What the National Academies Report Says About Technology

15th Biennial Conference on Transportation and Energy
Asilomar 2015
August 20, 2015

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Member – NRC Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2

What Technology?

- Fuel economy technologies for light-duty vehicles

Why Does the National Academies Have Something to Say About Technology?

Energy Independence and Security Act (EISA 2007)

- Requested National Academy of Sciences reports evaluating vehicle fuel economy standards at 5 year intervals.
  - This is the second report.

2025 CAFE Final Rule

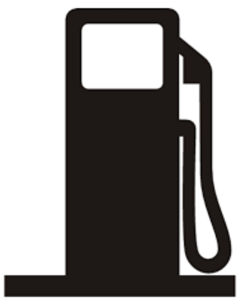
- "The agencies should seek expert peer-reviewed information including the National Academy of Sciences to answer a number of questions associated with the mid-term reviews. "

Ref: EPA/NHTSA, "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards - Final Rule", October 15, 2012

National Research Council (NRC) Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles (2017 – 2030 Timeframe)

- 3+ year study (2012 – 2015)
- 18 volunteer members
- 15 peer reviewers
- Report relied on:
  - Regulatory Documents
  - NHTSA/EPA Experts
  - OEMs
  - Suppliers
  - Full System Simulations (U of Michigan)
  - Literature
  - Press Accounts
  - Committee's Expertise

CAFE – Corporate Average Fuel Economy

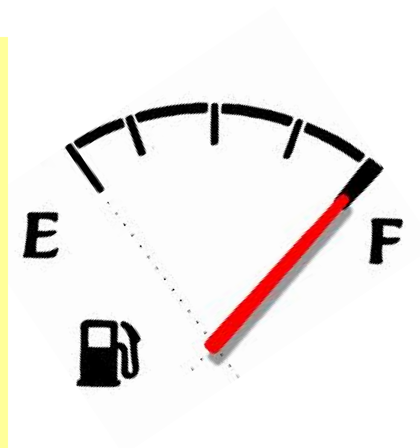


"54.5 MPG"

If all reductions for EPA's 163 g/mi CO_2 standard were met with fuel economy improvements

48.7 – 49.7 MPG

NHTSA's CAFE estimate with flexibility and credits

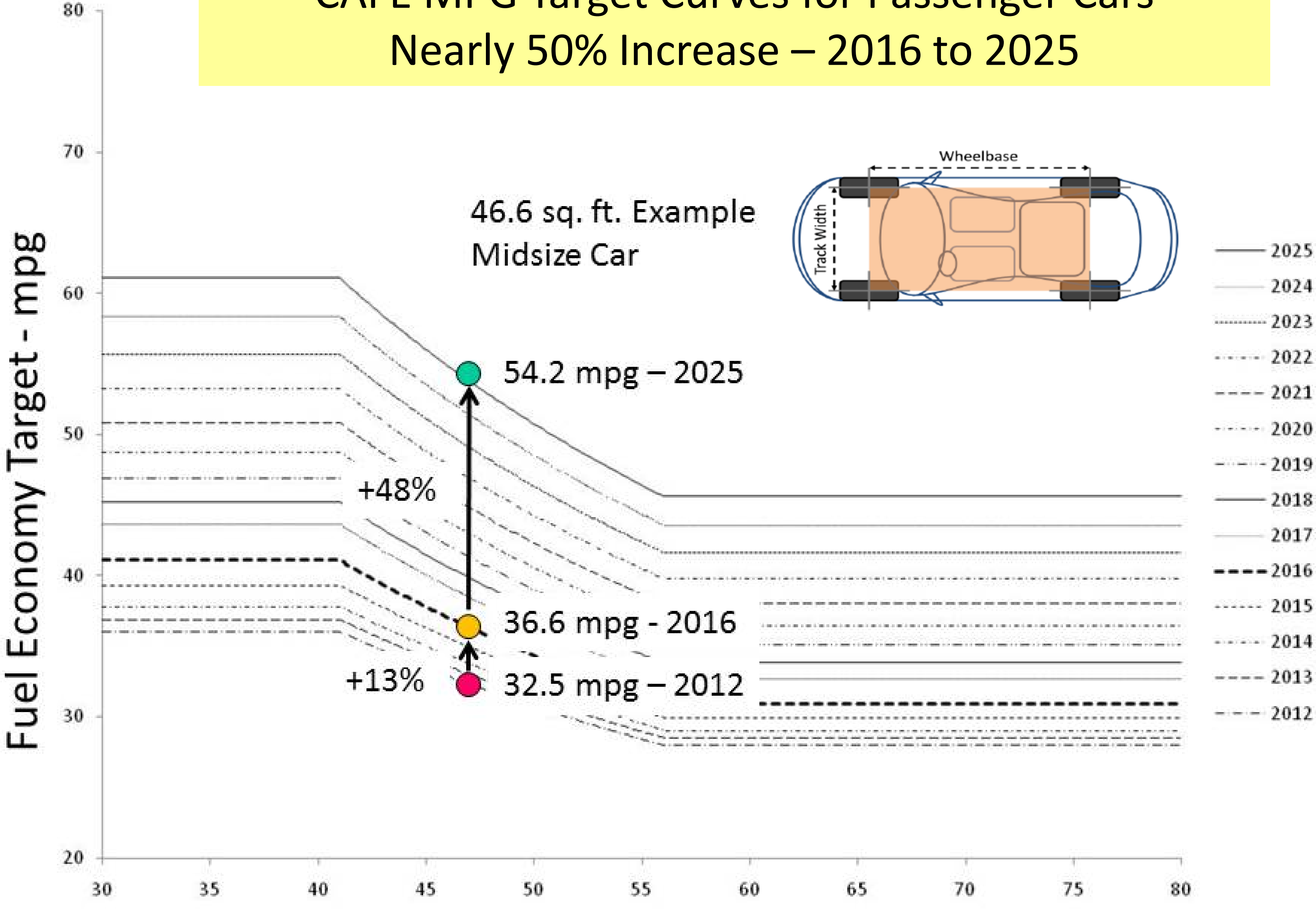


Fleet-wide average in 2025 MY

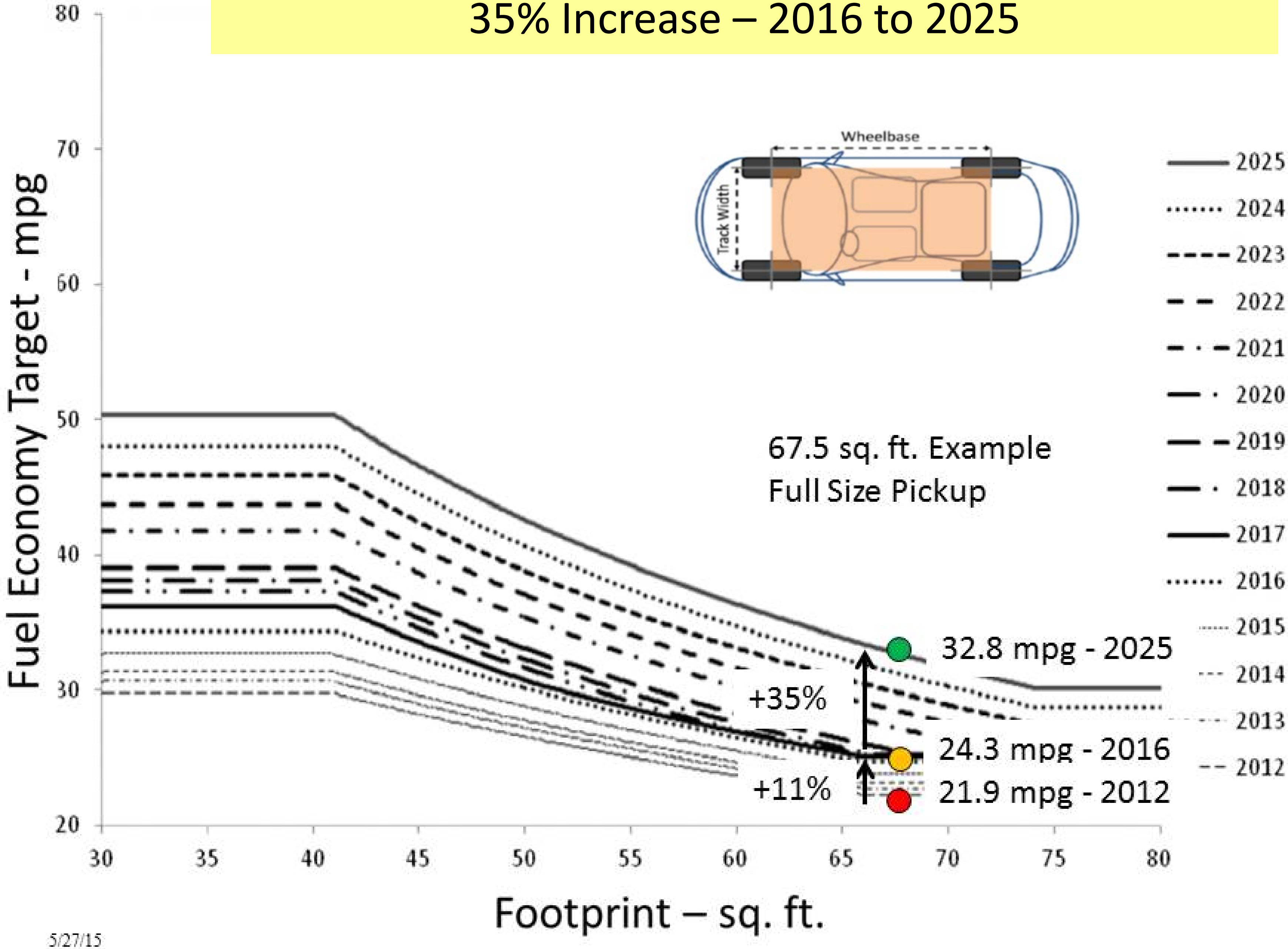
Cars, Light-Duty Trucks, Medium-Duty Passenger Vehicles

