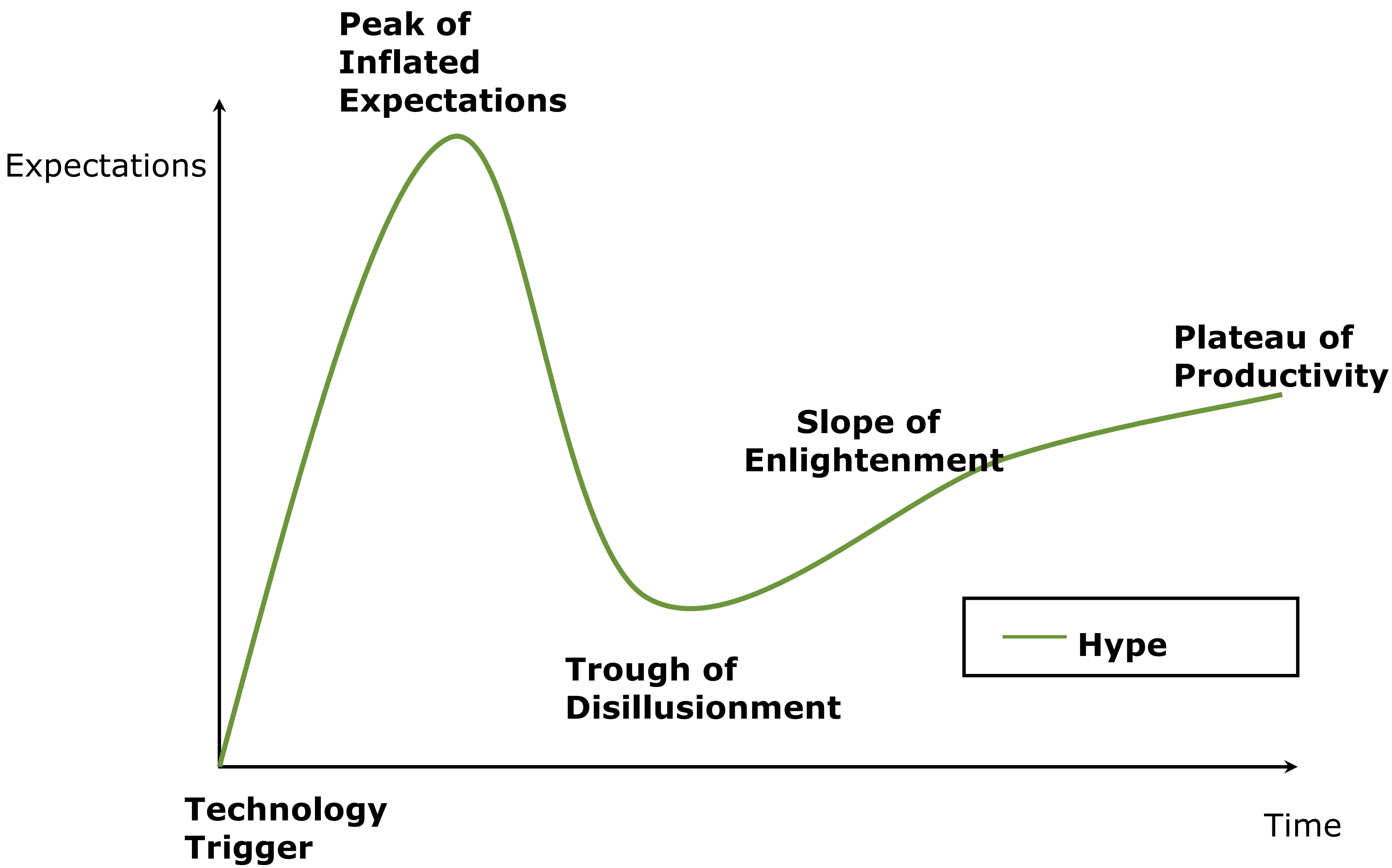
Future LDV Fleet Vision

John German

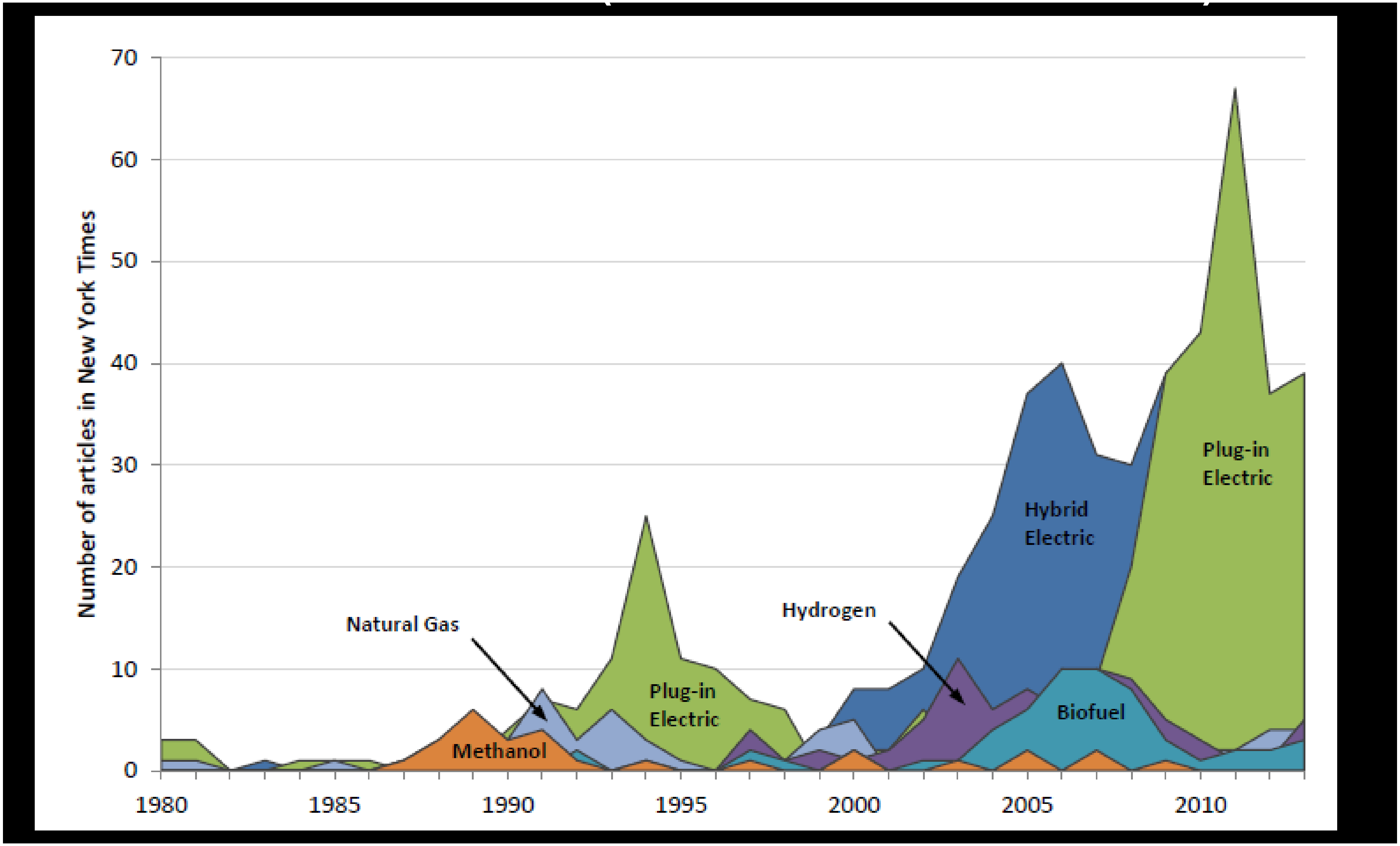
High Efficiency Hybrid Vehicles Workshop, ARPA-E
October 12, 2017, Southfield MI

