Evaluation and Adaption of 5-Cycle FE Testing and Calculations for HEV

2012 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

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Project ID # VSS065

Overview

- **Timeline**
  - Summer 2011 Literature review and planning phase
  - Summer/Fall 2011 Testing phase
  - Fall 2011 OEM PHEV TADA testing and 5 cycle investigation
  - Fall 2011/Winter 2012 Data analysis phase
- **Budget**
  - 2012FY $100k

- **DOE strategic goals/barriers addressed:**
  - D. Lack of standardized test protocols.
  - F. Constant advances in technology.
- **Partners:**
  - Virginia Tech (research student in mechanical engineer masters program and faculty advisor)
  - EPA: sharing of study plan, data and results

80% complete on FY2012 tasks

Relevance: *Is There an Unintended Issue with 5-cycle Fuel Economy Calculations for Hybrid Electric Vehicles?*

- Objectives:

  EPA fuel economy calculation methods use test results from individual phases of certain drive cycles which are not required to have battery charge balance on hybrid vehicles. How does that affect the label fuel economy?

- Background

  To reflect the 'real world FE' customers may experience, the EPA redefined the FE label calculations based on real world driving data sets. The derived calculations were based on conventional vehicles.

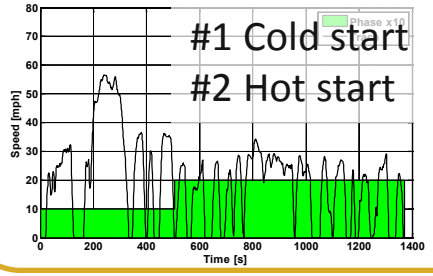
- Investigative questions:
  - If there is charge imbalance on a phase, is it possible to develop a ***correction line*** for it?
  - What effect do the phase charge imbalances have on ***the final fuel economy label rating***?
  - Does the 5-cycle method encourage ***different design decisions*** than the 2-cycle method?

Background: Since 2008, EPA's Fuel Economy Calculation Method Weights Results from 5 Cycles

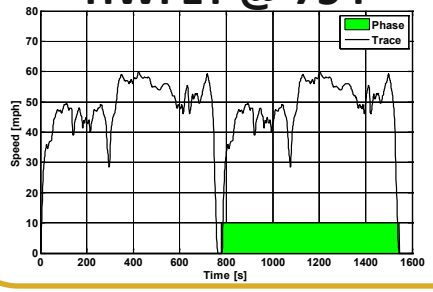
- 2008+ goals: reflect real-world operation in terms of, Driving patterns (speeds/accels), Air conditioning and Heater usage, Hot and Cold temperatures

Classic cycles!

FTP UDDS @ 75

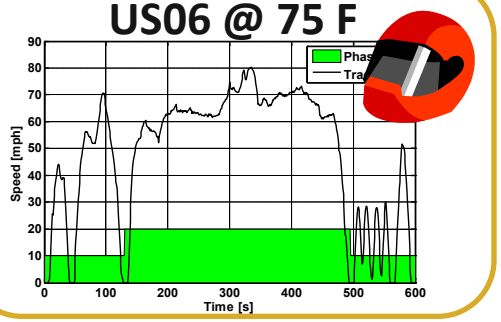


HWFET @ 75 F



Aggressive cycle!

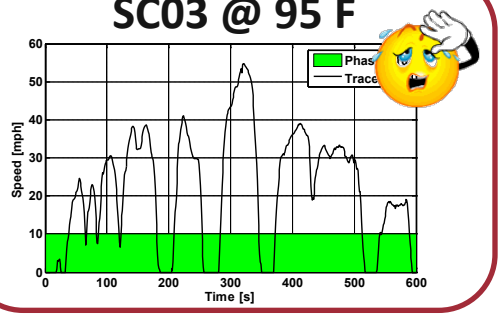
US06 @ 75 F



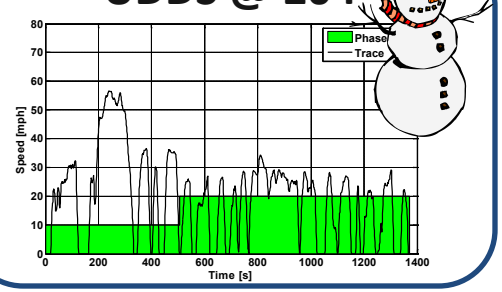
All 5 cycles existed previously for emissions testing purposes (but had not all been used to calculate fuel economy)

Extreme Temperatures!