Source: www.shutterstock, www.pixabay

CAFE MPG Target Curves for Passenger Cars
Nearly 50% Increase – 2016 to 2025



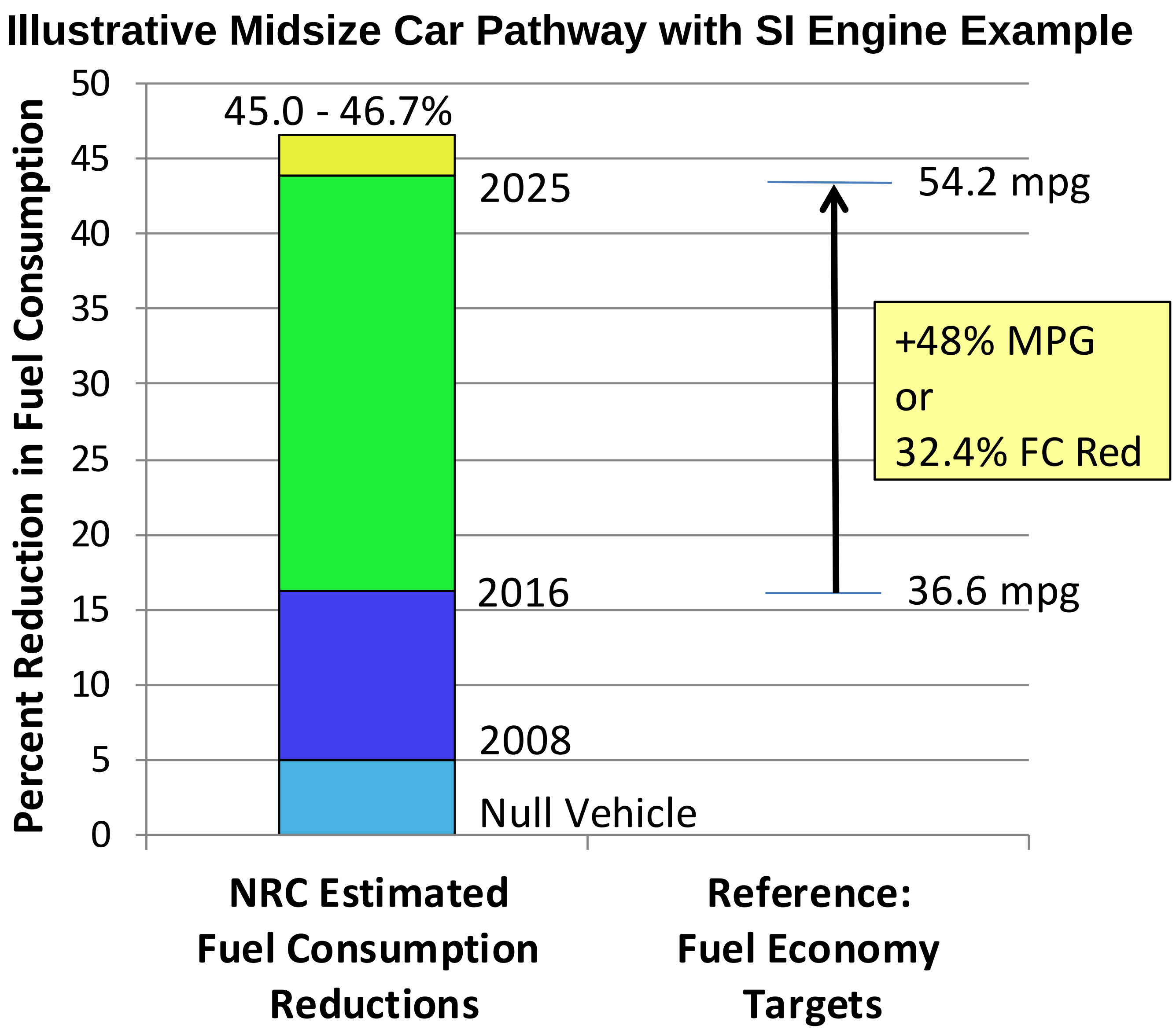
CAFE MPG Target Curves for Trucks
35% Increase – 2016 to 2025



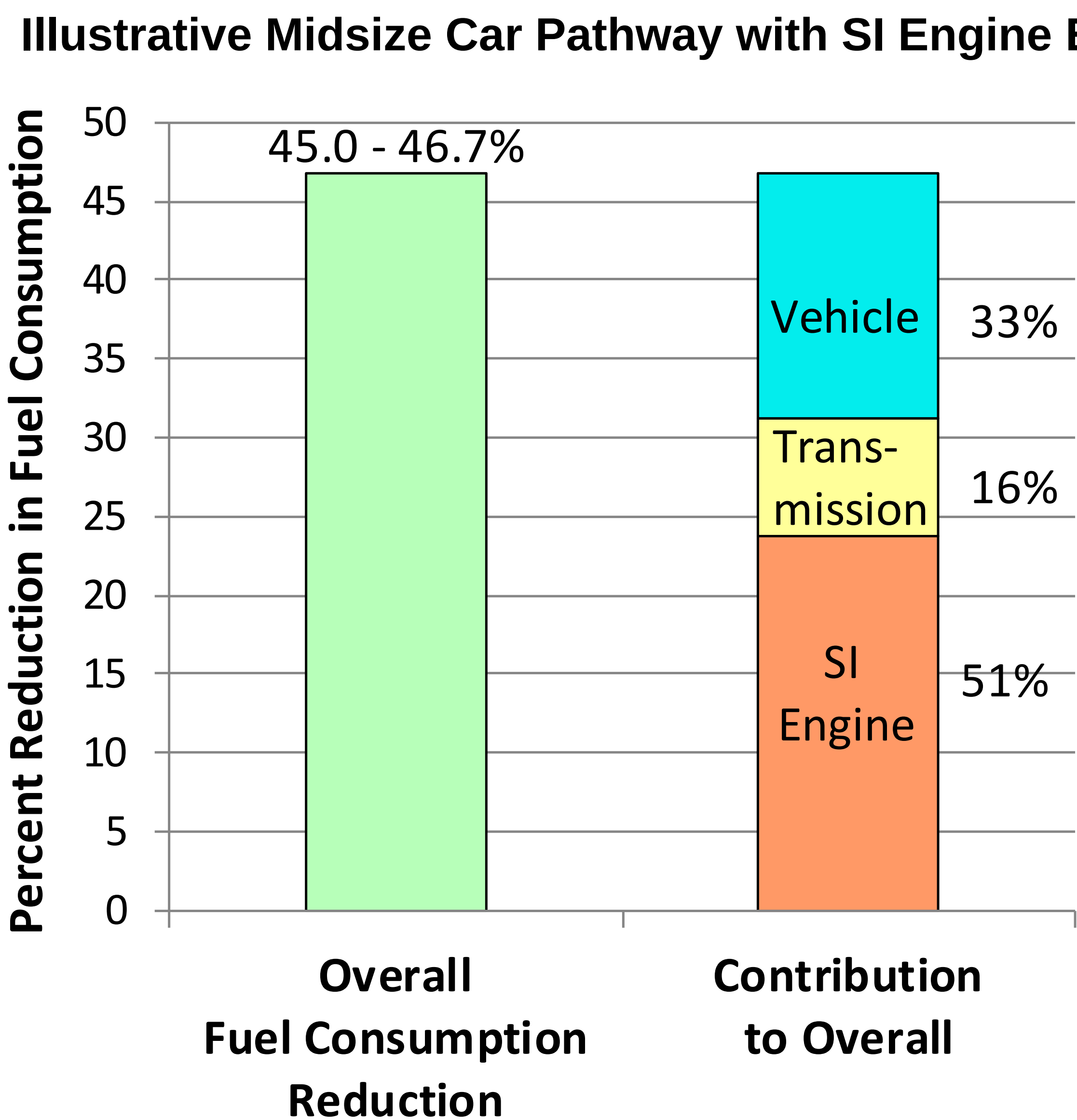
Major Finding of the Committee

Analysis conducted by NHTSA/EPA in developing the 2017-2025 standards was thorough and of high caliber, and served as the reference point for most of the committee’s effectiveness and cost analysis.