Hype cycle phases



Source: Gartner (July 2009)

Following Media Attention for Different Alternative Fuels (New York Times 1980 – 2013)



Source: Melton, Axsen & Sperling, *Nature Energy*, March 2016

Consumers are, in general, LOSS AVERSE

2002 Nobel Prize for Economics
(Tversky & Kahnemann, J. Risk & Uncertainty 1992

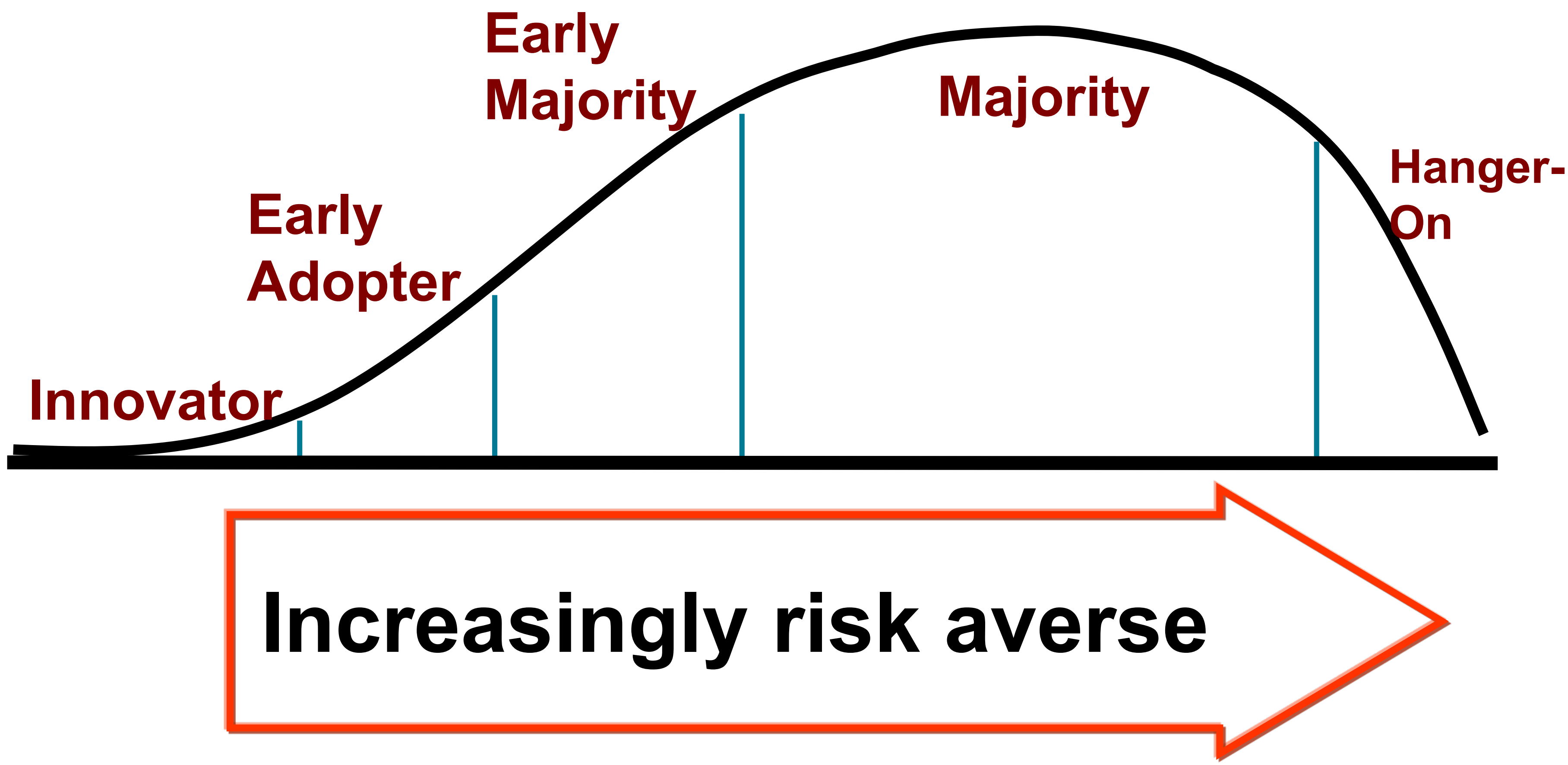
- Uncertainty about future fuel savings makes paying for more technology **a risky bet**
  - What MPG will I get (your mileage may vary)?
  - How long will my car last?
  - How much driving will I do?
  - What will gasoline cost?
  - What other tradeoffs are there?

"A bird in the hand is worth two in the bush."

Causes the market to produce less fuel economy than is economically efficient

New Customer Profile

Early Majority won't even accept full hybrids



ICE Technology Progress

ICCT/Supplier Technology Papers

- Analyses for 2017-25 standards were done in 2012
- Each technology paper evaluated:
  - How the current rate of progress (cost, benefits, market penetration) compares to analyses in the rule
  - Recent technology developments that were not considered in the rule and how they impact cost and benefits
  - Customer acceptance issues, such as real-world fuel economy, performance, drivability, reliability, and safety.

Technology Briefing Series

Company	Gasoline Turbo	Gasoline Nat. Asp.	Diesel	Trans-missions	Light-weighting	Thermal management
Aluminum Association					X	
BorgWarner	X	X	X	X		X
Dana				X		
Detroit Materials					X	
Eaton	X	X				
FEV				X	X	
Honeywell	X		X			
ITB	X	X	X	X	X	X
JCI	X					
Ricardo	X				X	
SABIC					X	

Several other suppliers and one OEM participated anonymously

Also reports on:

- Hybrids (2015, ICCT), to serve as a template for supplier tech briefs
- EU Technology Assessments (2015, FEV-Europe for ICCT)
- Technology paper on electric vehicles (2016, ICCT)

Technologies not in the 2025 rulemaking

- Technologies already in production or for which production plans have been announced, even though were not anticipated or even considered in the 2017-2025 rule:
  - **High-efficiency naturally aspirated engines** with Atkinson cycle *and* high compression ratio
  - **Dynamic cylinder deactivation** - each individual cylinder is shut off every other revolution of the engine
  - **Miller cycle** for turbocharged engines
  - **Variable Compression Ratio**
  - **E-boost** – small, 48v electric compressor motor within a turbocharger or electric supercharger
  - **48-volt hybrid systems**
  - Improved **Continuously-variable transmissions (CVTs)**
  - **Lightweighting** advances
  - Numerous **Thermal Management** technologies

Technology Potential: Project scope

- Assess technology potential for 2025-2030 standards
  - Modeling
    - Technology cost/benefit inputs and packages, based on the U.S. EPA Lumped Parameter Model for the recent Proposed Determination
    - Fleet modeling: U.S. EPA OMEGA
  - ICCT applied updates for improved CO_2 effectiveness and cost
    - ICCT/supplier technology papers: Turbo, hybrids, lightweighting, naturally aspirated, transmission, thermal management
    - ICCT technology paper: Electric vehicles
    - Focus on technologies for more widespread 2025-2030 introduction
  - Key research questions
    - What is the cost of 2025 compliance with less conservative technology assumptions?
    - What is the cost of a 2030 fleet with 4-6% lower CO_2 per mile annually from 2025-2030?

