MTE Technologies and Costs

2022-2025 GHG Emissions Standards

Briefing to the National Research Council of the National Academies Committee on Fuel Economy of Light-Duty Vehicles

July 31, 2014

Office of Transportation and Air Quality
Office of Air and Radiation
U.S. Environmental Protection Agency

Agenda

1. Introductions
2. **NCAT* Benchmarking Activities**
   a) **ALPHA and Vehicle Validation** (GM Malibu w/ 2.5 liter EcoTec)
   b) **Shifting Study** (6-spd Malibu & 8-spd Chrysler 300)
   c) **Engine Mapping** (US Ford Escape w/1.6 liter EcoBoost)
   d) **Study of future engines**
3. Lumped Parameter Model Application
4. Mild Hybrid Tear-down Study
5. Silverado Mass Reduction Study
6. ICM Study
7. Other NAS specific topics not covered above (as required)
8. Wrap-up
9. NCAT Lab Review

**NCAT –National Center for Advanced Technologies*

Vehicle Simulation Tool for the MTE

Goals for EPA Modeling for 2022-2025 analysis…

- Build off of the HD GEM* framework to build LD ALPHA*
  - GEM had to be developed in-house in 2010 because of its key role in HD Certification
  - Models utilize same code and structure (Matlab/Simulink)
  - Apply EPA's extensive experience and expertise in testing, advanced technology and modeling
- Developing detailed engineering models is a great way for EPA to develop deep expertise in advanced technologies and how they interact with other technologies
- Full transparency – models are open and free for the public
- Faster turn around for adopting new information for scenario analyses
- Validate models using data inputs generated from its in-house lab testing and other sources

* **GEM** – **G**reenhouse Gas **E**missions **M**odel
* **ALPHA** – **A**dvanced **L**ight-Duty **P**owertrain and **H**ybrid **A**nalysis

Tools to Model Future Fleet

REVIEW

"**O**ptimization **M**odel for reducing **E**missions of **G**reenhouse gases from **A**utomobiles"

OMEGA is used to evaluate a future fleet's potential compliance path with LD GHG standards

- ✓ Feasibility analysis of how a fleet might utilize these technologies to comply with LD standards, not a market prediction
  - Manufacturer's engineering, marketing, or other considerations may lead them to a different path
  - Model assumes that technology availability and cost is equivalent across manufacturers
- ✓ Detailed fleet baseline on relevant technologies for ~1300 current models in the light duty fleet (modeled as ~250 vehicle platforms)
- ✓ Future vehicle sales are based on Economic projections from DOE/EIA, and Industry forecasts from JD Powers and CSM (Now IHS)

Lots of DATA!

Component Data
- ✓engine
- ✓transmission
- ✓electrical components
- ✓chassis, etc.

Vehicle Data
- ✓steady-states
- ✓transient cycles

ALPHA Model

Assesses Combinations of Light-Duty Technologies

- ✓ ALPHA is a full forward looking physics based vehicle simulation model programmed in Matlab/Simulink
- ✓ Quantifies effectiveness of a technology or groups of technologies
- ✓ Helps assess feasibility of light-duty standards

OMEGA Model

Assesses Potential Compliance Path with New LD GHG Rules

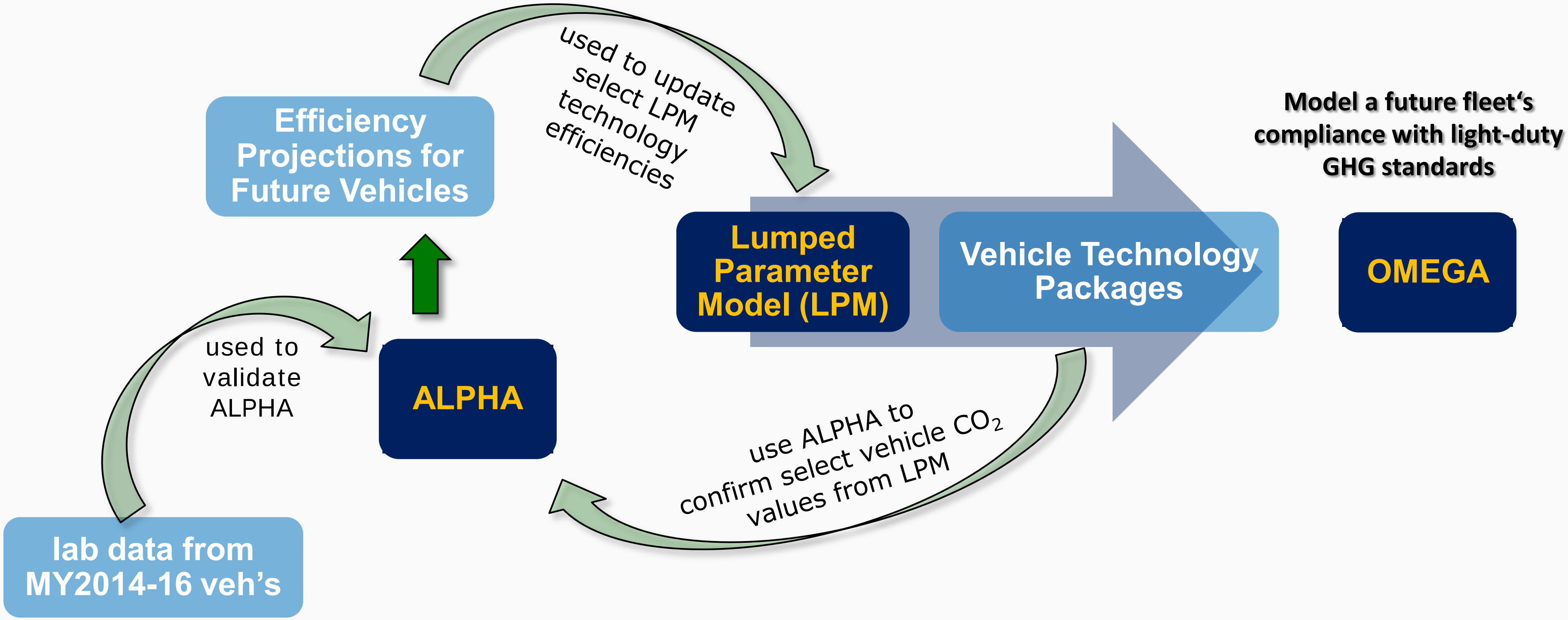
- ✓ Determines cost efficient path(s) of adding technology to vehicles in order to achieve regulatory compliance
- ✓ Quantifies economic and environmental impacts of technology changes/improvements in vehicle fleets
- ✓ Requires many scenarios of future vehicle technologies and their effectiveness (among many other model inputs) on reducing GHG emissions

Modeling Tools: ALPHA, Lumped Parameter Model (LPM) and OMEGA

REVIEW

Transparent processes will generate "technology effectiveness" inputs for the OMEGA model

- Use EPA lab and other data to validate ALPHA model
- Use ALPHA model to verify and supplement 2008 & 2011 Ricardo simulations
- Use ALPHA simulation results (and other data sources) to update LPM as appropriate
- Use LPM to generate vehicle technology packages (used as inputs to OMEGA)



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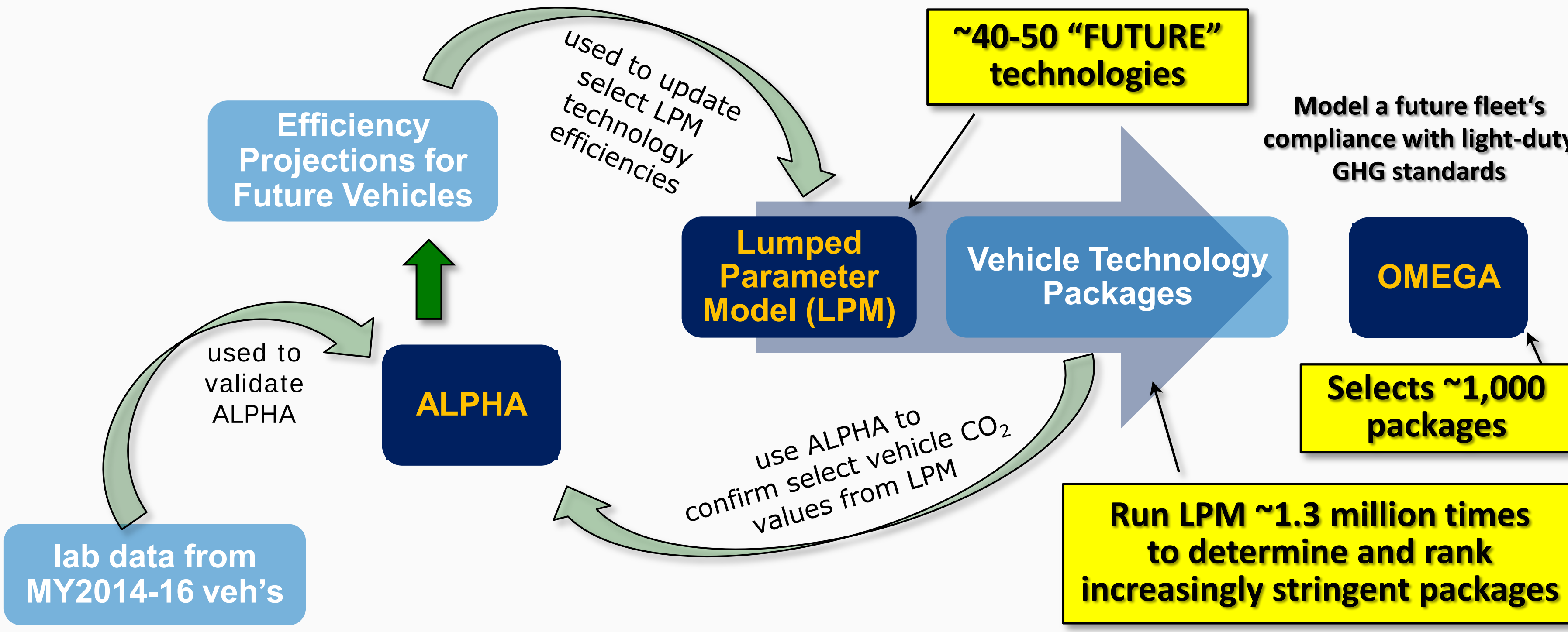

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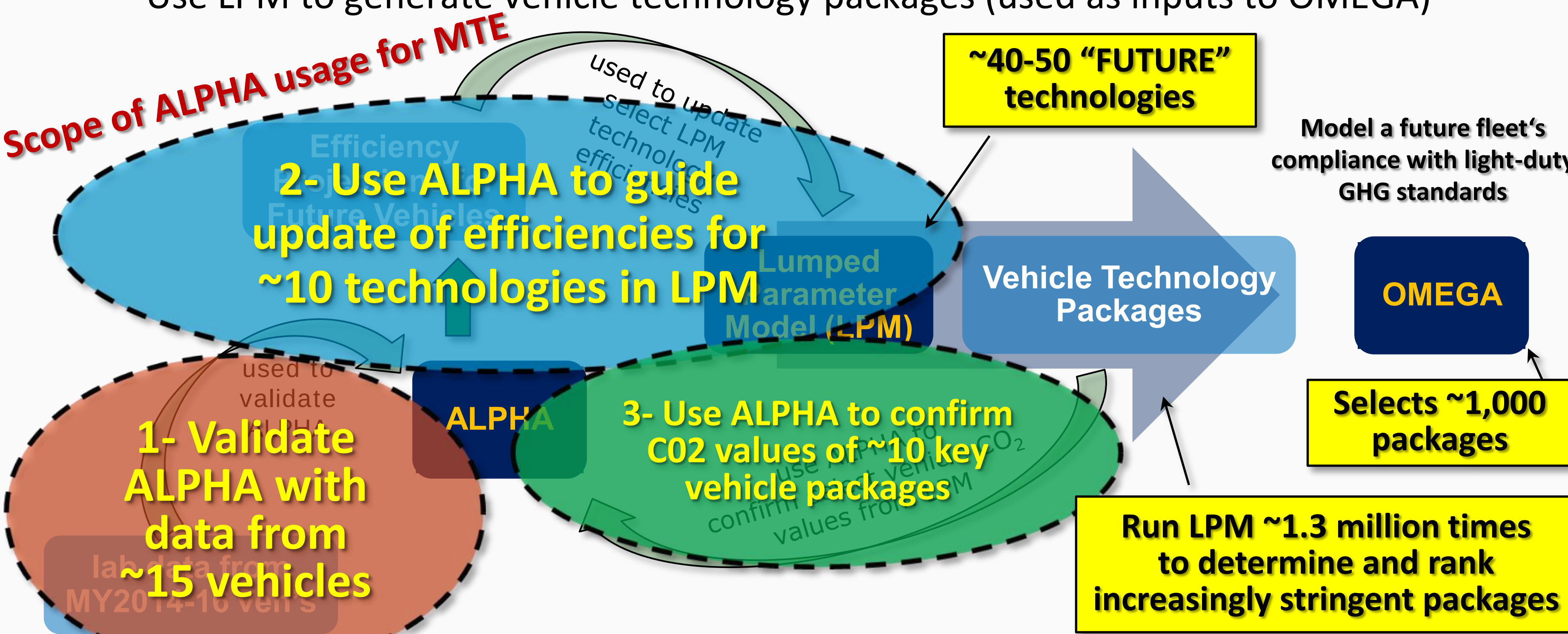


Completed Vehicle Models

- Updated base code for conventional and hybrid vehicle models in ALPHA to facilitate data entry, traceability, and code readability when we share it with stakeholders (structure, libraries, terms, routines, etc)

Models Completed

- Engines
  - Map-based engine models
  - NA and TC engines
- Transmissions
  - MT, AT, and DCT models
  - Gear shifts based on pre-defined shift schedule and AutoShift code
- Accessories
  - Map-based accessory models (alternator, water pump, A/C)
- Electrical Components
  - Starter, alternator, battery, motor models

ALPHA Development and Validation Plans

- **Additional Model Development**
  - Conventional Vehicle Model
    - Engine
      - Are considering adding dynamic engine model
        (to address engine thermal behavior, account for turbo lag, external EGR lag, etc.)
    - Transmission
      - Add CVT model
      - Upgrade DCT model
  - Hybrid Vehicle Model
    - Mild Hybrid
    - Plug-In Hybrid

- **Model Validation**
  - Conventional Vehicle Model
    - Vehicles with 8/9/10-speed AT, DCT
    - Vehicles with CVT
    - Pick-Up Trucks
  - Hybrid Vehicle Model
    - Mild Hybrid (e.g. Malibu Eco)
    - Plug-In Hybrid (e.g. Prius Plug-In)

1- Validate ALPHA with data from ~15 vehicles

ALPHA Validation Activities

- **Hybrid Vehicle Models**
  - Initial validation of "power-split hybrid" model using data from a 2010 Toyota Prius NA engine (SAE paper*)
  - Initial validation of "P2 hybrid" model using data from a 2011 Hyundai Sonata Hybrid NA engine w/6-speed AT (SAE paper*)
  - *Confirm/improve "P2 hybrid" model using data from a 2013 VW Jetta Hybrid: P2 hybrid, TC engine with 7-speed DCT (underway)*

- **Conventional Vehicle Model**
  - Initial validation of "conventional vehicle" model using data from a 2013 European Ford Focus turbo-charged engine with 6-speed MT (SAE paper**)
  - Full validation of "conventional vehicle" model using a 2013 Malibu NA engine with 6-speed AT *(nearly complete)*
  - Improved "conventional vehicle" model using 8-spd AT shifting from a 2013 Chrysler 300 w/NA engine *(nearly complete)*
  - Confirm/improve "conventional vehicle" model using data from a 2013 Ford Escape turbo-charged engine with 6-speed AT *(nearly complete)*

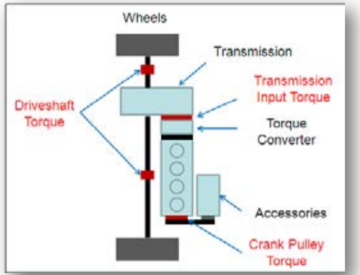
*SoDuk Lee, Byungho Lee, Joseph McDonald, L. James Sanchez, Edward Nam, "**Modeling and Validation of Power-Split and P2 Parallel Hybrid Electric Vehicles**", SAE Technical Paper 2013-01-1470.

** Byungho Lee, SoDuk Lee, Jeff Cherry, Anthony Neam, James Sanchez, Edward Nam, "**Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool**", SAE Technical Paper 2013-01-0808.

Review: NCAT Lab Testing

Approach to In-Vehicle Benchmarking

Adding sensors to measure torques



Monitoring operating CAN data

VW JETTA HYBRID SIGNAL LIST	
Engine Torque	Transmission Oil Temperature
Engine Speed	Transmission Gear Actual
A/F Ratio	Transmission Gear Commanded
Ambient Pressure	Transmission Output Shaft Speed
Ambient Temperature	Transmission Input Shaft Speed
Throttle Angle	Accelerator Pedal Position
Fuel Flow Rate Commanded	Brake Pedal Position
Fuel Flow Rate Measured	Vehicle Speed
Mass Air Flow	Hybrid Battery State of Charge
Intake Manifold Pressure	Hybrid Battery Voltage
Intake Manifold Temperature	Hybrid Battery Current
Exhaust Manifold Temperature	Emotor Voltage
Coolant Temperature In	Emotor Current
Coolant Temperature Out	Emotor Speed
Engine Oil Temperature	

Testing vehicles using various cycles

- ✓ Transient cycles on chassis dyno (FTP, HWFET, US06, etc...)
  - CO_2 and fuel consumption
  - Criteria pollutants
  - Battery state of charge
- ✓ Steady state operation on chassis dyno
  - Generate engine efficiency map
  - Generate transmission efficiency map
  - Characterize torque converter
- ✓ Vehicle speed sweeps on chassis dyno
  - Generate shift/timing maps
  - Torque converter lock-up

Capturing wide range of data signals

- ✓ Added torque sensors
- ✓ Operating CAN data
- ✓ Other added instrumentation

NRC Comm

Approach to Advanced Engine Testing

Engine benchmarking/development:

- ✓ **GDI engines** – a key enabling technology - are rapidly penetrating the market
  - i. Turbocharged & downsized engines
  - ii. High compression ratio naturally aspirated engines
- ✓ **Considering challenges:** turbo lag, engine stability, NVH

Technical Approach:

- ✓ Test engine **tethered to chassis** to take advantage of chassis controller
- ✓ Develop **operational maps** and reverse engineer engine control strategy
- ✓ Explore **limits of engine control** (eg: flexibility from multiple injections)
- ✓ Explore **new technology** independently and with supplier partnerships (eg: cooled EGR to reduce throttling losses and eliminate enrichment)

Cell 9 – tethered Ford Focus

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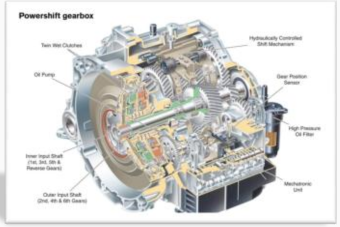
Transmissions and Shift Logic

Transmission technology is evolving rapidly

- Over 60% of today's new vehicles have 6 or more gears
- Use of CVT's is growing rapidly
- Dual Clutch Transmissions (DCTs) are in the market

Controls (shift logic) are critical to effectiveness

- We are looking at efficiency attainable using advanced engines coupled with advanced transmissions/shift strategies
- Manufacturers are balancing efficiency, launch performance, NVH and customer acceptance



Dual Clutch Transmission

Reference: Getrag - *http://www.autolatest.ro/news-cars/getrag-is-doing-well-in-2012-turnover-rises-to-3-1-billion-euros*

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Full Validation of Conventional LD Vehicle Model *

1- Validate ALPHA with data from ~15 vehicles

2013 Chevy Malibu 1LS

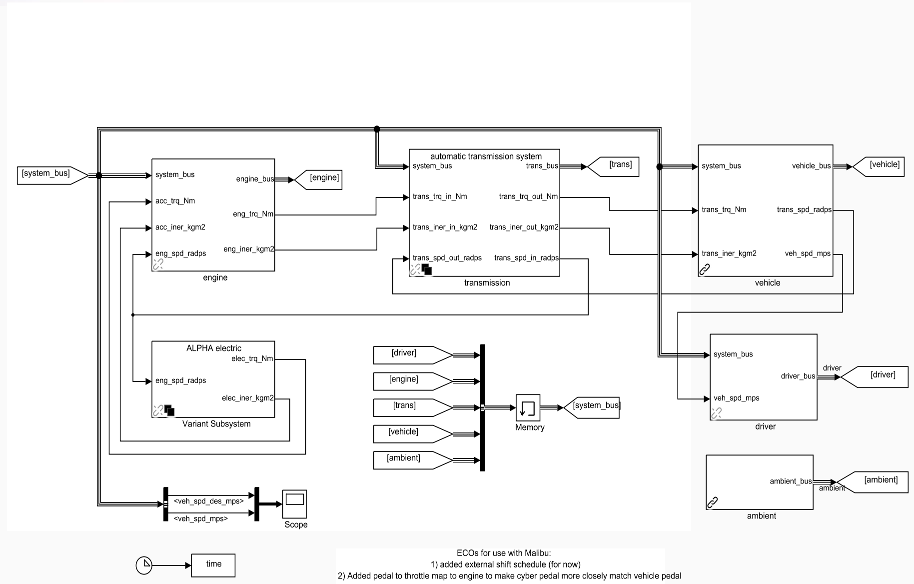
2.5L I4 GDI
Non-Hybrid
22 City / 34 Highway / 26 Comb

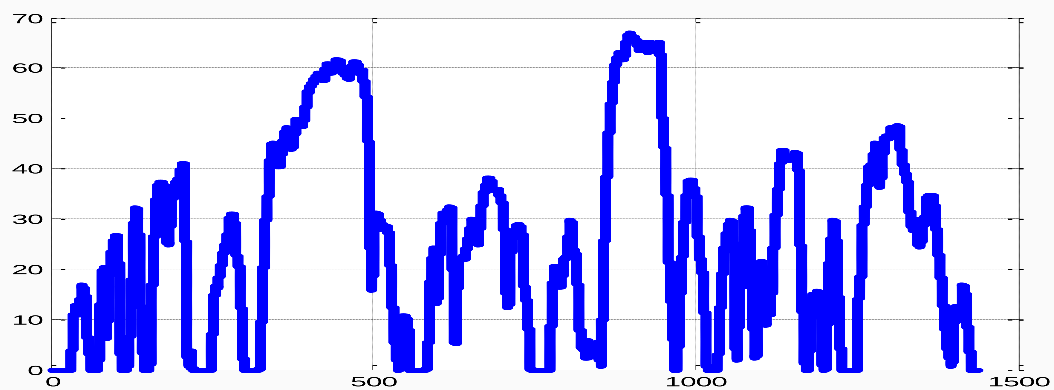
Chosen as representative of an average midsize car and we also have the Malibu ECO hybrid to compare and contrast with.

**FYI – a similar full validation program is being run on the code with data from HD trucks*

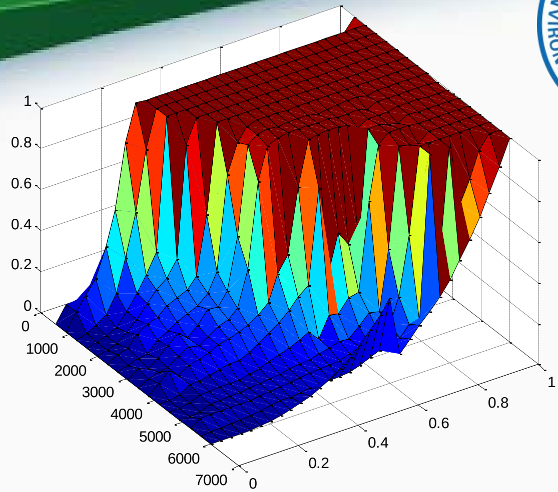
ALPHA Validation

- What are we modeling?
- What inputs are required to run the model?
- What methods are we using to convert raw data into model inputs?
- How are we comparing the modeling results to the measured results?
- Were there any “surprises”?
- What are some of the open issues?
- What are the current results?
- What are the next steps?





