Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market, Additional Case Studies (Phase 2)

Analysis Report BAV 11-683-001

Prepared for:

International Council on Clean Transportation
1225 I Street NW, Suite 900
Washington DC, 20005
http://www.theicct.org/

Submitted by:

FEV
4554 Glenmeade Lane
Auburn Hills, MI 48326
Phone: (248) 373-6000 ext. 2411
Email: kolwich@fev.com

September 27, 2012

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A. Executive Summary

A.1 Project Overview

The International Council on Clean Transportation (ICCT) contracted with FEV, Inc. to define the net incremental costs for a set of advanced light-duty vehicle technologies for the European vehicle market. The technologies selected are on the leading edge for reducing fuel consumption and emissions of greenhouse gases in the future, primarily in the form of tailpipe carbon dioxide (CO_2).

The cost analysis work covered in this report is a continuation of the work initiated in phase 1 of the project. The phase 1 analysis focused on the transfer and conversion of information and results from existing advance vehicle powertrain cost analysis studies performed by FEV, based on U.S. market trends and manufacturing cost structures, into comparable European cost studies. The original U.S. cost studies were performed by FEV for the United States Environmental Protection Agency (EPA). Advance powertrain technologies studied in the phase 1 analysis work included downsized, turbocharged, gasoline direct injection engine case studies, 6-speed versus 8-Speed automatic and dual clutch transmission case studies, and power-split and P2 hybrid electric vehicle case studies. Additional details may be found in ICCT published report "Light-Duty Vehicle Technology Cost Analysis –European Vehicle Market (Phase 1)".

In the phase 2 analysis work, new advance powertrain technologies were evaluated. Since the technologies were not previously studied, as either part of ICCT or EPA work assignments, new teardowns, hardware assessments, and cost modeling was required as discussed below. Case studies included in the phase 2 work included:

<u>Diesel Engines Analyses</u>

- Engine Downsizing (I4→I3, I4→Smaller I4, I6→I4, V8→I6)
- High Pressure Injection, 2500 Bar Compared to 1800 Bar System
- Variable Valve Timing and Lift System Compared to Conventional Valvetrain System
- High Pressure, Low Pressure Cooled Exhaust Gas Recirculation (EGR) System Compared to High Pressure Cooled EGR System

<u>Gasoline Engines Analysis</u>

- Low Pressure Cooled EGR Compared to Low Pressure Uncooled EGR System
- Addition of Low Pressure Cooled EGR to Conventional ICE without External EGR

<u>Transmission Analysis</u>

- 6-Speed Dry Dual Clutch Transmission Compared to 6-Speed Manual Transmission

Micro Hybrid Analysis

- Conventional Powertrain with Addition of Belt-Driven, Starter-Generator (BSG) Stop-start System Compared to Conventional Powertrain without Stop-start System.

A.2 Analysis Methodology

The cost assessment methodology, similar to that applied in previous EPA analyses, is based on detailed teardowns, hardware comparisons, and costing of key components and assemblies. For each analysis a new technology configuration selected (i.e., the advance technology offering) is evaluated against a baseline vehicle technology configuration (i.e., current technology becoming the standard in the industry) having similar overall driving performance. Both the new and baseline technology configurations are completely dis-assembled to a point were accurate assessments on component differences between both technology configurations can be made. Components assessed as equivalent in value, between the new and baseline technology, are eliminated from any further analysis. Components which are different (i.e., added, deleted and/or modified) are evaluated for costs. The component differences are costed using detailed cost models representative of automotive part suppliers and OEM vehicle manufacturing processes and cost factors.

When conducting the cost analysis for each technology configuration, a number of assumptions and boundary conditions are made upfront in the analysis (e.g. manufacturing location, manufacturing volumes, product maturity). The same assumptions and boundary conditions are applied to both the new and baseline technology configurations establishing a consistent framework for all costing, resulting in a level playing field for comparison. All technology configurations evaluated in this study use the same universal boundary conditions. Since the long term cost effectiveness of these technologies are being sought, boundary conditions representing mature, mass-produced components were assumed (e.g. mature product designs, high production volume, products in service for several years at high volume, significant market place competition). Important to note, no long-term forecasting of material costs, labor costs or manufacturing costs are utilized in the analysis. The costs calculated in the analysis are based on production costs in the 2010/2011 timeframe.

The costs presented in this report are comprised of three parts: incremental direct manufacturing costs, addition of OEM indirect manufacturing costs, and cost adjustment based on learning factors. The incremental direct manufacturing cost is the incremental difference in cost of components, to the OEM, between the new technology configuration and the baseline technology configuration. Included in the incremental direct manufacturing costs are fixed and variable manufacturing costs (i.e., material, labor and manufacturing overhead costs) and supplier mark-up costs (end-item scrap, selling, general and administrative costs, engineering, design and testing costs, and profit).

To account for OEM indirect costs, which includes OEM mark-up and other cost factors (e.g., production tooling), indirect cost multipliers (ICMs) are applied to the calculated incremental direct manufacturing cost. The ICM values used for the technologies evaluated in the ICCT European analysis are the same as those used by the United States Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) in developing the "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards & Corporate Average Fuel Economy Standards". (Report EPA-420-D-11-901, November 2011).

As discussed above, for all technologies evaluated, the same set of boundary conditions are assumed in developing the incremental direct manufacturing costs. To account for differences between the boundary conditions assumed in each analysis, and the estimated market place conditions, as a function of production year, learning factors are applied to the increment direct manufacturing costs. The learning factors are assigned based on technology complexity and maturity; impartial to cost impact. Based on the EPA methodology, a new technology configuration which has a direct manufacturing cost savings over the baseline configuration will have less of a savings in the future relative to the present.

The learning factors used in the phase 2 ICCT analysis are also referenced from the EPA and NHTSA draft joint technical support document with the exception of one result outcome. For new technology configurations which resulted in a savings relative to the baseline technology configuration, the learning factor was held constant at one (1) for all production years evaluated (i.e., 2012 thru 2025). This signifies no change in cost savings as the technology matures. In contrast, the EPA methodology treats new technology configurations with a cost increase or decrease the same.

For each of the studies evaluated, the incremental direct manufacturing costs are provided separately and with the added indirect cost multipliers and learning factors applied for production years 2012, 2016, 2020 and 2025.

Initially, only one case study was evaluated for each technology configuration (e.g. diesel high pressure injection, dry dual clutch transmission, micro hybrid electric vehicle). Technical teams helped in the hardware selection process to ensure the hardware under evaluation, for both the baseline and new technology configurations, were most representative of the current technology in the industry, and the new technology, most likely candidate to succeed in the future. Once the primary case studies were completed for each technology configuration, scaling factors were applied to scale the technology costs to alternative vehicle segments and powertrain configurations. Six (6) different vehicle segments were evaluated in the analysis. In some cases multiple powertrain configurations were evaluated for a given vehicle segment. For example, the subcompact vehicle segment has either an I3 or I4 engine configuration available. In the diesel high pressure injection system analysis, two cost analyses were required to account for the differences in the I3 versus I4 fuel induction system. In other analyses, like the 6-speed MT compared to the 6-speed dry DCT, the engine configuration differences had no bearing on the transmission costs, so only one powertrain configuration was evaluated in the subcompact vehicle segment.

A.3 Analysis Results

Tables A-1 through **A-8** provide a summary of the calculated incremental costs for each of the technologies and six (6) vehicle segments evaluated for the European market analysis. Each cost analysis has a case study number (3rd column in table). The first two digits identify the technology (i.e., 02** = engine downsizing analysis) and the second two digits identify the vehicle segment (i.e., **00 = subcompact passenger vehicle segment). The letter following the four digit number represents one possible powertrain option in that particular vehicle segment (i.e., 0200B = engine downsizing analysis, subcompact passenger vehicle segment, I4 engine configuration). In this particular example the letter "A" would signify an I3 engine configuration for the same analysis and vehicle segment. For the downsizing analysis, the smallest engine downsizing case study evaluated was an I4 compared to an I3.

The tables present incremental direct manufacturing costs and net incremental costs (direct manufacturing and indirect costs) plus learning. The incremental direct manufacturing costs are calculated based on 2010/2011 economics, high production volumes (450K units/year), and mature market conditions. A complete list of boundary conditions assumed in the analysis is provided in the report. The net incremental costs, shown for production years 2012, 2016, 2020, and 2025, include factors to account for indirect manufacturing cost contributions and learning adjustments. An overview of the application of indirect cost multipliers (ICMs) and learning factors to the direct manufacturing are also included in the report. The ICM and Learning factors, along with application support, was provided by EPA to support the ICCT analysis.

Funding for this work was generously provided by Stiftung Mercator and the Climate Works Foundation.

Table A-1: Engine Downsizing Costs Analysis Results (Diesel Engines)

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	ICM and Learning Factor Categorization			Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied			
								Description	Percent Contribution	Calculated Values	2012	2016	2020	2025
Diesel Engine Downsizing	2	2000B	**Diesel I4 ICE** Ave. Displacement = 1.2-1.4L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Subcompact Passenger Vehicle	VW Polo	(€ 284)	n/a	n/a	n/a	(€ 215)	(€ 215)	(€ 229)	(€ 229)
	3	2001	**Diesel I4 ICE** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Compact or Small Passenger Vehicle	VW Golf	(€ 290)	n/a	n/a	n/a	(€ 220)	(€ 220)	(€ 234)	(€ 234)
	4	2002	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Midsize Passenger Vehicle	VW Passat	(€ 303)	n/a	n/a	n/a	(€ 229)	(€ 229)	(€ 245)	(€ 245)
	5	2003A	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Midsize or Large Passenger Vehicle	VW Sharan	(€ 303)	n/a	n/a	n/a	(€ 229)	(€ 229)	(€ 245)	(€ 245)
	6	2003B	**Diesel I6 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Downsized to Diesel I4 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Midsize or Large Passenger Vehicle	VW Sharan	(€ 437)	n/a	n/a	n/a	(€ 332)	(€ 332)	(€ 353)	(€ 353)
	7	2005	**Diesel I4 ICE** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	(€ 303)	n/a	n/a	n/a	(€ 229)	(€ 229)	(€ 245)	(€ 245)
	9	2006B	**Diesel V8 ICE** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Downsized to Diesel I6 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	Large SUV	VW Touareg	(€ 442)	n/a	n/a	n/a	(€ 335)	(€ 335)	(€ 357)	(€ 357)

Table A-2: High Pressure Fuel Injection System Cost Analysis Results (Diesel Engines)

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
High Pressure Fuel Injection, Diesel Engine	1	2100A	**Diesel I3 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I3 ICE Upgraded to 2500 Bar Fuel Injection System**	Subcompact Passenger Vehicle	VW Polo	€ 9	€ 12	€ 11	€ 9	€ 9
	2	2100B	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 1.2-1.4L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	Subcompact Passenger Vehicle	VW Polo	€ 11	€ 16	€ 14	€ 12	€ 12
	3	2101	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	Compact or Small Passenger Vehicle	VW Golf	€ 11	€ 16	€ 14	€ 12	€ 12
	4	2102	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	Midsize Passenger Vehicle	VW Passat	€ 11	€ 16	€ 14	€ 12	€ 12
	6	2103B	**Diesel I6 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I6 ICE Upgraded to 2500 Bar Fuel Injection System**	Midsize or Large Passenger Vehicle	VW Sharan	€ 17	€ 23	€ 21	€ 18	€ 17
	7	2105	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 11	€ 16	€ 14	€ 12	€ 12
	9	2106B	**Diesel V8 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Diesel V8 ICE Upgraded to 2500 Bar Fuel Injection System**	Large SUV	VW Touareg	€ 22	€ 31	€ 28	€ 24	€ 23

Table A-3: Discrete Variable Valve Time & Lift System Cost Analysis Results (Diesel Engines)

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
Variable Valve Timing and Lift	1	2200A	**Diesel I3 ICE** **Conventional Valvetrain** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I3 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Subcompact Passenger Vehicle	VW Polo	€ 89	€ 133	€ 121	€ 106	€ 98
	3	2201	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Compact or Small Passenger Vehicle	VW Golf	€ 96	€ 143	€ 130	€ 114	€ 105
	4	2202	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Midsize Passenger Vehicle	VW Passat	€ 96	€ 143	€ 130	€ 114	€ 105
	5	2203A	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Midsize or Large Passenger Vehicle	VW Sharan	€ 96	€ 143	€ 130	€ 114	€ 105
	6	2203B	**Diesel I6 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I6 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Midsize or Large Passenger Vehicle	VW Sharan	€ 112	€ 167	€ 152	€ 133	€ 123
	7	2205	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 96	€ 143	€ 130	€ 114	€ 105
	9	2206B	**Diesel V8 ICE** Conventional Valvetrain Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Diesel V8 ICE Upgraded with Discrete Variable Valve Timing and Lift**	Large SUV	VW Touareg	€ 192	€ 286	€ 261	€ 227	€ 210

Table A-4: High Pressure, Low Pressure Cooled EGR System Cost Analysis Results (Diesel Engines)

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
High Pressure, Cooled Low Pressure EGR	1	2300A	**Diesel I3 ICE** **Cooled High Pressure EGR** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I3 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Subcompact Passenger Vehicle	VW Polo	€ 89	€ 123	€ 112	€ 97	€ 90
	3	2301	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Diesel I4 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Compact or Small Passenger Vehicle	VW Golf	€ 89	€ 123	€ 112	€ 97	€ 90
	4	2302	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Diesel I4 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Midsize Passenger Vehicle	VW Passat	€ 89	€ 123	€ 112	€ 97	€ 90
	5	2303A	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I4 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Midsize or Large Passenger Vehicle	VW Sharan	€ 89	€ 123	€ 112	€ 97	€ 90
	6	2303B	**Diesel I6 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I6 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Midsize or Large Passenger Vehicle	VW Sharan	€ 89	€ 123	€ 112	€ 97	€ 90
	7	2305	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Diesel I4 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 89	€ 123	€ 112	€ 97	€ 90
	9	2306B	**Diesel V8 ICE** **Cooled High Pressure EGR** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Diesel V8 ICE** **Upgrade with High Pressure, Cooled Low Pressure EGR**	Large SUV	VW Touareg	€ 88	€ 123	€ 112	€ 97	€ 90

Table A-5: Cooled Low Pressure EGR (Compared to Uncooled Low Pressure EGR) System Cost Analysis Results (Gasoline Engines)

