EU vehicle technology study: Background and results of Phase I

ICCT International Workshop on greenhouse gas reduction potential and costs of light-duty vehicle technologies

John German

April 27, 2012

Brussels

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Agenda

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Introduction

Detailed technical data for EU rulemaking

- Setting (cost-)effective CO_2 standards **requires knowledge about technical reduction potential and associated costs**
- **Comprehensive, transparent data is needed** for fact-based discussion
- **Requires sufficient budget** to carry out vehicle simulations and detailed cost studies
- Current EU budget for cars & vans studies ≈ 1 million EUR
  Very limited availability of staff resources
- In the past relied much on industry surveys
  → limited transparency and tendency to overstate costs for required technologies

Basic idea of ICCT project

- Vehicle market is a global market with similar technologies worldwide
- Make use of existing technology studies in other markets
- US studies for 2017-25 LDV regulation are currently best-practice example

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Introduction

The US LDV greenhouse gas standards

- **US 2012-16 light-duty vehicle GHG standard**
  - Footprint-based
  - Fleet target (cars + light trucks) for 2016:
    250 g/mile = 155 g/km ≈ 170 g/km (in NEDC)
  - Status: adopted, phase-in began in 2012
- **US 2017-25 light-duty vehicle GHG standard**
  - Footprint-based
  - Fleet target (cars + light trucks) for 2025:
    165 g/mile = 103 g/km ≈ 110 g/km (in NEDC) (≈ 98 g/km for cars only)
  - Status: Notice of Intent, final proposal and adoption expected for 2012

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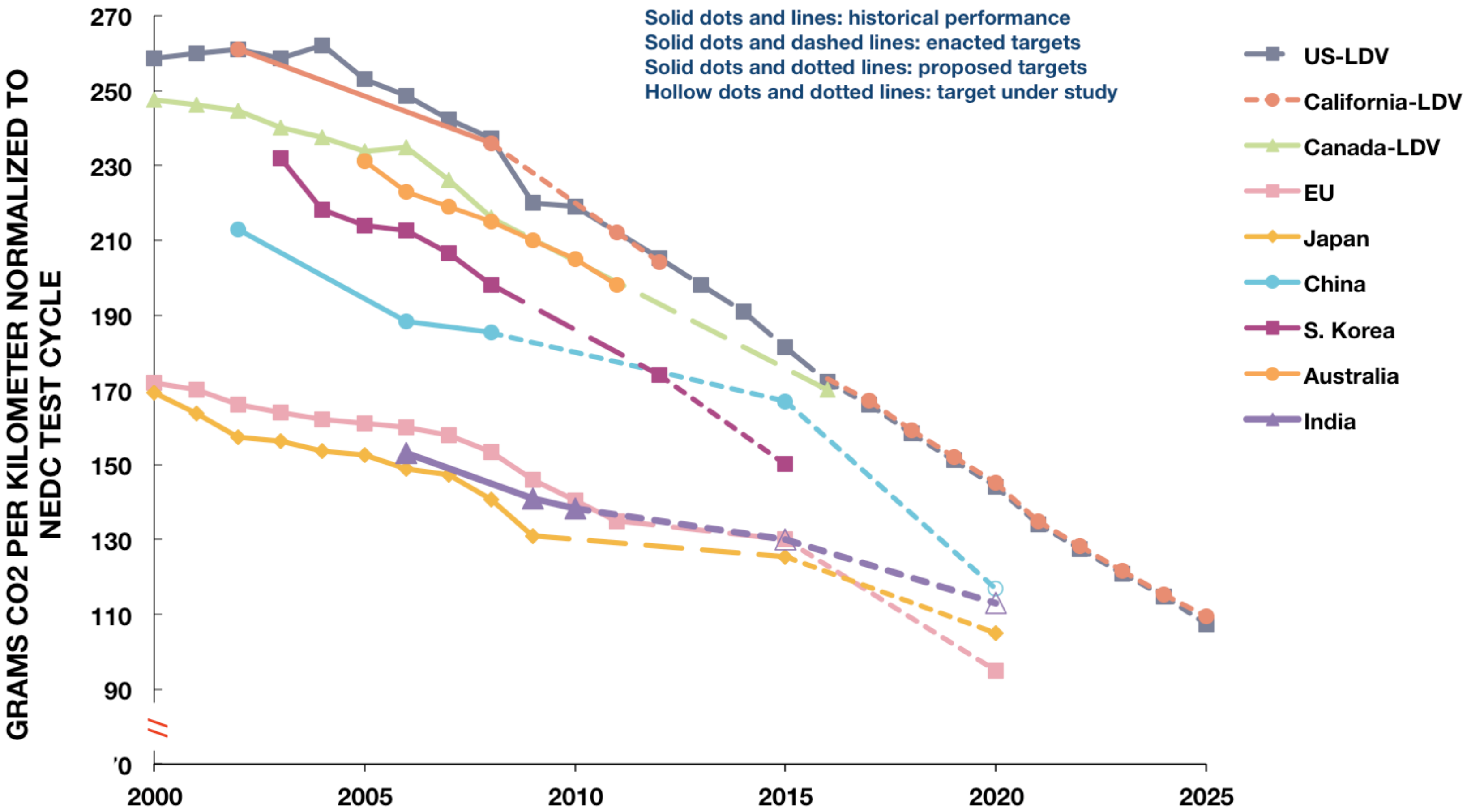
Global comparison of LDV CO_2 standards



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.

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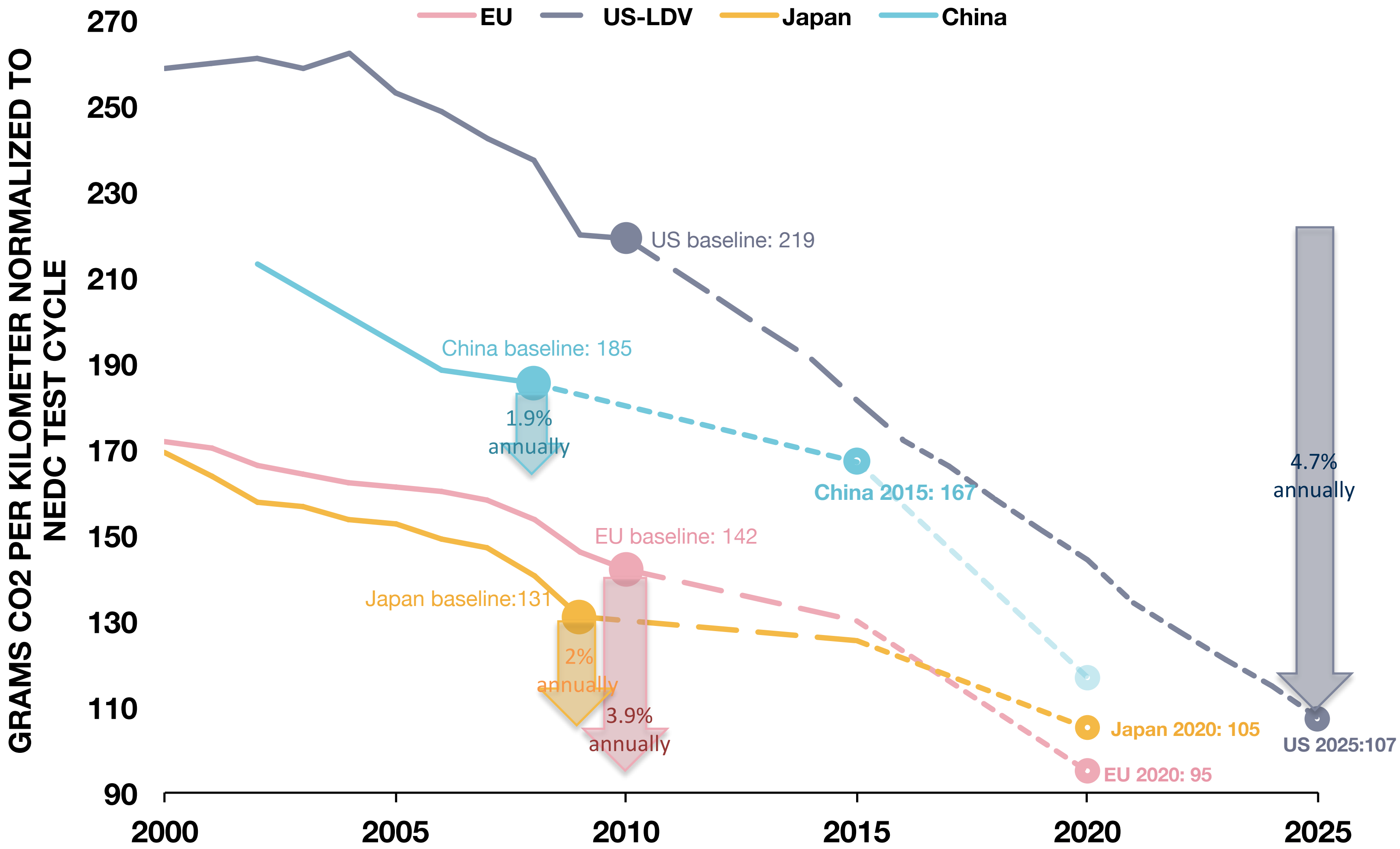
Introduction
Global comparison of LDV CO_2 standards



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light-commercial vehicles.
[3] Annual rate is calculated using baseline actual performance and target values.

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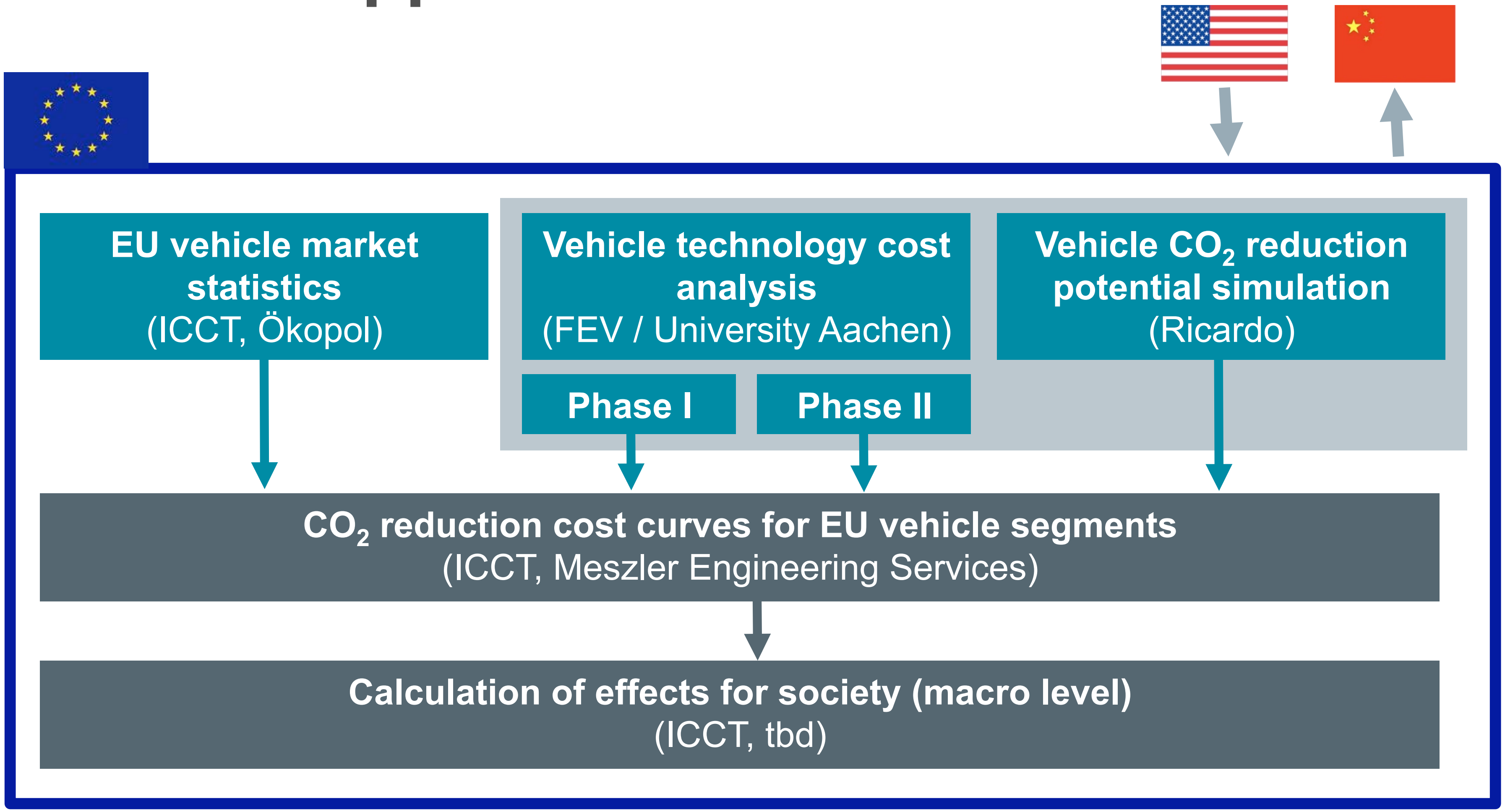
Introduction
Technical studies for US rulemakings