Required Model Inputs



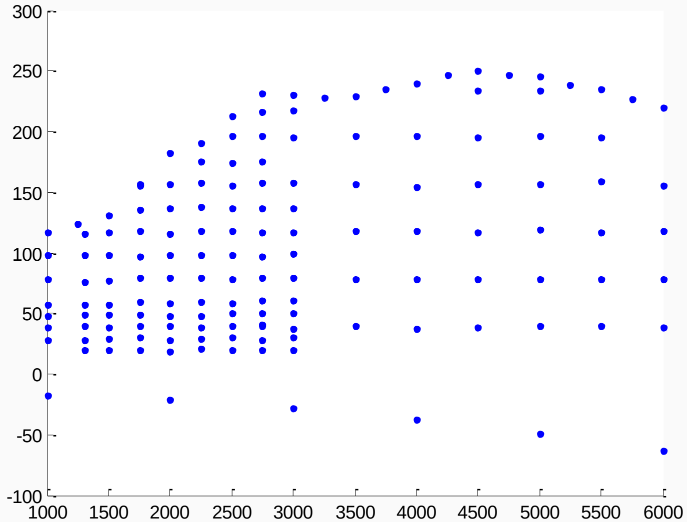
- Test
  - Drive cycle speed and grade
- Vehicle
  - Weight / inertia, road load, driveline type or vehicle class …
- Component
  - Engine fuel consumption map, torque curves …
  - Transmission gear ratios, spin losses, efficiencies, torque converter specs …
  - Accessory loads
- Behavior
  - Shift strategy, torque converter strategy, driver behavior, idle speed management, pedal map …

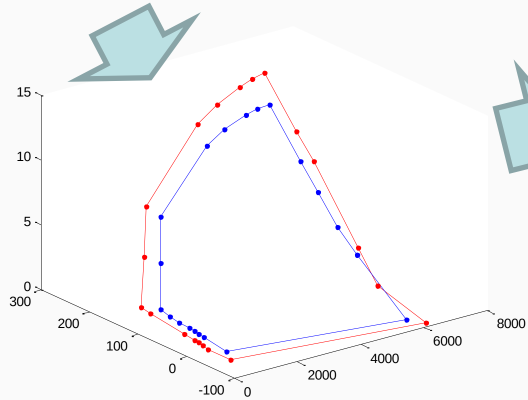
Converting Raw Data to Model Inputs

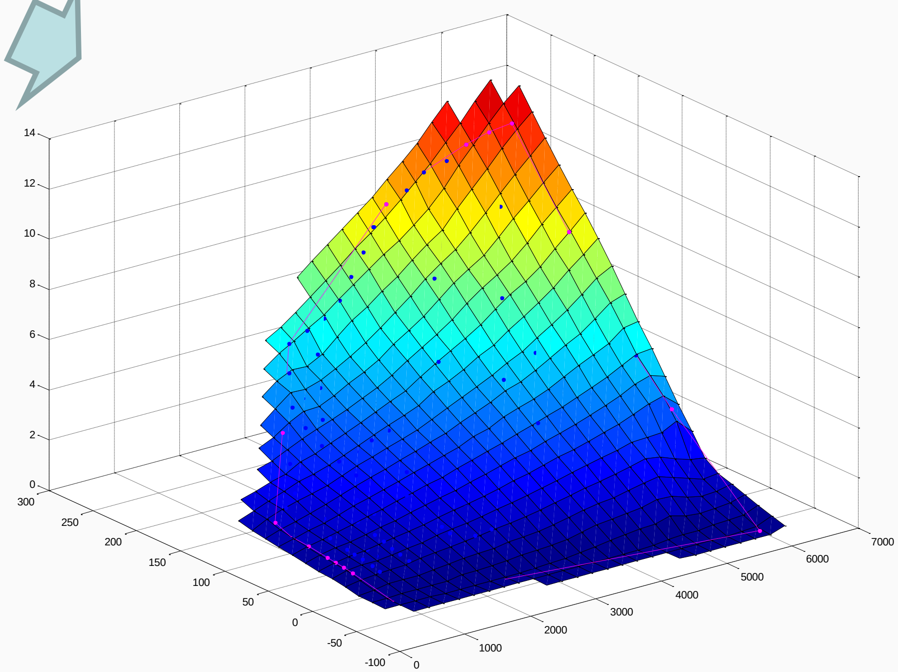
- Cut and Paste
  - Some parameters require no processing and become model inputs immediately
- Manual data processing
  - Transmission gear efficiencies had to be back-calculated from total efficiencies after factoring out spin/pump loss data
  - Engine fuel map data had to be extrapolated slightly
- Observation of vehicle behavior during testing

Engine Mapping Process

- Received Malibu 2.5L GDI engine map from FEV
- Torque, speed and fuel rate were used to create a set of mapped points
- Worked on a process for turning points to a table without introducing artifacts
- Mapped points were converted to a 25 x 25 table for use with the model



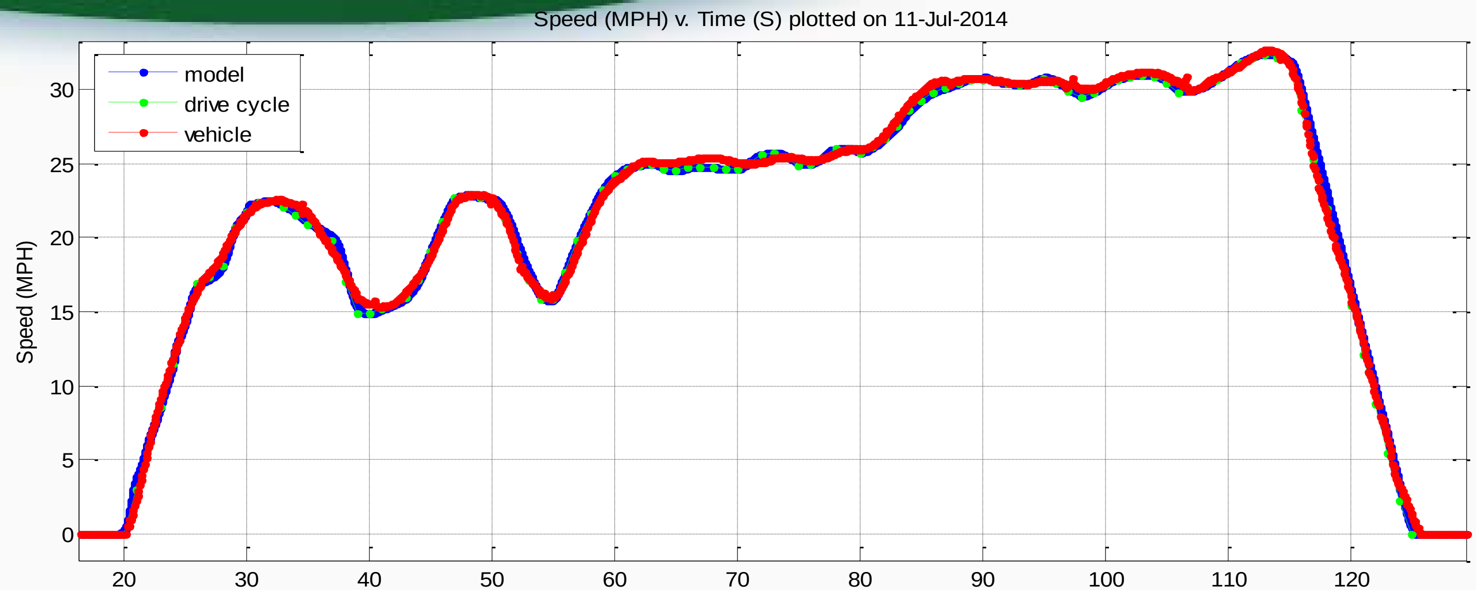


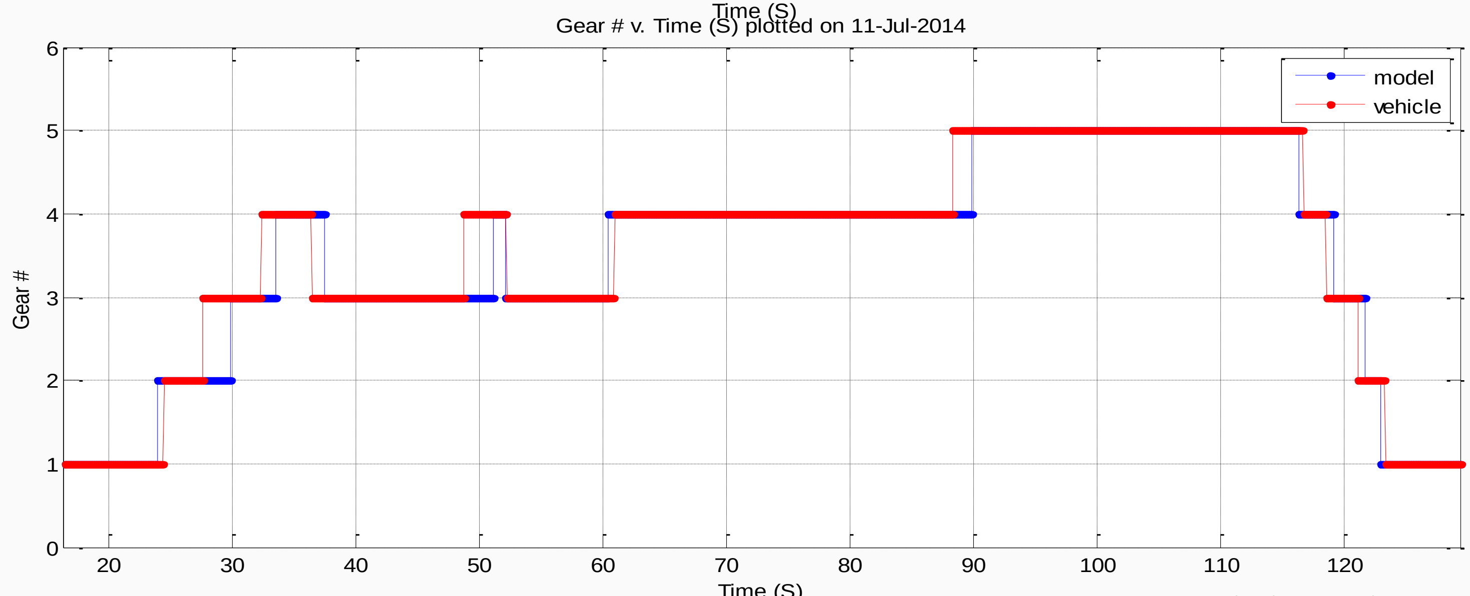


Comparison of Model Results to Vehicle Test Data

- Drive cycle fuel economy
- Second by second comparison
- Comparative histograms
- XY plots
- Running the model using vehicle data as inputs versus modeling assumptions

Sample Validation Data





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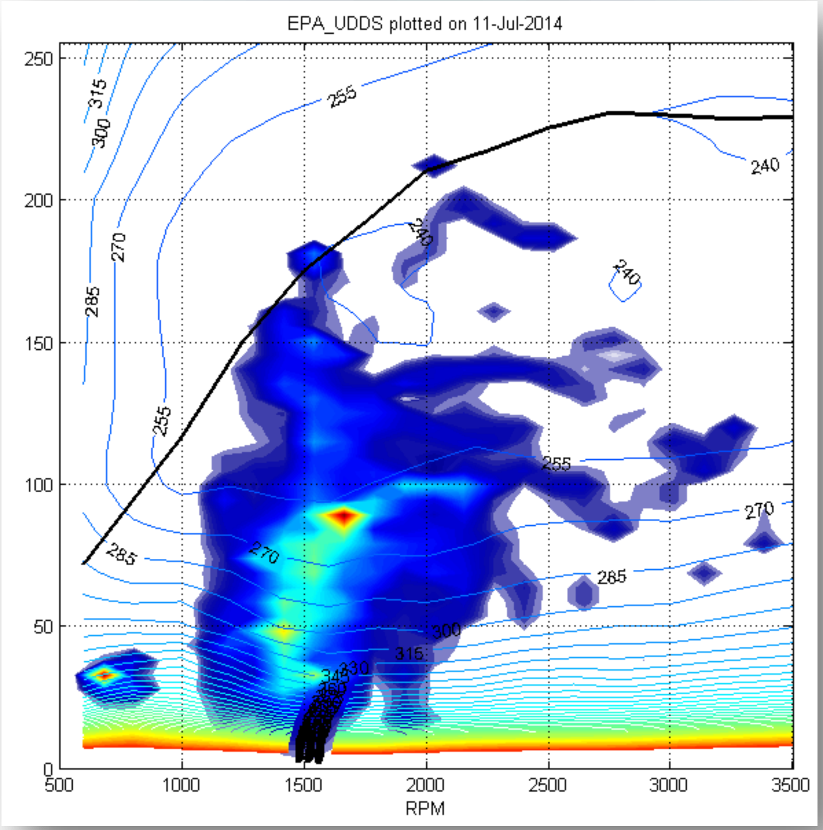

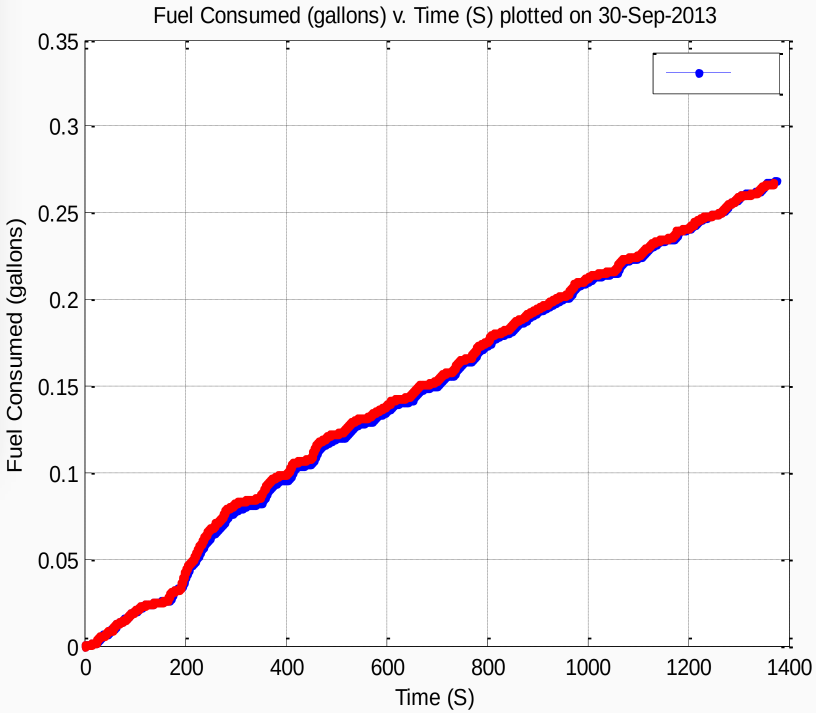

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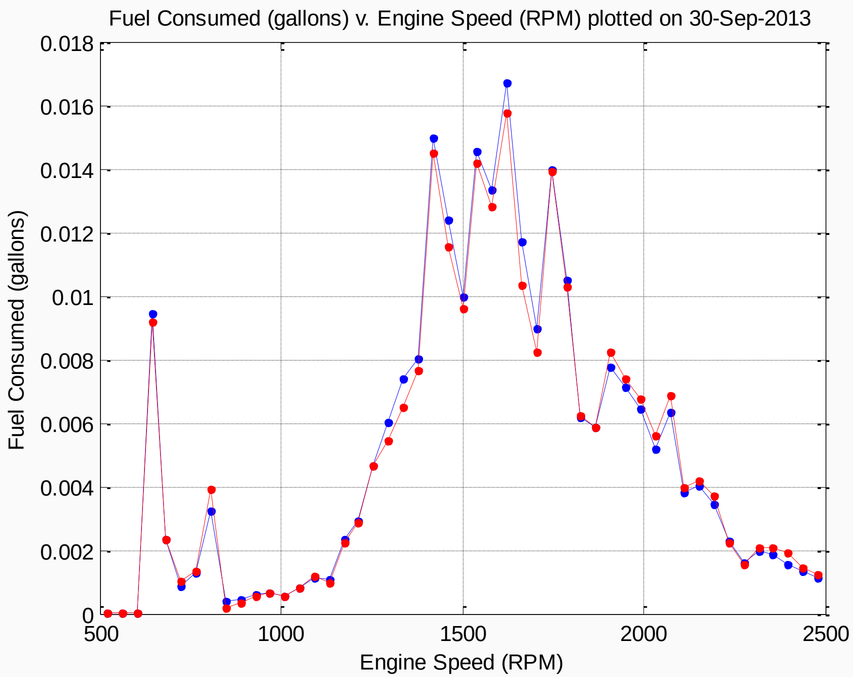
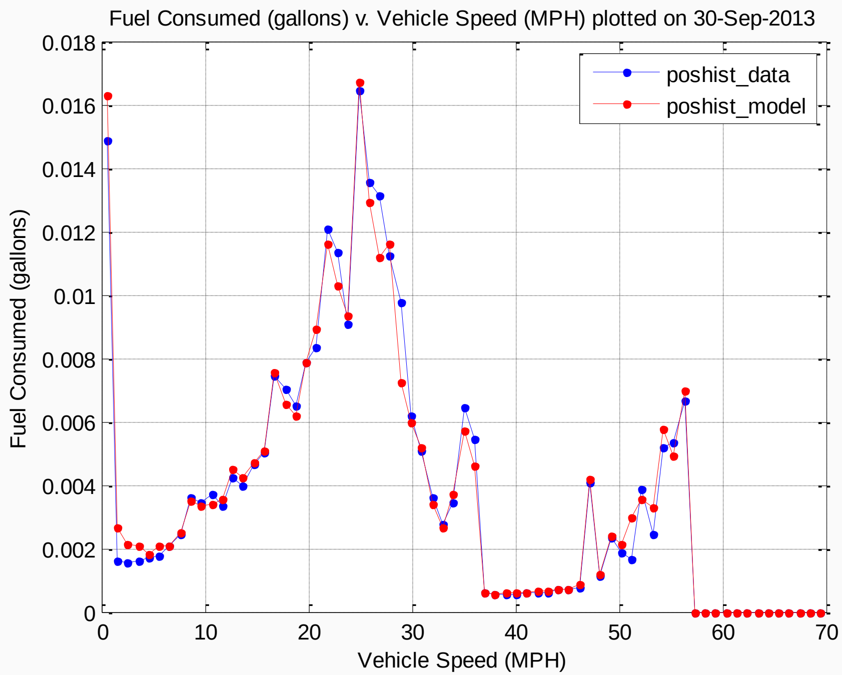
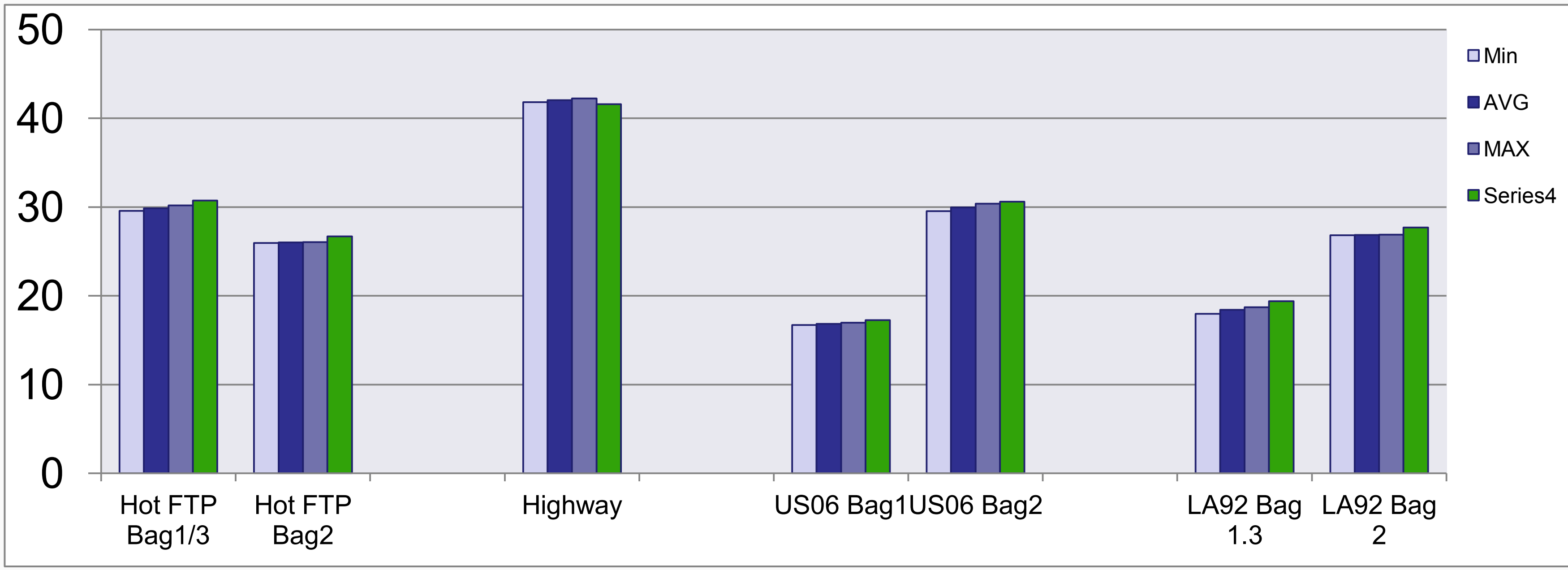




Sample Validation Data

Current Model Results 4000lb road load (“Series4” = ALPHA’s MPG)



% difference model v. average test result:

2.75 2.53 -1.08 2.46 2.09 5.14 3.02

Interesting Observations

- The torque converter rarely locks up fully but instead slips slightly, presumably to avoid “chuggle”
  - Modified torque converter efficiency during lockup
- The engine was mapped on E10 87 Octane pump gas but the vehicle testing was performed with 93 Octane Indolene
  - Had to obtain the fuel properties for both fuels to translate between the engine map and vehicle consumption data
  - Have started vehicle testing using E10 to minimized conversion factors
- The accessory load varies considerably depending on the test
  - Can use an overall average or use measured alternator current directly in the model
- The engine has a temporary “high idle” when approaching a stop after driving
  - Had to modify the idle air control to approximate this, not that it has much effect on FE

Further Improvements Planned or under Consideration

- EPA has setup more instrumentation on the Malibu and plan to run additional tests for this validation.
  - For example, FEV did not provide loaded or unloaded "idle" consumption data, which is a significant operating condition on tests with idle time
  - We also want more repeats of the various cycle tests
- Torque converter model could be modified to model "slippy" lockup
- Our fuel economy on highway cycle is slightly lower than vehicle data
  - Some amount of internal (transmission/brake) drag is incorporated into the target coefficients but we don't know how much (yet) and may be double counting some losses
- The engine torque curve could be adjusted to better reflect actual torque and consumption.
- Since FEV did not provide transmission inertia data, EPA estimated engine/torque converter input inertia with keyoff spindown test and the result seemed reasonable. EPA may want to confirm the estimates with additional testing.

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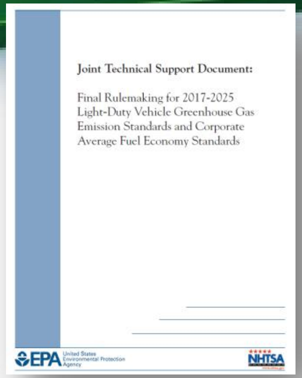
Review: Transmission technologies considered in the FRM*


Joint Technical Support Document:

Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards

EPA

NHTSA

COMPONENTS

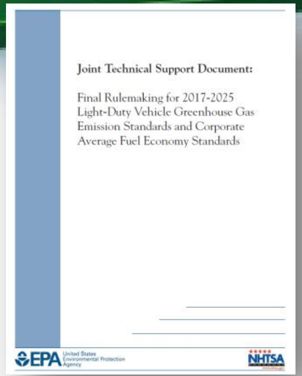
- **Manual 6-speed transmission** – offers an additional gear ratio, often with a higher overdrive gear ratio, than a 5-speed manual transmission.
- **Six- and seven-speed automatic transmissions** – the gear ratio spacing and transmission ratio are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions.
- **Eight-speed automatic transmissions** – the transmission gear ratios are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions. This technology is applied after 2016.
- **Dual clutch transmission** (DCT) - are similar to a manual transmission, but the vehicle controls shifting and launch functions. A dual-clutch automated shift manual transmission uses separate clutches for even-numbered and odd-numbered gears, so the next expected gear is pre-selected, which allows for faster, smoother shifting.
- **High-efficiency gearbox** (automatic, DCT or manual) – continuous improvement in seals, bearings and clutches, super finishing of gearbox parts, and development in the area of lubrication, all aimed at reducing frictional and other parasitic load in the system for an automatic, DCT or manual type transmission.

CONTROLS

- **Improved automatic transmission controls** – optimizes shift schedule to maximize fuel efficiency under wide ranging conditions, and minimizes losses associated with torque converter slip through lock-up or modulation.
- **Shift Optimization** – tries to keep the engine operating near its most efficient point for a given power demand. The shift controller emulates a traditional Continuously Variable Transmission by selecting the best gear ratio for fuel economy at a given required vehicle power level to take full advantage of high BMEP engines.

**Page 3-5 of the Joint Technical Support Document (August 2012 EPA-420-R-12-901).*

Review: Transmission Controls*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Improved Automatic Transmission Control**

Early torque converter lockup: "Calibrating the transmission shift schedule to upshift earlier and quicker, and to lock-up or partially lock-up the torque converter under a broader range of operating conditions can reduce fuel consumption and CO2 emissions."

Aggressive Shift Logic: "**ASL-level 1** is an early upshift strategy whereby the transmission shifts to the next higher gear "earlier" (or at lower RPM during a gradual acceleration) than would occur in a traditional automatic transmission. This early upshift reduces fuel consumption by allowing the engine to operate at a lower RPM and higher load, which typically moves the engine into a more efficient operating region. "

Additional Improved Transmission Control***

Aggressive Shift Logic: "**ASL-level 2** is a shift optimization strategy whereby the engine and/or transmission controller(s) continuously evaluate all possible gear options that would provide the necessary tractive power (while limiting the adverse effects on driveline NVH) and select the gear that lets the engine run in the most efficient operating zone. "

** Page 3-102 of the Joint Technical Support Document (August 2012 EPA-420-R-12-901).*
*** Both ASL-level1 and Early Torque Converter Lockup control strategies are included in the 2012-2016 and 2017-2025 final rules.*
**** ASL-level2 is only included in the 2017-2025 final rule.*

Emerging 8-10 Speed Transmissions

In-Production

1. **Aisin 8F35 (transverse):** Lexus RX
2. **Aisin TR-80SD and TL-80SN (longitudinal):** VW Touareg / Porsche Cayenne & Panamera / Lexus IS & GS & LS / Cadillac CTS
3. **ZF 8HP (longitudinal):** Chrysler 300 / Dodge Charger / Ram 1500 / BMW 2-series & 3-series & 4-series & 5-series & X1 & X3 & X5 / Audi A5 & A6 & A7 & A8 & allroad & Q5 & Q7 & SQ5 / Dodge Durango / Jeep Grand Cherokee / BMW 6-series & 7-series & X6 & Z4 / Audi S8 & A8L / Land Rover Range Rover & Range Rover Sport / Jaguar XF & XJ & F-type / Maserati Ghibli & Quattroporte / Bentley Continental & Mulsanne & Flying Spur / Rolls-Royce Phantom & Ghost & Wraith
4. **ZF 9HP (transverse nine speed):** Jeep Cherokee / Land Rover Range Rover Evoque
5. **Hyundai 8R40/50 (longitudinal):** Hyundai Genesis & Equus

Future

1. **Mercedes 9G-tronic 9-speed (longitudinal):** currently in European E-class, will possibly be in US in 2015
2. **Hyundai 10-speed (longitudinal):** possibly in 2015 Equus
3. **Honda DCT-8 (transverse):** planned for future Acuras
4. **GM 8L90 (longitudinal):** planned for 2015 Corvette

Completed Transmission Related Work

1. Acquire and analyze shift logic data from a 2013 4-cylinder Malibu base vehicle w/ 6-speed AT (**midsize car**).
2. Acquire and analyze shift logic data from a 2013 6-cylinder Chrysler 300 w/ 8-speed AT (**large car**).
3. Compare OEM shift strategies to the Ricardo shifting predictions contained in the TSD for 8-speed transmission.
4. Code an advanced shift logic model to use for vehicle simulation in the ALPHA model (named **AutoShift**).

Testing designed to address:

Questions about Controls…

- How has early torque converter lockup been implemented?
- How have early up-shift and shift optimization strategies been implemented?
- Are there any obvious implications on driveability in these production vehicles?

Questions about Efficiency…

- What are transmissions' efficiency and power loss?
- What is the combined engine + transmission efficiency (including shifting strategy)?

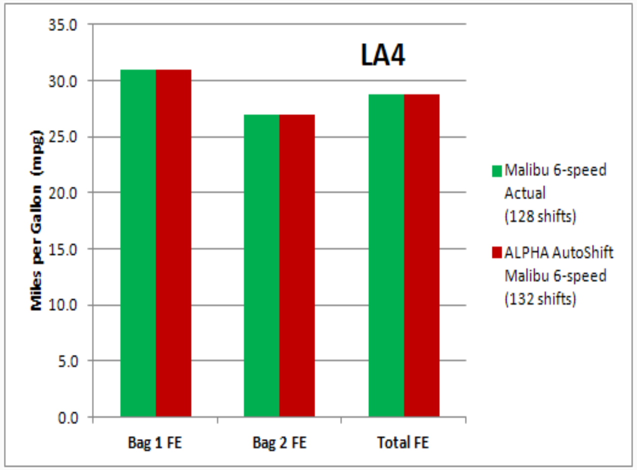
Results: # Shifts and FE of "Midsized Car" (Malibu)

4-cylinder 2.5L Malibu with 6-speed transmission

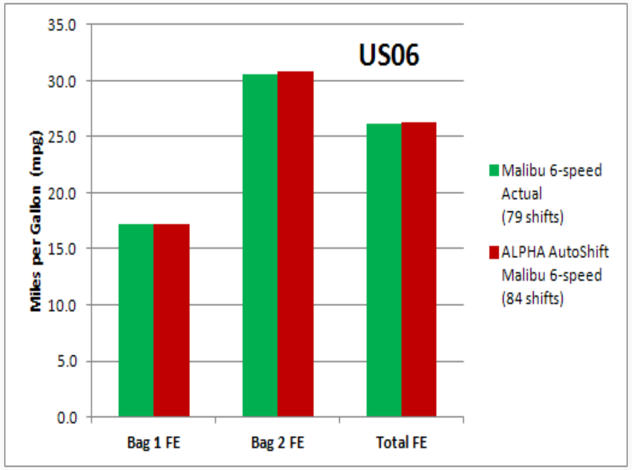
4-cyl Midsized Car

LA4	Malibu 6-speed Actual (128 shifts)	ALPHA AutoShift Malibu 6-speed (132 shifts)
Bag 1 FE	31.0	31.0
Bag 2 FE	27.0	27.0
Total FE	28.8	28.8
# Shifts	128	132

NOTE: These LA4 tests were "warm start" tests. An LA4 drive cycle is equivalent to the 1st two bags of the 3 or 4-bag FTP.