Technologies not in the 2016 TAR/PD

- Technologies already in production or for which production plans have been announced, even though were not considered in the July 2016 TAR:
  - **Dynamic cylinder deactivation** - each individual cylinder is shut off every other revolution of the engine
  - **Variable Compression Ratio**
  - **E-boost** – small, 48v electric compressor motor within a turbocharger

- In addition:
  - **Lightweighting** reductions remained at 8%
  - **Miller cycle** penetration was only 4%
  - **Cost reductions** for GDI, cooled EGR, Miller cycle, EVs

ICCT's modified individual technology inputs

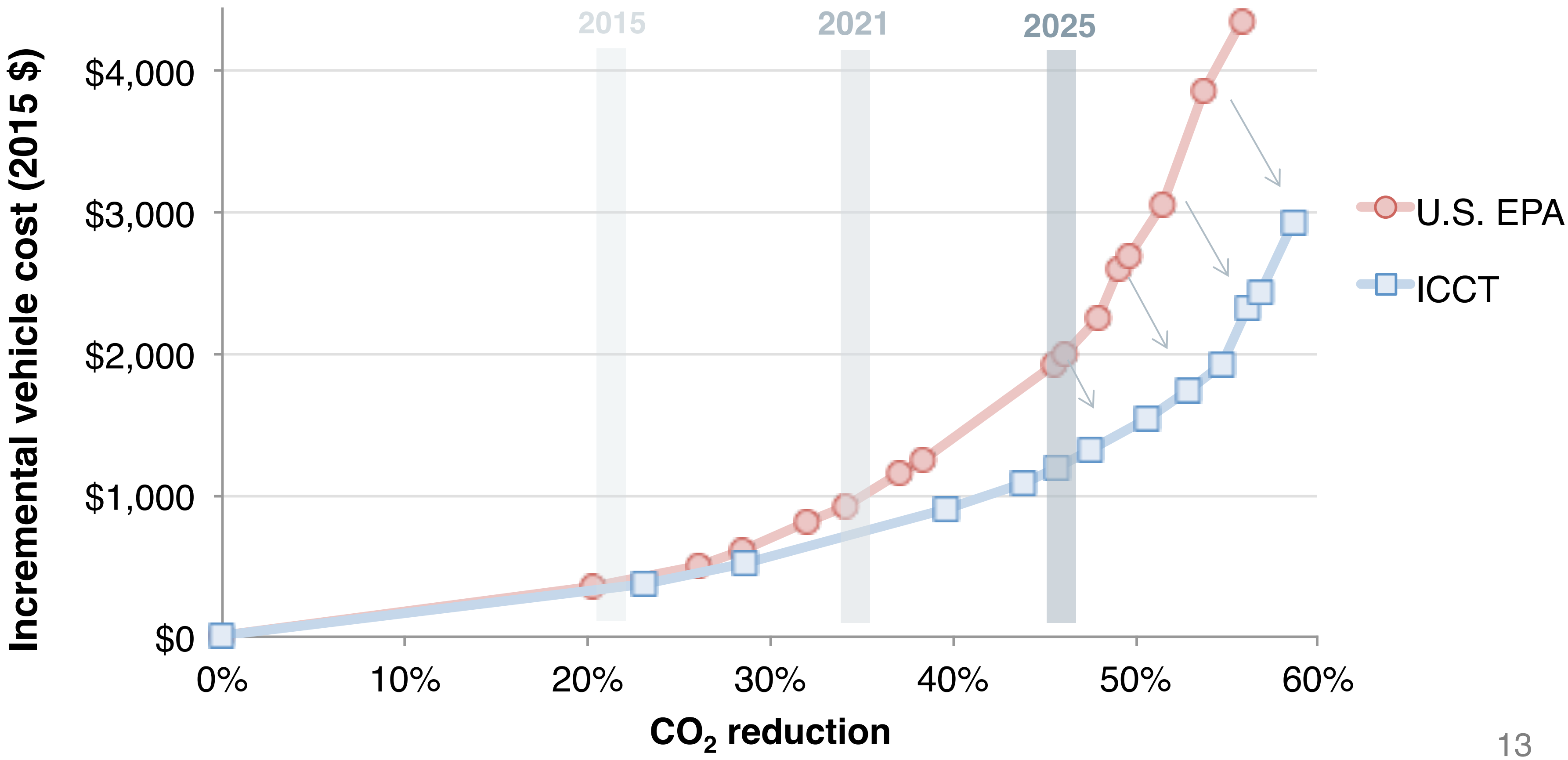
- ICCT updated several areas for 2025-2030 technology potential and costs, as compared to **EPA's Proposed Determination** analysis for 2022-2025

	Fuel consumption and CO_2 reduction (average) [a]		Direct manufacturing cost (average) [b]	
	U.S. EPA	ICCT	U.S. EPA	ICCT
Cylinder deactivation	3.5%-5.8%	No change	$75-$149	No change
Dynamic cylinder deactivation [c]	Not included	6.5%-8.3%	Not included	$138-$256
Direct Injection [d]	1.5%	No change	$196-$356	$91-$185
Cooled exhaust gas recirculation	1.7%-5.3%	No change	$216	$95-$114
Advanced diesel	20%-25%	No change	$2,104-$2,950	$1,491-$2,096
E-boost	Not included	5.0%	Not included	$338
Mild hybrid (48-volt)	7.0%-9.5%	10.5%-12.9%	$580	No change
High compression ratio [e]	3.4%-7-7%	10.1%-14.1%		
Miller cycle [f]	12%-20%	No change	Varies	$93-$222 lower
Plug-in hybrid electric vehicle [g]	72-84%	No change	$5,534-$10,371	$3,564-$7,805
Battery electric vehicle [g]	100%	No change	$5,131-$10,663	$2,410-$9,098
Mass Reduction (20%)	11.2%-13.7%	11.6%-13.7%	$0.17-$1.15 per pound	No change

[a] *Benefits vary by vehicle type, engine size; improvements shown for individual technology; effects for multiple technologies handled in lumped parameter model*
[b] *Costs are direct manufacturing costs and vary by vehicle type and engine size*
[c] *Includes variable valve lift technology*
[d] *Direct injection technology without synergistic technologies such as cooled exhaust gas recirculation and turbocharging*
[e] *Includes Atkinson cycle, direct injection, and cooled exhaust gas recirculation*
[f] *Includes Atkinson cycle, 24 bar turbocharging, cooled exhaust gas recirculation, and engine downsizing;*
[g] *Range shown for vehicle type #1 through #6, including low and high electric range and in-home charger*

Technology package cost curve

- With ICCT's technology input updates, the 2025+ CO_2-reduction technology frontier expands and costs are lower
  - For given cost, ~8-9% greater CO_2 reduction achievable with advanced combustion
  - Meeting 2025 standards: Advanced technology ~45% CO_2 reduction
  - Technology cost for 2025: EPA $1,900 versus ICCT $1,300