SC03 @ 95 F

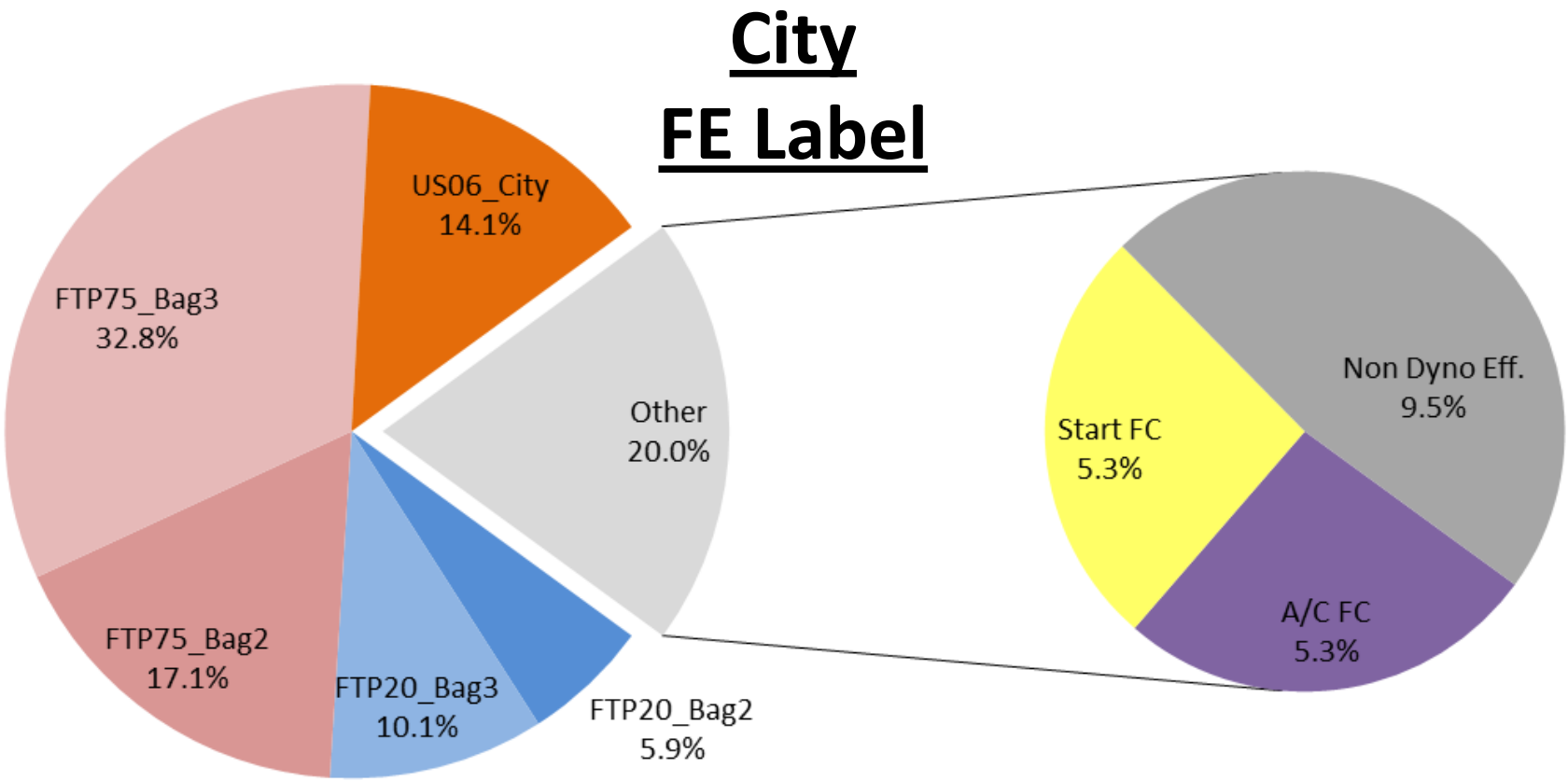


UDDS @ 20 F



Background: 5 Cycle City FE Label Composition

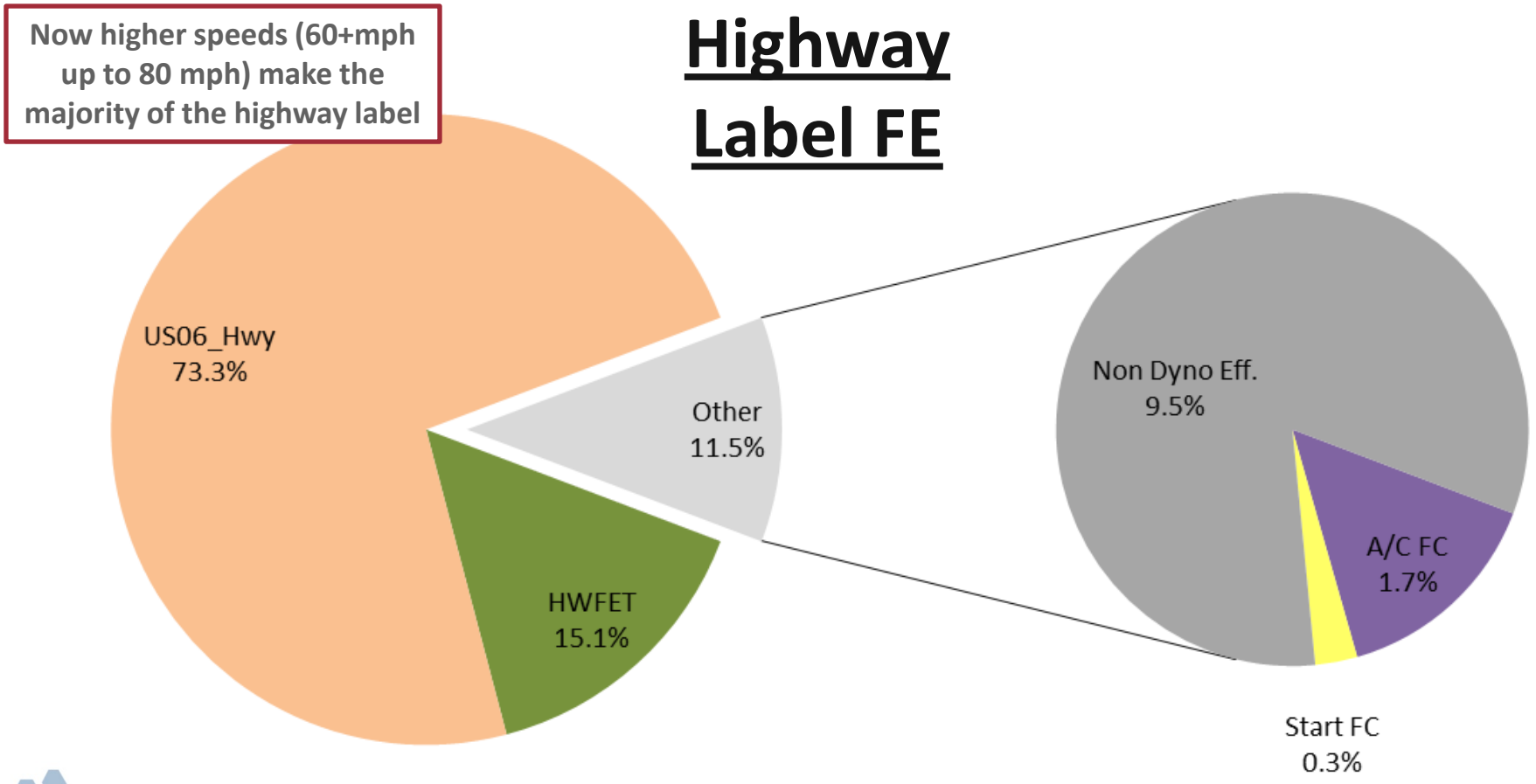
- 2010 Toyota Prius example (not all cars will have same %)



Background: 5 Cycle Highway FE Label Composition

- 2010 Toyota Prius example (not all cars will have same %)