US06	Malibu 6-speed Actual (79 shifts)	ALPHA AutoShift Malibu 6-speed (84 shifts)
Bag 1 FE	17.2	17.3
Bag 2 FE	30.6	30.9
Total FE	26.1	26.3
# Shifts	79	84



Initial calibration of AutoShift

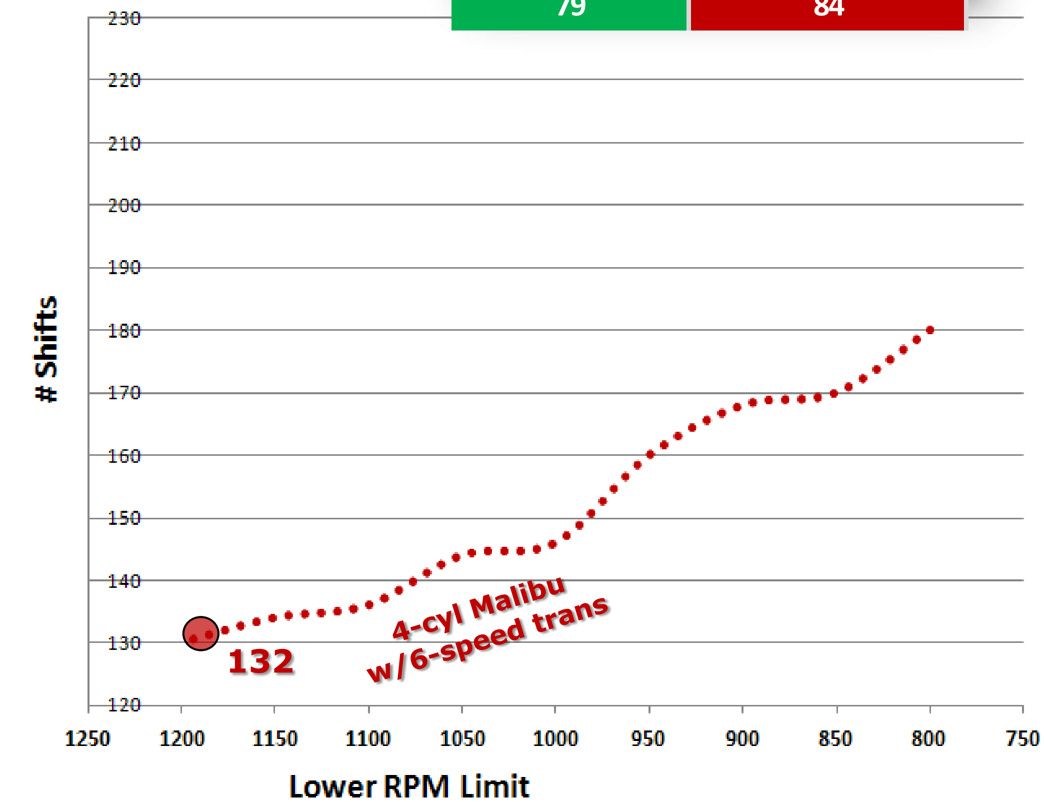
AutoShift Shifting Sensitivity Study:
Shifts versus Minimum Engine RPM

4-cyl Midsized Car

Using AutoShift to show potential # of shifts if the RPM limit is lowered

4-cyl Malibu w/6-spd trans

Actual Malibu 6-speed	ALPHA AutoShift Malibu 6-speed
128	132
79	84



***NOTE**: These # shifts are based on driving an LA4 cycle. An LA4 drive cycle is equivalent to the 1st two bags of the 3 or 4-bag FTP.*

AutoShift Shifting Sensitivity Study:

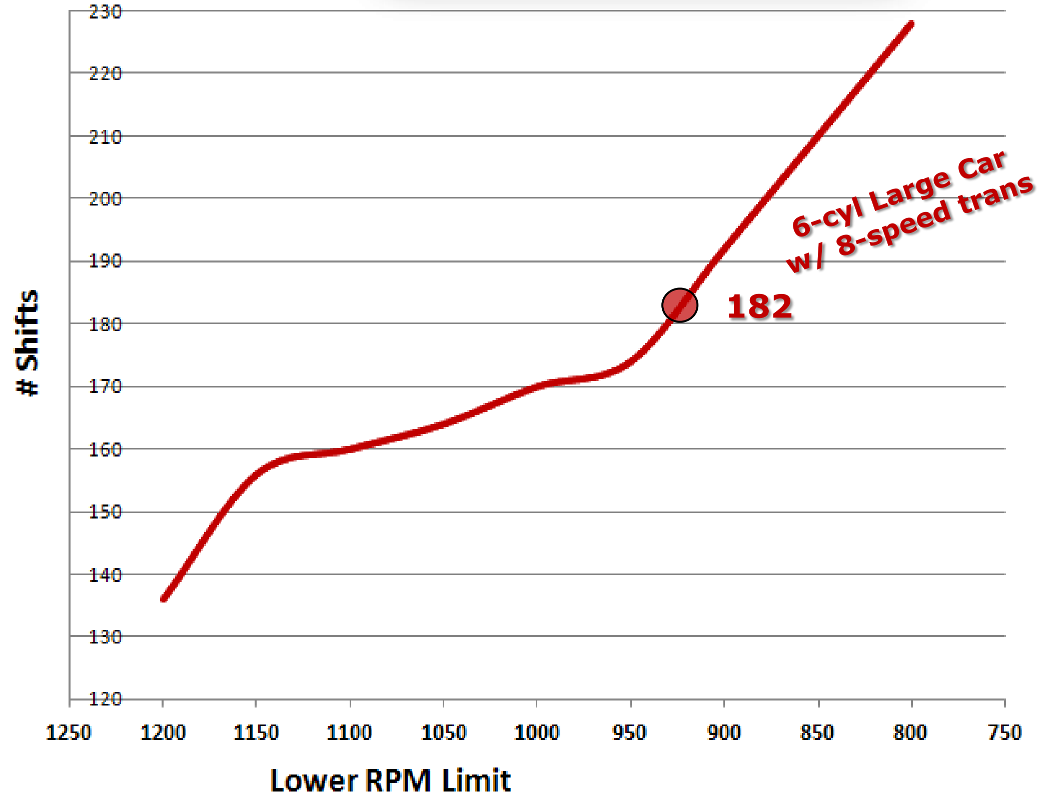
Shifts versus Minimum Engine RPM

6-cyl Large Car w/ 8-spd trans

Actual Chry 300 8-speed	ALPHA AutoShift Large Car 8-speed
189	182

6-cyl Large Car

Using AutoShift to estimate # of shifts for a 6-cylinder Large Car with 8-speed transmission



NOTE: *These # shifts are based on driving an LA4 cycle. An LA4 drive cycle is equivalent to the 1st two bags of the 3 or 4-bag FTP.*

AutoShift Shifting Sensitivity Study:

Shifts versus Minimum Engine RPM

6-cyl Large Car w/ 8-spd trans

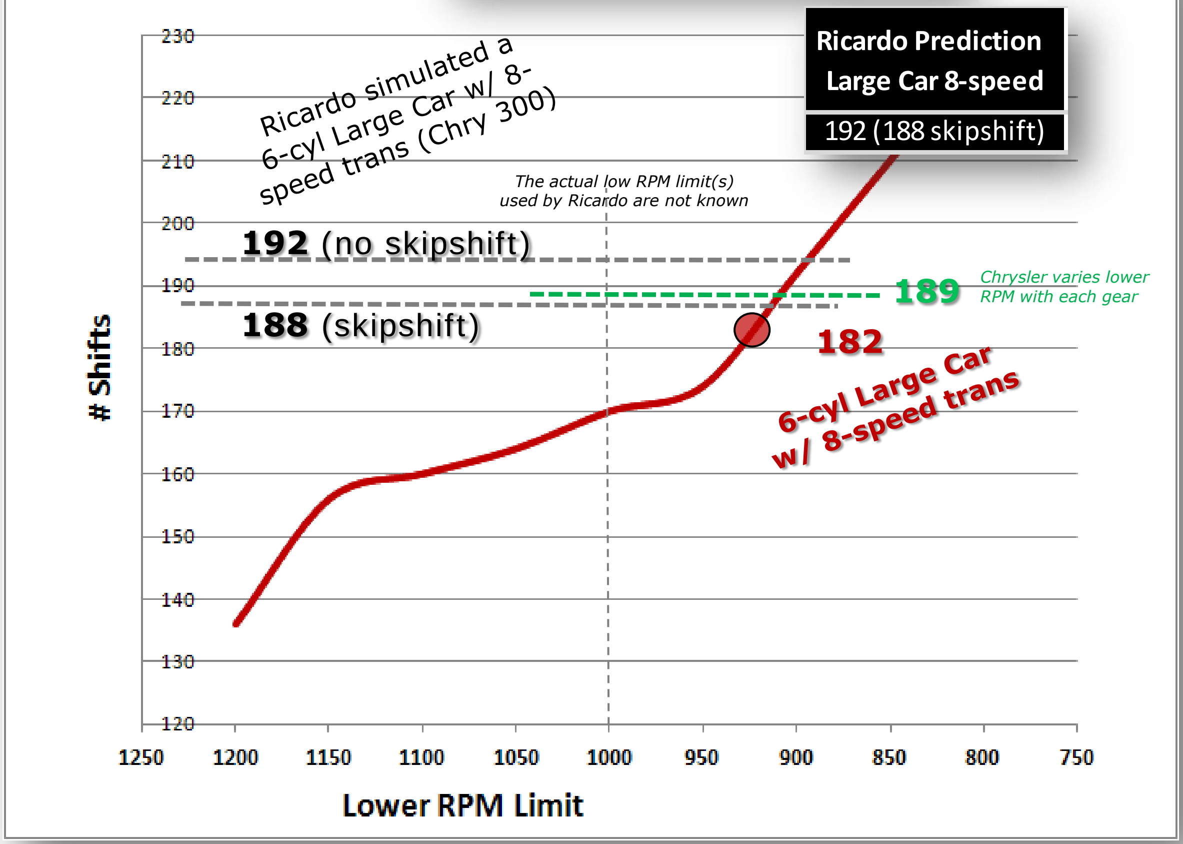
Actual Chry 300 8-speed	ALPHA AutoShift Large Car 8-speed
189	182

6-cyl Large Car

Ricardo's "Dynamic Shift Schedule"

Ricardo was asked to develop a dynamic shift schedule.

- Time between up shifts must be at least 1.5 seconds
- Shifts must be sequential
- Downshifts can occur any time to meet requested torque
- Engine speed can never exceed the maximum speed for the engine
- **Engine speed can never be below 1000 due to a shift**
- Shift to the best BSFC point available given the previous rules



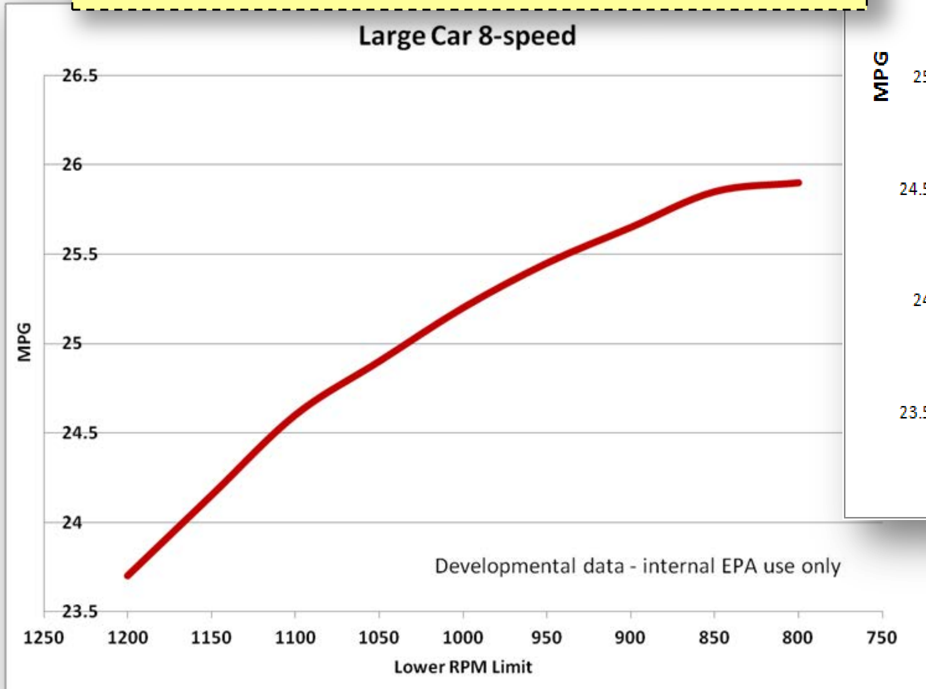
NOTE: These # shifts are based on driving an LA4 cycle. An LA4 drive cycle is equivalent to the 1st two bags of the 3 or 4-bag FTP.

AutoShift MPG Sensitivity:

Example of MPG versus # Shifts

# of Shifts & MPG depend on:

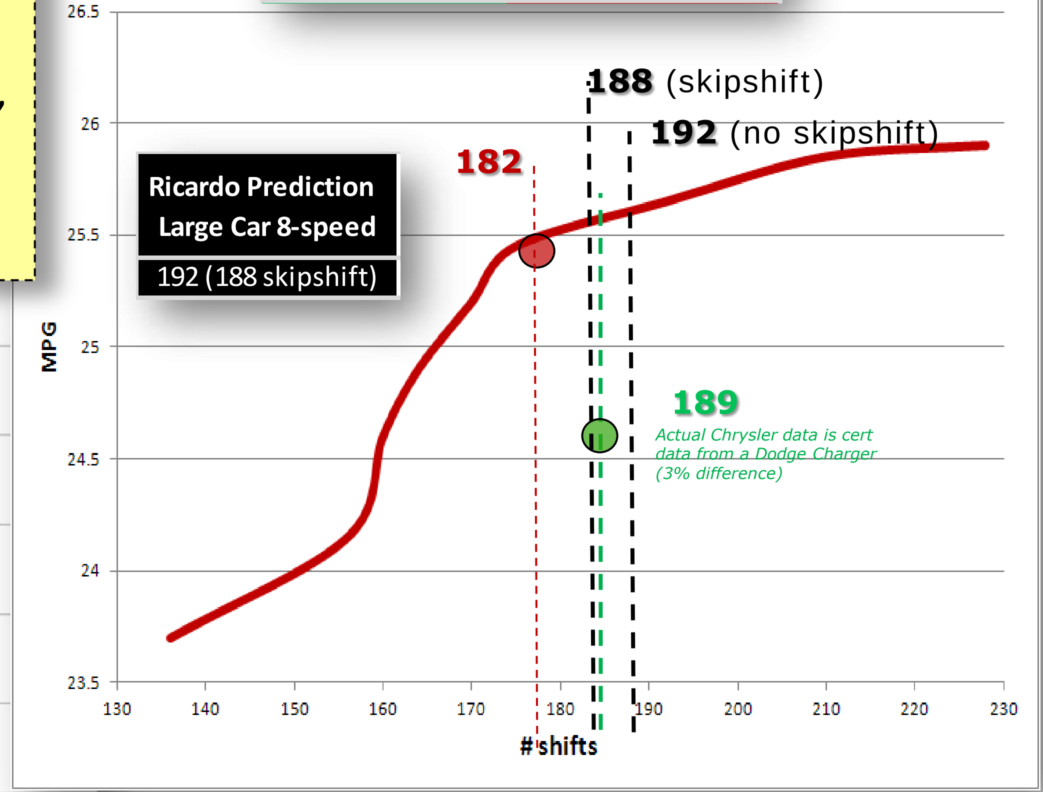
1) # of gears
2) Low limit on engine RPM (varies with 4-cyl and 6-cyl)
3) NVH technologies (dual-mass flywheel, mounts, controls, etc.)
4) Transmission design/durability
5) MPG knee



Lowest engine speed allowed

6-cyl Large Car w/ 8-spd trans

Actual Chry 300 8-speed	ALPHA AutoShift Large Car 8-speed
189	182



***NOTE**: These # shifts are based on driving an LA4 cycle. An LA4 drive cycle is equivalent to the 1st two bags of the 3 or 4-bag FTP.*

Summary Analysis

4-cyl Malibu 6-speed AT

- It is possible to tune the AutoShift algorithm to behave comparably to the observed Malibu shift points.
- Allowing lower minimum RPM after shifting might require a dual mass flywheel for operation below 1000 RPM which could affect overall cost benefit.

6-cyl Chrysler 300 with 8-speed AT

- We sized a generic 6-cylinder engine map to simulate a large car platform.
- Chrysler 300 fuel economy data could not be estimated precisely using ALPHA since we did not have an engine map for that specific vehicle.
- No transmission data (other than ratios) was available for the Chrysler 300 so assumptions were made and some data was lifted from the Malibu model (TC K-factor curves, spin losses, etc).
- The torque converter K factor was estimated from stall RPM and engine reported torque.
- The torque converter appears to lockup fully, at least in higher gears, compared to Malibu’s “slippy” torque converter.

Next Steps: Transmissions

- It is assumed that 6-speed transmissions will not have much fleet penetration in the 2022 to 2025 time period, so we do not plan to devote more resources to trying to determine if 6-speed transmissions can be further optimized.
- However, we do plan to compare “shift behavior” and “fuel economy improvement” of a 5-speed 2014 Dodge Charger versus an 8-speed 2014 Dodge Charger.
- Evaluate 7- 10 speed AT/DCTs and CVTs during other vehicle benchmarking
- Develop and evaluate final version of AutoShift for use in ALPHA
- Develop and calibrate ALPHA model for new transmissions

Question #4a –
re: Shift Optimization

4a. Argonne National Laboratory was not able to identify fuel consumption reductions from shift optimization in its simulation work for the 2017-2025 rule (Rule p. 63092). In addition, at our June meeting, NHTSA expressed uncertainly about shift optimization. The Ricardo simulation report attributes 5% to shift optimization on page 41, but there is a concern about what baseline is used, as most vehicles already have some degree of shift optimization that is already aggressive. Does EPA have any new information in support of the claim that shift optimization can indeed provide substantial savings?

- Real-world fuel economy benefits of advanced transmissions depend on the engine and transmission ***package***.
- Likewise, Ricardo simulation results on transmission effectiveness are dependent on both engine and transmission.
- Different engines require different transmissions and different operation – optimized for the engine-transmission pair.

Question #4a –
re: Shift Optimization

Shift Optimization Background

- Adopting the traditional "table-based" shifting strategy in Ricardo's initial modeling would have required a very tedious manual tuning for ~200,000 vehicle/technology combinations analyzed for the rule.
- The solution was to have Ricardo apply an "appropriately-optimized, rule-based" shift logic (an algorithm free of fixed tables), which uses parameters bounded with reasonable values (taking into consideration NVH, time between shifts, drivability, etc.), reflecting industry standard approaches for shift tuning in today's modern transmissions.
- Simply stated, the difference of % improvement between the <u>un-tuned, non-optimized "table-based" shift results</u> and the <u>"appropriately-optimized, rule-based" shift results</u> became known as "ASL2" – shift optimization.

Question #4a –
re: Shift Optimization

ASL2 is NOT a standalone additive technology that can be layered upon any transmission.

- For the 17-25 rulemaking, EPA separated out ASL2 as a way to account for cost associated with tuning a transmission's shifting strategy for the advanced engine-transmission pair, possibly making it appear to be standalone.
- A transmission with a fully tuned table-based shift schedule already has most of the necessary elements of ALS2.
- Thus, comparing a transmission with an appropriately-optimized, rule-based algorithm to one with a fully optimized table-based shift schedule, as done in the ANL report, should show only a minimal improvement.

Question #4a –
re: Shift Optimization

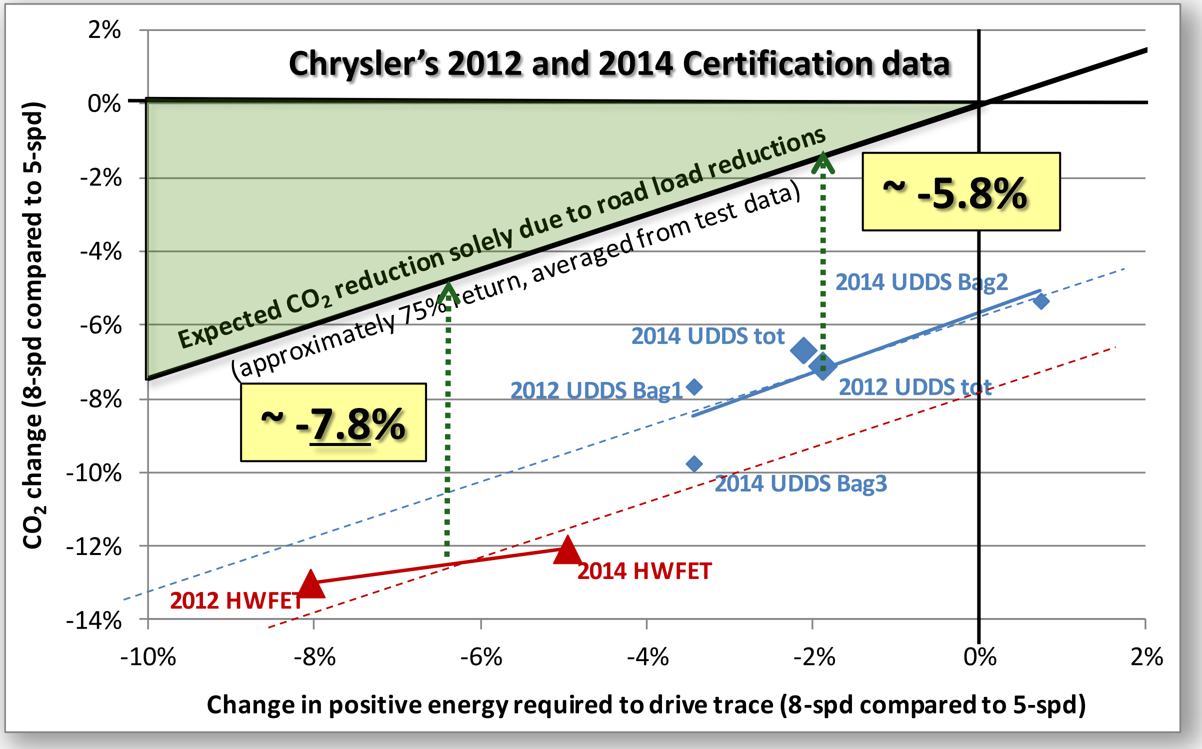
The total % improvement estimates of advanced transmissions in the rule were not affected by separately identifying the ASL2 portion of a transmission's overall effectiveness.

- Going forward, we are considering removing the "ASL2" (shift optimization) checkbox from the LPM and instead begin using just a total effectiveness number for each advanced transmission, which includes ASL2 when appropriate.
- Based on our preliminary MTE review of transmissions on the road today, the total % improvement estimates for these advanced transmissions appear to still be accurate.
- We currently have test programs underway to confirm the projected transmission efficiency improvement.
- We also have heard from suppliers & some OEMs that there are additional advancements in transmissions still to be gained.

Dodge Charger: 5-speed to 8-speed

(Same drive train as in the Chrysler 300)

- Want an opportunity to compare different transmissions with the same engine.
- Dodge Charger is a good target – available with 5- and 8-speed trans.
- We took a peek at certification data, but it was done w/ different road loads.



% CO2 reduction

~ **6.7%** (combined)

~ 5.8% (EPA city)

~ 7.8% (EPA hwy)

FYI - The Lumped Parameter Model yields a **5.6%** CO_2 reduction when upgrading a large car from a 5-speed to 8-speed transmission.

- This analysis attempts to factor out CO_2 reductions due to road load changes.
- We currently have test a program underway to confirm these efficiencies.
- Testing can also pinpoint operational and efficiency differences.

New Transmissions from Mercedes-Benz and BMW*

- **“THE NEW AUTOMATIC TRANSMISSION 9G-TRONIC from Mercedes-Benz”** - Christoph Dörr, Manfred Homm, Guenter Indlekofer (Daimler AG)

  “The fuel economy advantage of the 9G-TRONIC [compared to the 7G-TRONIC] is ***on average 6.5% in the NEDC****.”*

  - about 4.5% is from reducing parasitics
  - about 2% is from different gearing

- **“BMW’s Flexible Powertrain Family with a New Generation of Transverse Automatic Transmissions”** - Markus Nell (BMW Group)

  “Compared to the predecessor generation,
  a fuel consumption reduction of ***over 14% in the NEDC****,*
  due to the use of the new transmission generation, was achieved.”

  Nell also said verbally that the BMW 8-spd has an additional 3-4% FE benefit

  - comparing 6-speed new to 6-speed old
  - about 8-10% is from reducing parasitics
  - about 2% is from down-speeding
  - about 1% is from TC lockup
  - about 2-3% is from engine decoupling at idle

* *Information presented at the 8th International CTI Symposium, May 12-15 2014, Rochester MI*

Question #4b –
re: Incremental FC benefits

4.b. In the FEV teardown studies of the ZF 8spd, FEV broke out the cost of any items not related to the increased number of gears, such as more advanced valves, off axis vane pump, improved solenoids, etc. The costs of those components were not included in the cost to upgrade from a 6AT to a 8AT ($80 in 2017, per the TSD). However, those components greatly contribute to the ZF 8spd's improved efficiency . Did the EPA separate the incremental FC benefit from increasing from 6 to 8 speeds from the benefits of the higher efficiency technologies?

- Yes, EPA did separate the benefits due to a higher number of gears from improvements in transmission mechanical efficiency. The lumped parameter model has a separate line item for "high efficiency gearbox" which reflects these mechanical efficiency improvements. For example, in the case of an advanced 2020 8-speed transmission both the 8 speed transmission and the high efficiency gearbox are selected in the LP model.