- **Underlying technical studies:**
  - Vehicle simulation work (Ricardo)
  - Teardown engineering cost assessment (FEV)
  - Weight reduction assessment (Lotus Engineering, FEV)
  - Battery modeling for electric vehicles (US energy laboratory)
  - Confidential business information from manufacturers
  - …
- **3 agencies (EPA, NTHSA, CARB)**
  Total budget for technical studies ≈ 15 million $
  Total technical staff working on LDV standards ≈ 50
- **Links to detailed reports on methodology and results:**
  http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies

GHG reduction potential and cost analyses
The ICCT approach



accompanying workshops, briefings and publications

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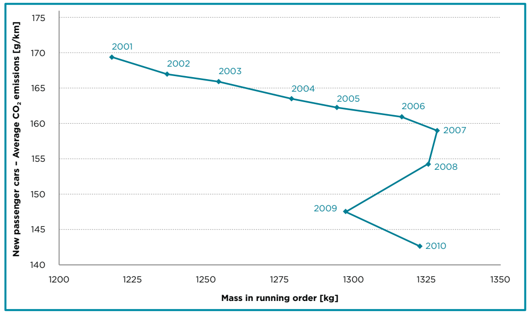
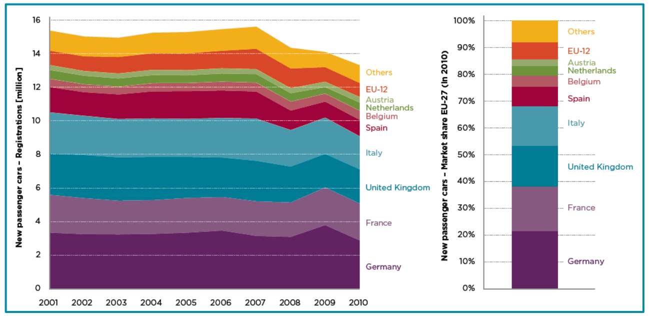
EU vehicle market statistics
ICCT Pocketbook





- First edition published in Jan 2012
- **2001-2010 EU-27 passenger cars**
  2009-2010 EU-27 vans
- Provides data beyond official CO_2 monitoring data
- **Data sources:** Polk, KBA, VCA, Automobil Revue, manufacturers, suppliers
- **Update planned for summer 2012**

➔ http://www.theicct.org/european-vehicle-market-statistics

EU vehicle market statistics
ICCT Pocketbook

numerous technical parameters

Engine power [KW]	Engine size [ccm]	Number of cylinders	Compression rate (gasoline)	Compression rate (diesel)	Number of gears	Performance 0-100 km/h (gasoli	Performance 0-100 km/h (diesel)	Mass in running order [kg]	Gross weight [kg]
81	1619	4.0	10.5	17.7	5.3	12.6	11.6	1347	179C
87	1667	4.0	10.4	17.5	5.4	12.5	10.4	1399	1822

	Total s	Total s
EU-27	14,091,605	100'
Germany	3,789,564	27%
France	2,242,894	16%
Italy	2,165,081	15%
United Kingdom	1,988,957	14%
Spain	953,116	7%
EU-12	870,021	6%
Belgium	474,927	3%
Netherlands	387,279	3%
Austria	319,228	2%

by member state

VW	1,602,712	11%
Ford	1,270,907	9%
Renault	1,065,300	8%
Fiat	1,003,052	7%
Peugeot	972,341	7%
Citroën	855,937	6%
Opel	808,953	6%

by brand

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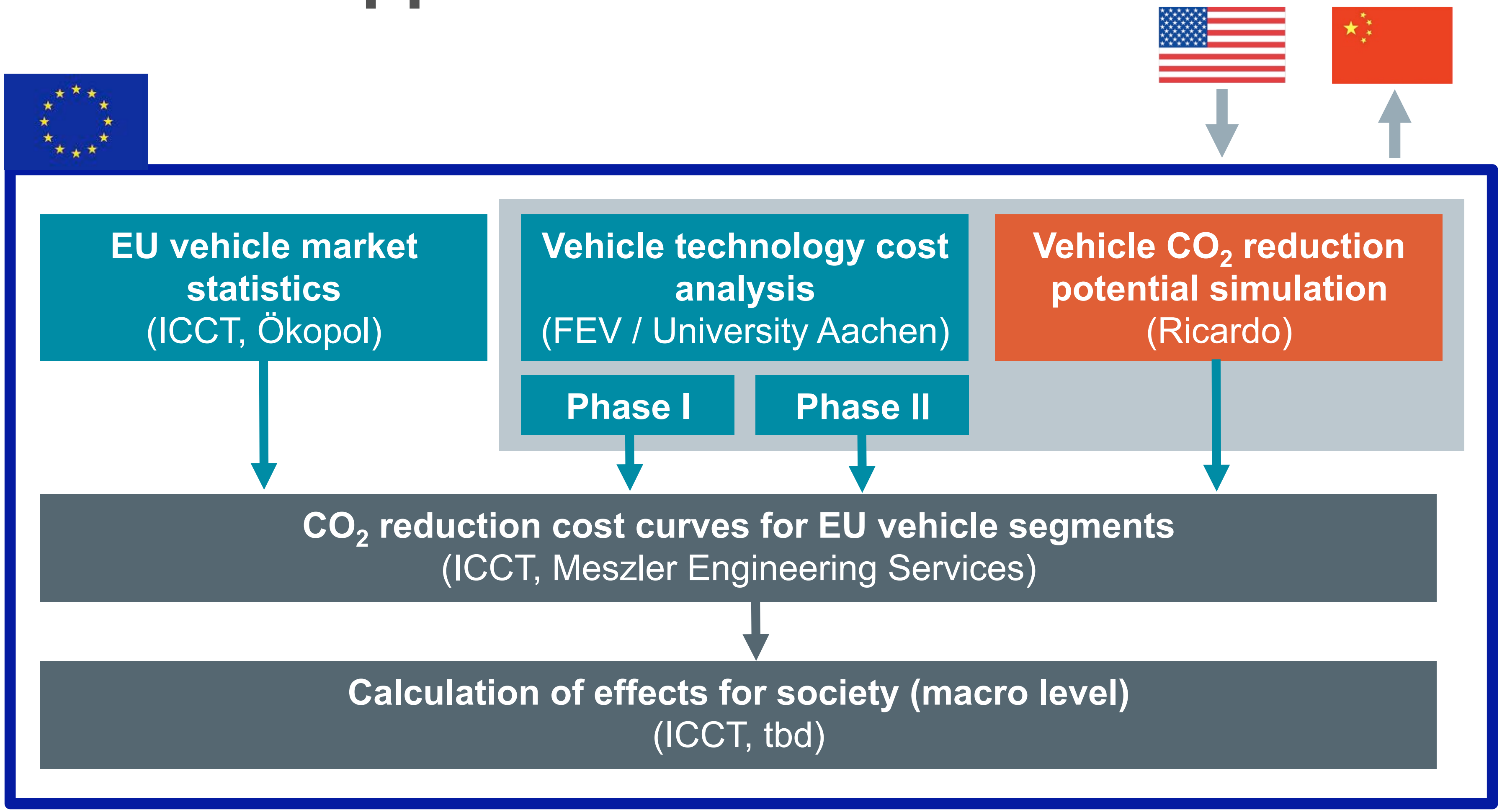
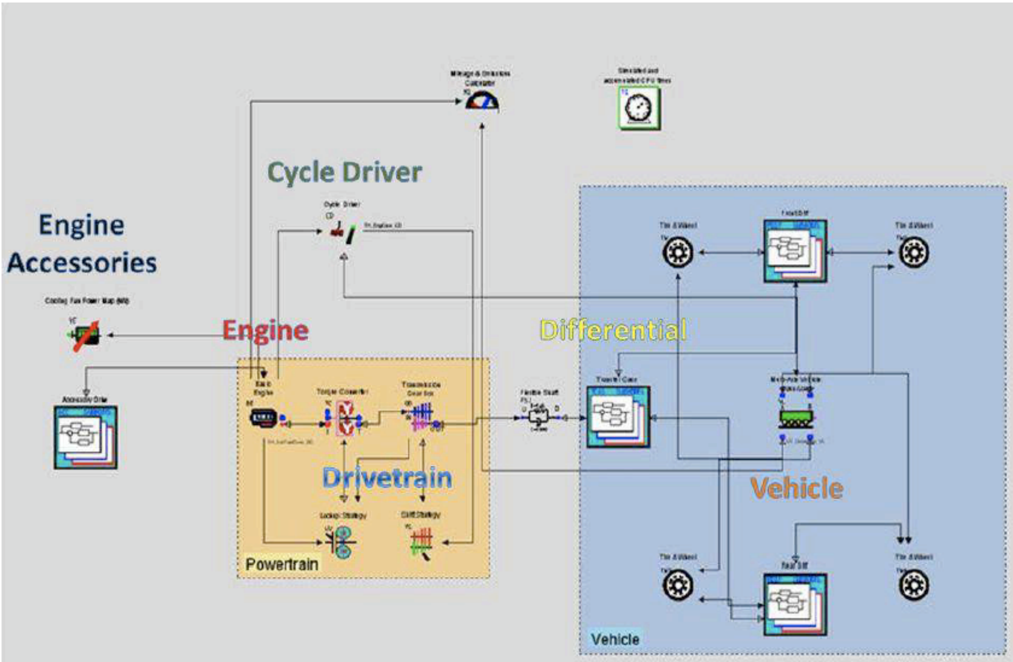
GHG reduction potential and cost analyses
The ICCT approach



accompanying workshops, briefings and publications

Ricardo vehicle simulations
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



Ricardo vehicle simulations
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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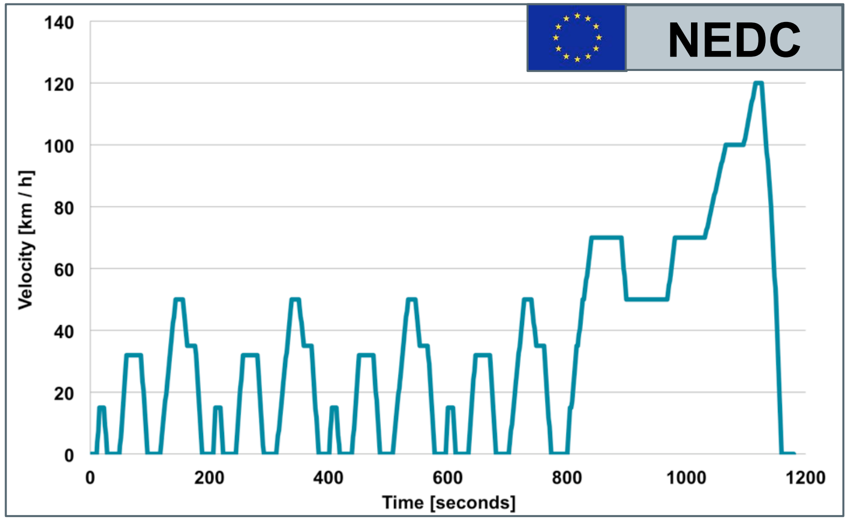
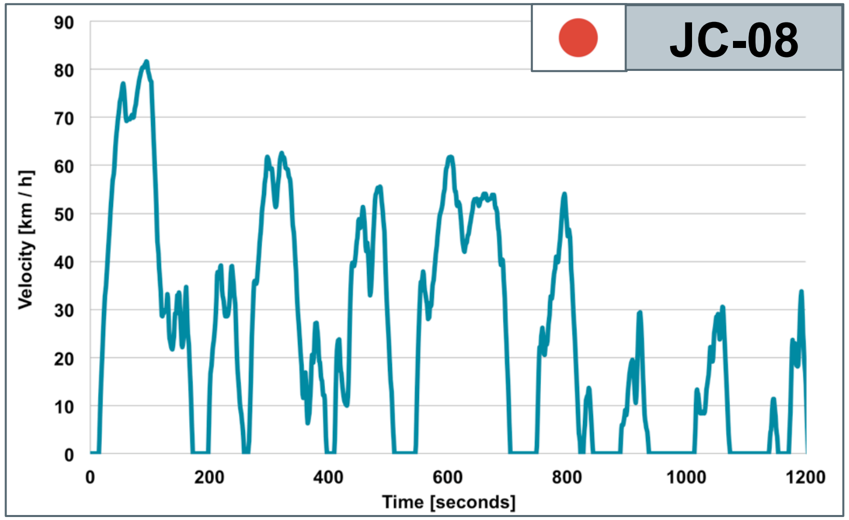
Ricardo vehicle simulations
Differences EU vs. US project