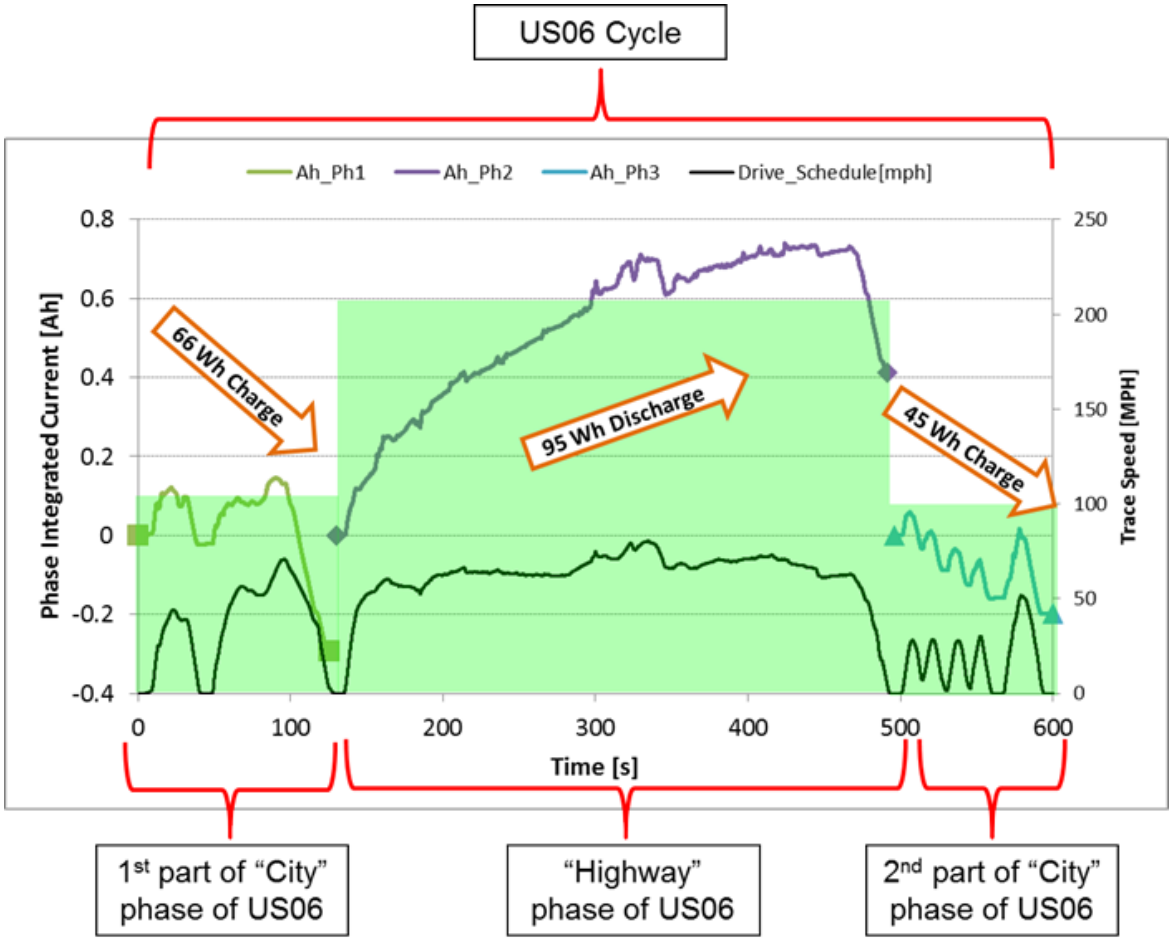
Now higher speeds (60+mph up to 80 mph) make the majority of the highway label



Approach/Strategy: Charge Sustaining HEV Behavior on a Drive Cycle vs. Cycle Phase

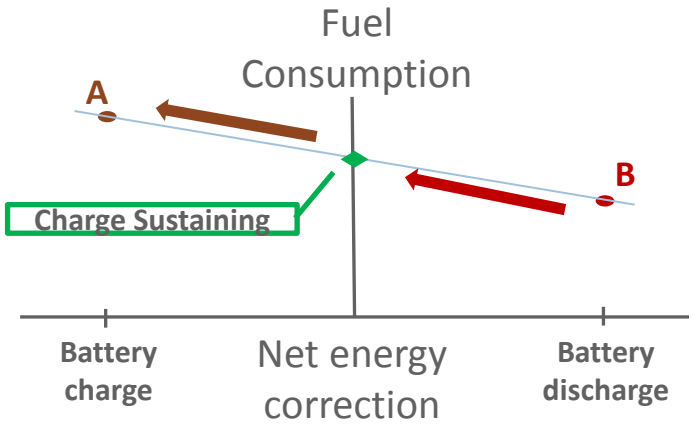
- SAE J1711 only explicitly addresses **full cycle** charge balance requirements and correction methods
- Net energy change (NEC) = net battery energy delta, expressed as percentage of the fuel energy consumed on cycle
- Requirement: +/- 1 % NEC of fuel energy