Agenda

1. Introductions
2. **NCAT* Benchmarking Activities**
   a) **ALPHA and Vehicle Validation** (GM Malibu w/ 2.5 liter EcoTec)
   b) **Shifting Study** (6-spd Malibu & 8-spd Chrysler 300)
   c) **Engine Mapping** (US Ford Escape w/1.6 liter EcoBoost)
   d) **Study of future engines**
3. Lumped Parameter Model Application
4. Mild Hybrid Tear-down Study
5. Silverado Mass Reduction Study
6. ICM Study
7. Other NAS specific topics not covered above (as required)
8. Wrap-up
9. NCAT Lab Review

**NCAT –National Center for Advanced Technologies*

EcoBoost Engine Program

Agenda TOPICS

- **Test Setup**
  - Tether
  - SS points
- **Test Procedure**
  - Process development
- **Results**
  - BSFC
  - Thermal Efficiency
- **Next Steps**
  - Model data
  - Basis for futuring hardware

US Ford Escape – 1.6 liter

a) Chassis dyno testing of Escape

b) Tethered Benchmarking (fuel and operational maps)

c) Cycle simulation development on engine dyno

d) Finalize test packet of the tethered benchmarking

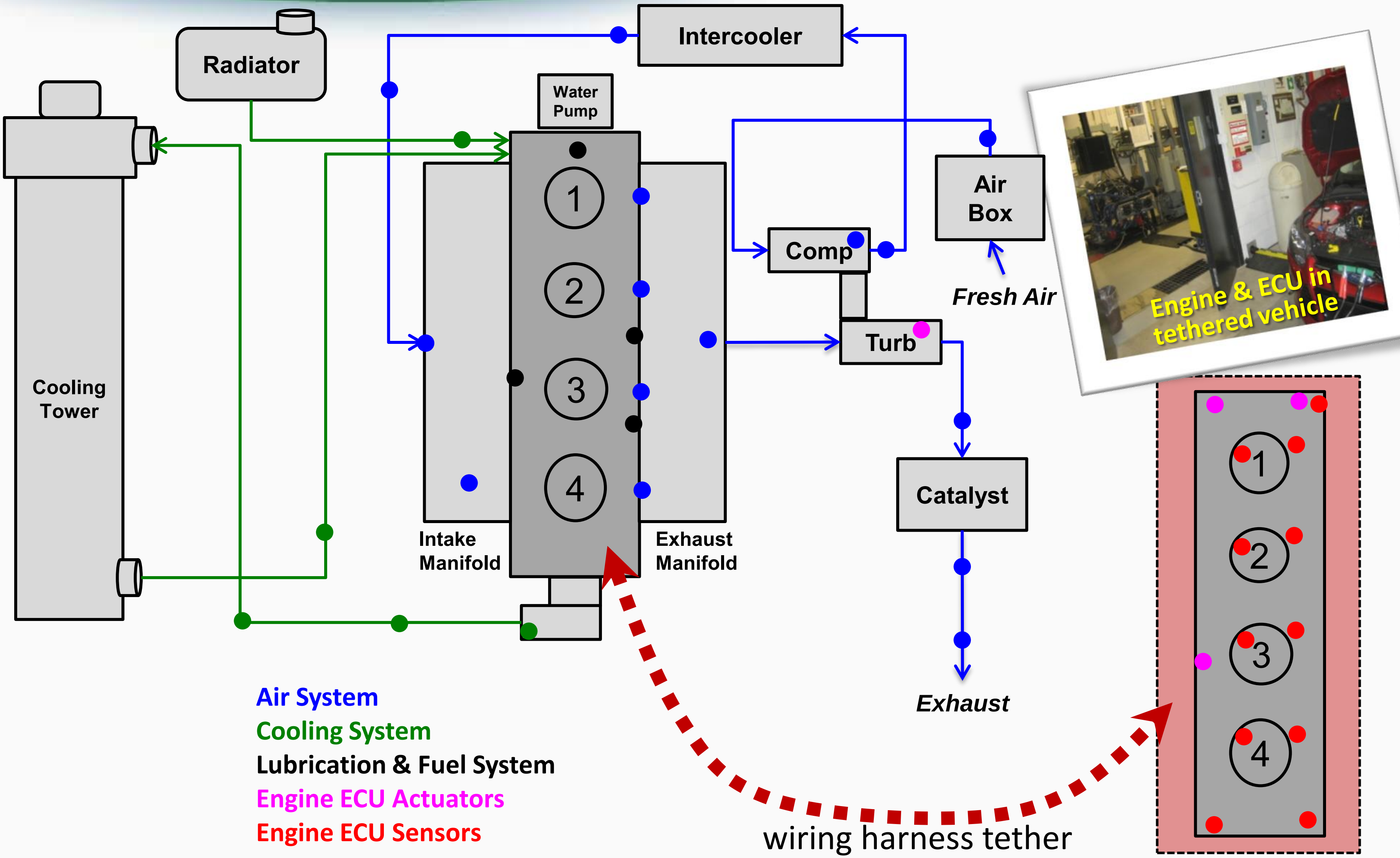
Test Engine

Vehicle	2013 Ford Escape
Engine	1.6 L EcoBoost
Rated Power	180 Hp @ 5700 RPM
Rated Torque	240 Nm @ 1600-5000 RPM
Fuel Requirement	87 octane AKI
Engine Features	Turbocharged Spray-guided direct injection

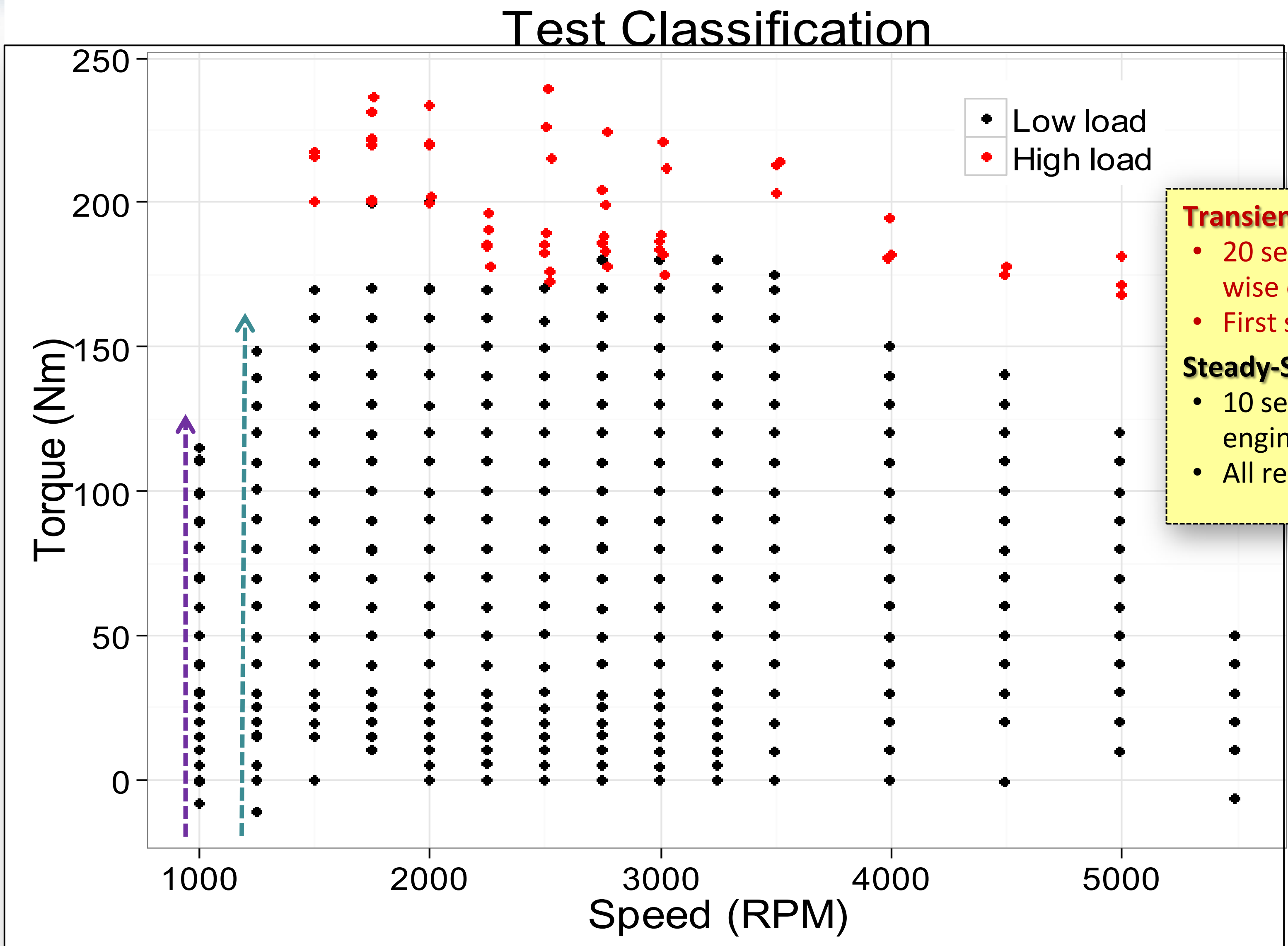
Test Setup

- Engine specs, note Tier 2 Bin 4
- Note no load on alternator in dyno setup
- Note stock exhaust
- Note stock intercooler with in-house cooling tower set to temps seen in vehicle

Engine in Engine Dyno Test Cell



"Mapping" Test Procedure



Transient, High Torque
- 20 seconds of step-wise engine activity
- First stable period used

Steady-State, Low Torque
- 10 seconds of constant engine activity
- All records averaged

Instrumentation
(for BSFC/Efficiency)

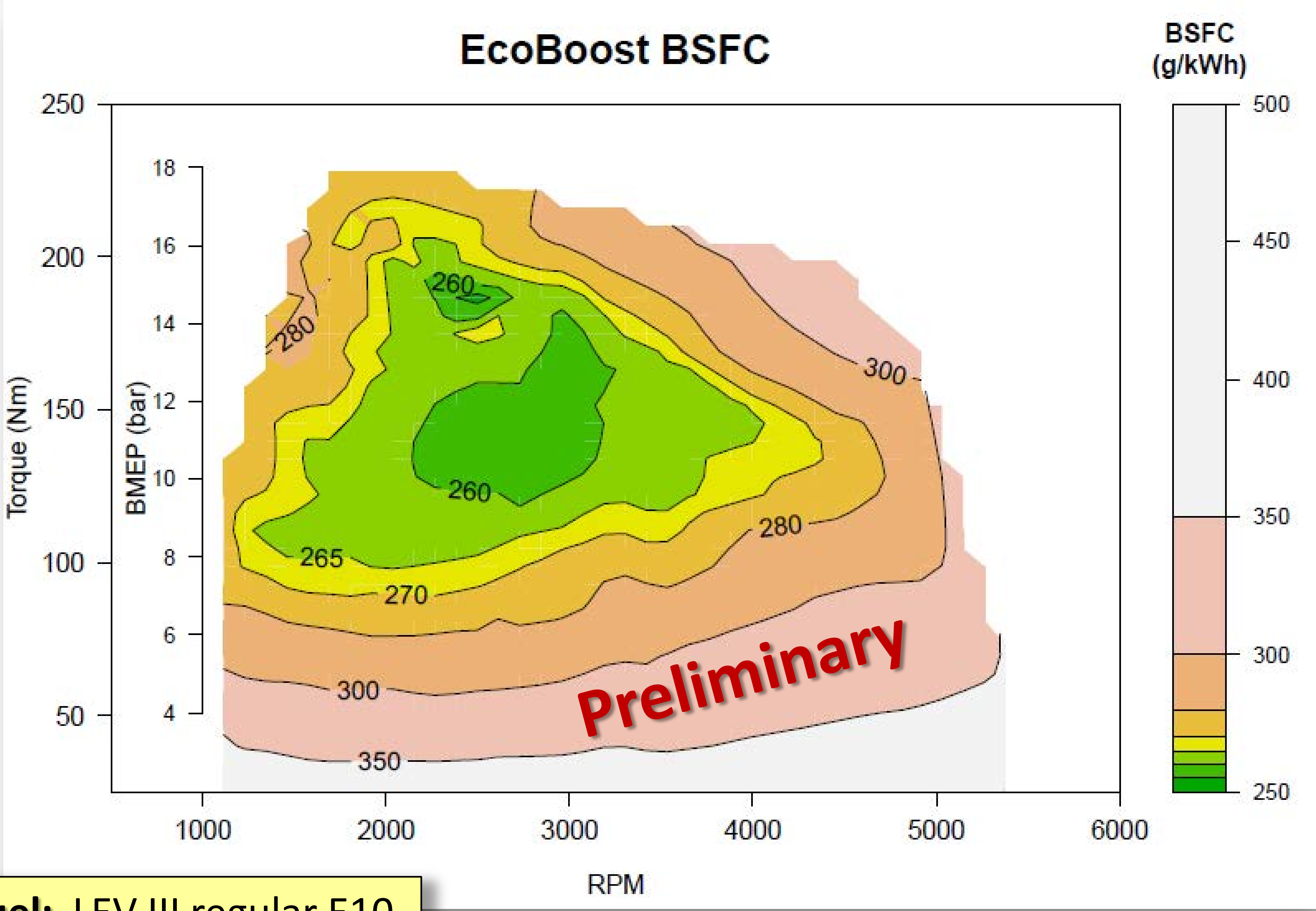
Instrument	Measurement Capabilities	Manufacturer
Dynamometer	Engine speed, Torque	Meidensha
CVS dilution tunnel	Dilution, Exhaust flow	EPA
Coriolis fuel meter	Fuel flow rate	Micromotion
Laminar flow element*	Air flow rate	Merriman
Emissions bench*	CO, THC, NOx, CH4, CO2	MEXA

** These instruments were not used to gather data for this dataset.*

Engine control and analysis software

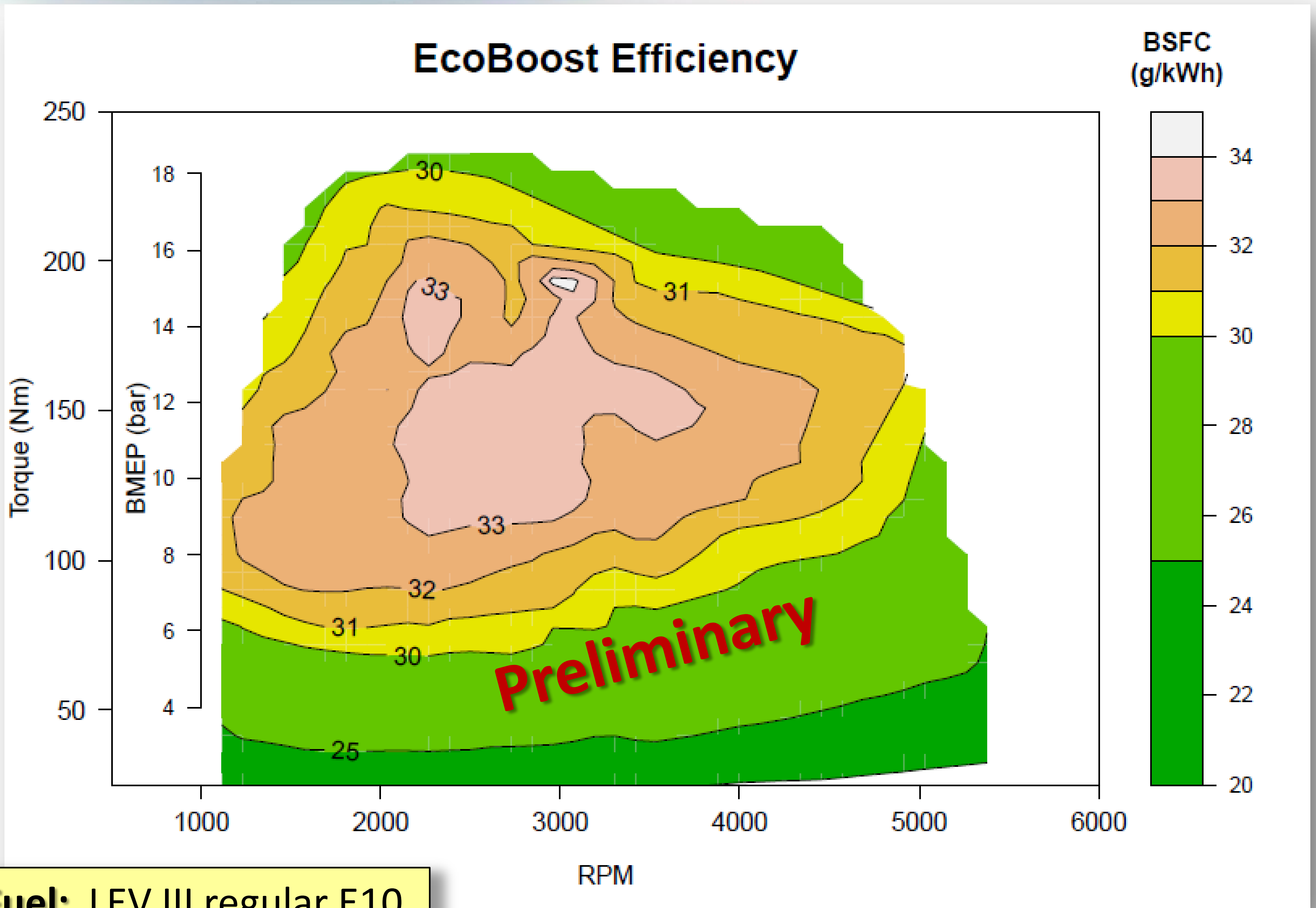
Software	Developer	Description	Data Rate
CAN	Engine OEM	Collects/monitors ECU output	variable
iTest	A&D Technology, Inc.	Controls dyno Collects test cell data	10 hz
CAS	MTS Systems Corporation	Combustion analyzer	720/rev
RPECS final	Southwest Research Institute	Commands pedal Collects supplemental data Master data logger	1/cycle

Escape EcoBoost BSFC



Fuel: LEV III regular E10

Thermal Efficiency



Fuel: LEV III regular E10

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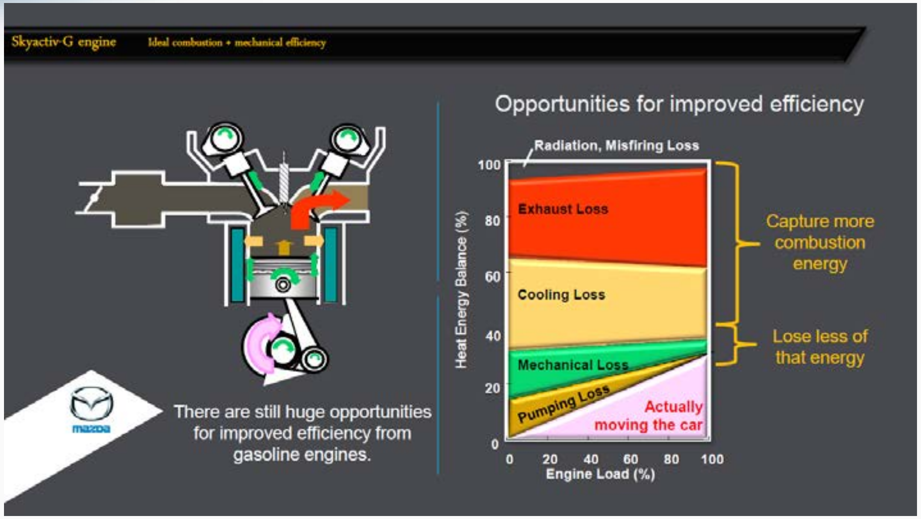
**NCAT –National Center for Advanced Technologies*

Next Steps – "Futuring" Engine Technology

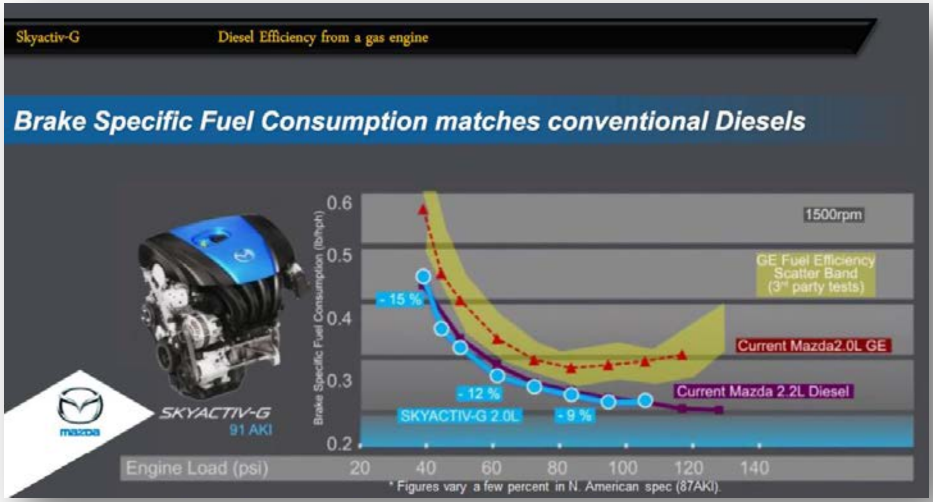
- Demonstrate effectiveness of select promising engine technologies, such as higher BMEP and cooled EGR
- Confirm effectiveness maps of the "future" engines used to simulate MY 2020-2025 vehicles
- Use engine maps to "validate" ALPHA's simulation models

SkyActiv Engine NA Demo Engine

- **Establish OEM Baseline**
  - Steady state mapping
  - Cell 8 upgrade
  - Cycle performance
- **Tier 3 demonstration**
  - Open ECU
  - Cycle testing/emissions calibration
- **BSFC improvement development**
  - Cooled EGR and 14:1
  - Tier 3 fuel
  - Recalibration



Mazda presentation at Center for Automotive Research (CAR) Management Briefing Seminars, Aug 6-9, 2012



Mahle Boosted Demonstration Engine

- **Re-baseline vs. original Mahle dataset**
  - Tier 2 certification fuel ≈ European fuel
  - Steady state mapping
- **Tier 3 demonstration**
  - Hardware updates (FIE)
  - Cycle testing/emissions calibration
- **BSFC improvement development**
  - Cooled EGR
  - Tier 3 fuel
  - Recalibration

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**NCAT –National Center for Advanced Technologies*

Background

- **EPA originally created the Lumped Parameter Model (LPM) in support of the 2012-2016 light-duty vehicle rule**:
  - To address **synergies** that develop with application of multiple technologies on a vehicle package
  - To rapidly evaluate the effectiveness of 1000s of technology combinations as part of the rulemaking analysis
  - Validated to the 2008 Ricardo full vehicle simulation study

- **The LPM was further developed to support the 2017-2025 light-duty vehicle rule:**
  - Additional technologies added
  - Additional vehicle classes added
  - Efficiently evaluates millions of vehicle and technology combinations required for OMEGA
  - Validated to the 2011 Ricardo full vehicle simulation study

LPM Calibration to the 2011 Ricardo Simulation

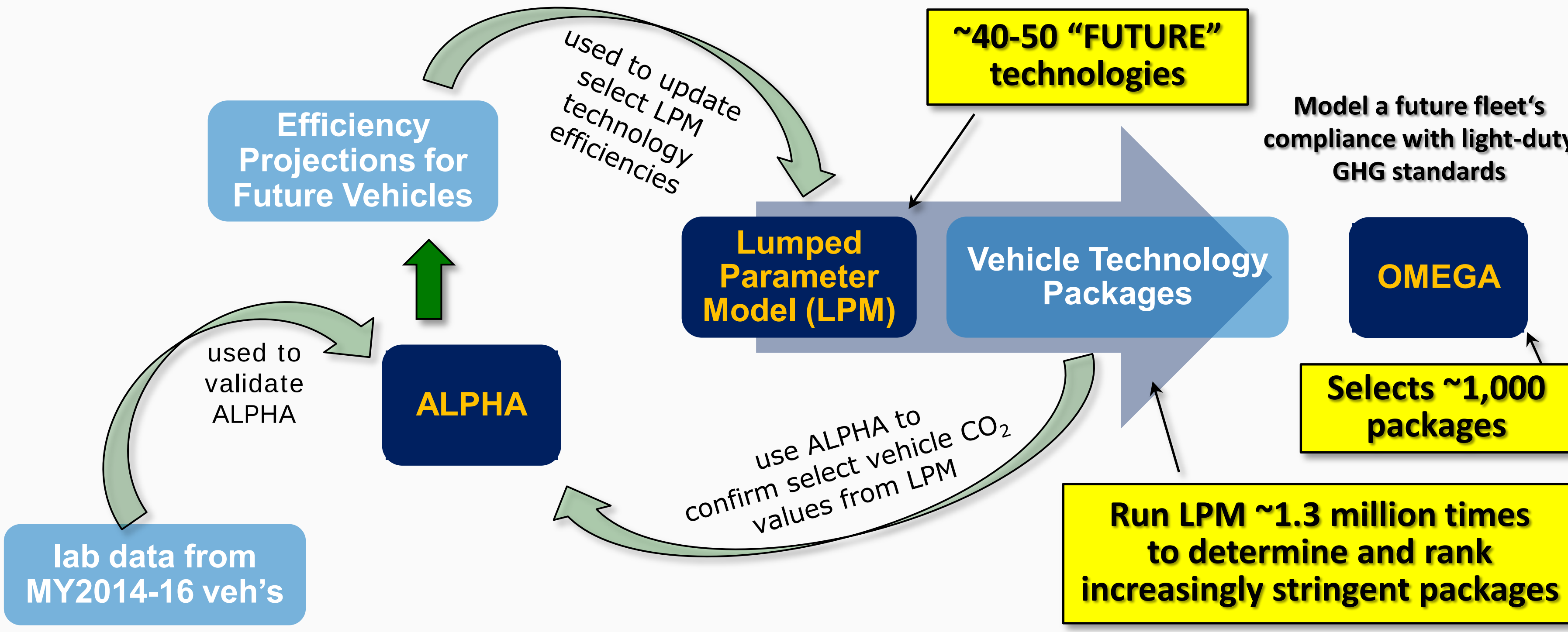
Class	Engine	Trans	GHG g/r	GHG reduction vs. 2007 baselin	Combined LP estimat	GHG g/	GHG reduction LP estimat	LP % Error vs. Ricard	FTP	HWFE	US06	Combin
Small Car (Toyota Yaris)	2010 baseline	2010 baseline	210	4.3%	44.1	206	6.0%	1.6%	39.8	48.7	30.3	43.4
Small Car (Toyota Yaris)	STDI	6 spd auto	135	38.3%	69.7	130	40.5%	2.2%	65.0	70.0	39.8	67.2
Small Car (Toyota Yaris)	STDI	6 spd DCT	131	40.1%	72.1	126	42.5%	2.4%	67.2	71.9	42.6	69.2
Small Car (Toyota Yaris)	LBDI	6 spd auto	129	41.1%	71.0	128	41.6%	0.5%	68.9	72.4	40.0	70.4
Small Car (Toyota Yaris)	LBDI	6 spd DCT	126	42.5%	73.8	123	43.8%	1.3%	71.0	73.6	42.8	72.2
Small Car (Toyota Yaris)	EGRB	6 spd auto	130	40.7%	72.3	126	42.6%	1.9%	67.6	73.1	41.7	70.0
Small Car (Toyota Yaris)	EGRB	6 spd DCT	126	42.5%	74.8	121	44.6%	2.0%	70.2	74.9	44.7	72.2
Small Car (Toyota Yaris)	Adv Diesel	6 spd auto	132	39.8%	80.4	126	42.7%	2.9%	71.8	83.2	56.1	76.5
Small Car (Toyota Yaris)	Adv Diesel	6 spd DCT	127	41.9%	83.3	121	44.7%	2.8%	75.2	85.0	57.2	79.3
Standard Car (Toyota Camry)	2010 baseline	2010 baseline	261	8.1%	34.7	262	7.6%	-0.5%	30.0	43.5	29.1	34.9
Standard Car (Toyota Camry)	STDI	8 spd auto	153	46.0%	58.6	155	45.3%	-0.6%	53.9	67.6	40.8	59.3
Standard Car (Toyota Camry)	STDI	8 spd DCT	149	47.6%	60.7	150	47.2%	-0.4%	56.3	68.3	42.2	61.2
Standard Car (Toyota Camry)	LBDI	8 spd auto	145	48.8%	59.8	152	46.4%	-2.4%	57.3	70.6	42.8	62.6
Standard Car (Toyota Camry)	LBDI	8 spd DCT	141	50.4%	61.9	147	48.2%	-2.2%	60.0	71.5	44.9	64.6
Standard Car (Toyota Camry)	EGRB	8 spd auto	147	48.1%	60.8	149	47.3%	-0.8%	56.2	70.1	42.3	61.7
Standard Car (Toyota Camry)	EGRB	8 spd DCT	143	49.6%	63.0	144	49.2%	-0.5%	58.6	71.1	43.7	63.6
Full Size Car (Chrysler 300)	2010 baseline	2010 baseline	331	6.9%	27.3	333	6.5%	-0.4%	23.8	33.7	23.6	27.4
Full Size Car (Chrysler 300)	STDI	8 spd auto	184	48.4%	48.7	187	47.5%	-0.9%	46.5	53.8	33.3	49.5
Full Size Car (Chrysler 300)	STDI	8 spd DCT	178	49.8%	50.4	180	49.3%	-0.5%	48.5	54.2	34.5	50.9
Full Size Car (Chrysler 300)	LBDI	8 spd auto	178	50.1%	49.6	183	48.5%	-1.6%	48.4	55.0	35.0	51.2
Full Size Car (Chrysler 300)	LBDI	8 spd DCT	172	51.5%	51.3	177	50.2%	-1.3%	49.8	56.7	36.7	52.7
Full Size Car (Chrysler 300)	EGRB	8 spd auto	176	50.5%	50.5	180	49.5%	-1.0%	48.5	55.9	34.8	51.6
Full Size Car (Chrysler 300)	EGRB	8 spd DCT	171	51.8%	52.2	174	51.1%	-0.7%	50.3	56.8	36.1	53.0
Full Size Car (Chrysler 300)	Adv Diesel	8 spd auto	191	46.4%	56.5	179	49.7%	3.3%	48.5	59.7	41.9	53.0
Full Size Car (Chrysler 300)	Adv Diesel	8 spd DCT	181	49.1%	58.4	173	51.4%	2.3%	51.8	61.5	43.8	55.8

- 10% RR, 20% aero, 20% mass reduction; equivalent performance

Modeling Tools: ALPHA, Lumped Parameter Model (LPM) and OMEGA

Transparent processes will generate "technology effectiveness" inputs for the OMEGA model

- Use EPA lab and other data to validate ALPHA model
- Use ALPHA model to verify and supplement 2008 & 2011 Ricardo simulations
- Use ALPHA simulation results (and other data sources) to update LPM as appropriate
- Use LPM to generate vehicle technology packages (used as inputs to OMEGA)



Question from NAS Committee

1.a. What evidence does EPA have beyond what is presented in the rule documents to support the claim that turbocharged engines with 33% downsizing can achieve the agencies' fuel savings estimates without requiring premium fuel or compromising driveability? These engines to date have shown substantially less fuel savings benefit relative to NA engines than the rule estimates. (See Attachment 1) Does EPA have more recent test data that show savings approaching the rule estimates?