NRC Estimated Fuel Consumption Reductions Compared to CAFE Fuel Economy Targets

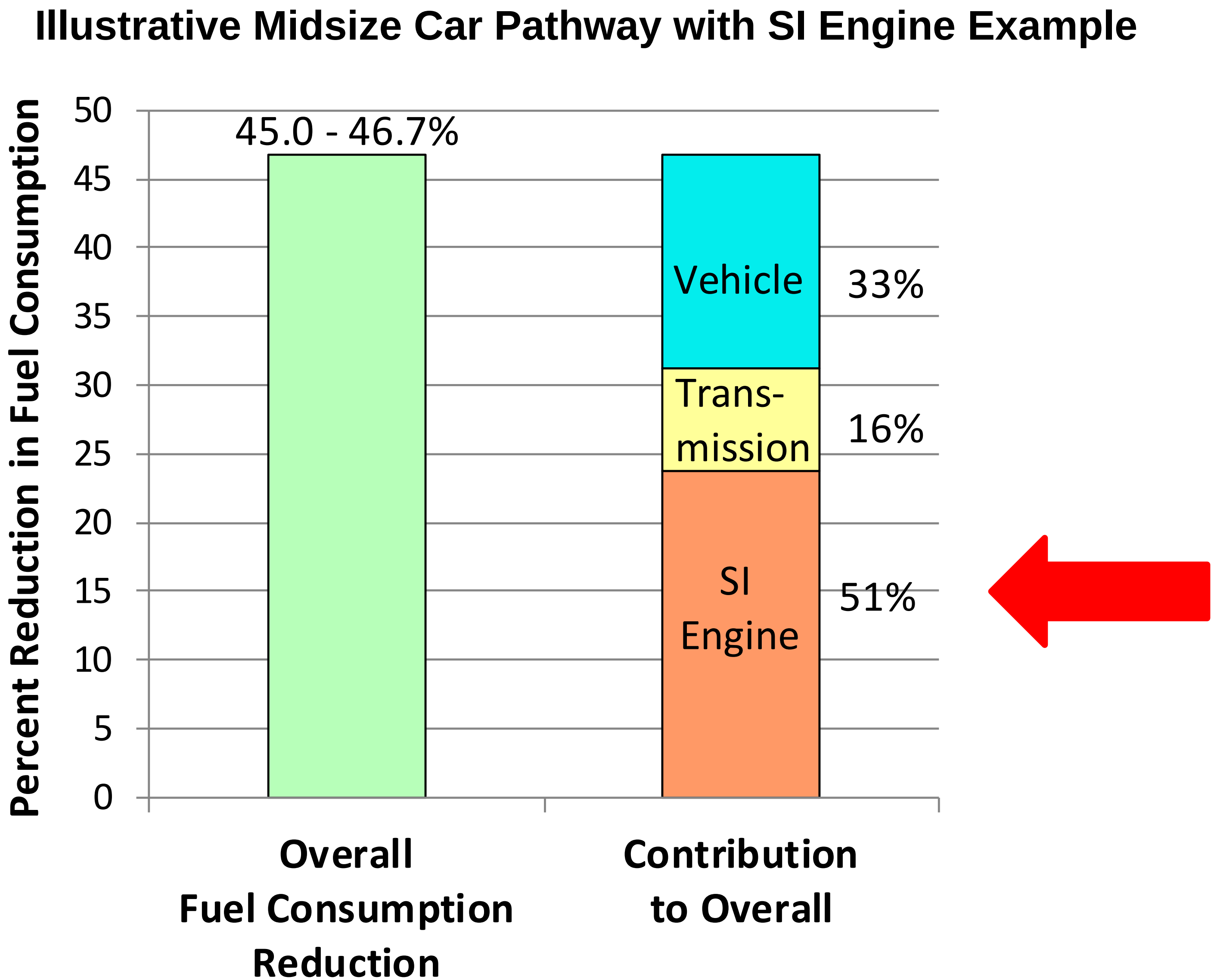


Components of Overall Fuel Consumption Reduction



Fuel Consumption Reductions Combine Multiplicatively: (1-%FC/100) x (1-%FC/100), etc.

Spark Ignition Engine Technologies



Spark Ignition Engine Technologies

Expected to be the dominant powertrain through 2025 and likely beyond.

NHTSA/EPA Technologies	Fuel Cons. Red. 1/
Low Friction Lubricants	0.7 – 0.8%
Engine Friction Reduction	3.6 – 4.1%
Variable Valve Timing (Dual Cam Phasing)	4.9 – 5.4%
Variable Valve Lift (Continuously Variable)	4.3 – 4.9%
Cylinder Deactivation	0.7% (5.5% w/o VVT/L)
Gasoline Direct Injection	1.5%
Turbocharging and Downsizing 18 - 27 bar BMEP 33% - 56% downsizing	6.8 – 8.3% (18 bar) 3.1 – 3.7% (24 bar) 1.2 – 1.4% (27 bar)
Cooled EGR	3.0 – 3.6% (at 24 bar)

1/ Fuel Cons. Red. Relative to Previous Technology

Turbocharging & Downsizing
93% Penetration in 2025*
(*NHTSA/EPA Possible Cost-Effective Compliance Path)

6=8, 4=6, 3=4

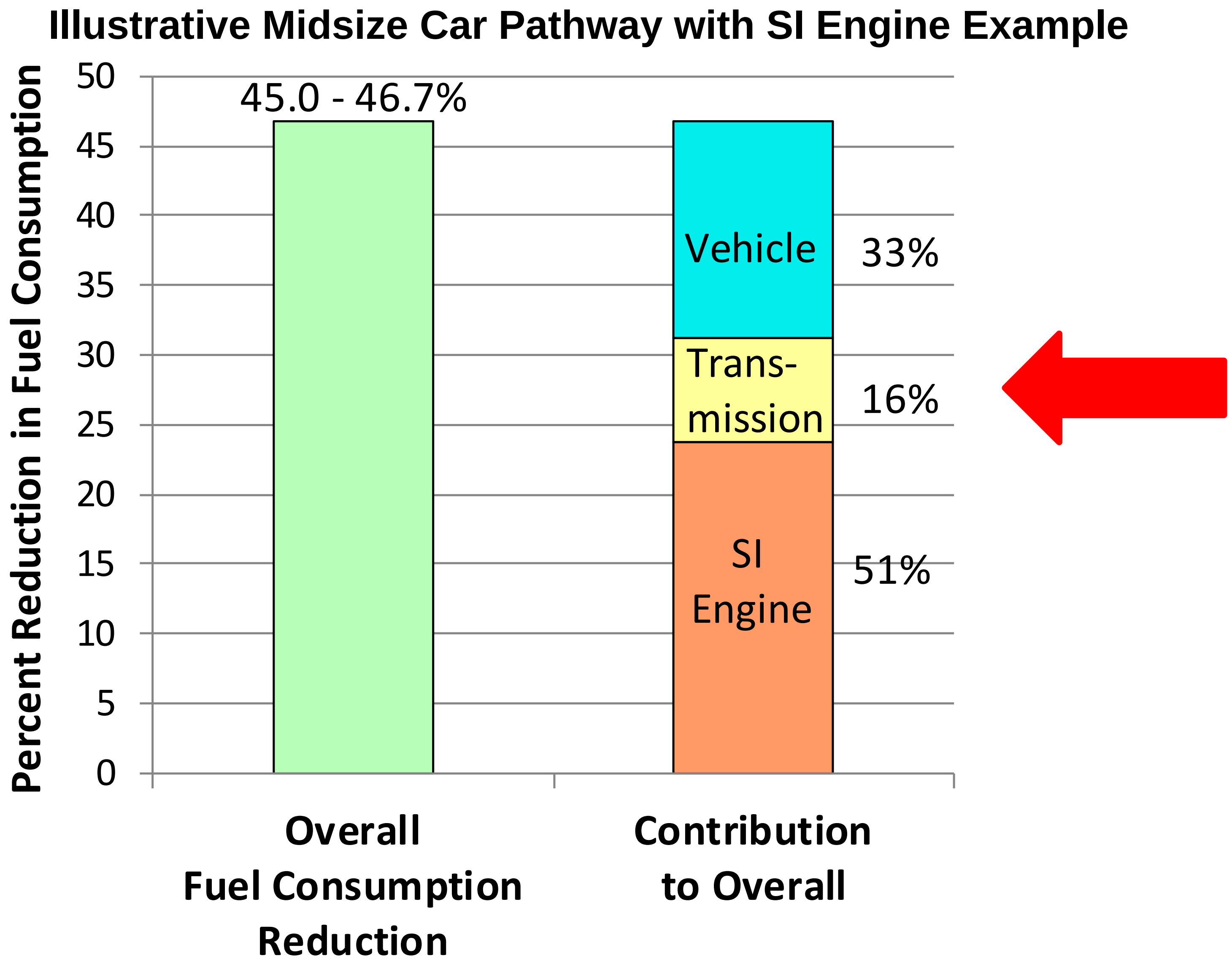
Source: Ford in the News, March 16, 2009, http://www.fordinthenews.com/ford-resumes-production-for-ecoboost-engine/