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
Gasoline, Cooled Low Pressure EGR (Compared to Uncooled Low Pressure EGR)	1	3100A	**Gasoline I3 ICE Uncooled Low Pressure EGR** Ave. Displacement = 1.2-1.4L Ave. Power = 74kW (100HP) Ave. Torque = 146N*m (108lb*ft) Typical Transmission Type: 5-Speed MT Curb Weight: 1084kg (2390lb)	**Gasoline I3 ICE Upgraded with Cooled Low Pressure EGR System**	Subcompact Passenger Vehicle	VW Polo	€ 43	€ 60	€ 55	€ 52	€ 44
	3	3101	**Gasoline I4 ICE Uncooled Low Pressure EGR** Ave. Displacement = 1.4-1.6L Ave. Power = 89kW (121HP) Ave. Torque = 179N*m (132lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1271kg (2803lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Compact or Small Passenger Vehicle	VW Golf	€ 47	€ 65	€ 59	€ 56	€ 48
	4	3102	**Gasoline I4 ICE Uncooled Low Pressure EGR** Ave. Displacement = 1.6-2.0L Ave. Power = 115kW (157HP) Ave. Torque = 236N*m (174lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1496kg (3299lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Midsize Passenger Vehicle	VW Passat	€ 52	€ 73	€ 66	€ 63	€ 53
	5	3103A	Gasoline I4 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Midsize or Large Passenger Vehicle	VW Sharan	€ 65	€ 90	€ 82	€ 78	€ 66
	6	3103B	Gasoline I6 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I6 ICE Upgraded with Cooled Low Pressure EGR System**	Midsize or Large Passenger Vehicle	VW Sharan	€ 65	€ 90	€ 82	€ 78	€ 66
	7	3105	Gasoline I4 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 1.2-3.0L Ave. Power = 131 kW (178HP) Ave. Torque = 264N*m (195lb*ft) Typical Transmission Type: 6_Speed MT Curb Weight: 1590kg (3505lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 56	€ 78	€ 71	€ 67	€ 57
	9	3106B	Gasoline V8 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 3.0-5.5 Ave. Power = 268 kW (364HP) Ave. Torque = 491N*m (362lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 2207kg (4867lb)	**Gasoline V8 ICE Upgraded with Cooled Low Pressure EGR System**	Large SUV	VW Touareg	€ 87	€ 120	€ 110	€ 104	€ 88

Table A-6: Cooled Low Pressure EGR (Compared to ICE with No EGR) System Cost Analysis Results (Gasoline Engines)

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
Gasoline, Cooled Low Pressure EGR (Compare to ICE with no EGR)	1	3200A	**Gasoline I3 ICE** **No EGR** Ave. Displacement = 1.2-1.4L Ave. Power = 74kW (100HP) Ave. Torque = 146N*m (108lb*ft) Typical Transmission Type: 5-Speed MT Curb Weight: 1084kg (2390lb)	**Gasoline I3 ICE Upgraded with Cooled Low Pressure EGR System**	Subcompact Passenger Vehicle	VW Polo	€ 74	€ 102	€ 94	€ 88	€ 75
	3	3201	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 1.4-1.6L Ave. Power = 89kW (121HP) Ave. Torque = 179N*m (132lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1271kg (2803lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Compact or Small Passenger Vehicle	VW Golf	€ 77	€ 107	€ 98	€ 92	€ 79
	4	3202	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 1.6-2.0L Ave. Power = 115kW (157HP) Ave. Torque = 236N*m (174lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1496kg (3299lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Midsize Passenger Vehicle	VW Passat	€ 83	€ 115	€ 105	€ 99	€ 85
	5	3203A	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Midsize or Large Passenger Vehicle	VW Sharan	€ 96	€ 133	€ 121	€ 114	€ 98
	6	3203B	**Gasoline I6 ICE** **No EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I6 ICE Upgraded with Cooled Low Pressure EGR System**	Midsize or Large Passenger Vehicle	VW Sharan	€ 96	€ 133	€ 121	€ 114	€ 98
	7	3205	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 1.2-3.0L Ave. Power = 131 kW (178HP) Ave. Torque = 264N*m (195lb*ft) Typical Transmission Type: 6_Speed MT Curb Weight: 1590kg (3505lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 87	€ 120	€ 110	€ 103	€ 88
	9	3206B	**Gasoline V8 ICE** **No EGR** Ave. Displacement = 3.0-5.5 Ave. Power = 268 kW (364HP) Ave. Torque = 491N*m (362lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 2207kg (4867lb)	**Gasoline V8 ICE Upgraded with Cooled Low Pressure EGR System**	Large SUV	VW Touareg	€ 117	€ 163	€ 149	€ 140	€ 120

Table A-7: 6-Speed, Dry, Dual Clutch Transmission Cost Analysis Results

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
Dry Dual Clutch Transmission	1	2600A	**Diesel I3 ICE** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1084kg (2390lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	Subcompact Passenger Vehicle	VW Polo	€ 288	€ 400	€ 365	€ 317	€ 294
	3	2601	**Diesel I4 ICE** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1271kg (2803lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	Compact or Small Passenger Vehicle	VW Golf	€ 291	€ 404	€ 369	€ 321	€ 297
	4	2602	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1496kg (3299lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	Midsize Passenger Vehicle	VW Passat	€ 297	€ 412	€ 377	€ 327	€ 303
	5	2603A	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1700kg (3749lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	Midsize or Large Passenger Vehicle	VW Sharan	€ 304	€ 422	€ 385	€ 334	€ 310
	6	2603B	**Diesel I6 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1700kg (3749lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission (Ave. Max. Input Torque 592 N*m)**	Midsize or Large Passenger Vehicle	VW Sharan	€ 304	€ 422	€ 385	€ 334	€ 310
	7	2605	**Diesel I4 ICE** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1590kg (3505lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 298	€ 414	€ 378	€ 328	€ 304
	9	2606B	**Diesel V8 ICE** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 2207kg (4866lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	Large SUV	VW Touareg	€ 320	€ 443	€ 405	€ 352	€ 326

Table A-8: Belt-Driven, Starter-Generator (BSG) Stop-Start Hybrid Electric Vehicle System Cost Analysis Results

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 and Indirect Costs) with Applicable Learning Applied			
								2012	2016	2020	2025
Start-Stop Hybrid Electric Vehicle Technology	2	3000B	**Gasoline I4 ICE** **Conventional Powertrain** Ave. Displacement = 1.2-1.4L Ave. Power = 74kW (100HP) Ave. Torque = 146N*m (108lb*ft) Typical Transmission Type: 5-Speed MT Curb Weight: 1084kg (2390lb)	**Gasoline I4 ICE, Manual Transmission, upgraded with Belt-Driven, Starter-Generator (BSG) System.**	Subcompact Passenger Vehicle	VW Polo	€ 298	€ 589	€ 414	€ 349	€ 311
	3	3001	**Gasoline I4 ICE** **Conventional Powertrain** Ave. Displacement = 1.4-1.6L Ave. Power = 89kW (121HP) Ave. Torque = 179N*m (132lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1271kg (2803lb)	**Gasoline I4 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	Compact or Small Passenger Vehicle	VW Golf	€ 311	€ 613	€ 431	€ 364	€ 324
	4	3002	**Gasoline I4 ICE** **Conventional Powertrain** Ave. Displacement = 1.6-2.0L Ave. Power = 115kW (157HP) Ave. Torque = 236N*m (174lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1496kg (3299lb)	**Gasoline I4 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	Midsize Passenger Vehicle	VW Passat	€ 329	€ 650	€ 456	€ 385	€ 343
	6	3003B	**Gasoline I6 or V6 ICE** **Conventional Powertrain** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I6 or V6 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	Midsize or Large Passenger Vehicle	VW Sharan	€ 352	€ 695	€ 488	€ 412	€ 367
	7	3005	**Gasoline I4 ICE** **Conventional Powertrain** Ave. Displacement = 1.2-3.0L Ave. Power = 131 kW (178HP) Ave. Torque = 264N*m (195lb*ft) Typical Transmission Type: 6_Speed **MT** Curb Weight: 1590kg (3505lb)	**Gasoline I4 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	Small or Midsize SUV/COV or Mini Van	VW Tiguan	€ 337	€ 666	€ 468	€ 395	€ 351
	9	3006B	**Gasoline V8 ICE** **Conventional Powertrain** Ave. Displacement = 3.0-5.5 Ave. Power = 268 kW (364HP) Ave. Torque = 491N*m (362lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 2207kg (4867lb)	**Gasoline V8 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	Large SUV	VW Touareg	€ 449	€ 887	€ 623	€ 526	€ 468

B. Introduction

B.1 Project Overview

The International Council for Clean Transportation (ICCT) contracted with FEV, Inc. to determine the net incremental costs for a set of advanced light-duty vehicle technologies for the European vehicle market. The technologies selected are on the leading edge for reducing fuel consumption and emissions of greenhouse gases in the future, primarily in the form of tailpipe carbon dioxide (CO2).

The cost analysis work covered in this report is a continuation of the work initiated in phase 1 of the project. The phase 1 analysis focused on the transfer and conversion of information and results from existing advance vehicle powertrain cost analysis studies performed by FEV, based on U.S. market trends and manufacturing cost structures, into comparable European cost studies. The original U.S. cost studies were performed by FEV for the United States Environmental Protection Agency (EPA). Advance powertrain technologies studied in the phase 1 analysis work included downsized, turbocharged, gasoline direct injection engine case studies, 6-speed versus 8-Speed automatic and dual clutch transmission case studies, and power-split and P2 hybrid electric vehicle case studies. Additional details may be found in ICCT published report "Light-Duty Vehicle Technology Cost Analysis –European Vehicle Market (Phase 1)".

In the phase 2 analysis work, new advance powertrain technologies, more common found the European market were evaluated. Since the technologies were not previously studied, as either part of ICCT or EPA work assignments, new teardowns, hardware assessments, and cost modeling was required as discussed below.

As shown in **Figure B-1** below, the process of developing net incremental costs, for adding advance light-duty powertrain technologies to convention/baseline powertrain configurations, can be summarized in three steps. In step one (1) the Net Incremental Direct Manufacturing (NIDMC) are calculated for each of the defined technology configurations using a similar costing methodology to that employed in the United States Environmental Protection Agency (EPA) cost studies. For each technology configuration studied, a set of hardware representative of the current industry standard, or becoming the industry standard, is selected for the new and baseline technology configurations. The selected hardware, and associated vehicle segment, is considered the lead case study for developing the NIDMC for the selected technology configuration. In step two (2), Net Incremental Direct Manufacturing Costs from the lead case study are scaled to alternative vehicle segments. There are six vehicle segments considered in the analysis. Due to timing and funding constraints, the NIDMC results from the lead case study are scaled to the remaining vehicle segments, using relevant powertrain attributes. In the final step, step three of cost analysis process, factors are applied to the NIDMCs to account for technology maturity differences and OEM indirect costs. The learning factors account for differences in the costs associated with the assumptions made in the cost analysis relative to product and market maturity versus real world conditions (e.g. production volumes, market place competition, product maturity, etc.). The application of OEM indirect cost factors [also referred to as indirect cost multipliers (ICMs)] account for items such as OEM corporate overhead/SG&A, OEM engineering, design and testing (ED&T)/R&D, OEM owned tooling, OEM warranty, etc. Both the learning curve factors and indirect cost multiples were developed and provided by the United States EPA. More details on all three steps of the cost analysis process are covered in **Section B.3**.

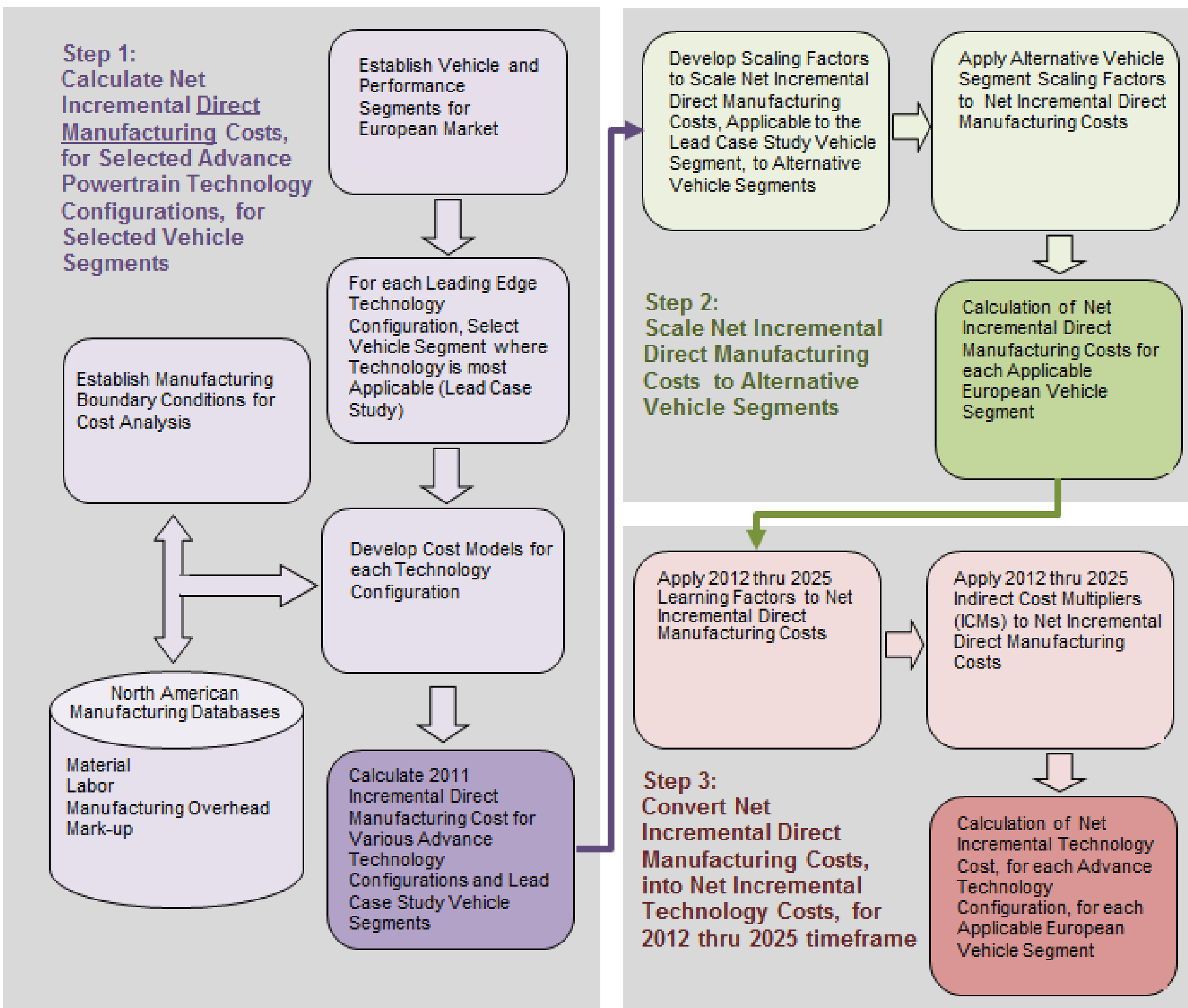


Figure B-1: Process Steps for Developing Net Incremental Costs for New Advance Powertrain Technology Configurations

B.2 Technologies Analyzed in the Phase 2 Analysis

The following list is the technology configurations evaluated. Each technology selected is evaluated against a baseline vehicle technology configuration representative of the current state of design with similar overall driving performance. Components that are unique to the new technology, as well as components modified to account for the new technology adaptation, are identified and analyzed to establish the incremental direct manufacturing costs.

