Vehicle Technology for 2020 and Beyond: Potential and US/EU Evaluation Methods

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

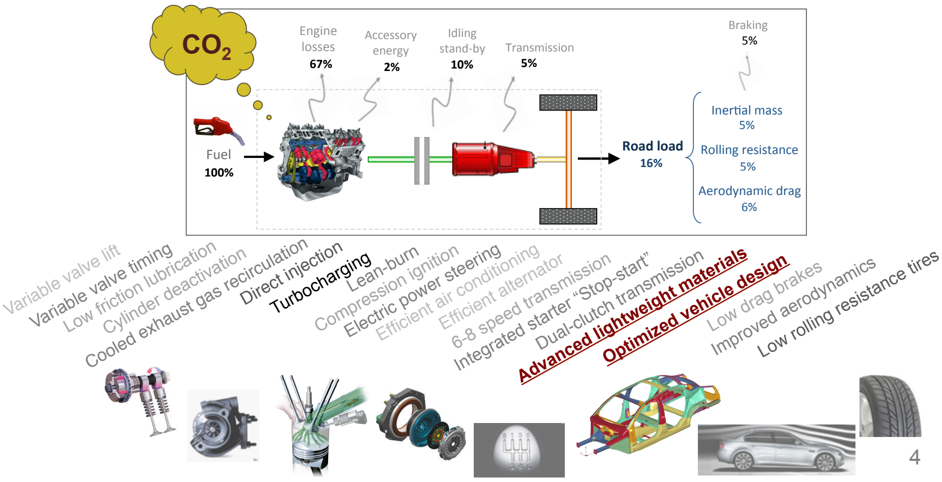
1. Current Technology Improvements
2. Ricardo Efficiency Simulations
3. FEV Tear-Down Cost Analyses
4. Lightweight Material Analyses
5. Cost Curves

Current Vehicle Efficiency Technology Trends

Pace of technology development & market penetration is accelerating

Technical Background: Vehicle Efficiency

- The modern automobile, at roughly 15-20% efficiency, has many efficiency losses – and many efficiency opportunities



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Sources: Lutsey, 2012; Kromer and Heywood, 2007; U.S. EPA (http://www.fueleconomy.gov/feg/atv.shtml)

The Real Technology Breakthrough

- **Computers**
  - Computer design, computer simulations, and on-vehicle computer controls are revolutionizing vehicles and powertrains
- The high losses in the internal combustion engine are an opportunity for improvement
- Also reducing size and cost of hybrid system
- Especially important for lightweight materials
  - Optimize hundreds of parts – size and material
  - Capture secondary weight – and cost – reductions

Accelerating Technology Introduction

	GDI	Turbo	6-speed Auto
2009	4.2%	3.6%	25%
2010	8.3%	3.5%	38%
2011	13.7%	7.4%	52%

Source: 2011 EPA Fuel Economy Trends Report

2010	2012	2010
Ford Focus	**Ford Focus EcoBoost**	**C-class diesel avg.**
1.6L, 4 cyl., 74 kW	1.0L, 3 cyl., 74 kW	1.7L
---	SS+DI+turbo	
1,175 kg	1,195 kg	
M5	M5	
14.6 km/l	**21.4 km/l**	**17.4 km/l**

+47%

2010	2012
Audi A3	**Audi A3**
1.6L, 4 cyl., 75 kW	1.2L, 4 cyl., 77 kW
---	SS+DI+turbo+7DCT
1,185 kg	1,150 kg
M5	7DCT
14.4 km/l	**20.1 km/l**

+40%

New powertrains introduced in Europe

Pace of Technology Innovation is Accelerating

Technology	Source	Benefit	Cost
Turbo-charging and downsizing (no cyl. reduction)	2001 NRC Report	5-7%	$250-$400
	Draft RIA – 18 bar	12-15%	$342
	Draft RIA – 24 bar	16-20%	$550
	Draft RIA – w/ boosted EGR	20-25%	$967
4- to 6-speed automatic	2001 NRC Report	3-4%	$150-$300
	Draft RIA	3-4%	($ 15)
Automatic to DCT	Draft RIA	4-6%	($154-$223)

x 2 efficiency

New technology: x 2 efficiency again

from cost increase to decrease

New technology: more efficient and cheaper

- Cost is direct manufacturing cost
- NRC Report is Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, 2002
- Draft RIA is for NHTSA/EPA proposed standards for 2017-25 light-duty vehicles

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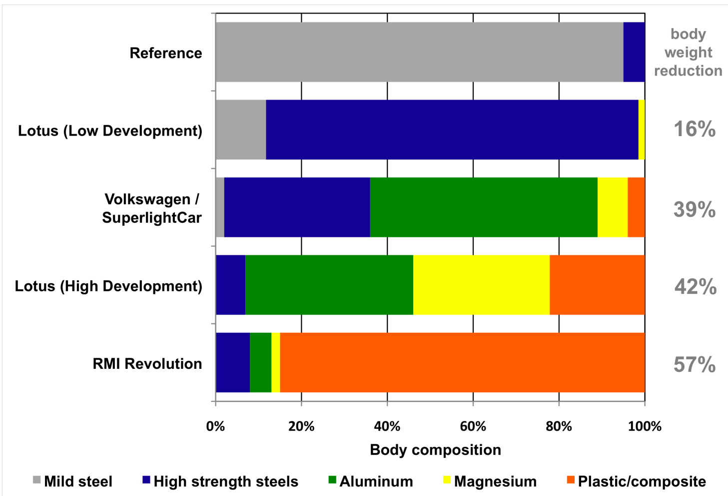
Lightweight Materials Offer Great Potential

Material composition of lightweight vehicle body designs:

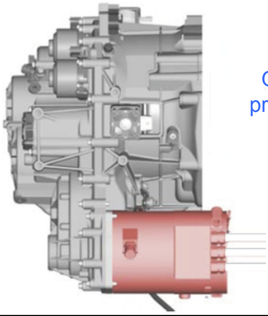


Also incremental improvements in aerodynamics and tire rolling resistance

Slide 8

Future Low Cost Hybrid System

- Advanced P2 hybrid system – not yet in production
  - Small, single motor integrated into automated manual transmission
    - Major reductions in cost of hybrid system
    - although high capitol costs to redesign transmission
  - Reduction in transmission clutch cost, possibly use of single-clutch manual transmission
- New, higher-power Li-ion batteries – smaller, lighter, and lower cost



Getrag prototype

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Ricardo Technology Simulation Modeling

Ricardo Worldwide

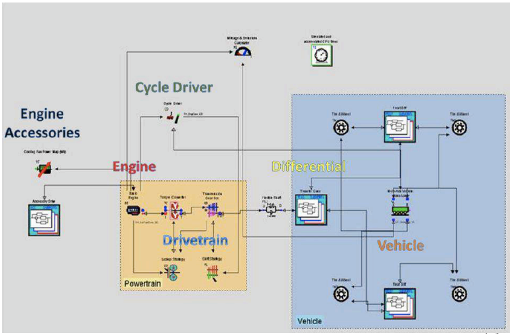
> 1,500 employees
> 1,300 technically qualified and engineering staff

Ricardo Client Base

Passenger Car	High Performance Vehicles & Motorsport	Commercial Vehicles	Agricultural & Industrial Vehicles	Motorcycles & Personal Transportation
Marine	Rail	Clean Energy & Power Generation	Defence	Government

How does vehicle simulation work?

- **Principle idea:**
  1. Input data (engine maps, road load data, etc.) fed into software tool to calculate fuel consumption / CO_2 emissions over a drive cycle
  2. Software model is validated by comparing calculated results against known data for an existing vehicle model
  3. Input data is changed (e.g. new engines maps) to account for future changes in technology and model is re-run



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What is so special about the simulations?

- **Generally accepted approach:**
  - To study future CO_2 reduction potential, **technology interactions** have to be accounted for (by grouping technologies into packages) → **vehicle simulations takes interactions into account**
  - Ricardo's vehicle simulation methodology **follows closely industry-internal approach** of vehicle development and was **confirmed by an independent peer review:** http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies
- **Deliverables of the Ricardo vehicle simulations project:**
  - **Report** describing methodology and results
  - **Software tool for public use** to allow users to change vehicle parameters and calculate resulting CO_2 emissions themselves
  - See ICCT website for details

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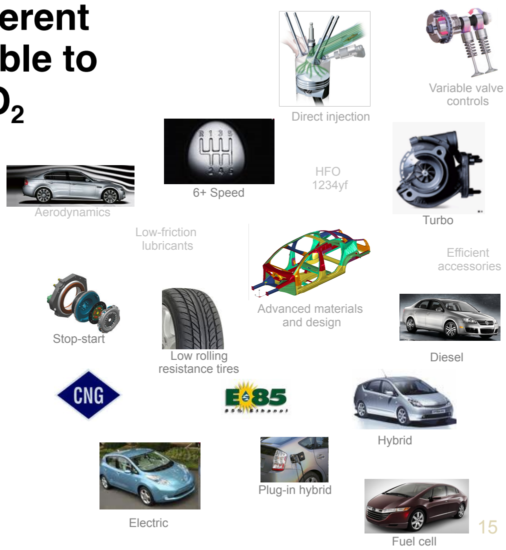
Efficiency, low CO_2 technologies

- **There are many different technologies available to reduce vehicles' CO_2 emissions**
- Petroleum efficiency
  - Gasoline
  - Diesel
  - Hybrid
- Alternative fuels
  - Compressed natural gas
  - Biofuels
- Electric-drive
  - Plug-in hybrid electric
  - Electric
  - Fuel cell electric



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Technologies Simulated

Technologies added with work sponsored by ICCT work in red

- Start-stop incl. energy-recuperation
- Gasoline direct injection (DI), turbocharging and downsizing (stoichiometric)
- Gasoline DI, turbocharging and downsizing (lean-stoich.)
- Gasoline exhaust gas recirculation (EGR) DI turbo
- Gasoline Atkinson cycle engine with cam profile switching (CPS)
- Gasoline Atkinson cycle engine with digital valve actuation (DVA)
- Gasoline P2 hybrid
- Gasoline PowerSplit hybrid
- **Diesel advanced 2020+ engine**
- Advanced transmission technologies
  (6/8-speed automatic, dual clutch transmission)
- **Manual transmission sensitivity analysis**

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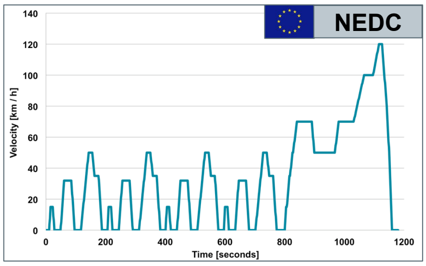
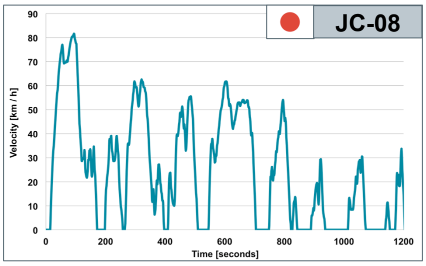
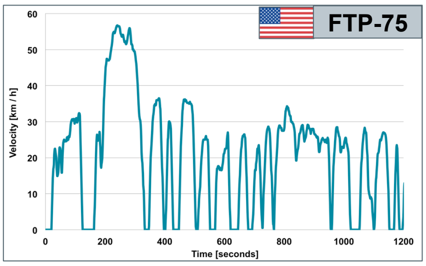
Drive Cycles





ICCT sponsored work to add NEDC and JC-08 cycles



ICCT is sponsoring work to add new World Harmonized Driving Cycle (WLTP)

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Vehicle Classes: US and EU projects

A	B	C	D	E	small SUV	small N1	large N1
Peugeot 107	Toyota Yaris	VW Golf	Toyota Avensis	BMW 5 series	BMW X3	Renault Kangoo	Mercedes Sprinter
11%	28%	32%	11%	3%	<5%	≈50%	≈50%

ICCT sponsored work to add all European vehicle classes

Ricardo Technologies and Assumptions

Table 5.1: Engine technology package definition.