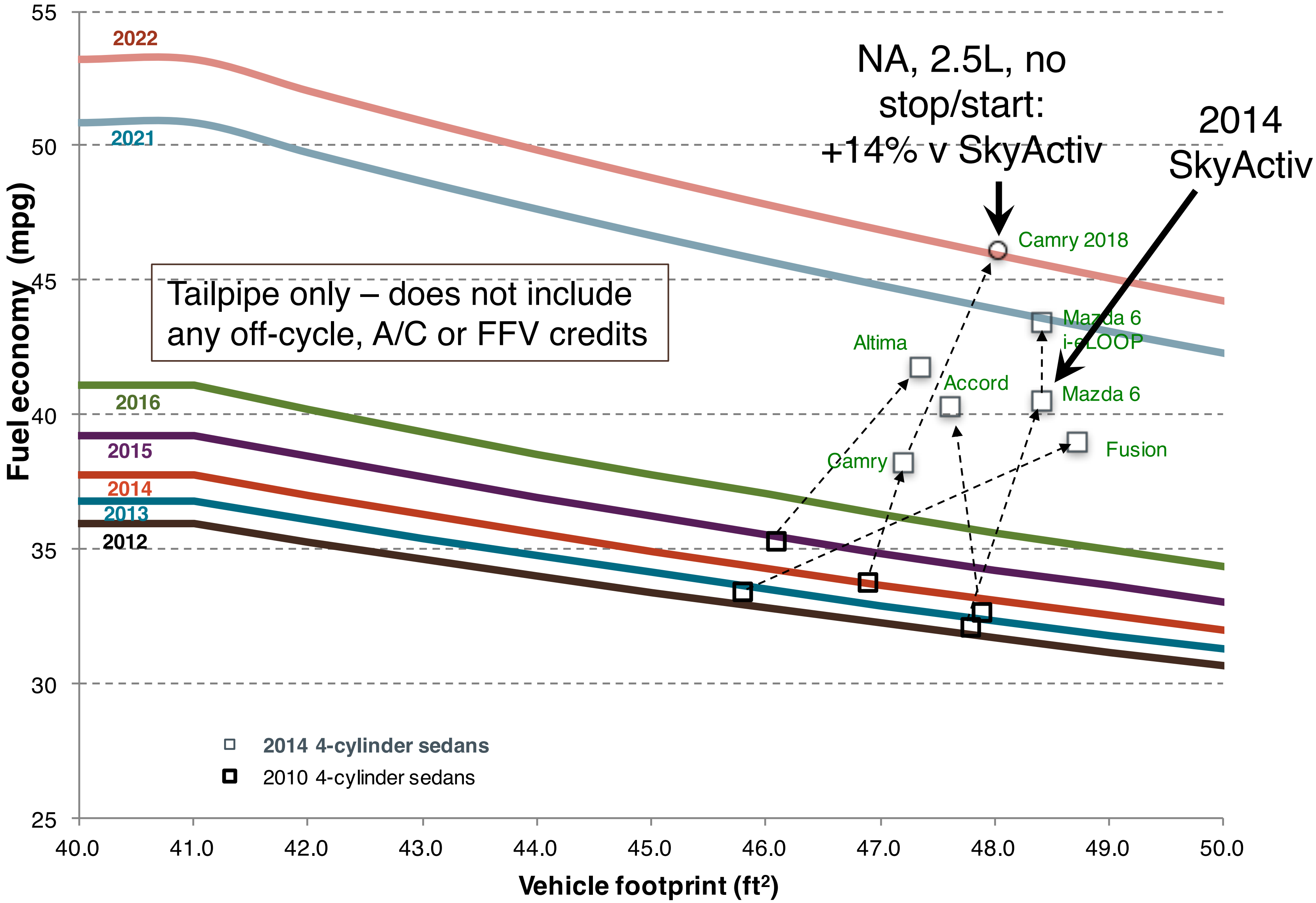
Vehicle type #6, near mid point of passenger car CO_2; includes cars and light truck crossovers; air conditioning technologies and costs are not shown

Technology Penetration and Cost to Meet 2025 Standards

Area	Technology	2012 U.S. EPA	2016 U.S. EPA	ICCT
Advanced combustion (nonhybrid)		93%	75%	93%
Hybrid	Mild hybrid	26%	18%	0%
	Full hybrid	5%	2%	2%
Electric	Plug-in hybrid electric	0	2%	2%
	Battery electric	2%	3%	3%
Incremental technology cost from 2021 standards		$1,070	$875	$551

Technology Leapfrog

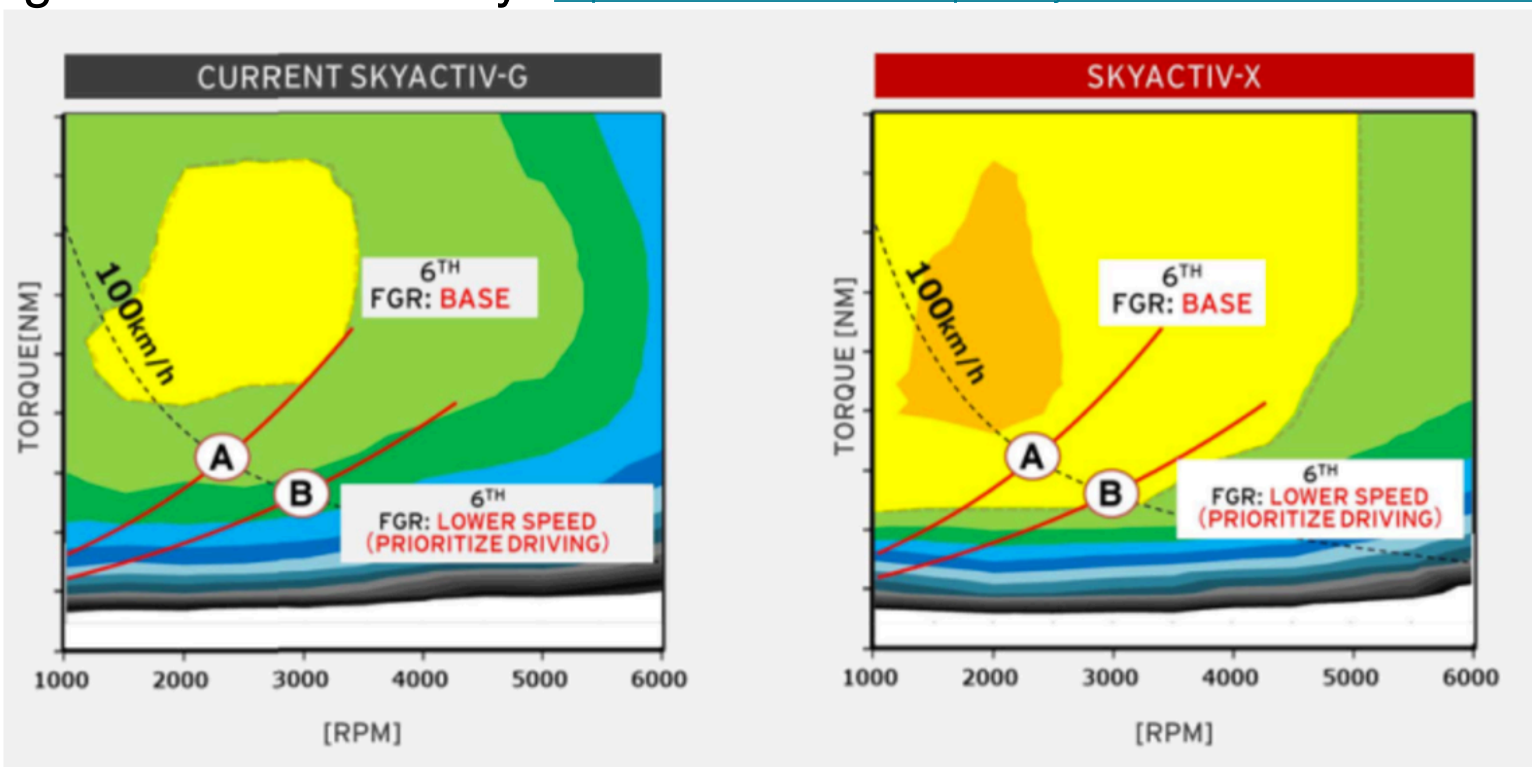
Groundtruthing our technology results



Mazda SPCCI for 2019

Mazda's Spark Controlled Compression Ignition (SPCCI) system solves the control issues with Homogenous Charge Compression Ignition by combining HCCI with a spark, to control the timing of ignition.