Diesel Engines Analyses

- Engine Downsizing
  - Lead Case Study: #2002, Midsize Passenger Vehicle Segment
    - Baseline Technology Configuration: 2.0L I4, 105kW, 300N•m BMEP 20 Bar, Compression Ration 16.5, Peak Firing Pressure 150 Bar
    - New Technology Configuration: (Theoretical) 1.5L I3, 105kW, 300N•m BMEP 27 Bar, Compression Ration 15.5, Peak Firing Pressure 180 Bar
- High Pressure Fuel Injection System Comparison
  - Lead Case Study: #2102, Midsize Passenger Vehicle Segment
    - Baseline Technology Configuration: 2.0L I4, 130kW, 350N•m, 1800 Bar Fuel Injection System
    - New Technology Configuration: (Theoretical) 2.0L I4, ≈130kW ≈350N•m, 2500 Bar Fuel Injection System
- Variable Valve Timing and Lift (VVTL) System Comparison
  - Lead Case Study: #2203A, Midsize to Large Passenger Vehicle Segment
    - Lead Case Study: Baseline Technology Configuration: 2.0L I4, 150kW, 400N•m, Conventional Valvetrain (i.e., no VVT or VVL system)
    - New Technology Configuration: (Theoretical) 2.0L I4, 150kW 400N•m, FEV High Efficient Combustion System (HECS) VVTL System
- Diesel Exhaust Gas Recirculation (EGR) System Comparison
  - Lead Case Study: #2302, Midsize Passenger Vehicle Segment
    - Baseline Technology Configuration: 2.0L I4, 103kW, 320N•m, Cooled High Pressure EGR System
    - New Technology Configuration: 2.0L I3, 103kW, 320N•m, High Pressure and Cooled Low Pressure EGR

Transmission Analysis

- 6-Speed Transmission System Comparison
  - Lead Case Study: #2602, Midsize Passenger Vehicle Segment
    - Baseline Technology Configuration: 350N*m 6-Speed Manual Transmission (MT)
    - New Technology Configuration: 350N*m 6-Speed Dry Dual Clutch Transmission (DCT)

Micro Hybrid Analysis

- Addition of Stop-start System Technology
  - Lead Case Study: #3000B, Subcompact Passenger Vehicle Segment
    - Baseline Technology Configuration: 1.5L I4, 70kW Gasoline Engine with 5-Speed MT.
    - New Technology Configuration: Baseline Powertrain Configuration (as defined above) with the addition of a Belt-Driven, Starter-Generator (BSG) Stop-start System

Gasoline Engines Analysis

- Gasoline Exhaust Gas Recirculation (EGR) System Comparison
  - Lead Case Study: **#3103A** Midsize to Large Passenger Vehicle
    - Baseline Technology Configuration: Uncooled Low Pressure EGR
    - New Technology Configuration: Cooled Low Pressure EGR
- Gasoline Exhaust Gas Recirculation (EGR) System Comparison
  - Lead Case Study: **#3203A** Midsize to Large Passenger Vehicle
    - Baseline Technology Configuration: No External EGR
    - New Technology Configuration: Cooled Low Pressure EGR

In addition to the new technology configurations listed above, a Toyota Venza mass-reduction and cost analysis project was also conducted. The project, similar in work scope to the phase 1 ICCT analysis, focused on the transfer and conversion of information and results from a North American analysis into a comparable European analysis. The North American analysis was co-funded by ICCT and the Unites States EPA.

The primary objective of the EPA and ICCT North American Toyota Venza Mass-reduction and cost analysis project was to evaluate, and build upon the mass-reduction opportunities presented in a prior published Lotus Engineering report. The report, entitled "An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program," was submitted to the Internal Council on Clean Transportation for release during March 2010.

The target mass-reduction for the project was 20% of the baseline vehicle mass (1710kg) or approximately 342kg. In addition to evaluating various mass-reduction ideas for functional and performance feasibility, manufacturing feasibility was also evaluated ensuring the mass-reduction concepts could be implementation ready for the 2017 timeframe. Using the same costing methodology as in previous EPA and ICCT studies, detailed cost models were developed to assess the financial impact of the mass-reduction concepts. The maximum allowable increase in direct manufacturing costs was set at 10% or approximately $1670.

A report summarizing the work completed on the Toyota Venza mass-reduction and cost analysis, based on a European manufacturing cost structure, will be issued in the later part of 2012.

B.3 Process Overview

As discussed, **Section B.1,** the costing methodology is broken into three (3) high level steps:

1. Develop Net Incremental Direct Manufacturing Cost for selected technology configurations and lead vehicle segments.
2. Develop and apply scaling factor to translate costs from lead case study vehicle segment to alternative vehicle segments
3. Apply Learning Factors and Indirect Cost Multiplier (ICMs) to Net Incremental Direct Manufacturing Costs, to each technology configuration and vehicle segment analyzed, establishing the Net Incremental Technology Costs for each technology and vehicle segment combination.

Additional details on each of the high levels steps discussed above are covered in the following three (3) subsections.

B.3.1 Development of Net Incremental Direct Manufacturing Costs

The Net Incremental Direct Manufacturing Costs (NIDMCs) costing methodology is based heavily on teardowns of both new and baseline technology configurations that have similar driving performance metrics. Only components identified as being different, within the selected new and baseline technology configurations, as a result of the new technology adaptation are evaluated for cost. Component costs are calculated using a ground-up costing methodology analogous to that employed in the automotive industry. All incremental costs for the new technology are calculated and presented using transparent cost models consisting of eight (8) core cost elements: material, labor, manufacturing overhead/burden, end item scrap, SG&A (selling general and administrative), profit, ED&T (engineering, design, and testing), and packaging.

As presented in **Section B.2**, seven advance powertrain technology configurations were evaluated. For each technology configuration a vehicle segment was chosen for the lead case study. Selection of the lead vehicle segment was generally based on ”best-fit” of technology based on FEV technical team input, and availability of good comparison hardware for both the baseline and new technology configurations.

For the ICCT analysis, six (6) primary vehicle segments were considered relative to adding new advanced powertrain technology configurations. The vehicle segment ID, segment descriptions, and vehicle examples representative of the segment are shown in **Table B-1** below. In some cases vehicle segments were further subdivided; primarily on typical engine configurations available in the vehicle segment. A letter following the vehicle segment (i.e., 00A) is used to designate engine configuration differences within the vehicle segment.

Table B-1: Vehicle Segments Classification Defined in Analysis

Vehicle Segment ID	Vehicle Segment Description	Typical Engine Configuration	Vehicle Examples
00A	Subcompact Passenger Vehicle	Inline Three Cylinder (I3) Engine	VW Polo, Ford Fiesta
00B	Subcompact Passenger Vehicle	Inline Four Cylinder (I4) Engine	VW Polo, Ford Fiesta
01	Compact or Small Passenger Vehicle	Inline Four Cylinder (I4) Engine	VW Golf, Ford Focus
02	Midsize Passenger Vehicle	Inline Four Cylinder (I4) Engine	VW Passat, BMW 3 Series
03A	Midsize or Large Passenger Vehicle	Inline Four Cylinder (I4) Engine	VW Sharan, BMW 5 Series
03B	Midsize or Large Passenger Vehicle	Inline Six Cylinder (I6) Engine	VW Sharan, BMW 5 Series
04	Executive, Large Size Passenger Vehicle (Not Included in Analysis)		
05	Small or Midsized, Sport Utility, or Cross Over, or Mini Van Vehicle	Inline Four Cylinder (I4) Engine	VW Tiguan, BMW X1/X3
06A	Large Sport Utility Vehicle	Inline Six Cylinder (I6) Engine	VW Touareg, BMW X5/X6
06B	Large Sport Utility Vehicle	V-Eight Cylinder (V8) Engine	VW Touareg, BMW X5/X6

Listed below, with the aid of **Figure B-4** and **Figure B-5,** is a high-level summary of the thirteen (13) major steps taken during the EPA detailed teardown cost analysis process. A comprehensive discussion of the costing methodology used to develop the Net Incremental Direct Manufacturing Cost can be found in the EPA published report "Light-Duty Technology Cost Analysis Pilot Study" (EPA-420-R-09-020).

For additional information concerning the terminology used within these steps, please reference the glossary of terms at the end of this report.

Step 1: Using the ***Powertrain-Vehicle Class Summary Matrix (P-VCSM)***, a technology configuration and vehicle segment is selected for cost analysis.

Step 2: Existing vehicle models, representing the new technology configuration (i.e., the advance technology offering) and a baseline vehicle technology configuration (i.e., current technology becoming the standard in the industry), are identified for teardown to provide the basis for detailed incremental cost calculations.

Step 3: Pre-teardown ***Comparison Bills of Materials (CBOMs)*** are developed, covering hardware that exists in the new and base technology configurations. These high-level CBOMs are informed by the team's understanding of the new and base technologies and serve to identify the major systems and components targeted for teardown.

Step 4: Phase 1 (high-level) teardown (**Figure B-2**) is conducted for all subsystems identified in Step 3 and the assemblies that comprise them. All high-level processes (e.g., assembly process of the high-pressure fuel pump onto the cylinder head assembly) are recorded during the disassembly.

Figure B-2: Sample of Components Removed During High Level Teardown of Fuel Induction System

Step 5: A ***cross-functional team (CFT)*** reviews all the data generated from the high-level teardown and identifies which components and assumptions should be carried forward into the cost analysis. The CBOMs are updated to reflect the CFT input.

Step 6: When conducting the cost analysis for each technology configuration, a number of assumptions and boundary conditions are required up front in the analysis prior to the start of any costing work. The same assumptions and boundary conditions are applied to both the new and baseline technology configurations, establishing a consistent framework for all costing, thereby resulting in a level playing field for comparison. These boundary conditions include items such as average annual production volumes, manufacturing locations, production year, and technology maturity.

Step 7: Phase 2 (component/assembly level) teardowns are initiated based on the updated CBOMs. Components and assemblies are disassembled and processes and operations are mapped in full detail. Photographs of the disassembly process and individual parts are captured in **Figure B-3**. The CBOMs are updated with the additional parts acquired from the further level of teardown. At this level of teardown component physical attributes are gathered, component materials established, and manufacturing process identified.

Nr.	Component
	Nozzle module incl.
1	--Nozzle body
2	--Nozzle needle
3	--Supporting
4	--Needle bushing
5	--Nozzle spring
	Servo valve plate incl.
6	--Plate
7	--Servo valve
8	--Servo valve spring
9	Adapter plate
10	--Positioning pins
	Coupler Module incl.
11	--Tube Spring
12	--Driving piston
13	--Driven piston incl. Spring
14	--Spring driven piston
15	--Adapter plate
16	--Coupler body
17	Clamping nut
18	Adjustment plate coupler
19	Injector body
20	Piezo module
21	Edgefilter
22	Seal ring
23	Connector body incl.
24	--Return line connector
25	Thread seal

Figure B-3: Initial Level of Injector Teardown

<u>Step 8:</u> During the teardown process, all manufacturing operations are captured including all key part input data and part specific manufacturing data. For simpler processes and/or serial type processes, DFMA® software is used to calculate part manufacturing data based on entered part attribute data. For more complex and custom operations and processes, external process parameter models are developed.

In the custom process parameter models, which are developed using Microsoft Excel, part input parameters (e.g., material specifications, mass, volume, part geometry, part features, etc.) are fed into the models generating key output parameters (e.g., equipment type, equipment size, operation cycle times, material usage, etc.).

Subject matter experts develop and validate the process parameter models. Models are refined and validated by running surrogate parts through the analysis, which have existing industry data.

The key calculated manufacturing process data is then uploaded into MAQS worksheets **(Step 9)** to develop the final manufacturing cost.

<u>Step 9:</u> ***Manufacturing Assumption and Quote Summary (MAQS) worksheets*** are generated for all parts undergoing the cost analysis. The MAQS details all cost elements making up the final unit costs: material, labor, burden, end item scrap, SG&A, profit, ED&T, and packaging.

Step 10: Parts with high or unexpected cost results are subjected to a ***marketplace cross-check,*** such as comparison with supplier price quotes or wider consultation with company and industry resources (i.e., subject matter experts) beyond the CFT.

Step 11: All costs calculated in the MAQS worksheets are automatically inputted into the ***Subsystem Cost Model Analysis Templates (CMAT)***. The Subsystem CMAT is used to display and roll up all the differential costs associated with a subsystem. For example, the crank-drive subsystem (reference **Figure B-6**) is comprised of several sub-subsystems (e.g., connecting rod sub-subsystem, piston sub-subsystem, crankshaft sub-subsystem). The sub-subsystems comprise of several components and assemblies. As shown in **Figure B-6,** the Connecting Rod sub-subsystem contains several components, including the rod-connecting, cap-rod connecting, bearing-rod connecting, and bolt-rod connecting. In the Subsystem CMAT Component/Assembly costs are grouped together in their respective sub-subsystems, which, in turn, are grouped together providing an incremental subsystem cost.

All parts in a subsystem that are identified for costing in the CBOM are entered into the Subsystem CMAT. Also, both the base and new technology configurations are included in the same CMAT to facilitate differential cost analysis.

Step 12: The ***System CMAT*** rolls up all the subsystem differential costs to establish a final system unit cost. The System CMAT, similar in function to the subsystem CMAT, is the document used to display and roll-up all the subsystem costs associated within a system as defined by the CBOM. In a System CMAT only the rolled-up subsystem costs are provided. For example, for the engine system (**Figure B-6**), the CMAT would capture the cost contribution of each major subsystem: crank-drive subsystem, cylinder block subsystem, cylinder head subsystem, valvetrain subsystem, etc. In many study cases, the cost analysis is based on comparing the cost differences for a single system (i.e., new engine technology configuration versus baseline engine). In these single system case studies, the system CMAT provides the incremental direct manufacturing impact.

Step 13: In case studies where multiple vehicle systems are evaluated, a vehicle level CMAT is required to capture the vehicle Net Incremental Direct Manufacturing Cost (NIDMC) impact. In a vehicle CMAT, sub-totals for each vehicle system are presented along with a total vehicle incremental direct manufacturing cost. **Figure B-6** highlights some of the systems which are found in a vehicle analysis, such as Engine, Transmission, Body, and Suspension.