Engine	Air System	Fuel Injection	EGR	Valvetrain CPS	Valvetrain DVA
2010 Baseline	NA	PFI	No	No	No
Stoich DI Turbo	Boost	DI	No	Yes	No
Lean-Stoich DI Turbo	Boost	DI	No	Yes	No
EGR DI Turbo	Boost	DI	Yes	Yes	No
Atkinson with CPS	NA	DI	No	Yes	No
Atkinson with DVA	NA	DI	No	No	Yes
Diesel	Boost	DI	Yes	Yes	No

Table 5.2: Hybrid technology package definition.

Function	Powertrain Configuration: 2010 Baseline	Stop-Start	P2 Parallel	Powersplit
Engine idle-off	Yes	Yes	Yes	Yes
Launch assist	No	No	Yes	Yes
Regeneration	No	No	Yes	Yes
EV mode	No	No	Yes	Yes
CVT (Electronic)	No	No	No	Yes
Power steering	Belt	Electrical	Electrical	Electrical
Engine coolant pump	Belt	Belt	Electrical	Electrical
Air conditioning	Belt	Belt	Electrical	Electrical
Brake	Standard	Standard	Blended	Blended

Table 5.3: Transmission technology package definition.

Transmission	Launch Device	Clutch
Baseline Automatic	Torque Converter	Hydraulic
Advanced Automatic	Multidamper Control	Hydraulic
Dry clutch DCT	None	Advanced Dry
Wet clutch DCT	None	Advanced Damp

Blanket 3.5% improvement in fuel consumption coming from a combination of friction improvements in future engines

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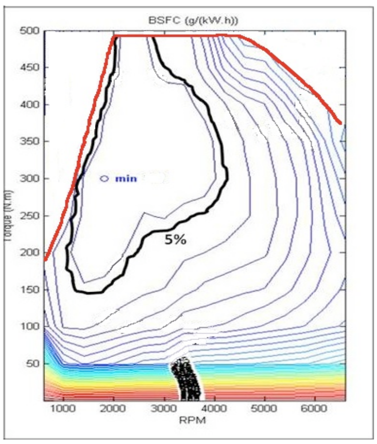
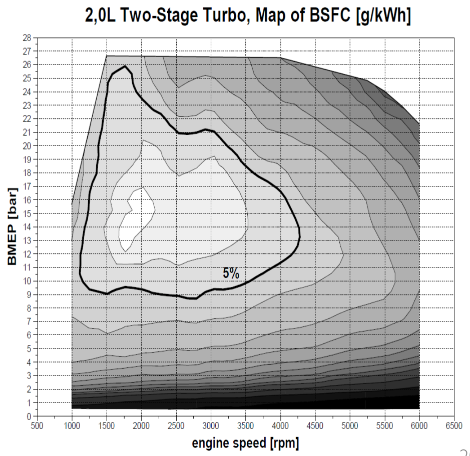
Ricardo model inputs - example

Stoichiometric, Direct Injection Turbocharged Engine

Efficiency map generated by Ricardo for EPA program (left) is based on benchmarking and research data, and compares favorably to research results from 2011 General Motors paper (right) from demonstration engine.





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Source: Ricardo Analysis

Source: Schmuck-Soldan, S., A. Königstein, and F. Westin, 2011

Ricardo Model Input – Example

Electric Motor Map

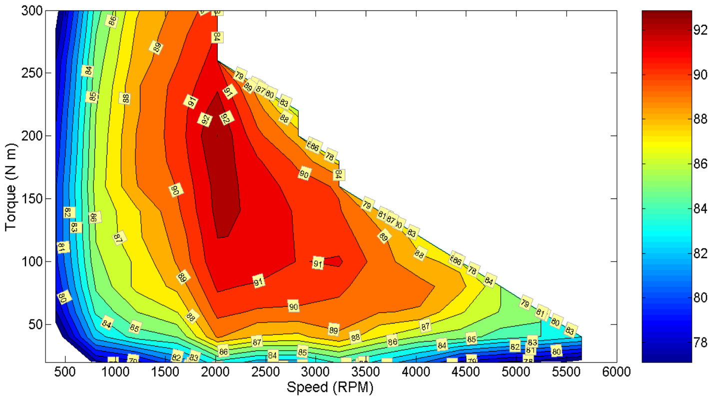
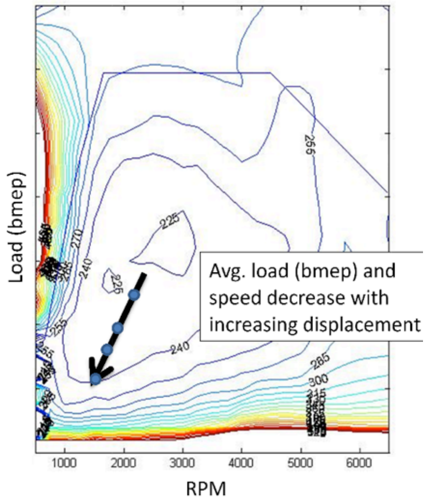
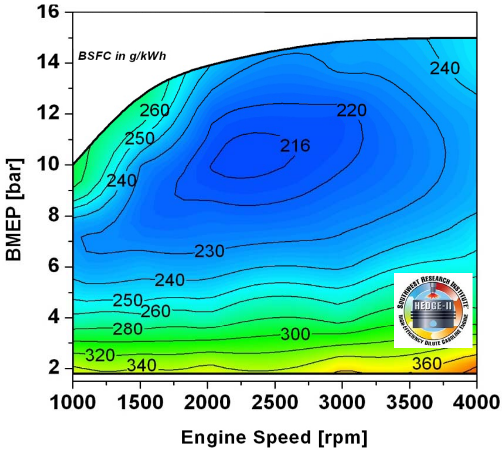


Figure 3-5: 2007 Camry Hybrid motor-inverter efficiency map (Burress, et al, 2008[30])

Some Ricardo Maps May be Conservative



Ricardo: Advanced engine BSFC map (27-bar cooled EGR turbocharged GDI engine for large car)



High Efficiency Dilute Gasoline Engines (HEDGE) Application [2.4L I4, 11.4:1 CR, Max EGR ~ 30%, boost limited (turbocharger hardware could not provide sufficient air), proprietary SwRI ignition system.] extracted from “Examples of HEDGE Engines”, Dr. Terry Alger, SwRI, February 2010

HEDGE consortium is already working on a two-stage turbocharger system that will enable larger amounts of EGR, higher compression ratio, lower minimum BSFC, and a broader range of lower fuel consumption.

Example EU Baseline Vehicles – C class

--- revised C class vehicle ---

C-segment
(32% market, 38% diesel)

	Gasoline		Diesel	
	Ricardo	**EU-27**	**Ricardo**	**EU-27**
Vehicle model	Ford Focus	n/a	Ford Focus	n/a
Engine size	4 cyl., 1.6 l	4 cyl., 1.6 l	4 cyl., 1.6 l	4 cyl., 1.7 l
Engine power	88 kW	86 kW	75 kW	83 kW
Engine type	PFI	PFI (MS DI≈19%)	n/a	n/a
Vehicle weight	1,257 kg	1,270 kg	1,413 kg	1,360 kg
Transmission	6-MT	5-MT (MS≈49%)*	6-AT	5-MT (MS≈49%)*
Acceleration 0-100 km/h	---	11.3 s	10.0 s	11.6 s
CO_2 in NEDC	139 g/km	156 g/km	124 g/km	131 g/km
Remarks	Start-Stop/Reg. Euro 5 eq.	no Start-Stop Euro 4 (MS≈60%)	Start-Stop/Reg. Euro 5	no Start-Stop Euro 4 (MS≈60%)

Ricardo simulations baseline vehicle vs. EU-27 average new vehicle in 2010
Abbreviations: PFI (port fuel injection), DFI (direct fuel injection), MS (market share), AT (automatic transmission), MT (manual transmission), vehicle weight is given in mass in running order (includes 68 kg driver and 7 kg of luggage)
** MS 5-MT and 6-MT together ≈ 91%*

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Gasoline Simulation Results

C-segment (gasoline)
only engine + transmission

	cyl.	[l]	inj.	[kg]	trans.	[s]	[g/km]	em.	red.
EU-27 2010 average	4	1.6	PFI	1,270	5-MT	11.3	156	EU4	+X%
Ricardo baseline (start stop)	**4**	**1.6**	**PFI**	1,257	6-MT	9.1	139	EU5	---
STDI (start stop + stoich. direct injection + downsizing)	**3**	**0.8**	**DI**	1,257	8-AT 8-DCT	9.0 9.1	101 99	EU6	-27% -28%
LBDI (start stop + lean-stoich direct injection + downsizing)	**3**	**0.8**	**DI**	1,257	8-AT 8-DCT	9.0 9.1	99 96	EU6	-28% -31%
EGBR (start stop + high load EGR DI + downsizing)	**3**	**0.8**	**DI**	1,257	8-AT 8-DCT	9.0 9.1	97 95	EU6	-30% -32%
Atkinson CPS (P2)	**4**	**1.9**	**DI**	1,324	8-DCT	9.1	78	EU6	-44%

cyl. = number of cylinders, [l] = engine displacement, inj. = engine type, [kg] = vehicle weight, trans. = transmission, [s] = acceleration 0-100 km/h, em. = emission standard, red. = CO_2 reduction compared to Ricardo baseline vehicle
STDI = stoichiometric turbocharged gasoline direction injection, LBDI = lean-stoichiometric turbocharged gasoline direct injection, EGR = exhaust gas recirculation, DCT = dual clutch transmission, AT = automatic transmission, MT = manual transmission, PFI = port fuel injection // more technologies in project report // note that vehicle weight is not adapted for individual packages in the original Ricardo report but was adjusted for this summary (additional weight for hybrid configuration)

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Gasoline Simulation Results with load reduction

