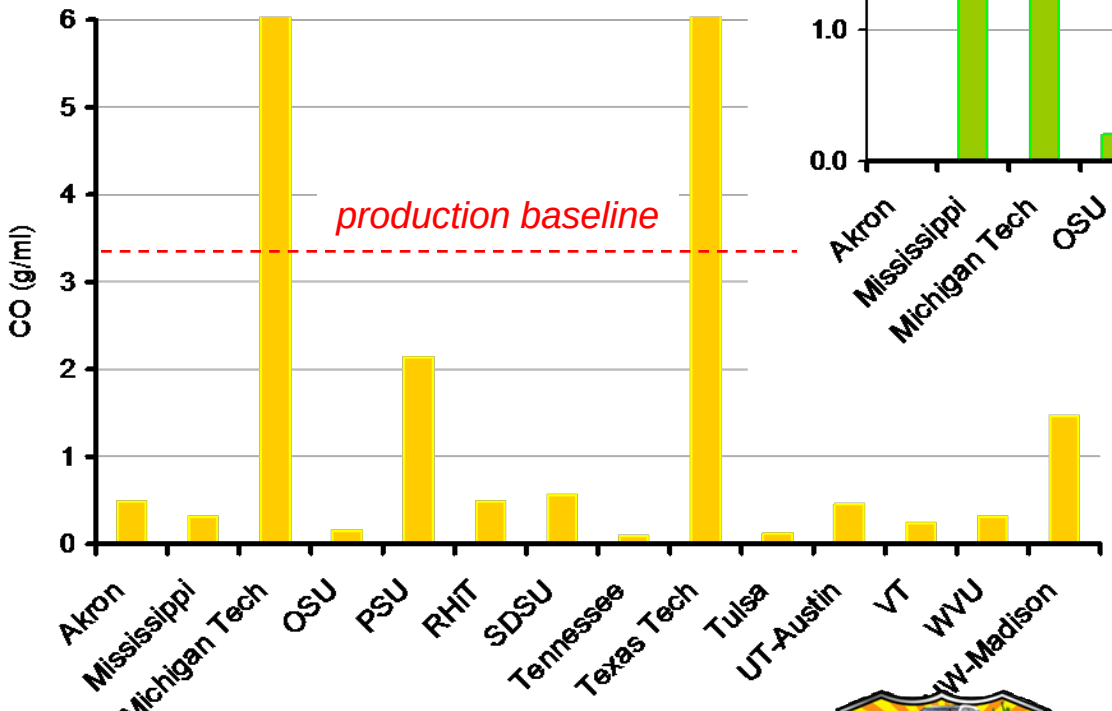


CHALLENGE X 2008 COAST TO COAST

Challenge X 2007 On Road Emissions Results 1

Many teams generated less HC emissions than production benchmark

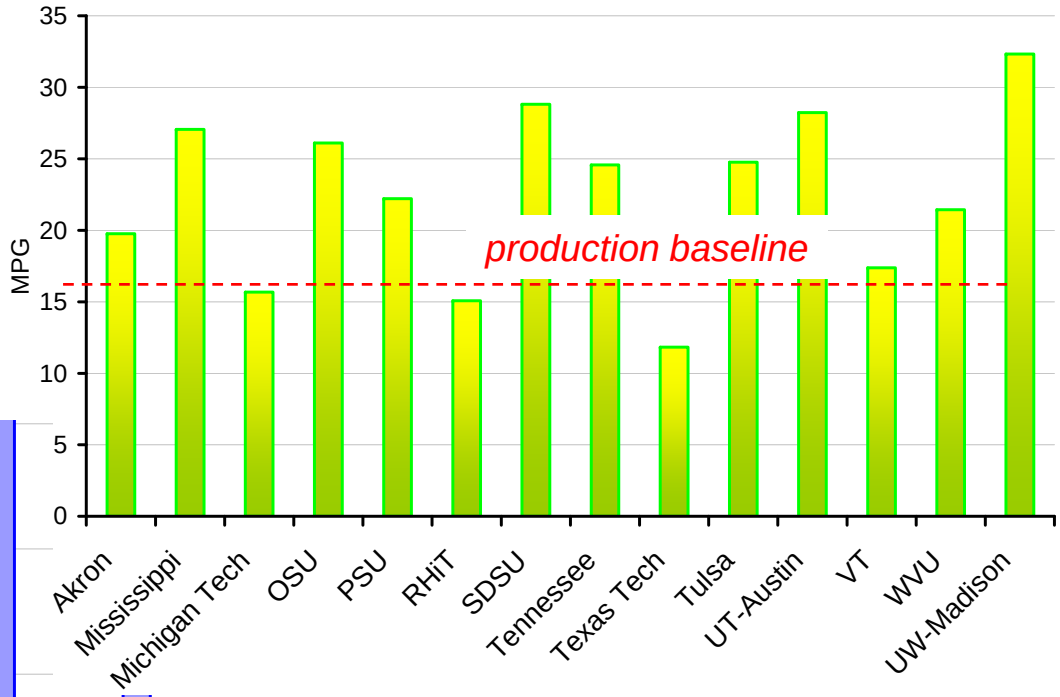


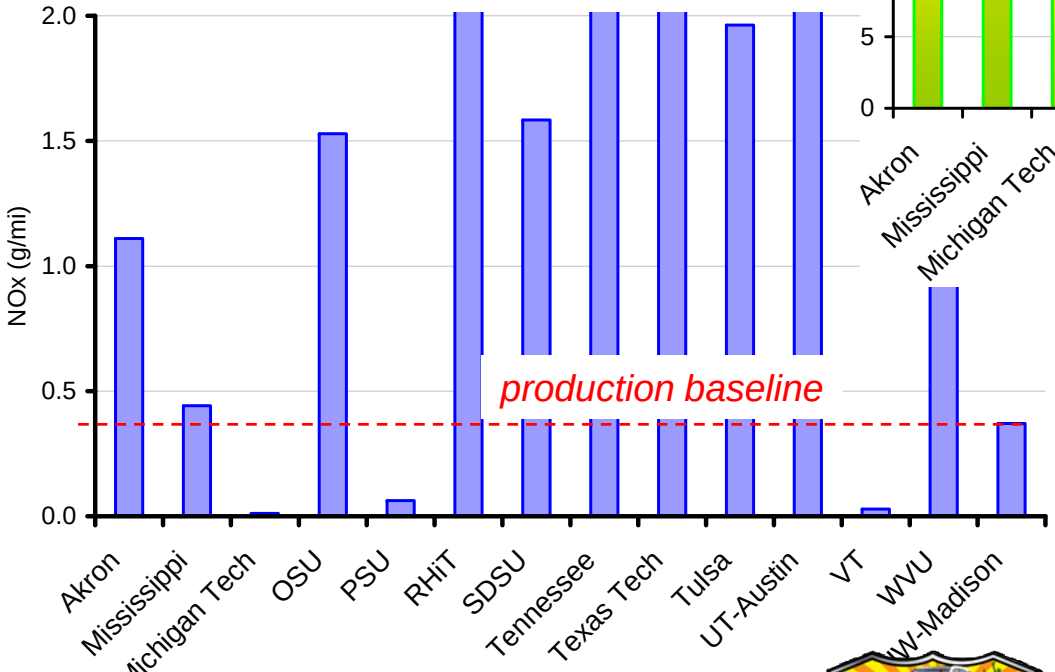


Most teams generated less CO emissions than production benchmark

Challenge X 2007 On Road Emissions Results 2

Most teams improved the production benchmark fuel economy for the on-road emissions event





Three teams generated less NOx than production counterpart

Performance Measures: Funding Leverage From Past AVTC's

FutureTruck 2003-4

- DOE contributed $900K
- Ford contributed $480,878 in cash; $713,661 in kind (excluding staff time)
- Other sponsors donated $299,500 in cash; $9,162,500 in kind (excluding staff time)

DOE cash contribution:	$900,000.00
DOE in-kind contribution:	$0.00
Total DOE Contribution:	$900,000.00
Non-DOE cash contribution :	$780,378.00
Non-DOE in-kind contribution :	$9,876,161.00
Total non-DOE Contribution :	$10,656,539.00
Total budget:	$11,556,539.00

DOE contribution leveraged by 1184% for FutureTruck 2003-2004
Challenge X analysis underway and expected to show similar results

Performance Measures: Talent Development

- Of the 6000+ competition graduates, many have assumed technical and leadership positions: BAS and Two Mode HEVs, advanced combustion research, ethanol and diesel engine development, battery technology, fuel cell development, plug-in, and other transportation technology fields

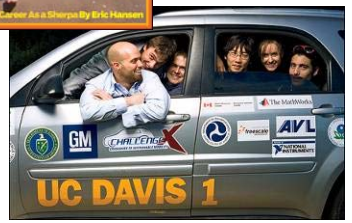
- Majority of competition graduates work in automotive field. DOE and the its national laboratories have acquired talent with competition experience (ANL, ORNL, and NREL)