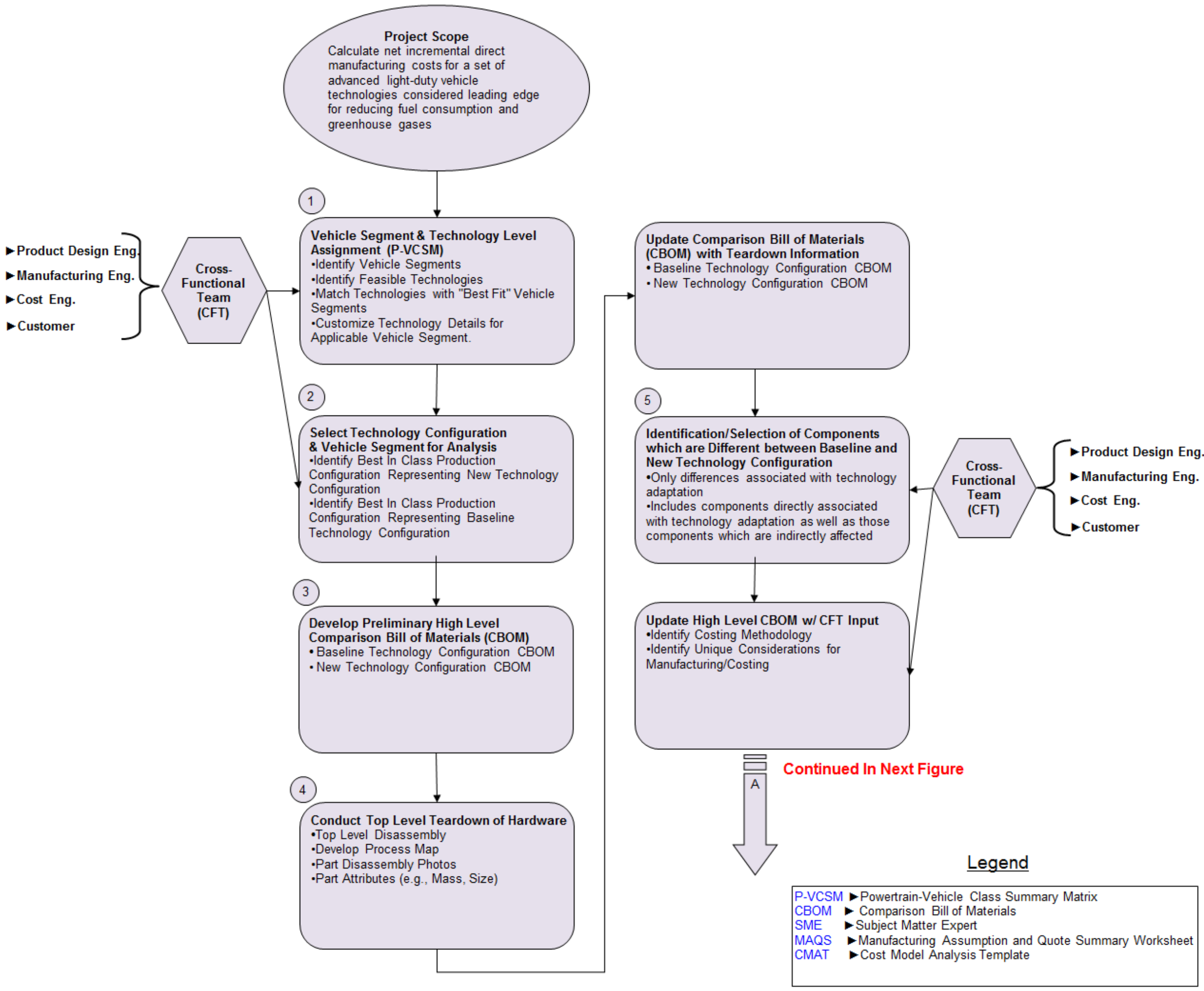


Figure B-4: Step 1 - Calculate Net Incremental Direct Manufacturing Costs, for Selected Advance Powertrain Technology Configurations, for Selected Vehicle Segments Interaction (Part 1 of 2)

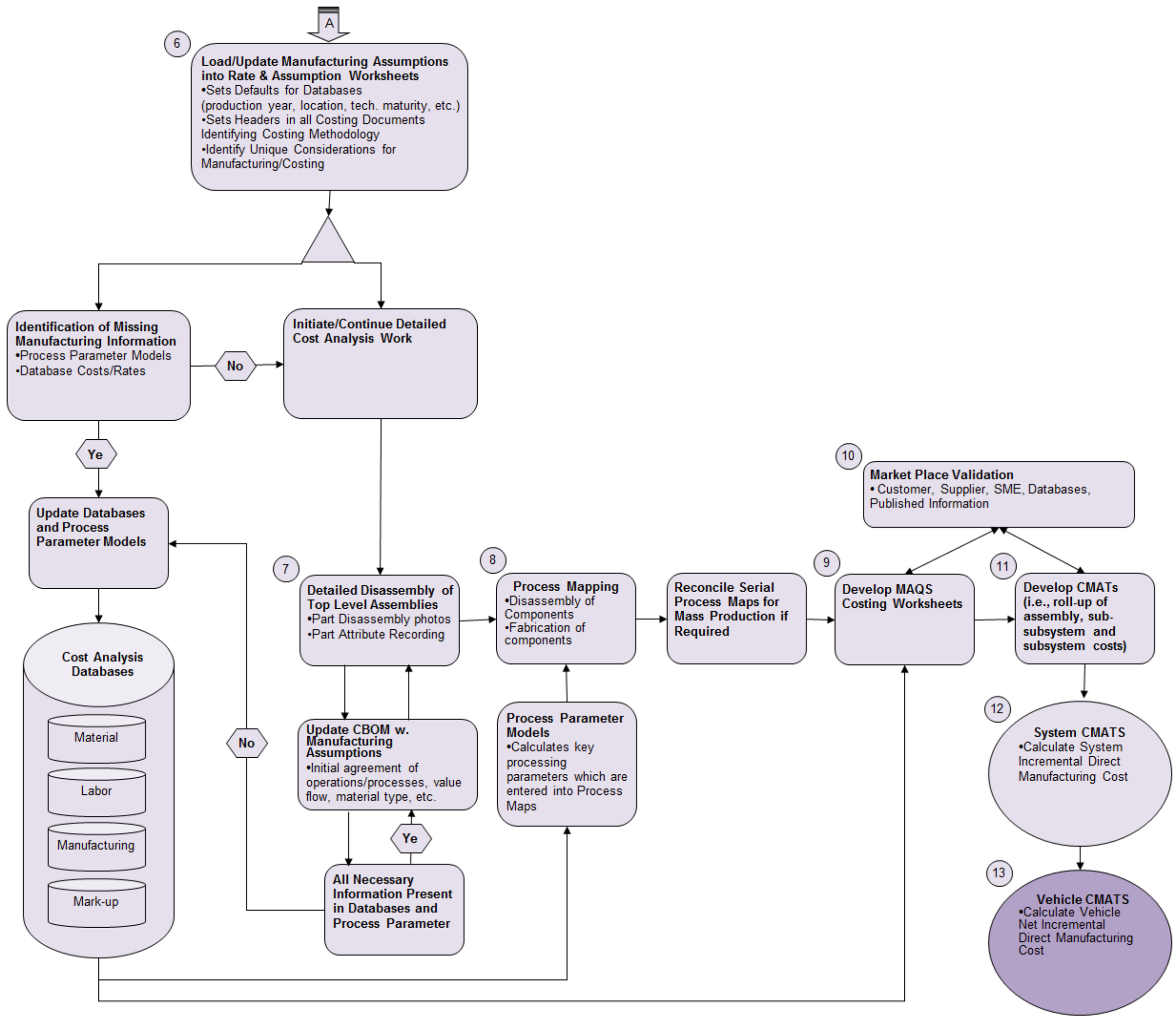


Figure B-5: Step 1 - Calculate Net Incremental Direct Manufacturing Costs, for Selected Advance Powertrain Technology Configurations, for Selected Vehicle Segments Interaction (Part 2 of 2)

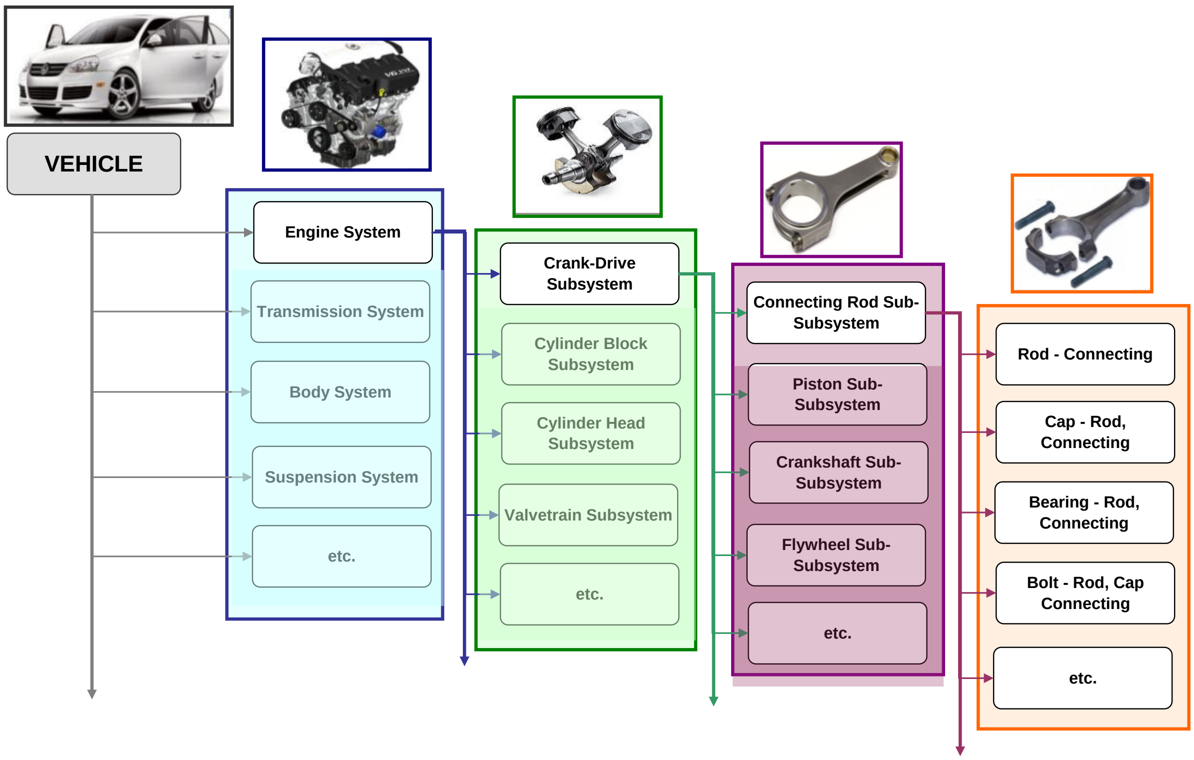


Figure B-6: Illustration of Bill of Material Structure used in Cost Analysis

B.3.2 Development and Application of Scaling Factors to Translate NIDMC from Lead Case Study to Alternative Vehicle Segments

In order to calculate the cost impact of a new technology configuration on multiple vehicle segments a cost scaling process was employed. Physical attributes (e.g. quantity, mass, geometric size) and performance attributes (e.g. torque, power) of the technology under evaluation, are analyzed between the lead case study vehicle segment and the remaining vehicle segment. Based on identified attributes differences, cost scaling factors are established to translate the Net Incremental Direct Manufacturing Costs (NIDMCs) from the lead case study vehicle segment to alternative vehicle segments.

Listed below, with the aid of **Figure B-7**, is a summary of the steps required to scale the NIDMCs between different vehicle segments.

Step 1: Select previously complete net incremental direct manufacturing cost case study (i.e., technology configuration and vehicle segment) for scaling analysis. In order to conduct a scaling analysis, a detailed direct manufacturing cost analysis (minimum one) must first be completed.

Step 2: Identify alternative vehicle segments where the new technology configuration may also be adoptable. New advance technology configurations may be a better fit for selected vehicle segments. For example, dry dual clutch transmissions (DCTs) today are generally limited to smaller car segments as a result of lower torque specifications facilitating the ability to achieve smooth shift quality. As DCT technology advances, the hope is dry DCT technology can infiltrate larger vehicle segments.

For this cost analysis, FEV made the general assumption that all technologies evaluated could be integrated into each of the six vehicle segments evaluated. No consideration was given to the technology hurdles required to make this possible and the timeframe which it could happen.

Step 3: For each technology configuration, identify physical and performance attribute differences in the hardware which exist between the lead case study vehicle segment and the alternative vehicle segments. The level (e.g. system, subsystem, sub-subsystem/ assembly) at which scaling factors are developed is dependent on the technology. For technology configurations where the hardware differences between vehicle segments is uniformly upsized or downsized based on performance attributes (e.g. power, torque), scaling factors are developed at the subsystem and/or system level. An example of this higher level scaling methodology was conducted on the dry dual clutch transmission analysis. For technology configurations where non-uniformity of both physical and performance attributes exist, such as the engine downsizing analysis, a more detailed scaling methodology is employed. For example in the engine downsizing analysis, the valvetrain component differences between an I4 and I3, and V8 and I6, are considerably different. Some component costs can be adjusted based on part usage counts, where others are adjusted for cost based on physical changes to the part. In the engine downsizing analysis, developing scaling factors at the sub-subsystem/assembly level was required to accurately translate the NIDMCs to other vehicle segments. The scaling factors used in each analysis are included in the case study results section, **Section E**.

Step 4: Cost Model Analysis Templates (CMATs), at all applicable levels (i.e., sub-subsystem, subsystem, system, and vehicle), for all lead case-studies, are updated to include the selected alternative vehicle segments. The scaling factors derived in step three (3) are also uploaded into the CMAT worksheets.

Step 5: In the final step, the calculated scaling factors are applied to the lead case study incremental direct manufacturing costs to arrive at the net incremental direct manufacturing costs for the alternative selected vehicle segments.