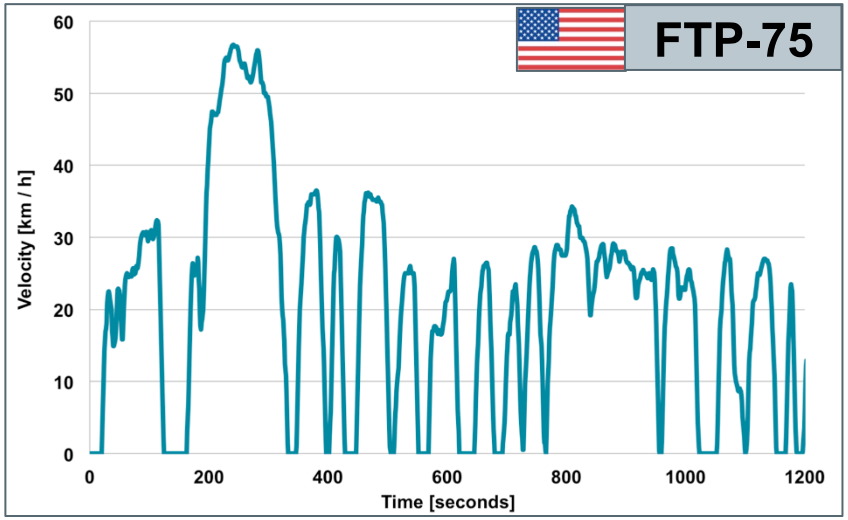
- **Additional driving cycles**
- **Additional vehicle segments**
- **Additional technologies**
- **Adapted underlying assumptions**

Ricardo vehicle simulations
Differences EU vs. US project

- **Additional driving cycles**







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Ricardo vehicle simulations
Differences EU vs. US project

- **Additional vehicle segments**

	Toyota Yaris	New	Toyota Camry	Chrysler 300C	Saturn Vue	New	Dodge G. Caravan

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%

Ricardo vehicle simulations
Differences EU vs. US project

- **Additional technologies**

  - 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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Ricardo vehicle simulations
Differences EU vs. US project

- **Adapted underlying assumptions**
  - Making use of EU applicable engine maps
  - Future gasoline vehicles will meet California LEV III requirements (equivalent to Euro 6+)
  - Baseline diesel vehicles meet Euro 5 standard
  - Future diesel vehicles will meet Euro 6+ standards
  - Ricardo results do not account for weight changes; to be handled separately using provided software tool
  - Blanket 3.5% improvement in fuel consumption coming from a combination of friction improvements in future engines
  - Ricardo baseline vehicles to be understood as ≈2010 model year vehicles with start-stop technology implemented

Ricardo vehicle simulations
The baseline vehicles

B-segment
(29% market, 38% diesel)

	Gasoline		Diesel	
	Ricardo	**EU-27**	**Ricardo**	**EU-27**
Vehicle model	Toyota Yaris	n/a	Toyota Yaris	n/a
Engine size	4 cyl., 1.5 l	4 cyl., 1.3 l	4 cyl., 1.2 l	4 cyl., 1.5 l
Engine power	82 kW	63 kW	59 kW	61 kW
Engine type	PFI	PFI (MS DI≈2%)	n/a	n/a
Vehicle weight	1,130 kg	1,090 kg	1,130 kg	1,160 kg
Transmission	6-AT	MT (MS≈94%)*	6-AT	MT (MS≈94%)*
Acceleration 0-100 km/h	9.9 s	13.2 s	12.2 s	13.3 s
CO_2 in NEDC	128 g/km	136 g/km	108 g/km	113 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)
**5-MT: 86%, 6-MT: 8%*

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Ricardo vehicle simulations
The baseline vehicles

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

	Gasoline		Diesel	
	Ricardo	**EU-27**	**Ricardo**	**EU-27**
Vehicle model	VW Golf	n/a	VW Golf	n/a
Engine size	4 cyl., 2.0 l	4 cyl., 1.6 l	4 cyl., 1.6 l	4 cyl., 1.7 l
Engine power	86 kW	86 kW	75 kW	83 kW
Engine type	PFI	PFI (MS DI≈19%)	n/a	n/a
Vehicle weight	1,413 kg	1,270 kg	1,413 kg	1,360 kg
Transmission	6-AT	MT (MS≈91%)*	6-AT	MT (MS≈91%)*
Acceleration 0-100 km/h	10.0 s	11.3 s	10.0 s	11.6 s
CO_2 in NEDC	165 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%*

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Ricardo vehicle simulations

The 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),
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** MS 5-MT: 49%, 6-MT: 42%*

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Ricardo vehicle simulations

The baseline vehicles

D-segment
(11% market, 80% diesel)

	Gasoline		Diesel	
	Ricardo	**EU-27**	**Ricardo**	**EU-27**
Vehicle model	Camry / Avensis	n/a	Camry / Avensis	n/a
Engine size	4 cyl., 2.4 l	4 cyl., 2.0 l	4 cyl., 2.0 l	4 cyl., 2.0 l
Engine power	118 kW	127 kW	122 kW	109 kW
Engine type	PFI	PFI (MS DI≈37%)	n/a	n/a
Vehicle weight	1,583 kg	1,440 kg	1,583 kg	1,500 kg
Transmission	6-AT	MT (MS≈81%)*	6-AT	MT (MS≈81%)*
Acceleration 0-100 km/h	8.3 s	9.3 s	7.6 s	9.9 s
CO_2 in NEDC	166 g/km	177 g/km	133 g/km	148 g/km
Remarks	Start-Stop/Reg. Euro 5 eq.	no Start-Stop Euro 4 (MS≈95%)	Start-Stop/Reg. Euro 5	no Start-Stop Euro 4 (MS≈95%)

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)
** 5-MT: 13%, 6-MT: 68%*

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Ricardo vehicle simulations
Efficiency, low CO_2 technologies

- **There are many different technologies available to reduce vehicles' CO_2 emissions**

- Technical efficiency, low-CO_2 options
  - 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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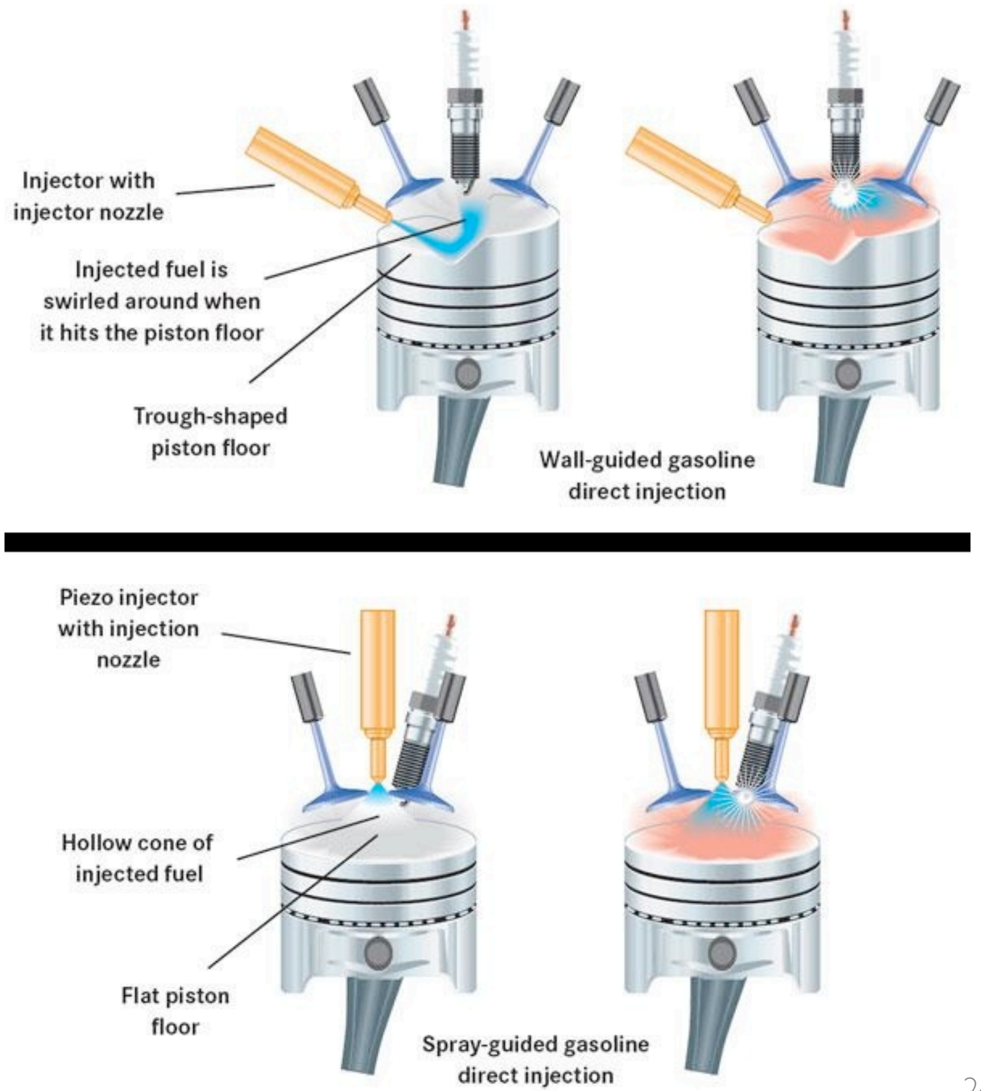
Ricardo vehicle simulations
Gasoline direct injection

- Cools intake mixture: especially important for turbocharging

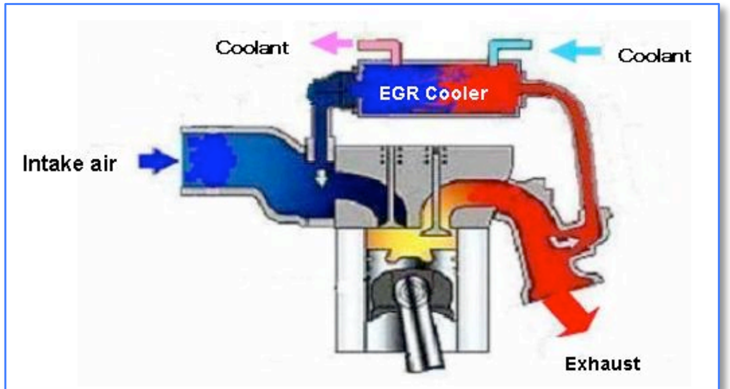
- Longer valve overlap increases low-rpm torque (fuel injected after valves close)