Other Spark Ignition Engine Technologies

Other Technologies	Fuel Cons. Red. 1/
Compression Ratio Increase	
With Regular Fuel	3.0%
With Higher Octane Regular Fuel	5.0%
13:1 CR, Exhaust Scavenging, GDI (a.k.a. Skyactiv, Atkinson cycle)	10.0%
Lean Burn (with low sulfur fuel)	5.0%

1/ Fuel Cons. Red.
Relative to Baseline

Transmission Technologies



Transmission Technologies

NHTSA/EPA Technologies	Fuel Cons. Red. 1/	
Aggressive Shift Logic and Early Torque Converter Lockup (IATC)	2.5 - 3.0%	✓
6 speed Automatic Transmission (Rel. 4 sp)	2.0 – 2.5%	✓
8 speed Automatic Transmission (Rel. 6 sp)	1.5 – 2.0%	✓
6 speed Dry Dual Clutch Transmission (DCT)	3.5 – 4.5%	
6 speed Wet Dual Clutch Transmission (DCT)	3.0 – 4.0%	
8 speed DCT	1.5 – 2.0%	
High Efficiency Gearbox (HEG1 &2)	4.9 – 5.4%	✓
Shift Optimizer	0.5 – 1.0%	✓

✓ Technology included in Pathway

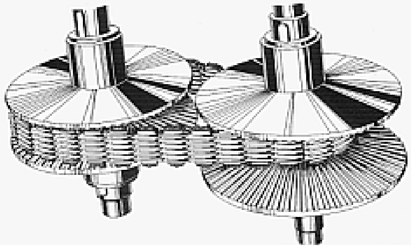
1/ Relative to Previous Technology

Other Transmission Technologies

Other Technologies	Fuel Cons. Red. 1/
9 and 10 speed Automatic Transmissions	0.3%
High Efficiency Gearbox (AT Beyond 2020)	1.6%
High Efficiency Gearbox (DCT)	2.0%
Continuously Variable Transmission (CVT)	3.5 – 4.5%
High Efficiency Gearbox (CVT)	3.0%

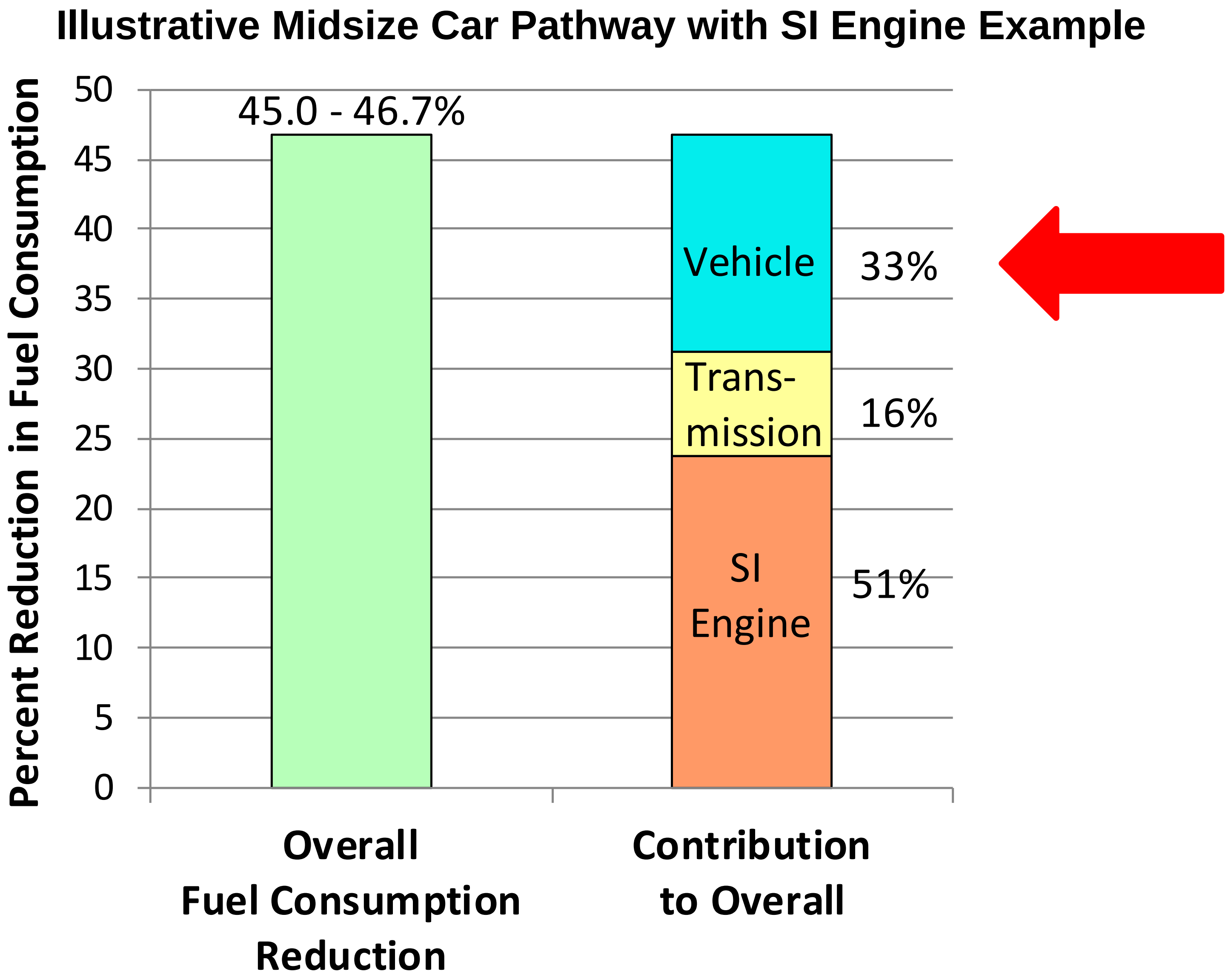
1/ Relative to Previous Technology

CVT Transmission
0% Penetration in 2025* [19.3% in 2014]
(*NHTSA/EPA Possible Cost-Effective Compliance Path)



CVT transmission
with a steel belt

Vehicle Technologies



Vehicle Technologies

- Low rolling resistance tires
- Aerodynamic drag reduction
- Low drag brakes
- Electrification of accessories

} ~ 14% reduction in fuel consumption

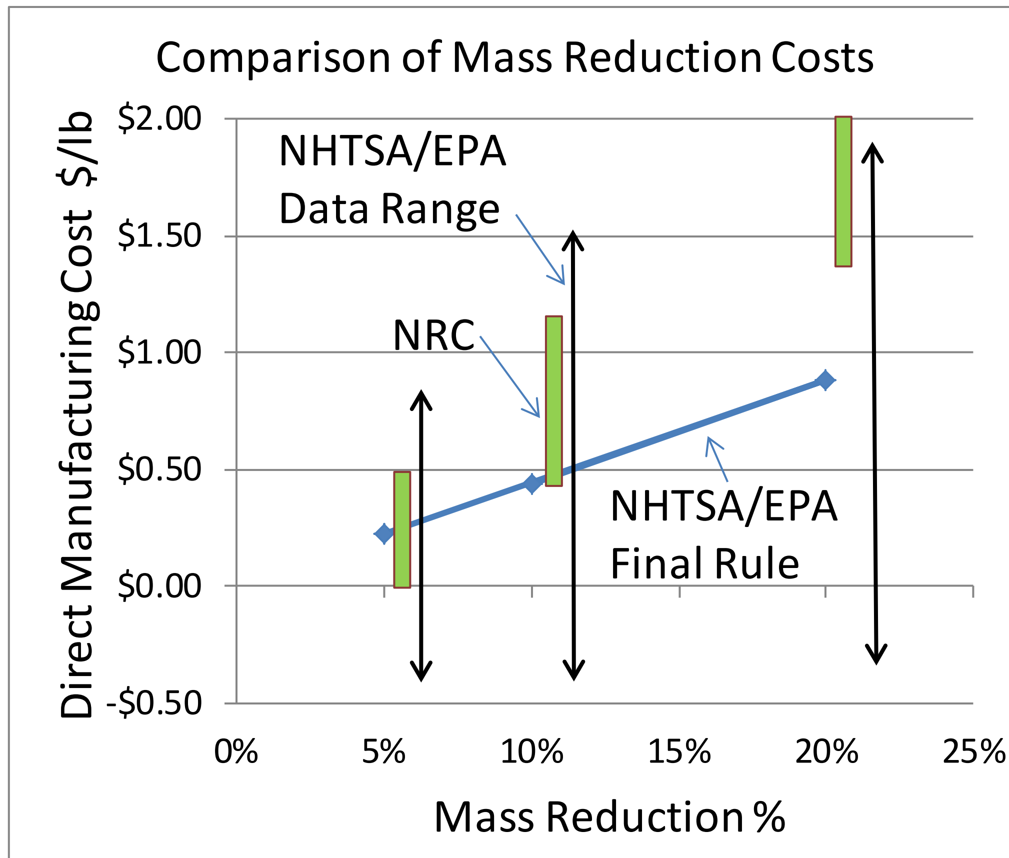
- Mass reduction (MR)
  - 10% MR = 6% reduction in fuel consumption
  - 25% MR = 15% reduction in fuel consumption (for cars, less for trucks)

Mass Reduction

Applications: Likely to be more aggressive for cars than NHTSA/EPA.