C-segment (gasoline)
including roadload reduction

	cyl.	[l]	inj.	[kg]	trans.	[s]	[g/km]	em.	red.
EU-27 2010 average	4	1.6	PFI	1,270	5-MT	11.3	156	EU4	+12%
Ricardo baseline (start stop)	**4**	**1.6**	**PFI**	1,257	6-MT	9.1	139	EU5	---
STDI (start stop + stoich. direct injection + downsizing) -15% mass, -10% RR/CdA	**3**	**0.7**	**DI**	1,058	8-AT 8-DCT	9.0 9.1	89 87	EU6	-36% -37%
LBDI (start stop + lean-stoich direct injection + downsizing) -15% mass, -10% RR/CdA	**3**	**0.7**	**DI**	1,058	8-AT 8-DCT	9.0 9.1	87 85	EU6	-37% -39%
EGBR (start stop + high load EGR DI + downsizing) -15% mass, -10% RR/CdA	**3**	**0.7**	**DI**	1,058	8-AT 8-DCT	9.0 9.1	85 83	EU6	-39% -40%
Atkinson CPS (P2) -15% mass, -10% RR/CdA	**4**	**1.6**	**DI**	1,117	8-DCT	9.1	68	EU6	-51%

cyl. = number of cylinders, [l] = engine displacement, inj. = engine type, [kg] = vehicle weight, trans. = transmission, [s] = acceleration 0-100 km/h, em. = emission standard, red. = CO_2 reduction compared to Ricardo baseline vehicle
STDI = stoichiometric turbocharged gasoline direction injection, LBDI = lean-stoichiometric turbocharged gasoline direct injection, EGR = exhaust gas recirculation, DCT = dual clutch transmission, AT = automatic transmission, MT = manual transmission, PFI = port fuel injection // more technologies in project report // note that vehicle weight is not adapted for individual packages in the original Ricardo report but was adjusted for this summary (additional weight for hybrid configuration)

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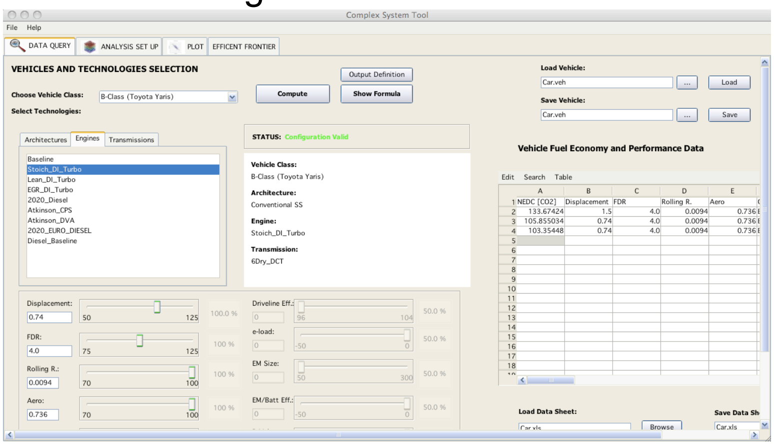
Response Surface Model software tool

- Tool and user guide available on ICCT website



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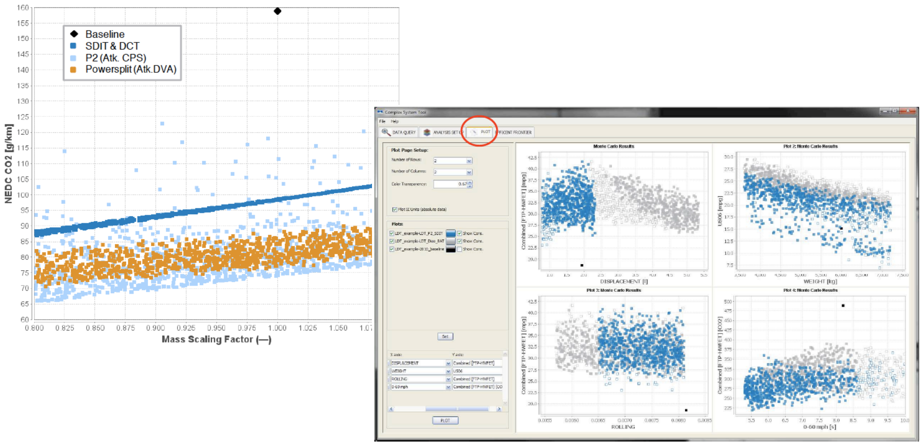
Response Surface Model software tool

- Tool also allows Monte-Carlo simulations



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FEV Tear-Down Cost Assessments

FEV Worldwide

Company profile:
- Founded in 1978
- Independent family-owned company
- Working for major car and engine manufacturers worldwide
- Close collaboration with the Technical University in Aachen
- 2,100 employees
- > 110 engine / powertrain test cells
- Innovative: >1300 patents

Engineering services and products
- Automotive and commercial vehicles
- Engine and powertrain
- Vehicle integration, application and electronics
- Test systems
- Advanced applications in aeronautics and transportations
- Clean energy, energy industry

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FEV's Areas of Expertise

Vehicle Technology


Engine & transmission


Vehicle application & calibration


Demonstration cars


E-vehicle development


Powertrain testing & test facilities

FEV has emerged as one of the market leader for vehicle technology and offers today engineering services for diverse industry areas

Industry Areas


Power engineering


Marine


Off-Highway


Aeronautics


Rail

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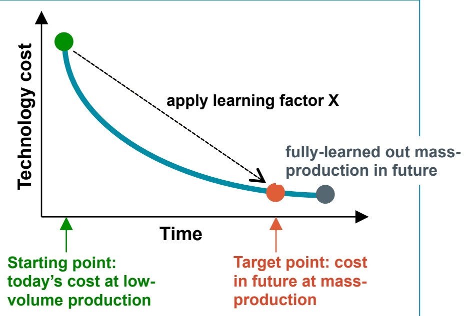
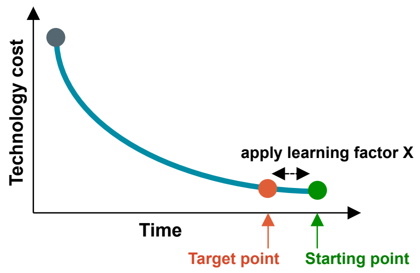
Principle idea of tear-down cost analysis

"Conventional" approach



- Low-volume production methods very different from future mass-production
- Learning factor X applied over a long time range (introducing uncertainty)

Tear-down approach



- Cost at learned-out mass production can be determined quite accurate
- Learning factor X applied over short range only (less uncertainty)

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The tear-down approach in comparison

- **Key advantages of the tear-down cost analysis approach:**
  - great level of transparency
  - reduced uncertainty of results by avoiding learning factors
  - following closely industry-internal approach for costing
  - better transferability to other regions
- **Downside of the approach:**
  - very expensive
  - can only cost technologies in production, or variations
- **Approach has been subject to independent peer-review:**
  - http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies

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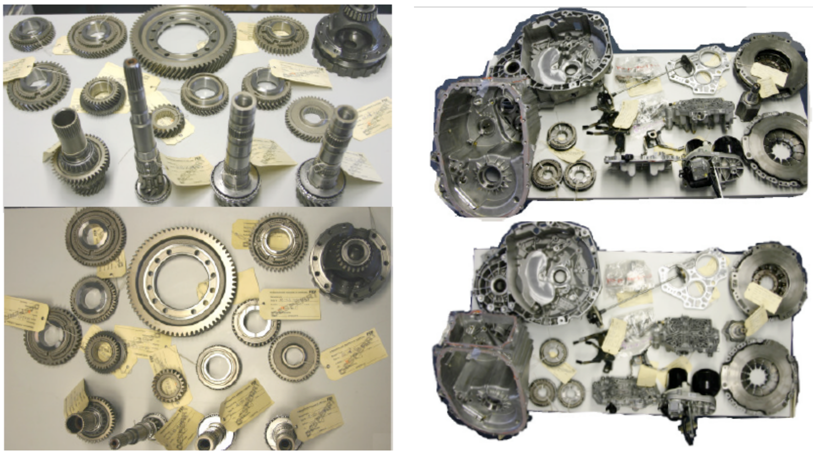
Tear-down really means "nuts and bolts"



General approach for tear-down analysis

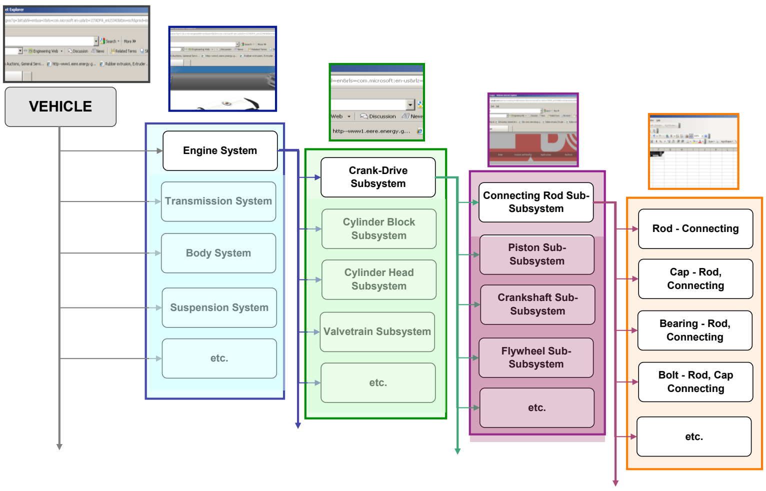
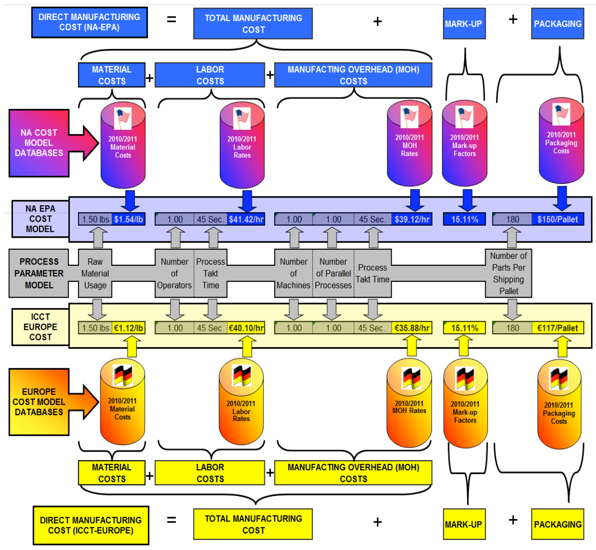


Illustration of analysis process



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Transparency of methodology and results

All details on parts and manufacturing processes available publicly

Technology Level: Downsized, Turbocharged, Gasoline Direct Inject (GDI) Engine/ Compact Vehicle Class
Vehicle Class: Compact/Economy 2-4 Passenger
Study Case#: N0101 (N = New, 01 = Technology Package, 01 = Vehicle Class)
System Description: 2007 Mini Cooper S. 1.6L I4, 16V DOHC GDI Turbo
Component Description: OEM Assembly of Fuel Induction Components to Engine — **Part Number:** 1100
Component Quote Level: ☐ Full Quote ☐ Modification ☑ Differential Quote (Quote Summary includes