"*I want you guys to know that Challenge X is by far the best thing I have ever done. I have been fortunate to have been involved in many valuable projects throughout my very long student career thus far, but CX was hands down the most valuable overall.*"

– Melanie Fox, PSU

Performance Measures: Media Coverage

- cX 07 generated 103+ unique print news stories; 39 local TV, 95 radio, and 55 online stories – many generated from the team's local Outreach Programs
- Key print stories appeared in *New York Magazine, Popular Mechanics, USA Today*, the *Wall Street Journal,* on TV shows aired on the Canadian Discovery Channel, as well as Motorweek
- cX 07 PR/Media efforts reached an estimated audience of over 23.3 million (some outlets do not track audiences)
- cX 07 Online coverage generated ~214 million hits (from sites such as Google, Yahoo! and MSN; on news sites such as Google News, Yahoo! News, WSJ.com, PR Newswire and Forbes.com; and on video sites such as YouTube, MetaCafe and Yahoo! Video)
- cX 08 is expected to far exceed 07 results. More than 30 media attended the competition including three documentary film crews. More than 35 stories have been generated, including a feature on Bloomberg TV's *Night Talk*



Performance Measures: Technical Publications*

- "*Combining Passion with Fundamentals- Applying Model-Based Design to Education,*" Marc E. Herniter, Zachariah Chambers, Sameer M. Prabhu, Elizabeth Callanan, Submitted to the 2008 SAE World Congress, Paper No. 2008-01-1292, April 14-17, 2008, Cobo Center, Detroit, Michigan.
- "*Development of Model Based Design Curriculum,*" Sameer Prabhu, Liz Callanan, Zach Chambers, and Marc Herniter, Presented at the 2007 ASEE Annual Conference and Exposition, Paper No. AC 2007-953, June 24-27, 2007, Honolulu, Hawaii.
- "*Hybrid-Electric Vehicle Controller Development - Levels of Simulation and Verification*," Marc E. Herniter, Zachariah Chambers, Caleb N. Harper, Jeffrey S. Parks, Matthew DeVries, Benjamin T. Ciavola, Adam M. Williams, Edgar A. Vargas, and Gary V. Wieneke, 2007 SAE World Congress paper No. 2007-01-1067, April 16-19, 2007, Cobo Center, Detroit, Michigan.
- "*Simulation Results of a Power-Split Architecture Hybrid Electric Vehicle,*" Marc E. Herniter and Zachariah Chambers, Presented at The 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition, EVS 2006 paper No. P10019-001, October 23-28, Yokohama, Japan.
- Jih-Sheng (Jason) Lai, and Douglas J. Nelson, "*Energy Management Power Converters in Hybrid Electric and Fuel Cell Vehicles*", IEEE Proceedings - Special Issue on Electric, Hybrid & Fuel Cell Vehicles, Vol 96, No.4, April 2007, pp. 766-777 (invited review paper).
- Steven Boyd, J. Lee and Douglas J. Nelson (2007), "*A Simplified Battery Model for Hybrid Vehicle Drive Cycle Efficiency Estimation*", Paper 2007-01-0301, SAE International World Congress, Detroit, Mi, April 16-19, 2007.
- E. Wilhelm, M. Wahlstrom, M.B. Stevens, C. Mendes, C. Lawrence, D. Sellan, C. Haliburton, Dr. M.W. Fowler, Dr. R.A. Fraser 2007 "*Implementation and Optimization of a Fuel Cell Hybrid Powertrain*" SAE World Congress April 16-19 2007, Detroit.

*Note: publications shown are a partial listing from 3 teams in Y3 of the competition

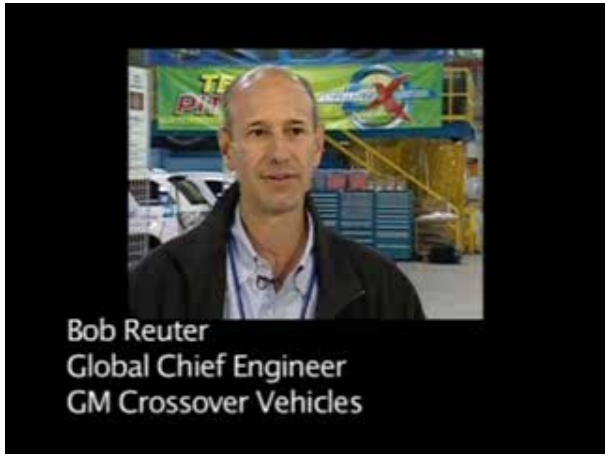
Performance Measures: Technical Publications*