- Spray-guided reduces wall impingement and particulate emissions



Ricardo vehicle simulations
Next generation gasoline engines

Fiat MultiAir
Digital Valve Actuation

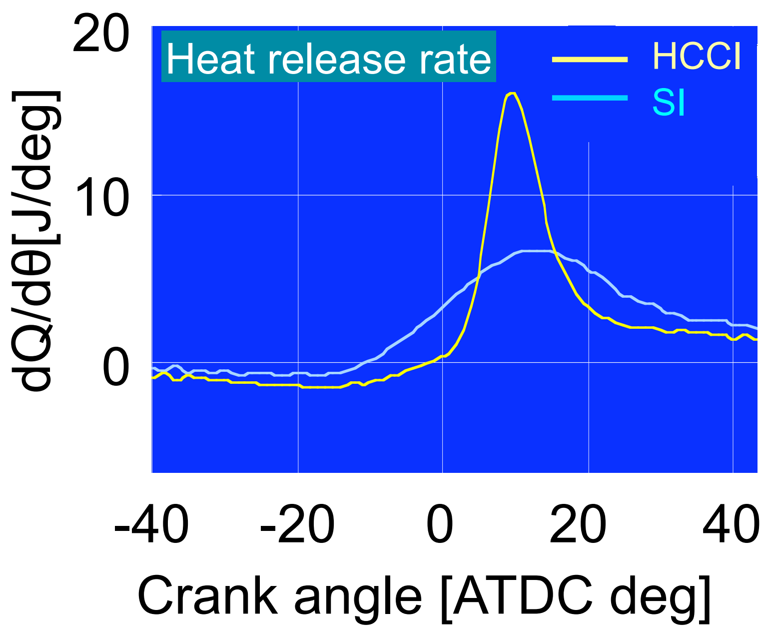


Dual-loop high/low pressure cooled exhaust gas recirculation

HCCI Engine

Improvement in fuel economy: **30%**

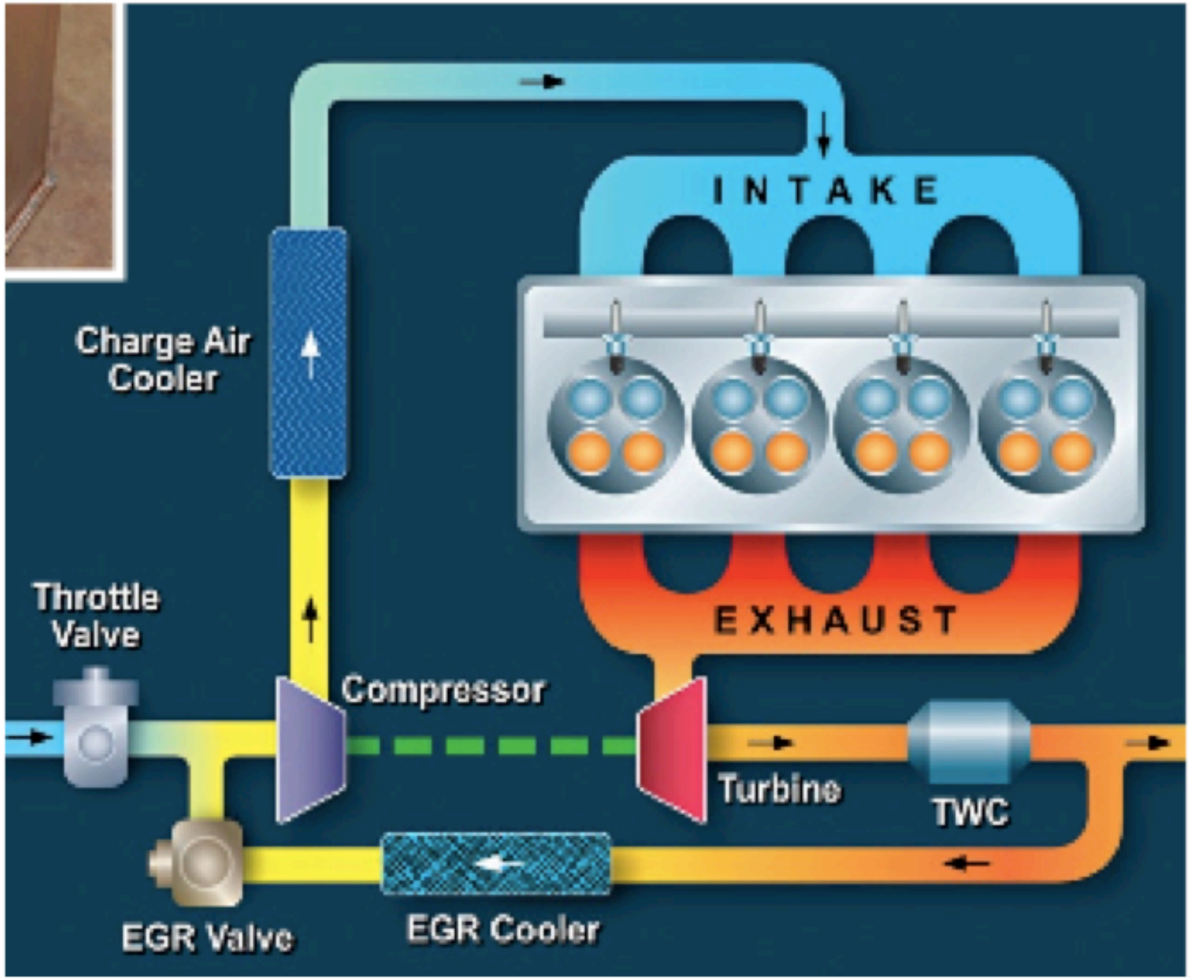
Honda Prototype Engine Base
(Electro-magnetic valve)



Requires increasing the self-ignition region

Ricardo vehicle simulations
Turbo boosted-EGR systems

- Highly dilute combustion – considerable efficiency improvement
- Advanced ignition systems required

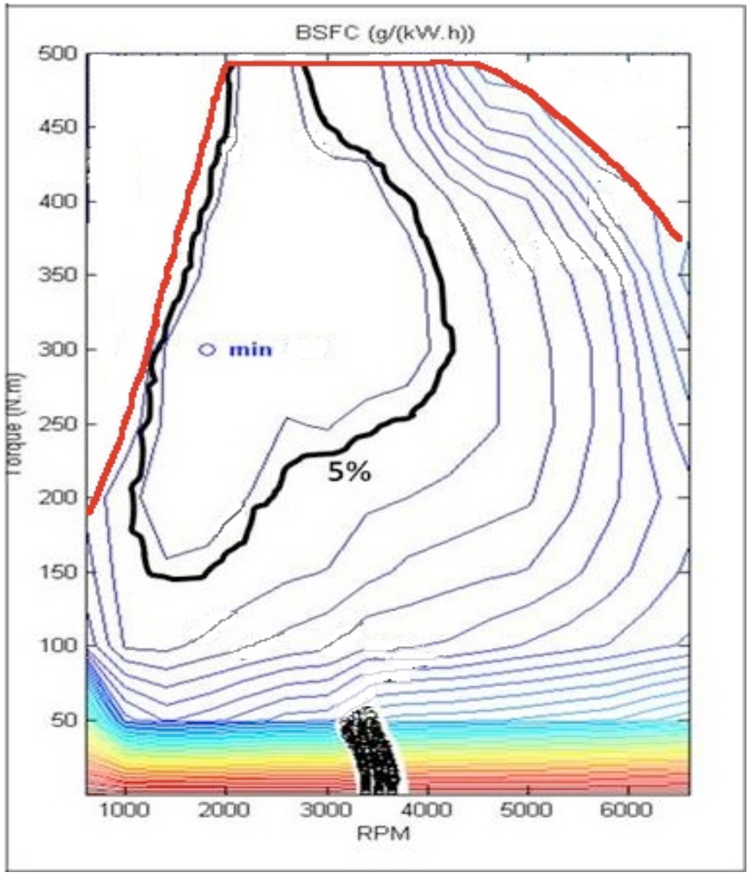


Terry Alger, Southwest Research Institute, “Clean and Cool”, Technology Today, Summer 2010

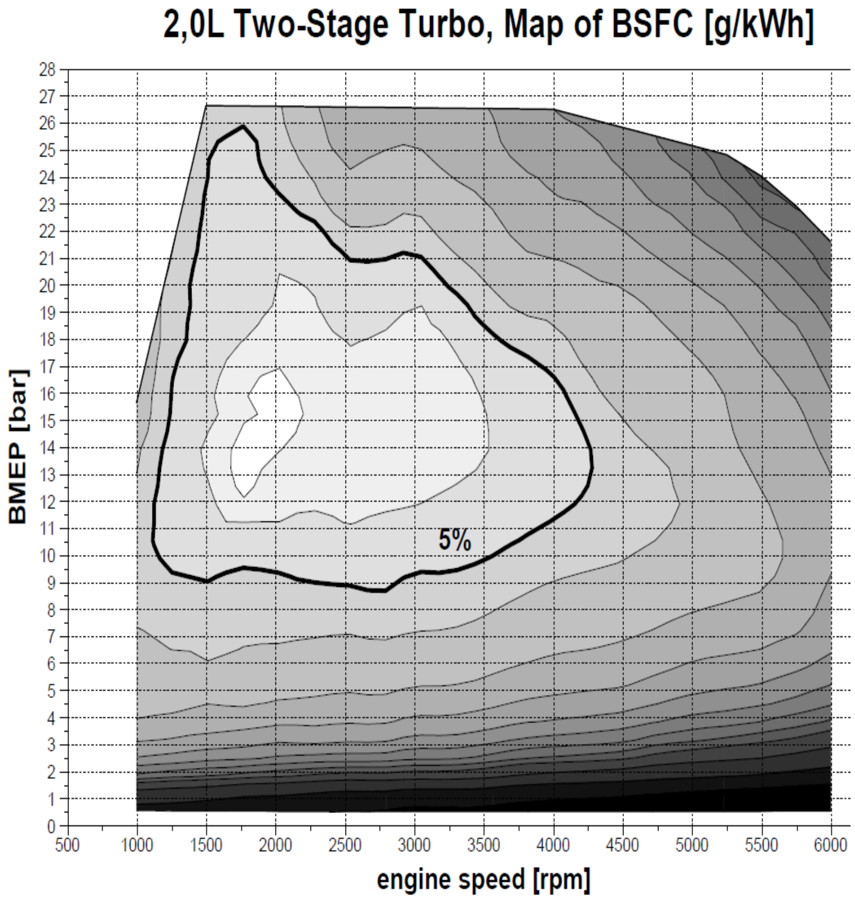
Ricardo vehicle simulations
Ricardo developed model inputs

paper (right) from demonstration engine.

e.g., Stoichiometric, Direct Injection Turbocharged Engine



Source: Ricardo Analysis



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

Ricardo vehicle simulations
Input Powersplit: Planetary gearing

- Toyota and Ford: Optimizes city efficiency, inexpensive CVT
- Achilles' Heel: Fixed torque split between engine and generator

and low-friction.

Power Split Device

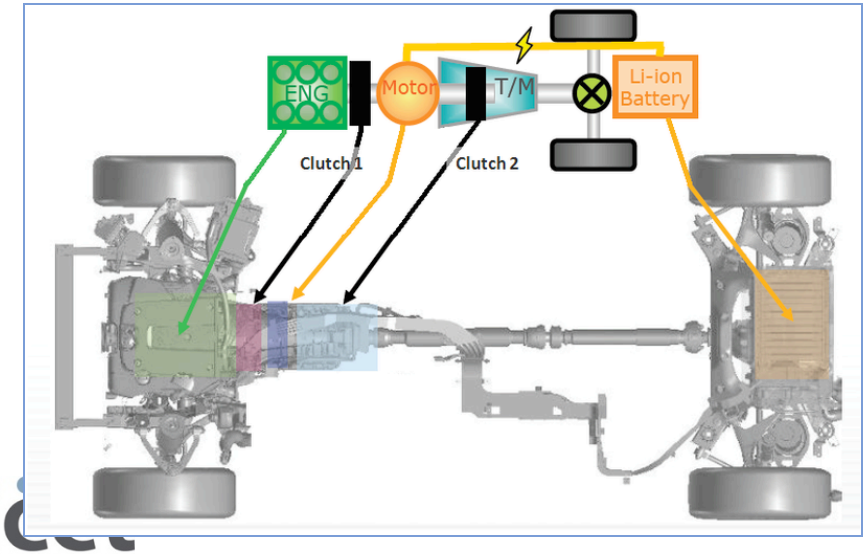
The power split device uses a planetary gear. The rotational shaft of the planetary carrier inside the gear mechanism is directly linked to the engine, and transmits the motive power to the outer ring gear and the inner sun gear via pinion gears. The rotational shaft of the ring gear is directly linked to the motor and transmits the drive force to the wheels, while the rotational shaft of the sun gear is directly linked to the generator.