GENERAL COMPONENT INFORMATION				GENERAL MANUFACTURING INFORMATION					MAN			
Reference #	Part Description	Part Number	QTY Per Assembly	Primary Process Description	OEM/Supplier Classification	Material Specification	Labor Classification	Burden Classification	Finished Pieces Per Hour	Number of Operators	Number of Lines	Parallel Processing Multiplier
Tier 1 Supplier or OEM Processing & Assembly (Full Cost mapping)												
1A	Fuel Rail - High Pressure	1101-N0101-02	1	Install Fuel Rail to Cylinder Head **(Two Additional Fasteners Over Base GEMA Engine)**	OEM Assembly, Mark-up Applied @ Bottom.	Not Applicable	General Assembly-OEM	Engine Assembly, OEM	257	1	1	1
2A	Fuel Injector Assembly - Solenoid, 7 Hole	1104-N0101-01	4	**Install Fuel Injectors to Cylinder Head, Considered Wash to Base Engine**	OEM Assembly, Mark-up Applied @ Bottom.	Not Applicable	Not Applicable	Not Applicable	451	1	1	1
	Fuel Pump - High Pressure w. Vol.Control Valve (Driven-Off Intake Cam)	1107-N0101-01	1	Install Fuel Pump to Cylinder Head, 3 Fasteners	OEM Assembly, Mark-up Applied @ Bottom.	Not Applicable	General Assembly-OEM	Engine Assembly, OEM	171	1	1	1
	Pipe Assembly - Fuel, High Pressure, Pump to Rail	1170-N0101-01	1	Install High Pressure Pipe Between Fuel Rail and Pump. Run Down Two Tube Nuts	OEM Assembly, Mark-up Applied @ Bottom.	Not Applicable	General Assembly-OEM	Engine Assembly, OEM	257	1	1	1

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Technologies assessed

FEV cost analysis (Phase I) ➔ **transferring US results to the EU**

- ✓ Gasoline direct injection and downsizing
- ✓ Automatic and dual-clutch transmissions
- ✓ Start-stop hybrid (belt alternator type)
- ✓ P2 and PowerSplit hybrid
- ✓ Electrical air conditioning compressor

FEV cost analysis (Phase II) ➔ **new technologies specifically for EU**

- ✓ Advanced diesel technology
- ✓ Manual and dual-clutch transmissions
- ✓ EGR direct injection turbo engine (diesel)
- o EGR direct injection turbo engine (gasoline)
- ✓ Advanced start-stop technology

- o Lightweighting measures ➔ **joint US-EU project**

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Vehicle segments used for EU study

Powertrain - Vehicle Class Summary Matrix (P-VCSM)	European Vehicle Segments					
Veh. ID#	00	01	02	03	05	06
= Custom Models, Single Vehicle Segment = Scaleable Models, Multiple Vehicle Segments = Scaleable Models, Multiple Vehicle Segments and Technologies Modifications relative to Custom Model = Custom Models, Single Vehicle Segment Result Scaled to Alternative Vehicle Segments	Subcompact car typically powered by an inline 4 cylinder engine, naturally aspirated, port fuel injection, 5-speed manual transmission (MT).	Compact or small car typically powered by an inline 4 cylinder engine, naturally aspirated, port fuel injection, 6-speed manual transmission or 7-speed dual clutch transmission (DCT).	A midsize passenger car typically powered by a 4 cylinder turbocharged, direct fuel injection, 6-speed MT and AT or 7-speed DCT, Start/Stop system.	A midsize or large passenger car typically powered by 4 and 6 cylinder turbocharged, direct fuel injection, 6-speed MT or ≥ 6 speed AT.	A small or mid-sized sports-utility or cross-over vehicle, or a small-midsize SUV, or a Mini Van powered by a 4 cylinder turbocharged engine, direct fuel injection, 6-speed MT or AT & 7 DCT.	Large sports-utility vehicles, typically powered by a 8 cylinder naturally aspirated engine, direct fuel injection, ≥ 6-speed AT.
Vehicle Category Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series	VW Sharan BMW 5 Series	VW Tiguan BMW X1/X3	VW Touareg BMW X5/X6
Typical Engine Size Range (Liters)	1.2-1.4	1.4-1.6	1.6-2.0	2.0-3.0	1.2-3.0	3.0-5.5
Ave. Curb Weight (lb)(1)	2,390	2,803	3,299	3,749	3,505	4,867
Ave. Power (hp)(1)	100	121	157	234	178	364
Ave. Torque (lb*ft)(1)	108	132	174	237	195	362
Weight-to-Power Ratio (lb/hp)	24	23	21	16	20	13

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Key assumptions for EU Costs

- **Cost structure timeframe** (labor rates, material costs, etc.): 2010
- **Direct manufacturing costs**
  = cost of components and assembly to the OEM
- **Indirect manufacturing costs** includes:
  OEM corporate overhead (sales, marketing, warranty, profit, etc.),
  OEM engineering, design, and testing costs (internal and external),
  OEM owned tooling
- **OEM manufacturing location:** Germany
- **Supplier manufacturing location:** Germany
- **Annual capacity planning volume:** 450,000 units

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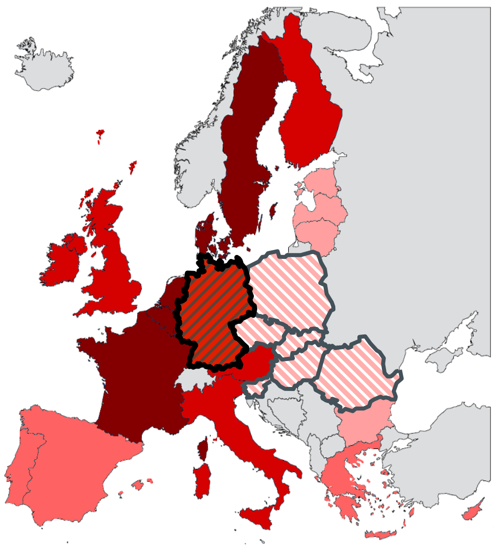
Germany as manufacturing base for EU study

Labor cost in Europe

- 1 to 10 €/h
- 10 to 20 €/h
- 25 to 30 €/h
- 30 €/h and more

Approach to meet European average

- Consideration of German labor costs as representative of Western European conditions
- Definition of one percent relation between German labor costs and an average of Eastern European countries
- **Sensitivity analysis for manufacturing base located in Eastern Europe**



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Different levels of detail for results available

ICCT Europe Analysis:
Downsized, Turbocharged, Gasoline Direct Injection Engine Technology Configurations

System ID	System Description	Calculated Incremental Manufacturing Cost - Downsized, Turbocharged, Gasoline Direct Injection Engines: Subcompact Segment, Passenger Seating: 2-4
	Vehicle Example	VW Polo
Basic Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4
	Average Curb Weight (lb)	2390
	Average Power (hp)	100
	Average Torque (lb*ft)	108
	Weight-to-Power Ratio (lb/hp)	24
	Baseline Technology Configuration	1.4L, I4, 4V, DOHC, NA, PFI, dVVT, ICE
	New Technology Configuration	1.0L, I3, 4V, DOHC, Turbo, GDI, dVVT, ICE
A	Engine Frames, Mounting & Bracket Subsystem	SA(1)
B	Crank Drive Subsystem	SA(1)
C	Counter Balance Subsystem	SA(1)
D	Cylinder Block Subsystem	SA(1)
E	Cylinder Head Subsystem	SA(1)
F	Valvetrain Subsystem	SA(1)
G	Timing Drive Subsystem	SA(1)
H	Accessory Drive Subsystem	SA(1)
I	Intake Subsystem	SA(1)
J	Fuel Subsystem	SA(1)
K	Exhaust Subsystem	SA(1)
L	Lubrication Subsystem	SA(1)
M	Cooling Subsystem	SA(1)
N	Induction Air Charging Subsystem	SA(1)
O	Exhaust Gas Re-Circulation Subsystem- Not Applicable In Analysis	SA(1)
P	Breather Subsystem	SA(1)
Q	Engine Management, Engine Electronic and Electrical Subsystems	SA(1)
R	Accessories Subsystem (Starter Engines, Alternators, Power Steering Pumps, etc)	SA(1)
	Net Incremental Direct Manufacturing Cost	€ 230

Notes: (1) Results calculated by scaling detailed costs, from surrogate analyses,

ICCT Europe Analysis:
Downsized, Turbocharged, Gasoline Direct Injection Engine Technology Configurations

System ID	System Description	Calculated Incremental Manufacturing Cost - Downsized, Turbocharged, Gasoline Direct Injection Engines					
		Subcompact Segment, Passenger Seating: 2-4	Compact or Small Segment, Passenger Seating: 2-5	Mid Size Segment, Passenger Seating: 4-5	Mid to Large Size Segment, Passenger Seating: 4-7	Small to Mid Size Sports Utility and Cross Over Segment, Passenger Seating: 4-5	Large Sports Utility Segment, Passenger Seating: 4-7
	Vehicle Example	VW Polo	VW Golf	VW Passat	VW Sharon	VW Touran	VW Touareg
Basic Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4	1.4-1.6	1.6-2.0	2.0-3.0	1.2-3.0	3.0-5.5
	Average Curb Weight (lb)	2390	2803	3299	3749	3505	4867
	Average Power (hp)	100	121	157	234	178	364
	Average Torque (lb*ft)	108	132	174	237	195	362
	Weight-to-Power Ratio (lb/hp)	24	23	21	16	20	13
	Baseline Technology Configuration	1.4L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	1.6L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	2.4L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	3.0L, V6, 4V, DOHC, NA, PFI, dVVT, ICE	Results from case study 0102 or 0103 applicable to vehicle segment - dependent on baseline powertrain size	5.4L, V8, 3V, SOHC, NA, PFI, sVVT, ICE
	New Technology Configuration	1.0L, I3, 4V, DOHC, Turbo, GDI, dVVT, ICE	1.2L, I4, 4V, DOHC, Turbo, GDI, dVVT, ICE	1.6L, I4, 4V, DOHC, Turbo, GDI, dVVT, ICE	2.0L, I4, 4V, DOHC, Turbo, GDI, dVVT, ICE		3.5L V6, 4V, DOHC, Turbo, GDI, dVVT, ICE
A	Subsystem Compilation of Direct Injection Cost Impact	€ 132	€ 138	€ 142	€ 147	---	€ 246
B	Subsystem Compilation of Turbocharging Cost Impact	€ 232	€ 237	€ 255	€ 279	---	€ 522
C	Subsystem Compilation of Downsizing Cost Impact	(€ 134)	(€ 15)	(€ 30)	(€ 345)	---	(€ 119)
	Net Incremental Direct Manufacturing Cost	€ 230	€ 360	€ 367	€ 80	---	€ 648