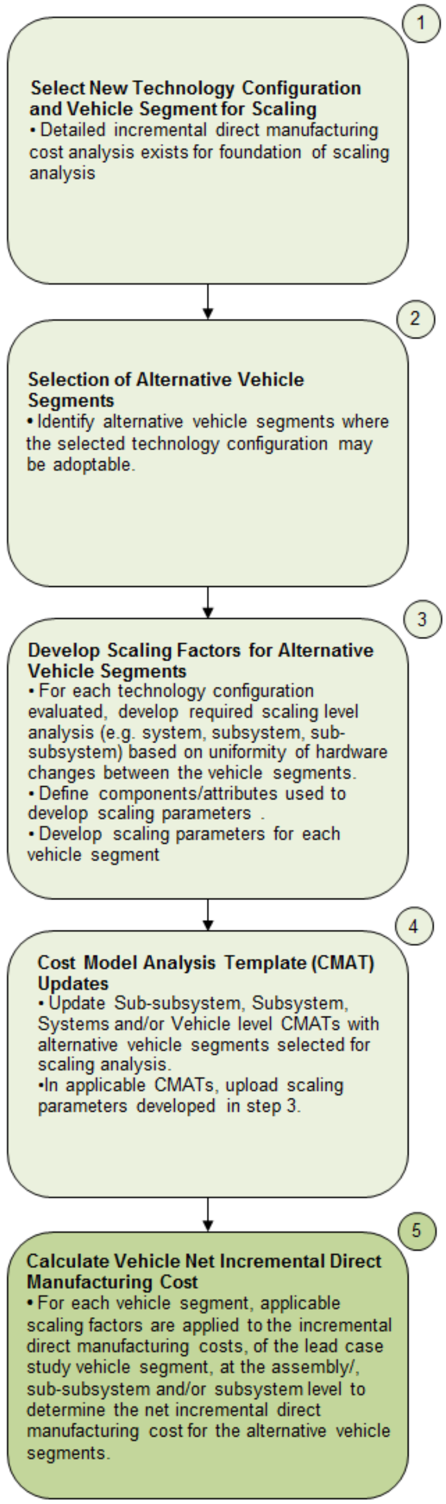


Figure B-7: Process Step Overview for Scaling Incremental Direct Manufacturing Costs to Alternative Vehicle Segments

B.3.3 Application of Learning Factors and Indirect Cost Multiplier (ICMs) to Net Incremental Direct Manufacturing Costs

Two factors, both production-year dependent, are applied to the NIDMCs to arrive at Net Incremental Technology Costs (NITC). The NITC is the estimated incremental cost an OEM would be expected to sell the new technology configuration at, relative to the baseline technology configuration, in a given production year.

The indirect cost multiplier (ICM) factor addresses the OEM indirect costs associated with manufacturing new components and assemblies. At a high level, the costs to an OEM, associated with implementation of a new vehicle technology, can be broken into two (2) categories: direct manufacturing costs and indirect costs. The "net incremental direct manufacturing cost," as defined in the context of this project, includes all the direct costs to the OEM to add the new technology configuration to the baseline configuration. The indirect costs (costs associated with OEM research and development, corporate operations, dealership support, sales and marketing material, legal, and OEM owned tooling) are calculated by applying an ICM factor to the direct manufacturing cost.

The ICM methodology and values was first developed by the United States EPA as an alternative method for accounting indirect costs to the existing retail price equivalent (RPE) methodology. The EPA felt that some of the contributors to RPE, like fixed depreciation costs, health care costs of retired workers, and pension costs, may not be affected by the addition of all new vehicle technologies as a result of imposed regulation. Hence, the EPA developed this modified multiplier referred to as the ICM. In addition, the EPA developed a range of ICMs accounting for differences in technology complexity levels and technology maturity. More details on the development of ICMs can be found in the EPA published report "Automobile Industry Retail Price Equivalent and Indirect Cost Multiplier" EPA-420-R-09-003, February 2009.

For the ICCT phase 2 analysis, the EPA provided the recommended ICM values. As mentioned, there is a range of ICM factors utilized, dependent on technology complexity and production maturity. The ICM values used for each technology evaluated in the ICCT European analysis are the same as those used by EPA and NHTSA in developing the "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards & Corporate Average Fuel Economy Standards". Reference EPA & NHTSA report EPA-420-D-11-901, November 2011 for additional details on the development and application of ICM factors.

In addition to the application of the indirect cost multiplier, to the incremental direct manufacturing cost, a second factor referred to as "the learning curve factor," or "experience curve factor," is also applied. The learning curve factor addresses the anticipated reduction in direct manufacturing costs as a result of "getting smarter" on the product design and /or manufacturing of the product as a function of the number of units produced. The number of units produced can also be represented by the number of years in production. From the product design side, an increase in the familiarity of the product, including interaction within the vehicle systems, allows the product engineer team to refine designs and find lower-cost solutions for similar function. The design modifications may include material substitutions, simplification of parts, reduction of parts, and the adaptation of lower-cost technology alternatives. In addition to design modifications that can drive down the cost, continuous improvements in production can also have significant impact on unit cost reductions. The savings can range from increased efficiencies in various manufacturing operations (e.g., combining operations, reducing part handling, reducing machine takt times) to improving first time yield (i.e., reducing quality defects and rework), to the reducing procurement costs of Tier 2 and Tier 3 components.

Similar to the acquisition of the ICMs values, learning factors developed by EPA for the "Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards & Corporate Average Fuel Economy Standards", were also utilized in the ICCT analysis.

As with the phase 1 analysis, one modification was made in application of learning factors in the ICCT analysis relative to the methodology used by EPA. For new technology configurations which resulted in a savings relative to the baseline technology configuration, the learning factor was held constant at one (1) for all production years evaluated (i.e., 2012 thru 2025). This signifies no change in cost savings as the technology matures. In contrast, the EPA methodology treats new technology configurations with a cost increase or decrease the same. The learning factors are assigned based on technology complexity and maturity; impartial to cost impact. Based on the EPA methodology, a new technology configuration which has a direct manufacturing cost savings over the baseline configuration will have less of a savings in the future relative to the present.

Similar to indirect cost multipliers (ICMs), different curves were applied to different technologies based on several factors including technology complexity and maturity in the market place.

Listed below, and support with **Figure B-8**, is an overview of the process steps required to calculate the Net Incremental Technology Costs (NITC).

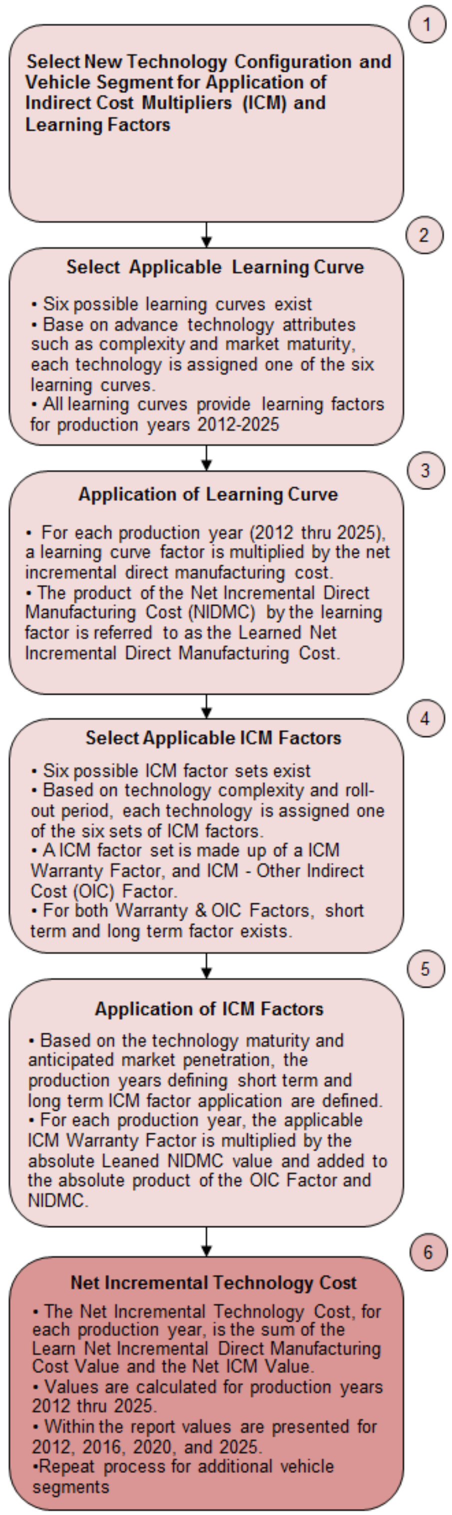


Figure B-8: Process Steps to Develop Net Incremental Technology Cost

Step 1: Select technology configuration and load in the Net Incremental Direct Manufacturing Costs (NIDMCs) for each of the vehicle segments evaluated. To help illustrate the process flow key sections of the NITC calculator template, for the addition of stop-start system technology to a conventional powertrain, are referenced (**Figure B-9** below**)**.

New Technology Configuration: Addition of Stop-Start System Technology
Case Study Number: 30XX

NIDMC	€ 298.17
Learning Curve	
ICM Complexity	
ICM Term Date	

ICM-Warranty		ICM-Other Indirect Costs	
Short Term	Long Term	Short Term	Long Term

	2012	2013	2014	2015	2016	2017	2018	2019
Learning factors								
L-NIDMC	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Indirect costs	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total costs	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00

Vehicle Segment ID	NIDMC	Net Incremental Technology Costs							
		2012	2013	2014	2015	2016	2017	2018	2019
00A	€ 298.17								
00B	€ 298.17								
01	€ 310.58								
02	€ 329.02								
03A	€ 351.71								
03B	€ 351.71								
05	€ 337.17								
06A	€ 386.82								
06B	€ 386.82								

Figure B-9: Net Incremental Technology Cost Calculator Template w/ NIDMCs Loaded

Step 2: Based on technology attributes such as complexity and market maturity, each technology is assigned one of six (6) possible learning curves. For the phase 2 ICCT analysis (similar to the phase 1 analysis approach), recommendations on which learning curves best suited each technology configuration were provided by United States EPA. For the Stop-Start technology system, learning curve 16 was selected as shown in **Figure B-10** below. Leaning factors, corresponding to learning curve 16, are loaded into the NITC calculator template.

Step 3: Learned Net Incremental Direct Manufacturing Costs (L-NIDMCs) are calculated for each year by multiply the learning factors for each year by the Net Incremental Direct Manufacturing Cost (NIDMC). In **Figure B-10**, the L-NIDMC for 2012 is €465.89 (1.56LF x €298.17 NIDMC)

New Technology Configuration: Addition of Stop-Start System Technology
Case Study Number: 30XX

NIDMC	€ 298.17
Learning Curve	16
ICM Complexity	
ICM Term Date	

ICM-Warranty		ICM-Other Indirect Costs	
Short Term	Long Term	Short Term	Long Term

	2012	2013	2014	2015	2016	2017	2018	2019
Learning factors	1.56	1.56	1.25	1.00	1.00	0.97	0.94	0.91
L-NIDMC	€ 465.89	€ 465.89	€ 372.71	€ 298.17	€ 298.17	€ 289.22	€ 280.55	€ 272.13
Indirect costs	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
Total costs	€ 465.89	€ 465.89	€ 372.71	€ 298.17	€ 298.17	€ 289.22	€ 280.55	€ 272.13

Vehicle Segment ID	NIDMC	Net Incremental Technology Costs							
		2012	2013	2014	2015	2016	2017	2018	2019
00A	€ 298.17								
00B	€ 298.17								
01	€ 310.58								
02	€ 329.02								
03A	€ 351.71								
03B	€ 351.71								
05	€ 337.17								
06A	€ 386.82								
06B	€ 386.82								

Figure B-10 : Net Incremental Technology Cost Calculator Template w/ L-NIDMCs

Step 4: ICM factors and the ICM Term Date values are selected. The ICM Term Date is the date when the ICM factors flips from short-term to long-term. Similar to the learning curves, the US EPA provided recommendations on the ICM and ICM Term Date values for each technology configuration analyzed in the ICCT phase 2 work. For the stop-start system technology analysis, the Medium 2 ICM factors with a Term Date of 2018 were recommended (**Figure B-11** below).

Step 5: ICM factors are applied to the NIDMCs and L-NIDMCs to arrive at Indirect cost contribution. The indirect cost contribution for production year "X" is calculated by summing the product of the "ICM-Warranty Factor" and "L-NIDMC" (for production year "X") and adding it to the product of the "ICM-Other Indirect Costs" and "NIDMC". For production year 2014, the indirect cost contribution equals €118.79 [(0.045 x €372.71) + (0.343 x €298.17)}]. **Figure B-11** below provides the referenced values.

For production years 2012 through 2018, short-term ICM factors are utilized. Long-term ICM factors are used for production years 2019 through 2025 as defined by the ICM Term Date.

New Technology Configuration: Addition of Stop-Start System Technology
Case Study Number: 30XX

NIDMC	€ 298.17
Learning Curve	16
ICM Complexity	Medium 2
ICM Term Date	2018

ICM-Warranty		ICM-Other Indirect Costs	
Short Term	Long Term	Short Term	Long Term
0.045	0.031	0.343	0.259

	2012	2013	2014	2015	2016	2017	2018	2019
Learning factors	1.56	1.56	1.25	1.00	1.00	0.97	0.94	0.91
L-NIDMC	€ 465.89	€ 465.89	€ 372.71	€ 298.17	€ 298.17	€ 289.22	€ 280.55	€ 272.13
Indirect costs	€ 122.94	€ 122.94	€ 118.79	€ 115.46	€ 115.46	€ 115.06	€ 114.68	€ 85.57
NITC/Total Costs								

Vehicle Segment ID	NIDMC	Net Incremental Technology Costs							
		2012	2013	2014	2015	2016	2017	2018	2019
00A	€ 298.17								
00B	€ 298.17								
01	€ 310.58								
02	€ 329.02								
03A	€ 351.71								
03B	€ 351.71								
05	€ 337.17								
06A	€ 386.82								
06B	€ 386.82								

Figure B-11: Net Incremental Technology Cost Calculator Template w/ Indirect Costs

<u>**Step 6:**</u> For each production year, Net Incremental Technology Costs (NITC) are derived by summing the Learned Net Incremental Direct Manufacturing Costs (L-NIDMC) with the Indirect Costs for each production year. The process is repeated for each vehicle segment within the evaluated technology configuration (**Figure B-12**)

New Technology Configuration: Addition of Stop-Start System Technology
Case Study Number: 30XX

NIDMC	€ 298.17
Learning Curve	16
ICM Complexity	Medium 2
ICM Term Date	2018

ICM-Warranty		ICM-Other Indirect Costs	
Short Term	Long Term	Short Term	Long Term
0.045	0.031	0.343	0.259

	2012	2013	2014	2015	2016	2017	2018	2019
Learning factors	1.56	1.56	1.25	1.00	1.00	0.97	0.94	0.91
L-NIDMC	€ 465.89	€ 465.89	€ 372.71	€ 298.17	€ 298.17	€ 289.22	€ 280.55	€ 272.13
Indirect costs	€ 122.94	€ 122.94	€ 118.79	€ 115.46	€ 115.46	€ 115.06	€ 114.68	€ 85.57
NITC/Total Costs	€ 588.83	€ 588.83	€ 491.50	€ 413.63	€ 413.63	€ 404.29	€ 395.22	€ 357.70

Vehicle Segment ID	NIDMC	Net Incremental Technology Costs							
		2012	2013	2014	2015	2016	2017	2018	2019
00A	€ 298.17	€ 588.83	€ 588.83	€ 491.50	€ 413.63	€ 413.63	€ 404.29	€ 395.22	€ 357.70
00B	€ 298.17	€ 588.83	€ 588.83	€ 491.50	€ 413.63	€ 413.63	€ 404.29	€ 395.22	€ 357.70
01	€ 310.58	€ 613.34	€ 613.34	€ 511.96	€ 430.85	€ 430.85	€ 421.12	€ 411.67	€ 372.59
02	€ 329.02	€ 649.75	€ 649.75	€ 542.35	€ 456.43	€ 456.43	€ 446.12	€ 436.12	€ 394.71
03A	€ 351.71	€ 694.57	€ 694.57	€ 579.76	€ 487.91	€ 487.91	€ 476.89	€ 466.20	€ 421.93
03B	€ 351.71	€ 694.57	€ 694.57	€ 579.76	€ 487.91	€ 487.91	€ 476.89	€ 466.20	€ 421.93
05	€ 337.17	€ 665.86	€ 665.86	€ 555.79	€ 467.74	€ 467.74	€ 457.17	€ 446.93	€ 404.49
06A	€ 386.82	€ 763.89	€ 763.89	€ 637.62	€ 536.61	€ 536.61	€ 524.48	€ 512.73	€ 464.04
06B	€ 386.82	€ 763.89	€ 763.89	€ 637.62	€ 536.61	€ 536.61	€ 524.48	€ 512.73	€ 464.04

Figure B-12: Net Incremental Technology Cost Calculator Template – Complete

B.4 Manufacturing Assumption Overview

For all case studies evaluated, a universal set of assumptions was developed in order to establish a constant framework for all costing. A common framework for all costing permitted reliable comparison of costs between (1) new and baseline technology configurations evaluated in the same analysis, and (2) between competing new technology configurations from two different analyses. In addition, having a good understanding of the analysis boundary conditions (i.e., what assumptions are made in the analysis, the methodology utilized, what parameters are included in the final numbers, etc.), a fair and meaningful comparison can be made between results developed from alternative costing methodologies and/or sources.