But, it is the phase results that are used in FE calculation



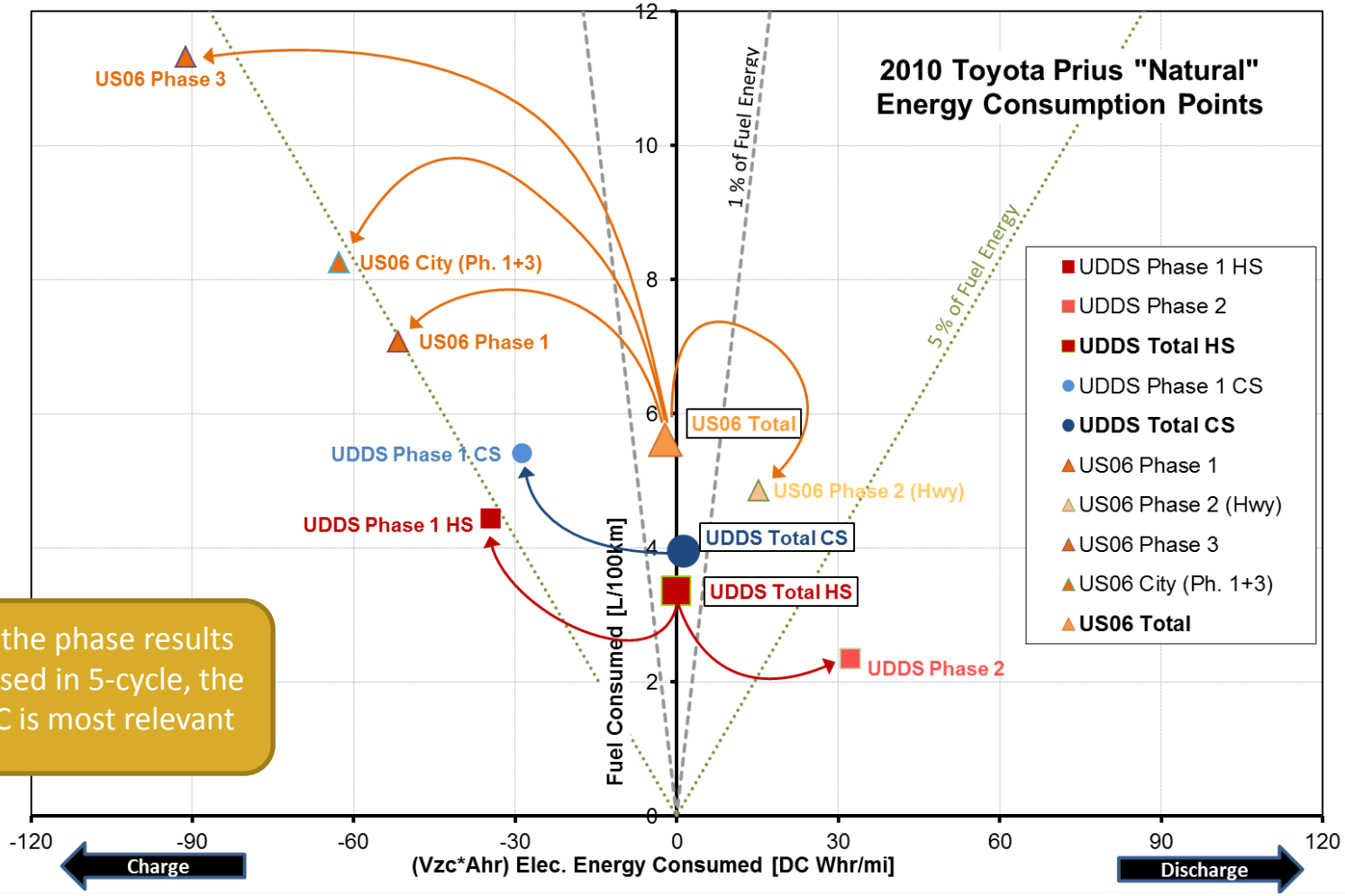
Approach/Strategy: Determine the Charge Corrected FC for all the Phases to Calculate Label FE