Selected results from Phase I

Gasoline direct injection, turbocharging & downsizing

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	European Market Segment	European Vehicle Segment Example	Calculated Incremental *Direct* Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (*Direct + Indirect Costs*) with Applicable Learning Applied: 2012	2016	2020	2025
Engine			Downsized, Turbocharged, Gasoline Direct Injection Internal Combustion Engines								
	1	0100	1.4L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	1.0L, I3, 4V, DOHC, Turbo, GDI, dVVT, ICE	Subcompact	VW Polo	€ 230	€ 371	€ 327	€ 267	€ 237
	2	0101	1.6L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	1.2L, I4, 4V, DOHC, Turbo, GDI, dVVT, ICE	Compact/ Small	VW Golf	€ 360	€ 505	€ 460	€ 398	€ 367
	3	0102	2.4L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	1.6L, I4, 4V, DOHC, Turbo, GDI, dVVT, ICE	Midsize	VW Passat	€ 367	€ 520	€ 473	€ 407	€ 375
	4	0103	3.0L, V6, 4V, DOHC, NA, PFI, dVVT, ICE	2.0L, I4, 4V, DOHC, Turbo, GDI, dVVT, ICE	Midsize/Large	VW Sharan	€ 80	€ 245	€ 194	€ 123	€ 89
	5	0106	5.4L, V8, 3V, SOHC, NA, PFI, sVVT, ICE	3.5L V6, 4V, DOHC, Turbo, GDI, dVVT, ICE	Large SUV	VW Touareg	€ 648	€ 946	€ 854	€ 726	€ 664
			Variable Valve Timing and Lift, Fiat Multiair System								
	6	0200	1.4L, I4, 4V, DOHC, NA, PFI, dVVT, ICE	1.4L, I4, 4V-MultiAir, SOHC, NA, PFI, ICE	Subcompact	VW Polo	€ 107	€ 159	€ 145	€ 126	€ 117

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Selected results from Phase I

PowerSplit hybrid

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	European Market Segment	European Vehicle Segment Example	Calculated Incremental *Direct* Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (*Direct + Indirect Costs*) with Applicable Learning Applied			
								2012	2016	2020	2025
Power-Split HEV	1	0500	Subcompact car typically powered by an inline 4 cylinder engine, naturally aspirated, port fuel injection, 5-speed manual transmission (MT).	Power-split HEV System Power: 64.6kW ICE Power: 52.7kW (I4 -> I3) Traction Motor: 43.2kW Generator: 30.3kW Li-Ion Battery: 140V, 0.743kWh	Subcompact	VW Polo	€ 1,809	€ 4,555	€ 3,506	€ 2,624	€ 2,158
	2	0501	Compact or small car typically powered by an inline 4 cylinder engine, naturally aspirated, port fuel injection, 6-speed manual transmission or 7-speed dual clutch transmission (DCT).	Power-split HEV System Power: 77.8kW ICE Power: 63.6kW (I4 - DS I4) Traction Motor: 52.0kW Generator: 36.5kW Li-Ion Battery: 162V, 0.857kWh	Compact/ Small	VW Golf	€ 2,012	€ 5,034	€ 3,883	€ 2,908	€ 2,397
	3	0502	A midsize passenger car typically powered by a 4 cylinder turbocharged, direct fuel injection, 6-speed MT and AT or 7-speed DCT, Start/Stop system.	Power-split HEV System Power: 101.2kW ICE Power: 82.6 kW (I4 -> DS I4) Traction Motor: 67.7kW Generator: 47.5kW Li-Ion Battery: 188V, 0.994kWh	Midsize	VW Passat	€ 2,230	€ 5,632	€ 4,331	€ 3,240	€ 2,663
	4	0503	A midsize or large passenger car typically powered by 4 and 6 cylinder turbocharged, direct fuel injection, 6-speed MT or ≥ 6 speed AT.	Power-split HEV System Power: 151.1 kW ICE Power: 123.4 kW (V6 -> I4) Traction Motor: 101kW Generator: 70.9kW Li-Ion Battery: 211V, 1.118kWh	Midsize/Large	VW Sharan	€ 2,215	€ 5,802	€ 4,410	€ 3,282	€ 2,671
			A small or mid-sized sports-utility or cross-over vehicle, or a small-	Power-split HEV System Power: 114.6 kW							

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Selected results from Phase I

P2 hybrid

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	European Market Segment	European Vehicle Segment Example	Calculated Incremental *Direct* Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (*Direct + Indirect Costs*) with Applicable Learning Applied			
								2012	2016	2020	2025
P2 HEV	1	0700	Subcompact car typically powered by an inline 4 cylinder engine, naturally aspirated, port fuel injection, 5-speed manual transmission (MT).	P2 HEV System Power: 64.6 kW ICE Power: 51.7 kW (I4 -> I3) Traction Motor: 12.9 kW Li-Ion Battery: 140V, 0.743kWh	Subcompact	VW Polo	€ 1,704	€ 4,391	€ 3,355	€ 2,502	€ 2,045
	2	0701	Compact or small car typically powered by an inline 4 cylinder engine, naturally aspirated, port fuel injection, 6-speed manual transmission or 7-speed dual clutch transmission (DCT).	P2 HEV System Power: 77.8 kW ICE Power: 62.3 kW (I4 -> DS I4) Traction Motor: 16 kW Li-Ion Battery: 162V, 0.857kWh	Compact/ Small	VW Golf	€ 1,915	€ 4,914	€ 3,760	€ 2,806	€ 2,297
	3	0702	A midsize passenger car typically powered by a 4 cylinder turbocharged, direct fuel injection, 6-speed MT and AT or 7-speed DCT, Start/Stop system.	P2 HEV System Power: 101.2kW ICE Power: 80.9 kW (I4 -> DS I4) Traction Motor: 20.23 kW Li-Ion Battery: 188V, 0.994kWh	Midsize	VW Passat	€ 2,080	€ 5,398	€ 4,115	€ 3,067	€ 2,502

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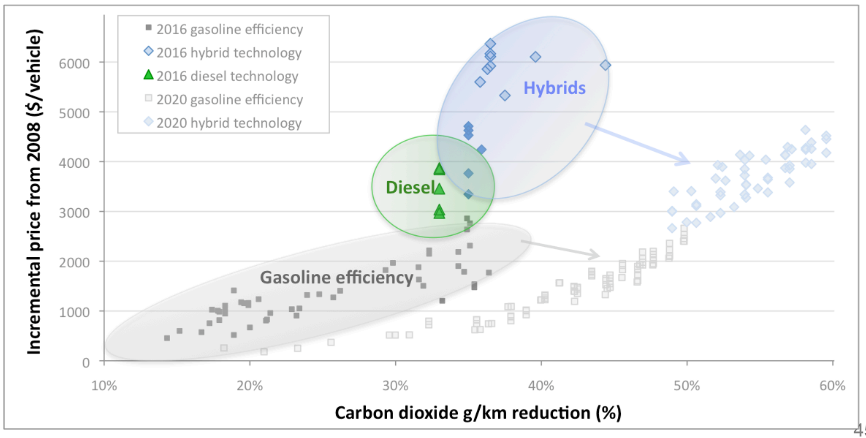
Technology cost dropping

Technology availability increases - and its costs decrease - over time

- Incremental vehicle costs and percent improvements versus MY2008 baseline
- Data from EPA/NHTSA 2012-2016 rulemaking and EPA/NHTSA/CARB *TAR* for 2020



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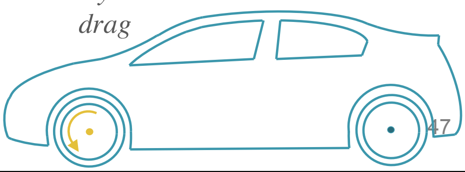
Emerging Mass Reduction Trends in Light Duty Vehicles

Background: Mass Reduction

- Primary drivers
  - Consumer demand for acceleration performance, fuel savings, safety
  - Automaker compliance with efficiency/climate regulations
  - More cost-effective technology step before electric-drive
- Technology enablers
  - Advances in materials, manufacturing techniques (steel, aluminum, plastics)
  - Improvements in computer aided engineering (CAE) modeling optimization

$$F_{Road} = \mathbf{m} \cdot a + C_{RR} \cdot \mathbf{m} \cdot g + \frac{1}{2} \rho \cdot C_D \cdot A_f \cdot v^2$$

Inertial acceleration — *Rolling resistance* — *Aerodynamic drag*



Individual Technologies

Area		Technology for CO_2 reduction	Technology share, MY2010	Potential CO_2 reduction
Powertrain	Engine	Low friction lubrication	-	0.5%
		Engine friction reduction	-	2-4%
		Variable valve timing/lift	86%	4-6%
		Cylinder deactivation	7%	5-6%
		Turbocharging	3%	2-5%
		Turbo, gasoline direct injection	9%	8-15%
		Cooled EGR, turbo, GDI	-	20-25%
		Compression ignition diesel	0.5%	15-25%
		Digital valve actuation	-	5-10%
	Transmission	Early torque converter lock-up	-	0.5%
		Optimized shifting	-	2-6%
		6+ speed	40%	2-8%
		Continuously variable	10%	8-11%
		Dual-clutch, automated manual	-	9-13%
Vehicle	Aerodynamics		-	2-5%
	Tire rolling resistance		-	2-4%
	Accessories (steering, air cond., alternator)		-	1-4%
	Lower refrigerant emissions (low-leak, low-GWP)		-	2-10%
	Mass-reduction	**Advanced material component**	**-**	**1-5%**
		Integrated vehicle design	**-**	**5-10%**
	Hybrid systems	Stop-start mild hybrid	<1%	6-8%
		Full hybrid electric system	3%	30-35%
	Plug-in electric		-	50-100%

Indirect benefits: powertrain downsizing and cost reduction

Mass-Reduction: Automaker Plans

- Mass reduction is expected from every automaker
  - But some will do much more (and others will do less)
- Below are public statements, anecdotes, quotes…

Company	Quote, statement, or commitment
Ford	• From 2011 to 2020: "Full implementation of known technology… weight reduction of 250-750 lbs" • "The use of advanced materials … offers automakers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements • "Reducing weight will benefit the efficiency of every Ford vehicle. However, it's particularly critical to improving the range of plug-in hybrid and battery electric vehicles
Toyota	• 10-30% weight reduction for small to mid-size vehicles
Volkswagen	• "Automotive light weight solutions are necessary more than ever to reduce CO_2 emissions " • "Multi-Material Concepts promise cost effective light weight solutions "
GM	• "One trend is clear - vehicles will consist of a more balanced use of many materials in the future, incorporating more lightweight materials such as nanocomposites and aluminum and magnesium." • Aims to shed 500 lb from trucks by 2016, as much as 1000 lbs in early 2020s
Mazda	• Reduce each model by 220 lb by 2015; another 220 lb by 2020
Nissan	• Average 15% weight reduction by 2015 • "We are… expanding the use of aluminum and other lightweight materials, and reducing vehicle weight by rationalizing vehicle body structure
Renault, Peugeot	• Target of 440-lb reduction (approx. 15%) by 2018