- "SKYACTIV-X even equals or exceeds the latest SKYACTIV-D diesel engine in fuel efficiency" http://www2.mazda.com/en/publicity/release/2017/201708/170808a.html



48-volt hybrids

- 60-70% of the benefits of a full hybrid at 30-40% of the cost
- Announcements to make 48v hybrids standard for every new model redesign:
  - Volvo starting 2019
  - Jaguar Land Rover starting 2020
- Risk aversion solved by making them standard – just another technology
- Development of extremely high power Li-ion batteries will reduce cost even further

2013 NAS Report

Transitioning to Alternative Vehicles and Fuels

Example: Camry

Conventional drivetrain					
	Baseline	**2030 mid**	**2030 opt**	**2050 mid**	**2050 opt**
Engine type	Baseline	EGR DI turbo	EGR DI turbo	EGR DI turbo	EGR DI turbo
Engine power, kW	118	90	84	78	68
Transmission type	6-sp auto	8-sp auto	8-sp auto	8-sp auto	8-sp auto
Drivetrain improvements					
Brake energy recovered through alternator, %	**	14.1	14.1	14.1	14.1
Reduction in transmission losses, %	n/a	26	30	37	43
Transmission efficiency, %	87.6	91	91	92	93
Reduction in torque converter losses, %	n/a	69	75	63	88
Torque converter efficiency, %	93.2	98	99	99	99
Reduction in pumping losses, %	n/a	74	76	80	83
Reduction in friction losses, %	n/a	39	44	53	60
Reduction in accessory losses, %	n/a	21	25	30	36
% increase in indicated efficiency	n/a	5.6	6.5	10.6	15.6
Indicated efficiency, %	36.3	38.4	38.7	40.2	42
Brake thermal efficiency, %	20.9	29.6	30.3	32.5	34.9
Load changes					
% reduction in CdA	n/a	15	24	29	37
CdA (m^2)	7.43	6.31	5.64	5.29	4.68
% reduction in Crr	n/a	23	31	37	43
Crr	0.0082	0.0063	0.0057	0.0052	0.0047
% reduction in curb weight	n/a	20	25	30	40
curb weight. Lb	3325	2660	2494	2328	1995
Fuel economy, test mpg	32.2	65.6***	74.9	88.5	111.6

Example: Camry Hybrid

Hybrid Drivetrain -- P2 hybrid with DCT8 transmission				
	2030 mid	2030 opt	2050 mid	2050 opt
Engine power, kW	88	82	77	68
Drivetrain improvements				
% additional pumping loss reduction*	80	80	80	80
% additional friction loss reduction*	30	30	30	30
% tractive energy provided by regen	20	22	24	26
Brake thermal efficiency, %	33.7	34.3	36.3	38.5
% of waste heat recovered	0	0	1	2
all load changes in conventional				
Fuel economy, test mpg	81.7**	95.1	115.8	150.9
Hybrid benefit over conventional, %	25	27	31	35
* Additional from conventional drivetrain in that year				
**Fuel economy with drivetrain changes only = 62.6 mpg				