- Two large motors
  - generator must handle part of engine output
  - Motor must handle generator plus battery output
- Cruising efficiency loss
  - Part of engine output always incurs losses in generator and motor
- Power recirculation possible

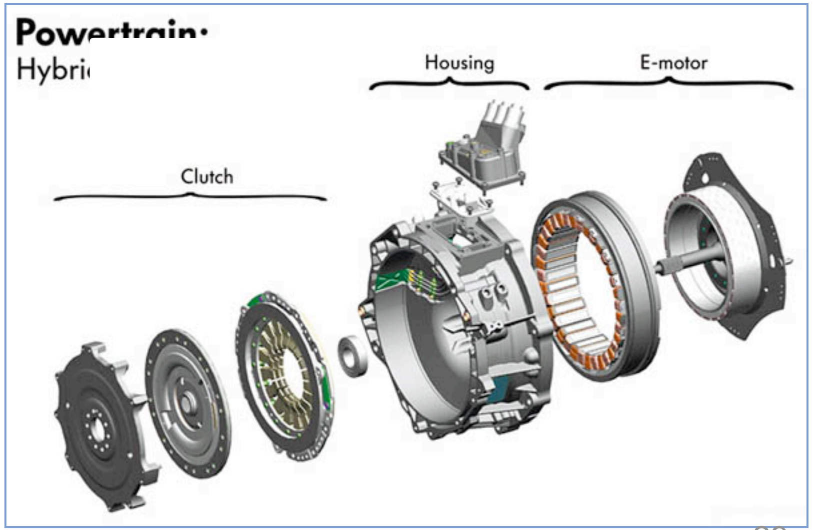
Source: Hybrid Synergy Drive, Toyota Hybrid System II, Toyota Motor Corp., May 2003

Ricardo vehicle simulations
P2 hybrid system

- New P2 hybrid – single motor with two clutches
  - Pre-transmission clutch: engine decoupling and larger motor
  - Nissan, VW, Hyundai, BMW, and Mercedes
- Achilles' Heel: Bump-starting engine
  - Hyundai: Separate BAS to start motor — **Cost**
  - Nissan: 2nd clutch designed to slip — **Drivability**
  - VW: Retained conventional torque converter — **Efficiency**



Nissan Fuga/M35 parallel hybrid layout



VW Touareg hybrid module

Ricardo vehicle simulations
Simulation results

- **Provided in project report and accompanying software tool**

Advanced DCT	EPA W C (
Vehicle - Engine	
B Class - STDI	2
B Class - LBDI	2
B Class - EGRB	2
B Class - 2020 Diesel	2
C Class - STDI	3
C Class - LBDI	3
C Class - EGRB	3
C Class - 2020 Diesel	3
D Class - STDI	3
D Class - LBDI	3
D Class - EGRB	3
D Class - 2020 Diesel	3
Small CUV - STDI	4
Small CUV - LBDI	4
Small CUV - EGRB	4
Small CUV - 2020 Diesel	4
N1 (large) - STDI	4
N1 (large) - LBDI	4
N1 (large) - EGRB	4
N1 (large) - 2020 Diesel	4
N1 (small) - STDI	3
N1 (small) - LBDI	3
N1 (small) - EGRB	3
N1 (small) - 2020 Diesel	3

P2 Hybrid								FUEL ECONOMY (mpg)					CO_2 (g/km)					PERFORMANCE								
Vehicle - Engine	EPA Weight Class	Mass (kg)	Displ. (L)	Peak Torq. (Nm)	Peak Power (kW)	Trans Spd-Type	Final Drive Ratio	EPA FTP	EPA HWY	EPA US06	NEDC	JC08	EPA FTP	EPA HWY	EPA US06	NEDC	JC08	0-10 mph (sec)	0-30 mph (sec)	0-50 mph (sec)	0-60 mph (sec)	0-70 mph (sec)	30-50 mph (sec)	50-70 mph (sec)	Speed on 5% Grd (mph)	Speed on 10% Grd (mph)
B Class - STDI	2625	1191	0.59	124	59	DCT6	4.00	68.2	57.3	37.0	60.6	73.6	83	99	153	93	77	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.4	70.6
B Class - LBDI	2625	1191	0.59	124	59	DCT6	4.00	68.4	57.7	37.3	61.4	74.9	82	98	151	92	75	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.4	70.6
B Class - EGRB	2625	1191	0.59	124	59	DCT6	4.00	70.2	59.9	38.8	63.5	76.2	80	94	146	89	74	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.4	70.6
B Class - Atkinson CPS	2625	1191	1.66	138	65	DCT6	4.00	70.8	59.0	38.1	62.6	74.8	80	96	148	90	75	1.4	3.7	7.5	10.0	13.6	3.8	6.1	85.4	62.1
B Class - Atkinson DVA	2625	1191	1.66	138	65	DCT6	4.00	71.7	60.5	39.2	64.2	78.4	79	93	144	88	72	1.4	3.7	7.5	10.0	13.6	3.8	6.1	85.4	62.1
C Class - STDI	3250	1474	0.62	131.6	62.4	DCT8	3.68	60.3	57.0	35.1	59.1	66.5	94	99	161	96	85	1.4	3.9	7.5	10.0	13.4	3.6	5.9	87.3	67.3
C Class - LBDI	3250	1474	0.62	131.6	62.4	DCT8	3.68	61.8	58.4	35.3	60.2	68.1	91	97	160	94	83	1.4	3.9	7.5	10.0	13.4	3.6	5.9	87.3	67.3
C Class - EGRB	3250	1474	0.62	131.6	62.4	DCT8	3.68	62.6	59.6	36.6	61.7	68.8	90	95	154	92	82	1.4	3.9	7.5	10.0	13.4	3.6	5.9	87.3	67.3
C Class - Atkinson CPS	3250	1474	1.74	145	68	DCT8	3.68	64.0	60.3	39.2	63.0	71.3	88	94	144	90	79	1.4	3.7	7.5	10.3	13.8	3.8	6.3	85.5	66.2
C Class - Atkinson DVA	3250	1474	1.74	145	68	DCT8	3.68	65.0	61.2	39.7	63.9	72.3	87	92	142	88	78	1.4	3.7	7.5	10.3	13.8	3.8	6.3	85.5	66.2
D Class - STDI	3625	1644	0.83	175.5	83	DCT8	3.23	61.9	57.2	36.9	59.0	64.6	91	99	153	96	87	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.0	77.3
D Class - LBDI	3625	1644	0.83	175.5	83	DCT8	3.23	62.9	58.0	36.7	59.9	66.7	90	97	154	94	85	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.0	77.3
D Class - EGRB	3625	1644	0.83	175.5	83	DCT8	3.23	65.1	59.7	38.4	61.7	67.0	87	95	147	92	84	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.0	77.3
D Class - Atkinson CPS	3625	1644	2.40	200.2	94	DCT8	3.23	64.6	59.7	39.8	61.5	66.0	87	95	142	92	86	1.2	3.4	6.5	8.6	11.4	3.1	4.9	101.3	78.4
D Class - Atkinson DVA	3625	1644	2.40	200.2	94	DCT8	3.23	65.9	61.0	40.5	62.7	67.8	86	93	139	90	83	1.2	3.4	6.5	8.6	11.4	3.1	4.9	101.3	78.4
Small CUV - STDI	4000	1814	0.90	189.8	90	DCT8	3.50	50.1	44.2	28.5	47.9	56.4	113	128	198	118	100	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.5	72.6
Small CUV - LBDI	4000	1814	0.90	189.8	90	DCT8	3.50	50.8	44.5	28.5	48.1	57.3	111	127	198	118	99	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.5	72.6
Small CUV - EGRB	4000	1814	0.90	189.8	90	DCT8	3.50	52.0	46.1	29.8	49.5	58.7	109	123	189	114	96	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.5	72.6
Small CUV - Atkinson CPS	4000	1814	2.60	217	102	DCT8	3.50	52.9	45.5	29.6	50.0	57.1	107	124	191	113	99	1.4	3.7	7.1	9.3	12.6	3.4	5.5	91.1	76.7
Small CUV - Atkinson DVA	4000	1814	2.60	217	102	DCT8	3.50	54.1	46.8	30.3	50.9	58.5	104	121	187	111	97	1.4	3.7	7.1	9.3	12.6	3.4	5.5	91.1	76.7
N1 (large) - STDI	4500	2041	1.05	221	105	DCT8	3.17	47.7	42.2	26.2	44.7	52.1	118	134	216	126	108	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.5
N1 (large) - LBDI	4500	2041	1.05	221	105	DCT8	3.17	47.4	42.6	26.8	45.2	52.7	119	132	211	125	107	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.5
N1 (large) - EGRB	4500	2041	1.05	221	105	DCT8	3.17	47.6	43.0	27.6	46.0	53.2	119	131	205	123	106	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.5
N1 (large) - Atkinson CPS	4500	2041	3.15	263	124	DCT8	3.17	48.3	42.4	27.5	45.9	51.0	117	133	205	123	111	1.4	3.6	6.7	8.8	11.6	3.1	4.9	95.4	82.3
N1 (large) - Atkinson DVA	4500	2041	3.15	263	124	DCT8	3.17	48.8	43.5	27.7	46.9	52.6	116	130	204	120	107	1.4	3.6	6.7	8.8	11.6	3.1	4.9	95.4	82.3

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Ricardo vehicle simulations
Simulation results

C-segment (gasoline)
only engine + transmission

- **Exemplary results:**

	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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Ricardo vehicle simulations
Simulation results

C-segment (gasoline)
including roadload reduction

- **Exemplary results:**

	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) -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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Ricardo vehicle simulations
Simulation results

C-segment (diesel)
only engine + transmission

- **Exemplary results:**

	cyl.	[l]	inj.	[kg]	trans.	[s]	[g/km]	em.	red.
EU-27 2010 average	4	1.7	---	1,360	5-MT	11.6	131	EU4	**+X%**
Ricardo baseline (start stop)	**4**	**1.6**	**---**	1,257	6-MT		122	EU5	**---**
Advanced diesel	**3**	**1.3**	**---**	1,257	8-AT 8-DCT	9.1 9.1	98 98	EU6	**-20%**