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Technical Literature on Mass-Reduction

- Technical assessment projects on mass-reduction opportunities:
  - National US energy laboratories, OEM suppliers, OEMs with universities, etc
- Studies demonstrate diverse options for mass-reduction
  - Part-specific design or material change (e.g., hood, B-pillar)
  - Material specific alternatives (e.g., aluminum-only, HSS-only)
  - System changes (e.g., entire body-in-white)
  - Full vehicle redesign and material substitution (e.g., body plus secondary effects)
- Studies differing value for regulatory assessment in terms of technical rigor, data/method transparency, comprehensiveness, crashworthiness validation

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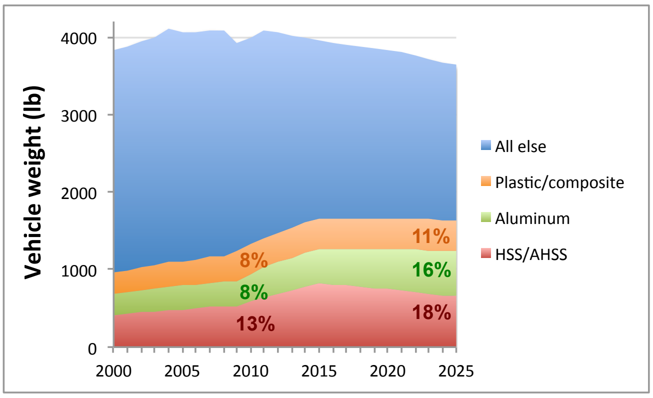
Mass Reduction: Material Trends

- Many approaches for mass reduction
  - Material substitution, parts integration, holistic optimization
  - Many new models will use far more AHSS, aluminum, composites for >10% reduction



For further information, see US EPA and NHTSA, 2011, Ducker Worldwide, 2011; Scheps, 2011

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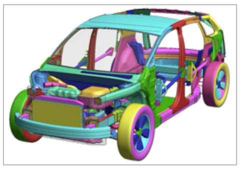
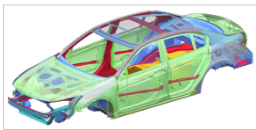
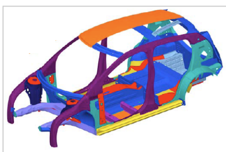
Major New Mass-Reduction Work

- Lotus Engineering (CARB)
  - Continuation of 2010 study (-20%, -33% mass Toyota Venza)
  - Includes crashworthiness safety (NHTSA FMVSS) validation
  - Demonstrates cost-effective 30% mass reduction at < $0/vehicle
- FEV (US EPA)
  - Technical assessment of -18% mass Toyota Venza at < $0/vehicle
  - Includes crashworthiness safety (NHTSA FMVSS) validation
- EDAG / Electricore (NHTSA)
  - Technical assessment of -22% mass Honda Accord at $319/vehicle
  - Includes crashworthiness safety (NHTSA FMVSS) validation
- EDAG WorldAutoSteel "Future Steel Vehicle"
  - 12-18% mass reduction, no additional cost, with only using steels







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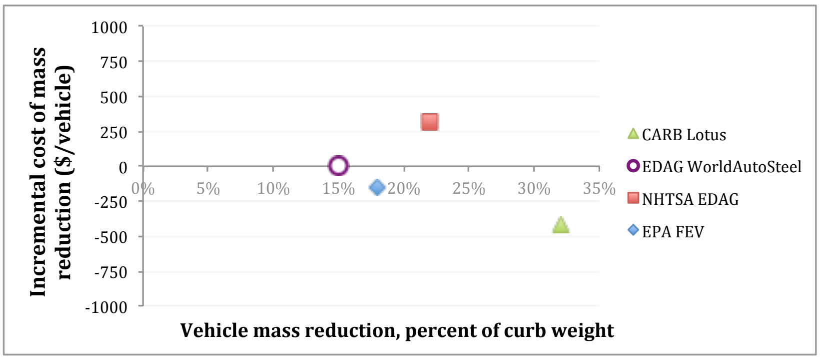
Mass-Reduction: Cost-Effective

- Results for four major studies
  - Include crashworthiness safety validation for front, side, roof, etc testing
  - Demonstrates highly cost-effective 15-32% vehicle mass reduction
  - Based on high volume long-term 2020+ technology deployment



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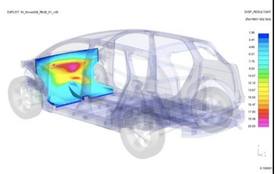
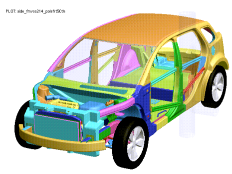
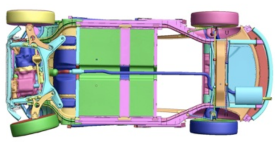
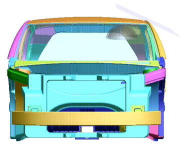
Mass-Reduction: Safety Validation

- Federal Motor Vehicle Safety Standard (FMVSS) and Insurance Institute for Highway Safety (IIHS) requirements
- Low-mass vehicle designs by Lotus, EDAG, and FEV tested specifically to meet US safety requirements:
  - Front impact (FMVSS 208)
  - Seatbelt loading (FMVSS 210)
  - Child tether loadings (FMVSS 213)
  - Side impacts and door beam intrusion (FMVSS 214)
  - Roof crush (FMVSS 216)
  - Rear impact (FMVSS 301)
  - Front and rear end chassis frame load buckling stability
  - Low-speed bumper impact loads









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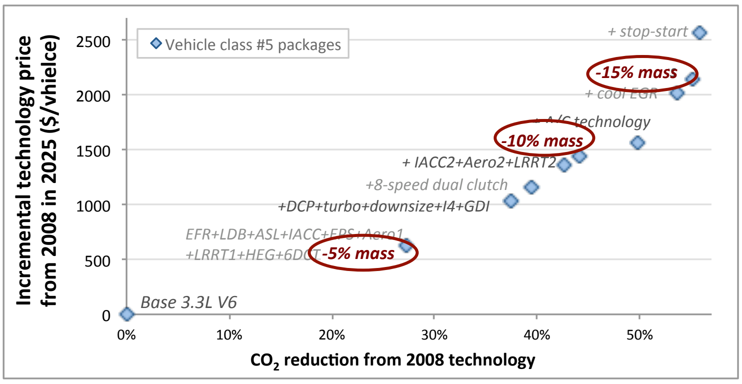
Technology Cost-vs-GHG Walk-Up

- Representative mid-size vehicle technology-cost progression
  - Increasing cost with increasing technology adoption
  - Lightweighting is one technology area – but a very important one



Notes: Vehicle class #5 (out of 19 classes) is shown; Emission levels based on combined 55% city / 45% highway US test procedure; See CARB LEVIII GHG ISOR and US EPA/NHTSA 2017-2025 rulemaking for technology details

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Lightweight Materials Conclusions

- Strong technical basis for mass-reduction as a prominent efficiency technology in the 2015-2025 timeframe
  - All automakers intend to utilize mass-reduction toward regulatory compliance
  - Technical assessments: Vehicles can reduce mass by 20% or more with near-zero net cost over the long-term at high volume
- Mass reduction includes a diverse set of technical approaches that can be utilized toward fuel economy and CO_2-reduction goals
  - Many different advanced materials, designs are being pursued across OEMs
  - Mass reduction is a core efficiency technology now and becomes an even more critical technology in the future

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Resources

- Federal United States rulemaking:
  - US Environmental Protection Agency (EPA) and National Highway Traffic Safety Admin. (NHTSA)
  - Website: *http://www.epa.gov/otaq/climate/regulations.htm*
- California Air Resources Board (CARB)
  - Website: *http://www.arb.ca.gov/regact/2012/leviiighg2012/leviiighg2012.htm*
- Other reports
  - Lutsey, N., 2010. Review of Technical Literature and Trends Related to Automobile Mass-Reduction Technology. *http://pubs.its.ucdavis.edu/publication_detail.php?id=1390*.
  - Lotus Engineering, 2012. Evaluating the Structure and Crashworthiness of a 2020 Model-Year, Mass-Reduced Crossover Vehicle Using FEA Modeling. Prepared for California Air Resources Board. *http://www.arb.ca.gov/msprog/levprog/leviii/leviii.htm*
  - Lotus Engineering: Peterson, G., 2011. Development of a Multi-Material Low Mass Body in White Structure and Potential Applications Ohio State University. September.
  - EDAG/NHTSA: Singh, H. 2012. Light-Weighting Options for Vehicle Structures for Model Year 2020. SAE International *http://www.sae.org/events/gim/presentations/2012/singh.pptx*
  - Singh, Harry, 2012. *Mass Reduction for Light-Duty Vehicles for Model Years 2017-2025*. National Highway Traffic Safety Administration. Report No. DOT HS 811 666. ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/811666.pdf
  - U.S. Environmental Protection Agency, 2012. Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle. Prepared by FEV. EPA-420-R-12-026. http://www.epa.gov/oms/climate/documents/420r12026.pdf
  - WorldAutoSteel, 2011. *Future Steel Vehicle: Phase 2 Report*. http://c315221.r21.cf1.rackcdn.com/FSV-EDAG_Phase2_Engineering_Report.pdf
  - Ducker Worldwide 2011 studies on aluminum and advanced high strength steel (AHSS)
  - Aluminum Association: Scheps, 2012. Growth & Development Trends of Automotive Aluminum. SAE International. *http://www.autoaluminum.org/downloads/ATG.SAEWorldCongress2012.pdf*

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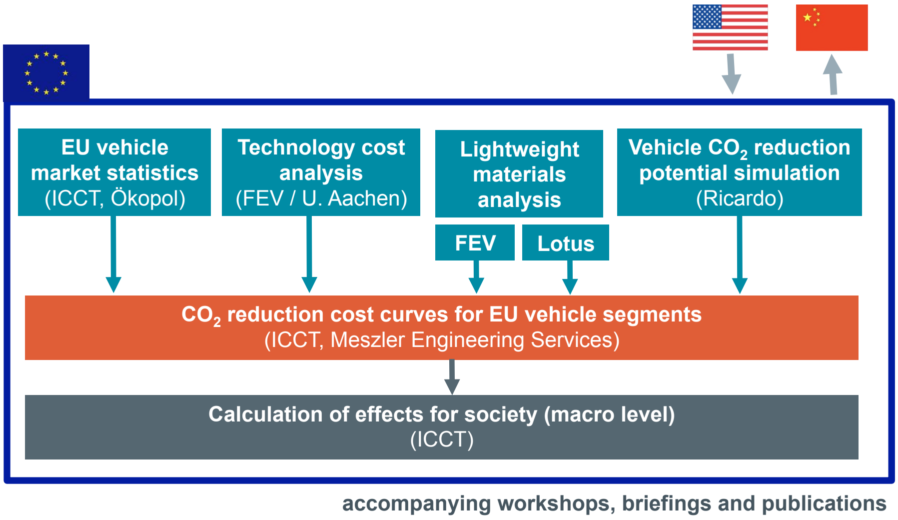
Development of Technology Cost Curves