Automatic Transmission Unless Noted

				EPA Label			CAFE Unadjusted			Comparable Power to Weight Ratio CAFE Unadjusted		
Model Year	Vehicle	Engine	Percent Downsizing	Comb FE MPG	% FE Improvement	% FC Reduction	Comb FE MPG	% FE Improvement	% FC Reduction	Adjusted MPG	% FE Improvement	% FC Reduction
2014	Cadillac CTS	3.6L Nat. Asp.		22			28.4			29.6		
		2.0L Turbo	44%	23	4.5%	-4.3%	30.5	7.4%	-6.9%		2.9%	-2.9%
2014	Chev. Cruze	1.8L Nat. Asp.		27			35.1			35.1		
		1.4L Turbo	22%	30	11.1%	-10.0%	40.1	14.2%	-12.5%		14.1%	-12.4%
2014	Chev. Sonic	1.8L Nat. Asp.		28			37.8			38.2		
		1.4L Turbo	22%	31	10.7%	-9.7%	41.4	9.5%	-8.7%		8.4%	-7.8%
2014	Dodge Dart	2.4L Nat. Asp		27			36.2			37.1		
	(Prem. Fuel)	1.4L Turbo	42%	32	18.5%	-15.6%	43.2	19.3%	-16.2%		16.3%	-14.0%
2014	Ford Edge	3.5L Nat. Asp.		22			28.6			29.8		
		2.0L Turbo	36%	24	9.1%	-8.3%	31.8	11.2%	-10.1%		6.7%	-6.2%
2014	Ford Escape	2.5L Nat. Asp.		25			32.9					
		1.6L Turbo	36%	26	4.0%	-3.85%	34.6	5.2%	-4.9%	34.9	6.1%	-5.7%
2014	Ford Explorer	3.5L Nat. Asp.		20			25.6			26.5		
		2.0L Turbo	43%	23	15.0%	-13.0%	29.8	16.4%	-14.1%		12.4%	-11.0%
2014	Ford F150	5.0L Nat. Asp		17			22.1					
		3.5L Turbo	30%	18	5.9%	-5.6%	23.8	7.7%	-7.1%	23.9	8.0%	-7.4%
2014	Ford Fiesta MT	1.6L Nat. Asp.		34			45.5					
		1.0L Turbo	38%	37	8.8%	-8.1%	49.9	9.7%	-8.8%	50.3	10.4%	-9.5%
2014	Ford Fusion	2.5L Nat. Asp.		26			34.6					
		1.5L Turbo	36%	28	7.7%	-7.1%	36.4	5.2%	-4.9%	36.5	5.6%	-5.3%
2014	Ford Taurus	3.5L Nat. Asp.		23			29.5			30.9		
		2.0L Turbo	43%	26	13.0%	-11.5%	33.8	14.6%	-12.7%		9.4%	-8.6%
2014	Hyundai Sonata	2.4L Nat. Asp.		28			36.6					
		2.0L Turbo	17%	25	-10.7%	12.0%	32.2	-12.0%	13.7%	34.8	-4.8%	5.1%
2014	Kia Forte	2.0L Nat. Asp.		28			37.4					
		1.6L Turbo	20%	24	-14.3%	16.7%	31.9	-14.7%	17.2%	33.1	-11.4%	12.8%
2014	VW Passat	2.5L Nat. Asp.		25			31.9					
		1.8L Turbo	28%	28	12.0%	-10.7%	36.2	13.5%	-11.9%	36.2	13.5%	-11.9%
Final Technical Support Document		EPA/NHTSA projections for Level 1	33% (18 bar BMEP)					13.8 - 17.5%	12.1 - 14.9%			
Page 3-91	(Total from base)	EPA/NHTSA projections for Level 2	50% (24 bar BMEP)					19.6 - 25.2%	16.4 - 20.1%			

Using LPM to Predict FE for New Vehicle Models

- Detailed vehicle technology content is required
- The new test vehicle database does not always contain the necessary technology details to run the LPM properly – ask key questions
  - **Do other technologies exist that could affect the comparison?**
    (e.g., engine friction, lubrication, valvetrain, transmission efficiency and shift patterns, torque converter characteristics)
  - **Is performance equivalent?**
    (power and torque curves, acceleration times… *not* just rated power)
  - **Are road loads the same?**
    (including mass)
- Baseline vehicles with higher technology content will show lower effectiveness with newly added technologies
- Current LPM is calibrated to the 2011 Ricardo study based on technology effectiveness expected in 2020.

Turbo + GDI Effectiveness Examples

33% Engine Downsizing + Turbo + GDI Effectiveness

This would be a "good" 2014 car

	2008 Large Car	2014 Large Car
Baseline Vehicle Technologies	• None (PFI, NA, Fixed Valve, 4AT)	• LUB + EFR1 • 10% Aero 10% Rolling • DCP • 8AT + HEG + ASL1 + TORQ • EPS + IACC1 + HEA
Improved Vehicle Technologies	• ***+33% TDS + GDI***	• LUB + EFR1 • 10% Aero 10% Rolling • DCP • 8AT + HEG + ASL1 + TORQ • EPS + IACC1 + HEA • ***+33% TDS + GDI***
LPM GHG reduction due to 33% TDS + GDI	**14.9%**	**10.0%**

4.9% Difference

- 4.9% difference is result of knowing complete technology list for both vehicles
- GHG reductions vary significantly based on technologies present in baseline veh.
- Only defined combinations of technologies are valid

Turbo + GDI Effectiveness Examples

33% Engine Downsizing + Turbo + GDI Effectiveness

This would be a "good" 2014 car

	2008 Small MPV	2014 Small MPV
Baseline Vehicle Technologies	• None (PFI, NA, Fixed Valve, 4AT)	• LUB + EFR1 • 10% Aero 10% Rolling • DCP • 8AT + HEG + ASL1 + TORQ • EPS + IACC1 + HEA
Improved Vehicle Technologies	• ***+33% TDS + GDI***	• LLUB + EFR1 • 10% Aero 10% Rolling • DCP • 8AT + HEG + ASL1 + TORQ • EPS + IACC1 + HEA • ***+33% TDS + GDI***
LPM GHG reduction due to 33% TDS + GDI	**12.1%**	**8.6%**

3.5% Difference

- 3.5% difference is result of knowing complete technology list for both vehicles
- GHG reductions vary significantly based on technologies present in baseline veh.
- Only defined combinations of technologies are valid

Agenda

1. Introductions
2. NCAT* Benchmarking Activities
   a) ALPHA and Vehicle Validation (GM Malibu w/ 2.5 liter EcoTec)
   b) Shifting Study (6-spd Malibu & 8-spd Chrysler 300)
   c) Engine Mapping (US Ford Escape w/1.6 liter EcoBoost)
   d) Study of future engines
3. Lumped Parameter Model Application
4. **Mild Hybrid Tear-down Study**
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Mild Hybrid Tear-down

GM eAssist Cost Study

Methodology for teardown and costing of eAssist system

- 2013 Chevrolet Malibu ECO purchased for teardown and analysis of the BAS system
- 2013 base model Chevrolet Malibu rented for systems and parts comparisons, along with OEM parts purchased for teardown
- All system that were effected or part of the BAS system were evaluated, torn down and costed
- All parts were photographed, weighed, tagged, torn down and costed with FEV costing data bases and cost sheets

Malibu ECO	Malibu Base
• Ion battery system • High & Low voltage cables • Starter Generator • Starter Generator Cooling • Belt tensioner • Trunk trim • Aux Trans cooling • Air compressor unit – pulley only • Bat. Fan system • Aux brake booster pump • Fuse Box • Control module ECU/ECM • BMS, Converter, Inverter	• Alternator • Belt tensioner • Trunk trim • Air compressor unit – pulley only • Fuse Box • Control module ECU/ECM

Major ION Battery Assemblies

Vehicle ION battery

Orange 115v volt cable from starter/generator & black 12v volt cable from main battery, connected to ION battery, runs from ION battery in trunk to starter/generator in engine compartment

ION battery fan intake for cabin

The ION battery fan takes air from the cabin and draws it down through the battery and exhausts into the wheel well

Battery, Modules, and Cells

Complete battery as removed from vehicle

Complete battery with cover removed

1 of 2 Battery modules

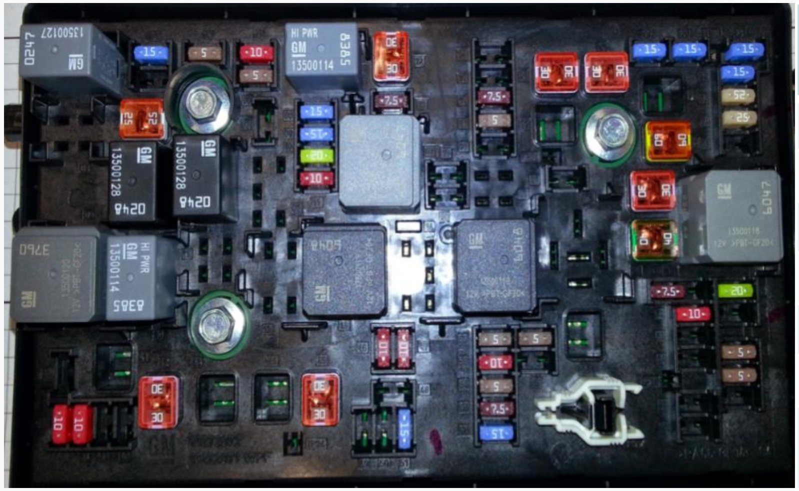
1 of 2 Battery modules cells exposed

1 Battery cell

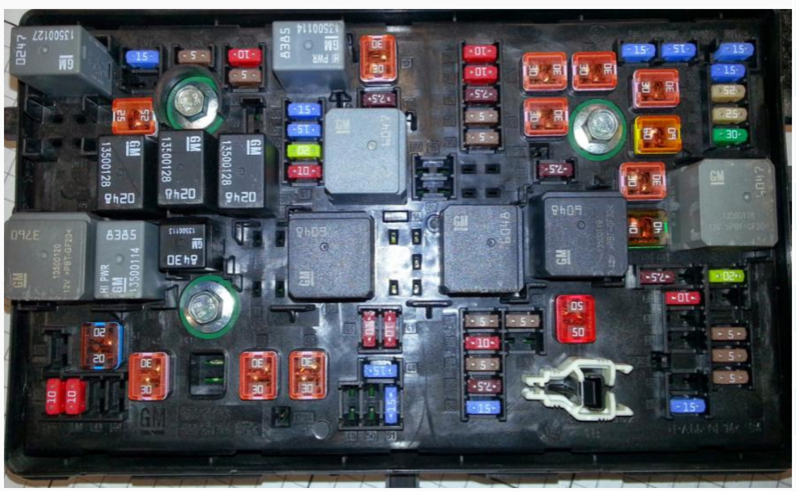
Smart Electrical Distribution Box

Base versus ECO

Base



ECO

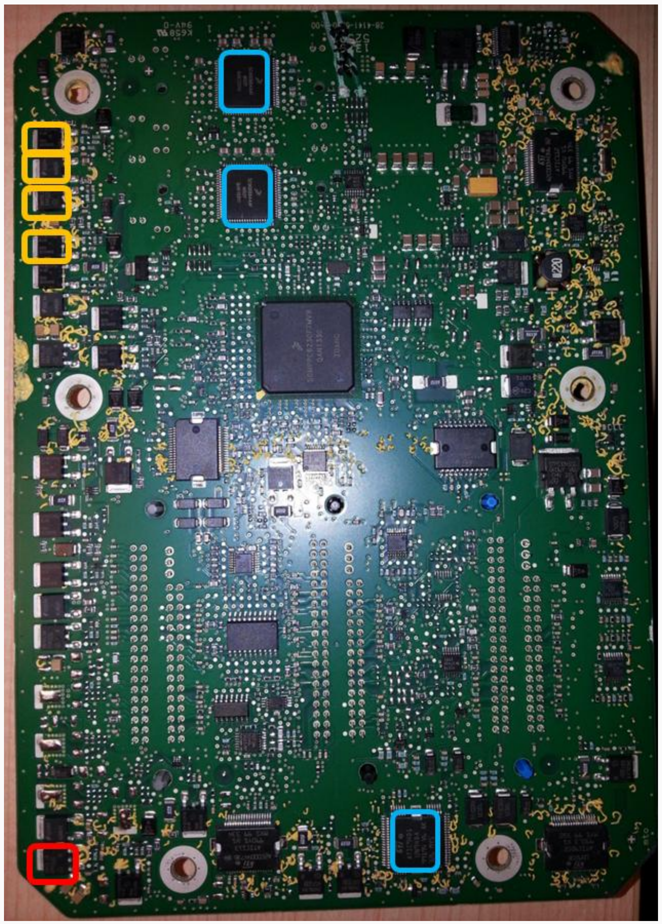


Fuse / Relay #	Type	Amps	Description	Comment
41	J-Case	20	Brake Vacuum Pump	BAS
11	Relay		Trans Aux Pump	BAS
6	Relay		Cabin Heater Cool Pump	BAS
44	J-Case	30	Trans Aux Pump	BAS
48	Mini	15	Fog Lamp	Option
14	Mini	10	Cabin Heater Cool Pump	BAS
15	Mini	10	Motor Generator Unit (MGU) Cool Pump	BAS
18	Mini	5	Vent Seat	Option
22	J-Case	30	Sun Roof	Option
23	Mini	7.5	BPIM Batt /eAssist Module	BAS
16	Relay		SEC Air pump	BAS
59	J-Case	50	SEC Air pump	BAS
25	J-Case	30	PEPS motor	
66	Mini	15	SAIR Sol	
35	Mini	30	Amplifier	Option
71	Mini	5	PEPS batt	

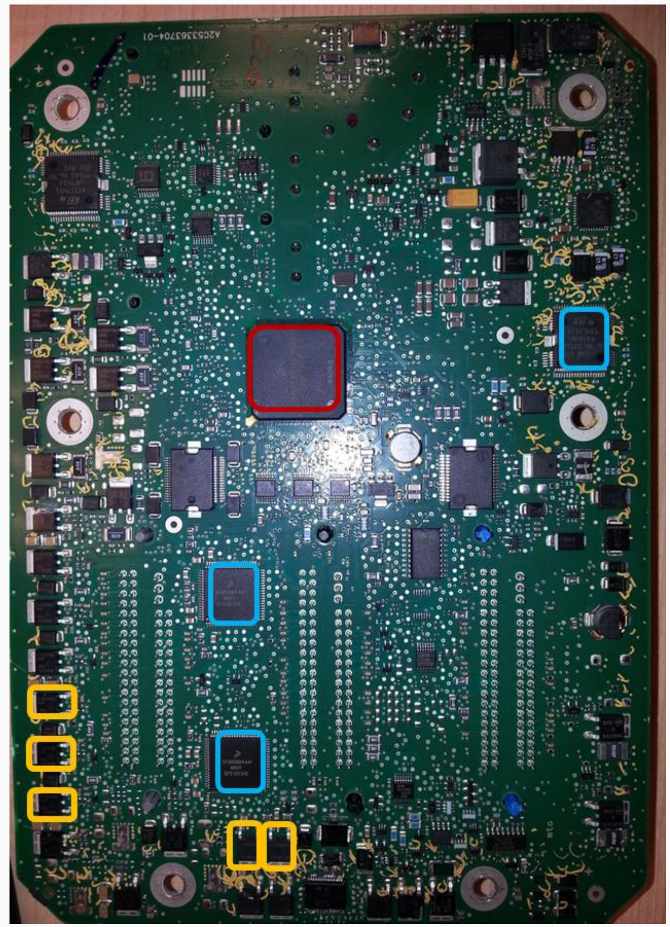
ECM – Top

Base versus ECO

Base



ECO



Moved

Additional drivers

Different PN

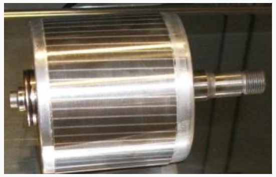
Starter/Generator

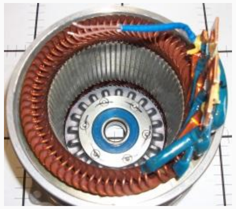
Starter/Generator in vehicle

Starter/Generator tagged, weighed, photographed

Starter/Generator outer cover

Starter/Generator stator and rotor





Total Study Cost

Part Numbering	Part Name/Description	QTY	Mass (ECO) Finished Unit Mass "kg"	Mass (BASE) Finished Unit Mass "kg"	Mass (DIFF) Differential Saved Mass "kg"	COST (ECO) Finished Unit Cost "$" (USD)	COST (BASE) Finished Unit Cost "$" (USD)	COST (DIFF) Differential Saved Cost "$" (USD)	COST (DIFF) Differential Saved Cost "%"	Cost/Mass (ECO) Cost / Mass Ratio "$/kg" (Base) (USD / KG)	Cost/Mass (BASE) Cost / Mass Ratio "$/kg" (NEW) (USD / KG)	Cost/Mass (DIFF) Cost / Mass Ratio "$/kg" (DIFF) (USD / KG)
01	**BAS vs. Non-BAS system**	-	82.251	16.423	65.829	$1,663.24	$248.87	1414.37	85.0%	$20.22	$15.15	$21.49
01 01	**Accessory Drive Subsystem**	-	4.837	3.397	1.440	$42.44	$21.54	20.90	49.2%	$8.77	$6.34	$14.51
01 01 01	Pulleys	1	2.148	2.468	-0.320	$13.14	$12.49	0.66	5.0%	$6.12	$5.06	-$2.06
01 01 02	Tensioners	1	2.563	0.839	1.724	$26.27	$7.13	19.14	72.9%	$10.25	$8.50	$11.10
01 01 03	Belts	1	0.126	0.090	0.036	$3.03	$1.93	1.10	36.4%	$24.06	$21.41	$30.67
01 03	**Cooling & Heating Subsystem**	-	3.815	0.000	3.815	$72.79	$0.00	72.79	100.0%	$19.08	--	$19.08
01 03 01	Starter/Generator Cooling unit assy	1	2.874	0.000	2.874	$50.96	$0.00	50.96	100.0%	$17.73	--	$17.73
01 03 02	Electric heater pump assy	1	0.941	0.000	0.941	$21.83	$0.00	21.83	100.0%	$23.20	--	$23.20
01 04	**Accessory Subsystem (Start Motor, Generator, etc.)**	-	17.259	7.148	10.111	$160.93	$95.61	65.32	40.6%	$9.32	$13.38	$6.46
01 04 01	Starter Motors ((No quote))	1	0.000	0.000	0.000	$0.00	$0.00	0.00	--	--	--	--
01 04 02	Starter/Generator	1	16.066	6.002	10.064	$154.04	$89.31	64.73	42.0%	$9.59	$14.88	$6.43
01 04 03	Air conditioning	1	1.193	1.146	0.047	$6.89	$6.31	0.58	8.5%	$5.77	$5.50	$12.41
01 05	**Transmission Subsystem**	-	2.405	0.000	2.405	$78.17	$0.00	78.17	100.0%	$32.51	--	$32.51
01 05 01	Auxiliary Hydraulic Trans Pump Motor	1	1.569	0.000	1.569	$32.77	$0.00	32.77	100.0%	$20.88	--	$20.88
01 05 02	Trans fluid pump	1	0.722	0.000	0.722	$40.21	$0.00	40.21	100.0%	$55.72	--	$55.72
01 05 03	Trans fluid pump Plugs & Pipes	1	0.114	0.000	0.114	$5.19	$0.00	5.19	100.0%	$45.56	--	$45.56
01 06	**Interior Trim and Ornamentation Subsystem**	-	7.251	5.114	2.137	$22.28	$16.13	6.15	27.6%	$3.07	$3.15	$2.88
01 06 01	Load Compartment Floor Trim	1	3.472	3.091	0.381	$7.48	$9.78	-2.30	-30.8%	$2.15	$3.16	-$6.05
01 06 02	Parcel Shelf / Blinds	1	0.571	0.000	0.571	$3.77	$0.00	3.77	100.0%	$6.61	--	$6.61
01 06 03	Load Compartment Transverse Trim	1	3.208	2.023	1.185	$11.03	$6.35	4.68	42.5%	$3.44	$3.14	$3.95
01 07	**Power Brake Subsystem**	-	1.653	0.000	1.653	$44.92	$0.00	44.92	100.0%	$27.18	--	$27.18
01 07 01	Pedels ((No diff))	1	0.000	0.000	0.000	$0.00	$0.00	0.00	--	--	--	--
01 07 02	Auxiliary Hydraulic Brake Pump	1	1.653	0.000	1.653	$44.92	$0.00	44.92	100.0%	$27.18	--	$27.18
01 07 03	Hydraulic Booster ((No Diff))	1	0.000	0.000	0.000	$0.00	$0.00	0.00	--	--	--	--
01 08	**EV Hybrid Fuel Cell Power Cabling Subsystem**	-	7.785	0.000	7.785	$74.89	$0.00	74.89	100.0%	$9.62	--	$9.62
01 08 01	ION Battery Wire Harness	1	1.125	0.000	1.125	$10.51	$0.00	10.51	100.0%	$9.34	--	$9.34
01 08 02	Power Cabling Items	1	0.958	0.000	0.958	$10.37	$0.00	10.37	100.0%	$10.82	--	$10.82
01 08 03	115v Power Cabling	1	4.094	0.000	4.094	$38.18	$0.00	38.18	100.0%	$9.33	--	$9.33
01 08 04	12v Power Cabling	1	1.467	0.000	1.467	$12.08	$0.00	12.08	100.0%	$8.23	--	$8.23
01 08 05	Misc. sensor wiring	lot	0.141	0.000	0.141	$3.76	$0.00	3.76	100.0%	$26.66	--	$26.66
01 09	**EV Hybrid Fuel Cell Subsystem**	-	27.915	0.000	27.915	$278.36	$0.00	278.36	100.0%	$9.97	--	$9.97
01 09 01	Bat Cooling Fan	1	1.725	0.000	1.725	$48.64	$0.00	48.64	100.0%	$28.20	--	$28.20
01 09 02	Bat Cooling Fan Duct	1	1.383	0.000	1.383	$12.15	$0.00	12.15	100.0%	$8.79	--	$8.79
01 09 03	Battery Covers	1	9.274	0.000	9.274	$28.87	$0.00	28.87	100.0%	$3.11	--	$3.11
01 09 04	Battery Power Dist Box	1	1.943	0.000	1.943	$149.12	$0.00	149.12	100.0%	$76.75	--	$76.75
01 09 06	Battery Modules and Cells	1	13.591	0.000	13.591	$39.58	$0.00	39.58	100.0%	$2.91	--	$2.91
01 10	**EV Hybrid Fuel Cell Communications and Electronics**	-	9.332	0.764	8.568	$888.46	$115.59	772.87	87.0%	$95.20	$151.29	$90.20
01 10 01	Controls Box Assy	1	8.398	0.000	8.398	$753.28	$0.00	753.28	100.0%	$89.70	--	$89.70
01 10 02	Engine Bay Fuse Box & ECU	1	0.464	0.319	0.146	$45.44	$30.33	15.11	33.3%	$97.93	$95.22	$103.85
01 10 03	Engine Bay ECU	1	0.471	0.446	0.025	$89.74	$85.26	4.48	5.0%	$190.74	$191.38	$179.28

Battery cells are not included in cost.
32 cells would add approx. $400 per FEV to the $1,663.24 cost for a total cost of $2,063.24 and a new delta cost of $1,814.37

New Incremental Cost for Mild-Hybrid:
$1,814.37* (with battery costs)
**pre-peer reviewed value*

FEV Motor Scaling

Background

- Professor Jacovides has raised the issue of directly scaling the "hot dog" style motors used in the power-split architecture to the "pancake" style motors used in the P2 architecture due to the significant differences in speed and torque characteristics.
  - Professor Jacovides is concerned that scaling based on power may be inappropriate when changing motor architecture

- Current Motor Scaling Methodology:
  - For NHTSA's 2011 CAFE Rule and the subsequent GHG rules, hybrid motor power was scaled by curb weight based on a typical motor size for a midsize car.
  - 2012~2017 GHG Rule used the motor size from the Fusion and scaled the motor based on curb weight differences between the specific application and the Fusion curb weight.