Table B-2 captures the primary universal cost analysis assumptions which are applicable to all technology configurations evaluated for the European analysis.

As captured in **Table B-2**, Germany labor rates were used for both the phase 1 and phase 2 analyses. To understand the potential impact of lower labor costs on the net incremental technology costs for each analysis, a sensitivity analysis was performed. Labor costs were reduced by 76.7% adjusting for the difference between Germany’s labor rates and rates more typical of Eastern Europe. During the 3rd quarter of 2012, a summary report will be released summarizing the phase 1 and phase 2 technology costs as originally calculated. In addition this report will include the labor rate sensitivity analysis for both phase 1 and phase 2 case studies.

Table B-2: Universal Case Study Assumption Utilized in European Analysis

Item	Description	Universal Case Study Assumptions
1	Incremental **Direct** Manufacturing Costs	A. Incremental **Direct** manufacturing cost is the incremental difference in cost of components and assembly, to the OEM, between the new technology configuration and the baseline technology configuration. B. This value does not include **Indirect** OEM costs associated with adopting the new technology configuration (e.g., tooling, corporate overhead, corporate R&D, etc.).
2	Incremental **Indirect** OEM Costs and the Indirect Cost Multiplier (ICM)	A. Indirect OEM Costs are handled through the application of "Indirect Cost Multipliers" (ICMs) which are applied outside the direct manufacturing cost models. The ICM covers items such as: a. OEM corporate overhead (e.g., sales, marketing, warranty, etc.) b. OEM engineering, design, and testing costs (internal and external) c. OEM owned tooling B. Reference EPA report EPA-420-R-09-003, February 2009, "Automobile Industry Retail Price Equivalent and Indirect Cost Multiplier" for additional details on the development and application of ICM factors.
3	Product/Technology Maturity Level and the Learning Factor	A. Mature technology assumption, as defined within this analysis, includes the following: a. Well-developed product design b. High production volume c. Products in service for several years at high volumes c. Significant marketplace competition B. Mature Technology assumption establishes a consistent framework for costing. For example, a defined range of acceptable mark-up rates: a. End-item-scrap 0.3-0.7% b. SG&A/Corporate Overhead 6-7% c. Profit 4-8% d. ED&T (Engineering, Design, and Testing) 0-6% C. The technology maturity assumption does not include allowances for product learning within the cost models. Learning curve factors are applied outside the cost models to the calculated incremental direct manufacturing cost for each analysis. The value of the applicable learning factor is dependent on parameters such as technology complexity and market inception date.

Item	Description	Universal Case Study Assumptions
4	Selected Manufacturing Processes and Operations	A. All operations and processes are based on existing standard/mainstream industrial practices. B. No additional allowance is included in the incremental direct manufacturing cost models for manufacturing learning. Learning curve factors, applied to the final incremental direct manufacturing cost, cover both product and manufacturing learning.
5	Annual Capacity Planning Volume	450,000 units
6	Supplier Manufacturing Location	Germany
7	OEM Manufacturing Location	Germany
8	Manufacturing Cost Structure Timeframe (e.g., Material Costs, Labor Rates, Manufacturing Overhead Rates)	2010/2011 production year rates
9	Packaging Costs	A. Calculated on all Tier One (T1) supplier level components. B. For Tier 2/3 (T2/T3) supplier level components, packaging costs are included in T1 mark-up of incoming T2/T3 incoming goods.
10	Shipping and Handling	A. T1 supplier shipping costs covered through application of the Indirect Cost Multiplier (ICM) discussed above. B. T2/T3 to T1 supplier shipping costs are accounted for via T1 mark-up on incoming T2/T3 goods.
11	Intellectual Property (IP) Cost Considerations	Where applicable, IP costs are included in the analysis. Based on the assumption that the technology has reached maturity, sufficient competition would exist suggesting alternative design paths to achieve similar function and performance metrics would be available minimizing any IP cost penalty.
12	Material Cost Reductions (MCRs) on analyzed hardware	Only incorporated on those components where it was evident that the component design and/or selected manufacturing process was chosen due to actual low production volumes (e.g., design choice made to accept high piece price to minimize tooling expense). Under this scenario, assumptions where made and cost analyzed assuming high production volumes.
13	Operating and End-of-Life Costs	No new, or modified, maintenance or end-of-life costs, were identified in the analysis.
14	Stranded Capital or ED&T expenses	No stranded capital or non-recovered ED&T expenses were considered within the scope of this analysis. It was assumed the integration of new technology would be planned and phased in minimizing non-recoverable expenses.

C. Database Updates

To develop Net Incremental Direct Manufacturing Costs parameterized models are utilized. The models are transparent and flexible, thus making them powerful tools for understanding the cost drivers associated with the manufacturing of a particular part. The cost model template is also referred to as a manufacturing assumption-quote summary (MAQS) worksheet. The MAQS worksheet is used to assemble and organize key manufacturing process and cost data, and calculate the direct manufacturing cost. In many aspects the MAQS worksheet is similar to an automotive OEM quote worksheet, with the exception that much more of the supporting manufacturing and costing data is included in the MAQS worksheet.

There are two (2) main sources of data which feed the MAQS worksheets: the process parameter models and cost model databases. The process parameter models support the cost models with key manufacturing data required for the cost analysis. Process parameters models determine outputs such as raw material usage, type and size of processing equipment, quantity of machinery required, number of operators required, and process takt time. Process parameter models used in the analysis include both custom and non-customs models. The non-custom models are supported with various industry available costing tools such as DFMA® and Facton®. Non-custom process parameter models are developed in Microsoft Excels. Manufacturing subject matter experts are utilized in constructing the models. They also support the team (e.g. manufacturing engineers, product engineers, cost engineering, component suppliers) in the validation of models.

The cost model databases support the cost models with the required financial data. For example, the material database contains all the materials referenced in the cost models along with the quoted material costs (e.g., cost/pound). The Labor Database provides loaded rates for the direct labor jobs references in the cost models. The Manufacturing Overhead (MOH) Database contains the hourly rates for the numerous pieces of equipment referenced in the cost models. In addition to the databases that support the Total Manufacturing Cost (TMC) (i.e., material, labor and manufacturing overhead), there are databases to address mark-ups and packaging costs. All values contained within the cost model database are based on Germany's 2010/2011 economic conditions.

There are five (5) databases total, containing a total of eight (8) different cost elements/factors (material, labor, manufacturing overhead, end-item-scrap, SG&A, profit, ED&T, and packaging). In the FEV costing process, the direct manufacturing cost is the summation of total manufacturing costs (TMC) plus mark-up plus packaging. The total manufacturing cost consists of material, labor, and manufacturing overhead costs; a database exists for each of these cost factors. The mark-up consists of end-item scrap, selling, general and administrative costs (SG&A), profit, and engineering, design and testing (ED&T). A single database addresses all four (4) mark-up factors. The fifth database is the packaging database.

For a detailed review of the direct manufacturing costing modeling methodology and tools (e.g., Manufacturing Assumption and Quote Summary (MAQS) worksheets, Cost Model Analysis Templates (CMATs), Costing Database, etc.) please reference the "Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1)" The phase 1 and phase 2 reports can be downloaded from the ICCT website (http://www.theicct.org/)

D. Case Study Results

Section D presents the incremental costs for the various technology configurations and vehicle segments evaluated. For each evaluation, the costs are provided both as Net Incremental Direct Manufacturing Costs (NIDMC) and Net Incremental Technology Costs (NITC), which includes the addition of the Indirect Cost Multiplier (ICM) Factor as well a Learning factor.

For each of the seven (7) technologies evaluated, the following topics are covered:

1. ***Technology Overview*** provides a high-level overview of the technology and some of benefits of the technology. Quantification of the fuel economy and emission benefits is outside the scope of the analysis.

2. ***Study Assumptions – Case Study Specific*** covers key attributes of the technology evaluated as part of the lead case study. Any modifications to the hardware evaluated, or important assumptions made as part of lead case study analysis, are documented in this section.

3. ***Study Hardware Boundary Conditions*** address which systems, subsystems, and sub-subsystems were considered and reviewed as part of the initial assessment on potential component differences between the new and baseline technology configurations.

4. ***Components Evaluated in the Analysis*** identifies the components evaluated as part of the incremental cost analysis. These are the components which are identified by the technical team as different (e.g., new, deleted, modified, etc.), between the new and baseline technology configurations, which are expected to drive a cost differential.

5. ***Cost Strategy Overview on Lead Case Study*** identifies the costing strategy/level for the majority of the components evaluated in the analysis. The “Costing Level” is generally referred to as “calculated” or “commodity.” Calculated component costs are derived from custom ground-up cost calculations. Different “Costing Types” are possible for calculated cost. For example, a full or absolute calculated cost of a component is equivalent to the full purchase cost of the component. A modification calculated cost only includes the ground-up cost calculation for the component modifications. Commodity component costs are acquired from FEV’s benchmark costing databases. Different “Costing Types” of commodity costs also exist. For example, a purchase commodity cost is a cost directly from the FEV database without any adjustments. Low-impact commodity costs are commodity costs that have been adjusted to account for differences between the components in the database versus the part in the analysis.

6. ***Vehicle Segment Scaling Methodology Overview*** provides details of the cost scaling factors used to translate the net incremental direct manufacturing costs from the lead case study to the additional vehicle segments.

7. ***Cost Analysis Results Summary*** section contains two summary tables of the incremental cost. The first table provides a summary of the NIDMCs for the each of the vehicle segments. The costs are summarized at the sub-subsystem and subsystem level for each vehicle segment. For each technology configuration, all six vehicle segments are evaluated. For some technology configurations, two NIDMCs are calculated for a single vehicle segment based on cost differences associated with different engine configurations (i.e., I3 compared to I4, I4 compared to I6, I6 compared to V8).

   The second cost summary table provides the NITCs for each of the vehicle segments evaluated. The NITCs are provided for production years 2012, 2016, 2020, and 2025. In addition, the ICM factors and Learning factors for the same production years (i.e., 2012, 2016, 2020, and 2025) are provided.

D.1 Engine Downsizing Analysis, Diesel Engines

D.1.1 Technology Overview

Against a background of discussions concerning CO_2 emissions and the expected tightening of CO_2 legislation worldwide, fuel consumption is an important factor in the design of new engines. Through innovative technology, conventional combustion engines still offer noteworthy fuel saving potential. State-of-the-art direct injection technology and downsizing, for example, have already led to dramatic increases in gasoline engine fuel economy. Diesel engines, likewise, are subject to similar requirements to further reduce fuel consumption.

Traditionally downsizing is an engine concept in which small displacement engines provide the same performance as engines with bigger displacement. In order to provide the same maximum performance, the engine with the smaller displacement is equipped with either a supercharger and/or a turbocharger. In the past, this concept was used primarily when only limited package space was available, which prevents packaging of bigger and more powerful powertrains. The cost factor of more advanced air induction systems had kept the market penetration of smaller, equivalently powered diesel engines from becoming mainstream. Over the last decade, advance turbocharging has grown significantly, making this technology more cost competitive in comparison to larger, conventional diesel engines.

In addition to the direct fuel economy improvements associated with engine downsizing (i.e., reduced friction, lower pumping losses, shifting operation to more efficient load points), smaller engines, from both weight and volume perspectives, can also help in areas like vehicle handling (e.g., improved weight distribution) and vehicle safety (e.g., engine compartment crush zones, vehicle-to-vehicle crash energy).

D.1.2 Study Assumptions – Case Study Specific

The target of this case study is an analysis of delta-costs between a mainstream I4 diesel engine and a downsized I3 diesel engine with higher BMEP and same engine power as the I4 engine.

The technical definition of the baseline and downsized engine taken into account for the comparison are listed in **Table D-1**.

Table D-1: Comparison of Baseline and Downsized Engine

	Baseline Engine (I4)	Downsized Engine (I3)
Displacement	2 l	1,5 l
Power Output	105 kW	105 kW
Power Output per liter	52,5 kW/l	70 kW/l
Max. Torque	320 Nm	320 Nm
BMEP	20 bar	27 bar
Compression ratio	16,5	15,5
Injection System	1800 bar Piezo	2500 bar Piezo
EGR-System	HP-EGR	HP-EGR
Intercooler	Yes	Yes (10% more cooling power)
Swirl Flap Mechanism	No	Yes
Mass balancing	2 shafts with intermediate gear	One shaft with counter weight
Peak Firing Pressure	150 bar	180 bar
Cylinder Block Material	Aluminum	Aluminum
Cylinder Head Material	Aluminum	Aluminum

Engine components were chosen from FEV´s engine benchmark database to define modifications and analyze component differences. FEV´s design engineers then determined how components should be modified to realize a downsizing concept.

D.1.3 Study Hardware Boundary Conditions

The analysis showed that components in every engine subsystem needed to be changed in order to downsize the engine. FEV's approach for this case study was to eliminate one cylinder off the baseline engine (reference **Figure D-1**).