The ICCT approach for EU cost curves



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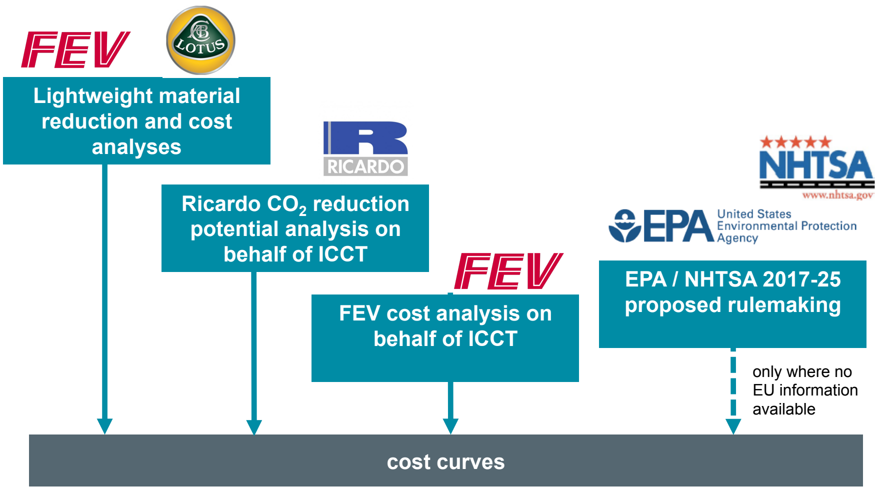
Data sources



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Arriving at the starting point

- Ricardo baseline vehicles include start-stop and improved alternator
  - Factoring out alternator efficiency improvement (55% vs. 70%)
    → ≈ -3% effect
  - Factoring out effect of start-stop system, taking into account idling times in European driving cycle → ≈ -10% effect
- Ricardo baseline vehicles include automatic transmissions in some cases
  - For all EU segments: manual transmission as starting point

Example baseline vehicles

--- revised C class vehicle ---

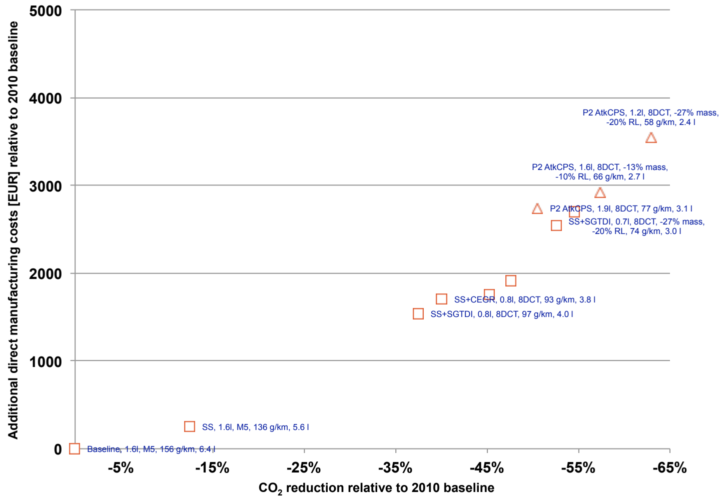
C-segment
(32% market, 38% diesel)

	Gasoline		Diesel	
	Ricardo	**EU-27**	**Ricardo**	**EU-27**
Vehicle model	Ford Focus	n/a	Ford Focus	n/a
Engine size	4 cyl., 1.6 l	4 cyl., 1.6 l	4 cyl., 1.6 l	4 cyl., 1.7 l
Engine power	88 kW	86 kW	75 kW	83 kW
Engine type	PFI	PFI (MS DI≈19%)	n/a	n/a
Vehicle weight	1,257 kg	1,270 kg	1,413 kg	1,360 kg
Transmission	6-MT	MT (MS≈91%)*	6-AT	MT (MS≈91%)*
Acceleration 0-100 km/h	---	11.3 s	10.0 s	11.6 s
CO_2 in NEDC	139 g/km	156 g/km	124 g/km	131 g/km
Remarks	Start-Stop/Reg. Euro 5 eq.	no Start-Stop Euro 4 (MS≈60%)	Start-Stop/Reg. Euro 5	no Start-Stop Euro 4 (MS≈60%)

Ricardo simulations baseline vehicle vs. EU-27 average new vehicle in 2010
Abbreviations: PFI (port fuel injection), DFI (direct fuel injection), MS (market share), AT (automatic transmission), MT (manual transmission), vehicle weight is given in mass in running order (includes 68 kg driver and 7 kg of luggage)
** MS 5-MT: 49%, 6-MT: 42%*

Plotting technology packages

- **C-segment gasoline**



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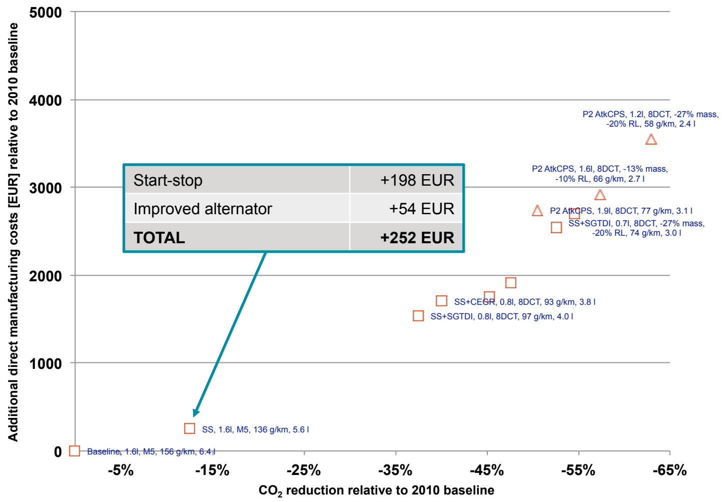
Plotting technology packages

- **C-segment gasoline**



Start-stop	+198 EUR
Improved alternator	+54 EUR
TOTAL	**+252 EUR**

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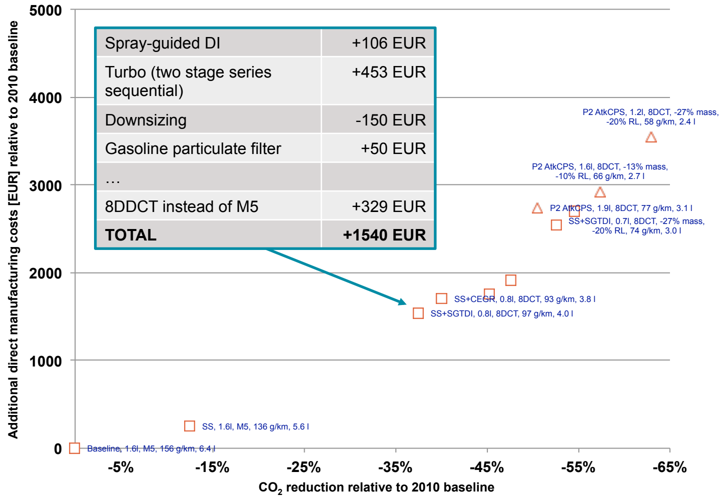
Plotting technology packages

- **C-segment gasoline**



Spray-guided DI	+106 EUR
Turbo (two stage series sequential)	+453 EUR
Downsizing	-150 EUR
Gasoline particulate filter	+50 EUR
…	
8DDCT instead of M5	+329 EUR
TOTAL	**+1540 EUR**

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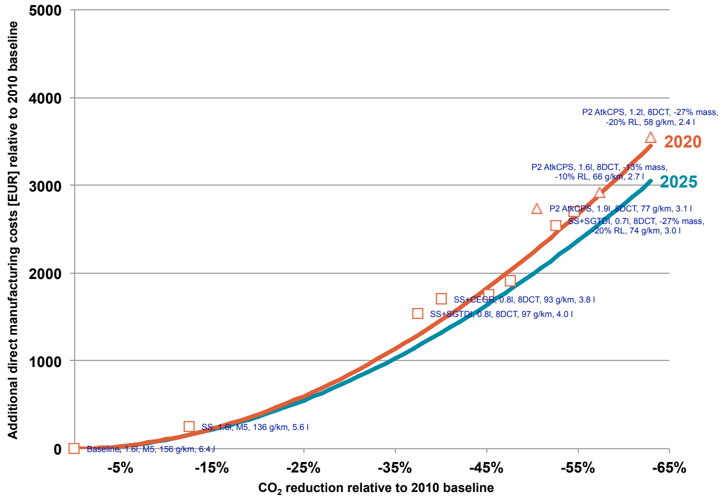
Fitting the cost curves

- **C-segment gasoline**



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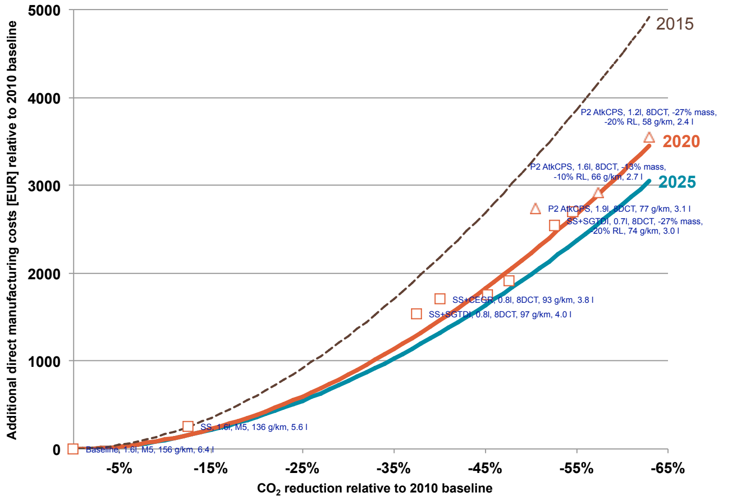
2015 curve for illustrating purposes

- **C-segment gasoline**



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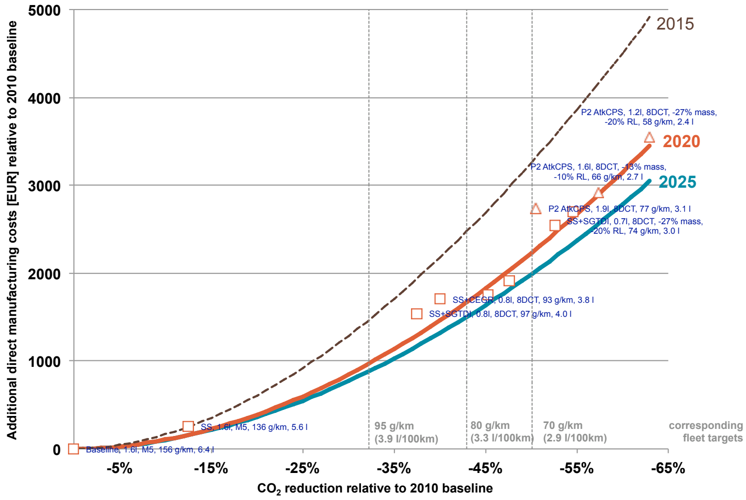
Preliminary results: C-segment cost curve