Estimated Test Fuel Economy for Average New Vehicles

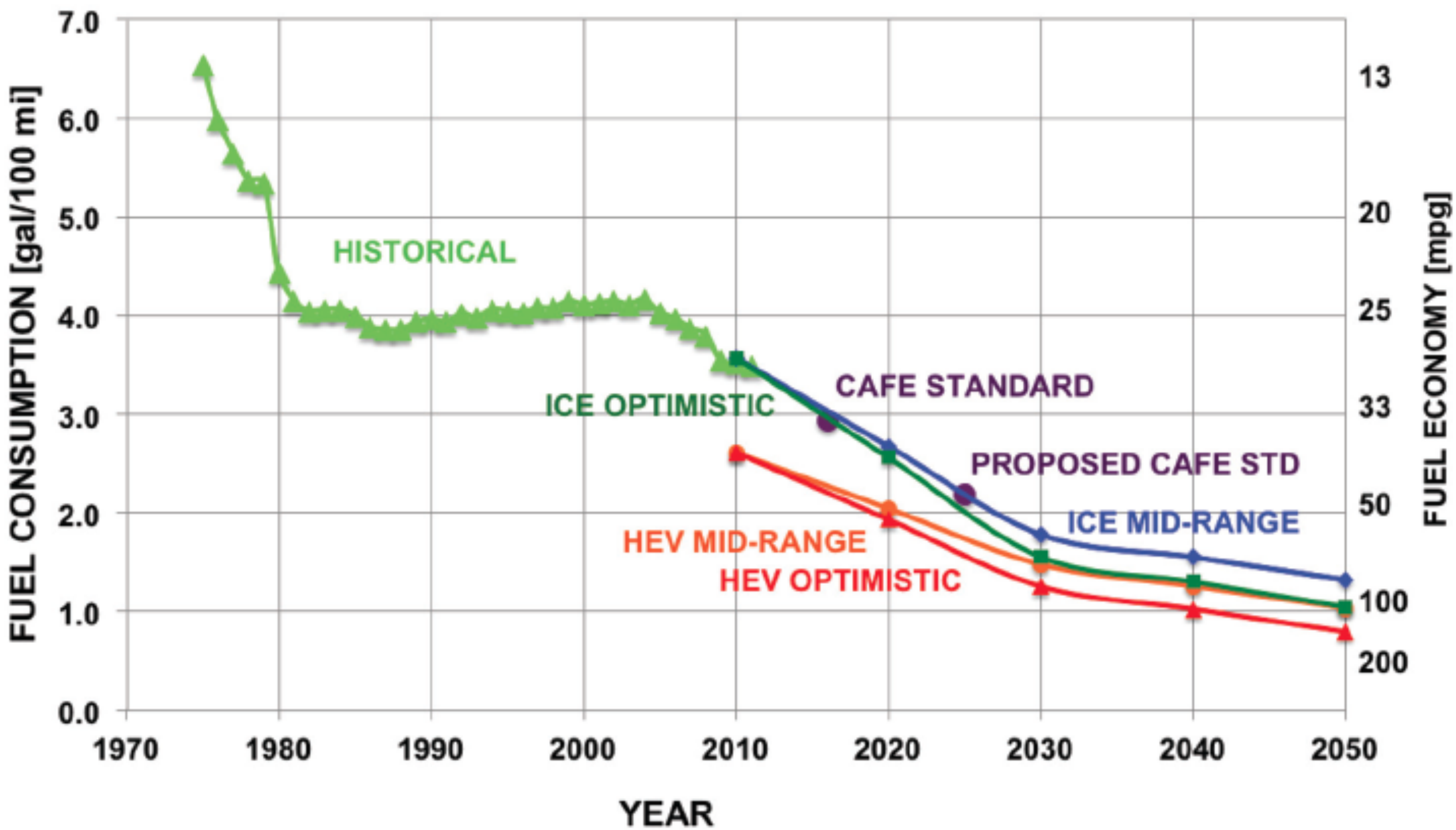
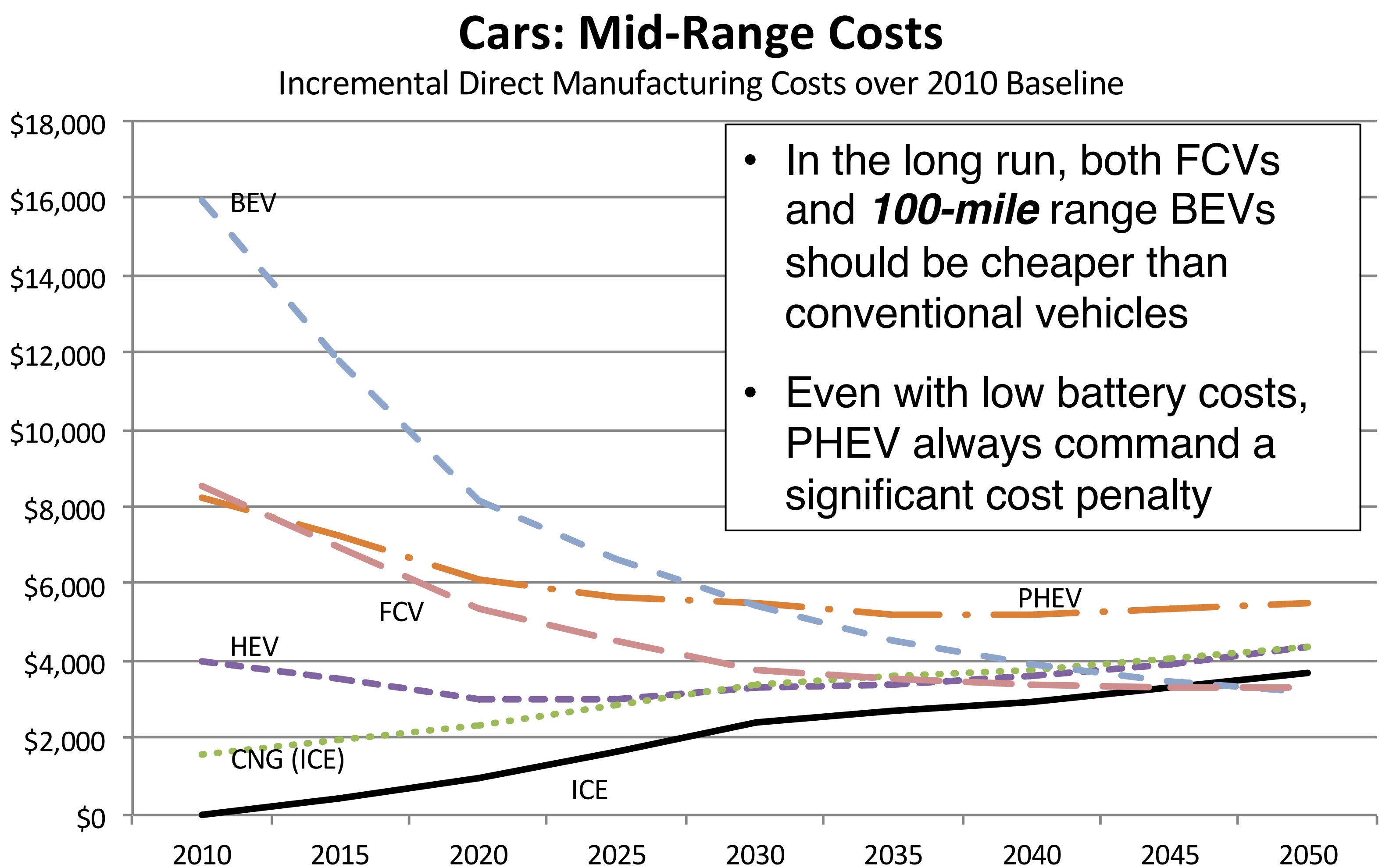
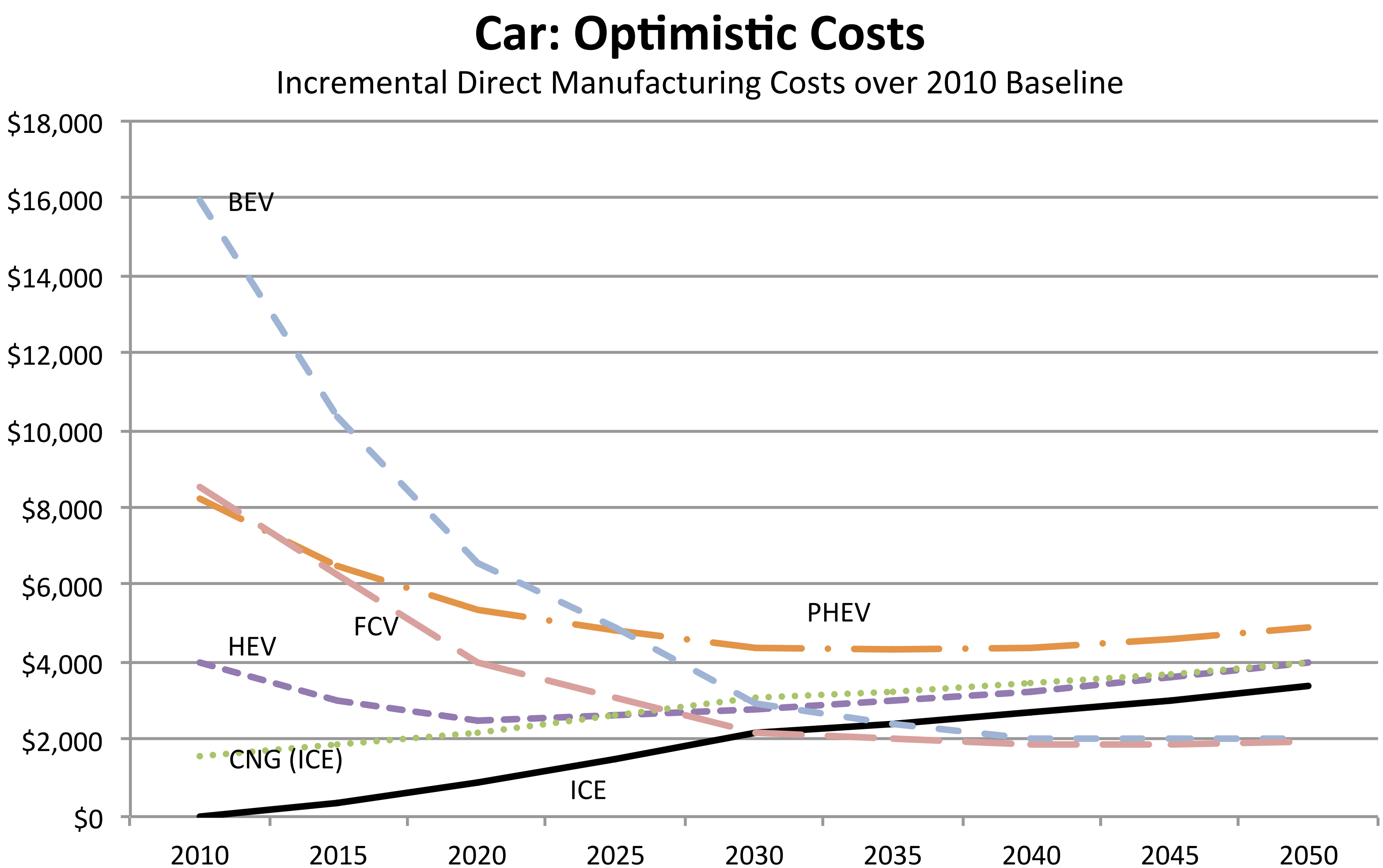


Figure 2-1 Historical and Projected Light-duty Vehicle Fuel Economy
Note: All data is new fleet only using unadjusted test values, no in-use fuel consumption.
FTP values, projections assume light duty fleet is 38% light duty trucks