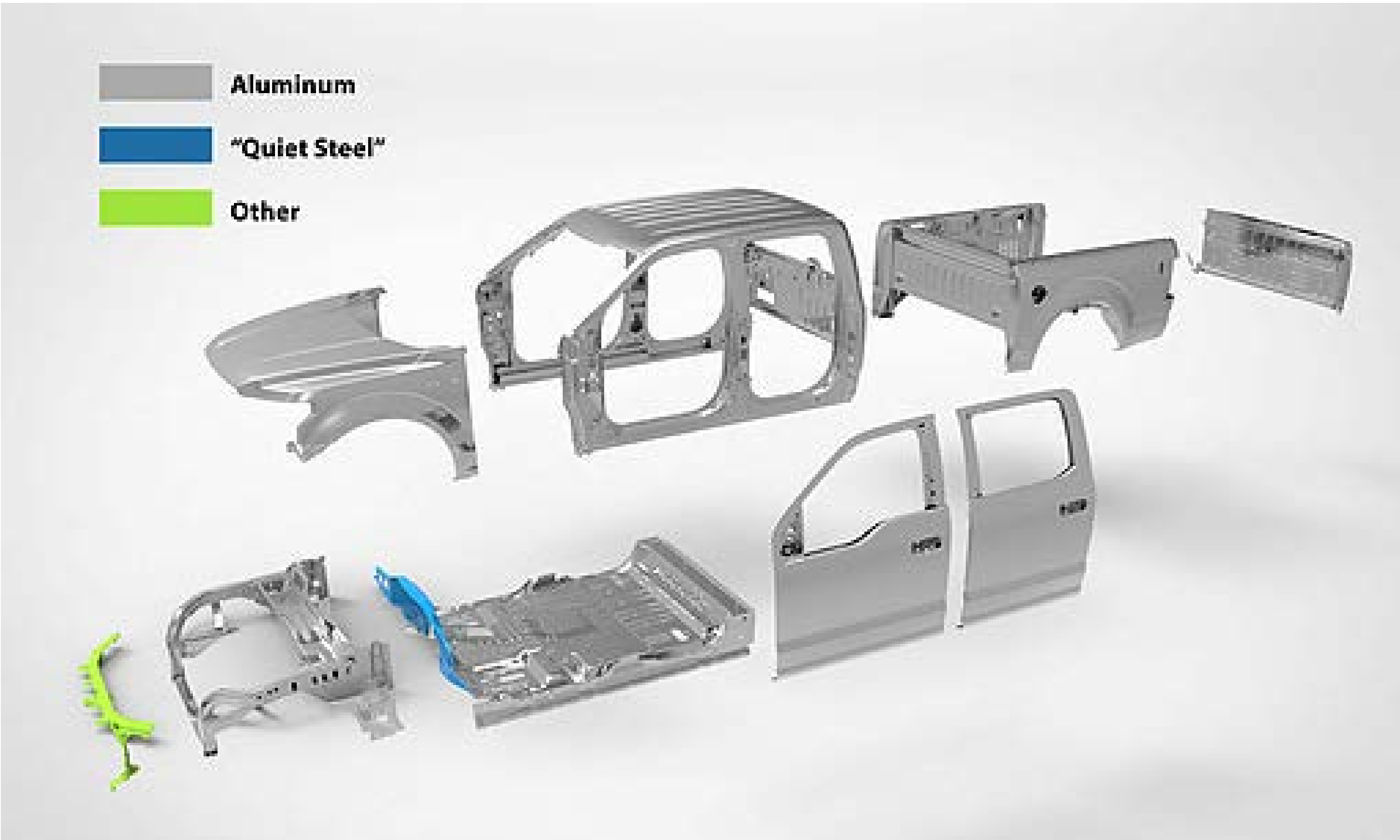
Vehicle	NHTSA/EPA	NRC
Midsize Car	3.5%	10%
Large Car	10%	15%
Large Light Truck	20%	20%

Costs: NRC based on design optimization and materials substitution.



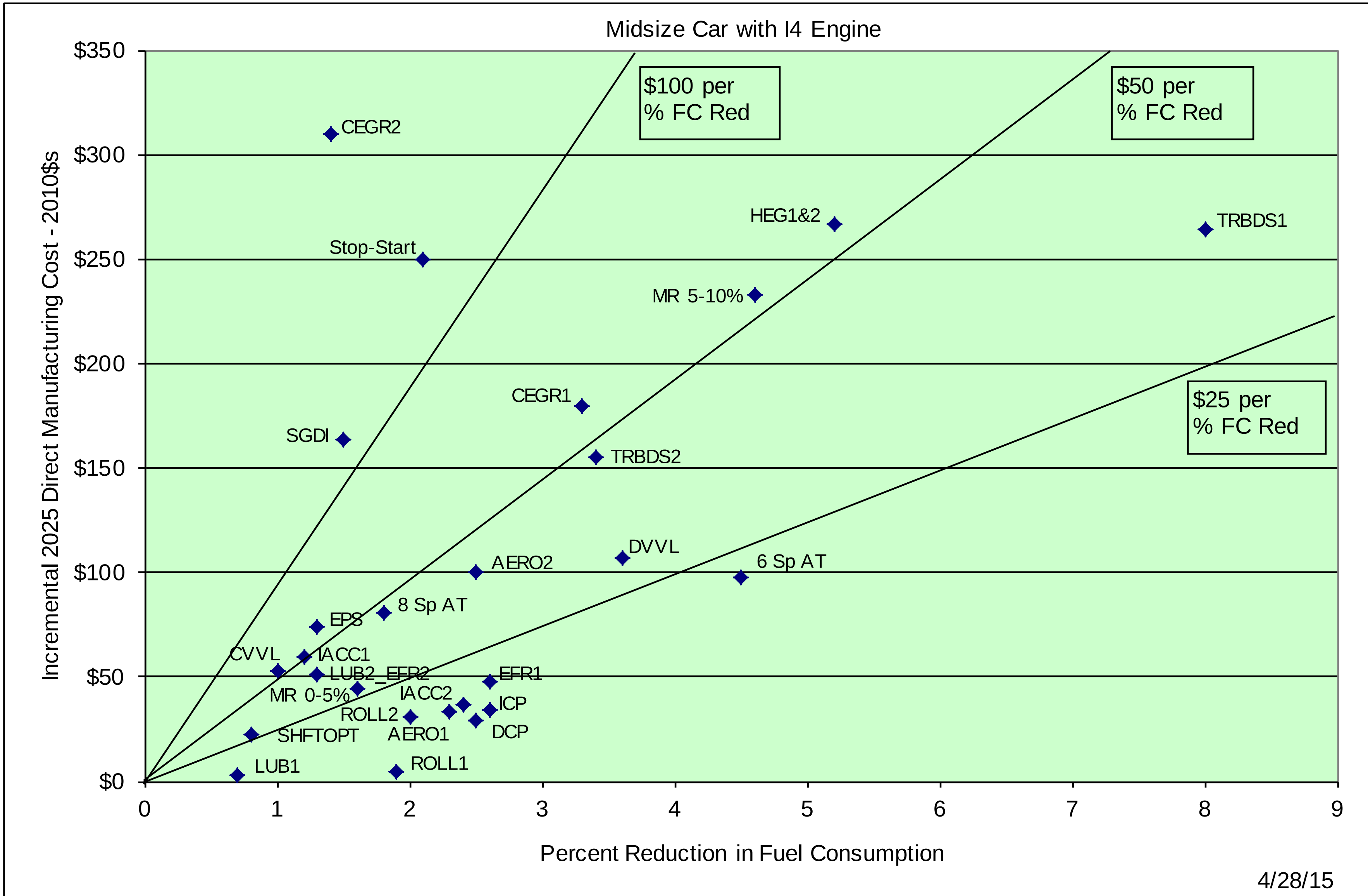
Ref: NHTSA/EPA derived costs from aggregation of different studies.