- Kurt Johnson, Irene Berry, Erin Hissong, Jeevan Nalli, Ryan Pawlowski, and Douglas J. Nelson (2008), "*Validation, Testing, and Refinement of the Equinox REVLSE E85 Hybrid Electric Vehicle*", Paper 2008-01-0435, 2008 SAE International World Congress, Detroit, Mi, April 14-17, 2008.
- Steven Boyd, and Douglas J. Nelson (2008), "*Hybrid Electric Vehicle Control Strategy Based on Power Loss Calculations*", Paper 2008-01-0084, 2008 SAE International World Congress, Detroit, Mi, April 14-17, 2008.
- Bryan Shevock and Douglas J. Nelson (2008), "*System Level Transient Model of a Fuel Cell System*" SAE paper 2008-01-0636, 2008 SAE World International Congress, April 14-17, Detroit, Mi.
- Bryan Shevock (2008), "*System Level Modeling of Thermal Transients in a PEM Fuel Cell System*", MS Thesis, VPI&SU, Blacksburg, Va.
- John Janczak (2007), "*Implementation of a Hardware-in-the-Loop System Using Scale Model Hardware for Hybrid Electric Vehicle Development*".
- "*Model-Based Design for Hybrid Electric Vehicle Development,*" Marc E. Herniter, Zachariah Chambers, Sameer M. Prabhu, Matthew Stevens, Roydon Fraser, and Michael Fowler, Presented at The 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition, EVS 2006 paper No. P10019-002, October 23-28, Yokohama, Japan.
- "*New Hybrid Technology Developed Through the Challenge X Competition,*" Zachariah Chambers, Marc E. Herniter, Brian Roser, Todd Richard, Clinton Anthony Hammes, 2006 SAE World Congress paper No. 2006-01-0518, April 3-7, Cobo Center, Detroit, Michigan.
- "*Vehicle Model Development and Verification Using MathWorks Simulink and National Instruments Virtual Instrumentation,*" Marc E. Herniter and Zachariah Chambers, 2006 SAE World Congress paper No. 2006-01-0516, April 3-7, Cobo Center, Detroit, Michigan.

*Note: publications shown are a partial listing from 3 teams in Y3 of the competition

Benefits Extend Throughout Government, Industry, and Academia

- AVTCs generate new strong working relationships between government sponsors, industry, and academia generating new business/collaboration/research opportunities
- Vast technology information exchange: DOE can explore technologies they may not have the resources to fund individually
- Universities gain cutting edge technology; develops highly trained, knowledgeable students