Motor Scaling for the MTE

- At the time of the Ford Fusion study, no examples of production P2 motors were available for a direct cost or scaling study.
  - FEV conducted a paper study to develop costs for P2 motors by scaling the power-split study results.

- EPA recognizes that there have been significant advancements in all motor designs.
  - P2 production vehicles have emerged since the 2010 study.
  - The recommendation for the MTE will be to perform a cost tear down and analysis of these new technologies.
  - Along with a cost study, we will also reevaluate the appropriate means of scaling motors for P2 applications.

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2. NCAT* Benchmarking Activities
   a) ALPHA and Vehicle Validation (GM Malibu w/ 2.5 liter EcoTec)
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   c) Engine Mapping (US Ford Escape w/1.6 liter EcoBoost)
   d) Study of future engines
3. Lumped Parameter Model Application
4. Mild Hybrid Tear-down Study
5. **Silverado Mass Reduction Study**
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Light Duty Truck
Mass Reduction Study Results

July 31, 2014

Office of Transportation and Air Quality
Office of Air and Radiation
U.S. Environmental Protection Agency

Mass Reduction Information Sources in 2017-2025 FRM

- **Cost and feasibility estimates were not based on any single study**
- **Wide range of sources considered**

Table 3-128 Mass Reduction Studies Considered for Estimating Mass Reduction Cost for this FRM studies

	Cost Year	Mass Reduction [lb]	Compounding Factor	Mass Reduction with Compounding [lb]	Baseline Vehicle Weight [lb]	Mass Reductioning w/Compounding [%]	Cost [$]	RPE	Dollar Multiplier to 2009	2009 Direct Manufacturing Cost [$]	Unit Cost of Mass Reduction [$/lb]
		Cost Information from Studies									
Individual Cost Data Points											
AISI, 1998 (ULSAB)	1998	103	1	103	2977	3.5%	-$32	1.0	1.28	-$41	-$0.40
AISI, 2000 (ULSAC)	2000	6	1	6	2977	0.2%	$15	1.0	1.24	$18	$2.99
Austin et al, 2008 (Sierra Research) - ULS Unibody	2008	320	1	320	3200	10.0%	$209	1.61	1.01	$131	$0.41
Austin et al, 2008 (Sierra Research) - AL Unibody	2008	573	1	573	3200	17.9%	$1,805	1.61	1.01	$1,134	$1.98
Austin et al, 2008 (Sierra Research) - ULS BoF	2008	176	1	176	4500	3.9%	$171	1.61	1.01	$107	$0.61
Austin et al, 2008 (Sierra Research) - AL BoF	2008	298	1	298	4500	6.6%	$1,411	1.61	1.01	$887	$2.98
Bull et al, 2008 (Alum Assoc.) - AL BIW	2008	279	1	279	3378	8.3%	$455	1.0	1.01	$460	$1.65
Bull et al, 2008 (Alum Assoc.) - AL Closure	2008	70	1	70	3378	2.1%	$151	1.0	1.01	$153	$2.17
Bull et al, 2008 (Alum Assoc.) - Whole Vehicle	2008	573	1	573	3378	17.0%	$122	1.0	1.03	$126	$0.22
Cheah et al, 2007 (MIT) - 20%	2007	712	1	712	3560	20.0%	$646	1.0	1.03	$667	$0.94
Das, 2008 (ORNL) - AL Body & Panel	2008	637	1	637	3363	19.0%	$180	1.5	1.01	$121	$0.19
Das, 2008 (ORNL) – FRPMC	2008	536	1.0	536	3363	15.9%	-$280	1.5	1.01	-$189	-$0.35
Das, 2009 (ORNL) - CF Body & Panel, AL Chassis	2009	933	1	933	3363	27.7%	$1,490	1.5	1.00	$993	$1.06
Das, 2010 (ORNL) - CF Body & Panel, Mg Chassis	2010	1173	1	1173	3363	34.9%	$373	1.5	1.00	$248	$0.21
EEA, 2007 - Midsize Car - Adv Steel	2007	236	1	236	3350	7.0%	$179	1.0	1.03	$185	$0.78
EEA, 2007 - Midsize Car - Plast/Comp	2007	254	1	254	3350	7.6%	$239	1.0	1.03	$247	$0.97
EEA, 2007 - Midsize Car – Al	2007	586	1.35	791	3350	23.6%	$1,388	1.0	1.03	$1,434	$1.81
EEA, 2007 - Midsize Car – Mg	2007	712	1.35	961	3350	28.7%	$1,508	1.0	1.03	$1,558	$1.62
EEA, 2007 - Light Truck - Adv Steel	2007	422	1	422	4750	8.9%	$291	1.0	1.03	$301	$0.71
EEA, 2007 - Light Truck - Plast/Comp	2007	456	1	456	4750	9.6%	$398	1.0	1.03	$411	$0.90
EEA, 2007 - Light Truck - Al	2007	873	1.35	1179	4750	24.8%	$1,830	1.0	1.03	$1,891	$1.60
EEA, 2007 - Light Truck - Mg	2007	1026	1.35	1385	4750	29.2%	$1,976	1.0	1.03	$2,042	$1.47
Geck et al, 2008 (Ford)	2008	1310	1	1310	5250	25.0%	$500	1.0	1.01	$506	$0.39
Lotus, 2010 – LD	2010	660	1	660	3740	17.6%	-$121	1.0	1.00	-$120	-$0.18
Lotus, 2010 – HD	2010	1217	1	1217	3740	32.5%	$362	1.0	1.00	$360	$0.30
Montalbo et al, 2008 (GM/MIT) - Closure - HSS	2008	25	1	25	4000	0.6%	$10	1.0	1.01	$10	$0.41
Montalbo et al, 2008 (GM/MIT) - Closure - AL	2008	120	1	120	4000	3.0%	$110	1.0	1.01	$111	$0.92
Montalbo et al, 2008 (GM/MIT) - Closure - Mg/AL	2008	139	1	139	4000	3.5%	$110	1.0	1.01	$111	$0.80
Plotkin et al, 2009 (Argonne)	2009	683	1	683	3250	21.0%	$1,300	1.0	1.00	$1,300	$1.90

Studies	Cost Year	Mass Reduction [lb]	Compounding Factor	Mass Reduction with Compounding [lb]	Baseline Vehicle Weight [lb]	Mass Reductioning w/Compounding [%]	Cost [$]	RPE	Dollar Multiplier to 2009	2009 Direct Manufacturing Cost [$]	Unit Cost of Mass Reduction [$/lb]
		Cost Information from Studies									
Cost Curves											
NAS, 2010	2010					1.0%					$ 1.41
	2010					2.0%					$ 1.46
	2010					5.0%					$ 1.65
	2010					10.0%					$ 1.52
	2010					20.0%					$ 1.88
OEM1	2010					8.0%					$ 6.00
	2010					9.0%					$ 7.00
	2010					9.5%					$ 8.00
	2010					10.0%					$ 12.00
	2010					11.0%					$ 25.00
OEM2	2010					0.4%					$ -
	2010					0.9%					$ 0.10
	2010					1.9%					$ 0.20
	2010					2.3%					$ 0.33
	2010					2.4%					$ 0.38
	2010					3.1%					$ 0.60
	2010					3.6%					$ 0.76
	2010					4.0%					$ 0.85
	2010					4.1%					$ 0.88
	2010					4.5%					$ 0.98
	2010					4.8%					$ 1.09
	2010					5.0%					$ 1.17
OEM3	2010					4.0%					$ 0.57
	2010					7.5%					$ 1.01
	2010					10.0%					$ 1.51
OEM4	2011					6.9%					$ 0.97
	2011					8.1%					$ 1.02
	2011					16.4%					$ 1.95

Overview of whole vehicle studies

1. Scoping
Low cost paper study to gain experience of exercise and determine next steps ($600k)

2010: Phase 1 Midsize CUV study (Energy Foundation) (used in LD GHG Phase 2 rulemaking) - peer reviewed

2. Main studies (include indepth Cost and CAE)
Expand approach from scoping study to include additional analyses, indepth cost and safety ($2M+)

2012: Phase 2 Midsize CUV Low Development (20%MR) for 2017 (EPA) – peer reviewed
2012: Lightweight Sedan (20%MR) (NHTSA) – peer reviewed
2012: Phase 2 Midsize CUV High Development (30%+MR) for 2025 (ARB) – In-depth Cost and CAE on BIW

3. Additional Main Studies - MTE**:**
Perform whole vehicle studies for additional vehicles / vehicle types($3M to $20.3M)

2012-2014: Light Duty Truck Light Weighting Study (20%MR) (EPA) (currently under Peer Review)
2014-?: Light Duty Truck Light Weighting Study (and apply to other vehicle types) (NHTSA)

Agenda

Light Duty Truck Mass Reduction Study Results

- Study Approach
- Results
- Application of findings to MTE analysis
- Ongoing mass reduction work for MTE

Why a Truck Mass Reduction Study?

Trucks are different from Passenger Cars

- **Consumer Requirements**
  - Towing and hauling capacity
  - Possible rough terrain operation
- **Construction**
  - Body-on-frame (versus Unibody and "non-towing" trucks)
  - Many configurations (cabin/bed, engine size, etc.)

… May affect Mass Reduction cost and feasibility

- Less secondary mass reduction?
- Feasibility of materials and technologies?

LD Pickup Truck Mass Reduction Study
Overview

Scope of Study

- Based on a 2011 4x4 Silverado 1500 Crew Cab
- Builds off of previous FEV/EDAG/Munro approach used for EPA's midsize CUV study*, but with significant tailoring for a pickup truck.
- Addition of Dynamic and Durability analyses
  - Dynamic analyses done with instrumenting vehicle and running on test track
  - Includes bed and frame durability under loaded conditions

Boundary Conditions

- No degradation in function, performance (including payload and towing capacities), or safety from the baseline vehicle
- Capable of being mass-produced in the 2020-2025 timeframe (defined as 450,000 units per year)
- 10 percent maximum increase in direct manufacturing costs

Report Timing:

- Peer review underway (sent out July 17th, comments due by August 20th)
- Will be publically released in late 2014/early 2015

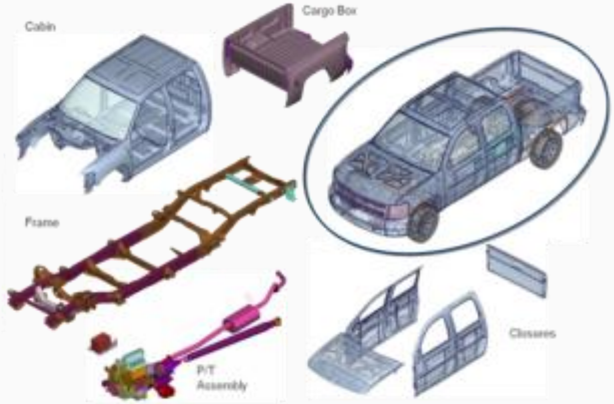
Major deliverables for LD MTE

- Inform the development of cost curves ($/kg per %MR)

*Venza Phase II, low development (FEV/EDAG)
http://www.epa.gov/otaq/climate/documents/420r12026.pdf

Teardown and CAE Baseline Model Development

- Based on 2007 Silverado donor CAE model
- Teardown 2011 Silverado
  - Component disassembly
    - Photographs, and mass, size, process map recorded
    - Bill of materials created
  - Use of white line scanning, as necessary (where geometry differences existed with 2007)
  - Measured body mount bushing properties
  - Measured static stiffness

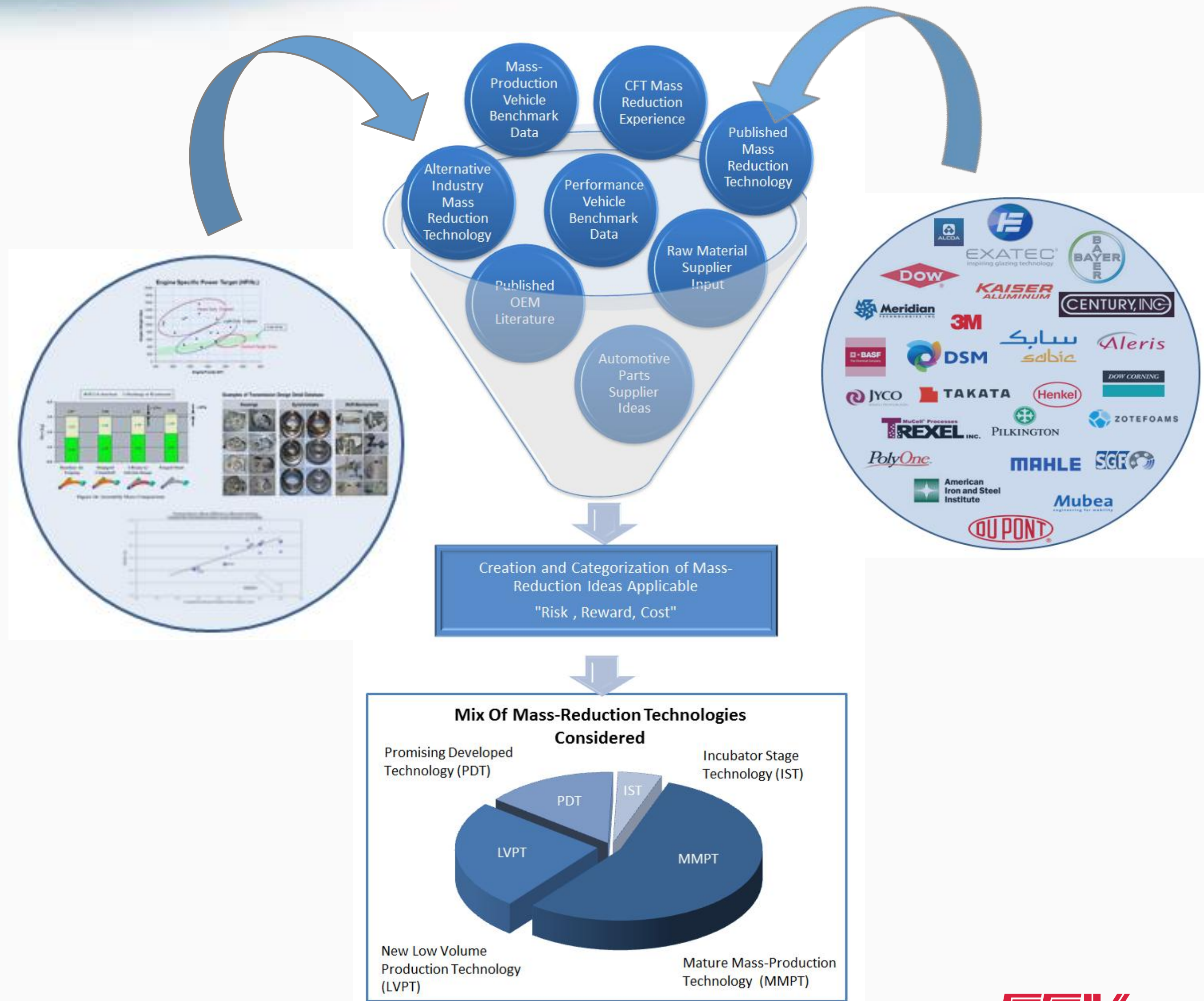


- Generated 2011 CAE model
  - Cabin: Updated 2007 CAE model to 2011 Silverado gauges and weld layout
  - Frame: 2011 Silverado

Idea Generation Resources

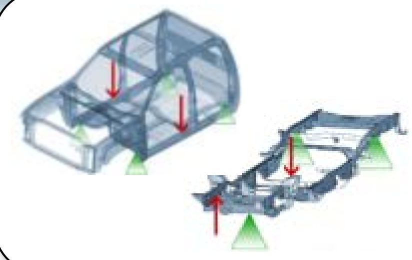
Idea Generation

- Idea generation founded on Value Engineering methodology (No idea a bad idea, No idea too small or big to consider)
- Experienced team
- Industry partnerships
- Supporting benchmark data (e.g. FEV, Munro, EDAG, A2Mac1)
- Cross industry knowledge sharing
- Light-Weighting project history
- Open consideration to all technology maturity levels



FEV

CAE Loadcases



NEW (Durability) / NEW (Vehicle Dynamics)

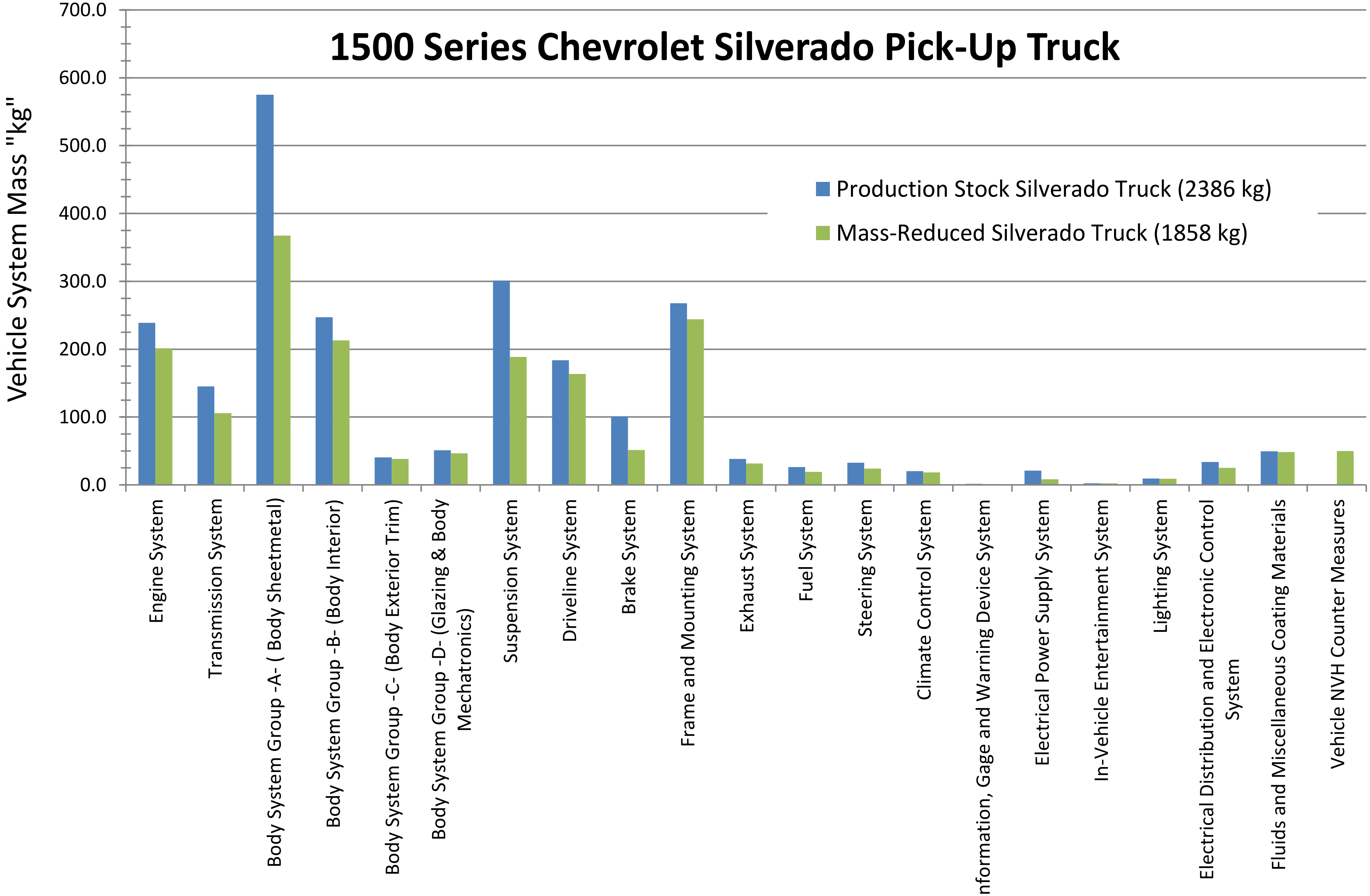
Discipline	System	Loadcase	Measures
Durability	Frame	Fatigue	Components Life cycle
	Doors	Frame rigidity	Stiffness
		Beltline compression	Stiffness
		Beltline expansion	Stiffness
		Torsion	Twist stiffness
		Sag	Vertical deformation
		Oil canning	Outer Panel deformation
	Hood	Bending	Stiffness
		Torsion	Twist stiffness
		Oil canning	Outer Panel deformation
	Tail gate	Torsion	Twist stiffness
		Oil canning	Outer Panel deformation
Vehicle Dynamics	Full Vehicle	Constant Radius	Understeer Gradient
			Cornering Compliance
			Roll Gradient
		J-Turn	Tire Load
		Frequency Response	Steering Response Gain
			Steering Response Phase lag
		Static Stability Factor (SSF)	Track width/(2 x CG height)

Discipline	System	Loadcase	Measures
NVH	Frame	Static Bending	Global bending stiffness
		Static Torsion	Global torsion stiffness
	Cabin	Static Bending	Global bending stiffness
		Static Torsion	Global torsion stiffness
	Cargo Box	Static Bending	Global bending stiffness
		Static Torsion	Global torsion stiffness
	Body On Frame	Static Bending	Global bending stiffness
		Static Torsion	Global torsion stiffness
Crash / Safety	Full Vehicle	FMVSS 208—35 mph flat frontal crash (US NCAP)	Pulse
			Crush
			Time-to-zero velocity
			Dash intrusions
		IIHS—35 mph ODB frontal crash	Pulse
			Crush
			Time-to-zero velocity
			Dash intrusions
		FMVSS 214—38.5 mph MDB side impact (US SINCAP)	B-Pillar velocity
			Side structure intrusions
		IIHS—31.0 mph MDB side impact	B-Pillar velocity
			B-Pillar intrusions
			Survival space
			Exterior crush
		FMVSS 214—20 mph 5th %ile pole side impact	B-Pillar velocity
			B-Pillar intrusions
			Structure intrusions
		FMVSS 301—50 mph MDB rear impact	Under structural zone deformation
			Door operability
			Fuel tank damage
		FMVSS 261a—Roof crush	Roof strength to weight ratio
		FMVSS 581—Bumper impact	Front end deformation

Results

Mass Reduction by Vehicle System

Preliminary results (under peer review)

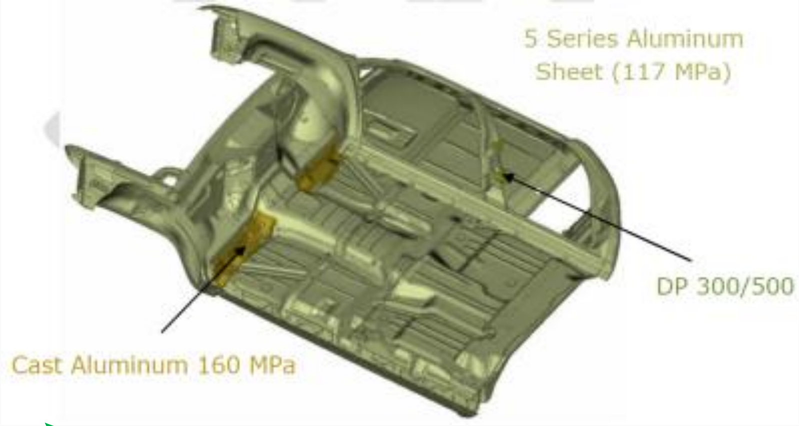


Cabin Highlights

Preliminary results (under peer review)

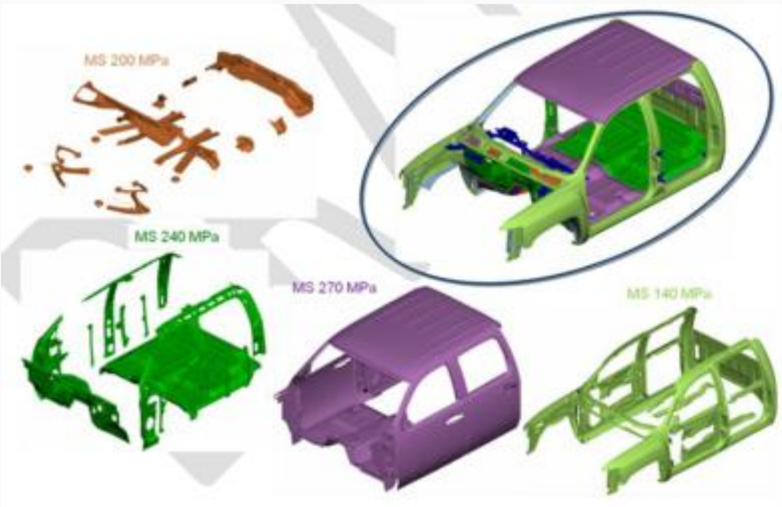
Original Mass
207.2 Kg

Mass Savings
75.4 Kg
3.2% Vehicle reduction



Optimized

Steel to Aluminum



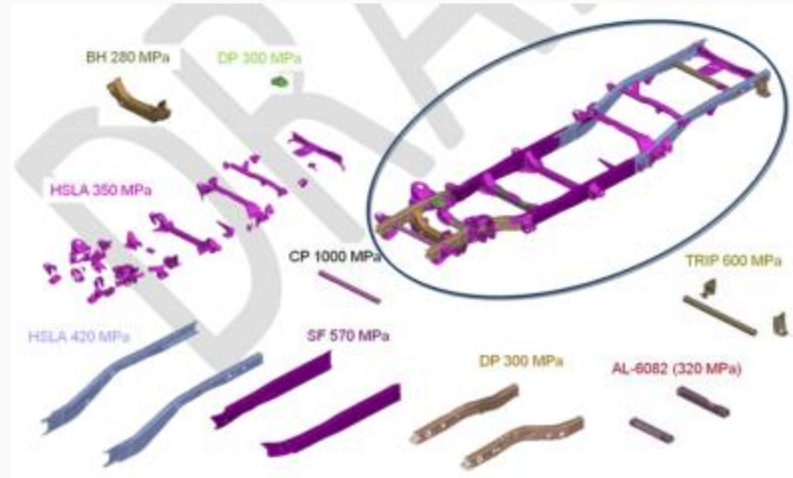
Baseline

Frame Highlights

Preliminary results (under peer review)