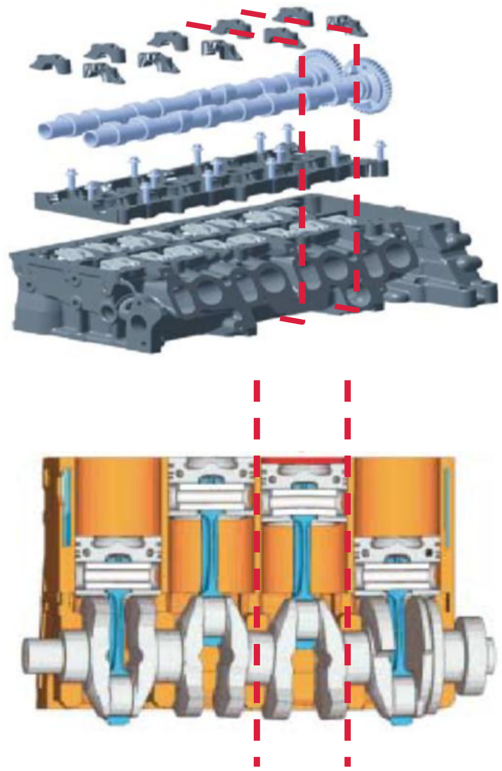


Figure D-1: Eliminating One Cylinder

FEV's costing team and its diesel design experts looked at a standard engine BOM and defined which parts would be added, substituted, left out, or modified in a downsized engine.

In addition more assumptions for the cost analysis are made. The downsized engine will have the following specifications:

- The intercooler needs 10% more cooling power
- A swirl flap mechanism
- The I3 engine needs only one balance shaft in contrast to the I4 engine, which hast two balance shafts (no modification from I6 to I4 or from V8 toV6)
- Due to this point, the I3 engine needs an additional counterweight for the balance shaft (no counterweight for balance shaft for I4, I6, V6, and V8)

- The flywheel of the I3 engine is defined as single-mass in contrast to the I4 engine, which has a dual-mass flywheel (like the I6, V6, and V8)
- Both engines have the same turbocharger (due to having same engine power)
- The material of the cylinder block and head is aluminum for both technologies

D.1.4 Components Evaluated in the Analysis

The result of the discussion in **Section D.1.3** is **Table D-2**, showing all relevant components and what has to be done with each part, if the engine will be downsized.

Table D-2 Differences of the "Advanced" Technology in Contrast to the "Baseline" Technology

	Components
Reduced number of components	**Cranktrain** ▪ Piston (incl. cooling jet) ▪ Connecting Rod ▪ Bearings ▪ Main bearing caps **Valvetrain** ▪ Intake/Exhaust valve ▪ Roller Finger Follower ▪ Hydraulic lash adjuster ▪ Cam Bearing Caps **Miscellaneous** ▪ Fuel injector with high pressure pipe ▪ Glow Plug ▪ Mass balancing shaft (incl. needle roller bearings and gear) ▪ Intermediate gear of mass balancing drive
Design modifications	▪ Crankshaft ▪ Balance Shaft ▪ Cylinder Block ▪ Cylinder Head ▪ Cam bearing frame ▪ Cylinder head cover ▪ Camshaft intake/exhaust ▪ Fuel Rail ▪ Intake/Exhaust Manifold ▪ Oil Pan
Substituted components	▪ Dual mass flywheel of the I4 engine would be replaced by a single mass flywheel. ▪ Gear on the balance shaft ▪ Intercooler
Additional components	▪ Counterweight on balance shaft (because of using just one balance shaft) ▪ Swirl flap mechanism

D.1.5 Cost Strategy Overview on Lead Case Study

FEV used two different costing levels in this project: calculated and commodity parts. Furthermore, the commodity components are divided into low-impact items and purchase parts. For the calculated costing level the differential analysis is used. For the commodity parts FEV has utilized its own database or has requested a quotation.

Table D-3 through **Table** D-6 show the costing methodologies for the downsizing project.

Table D-3: Costing Methodology for "Reduced Number of Components"

Reduced number of components	Costing level	Costing type
Piston (incl. cooling jet)	Commodity	Purchase Parts
Connecting Rod	Commodity	Low Impact
Bearings	Commodity	Purchase Parts
Main bearing caps	Commodity	Low Impact
Intake/Exhaust valve	Commodity	Purchase Parts
Roller Finger Follower	Calculated	Full
Hydraulic lash adjuster	Commodity	Purchase Parts
Cam Bearing Caps	Commodity	Low Impact
Fuel injector	Commodity	Purchase Parts
High pressure pipe	Commodity	Low Impact
Glow Plug	Commodity	Purchase Parts
Mass balancing shaft (incl. needle roller bearings)	Commodity	Low Impact
Intermediate gear of mass balancing drive	Commodity	Low Impact

Table D-4: Costing Methodology for "Design Modifications"

Design Modifications	Costing level	Costing type
Crankshaft	Calculated	Differential Analysis
Balance Shaft	Calculated	Differential Analysis
Cylinder Block	Calculated	Differential Analysis
Cylinder Head	Calculated	Differential Analysis
Cam bearing frame	Calculated	Differential Analysis
Cylinder head cover	Calculated	Differential Analysis
Camshaft intake/exhaust	Calculated	Differential Analysis
Fuel Rail	Calculated	Differential Analysis
Intake/Exhaust Manifold	Calculated	Differential Analysis
Oil Pan	Calculated	Differential Analysis

Table D-5: Costing Methodology for "Substituted Components"

Substituted Components	Costing level	Costing type
Dual mass flywheel of the I4 engine would be replaced by a single mass flywheel.	Commodity	Purchase Parts
Gear on the balance shaft	Commodity	Low Impact
Intercooler	Commodity	Purchase Parts

Table D-6: Costing Methodology for "Additional Components"

Additional components	Costing level	Costing type
Counterweight on balance shaft (because of using just one balance shaft)	Calculated	Full
Swirl flap mechanism	Commodity	Purchase Parts

D.1.6 Vehicle Segment Scaling Methodology Overview

The considered engine can be classified as vehicle segment 2 (base segment). The components are scaled by the number of cylinders (e.g., roller finger follower) and, if necessary, by the displacement per cylinder (e.g., piston). The scaling by displacement/cylinder is not assumed as proportional, so FEV has used the root function to balance the scaling.

Tables D-7 through **D-10** show the scaling factors referring to the estimated delta costs:

Table D-7: Scaling Methodology for "Reduced Number of Components"

Reduced number of components								
	Vehicle segments							
	0	1	2	3	3	5	6	6
Engine type	I4	I4	I4	I4	I6	I4	I6	V8
Displacement [Liter]	1,4	1,6	2	2	3	2	3	4
Roller Finger Follower	100%	100%	100%	100%	200%	100%	200%	200%
Conrod	84%	89%	100%	100%	200%	100%	200%	200%
Piston	84%	89%	100%	100%	200%	100%	200%	200%
Balance shaft	84%	89%	100%	100%	-245%	100%	-245%	0%
Valves	84%	89%	100%	100%	200%	100%	200%	200%
Lash adjuster	100%	100%	100%	100%	200%	100%	200%	200%
Injectors	100%	100%	100%	100%	200%	100%	200%	200%
Remaining parts	100%	100%	100%	100%	200%	100%	200%	200%

Table D-8: Scaling Methodology for "Design Modifications"

Design Modifications								
	Vehicle segments							
	0	**1**	**2**	**3**	**3**	**5**	**6**	**6**
Engine type	I4	I4	I4	I4	I6	I4	I6	V8
Displacement [Liter]	1,4	1,6	2	2	3	2	3	4
Crankshaft	84%	89%	100%	100%	200%	100%	200%	151%
Balance Shaft	84%	89%	100%	100%	0%	100%	0%	0%
Cylinder block	84%	89%	100%	100%	200%	100%	200%	150%
Cylinder head	84%	89%	100%	100%	200%	100%	200%	200%
Cam bearing frame	84%	89%	100%	100%	200%	100%	200%	200%
Camshafts	100%	100%	100%	100%	200%	100%	200%	200%
Intake manifold	84%	89%	100%	100%	200%	100%	200%	200%
Fuel rail	100%	100%	100%	100%	200%	100%	200%	200%
Exhaust manifold	84%	89%	100%	100%	200%	100%	200%	200%
Oil pan	84%	89%	100%	100%	200%	100%	200%	200%

Table D-9: Scaling Methodology for "Substituted Components"

Substituted Components								
	Vehicle segments							
	0	**1**	**2**	**3**	**3**	**5**	**6**	**6**
Engine type	I4	I4	I4	I4	I6	I4	I6	V8
Displacement [Liter]	1,4	1,6	2	2	3	2	3	4
Gear balance shaft	100%	100%	100%	100%	0%	100%	0%	0%
Flywheel	100%	100%	100%	100%	0%	100%	0%	0%
Gasket cylinder head	84%	89%	100%	100%	200%	100%	200%	200%
Sealing cylinder head cover	84%	89%	100%	100%	200%	100%	200%	200%
Gasket exhaust manifold	84%	89%	100%	100%	200%	100%	200%	200%
Gasket oil pan	84%	89%	100%	100%	200%	100%	200%	200%
Intercooler	84%	89%	100%	100%	200%	100%	200%	200%

Table D-10: Scaling Methodology for "Additional Components"

Additional Components								
	Vehicle segments							
	0	**1**	**2**	**3**	**3**	**5**	**6**	**6**
Engine type	I4	I4	I4	I4	I6	I4	I6	V8
Displacement [Liter]	1,4	1,6	2	2	3	2	3	4
Counterweight balance shaft	84%	89%	100%	100%	0%	100%	0%	0%
Swirl flap mechanism	96%	97%	100%	100%	125%	100%	125%	125%

D.1.7 Cost Analysis Results Summary

Presented in **Table D-11** and **Table D-12** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for Diesel Engine Downsizing.

Table D-11: Net Incremental Costs for Diesel Engine Downsizing (1 of 2)

ICCT Europe Analysis Diesel Internal Combustion Engine Downsizing Technology Configuration (Rev 6/4/2012)								
		Calculated Incremental Direct Manufacturing Cost - Diesel ICE Downsizing						
System Description		Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle
System Analysis ID		2000B	2001	2002	2003A	2003B	2005	2006B
	Vehicle Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4	1.6	2.0	2.0		2.0-3.0	3.0-4.2
	Typical Engine Configuration	I4	I4	I4	I4	I6	I4	V8
	Ave. Power "kW" (hp)	62.5 (85)	78.6 (107)	104 (141)	148.5 (202)		117.6 (160)	213 (290)
	Ave. Torque "N*m" (lb*ft)	201 (148)	246 (181)	321 (237)	416 (307)		336 (248)	623 (460)
	Typical Transmission Type	5-Speed MT	5 & 6-Speed MT or DCT	6-Speed MT or 8-Speed AT	6-Speed MT or DCT, 8-Speed AT		6-Speed MT or 8-Speed AT	8-Speed AT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)		1590 (3506)	2207 (4866)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	17.3 (28.1)	16.2 (26.2)	14.4 (23.4)	11.4 (18.6)		13.5 (21.9)	10.4 (16.8)
Technology Configuration Comparison	New Technology Configuration	I3	I3	I3	I3	I4	I3	I6
	Baseline Technology Configuration	I4	I4	I4	I4	I6	I4	V8
A	**Crank Drive Subsystem**	**(€ 100.94)**	**(€ 102.59)**	**(€ 106.23)**	**(€ 106.23)**	**(€ 66.22)**	**(€ 106.23)**	**(€ 62.73)**
A.1	Diff or Mod. - Crank Shaft	(€ 5.99)	(€ 6.34)	(€ 7.13)	(€ 7.13)	(€ 14.26)	(€ 7.13)	(€ 10.76)
A.2	Reduced# - Conrod	(€ 6.47)	(€ 6.85)	(€ 7.70)	(€ 7.70)	(€ 15.40)	(€ 7.70)	(€ 15.40)
A.3	Reduced# - Piston	(€ 15.36)	(€ 16.27)	(€ 18.28)	(€ 18.28)	(€ 36.56)	(€ 18.28)	(€ 36.56)
A.4	Sub. - Flywheel	(€ 73.12)	(€ 73.12)	(€ 73.12)	(€ 73.12)	€ 0.00	(€ 73.12)	€ 0.00
B	**Counter Balance Subsystem**	**(€ 4.18)**	**(€ 4.53)**	**(€ 5.29)**	**(€ 5.29)**	**€ 24.84**	**(€ 5.29)**	**€ 0.00**
B.1	Added - Count. Weight Bal. Shaft	€ 2.64	€ 2.80	€ 3.15	€ 3.15	€ 0.00	€ 3.15	€ 0.00
B.2	Diff or Mod - Bal. Shaft	€ 0.10	€ 0.10	€ 0.11	€ 0.11	€ 0.00	€ 0.11	€ 0.00
B.3	Reduced# - Bal. shaft	(€ 8.52)	(€ 9.02)	(€ 10.14)	(€ 10.14)	€ 24.84	(€ 10.14)	€ 0.00
B.4	Sub. - Gear Bal. Shaft	€ 1.59	€ 1.59	€ 1.59	€ 1.59	€ 0.00	€ 1.59	€ 0.00
C	**Cyl. Block Subsystem**	**(€ 35.49)**	**(€ 37.22)**	**(€ 41.02)**	**(€ 41.02)**	**(€ 82.03)**	**(€ 41.02)**	**(€ 64.77)**
C.1	Diff or Mod - Cyl. Block	(€ 29.00)	(€ 30.73)	(€ 34.53)	(€ 34.53)	(€ 69.05)	(€ 34.53)	(€ 51.79)
C.2	Reduced# - Remaining parts (2)	(€ 6.49)	(€ 6.49)	(€ 6.49)	(€ 6.49)	(€ 12.98)	(€ 6.49)	(€ 12.98)
D	**Cyl. Head Subsystem**	**(€ 34.65)**	**(€ 36.28)**	**(€ 39.89)**	**(€ 39.89)**	**(€ 79.77)**	**(€ 39.89)**	**(€ 79.77)**
D.1	Diff or Mod - Cyl. Head	(€ 22.76)	(€ 24.12)	(€ 27.10)	(€ 27.10)	(€ 54.19)	(€ 27.10)	(€ 54.19)
D.2	Diff or Mod - Cam Bearing Frame	(€ 3.16)	(€ 3.35)	(€ 3.77)	(€ 3.77)	(€ 7.53)	(€ 3.77)	(€ 7.53)
D.3	Reduced# - Remaining parts (3)	(€ 7.14)	(€ 7.14)	(€ 7.14)	(€ 7.14)	(€ 14.28)	(€ 7.14)	(€ 14.28)
D.4	Sub. - Gask. Cyl. Head	(€ 1.21)	(€ 1.28)	(€ 1.44)	(€ 1.44)	(€ 2.88)	(€ 1.44)	(€ 2.88)
D.5	Sub. - Sealing Cyl. Head Cover	(€ 0.37)	(€ 0.39)	(€ 0.44)	(€ 0.44)	(€ 0.89)	(€ 0.44)	(€ 0.89)
E	**Valvetrain Subsystem**	**(€ 27.27)**	**(€ 27.93)**	**(€ 29.39)**	**(€ 29.39)**	**(€ 58.77)**	**(€ 29.39)**	**(€ 58.77)**
E.1	Reduced# - Roller Finger Follow	(€ 9.48)	(€ 9.48)	(€ 9.48)	(€ 9.48)	(€ 18.95)	(€ 9.48)	(€ 18.95)
E.2	Diff or Mod - Camshafts	(€ 3.44)	(€ 3.44)	(€ 3.44)	(€ 3.44)	(€ 6.89)	(€ 3.44)	(€ 6.89)
E.3	Reduced# - Valves	(€ 11.10)	(€ 11.76)	(€ 13.22)	(€ 13.22)	(€ 26.44)	(€ 13.22)	(€ 26.44)
E.4	Reduced# - Lash adj.	(€ 3.25)	(€ 3.25)	(€ 3.25)	(€ 3.25)	(€ 6.49)	(€ 3.25)	(€ 6.49)
F	**Timing Drive Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
G	**Accessory Drive Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**