- **C-segment gasoline**



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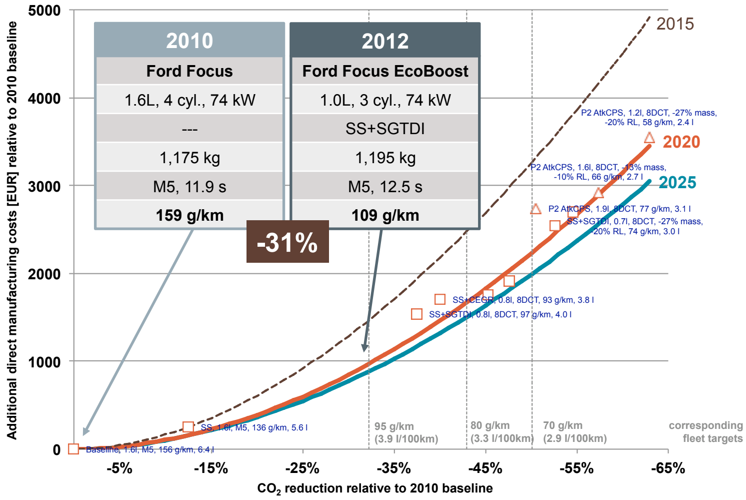
Comparison with vehicles on the market

- **C-segment gasoline**



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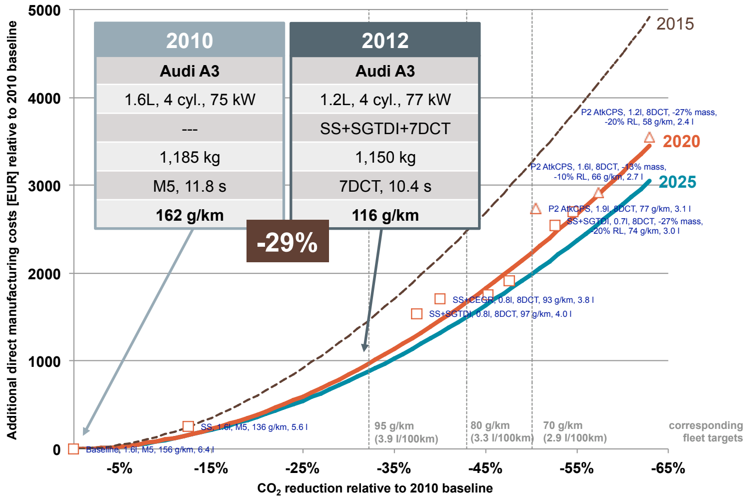
Data source for technical data: Automobil Revue

Comparison with vehicles on the market

- **C-segment gasoline**



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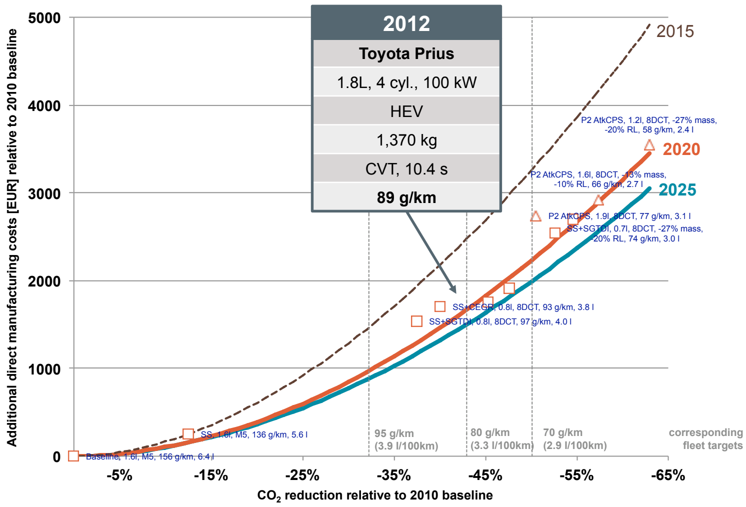
Data source for technical data: Automobil Revue

Comparison with vehicles on the market

- **C-segment gasoline**



Data source for technical data: Automobil Revue

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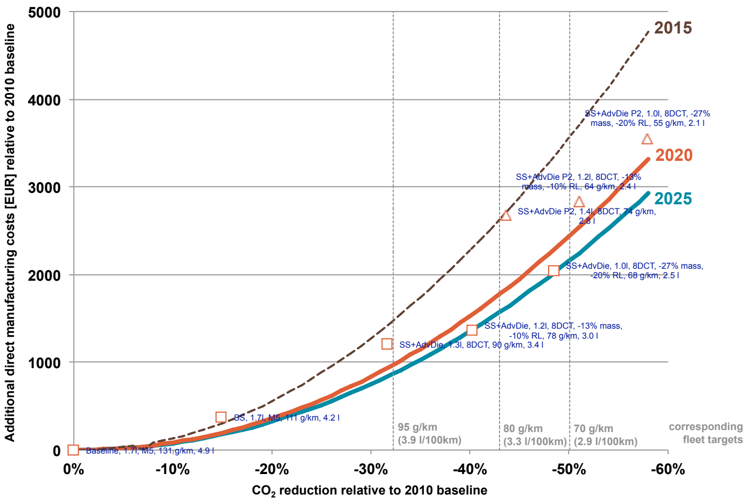
Preliminary results: C-segment cost curve

- **C-segment diesel**



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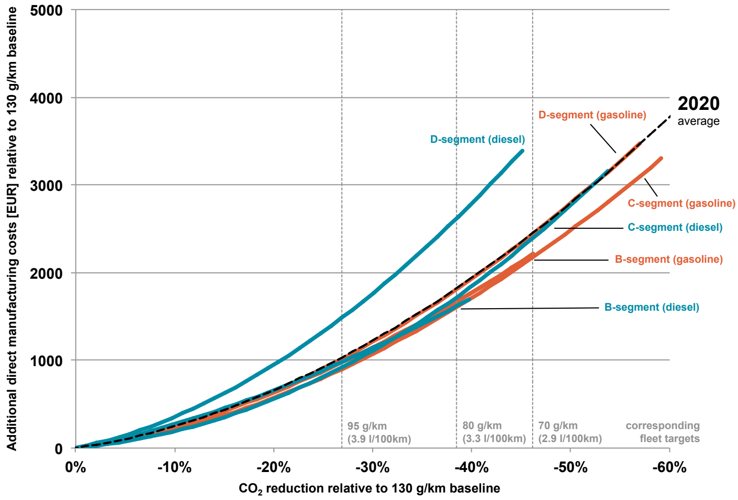
Preliminary results: All vehicle segments

- **From a 2020 perspective**



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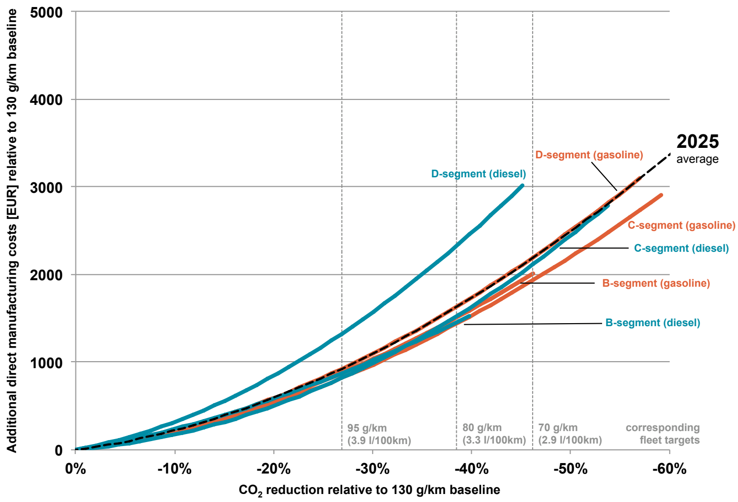
Preliminary results: All vehicle segments

- **From a 2025 perspective**



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Publications

- Ricardo: "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe", Dec. 2011.
  - Computer simulations of 6 baseline vehicles, gasoline direct injection with turbocharging, boosted EGR, Atkinson cycle (for hybrids), both parallel (P2) and powersplit hybrid systems, 6/8 speed advanced automatic transmissions, and dual-clutch automated manual transmissions (DCT).
  - http://www.epa.gov/otaq/climate/documents/420r11020.pdf
- Ricardo: "Analysis of GHG Emission Reduction Potential of Light Duty Vehicle Technologies in the European Union for 2020–2025", May 2012
  - Added NEDC and JC08 test cycles, added C class vehicle (Golf/Focus) and small commercial van (Ford Transit), updated diesel engine map, compared manual transmission to DCT efficiency
  - http://www.theicct.org/ghg-emission-reduction-potential-ldv-technologies-eu-2020-2025
- FEV: "Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1)", May 2012.
  - Created and used European materials, labor, overhead, and mark-up to translate US cost estimates to Europe for: Downsized turbocharged GDI; 6- and 8- speed auto transmission; 6 speed wet DCT; Variable valve timing (VVLT); Powersplit hybrid; P2 hybrid; Electrical air compressor
  - http://www.theicct.org/light-duty-vehicle-technology-cost-analysis-european-vehicle-market
- FEV: "Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market, Additional Case Studies (Phase 2)", Sept. 2012.
  - Diesel engine downsizing; 2500 bar diesel injection systems; Diesel VVLT; Two stage Diesel EGR; Cooled and uncooled low-pressure gasoline EGR; 6-spd dry DCT; start-stop system evaluation
  - http://www.theicct.org/light-duty-vehicle-technology-cost-analysis-european-vehicle-market
- ICCT: "Initial processing of Ricardo vehicle simulation modeling CO2 data", July 2012.
  - http://www.theicct.org/initial-processing-ricardo-vehicle-simulation-modeling-co2-data
- ICCT: "Summary of the EU cost curve development methodology", November 2012.
  - http://www.theicct.org/eu-cost-curve-development-methodology

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Next Steps

- Updated Ricardo simulation modeling for ICCT
  - New simulations of baseline vehicles without stop/start and improved alternators and with manual transmissions
  - Add simulations over new worldwide harmonized test procedure (WLTP) cycle
- Additional cost work by FEV for ICCT:
  - Improved method of assessing indirect costs and updated indirect cost multipliers (ICM)
  - Lightweighting cost analysis for EU context
  - Sensitivity of costs to manufacturing in Eastern European instead of Germany
- Incorporate new lightweight material data from FEV and Lotus into cost curves

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