Aluminum Body Ford F150 Pickup Truck
Up to 700 pounds lighter (~13% mass reduction)

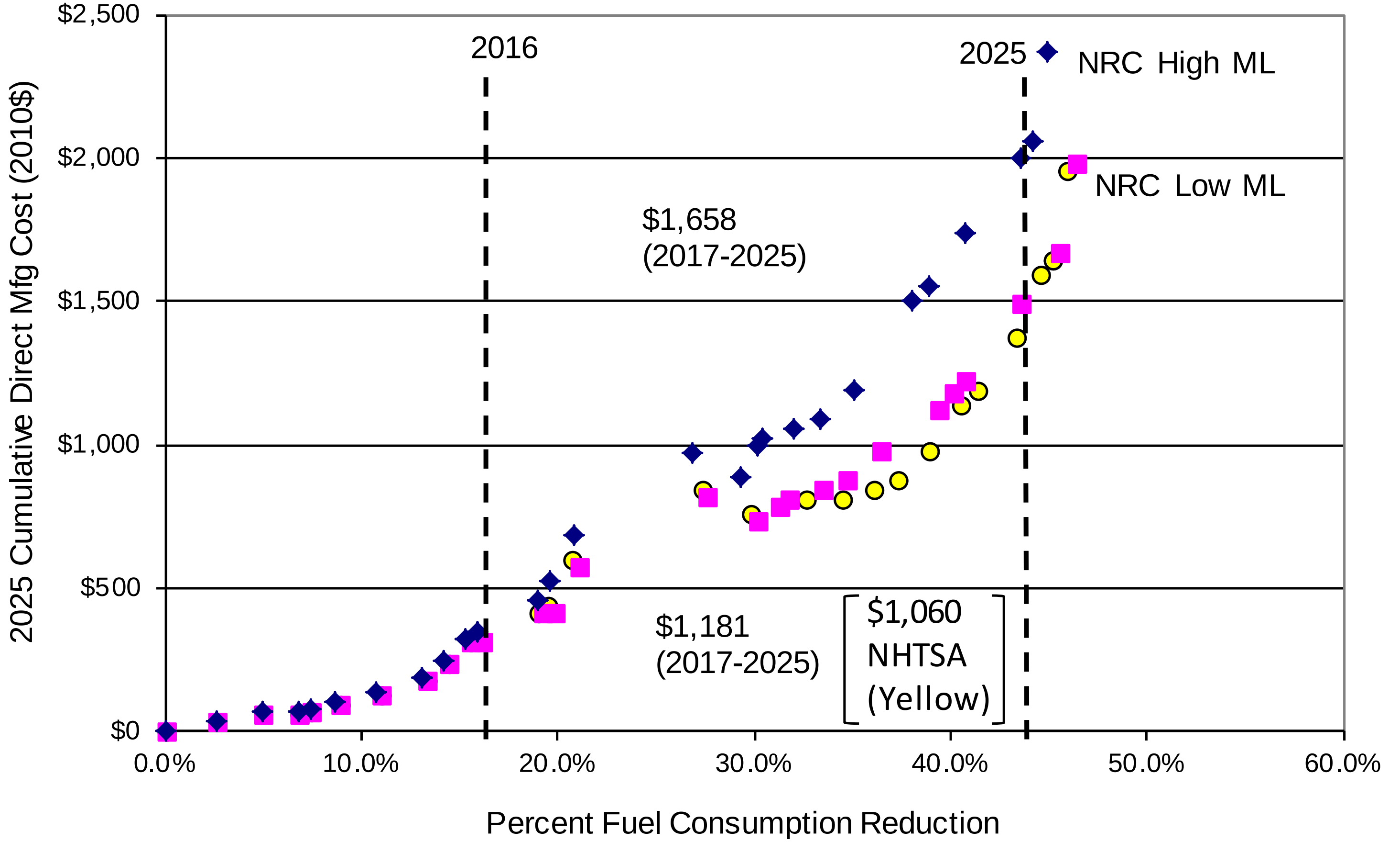


Ref: SAE.org, Nov 18, 2014

NRC Estimated Incremental Direct Manufacturing Cost vs. Percent Reduction in Fuel Consumption – NHTSA Individual Technologies



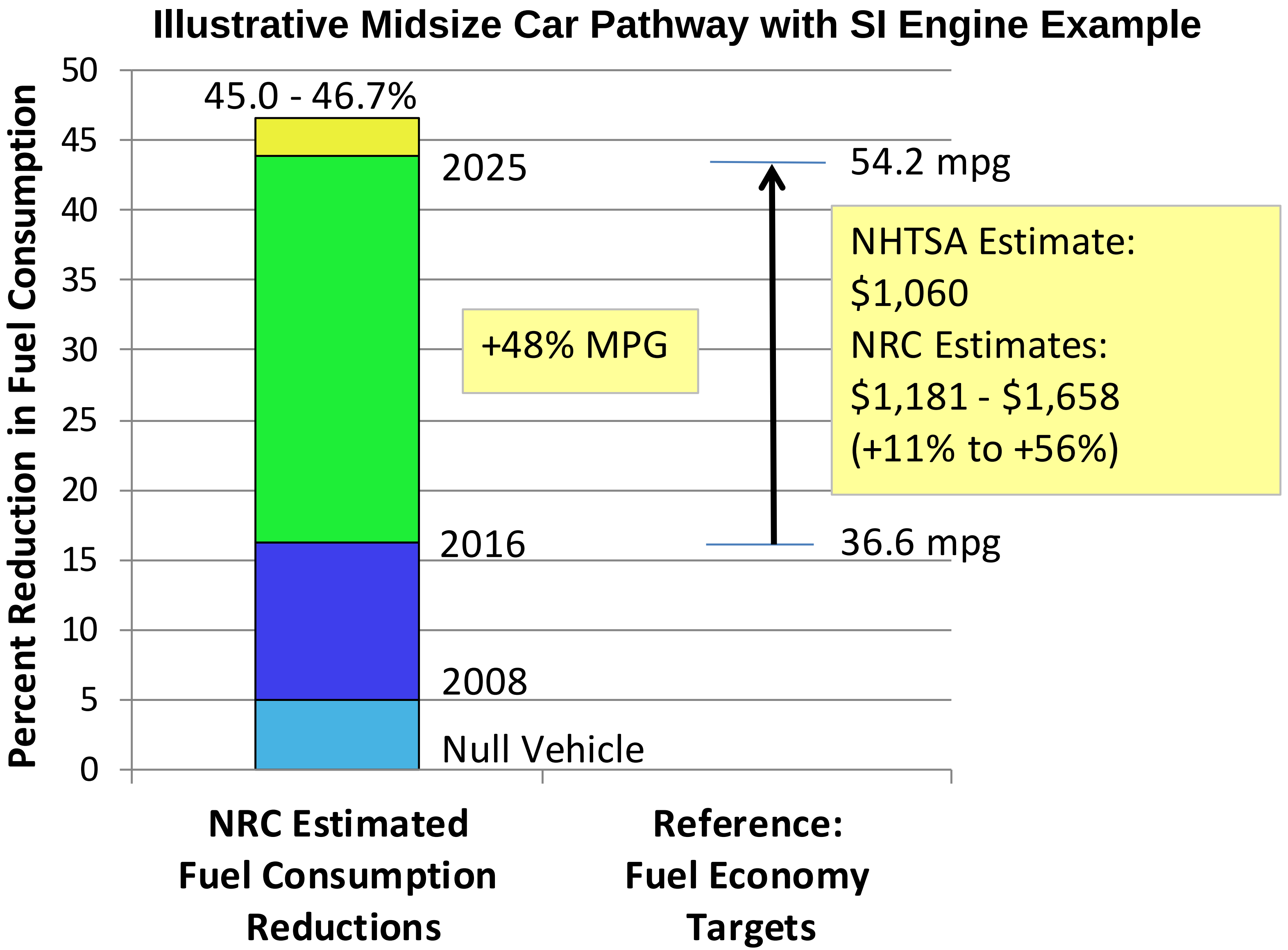
Illustrative Pathway for Midsize Car with I-4 SI Engine
NRC vs. NHTSA Estimates