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

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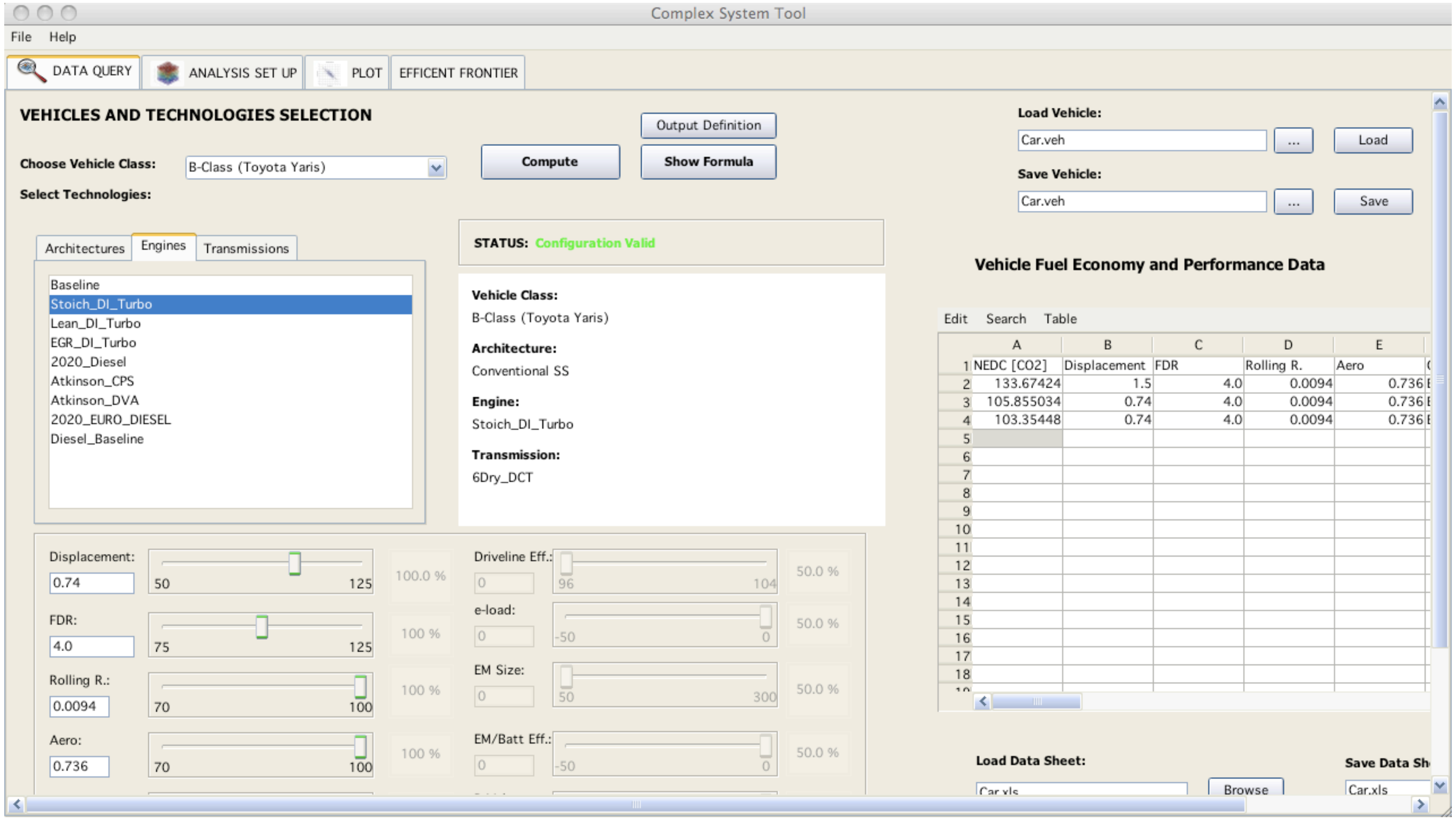
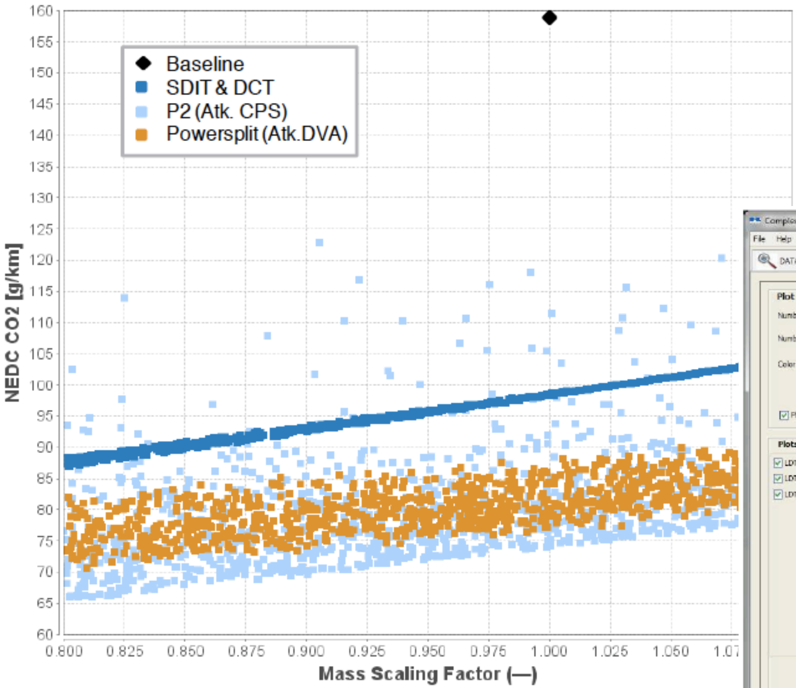
Ricardo vehicle simulations
Response Surface Model software tool

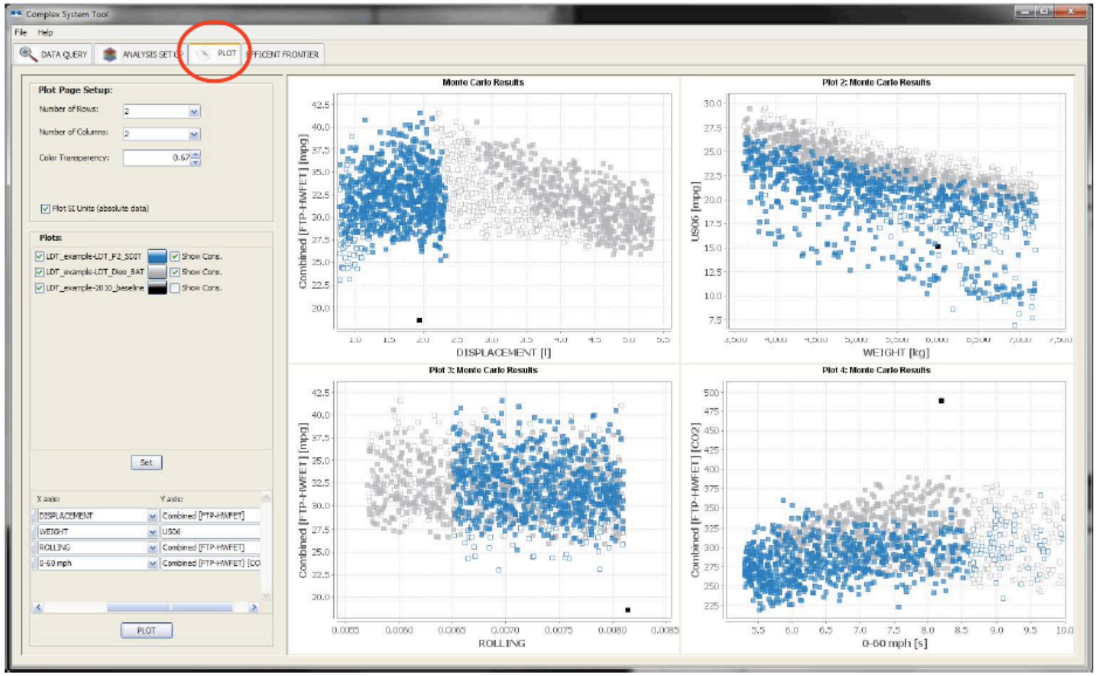
- **Tool and user guide available on ICCT website**



Ricardo vehicle simulations
Response Surface Model software tool

- **Tool also allows Monte-Carlo simulations**

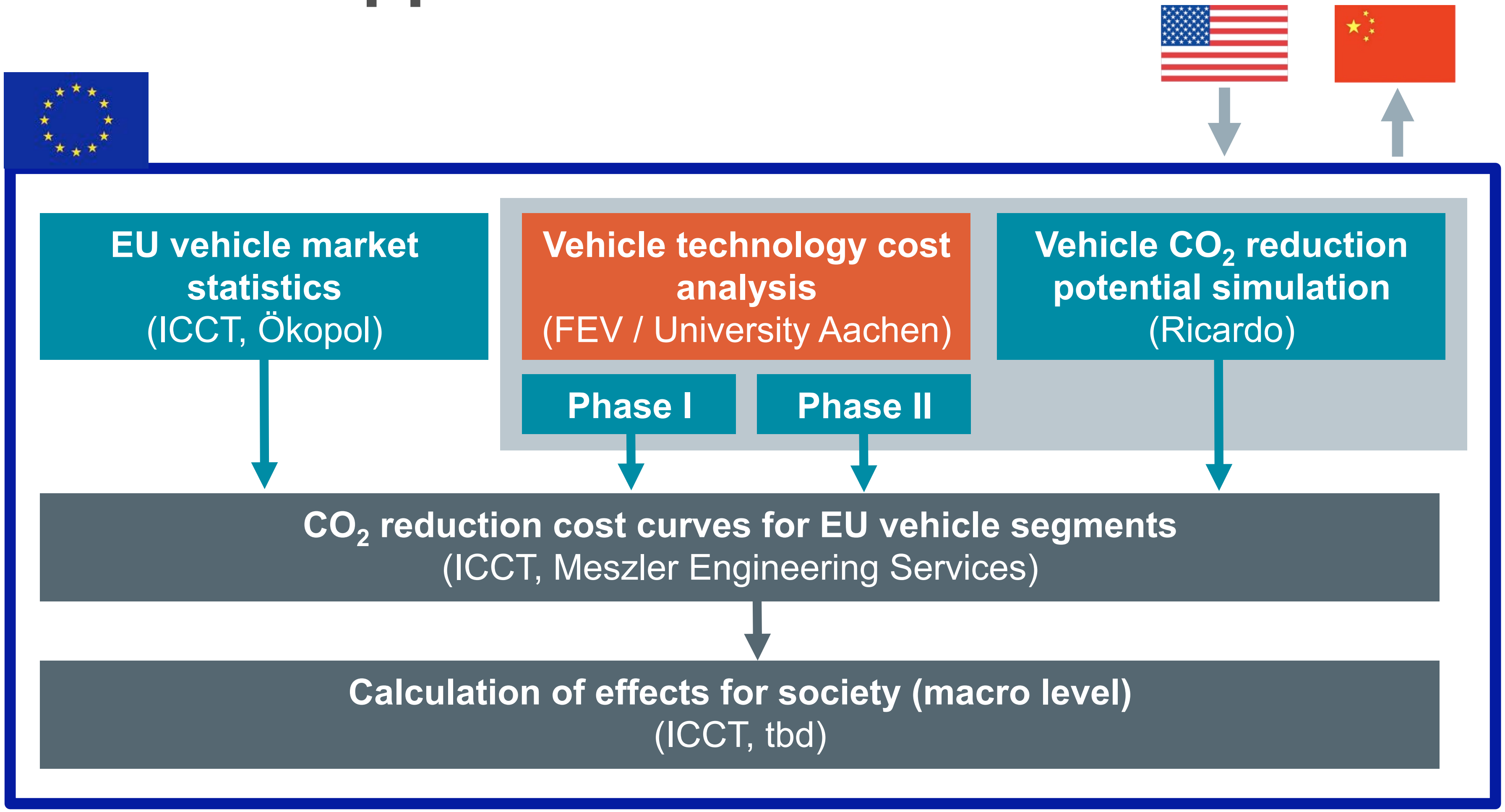




Ricardo vehicle simulations
Outlook

- **Potential additions for the future:**
  - Diesel hybrid
  - 2-cylinder gasoline DI engine
  - A-segment vehicle
  - E-segment vehicle
  - New world harmonized driving cycle (WLTP)

GHG reduction potential and cost analyses
The ICCT approach



accompanying workshops, briefings and publications

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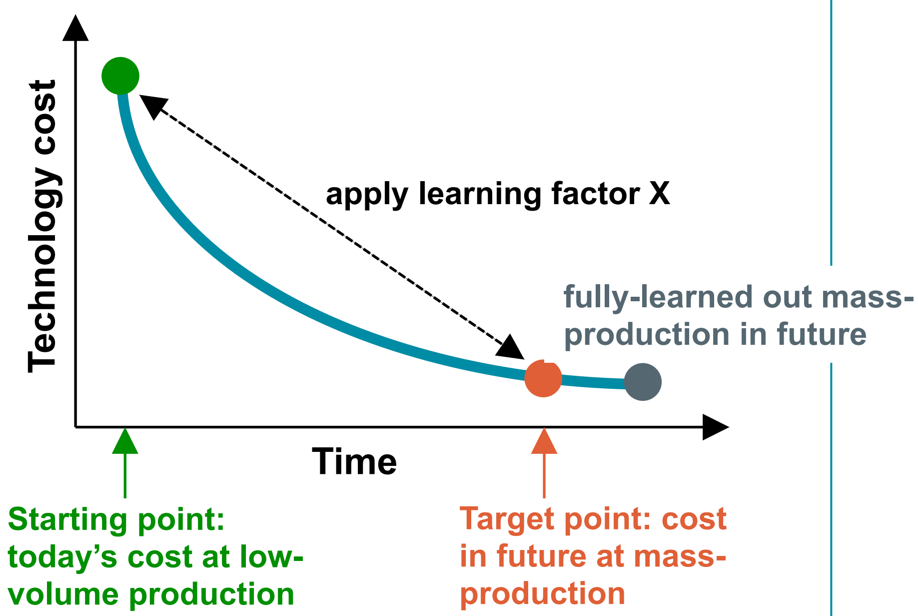
FEV cost analysis Phase I