- Determine the FE Charge Correction Line for all the Phases by testing a 2010 Toyota Prius HEV on the chassis dynamometer
- As defined in SAE J1711, multiple tests at varying battery state of charge (electric energy) can be used to form a correction line



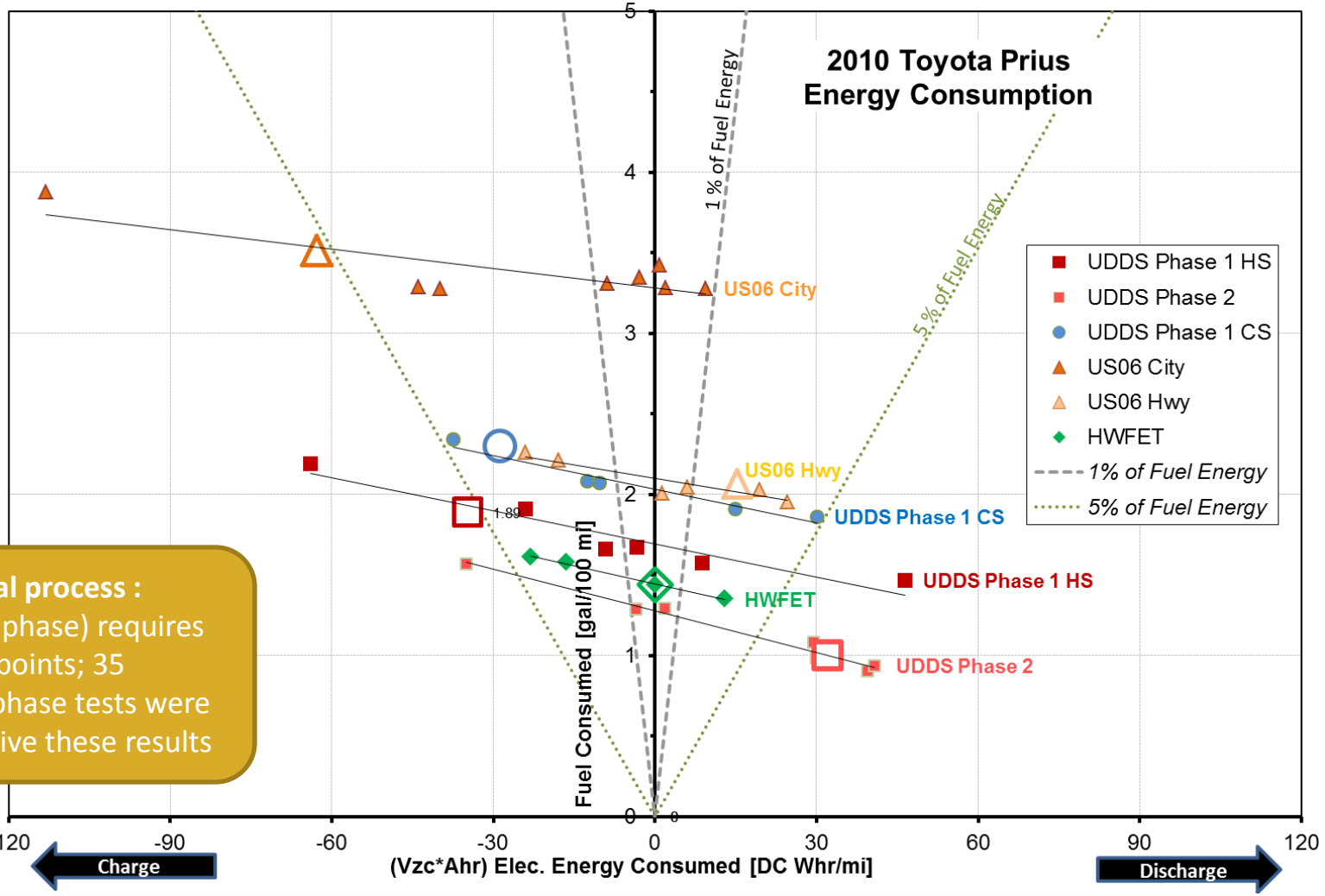
Technical Accomplishments: On Charge-Balanced Cycles, the Individual Phases will Charge or Deplete