Original Mass
252.3 Kg

Mass Savings
23.7 Kg
1.0% Vehicle reduction



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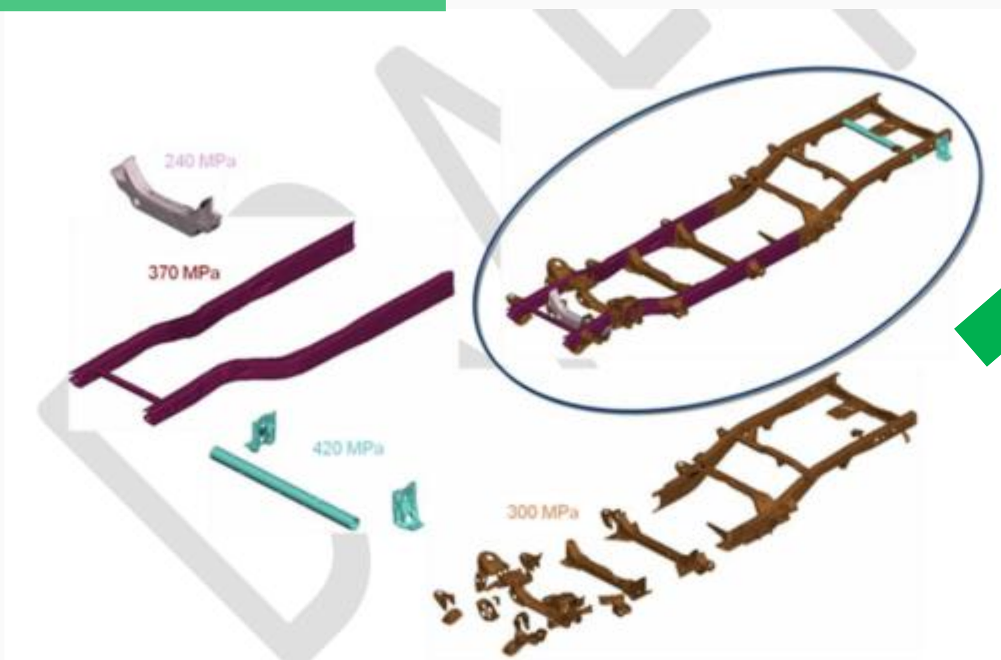


Baseline

Use of higher strength steel (+ some Aluminum)

Body System Group –A- Mass Reduction

Preliminary results (under peer review)

System	Subsystem	Sub-Subsystem	Description	Net Value of Mass Reduction					
				Base Mass "kg"	Mass Reduction "kg" (1)	Cost Impact NIDMC "$" (2)	Average Cost/ Kilogram "$/kg" (2)	Mass Reduction "%"	Vehicle Mass Reduction "%"
03	**00**	**00**	**Body System Group -A-**	**567.40**	**206.40**	**-1195.70**	**-5.79**	**36.38%**	**8.65%**
03	**01**	**00**	**Body Structure Subsystem**	**207.20**	**75.40**	**-506.61**	**-6.72**	**36.39%**	**3.16%**
03	01	01	Cabin	207.20	75.40	-506.61	-6.72	36.4%	3.16%
03	**02**	**00**	**Front End Subsystem**	**31.00**	**11.60**	**-62.92**	**-5.42**	**37.42%**	**0.49%**
03	02	01	Radiator Asm	12.90	5.70	-10.36	-1.82	44.2%	0.24%
03	02	02	Radiator Support	12.10	5.90	-52.56	-8.91	48.8%	0.25%
03	02	12	Tow Hooks	2.25	0.00	0.00	0.00	0.0%	0.00%
03	02	13	Hood Hinges	3.75	0.00	0.00	0.00	0.0%	0.00%
03	**03**	**00**	**Body Closure Subsystem**	**153.70**	**60.00**	**-288.90**	**-4.82**	**39.04%**	**2.51%**
03	03	01	Panel Fender Outer LH	14.90	7.50	-19.34	-2.58	50.3%	0.31%
03	03	01	Panel Fender Outer RH	14.00	7.00	-18.21	-2.60	50.0%	0.29%
03	03	02	Hood	22.70	11.00	-35.19	-3.20	48.5%	0.46%
03	03	03	Door Asm, Front LH	29.00	10.20	-58.99	-5.78	35.2%	0.43%
03	03	03	Door Asm, Front RH	28.90	10.10	-58.73	-5.81	34.9%	0.42%
03	03	04	Door Asm, Rear LH	22.00	7.00	-49.31	-7.04	31.8%	0.29%
03	03	04	Door Asm, Rear RH	22.20	7.20	-49.14	-6.83	32.4%	0.30%
03	**19**	**00**	**Bumpers Subsystem**	**48.40**	**16.40**	**-69.71**	**-4.25**	**33.88%**	**0.69%**
03	19	01	Bumper Front	28.50	9.90	-23.68	-2.39	34.7%	0.41%
03	19	02	Bumper Rear	19.90	6.50	-46.03	-7.08	32.7%	0.27%
03	**26**	**00**	**Cargo Box Subsystem**	**127.10**	**43.00**	**-267.56**	**-6.22**	**33.83%**	**1.80%**
03	26	01	Cargo Box	108.30	34.40	-241.46	-7.02	31.8%	1.44%
03	26	02	Tailgate	18.80	8.60	-26.10	-3.03	45.7%	0.36%
07	**00**	**00**	**Frame & Mounting System**	**267.64**	**23.70**	**-54.42**	**-2.30**	**8.86%**	**0.99%**
07	**01**	**00**	**Frame Subsystem**	**252.27**	**23.70**	**-54.42**	**-2.30**	**9.39%**	**0.99%**
07	01	01	Front Cross Member	4.90	1.60	-3.67	-2.30	32.7%	0.07%
07	01	01	Trans Cross Member	4.90	1.60	-3.67	-2.30	32.7%	0.07%
07	01	01	Other Components…	232.20	20.50	-47.07	-2.30	8.8%	0.86%
07	01	03	Body Isolators	10.27	0.00	0.00	0.00	0.0%	0.00%
07	**03**	**00**	**Engine Transmission Mounting Subsystem**	**2.14**	**0.00**	**0.00**	**0.00**	**0.00%**	**0.00%**
07	03	02	Transmission Mount	2.14	0.00	0.00	0.00	0.0%	0.00%
07	**04**	**00**	**Towing and Coupling Attachments Subsystem**	**13.23**	**0.00**	**0.00**	**0.00**	**0.00%**	**0.00%**
07	04	01	Towing Provisions	13.23	0.00	0.00	0.00	0.0%	0.00%
				835.04	**230.10** (Decrease)	**-1,250.12** (Increase)	**-5.43** (Increase)	**27.56%**	**9.64%**

(1) "+" = mass decrease, "-" = mass increase

(2) "+" = cost decrease, "-" = cost increase

Response to NAS Question #5a: Material supply

5) The major studies on mass reductions, such as the Venza and Accord studies, are paper studies. How do you respond to the following concerns expressed by manufacturers that increase costs:

a) Inadequate supply chains for new materials and processing resulting in high risk for shortages and price increases (aluminum supply chain is already a bottleneck today and some studies specify unique and sometimes unavailable material gauge/grades that limit "optimization".)

EPA Response

- Advanced planning by aluminum suppliers and OEM's are resulting in sufficient supply of wrought aluminum through 2025
  - Wrought Aluminum is increasing in volume from current supply demand of 300M lbs to 4B lbs (North American)
  - Additional roll finishing lines are being added as OEM's demand
    - Lead time for adding finishing lines is 2 years. (based on launch of F150)
    - New companies are entering the marketplace
    - Facilities converting from rolling sheet for cans to automotive
      - China wants to provide more can stock (currently 30%)
    - 25%-30% of 2025 demand expected to be up and running by end of 2014
- Light Duty Truck study accounted for availability of material gauge/grades
  - Aluminum is manufactured to order and can come in tenth of a mm increments.
  - Steel gauge limited to commonly available thicknesses (HSS in frame)

Information resources:

- Ducker Worldwide "Executive Summary to the 2015 North American Light Vehicle Aluminum Content Study"
- http://www.aluminum.org/resources/industry-statistics

Response to NAS Question #5b: Platform sharing

5. The major studies on mass reductions, such as the Venza and Accord studies, are paper studies. How do you respond to the following concerns expressed by manufacturers that increase costs:
   b) Global platforms and sharing of components inhibiting model optimization (over 50% of vehicles are produced on global platforms)

EPA Response

- Range of performance requirements for global platforms continues to narrow
  - Convergence in consumer demand for major vehicle markets
  - Convergence in international safety and emissions requirements
- Shift in design approach by OEMs
  - In the past, a platform would be designed to meet the requirements of the worst load case
  - Today, platforms are designed to meet the requirements of highest volume vehicles, and add material or reinforce structures as necessary for high load variations
  - Examples: Bolt-on reinforcements in 2015 Ford Mustang Convertible,
    Bolt-on and weld-in reinforcements in 2014 Chevrolet Spark EV

Engine System Highlights

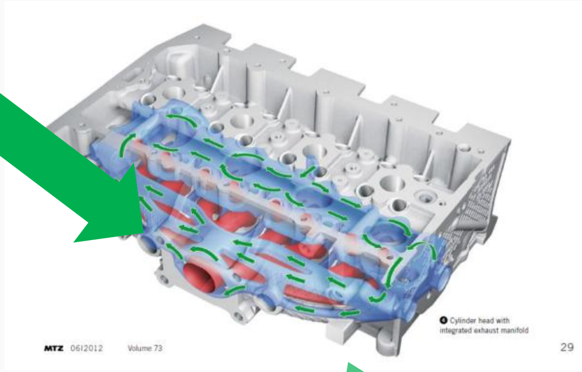
Preliminary results (under peer review)

Original Mass
283.7 Kg

Mass Savings
37.3 Kg
1.6% Vehicle reduction

Connecting Rods
from cast to forged
-1.1 kg

Cylinder Liner
from cast iron to plasma coated
-2.4 kg



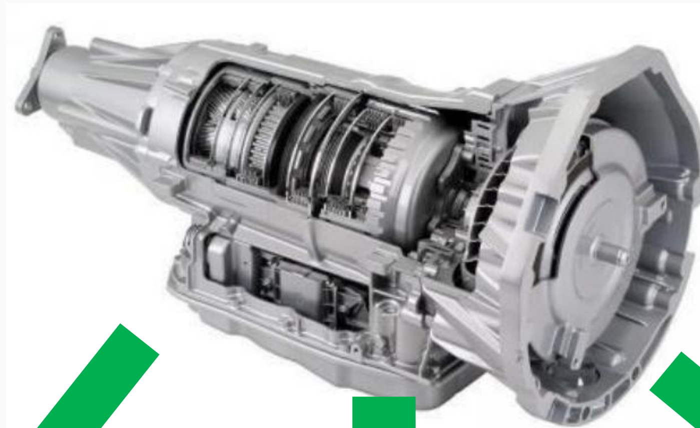
Integrated Exhaust Manifolds
-5.6 kg

Transmission System Highlights

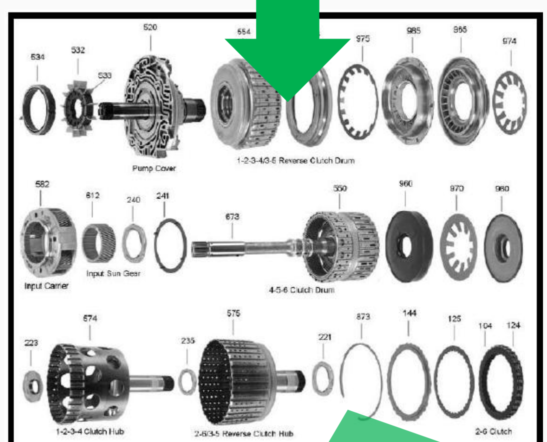
Preliminary results (under peer review)

Original Mass
145.3 Kg

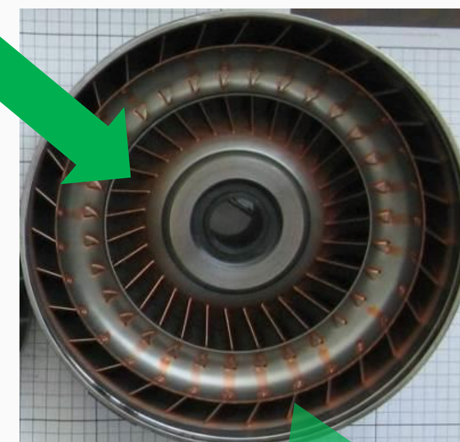
Mass Savings
34.2 Kg
1.7% Vehicle reduction



Changing Case Material from AL to Mg
-10.7 kg



Internal Clutch and Brake Hubs material to C61 and MMC
-2.4 kg



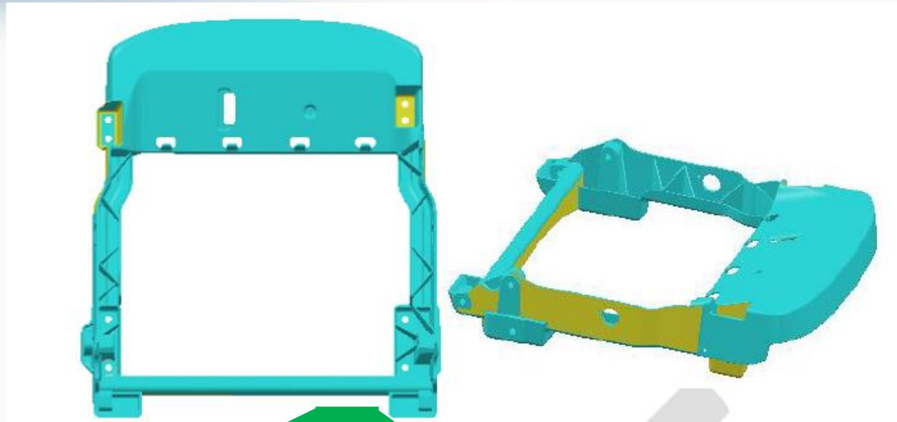
Aluminum Torque Convertor
-8.6 kg

Seating System Highlights

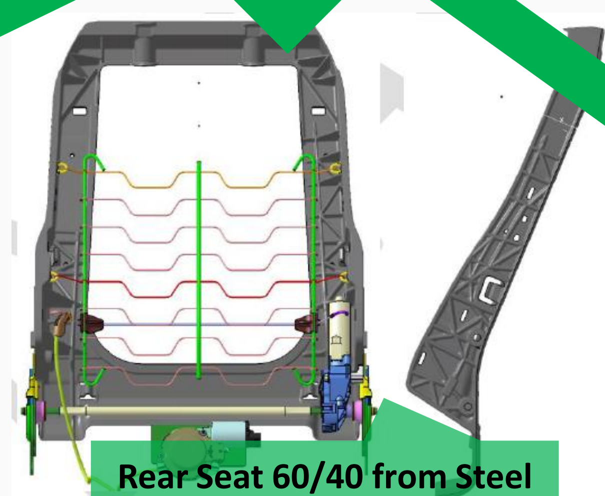
Preliminary results (under peer review)

Original Mass
247 Kg

Mass Savings
34 Kg
1.3% Vehicle reduction



Changing Seat Frame from Steel Welded to Laminate
-5.8 kg



Rear Seat 60/40 from Steel Welded to Die cast Mg
-8.4 kg

Cross Car Beam from Steel Welded to Die Cast Mg
-5.5 kg

Suspension System Highlights

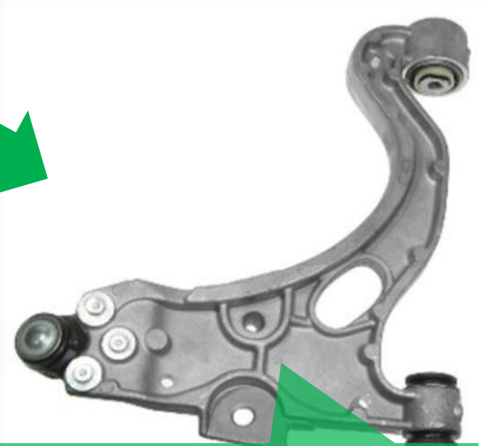
Preliminary results (under peer review)

Original Mass
301.2 Kg

Mass Savings
112.7 Kg
4.7% Vehicle reduction

Changing Steering Knuckles from steel to AL
-7.9 kg

Composite Leaf Springs
-31.4 kg



Changing Lower Control Arm from cast iron to AL
-7.7 kg

Brake System Highlights

Preliminary results (under peer review)

Original Mass
101 Kg

Mass Savings
49.5 Kg
2.1% Vehicle reduction

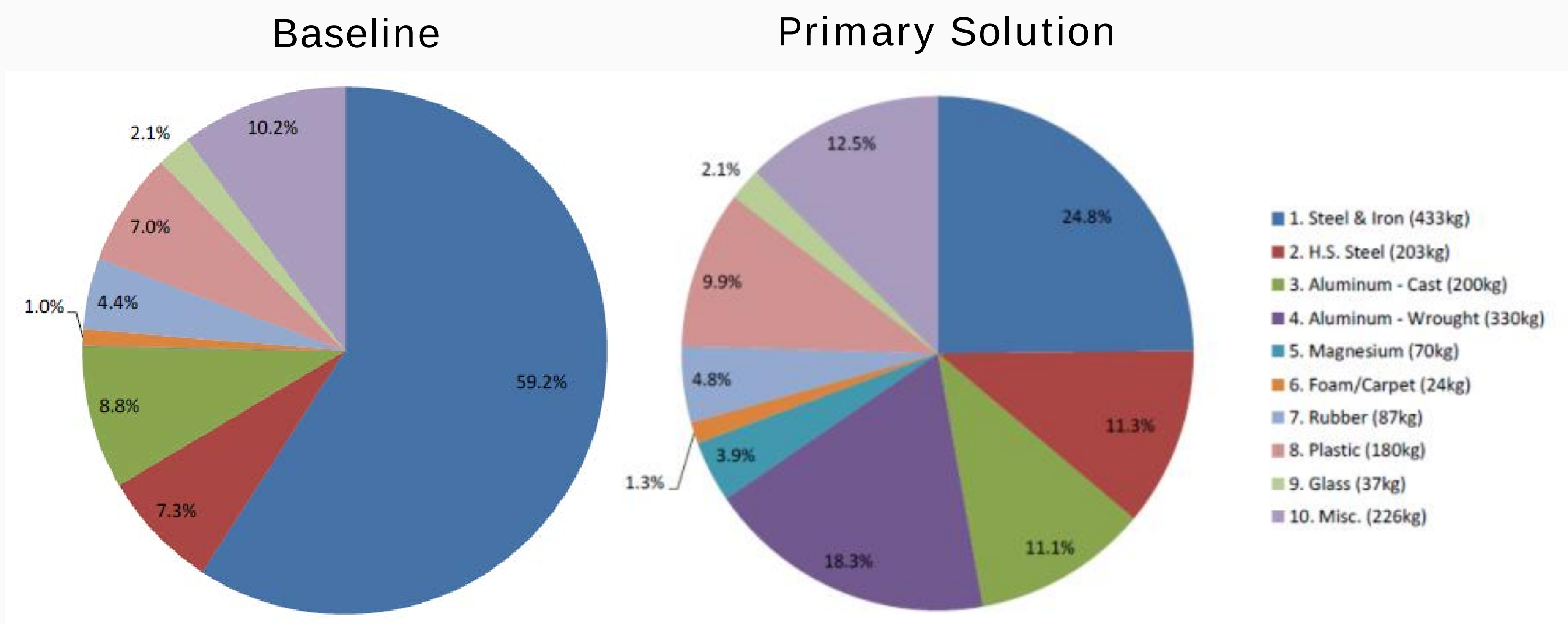
Changing Front Rotor 1 piece iron to 2 piece steel + AL, adding cross drilling, etc
-12.4 kg

Changing Rear Drum from cast iron to AL, adding cooling fins and cross drilling
-14.2 kg

Caliper Housing from cast iron to cast Mg
-6.4 kg

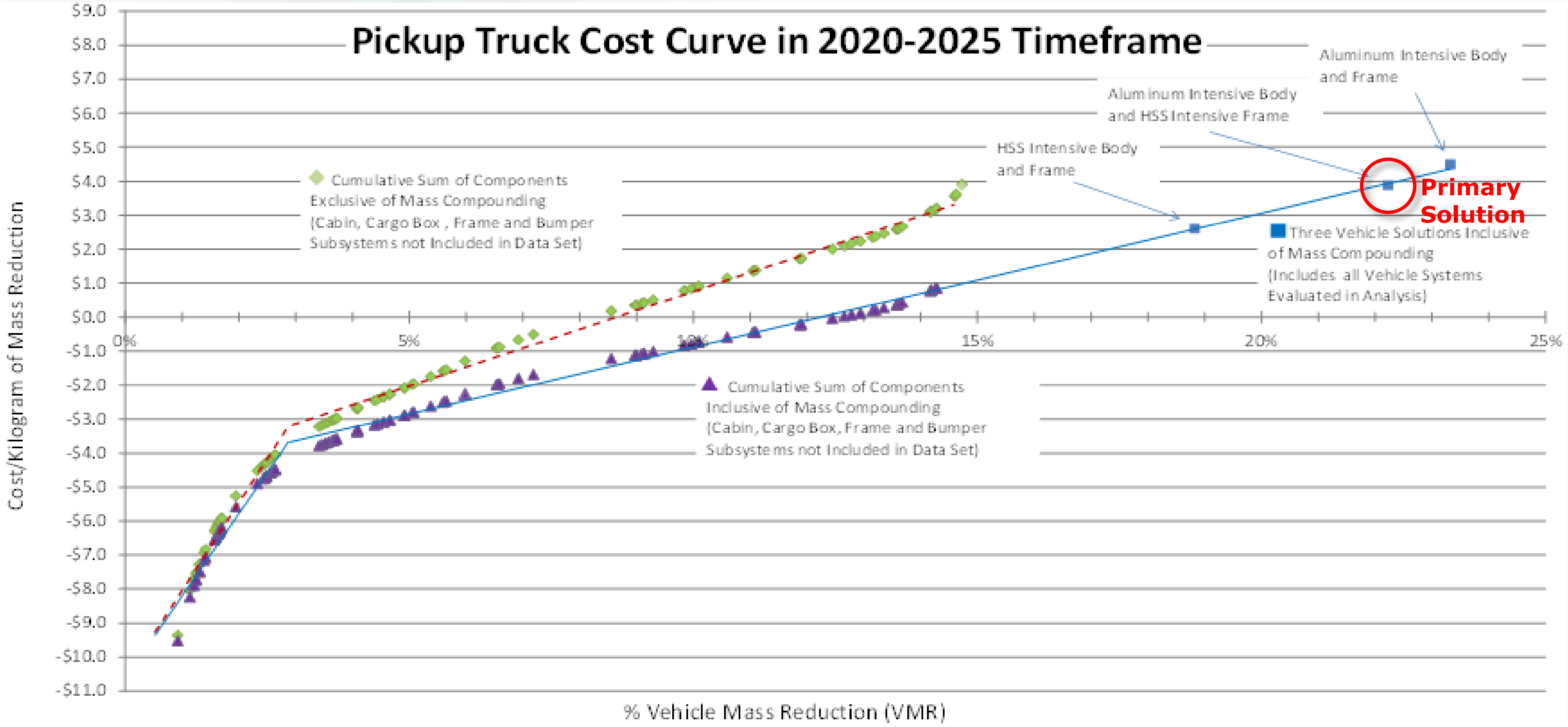
Material Makeup

Preliminary results (under peer review)



Full vehicle cost curve

Preliminary results (under peer review)

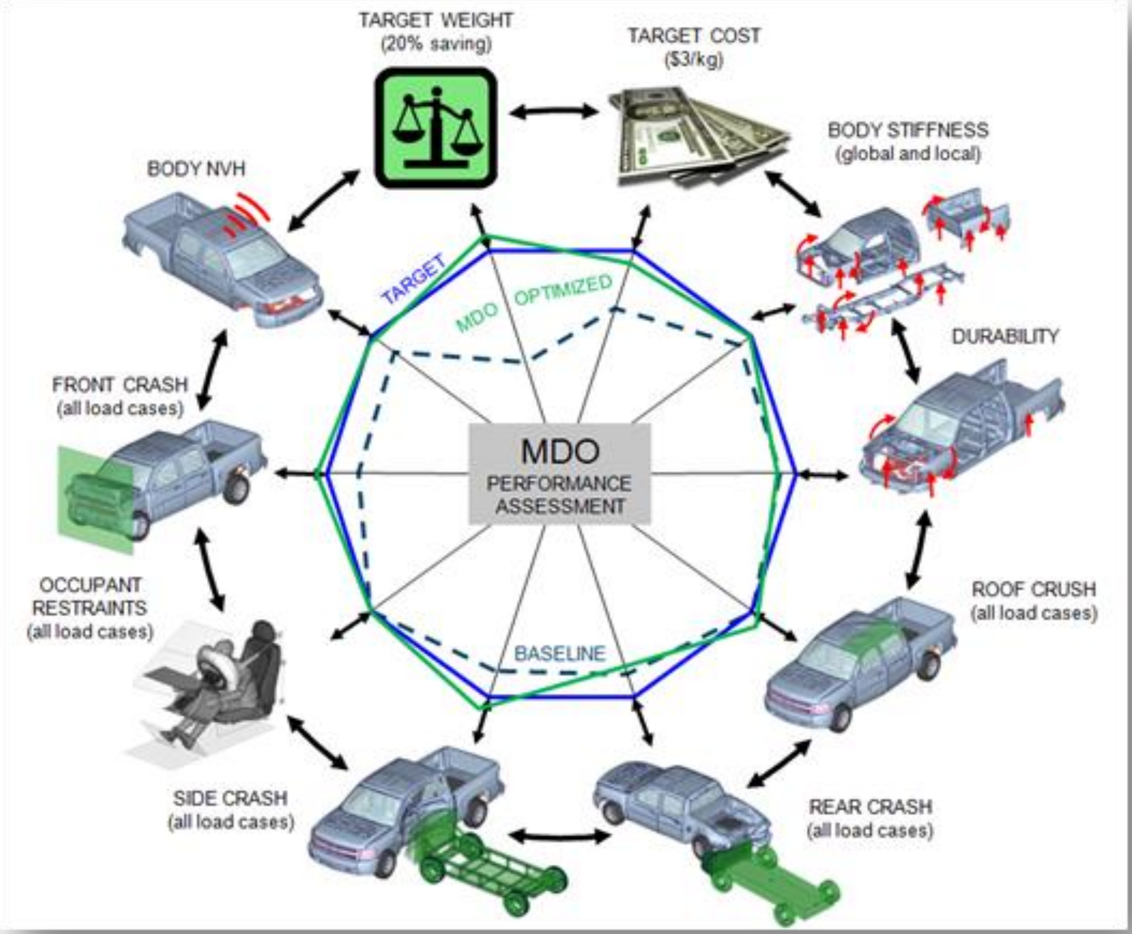


Trendline Description	Cost/Kilogram Mass-Reduction Formula	% Vehicle Mass Reduction Zone
Without Mass Compounding/Secondary Mass Savings	\$/kg = 258.7*(VMR) - 10.629 \$/kg = 55.585*(VMR) - 4.807	0% < VMR ≤ 2.9% 2.9% < VMR ≤ 14.3%
With Mass Compounding/Secondary Mass Savings	\$/kg = 242.4*(VMR) - 10.629 \$/kg = 39.359*(VMR) - 4.8168	0% < VMR ≤ 2.9% 2.9% < VMR ≤ 23.3%