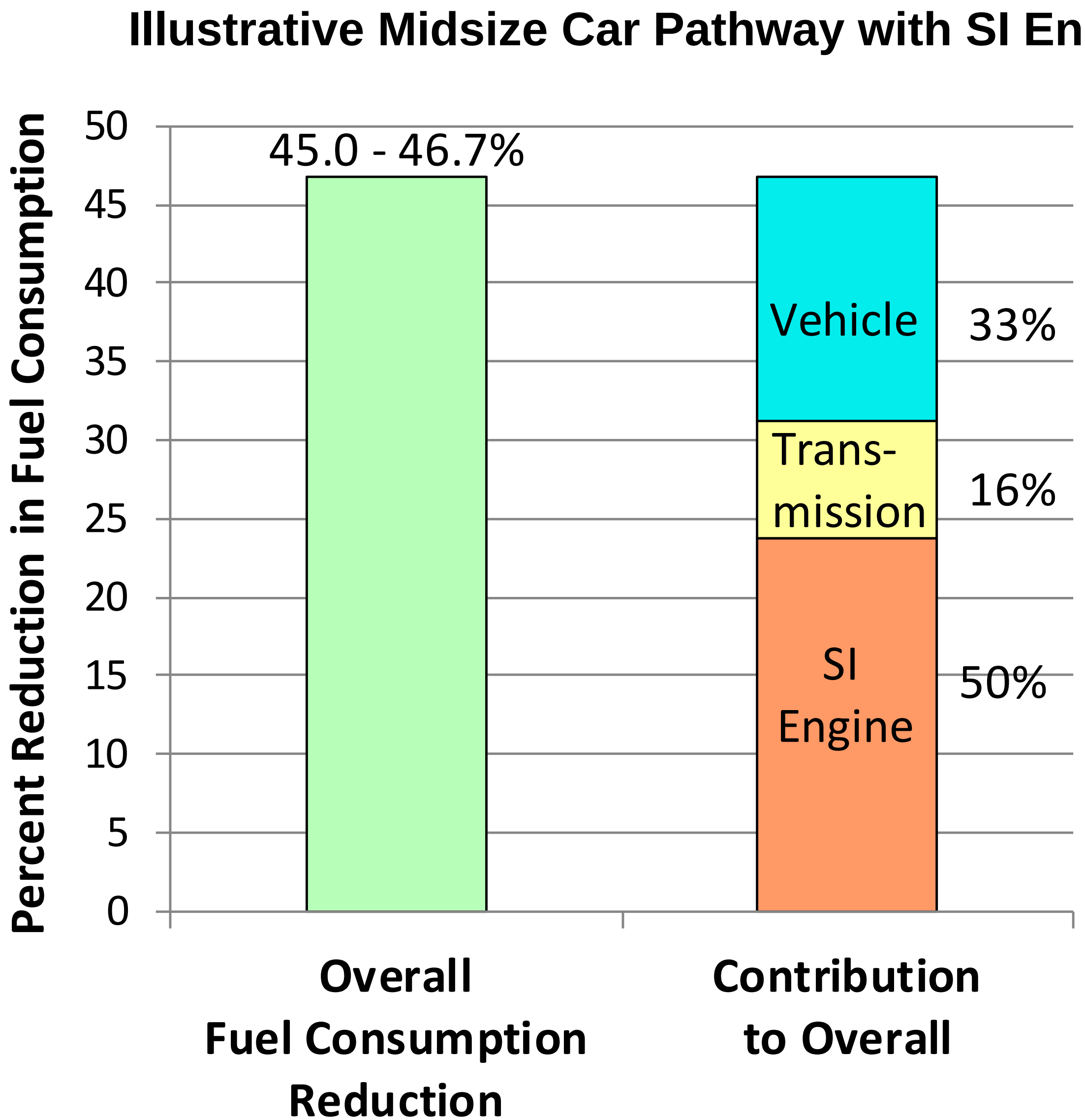
For some technologies:

- The committee held different views on the best estimate of cost and effectiveness.
- These are represented by low and high most likely values.

NRC Estimated Costs of Technology: 2016 to 2025



<u>Other</u> Powertrain Technologies



Other Powertrain Technologies

Diesel Engines
0% Penetration in 2025 * [Likely to be Higher]
(*NHTSA/EPA Possible Cost-Effective Compliance Path)

- 29.0 – 30.5% Reduction in Fuel Consumption.
- Additional Technologies: ~ 15% Reduction in fuel consumption
- 15% higher CO_2 per gallon ("carbon penalty" for GHG emissions)
- Tier 3 emission controls – May increase cost.

www.graffbaycityblog, www.ramtrucks.com

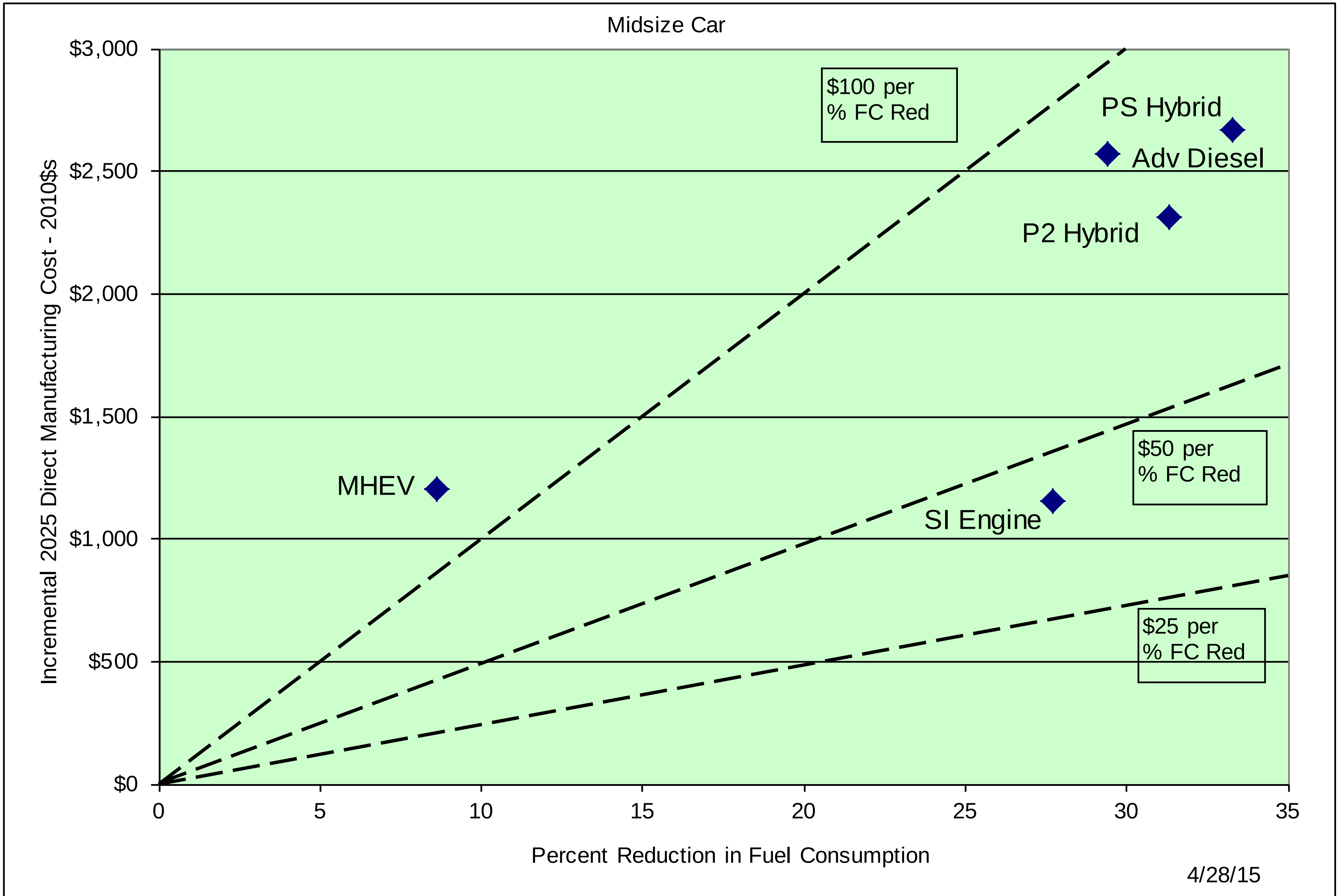
Electrified Powertrains – Defined by NHTSA/EPA

- Electrified powertrains provide significant reductions in fuel consumption.
- Electrification is increasing, but penetration remains low.

Technology	Fuel Cons. Red. 1/
Stop-Start (Micro-Hybrid)	1.3%
Integrated Starter Generator (Mild Hybrid)	6.5% 2/
Strong Hybrid – P2 (Parallel 2 Clutch System)	28.9 - 33.6%
Strong Hybrid – Power Split	33.0 – 33.5%
Plug-in Hybrid – 40 Mile EV Range (PHEV)	NA
Electric Vehicle – 75 Mile Range	NA
Fuel Cell Electric Vehicle (FCEV)	NA

1/ Relative to Baseline, except as noted
2/ Relative to Previous Technology

NRC Estimated Incremental Direct Manufacturing Cost vs. Percent Reduction in Fuel Consumption – Powertrain Technologies



Committee's Findings on Effectiveness (Fuel Consumption Reduction)

Technology	NRC Effectiveness (Fuel Consumption Reduction) Relative to NHTSA/EPA Estimates			
	Comparable	Extended Range Lower	Lower	Higher
Many Technologies	✓			
Turbo/Downsizing		✓		
P2 Hybrid		✓		
8 speed AT			✓	
Shift Optimization			✓	
High Eff. Gearbox				✓
Mass Reduction				✓

Committee's Findings on Direct Manufacturing Costs

Technology	NRC Direct Manufacturing Costs Relative to NHTSA/EPA Estimates		
	Comparable	Extended Range Higher	Higher
Some Technologies	✓		
Turbo/Downsizing		✓	
Variable Valve Timing & Lift		✓	
Several Transmission Technologies:			
6 & 8 Speed ATs		✓	
6 & 8 Speed DCTs		✓	
Several Electrified PT Technologies:			
Battery - Dependent on SOC Swing		✓	
Non-Battery - P2 Hybrid, PHEV, BEV		✓	
Diesel Engines			✓
Mass Reduction	✓	✓	✓

Committee Recommendations - NHTSA/EPA

- Continue to use full system simulations and teardown cost studies for reliable assessments of technology.
  - Focus on technologies where the committee has shown differences.
- Update penetration rates of various technologies, particularly for:
  - CVT, DCT, mass reduction
- Since indirect costs are needed to estimate overall total costs of technologies, the committee recommends research to develop an empirical basis for indirect costs (instead of the Agencies' consensus and Delphi approaches).