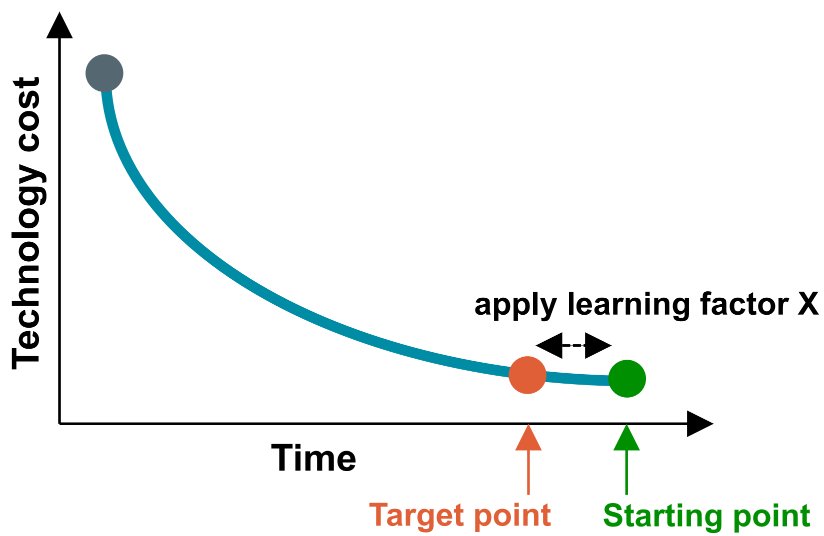
Principle idea of tear-down cost analysis

"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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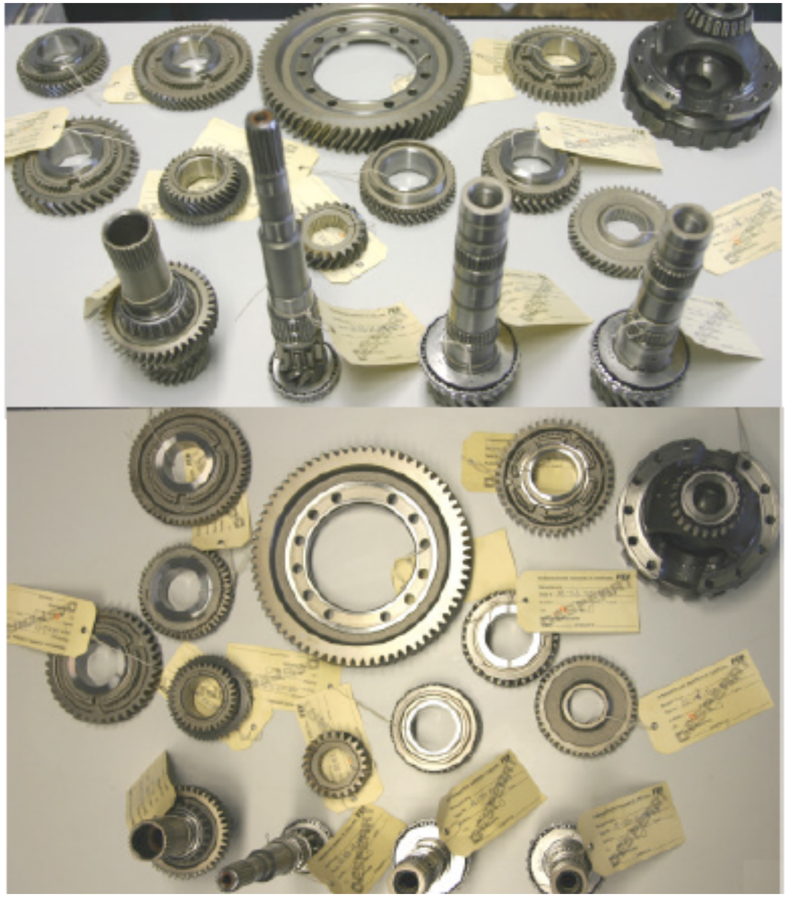
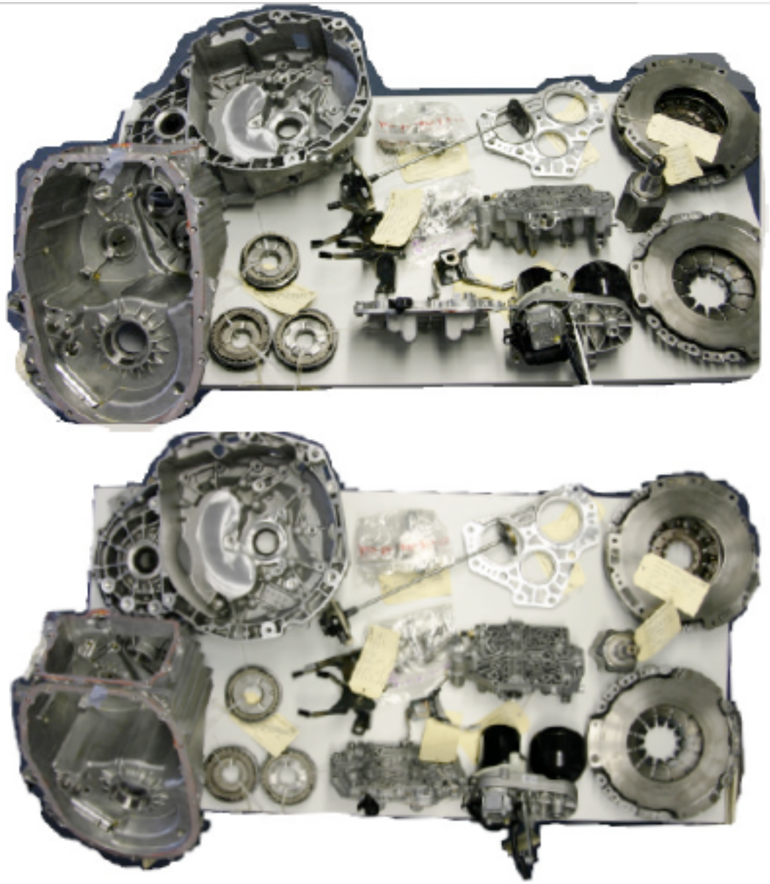
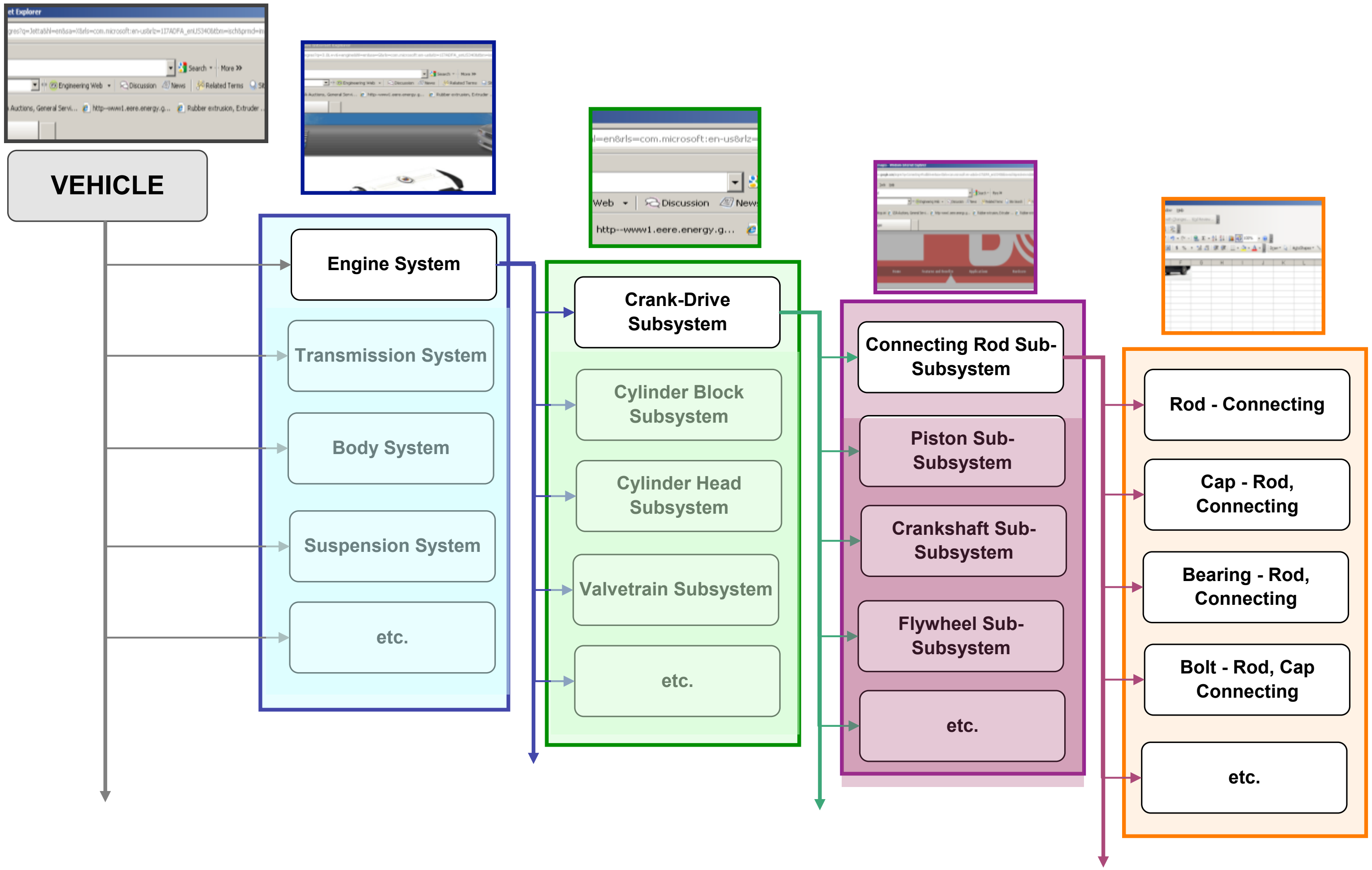
FEV cost analysis Phase I