Primary Vehicle Solution CAE Simulation Results Overview

Preliminary results (under peer review)

- This spider plot illustrates the relative CAE simluation performance of
  - Baseline (dashed)
  - Target (blue)
  - Primary solution “MDO optimized” (green)
- Results within acceptable tolerance of baseline , and exceed baseline performance for many load cases



Primary Vehicle Solution Cost and Mass Result Details

Preliminary results (under peer review)

- Net incremental direct manufacturing costs (NIDMC) + OEM tooling
- Primary solution: 527kg (22.1%) Mass Reduction at $3.88/kg increase (+$2045)

Item	System ID	Description	Base Mass "kg"	Mass Reduction "kg" (1)	Cost Impact NIDMC "$" (2)	Cost/ Kilogram NIDMC "$/kg" (2)	Cost/ Kilogram NIDMC + Tooling "$/kg" (2)	System Mass Reduction "%"	Vehicle Mass Reduction "%"
			Mass Reduction Impact by Vehicle System (Includes Secondary Mass Savings)						
		1500 Series Chevrolet Silverado Pick-Up Truck							
1	01	Engine System	238.7	37.3	-57.73	-1.55	-1.29	15.6%	1.6%
2	02	Transmission System	145.3	39.4	-96.57	-2.45	-2.47	27.1%	1.6%
3	03A	Body System Group -A- (Body Sheetmetal)	574.7	207.1	-1194.79	-5.77	-5.77	36.0%	8.7%
4	03B	Body System Group -B- (Body Interior)	247.0	34.0	-127.23	-3.74	-3.78	13.8%	1.4%
5	03C	Body System Group -C- (Body Exterior Trim)	40.5	2.1	2.73	1.28	1.28	5.3%	0.1%
6	03D	Body System Group -D- (Glazing & Body Mechatronics)	50.9	4.5	2.30	0.51	0.51	8.9%	0.2%
7	04	Suspension System	301.2	112.7	-26.01	-0.23	-0.24	37.4%	4.7%
8	05	Driveline System	183.8	20.4	38.01	1.86	1.89	11.1%	0.9%
9	06	Brake System	101.0	49.5	-140.06	-2.83	-2.93	49.0%	2.1%
10	07	Frame and Mounting System	267.6	23.7	-54.42	-2.30	-2.30	8.9%	1.0%
11	09	Exhaust System	38.4	6.9	-13.69	-1.97	-1.97	18.1%	0.3%
12	10	Fuel System	26.3	7.3	11.92	1.62	1.77	27.9%	0.3%
13	11	Steering System	32.5	8.5	-147.46	-17.44	-17.45	26.0%	0.4%
14	12	Climate Control System	20.3	1.9	14.71	7.59	7.59	9.5%	0.1%
15	13	Information, Gage and Warning Device System	1.6	0.2	0.66	2.66	2.97	15.7%	0.0%
16	14	Electrical Power Supply System	21.1	12.8	-172.73	-13.49	-13.44	60.6%	0.5%
17	15	In-Vehicle Entertainment System	2.2	0.0	0.00	0.00	0.00	0.0%	0.0%
18	17	Lighting System	9.6	0.4	-2.00	-5.18	-5.18	4.0%	0.0%
19	18	Electrical Distribution and Electronic Control System	33.6	8.5	61.44	7.26	7.27	25.2%	0.4%
20	00	Fluids and Miscellaneous Coating Materials	49.6	0.0	0.00	0.00	0.00	0.0%	0.0%
		a. Analysis Totals Without NVH Counter Measures →	**2386.0**	**577.3**	**-1900.90**	**-3.29**	**-3.28**	**n/a**	**24.2%**
		b. Vehicle NVH Counter Measures (Mass & Cost) →	0.0	-50.0	-150.00	n/a	n/a	n/a	n/a
		c. Analysis Totals With NVH Counter Measures →	**2386.0**	**527.3** (Decrease)	**-2050.90** (Increase)	**-3.89** (Increase)	**-3.88** (Increase)	**n/a**	**22.1%**

(1) Negative value (i.e., **-X.XX**) represents an increase in mass
(2) Negative value (i.e., **-$X.XX**) represents an increase in cost

Response to NAS Question #5d: Performance trade-offs / late changes

5. The major studies on mass reductions, such as the Venza and Accord studies, are paper studies. How do you respond to the following concerns expressed by manufacturers that increase costs:
   d) Performance tradeoffs - during real world vehicle development and testing, mass always increases to correct performance degradation issues (vibration, crashworthiness, ride/handling, etc.).

EPA Response

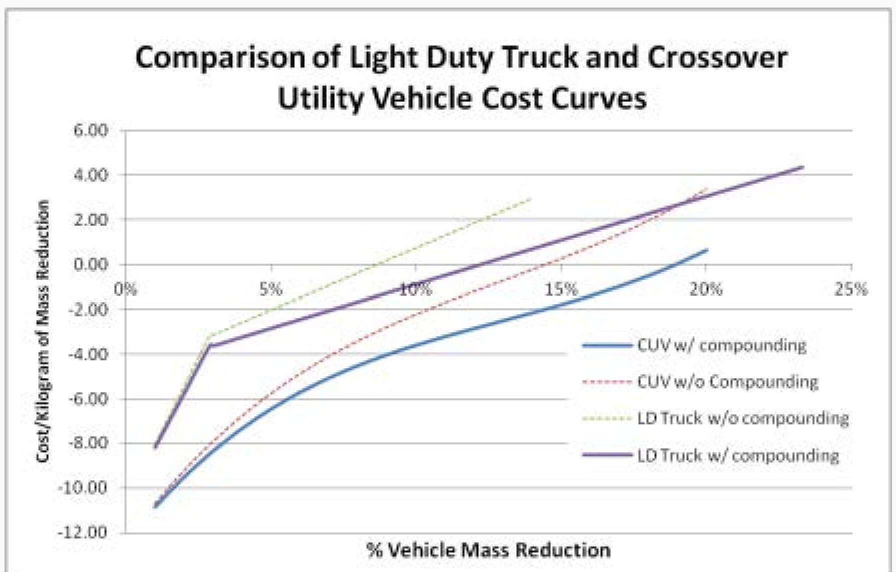
- Countermeasures applied at late stages in development process are often sub-optimal for cost and performance (not only mass)
- Pull-ahead of production tooling much earlier in the development process
  - Increased incentive for reducing last minute changes
  - Last minute structural modifications less common than in the past
- Simulation tools are now highly advanced
  - Particularly for body structure and crash simulation
  - Becoming more so for dynamic and nvh simulation
- Silverado study includes additional NVH "buffer"
  - Recognizes limitations of NVH simulation, especially without detailed interior model
  - Added mass and cost for unspecified NVH countermeasures (insulation, etc.)

Application of Findings to MTE Analysis

Applications of Findings to MTE analysis

Preliminary results (under peer review)

- OMEGA model estimates mass reduction cost based on % reduction in curb weight
- Now have an additional point of reference for mass reduction cost
- Silverado cost curve reflects unique characteristics of body-on-frame vehicles
- EPA is now evaluating whether to apply a separate cost curve for body-on-frame vehicles



Monitoring Trends in Mass Reduction:

Near term

- Observe OEM trends
  - During the time of this study (2012-2014):
    - Ford announced its aluminum F150
    - A number of Body on Frame SUV's redesigned to unibody
  - Incorporation of light weight materials
  - Vehicle curb weights
- Consider safety features that may add weight
  - IIHS narrow offset test
  - Backup camera, etc.

Longer term

- Developments in material supply and capacity (e.g. aluminum, magnesium)
- Sources for information:
  - Press releases, conferences, stakeholder meetings
    - MY 2018 Silverado 1500 adopting aluminum (?)
  - Contract with new information collection services..
    - A2Mac1
    - Ducker Worldwide
  - DOE funded work and developments

Response to NAS Question #5c: Phase-in of lightweight materials

5) The major studies on mass reductions, such as the Venza and Accord studies, are paper studies. How do you respond to the following concerns expressed by manufacturers that increase costs:

c) **Non-standard product and process changes to existing vehicle platforms needed to accommodate new, non-traditional materials require an incremental approach for implementation over at least two new vehicle design cycles (approximately 8 years or longer).**

EPA Response

- Incremental approach is already well-underway
  - Market penetration of aluminum hoods now at nearly 50%
  - Nearly every OEM has experience with one or more generations of vehicles with aluminum closures
- Recent examples of lightweight materials in body structures have occurred in one generation
  - Aluminum: 2015 Ford F-150, 2013 Land Rover Range Rover
  - Structural composites: 2014 BMW i3
- Examples of true multi-material body structures likely influenced by performance and cost considerations, and not simply lack of capacity or capability to produce all-aluminum vehicle
  - 2015 Mercedes C-Class
- EPA is reevaluating phase-in cap values to account for limitations in the rate of mass reduction adoption in light of the information that is being gathered for the mid-term evaluation

Ongoing and future whole vehicle studies

1. Scoping
Low cost paper study to gain experience of exercise and determine next steps ($600k)

2010: Phase 1 Midsize CUV study (Energy Foundation) (used in LD GHG Phase 2 rulemaking) - peer reviewed

2. Main studies (include indepth Cost and CAE)
Expand approach from scoping study to include additional analyses, indepth cost and safety ($2M+)

2012: Phase 2 Midsize CUV Low Development (20%MR) for 2017 (EPA) – peer reviewed
2012: Lightweight Sedan (20%MR) (NHTSA) – peer reviewed
2012: Phase 2 Midsize CUV High Development (30%+MR) for 2025 (ARB) – In-depth Cost and CAE on BIW

3. Follow-up Sub-Studies: BIW/Closures
Perform in-depth analyses on specific systems

2012: NHTSA: Investigation of Opportunities for Lightweight Vehicles Using Advanced Plastics and Composites (Light Duty Truck)
2013: Aluminum Association - Phase 2 Low Development BIW in aluminum (FEV/EDAG BIW design)

4. Additional Main Studies
Perform whole vehicle studies for additional vehicles / vehicle types($3M to $20.3M)

2012-2014: Light Duty Truck Light Weighting Study (20%MR) (EPA) (currently under Peer Review)
2014-?: Light Duty Truck Light Weighting Study (and apply to other vehicle types) (NHTSA)
2015: Multi-Material Lightweight Vehicles project – Mach 1 (25%MR) and Mach 2 (50%MR) -(DOE)

5. Main study Report Updates
Receive feedback and update studies ($500k+)

Agenda

1. Introductions
2. NCAT* Benchmarking Activities
   a) ALPHA and Vehicle Validation (GM Malibu w/ 2.5 liter EcoTec)
   b) Shifting Study (6-spd Malibu & 8-spd Chrysler 300)
   c) Engine Mapping (US Ford Escape w/1.6 liter EcoBoost)
   d) Study of future engines
3. Lumped Parameter Model Application
4. Mild Hybrid Tear-down Study
5. Silverado Mass Reduction Study
6. **ICM Study**
7. Other NAS specific topics not covered above (as required)
8. Wrap-up
9. NCAT Lab Review

**NCAT –National Center for Advanced Technologies*

Overview

Cost analysis markups & indirect costs in MYs 2016-2025

- Background on Indirect Cost Markups
  - ICMs in our rules
- Indirect costs in MYs 2016 thru 2025
  - “Effective markups” (i.e., total/direct costs)
- Questions

Background on Indirect Cost Markups

- **Retail price equivalents (RPE) vs Indirect cost multipliers (ICM)**
  - RPE is an estimate all indirect costs
    - All direct mfg costs face the same markup, which is an average over everything the company does
  - ICM seeks to estimate *only* the indirect costs impacted by a new rule
    - Perhaps not all indirect costs change (e.g., pensions for retired employees)
    - Perhaps some indirect costs are higher than normal during initial implementation (e.g., R&D)

- **ICMs in our rules – general thesis**
  - Indirect Cost Multipliers (ICMs) focus only on those elements that change with regulatory requirements
  - ICMs present the more appropriate measure of government imposed costs

RPE vs ICM – calculation approach

- **Both approaches consist of a factor applied to direct mfg costs (DMC)**
  - RPE, traditionally, has been a straight multiplier
    - Indirect costs (IC) decrease as DMC decreases with learning
    - Indirect costs scale directly with DMC year-over-year
  - ICM, recently, has been more complex in application
    - Non-warranty ICs stay constant year-over-year
    - Warranty ICs decrease as DMC decreases with learning
    - Indirect costs do not scale directly with DMC year-over-year
- **The ICM approach provides for different markups for different technologies**
  - The agencies have used complexity level determinations for different technologies resulting in different markups
  - RPE would apply the same markup to a basic tech (passive aero) as applied to a complex tech (hybridization)

ICMs in our rules – a history

- **Developed by RTI under contract to EPA,** EPA-420-R-09-003
  - Peer review report published June 2009, EPA-420-R-09-004
  - Work then published in the International Journal of Production Economics (2009), doi:10.1016/j.ijpe.2009.11.031.
- **ICM application in EPA rules**
  - First used in the MYs 2012-2016 rule (LD Phase 1)
  - 2010 Technical Assessment Report
  - HD GHG Phase 1
  - MYs 2017-2025 rule (LD Phase 2)
  - LD Highway Tier 3 rule
  - We plan to use in the HD GHG Phase 2 rule

Direct and Indirect Costs

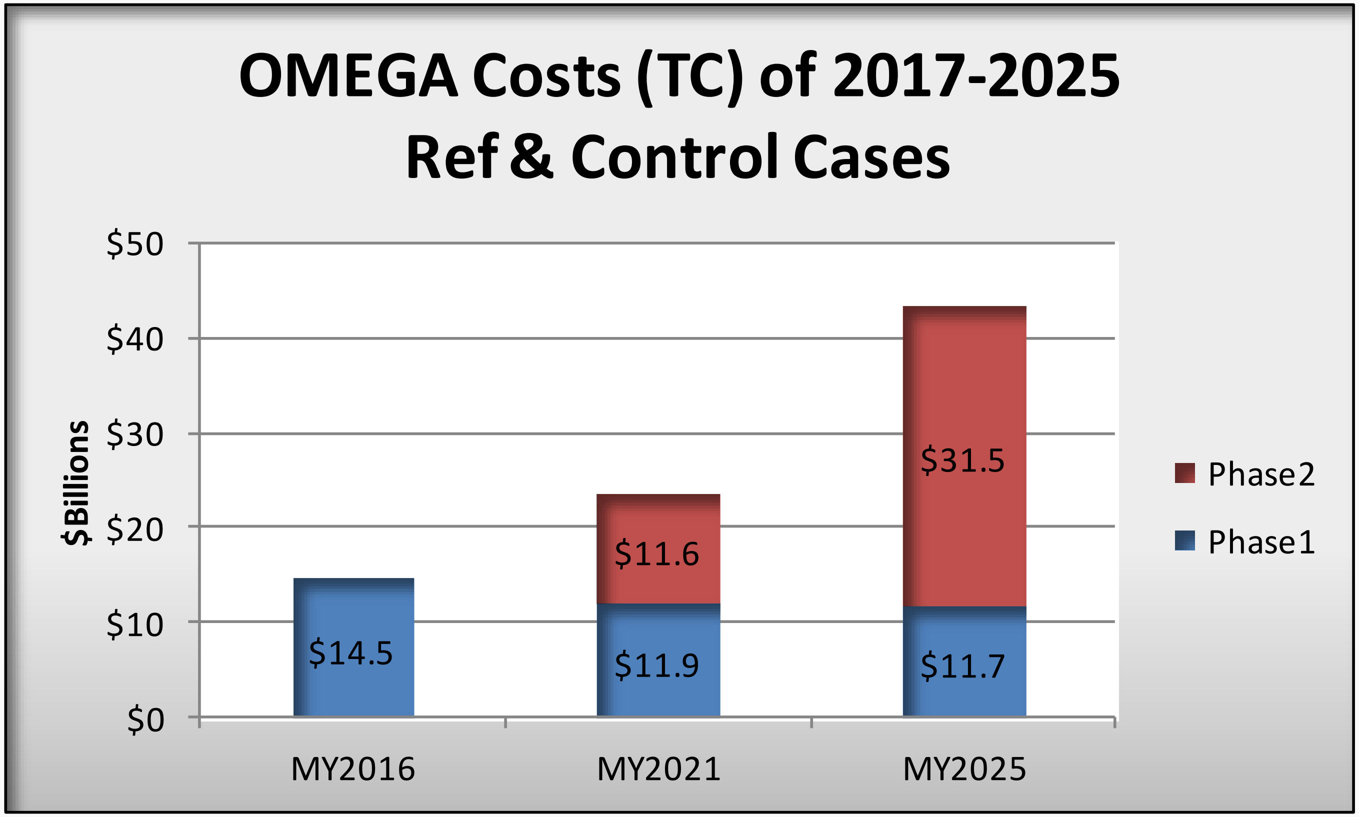
So, what is the breakdown of projected GHG-imposed direct & indirect costs over time?

- **OMEGA is well suited to determine the answer**
  - We know what packages have been applied to what platforms and at what penetration rates.
  - We know the total cost (DMC+IC) basis of those packages in the ref & control cases.
  - We can "easily" determine the direct cost basis of those packages in the ref & control cases.
  - The delta represents the indirect cost basis.

NOTE: This approach determines the cost of *ONLY those technologies* actually added to vehicles in our joint baseline fleet.

Total Costs

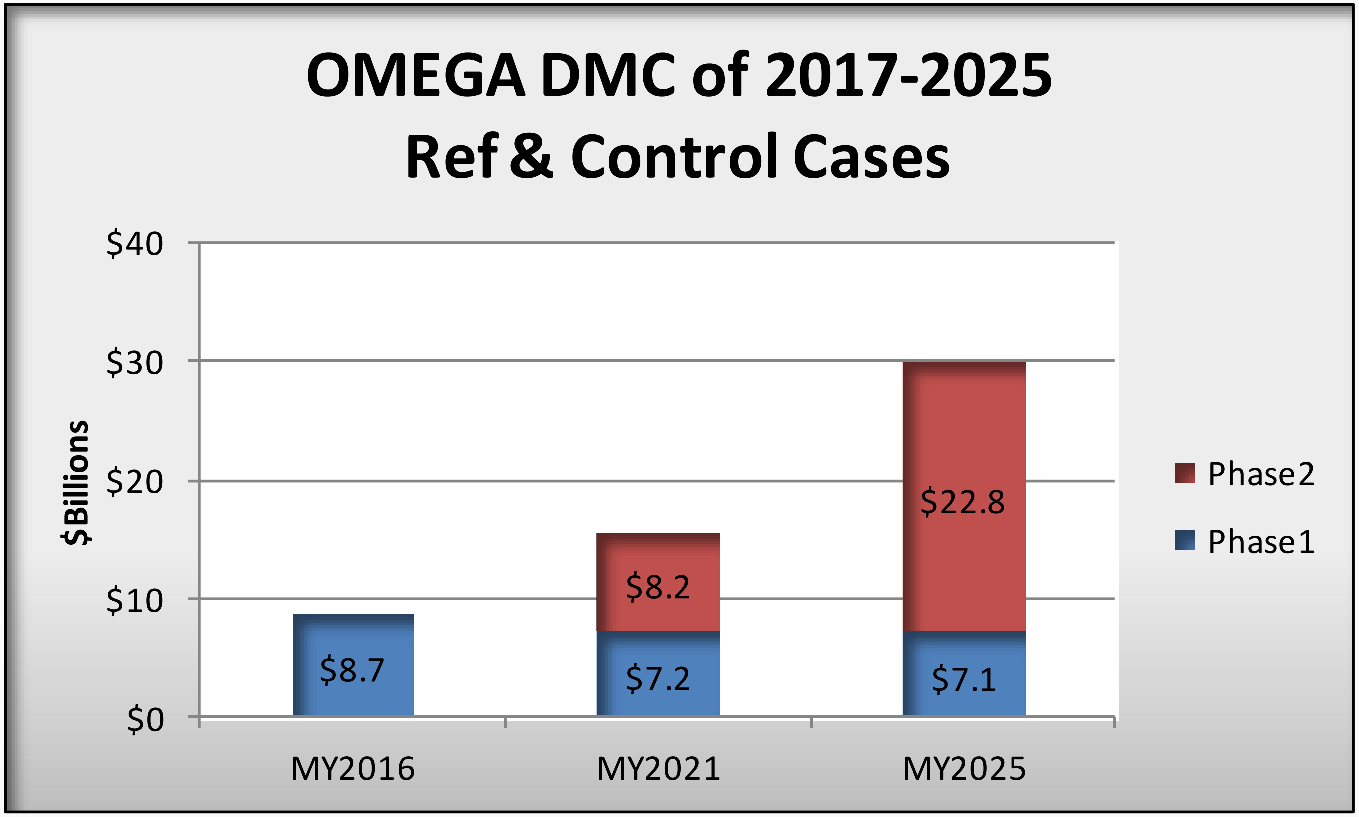
What are the total costs (TC) for both phases of GHG standards in the 2016-2025 timeframe? *



** OMEGA runs exclude A/C costs and use updated trans DMC values among other model updates; however, the results are virtually identical to those from the FRM.*

Direct Manufacturing Costs

What are the Direct Mfg Costs (DMC) for both phases of GHG stds in the 2016-2025 timeframe? *



** OMEGA runs exclude A/C costs and use updated trans DMC values among other model updates; however, the results are virtually identical to those from the FRM.*

Projected Costs

Breakdown of projected costs for the GHG stds*

Dollar values in $billions

Rule	Cost	MY2016	MY2021	MY2025
Phase1	DMC	$8.7	$7.2	$7.1
Phase1	TC	$14.5	$11.9	$11.7
Phase1	IC (TC-DMC)	$5.8	$4.6	$4.6
Phase1	TC/DMC	1.67	1.64	1.66
Phase2	DMC	$0.0	$8.2	$22.8
Phase2	TC	$0.0	$11.6	$31.5
Phase2	IC (TC-DMC)	$0.0	$3.4	$8.8
Phase2	TC/DMC		1.42	1.38
Phase1+2	DMC	$8.7	$15.4	$29.9
Phase1+2	TC	$14.5	$23.5	$43.2
Phase1+2	IC (TC-DMC)	$5.8	$8.1	$13.4
Phase1+2	TC/DMC	1.67	1.52	1.45

** OMEGA runs exclude A/C costs and use updated trans DMC values among other model updates; however, the results are virtually identical to those from the FRM.*

Some Observations Based on These Results

- **The "effective markups" (TC/DMC) shown are higher than the ICMs would suggest – How?**
  - Remember that we always calculate indirect costs using the absolute value of the direct cost
  - Many low complexity techs are already on vehicles in the baseline so do not impact the "effective markup"
- **The "effective markup" decreases over time…but RPE doesn't**
  - GHG efforts in early years presumably have a higher relative contribution to indirect costs than they do in later years as R&D, etc., resources are moved off GHG and back to other programs
  - Note the high effective markup in earlier years (i.e., >1.5x, or > than the traditional RPE)

Annual GHG costs

Phases 1&2 GHG costs ($billions)*

Year	DMC	IC	TC	TC/DMC
2016	$8.7	$5.8	$14.5	1.67
2017	$10.0	$6.3	$16.3	1.63
2018	$11.4	$6.7	$18.1	1.59
2019	$12.7	$7.2	$19.9	1.57
2020	$14.0	$7.6	$21.7	1.54
2021	$15.4	$8.1	$23.5	1.52
2022	$19.0	$9.4	$28.4	1.49
2023	$22.6	$10.7	$33.4	1.47
2024	$26.2	$12.1	$38.3	1.46
2025	$29.9	$13.4	$43.2	1.45
Total	**$169.9**	**$87.3**	**$257.2**	**1.51**

* *using results shown on previous slides with interpolations for 2017-2020 & 2022-2024.*

10 year markup = 1.51!

Cost questions from NAS

1.b. For turbocharged, downsized engines, information provided to the committee and our review of the regulatory documents by the agencies indicate there may be a need to account for upgraded turbochargers (e.g. twin scroll, higher exhaust temperature capability) and modifications to preserve driveability (NVH, driveline ratios). (See also Q.2 and Q. 3b for other cost questions relevant to TBDS.) Does EPA have any comments on such cost revisions that are detailed in Attachment 2.

- EPA response: In the 2017-2025 FRM, we applied scaling factors of 150% and 250% to our 18-bar BMEP turbo costs in estimating costs for 24 & 27-bar BMEP turbocharging. These scaling factors were meant to cover variable geometry turbochargers among other required changes. We intend to do additional cost analysis, either paper study or teardown, of newly available turbo/downsized engines which would allow us to update our current cost estimates.

Cost questions from NAS

2. By estimating Direct Manufacturing Costs as 20% (0.2) or 15% (0.15) of service part prices, one frequently obtains estimates for components that are greater than the agencies' estimates. (Please see TBDS example, Attached 2.) What methods did the agencies use to estimate costs when teardown results were not available, and why are the results lower than estimates derived from the prices of service parts?

- EPA Response: The agencies have generally relied on cost estimates presented in other studies when teardown results have not been available. Such studies include prior NAS reports (2002, 2006 (tires), 2010, etc.), the NESCCAF report of 2007 (costs done by Martec), and averaging of individual CBI values provided by industry. We tend not to focus much on service part prices as variability in markups is extremely broad, and we know of no study upon which a markup/markdown factor could be based. With a solid source for such a factor, we would consider using service part prices given the ease of obtaining them.

Cost questions from NAS

3.a. The committee would like a detailed explanation of your analysis showing that the average effect of Indirect Cost Multipliers, as used in the final rule, averages to a markup from Direct Manufacturing Cost to Retail Price Equivalent of 1.5.

- EPA response: See separate presentation slides.

Cost questions from NAS

3.b. Based on the attached example (Attachment 2), an ICM of 1.39 may be too low for medium complexity SI engine technologies. The example in the attachment shows that a reasonable estimate of product development costs for ICP in an I4 engine would be 18%, rather than the 5% used in the agencies' analysis. This change would increase the ICM for ICP on an I4 to 1.52. A similar analysis for a V6 produces an ICM of 1.46. This indicates an ICM of about 1.50 may be more appropriate than an ICM of 1.39. Do you see problems with this revised estimate or reasons that such a revision would not be appropriate for other SI engine technologies?

- <u>EPA Response:</u> The markups we use (ICMs) have, as their basis, the average industry-wide retail price equivalent (RPE) markup which was derived by looking at the direct and indirect costs contained in financial reports to the Securities and Exchange Commission.

- We do not believe that the revised estimate methodology is appropriate. The approach suggested by the question makes many assumptions which may or may not be accurate for estimating the <u>incremental cost</u> associated with ICP. (ie: annual volume, incremental number of engineers, incremental number of development vehicles, etc…)

Cost questions from NAS

4.b. How did the EPA develop its cost estimates for the High Efficiency Gearbox technology?

- EPA Response: As noted in the final joint TSD (at page 3-105), “The agencies estimate the DMC of the high efficiency gearbox at $200 (2009$). We have based this on the DMC for engine friction reduction in a V8 engine which, as presented in Table 3-24 is $197 (2010$). In the proposal, we rounded this value up to $200 (2009$) which becomes $202 (2010$) for the final analysis.”

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