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The full 612 page report is available at the National Academies Website: www/nap.edu

Thank you

Appendix

Committee's Approach

- Analysis focused on technologies with large potential benefits, and included technologies that may be available by 2030.
- Analysis focused on individual technologies, but also developed an illustrative analysis of a package of technologies prioritized by cost-effectiveness for a midsize car.

Null Vehicle

- Defined by NHTSA/EPA as a vehicle with the least common technology in the 2008 MY, and is typically representative of a pre-2008 MY vehicle.
- Reference point for measuring effectiveness and cost.
- Technologies in null vehicle:
  - Spark ignition engine – naturally aspirated
  - 4 valves per cylinder
  - Port fuel injection (PFI)
  - Fixed valve timing and lift
  - 4 speed automatic transmission
  - Vehicle materials
    - Primarily mild steel
    - Less than 10% aluminum

Transmission Technologies

- Conventional Planetary Automatic Transmissions (AT)
  - Expected to remain dominant through 2025 with new 8, 9, 10 speed ATs introduced to replace 6 speed ATs.
- Increasing Number of Ratios
  - Benefits diminish as new engine technologies are incorporated.
- Parasitic Loss Reduction
  - Benefits can exceed those of increasing the number of ratios.
- Market Penetration*
  - CVTs are increasing while DCTs have not increased at the expected rate.

*Relative to NHTSA/EPA possible cost-effective compliance path.

Mass Reduction Finding

Reducing vehicle mass across the entire fleet while holding vehicle footprint constant is estimated to have a beneficial effect on societal safety risk.

Major Reasons for Differences in Effectiveness and Cost
2025 Costs (2010$s)

- NHTSA to NRC Low Most Likely Pathways (+$121)
  - 8 speed AT, Shift Optimization – Significantly lower effectiveness.
  - High Efficiency Gearbox – Significantly higher effectiveness to partially compensate, but with higher cost.
  - Mass Reduction – Increased from 3.5 to 10% to partially compensate.
    - Approximately cost neutral: Cooled EGR deleted, CVVL added
- NRC Low to High Most Likely Pathways (+$477)
  - Turbo/Downsizing – Lower effectiveness; slightly higher cost.
  - 8 speed AT, Shift Optimization, High Efficiency Gearbox – Lower effectiveness; higher cost for 8 speed AT.
  - Mass Reduction – Significantly higher cost.
  - Compensation for lower effectiveness:
    - Cooled EGR at higher cost replaced CVVL.

Further details in following slides

Effectiveness (% FC Reduction) Differences NHTSA to NRC Low Most Likely Pathways

Technology	NHTSA	NRC Low ML	NRC Low ML - NHTSA
Different Estimates:			
8 speed AT	3.9%	1.7%	-2.2%
Shift Optimization	2.8%	0.7%	-2.1%
High Efficiency Gearbox	2.7%	5.4%	+2.7%
MR 0% - 2.5%	0.5%	NA	-0.5%
MR 2.5% - 5.0%*	0.7%	0.8%	+0.1%
Adds:			
MR 5.0% - 10.0%	NA	4.8%	+4.8%
CVVL	NA	1.0%	+1.0%
Deletes:			
Cooled EGR	3.5%	NA	- 3.5%
Total =	14.1%	14.4%	+0.3%

*MR = 3.5% for NHTSA Pathway

2025 Cost Differences (2010$)
NHTSA to NRC Low Most Likely Pathways

Technology	NHTSA	NRC Low ML	NRC Low ML - NHTSA
Different Estimates:			
Shift Optimization	$0	$22	+$22
High Efficiency Gearbox	$163	$267	+$104
MR 0% - 2.5%	$3	$0	-$3
MR 2.5% - 5.0%	$22	$0	-$22
Adds:			
MR 5.0% - 10.0%	NA	$151	+$151
CVVL	NA	$49	+$49
Deletes:			
Cooled EGR	$180	NA	-$180
Total =	$368	$489	+$121

Effectiveness (% FC Reduction) Differences NRC Low to High Most Likely Pathways

Technology	NRC Low ML	NRC High ML	NRC High ML – NRC Low ML
Different Estimates:			
Turbo/Downsized 1	8.3%	7.7%	-0.6%
Turbo/Downsized2	3.5%	3.2%	-0.3%
8 speed AT	1.7%	1.3%	-0.4%
Shift Optimization	0.7%	0.3%	-0.4%
High Efficiency Gearbox	5.4%	4.9%	-0.5%
Adds:			
Cooled EGR	NA	3.0%	+3.0%
Deletes:			
CVVL	1.0%	NA	- 1.0%
Total =	20.6%	20.4%	-0.2%

2025 Cost Differences (2010$)
NRC Low to High Most Likely Pathways

Technology	NRC Low ML	NRC High ML	NRC High ML – NRC Low ML
Different Estimates:			
DVVL	$99	$114	+$15
Turbo/Downsized 1	$245	$282	+$37
Turbo/Downsized 2	-$82	-$86	-$4
8 speed AT	$47	$115	+$68
MR 2.5% - 5.0%	$0	$66	+$66
MR 5.0% - 10.0%	$151	$315	+$164
Adds:			
Cooled EGR	NA	$180	+$180
Deletes:			
CVVL	$49	NA	-$49
Total =	$509	$986	+$477

Reasons for NHTSA to NRC Low Most Likely Pathway Differences

- 8 speed AT - Significantly lower effectiveness.
  (NRC: 1.5 - 2.0% vs. NHTSA/EPA: 4.6%)
  - NRC used Autonomie results which were consistent with OEM and supplier results for effect of increased ratios only.
  - NHTSA/EPA estimates were assumed to include some efficiency improvements (HEG1) not included in teardown cost study.
- Shift Optimization – Significantly lower effectiveness.
  (NRC: 0.5% - 1.0% vs. NHTSA/EPA: 3.9% - 4.1%)
  - Integral part of calibration process for transmissions, not a separate technology.
  - Shift “busyness” and NVH limit acceptable shift optimization.
- High Efficiency Gearbox – Higher effectiveness with higher cost.
  - HEG1 (which NHTSA included in 8 sp AT) + HEG2 effectiveness approximately equals NHTSA’s estimates, but NRC included costs for HEG1 as well as HEG2.

Percent effectiveness values are relative to null vehicle.
For pathways, percent effectiveness values are relative to previous technology with negative synergies applied.

Reasons for NRC Low to High Most Likely Pathway Differences

- Turbo/Downsizing – Lower effectiveness; slightly higher cost.
  (TRBDS1&2: NRC Low ML: 2 pct. pt. lower vs. NRC High ML: 16.4% - 20.1%)
  - Compression ratio may be limited with octane of U.S gasoline relative to NHTSA/EPA's Ricardo analysis which used European "regular" gasoline (similar to U.S premium gasoline).
  - Spark retard may be required to avoid knock.
  - Wider ratio transmissions and/or modified torque converters may be required to compensate for turbo lag during launch.
  - Higher cost due to:
    - Increased turbocharger cost for current technology (twin-scroll, higher temperature capability, wastegate controls/variable geometry turbine, reduced friction).
    - Increased charge air cooler cost.

Percent effectiveness values are relative to null vehicle.
For pathways, percent effectiveness values are relative to previous technology with negative synergies applied.

Reasons for NRC Low to High Most Likely Pathway Differences (Con't)

- 8 speed Transmission – Significantly higher cost.

  (NRC High ML: $115 vs. NRC Low ML: $47)
  - NRC added the following enhancements to FEV cost teardown results to ensure suitable functionality with increased number of ratios (modified hydraulic controls, enhance response time solenoid valves, enhanced speed and pressure sensors, lightweight magnesium case).
- Mass Reduction – Significantly higher cost.

  (MR 2.5% - 10%: NRC High ML: $381 vs. NRC Low ML: $151)
  - NRC Low ML assumes 6.25% mass reduction is available at zero cost.
  - NRC High ML assumes no mass reduction is available at zero cost.
    - Costs derived from analysis of material usage and costs, and included decompounding.