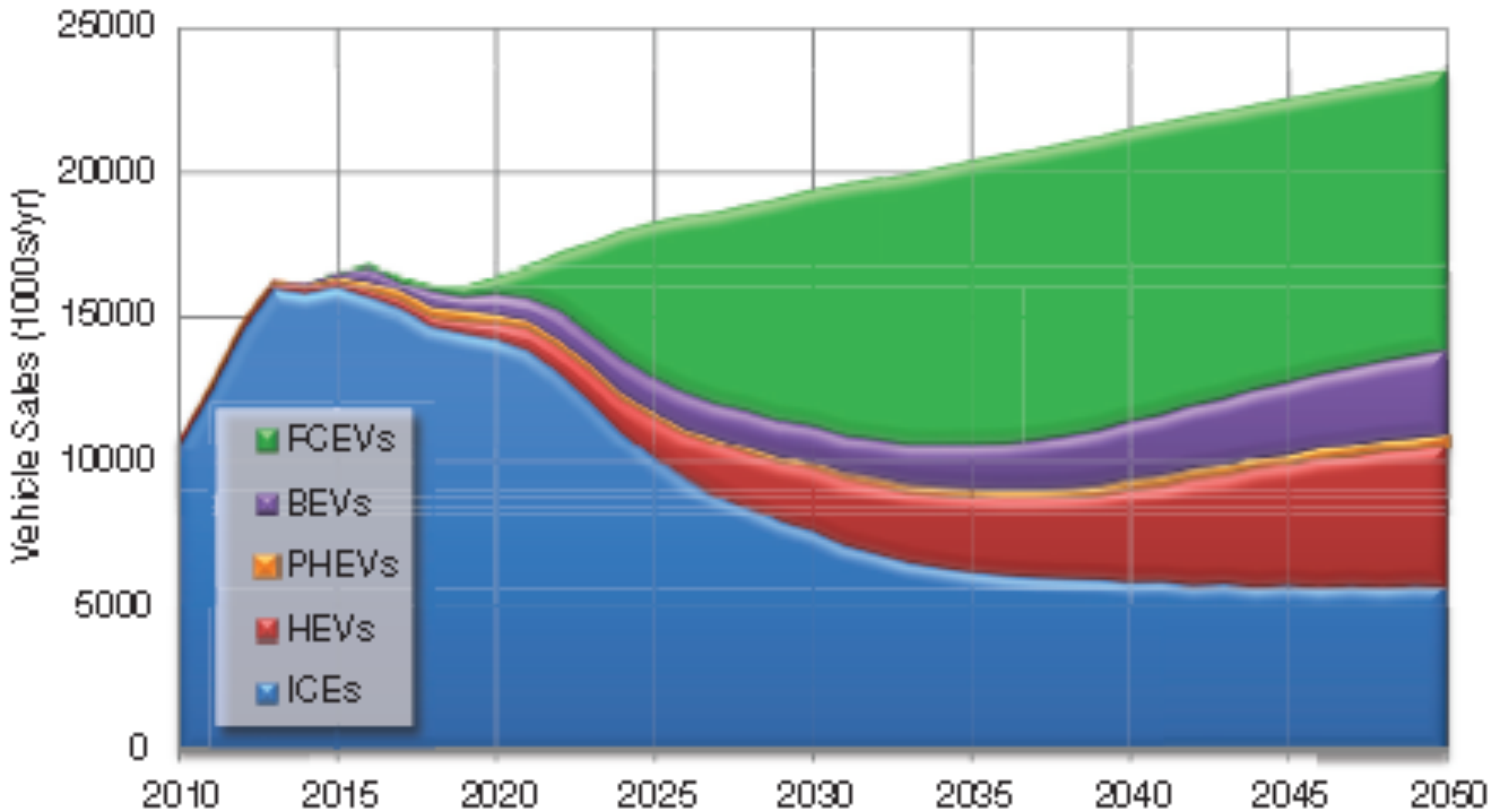
Car Incremental Cost over Baseline: High-Production Midrange Estimates



Car Incremental Cost over Baseline: High-Production Optimistic Estimates



A strategy promoting both FCVs and PEVs led to an 88% reduction in GHG emissions and a 100% reduction in petroleum use by 2050



Fuel Cell Vehicles

- FCVs are as good or better than ICE in every way
  - Same range and refill time
  - More efficient
  - Cheaper (in the long run)
  - Electric motor propulsion – quiet, instant response, high torque at low rpm, lower NVH, better packaging
  - Safer – 250,000 gasoline vehicle fires and 400 deaths annually
- Challenge is primarily delivery of H2 to refueling station – even long-term estimates are \$2-\$4/kg
  - Even if delivery costs can be solved, risk aversion will make it a slow transition

Key Question

- As ICE technology costs drop and efficiency improves – how do you get customers to move up to more expensive and risky plug-in technologies?

or

- If NEXTCAR succeeds, will you just create a larger barrier to plug-in electric vehicles?

Further Information

ICCT/supplier working papers

- http://www.theicct.org/lightweighting-technology-development-and-trends-us-passenger-vehicles
- http://www.theicct.org/downsized-boosted-gasoline-engines
- http://www.theicct.org/automotive-thermal-management-technology
- http://www.theicct.org/PV-technology-transmissions-201608
- http://www.theicct.org/naturally-aspirated-gas-engines-201606
- http://www.theicct.org/diesel-engines

ICCT technology briefs

- http://www.theicct.org/hybrid-vehicles-trends-technology-development-and-cost-reduction
- http://www.theicct.org/lightweighting-technology-developments-briefing
- http://www.theicct.org/downsized-boosted-gasoline-engines-briefing
- http://www.theicct.org/tech-brief-thermal-management-technology-nov2016
- http://www.theicct.org/transmissions-techbrief-oct2016
- http://www.theicct.org/naturally-aspirated-engines-techbrief-jun2016
- http://www.theicct.org/diesel-tech-developments-tech-brief

FEV EU report, ICCT electric vehicle report, 2025-2030 technology assessment

- http://www.theicct.org/sites/default/files/publications/PV-LCV-Powertrain-Tech-Analysis_FEV-ICCT_2015.pdf
- http://www.theicct.org/next-generation-electric-vehicle-technologies
- http://www.theicct.org/US-2030-technology-cost-assessment

Thank You

Thoughts, questions, suggestions?

FEV-EU Technology Assessments

- Except for Miller cycle and variable compression ratio, did not update efficiency assessments compared with Ricardo study 3 years previously
  - No increase in compression ratio
  - No engine downsizing with weight reduction or hybrids
  - No improvements in hybrid battery packs
- Did provide updated tear-down cost estimates

2025 Passenger Car and Light Commercial Vehicle Powertrain Technology Analysis

Final Report / September 2015

FEV – Project-No. P33597/ Issue v03/ Report-No. 1/ ICCT

Project Manager:
Dr.-Ing. Blanco-Rodriguez, David

[original-Signature 1]
Project Manager

[original-Signature 2, optional]
Vice President / Department Manager

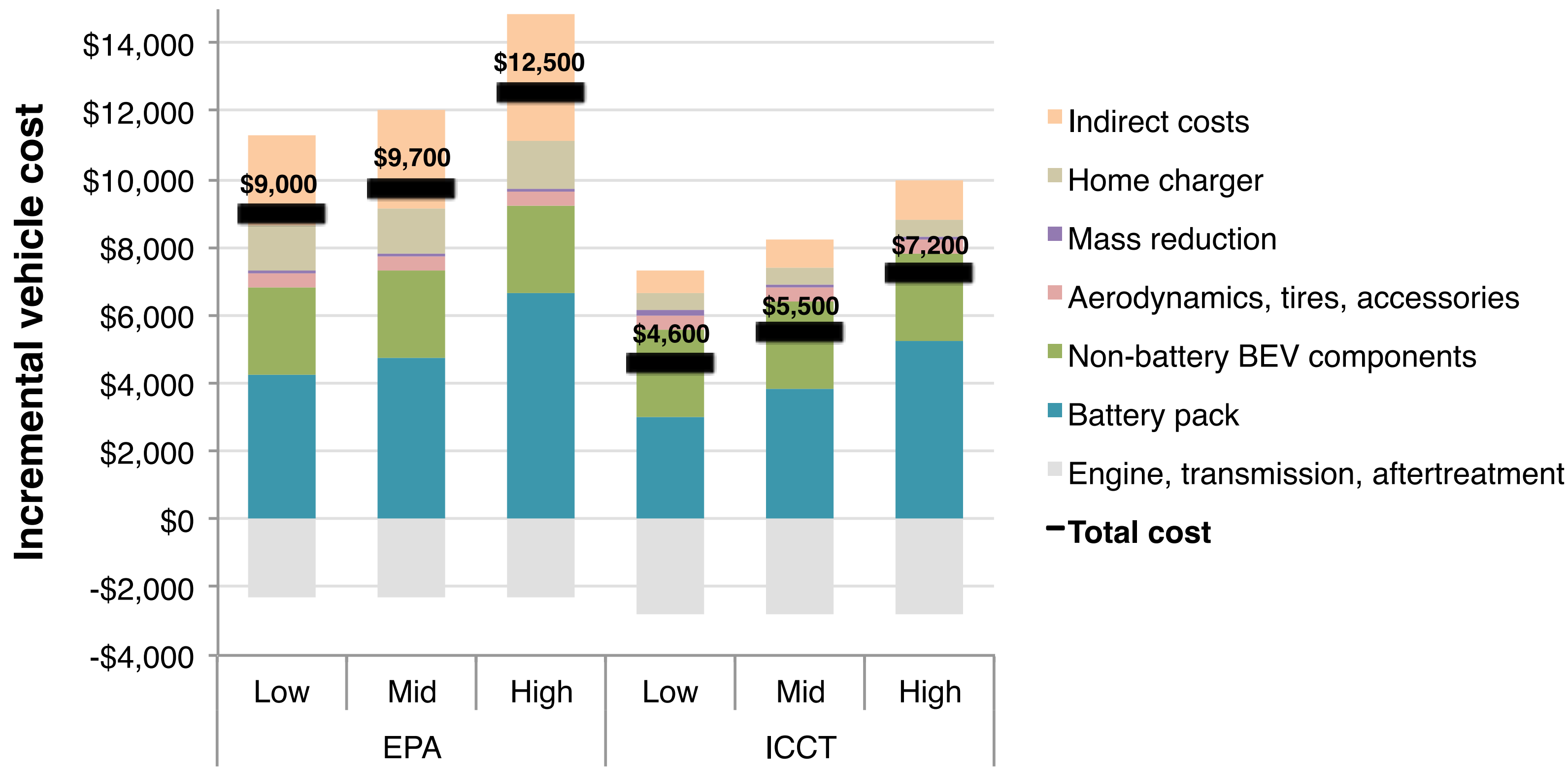
FEV Costs Generally lower than 2012 Rulemaking for 2017-2025