- Each phase result point is taken from the CS cycle shown



Since it is the phase results that are used in 5-cycle, the phase NEC is most relevant

Technical Accomplishments: Charge Correction Lines for Each of the Non-CS Phases



Impractical process :
Each line (phase) requires at least 4 points; 35 separate phase tests were run to derive these results

Technical Accomplishments: Affect on Phase FE Due to Correction Varied

Significant FC correction

Cycle	Raw Slope [gal/100 mi per Wh/mi]	Inverse Unit less Slope [Elec Energy / Fuel Energy]	Intercept [gal/100 mi]	*Corrected* Phase MPG	Phase MPG of CS cycle	% Error from CS FC
UDDS Phase 1 Hot Start (HS)	-0.00687	-0.436	1.69	59.1	53.1	11%
UDDS Phase 2	-0.00858	-0.349	1.28	78.3	100.1	-22%
UDDS Phase 1 Cold Start (CS)	-0.00694	-0.431	2.03	49.2	43.5	13%
US06 City	-0.00399	-0.751	3.28	30.5	28.5	7%
US06 Hwy	-0.00660	-0.454	2.08	48.1	48.4	-1%
HWFET	-0.00743	-0.403	1.45	69.2	69.4	0%

Technical Accomplishments: Correction on 5-Cycle Fuel Economy Label Much Smaller than On Any One Phase

5-cycle label for:	Uncorrected MPG	Corrected MPG	% diff in FC
City	47.1	46.8	+0.6 %
Highway	45.4	45.2	+0.4 %

Note: Cold CO results are estimated; effect on FC of charge correction assumed the same as for normal FTP

Collaborations and Coordination with Other Institutions

Virginia Polytechnic Institute and State University
College of Engineering
VirginiaTech

U.S. EPA National Vehicle and Fuel Emissions Laboratory
Shared test plans, data and analysis

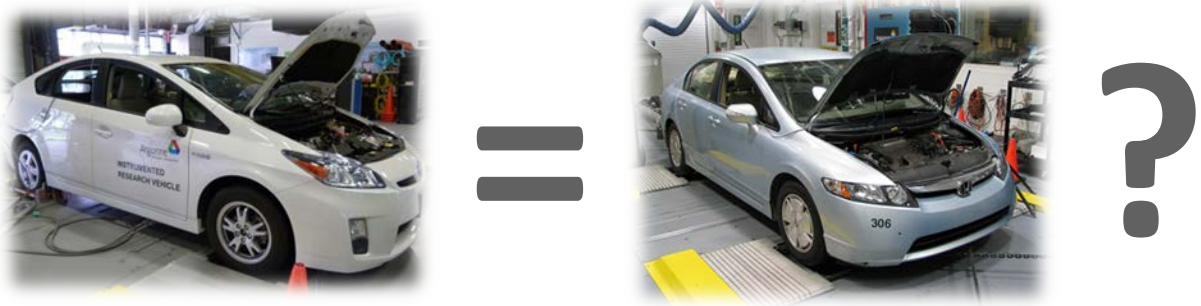
APRF

Autonomie
Support of modeling and simulation with data
AUTONOMIE

USCAR, tech teams and OEMs
Shared test plans, data and analysis
USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Proposed Future Work: Further Thermal Testing and Analysis of HEV and PHEV

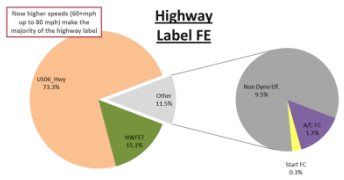
- Future work
  - Additional testing of different HEVs and PHEVs on the 5 cycle procedures
  - Further analysis with the test data using the 5 cycle FE label equations
  - Evaluate PHEVs which use larger battery capacity and different control strategies compared to HEVs

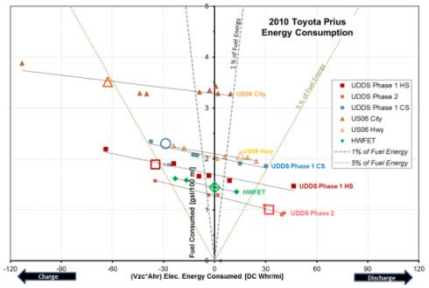


Proposed Future Work: U.S. DOE's Advanced Powertrain Research Facility is Now '*5 Cycle*' Capable!