Tear-down really means “nuts and bolts” …





FEV cost analysis Phase I
General approach for tear-down analysis



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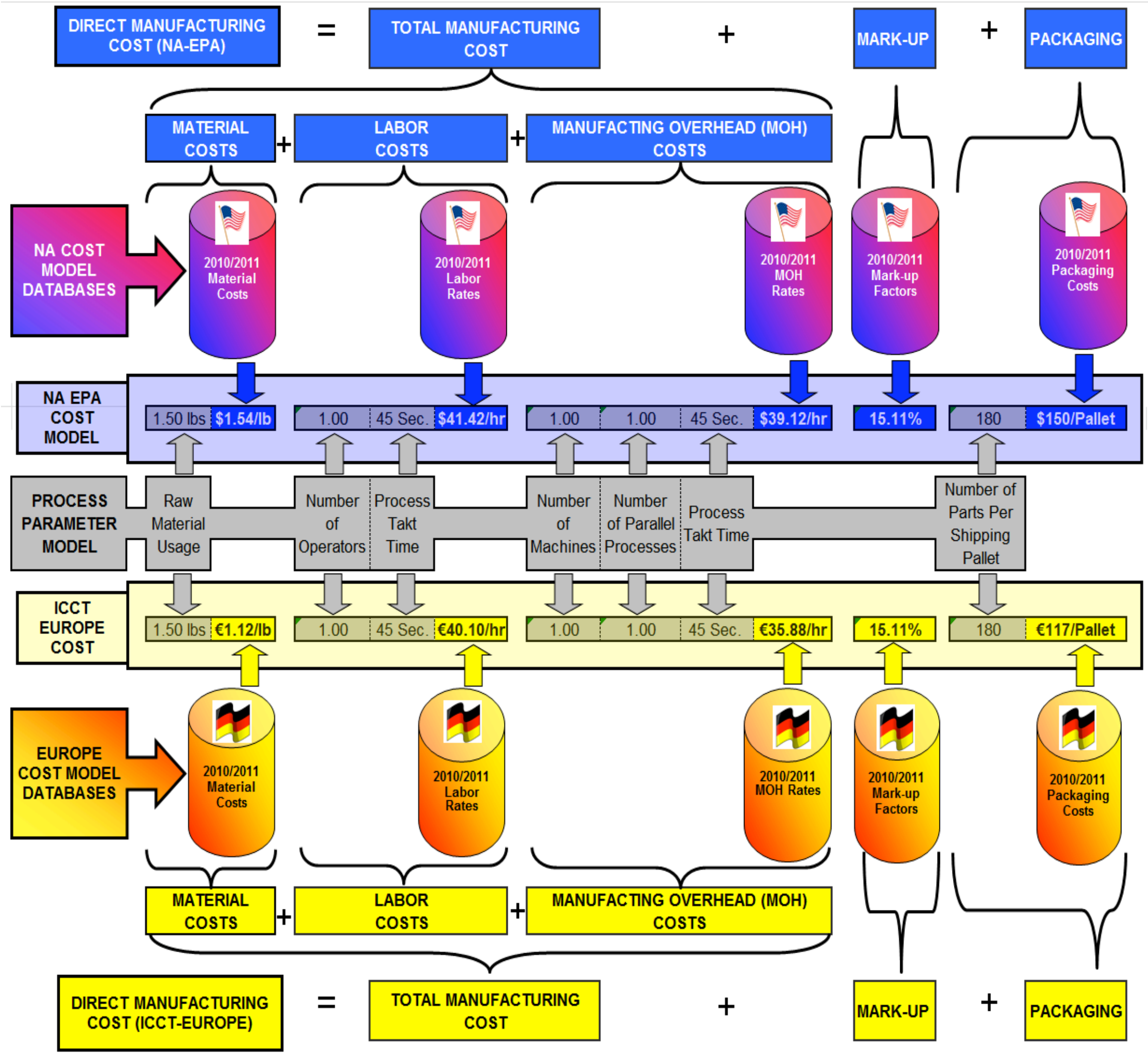
FEV cost analysis Phase I
Illustration of analysis process



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FEV cost analysis Phase I

Transparency of methodology and results

- **All details on parts and manufacturing processes available publicly**

FEV

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

FEV cost analysis Phase I
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
- **Approach has been subject to independent peer-review:**
  - http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies

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FEV cost analysis Phase I
Technologies assessed

FEV cost analysis (Phase I)	
✓ Gasoline direct injection and downsizing ✓ Automatic and dual-clutch transmissions ✓ Start-stop hybrid (belt alternator type) ✓ P2 and PowerSplit hybrid ✓ Electrical air conditioning compressor	➔ **transferring US results to the EU**

FEV cost analysis (Phase II)	
✓ Advanced diesel technology ✓ Manual and dual-clutch transmissions ✓ EGR direct injection turbo engine (diesel) ○ EGR direct injection turbo engine (gasoline) ✓ Advanced start-stop technology	➔ **new technologies specifically for EU**

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

FEV cost analysis Phase I

EU vehicle segments used for FEV study

Powertrain - Vehicle Class Summary Matrix (P-VCSM) — Veh. ID#	European Vehicle Segments					
	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

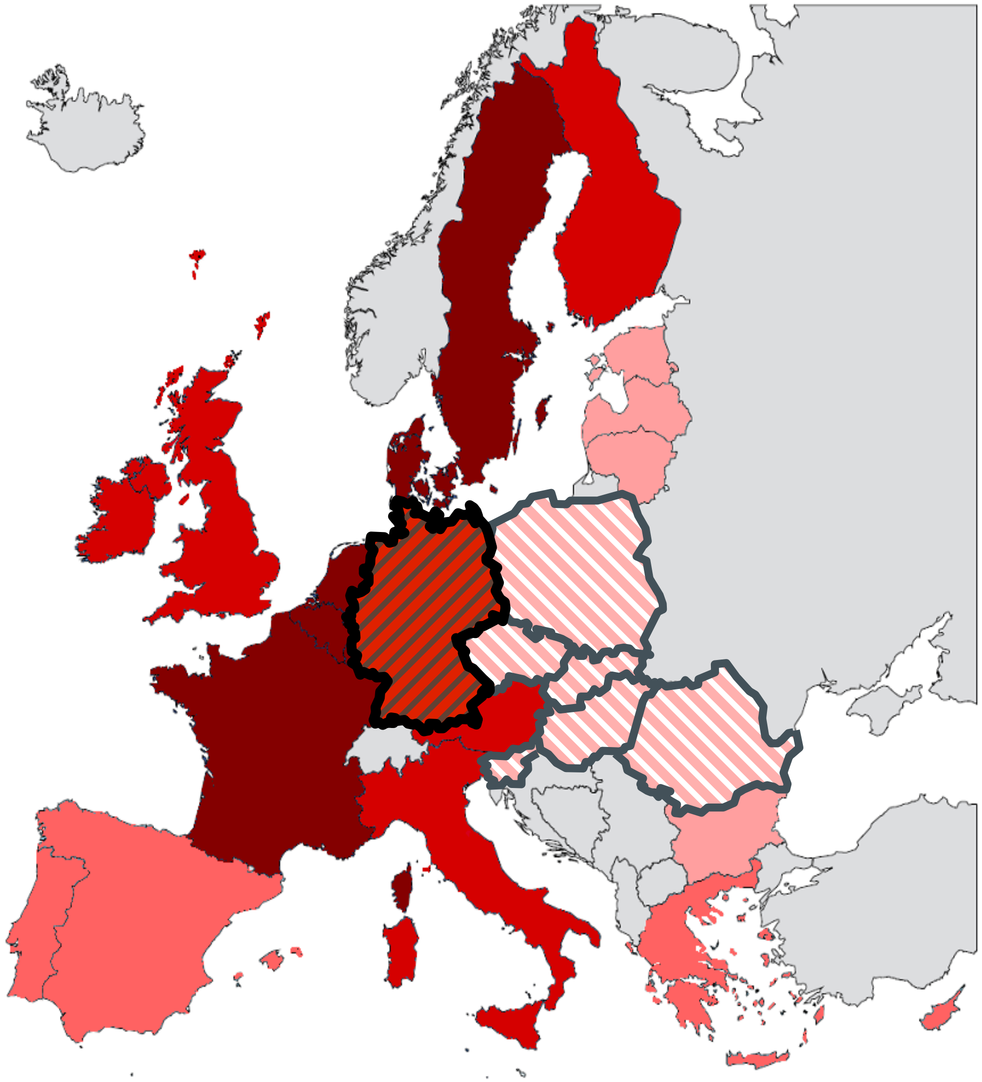
FEV cost analysis Phase I
Key assumptions

- **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

FEV cost analysis Phase I
Germany as manufacturing base for 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**

FEV cost analysis Phase I

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

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FEV cost analysis Phase I
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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FEV cost analysis Phase I
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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FEV cost analysis Phase I
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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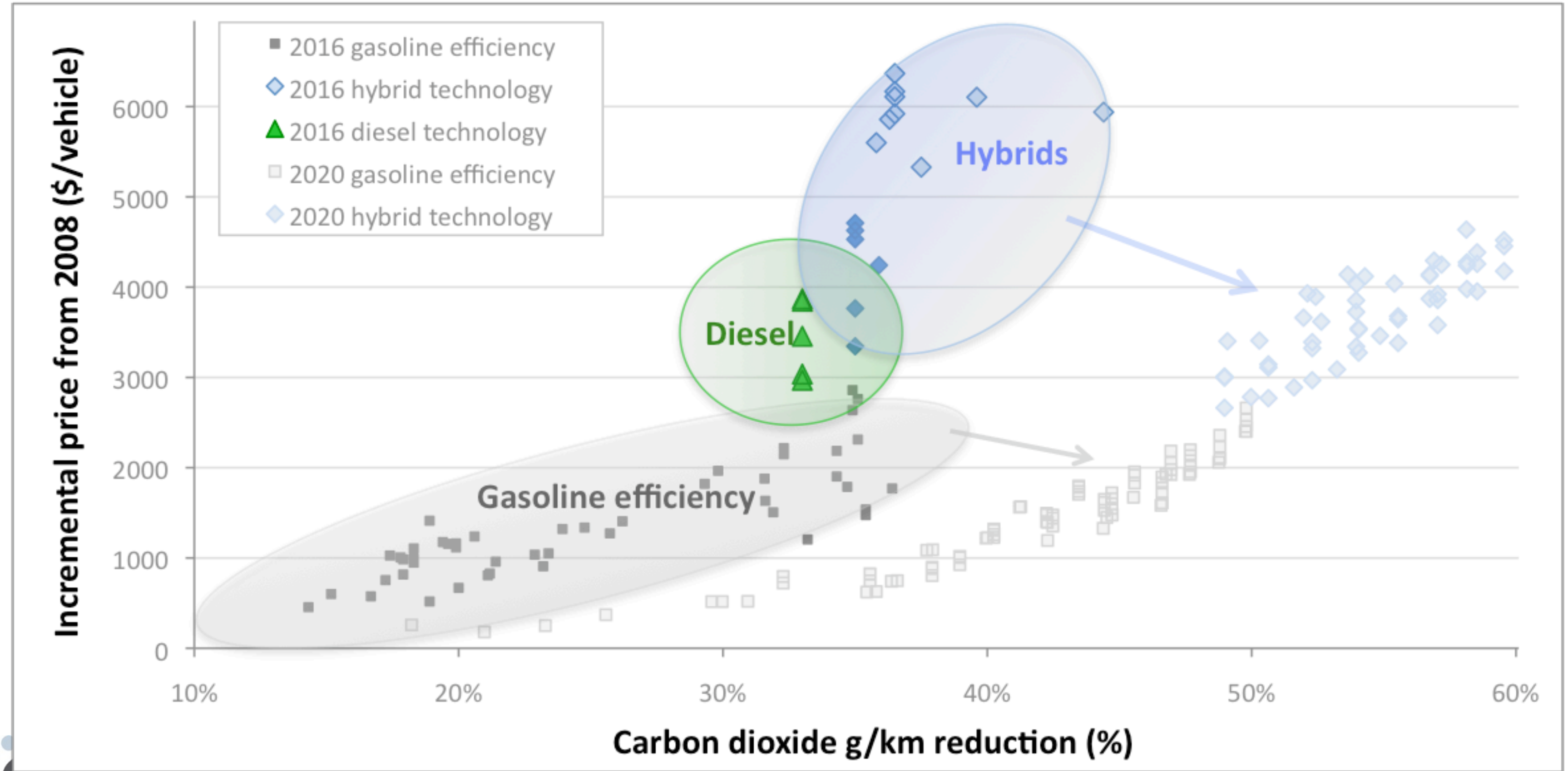
FEV cost analysis Phase I
Technology cost dropping

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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FEV cost analysis Phase I
Technology evolution

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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FEV cost analysis Phase I
P2 future improvements not in FEV analysis

- VW Golf (C-class) example. Base hybrid cost: €1,915
- High-power Li-ion batteries – smaller, lighter, lower cost
  - Reduce battery size 48%: - €328
- 25% vehicle load reduction – 25% smaller motor/battery
  - Battery cost: - €93 (incremental to high power battery)
  - Motor cost: - €40
- Integrate motor into transmission & system into vehicle
  - Eliminate motor case: - €70
  - Eliminate oil pump/filter: - €27
  - Eliminate electric A/C compressor (drive A/C off motor): - €113
  - Enable use of AMT instead of DCT: - €150
  - Simpler integrated braking system: - €80
- Total cost reduction: €900, or 47%

Contact details

John German
Senior Fellow, Regional Lead US
john@theicct.org

Peter Mock
Senior Researcher, Regional Lead EU
peter@theicct.org

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