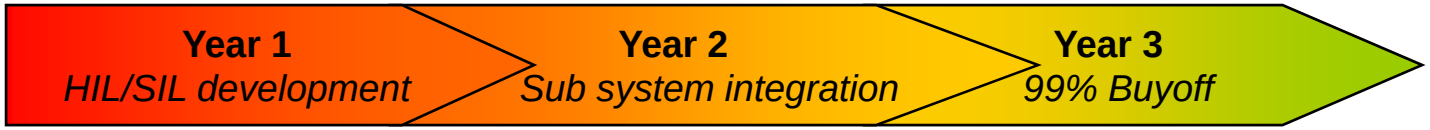


Rick Wagoner, Chairman and CEO of General Motors

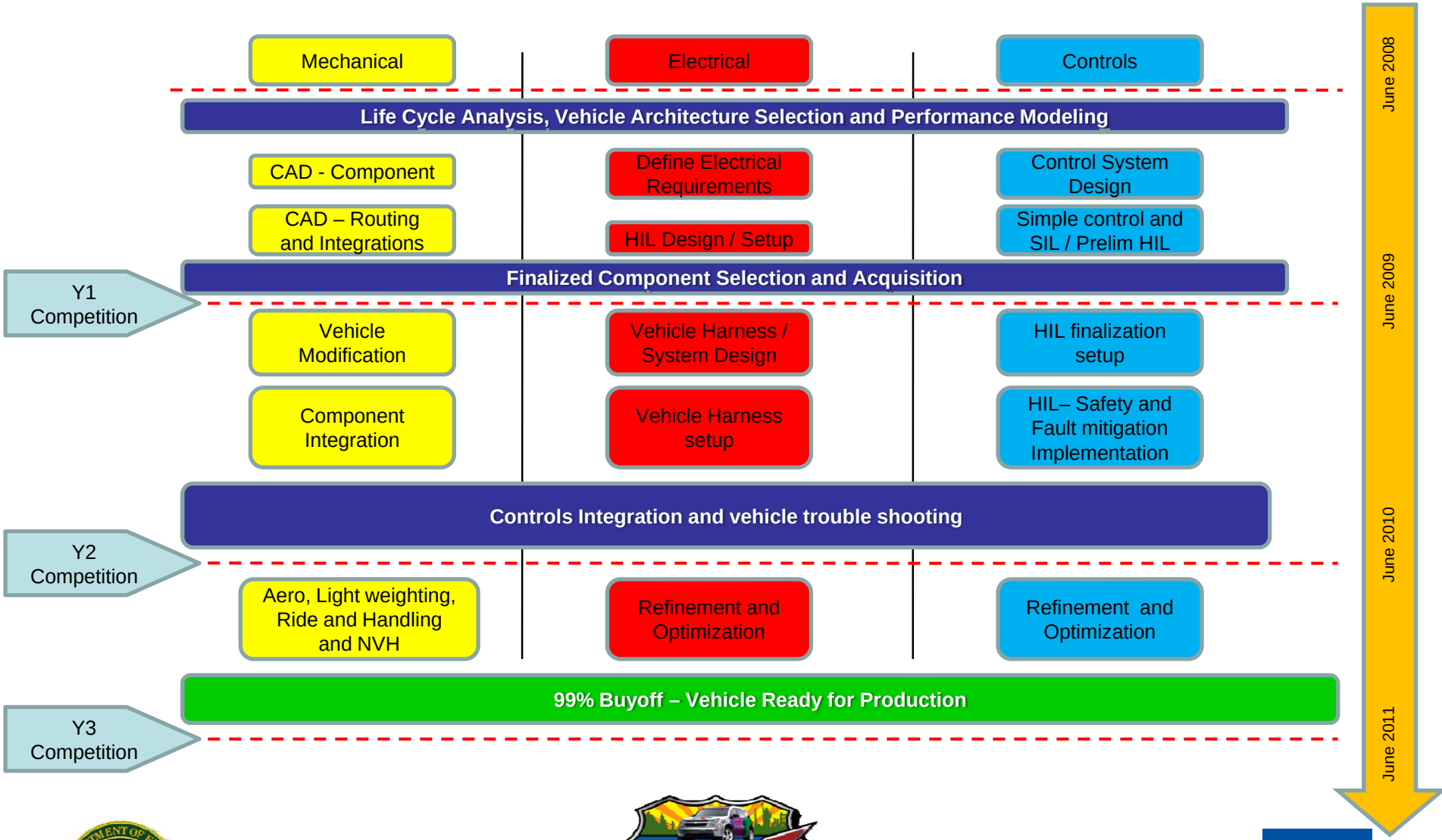
What's next?

EcoCAR Overview

- Three year engineering competition to develop advanced powertrain and fuel technologies loosely based on CARB ZEV mandate
- Multiple hybrid technologies developed:
  - Hybrid electric vehicle — < 50-kW peak electric motor power
  - Hybrid electric vehicle — > 50-kW peak electric motor power
  - Range-extending and full-function electric vehicles
  - Hydrogen fuel cell vehicles
- Based on GM's Global Vehicle Development Process utilizing math-based design tools and simulation: Y1 emphasis on HIL/SIL development
  - ✓ Increase energy efficiency and reduce fossil energy consumption based on a well-to-wheels analysis
  - ✓ Reduce criteria tailpipe emissions and greenhouse gases
  - ✓ Maintain or exceed consumer acceptability in performance, utility, and safety



EcoCAR Competition Format



Summary

- Challenge X 2007 one of the most successful AVTC's
  - ✓ 16 of 17 vehicles qualified; 16 competed in events
  - ✓ A record for second-year competition vehicles
  - ✓ Fully functional fuel cell competed in every event
- A number of teams achieved significant improvement over the production Chevrolet Equinox in all energy and emissions related comparisons utilizing RFG, E85, and B20
- Data was collected from vehicles using all powertrain, fuel, and material technologies being developed by DOE
- Challenge X 2007 produced more than the 23 million media hits, leading to one of the highest profile AVTC's in history
- Rick Wagoner, GM CEO, showed genuine interest in the competition spending several hours with students and organizers voicing his support
- EcoCAR, the next competition, is underway and will continue the largely successful AVTC program for the U.S. DOE