	EPA cost	FEV cost
GDI	$164	76 €
Turbo 18 bar – I4 to I4	$310	326 €
Turbo 18 bar – V6 to I4	$16 to -$110	-486 €
1-stage 18-bar to 2-stage 27-bar turbo	$465	178-200 €
Cooled EGR	$180	103-116 €
Atkinson/Miller (VVL+VVT)	$99-$204	$92-$120
Diesel	$1752-$2146	$996-$1893

Note: FEV numbers are for C and D segment cars (compact to mid-size)

Electric vehicle costs: EPA vs ICCT

- ICCT's electric vehicle costs ~40% lower than EPA's (2025)
  - Mostly this is due to lower battery costs (ICCT $140/kWh vs EPA 180-200/kWh)
  - Other factors: indirect costs, home charger, engine aftertreatment subtraction



ICCT Technology Paper on Electric Vehicles (2016)

Turbocharged Engine Improvements

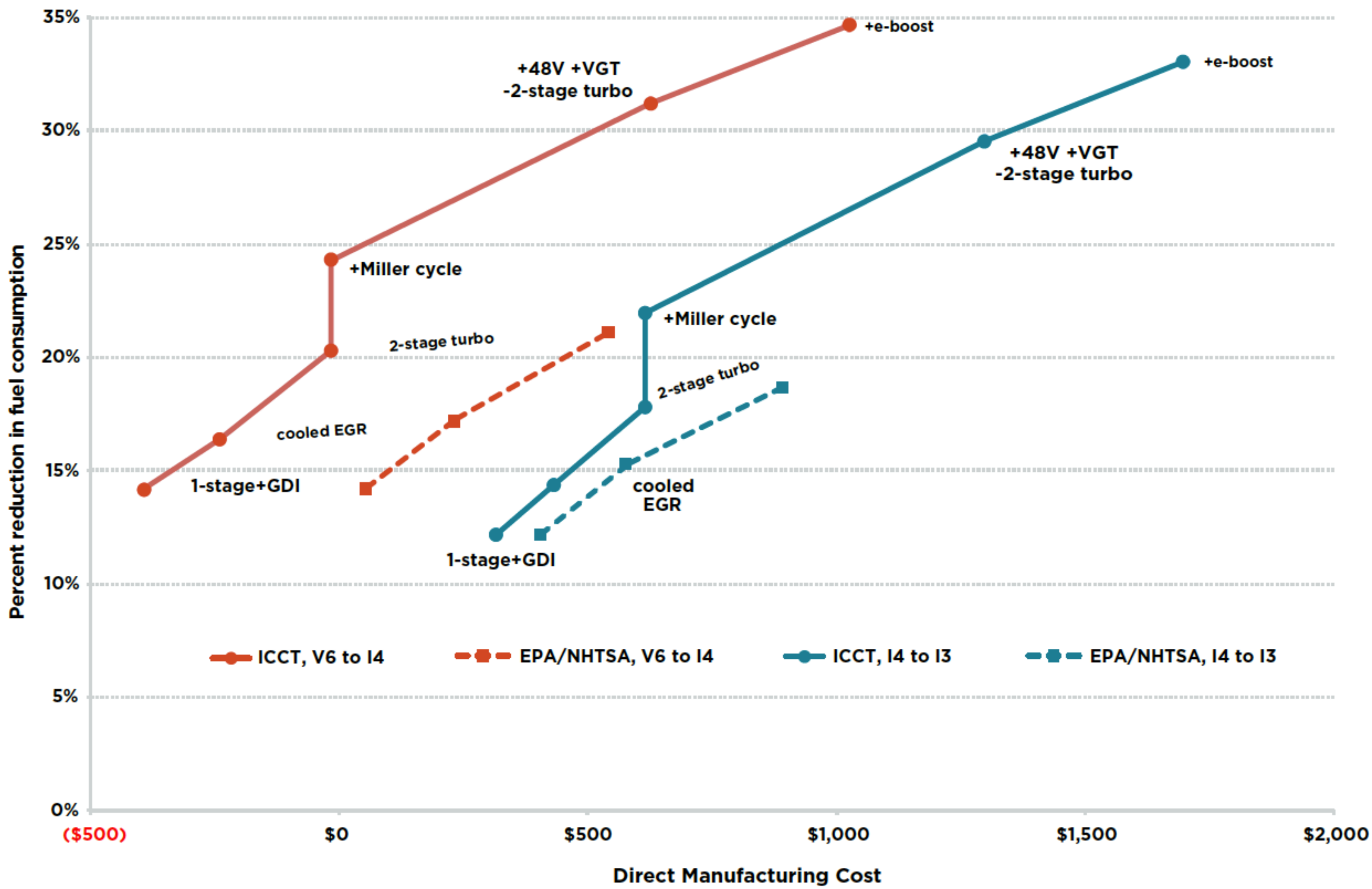


Figure 14 Comparison of ICCT/supplier and EPA/NHTSA costs and benefits of turbocharging and downsizing technologies.

Novation Analytics Study for Alliance

- Excellent analyses of 2014 vehicles and technology.
- 2014 Energy Conversion Efficiency results:
  - MY2014 sales-weighted average: 21.5%
  - Best naturally aspirated: 25.1% (Mazda 3 SkyActiv)
  - Best downsized turbo: 24.1% (Fiesta 1.0L 24 bar)
  - Average CI (diesel): 26.0%
- 2025: Assumed efficiency would match 90th percentile of 2014 vehicles:
  - Naturally aspirated: 22.8%
  - 18 bar turbo: 23.6%
  - 24 bar turbo: 24.1%
  - 24 bar turbo with cooled EGR: 27.2%

(with high ratio transmissions, without stop/start):

- **2014 SkyActiv is already 10% better than 2025 projection**
- Also, their method implicitly ignores all technology innovation that has occurred (and will occur) since 2014

Novation Analytics. Final Report - Technology Effectiveness – Phase I: Fleet-Level Assessment (version 1.1), prepared for: Alliance of Automobile Manufacturers Association of Global Automakers, October 19, 2015. http://www.autoalliance.org/cafe/cafe-research-reports