- Test cell features
  - ✓ 4WD chassis dyno
  - ✓ Data driven DAQ
  - ✓ Emission (Bag bench, raw benches, FTIR,…)
  - ✓ Alternative fuel capable
  - ✓ Power analyzers
  - ✓ Specialized instrumentation
  - ✓ Speed match fan
- Thermal test status
  - ✓ 20F for Cold tests
  - ✓ 72F for ambient tests
  - ✓ 95F and solar lamps for air conditioning
  - ✓ 0F achieved during commissioning

Summary





- 5-cycle potential HEV challenges
  - EPA 5-cycle FE labeling method considers wider range of driving and thermal conditions
  - It uses separate phases of existing cycles introducing charge-balance issues for HEVs
  - New highway FE label calculations may shift additional focus to vehicle aerodynamics with higher US06 speeds
- Identified and quantified charge-balance concern with calculated corrections
  - The 2010 Toyota Prius showed significant phase charge imbalance. FTP and US06 phases ≈ 5 % of fuel energy
  - Developed charge correction lines; showed that the effect on phase fuel consumption could reach 22 %
  - Vehicle behavior does not fulfill simple assumption of fuel energy -> electric energy conversion efficiency for charge correction on some phases (biggest issue: US06 city)
  - In the end, the effect on label FE is not as large as on any 1 phase
- Future work
  - Further Thermal Testing and Analysis of HEV and PHEV

Technical Back-Up slides

Total label fuel consumption subdivided into contributing portions; combined with equations

	Part	Description/Notes
1	Start fuel	Computed from difference in cold and hot start FTP test fuel consumptions at both 75 and 20 °F
2	Running fuel at 75 °F without A/C	Harmonically weights FC results from cycles (see next slide)
3	Effect of A/C	Compares SC03 fuel consumption to a comparably-weighted section of the FTP to find A/C fuel consumption
4	Effect of cold ambient temperatures	Incorporated into running fuel and start fuel through Cold FTP result
5	Adjustment for non-dynamometer effects	Increases final fuel consumption by 9.5 % to account for real-world factors not captured in dynamometer testing, e.g. fuel quality, tire pressure, wind, etc.

EPA reference: **Final Technical Support Document** - Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates http://www.epa.gov/fueleconomy/420r06017.pdf

5 Cycle City Fuel Economy Calculations

City Fuel Economy

$$City\ FE = 0.905 \times \frac{1}{Start\ FC + Running\ FC}$$ where

Overall adjustment for "non-dyno effects"

$$StartFC\ (gallons\ per\ mile) = 0.33 \times \left(\frac{(0.76 \times StartFuel_{75}) + (0.24 \times StartFuel_{20})}{4.1} \right),$$

$$Start\ Fuel_x = 3.6 \times \left[\frac{1}{Bag1\ FE_x} - \frac{1}{Bag3\ FE_x} \right]$$

Running fuel consumption

Warm

Cold

$$Running\ FC =$$

$$0.82 \times \left[\frac{0.48}{Bag2_{75}\ FE} + \frac{0.41}{Bag3_{75}\ FE} + \frac{0.11}{US06\ City\ FE} \right] + 0.18 \times \left[\frac{0.5}{Bag2_{20}\ FE} + \frac{0.5}{Bag3_{20}\ FE} \right]$$

$$+0.133 \times 1.083 \times [A/C\ FC]$$

$$A/C\ FC = \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag3_{75}\ FE} + \frac{0.39}{Bag2_{75}\ FE} \right) \right]$$

5 Cycle Highway Fuel Economy Calculations

Highway Fuel Economy

$$Highway\ FE = 0.905 \times \frac{1}{Start\ FC + Running\ FC}$$

Same adjustment; same definitions for Start Fuel, but…

$$StartFC\ (gallons\ per\ mile) = 0.33 \times \left(\frac{(0.76 \times StartFuel_{75}) + (0.24 \times StartFuel_{20})}{60} \right)$$

…factor here is (1/60) vs. (1/4.1) for City FE (less starts in highway driving)

Running fuel consumption

$$Running\ FC = 1.007 \times \left[\frac{0.79}{US06\ Highway\ FE} + \frac{0.21}{HFET\ FE} \right] + 0.133 \times 0.377 \times [A/C\ FC]$$

Here all tests at 75°F – temp effects are only under start fuel calculation and added A/C FC component, which is the same as in City FE