Table D-11: Net Incremental Costs for Diesel Engine Downsizing (2 of 2)

ICCT Europe Analysis
Diesel Internal Combustion Engine Downsizing Technology Configuration
(Rev 6/4/2012)

System Description		Calculated Incremental Direct Manufacturing Cost - Diesel ICE Downsizing						
		Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle
System Analysis ID		2000B	2001	2002	2003A	2003B	2005	2006B
	Vehicle Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4	1.6	2.0	2.0		2.0-3.0	3.0-4.2
	Typical Engine Configuration	I4	I4	I4	I4	I6	I4	V8
	Ave. Power "kW" (hp)	62.5 (85)	78.6 (107)	104 (141)	148.5 (202)		117.6 (160)	213 (290)
	Ave. Torque "N*m" (lb*ft)	201 (148)	246 (181)	321 (237)	416 (307)		336 (248)	623 (460)
	Typical Transmission Type	5-Speed MT	5 & 6-Speed MT or DCT	6-Speed MT or 8-Speed AT	6-Speed MT or DCT, 8-Speed AT		6-Speed MT or 8-Speed AT	8-Speed AT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)		1590 (3506)	2207 (4866)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	17.3 (28.1)	16.2 (26.2)	14.4 (23.4)	11.4 (18.6)		13.5 (21.9)	10.4 (16.8)
Technology Configuration Comparison	New Technology Configuration	I3	I3	I3	I3	I4	I3	I6
	Baseline Technology Configuration	I4	I4	I4	I4	I6	I4	V8
H	**Air Intake Subsystem**	**€ 16.04**	**€ 16.16**	**€ 16.58**	**€ 16.58**	**€ 19.54**	**€ 16.58**	**€ 19.54**
H.1	Diff or Mod - Intake Man.	(€ 0.96)	(€ 1.02)	(€ 1.14)	(€ 1.14)	(€ 2.29)	(€ 1.14)	(€ 2.29)
H.2	Reduced# - Remaining parts (4)	(€ 0.44)	(€ 0.44)	(€ 0.44)	(€ 0.44)	(€ 0.89)	(€ 0.44)	(€ 0.89)
H.3	Added - Swirl Flap Mec.	€ 17.44	€ 17.62	€ 18.17	€ 18.17	€ 22.71	€ 18.17	€ 22.71
I	**Fuel Induction Subsystem**	**(€ 89.59)**	**(€ 89.59)**	**(€ 89.59)**	**(€ 89.59)**	**(€ 179.19)**	**(€ 89.59)**	**(€ 179.19)**
I.1	Reduced# - Remaining parts (5)	(€ 3.68)	(€ 3.68)	(€ 3.68)	(€ 3.68)	(€ 7.36)	(€ 3.68)	(€ 7.36)
I.2	Diff or Mod - Fuel Rail	(€ 2.19)	(€ 2.19)	(€ 2.19)	(€ 2.19)	(€ 4.39)	(€ 2.19)	(€ 4.39)
I.3	Reduced# - Injectors	(€ 83.72)	(€ 83.72)	(€ 83.72)	(€ 83.72)	(€ 167.44)	(€ 83.72)	(€ 167.44)
J	**Exhaust Subsystem**	**(€ 2.04)**	**(€ 2.16)**	**(€ 2.43)**	**(€ 2.43)**	**(€ 4.86)**	**(€ 2.43)**	**(€ 4.86)**
J.1	Diff or Mod - Exhaust Man.	(€ 1.67)	(€ 1.77)	(€ 1.99)	(€ 1.99)	(€ 3.97)	(€ 1.99)	(€ 3.97)
J.2	Sub. - Gask.Exhaust Man.	(€ 0.37)	(€ 0.39)	(€ 0.44)	(€ 0.44)	(€ 0.89)	(€ 0.44)	(€ 0.89)
K	**Lubrication Subsystem**	**(€ 1.60)**	**(€ 1.70)**	**(€ 1.91)**	**(€ 1.91)**	**(€ 3.82)**	**(€ 1.91)**	**(€ 3.82)**
K.1	Diff or Mod - Oil Pan	(€ 1.58)	(€ 1.68)	(€ 1.89)	(€ 1.89)	(€ 3.77)	(€ 1.89)	(€ 3.77)
K.2	Sub. - Gask Oil Pan	(€ 0.02)	(€ 0.02)	(€ 0.02)	(€ 0.02)	(€ 0.04)	(€ 0.02)	(€ 0.04)
L	**Cooling Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
M	**Induction Air Charging Subsystem**	**€ 1.49**	**€ 1.58**	**€ 1.77**	**€ 1.77**	**€ 3.55**	**€ 1.77**	**€ 3.55**
M.1	Sub. - Intercooler	€ 1.49	€ 1.58	€ 1.77	€ 1.77	€ 3.55	€ 1.77	€ 3.55
N	**Exhaust Gas Re-Circulation Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
O	**Breather Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
P	**Engine Management, Electronic Subsystem**	**(€ 5.36)**	**(€ 5.36)**	**(€ 5.36)**	**(€ 5.36)**	**(€ 10.72)**	**(€ 5.36)**	**(€ 10.72)**
P.1	Reduced# - Remaining parts (1)	(€ 5.36)	(€ 5.36)	(€ 5.36)	(€ 5.36)	(€ 10.72)	(€ 5.36)	(€ 10.72)
Q	**Accessory Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
	Net Incremental Direct Manufacturing Cost	**(€ 283.60)**	**(€ 289.63)**	**(€ 302.74)**	**(€ 302.74)**	**(€ 437.46)**	**(€ 302.74)**	**(€ 441.54)**

Table D-12 : Net Incremental Technology Costs for Diesel Engine Downsizing

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	ICM and Learning Factor Categorization			Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
													ICM - Warranty		ICM - Other Direct Costs					
						Description	Percent Contribution	Calculated Values	2012	2016	2020	2025	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	2012	2016	2020	2025
Diesel Engine Downsizing	2	2000B	**Diesel I4 ICE** Ave. Displacement = 1.2-1.4L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 284)	n/a	n/a	n/a	(€ 215)	(€ 215)	(€ 229)	(€ 229)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00
	3	2001	**Diesel I4 ICE** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 290)	n/a	n/a	n/a	(€ 220)	(€ 220)	(€ 234)	(€ 234)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00
	4	2002	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 303)	n/a	n/a	n/a	(€ 229)	(€ 229)	(€ 245)	(€ 245)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00
	5	2003A	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 303)	n/a	n/a	n/a	(€ 229)	(€ 229)	(€ 245)	(€ 245)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00
	6	2003B	**Diesel I6 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Downsized to Diesel I4 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 437)	n/a	n/a	n/a	(€ 332)	(€ 332)	(€ 353)	(€ 353)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00
	7	2005	**Diesel I4 ICE** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Downsized to Diesel I3 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 303)	n/a	n/a	n/a	(€ 229)	(€ 229)	(€ 245)	(€ 245)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00
	9	2006B	**Diesel V8 ICE** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Downsized to Diesel I6 ICE with same per Cylinder Displacement as Baseline Technology Configuration**	(€ 442)	n/a	n/a	n/a	(€ 335)	(€ 335)	(€ 357)	(€ 357)	0.012	0.005	0.230	0.187	1.00	1.00	1.00	1.00

D.2 Advance High Pressure Injection Analysis, Diesel Engines

D.2.1 Technology Overview

A diesel engine is a type of internal combustion engine developed by Rudolf Diesel in 1893. It uses the heat of compression to initiate ignition to burn the fuel that is injected into the combustion chamber. Gasoline engines, in contrast, use a spark plug to ignite an air-fuel mixture.

Over the past century, many configurations of fuel injection have been used. Nowadays most diesel engines make use of a high-pressure direct-injection system. This basically consists of a high-pressure pump, which supplies fuel constantly at high pressure with a common rail to each fuel injector (one per each cylinder, mounted at the top of the combustion chamber).

This common rail system gives engine developers the freedom they need to reduce exhaust emissions. With its flexible division of the injection cycle into several stages – pre-, main, and post-injections – the common rail design allows the engine and the injection system to be matched to each other in the best possible way.

The fuel injectors have a nozzle needle that is actuated by a solenoid or a piezo module, operated by an electronic control unit. The piezo-actuated injectors offer the advantage of realizing a finer control by utilizing a more rapid response of the injection event.

The electronically controlled common rail system has many advantages:

• Increased Performance (more torque at low engine speeds)

• Reduced fuel consumption

• Less exhaust and emissions

• Quieter running engine

While today´s passenger car diesel engines run injection pressures between 1600 and 2000 bar, it is known from the industry that future systems will go up to 2500 bar or higher with piezo-actuated injectors. An increase of injection pressure makes the combustion more efficient by better carburation and air utilization. This reduces the soot particle and CO_2 emissions.

For this reason, the content of this technology analysis is a comparison of common rail diesel injection systems with two different pressure levels and solenoid actuation.

Figure D-2 illustrates the key components included in a fuel sub-system:

1: High-pressure pump
2: Primary fuel filter
3: Fuel tank
4: Pre-filter

5: Fuel rail
6: Rail pressure sensor
7: Fuel injector
8: Pressure regulator valve
9: Fuel transfer pump
10: High-pressure pipe (from pump to rail)
11: High-pressure pipe (from rail to injector)

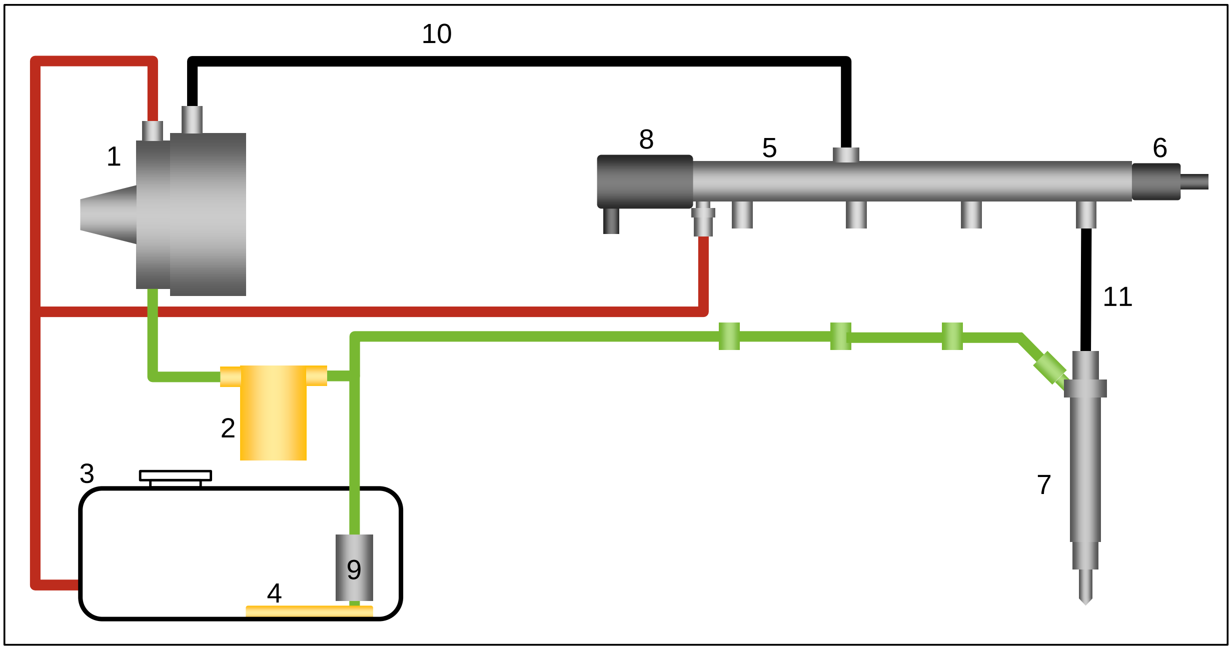


Figure D-2: Common Rail Diesel Injection System

The diesel fuel is drawn from the fuel tank (3) by a fuel transfer pump (9). After the transfer pump draws the fuel from the tank, it then passes through at least one primary fuel filter (2). A high-pressure pump (1) generates in an accumulator – the rail (5) – a pressure of up to 2000 bar in today´s passenger car engines, independent of the engine speed and the quantity of fuel injected. The fuel is fed through rigid pipes (11) to the injectors (7), which inject the correct amount of fuel via a fine spray into the combustion chambers. The Electronic Control Unit (ECU) precisely controls all the injection parameters – such as the pressure in the rail, and the timing and duration of the injection cycle – as well as performing other engine functions.

D.2.2 Study Assumptions – Case Study Specific

The purpose of this case study is to provide an analysis of delta-costs between injection systems of two different pressure levels. The baseline technology should cover a mainstream Diesel engine, while the advanced system should be representative for future injections pressures.

The baseline injection pressure for this case study was set to 1800 bar, while the pressure of the advanced system was 2500 bar.

One challenge for this study was the circumstance, that there was no mass production hardware from a passenger car available at project start that delivers more than 2000 bar injections pressure.

The approach was to purchase and analyze the hardware of the base technology (1800 bar) and another system with the highest pressure available (in this case 2000 bar). The necessary modifications for realizing the advanced system pressure of 2500 bar should be derived by analyzing the differences between 1800 and 2000 bar and extrapolation up to 2500 bar by the knowledge of FEV´s fuel injection experts and, if required, manufacturing experts in the industry.

D.2.3 Study Hardware Boundary Conditions

Before purchasing components, FEV´s costing team discussed with FEV's experts for diesel design and injections systems the influence of the injections pressure to the complete engine. The result of these discussions set the system boundary for the case study. By utilizing the same engine (with same displacement, power, and torque) there is no need for any modifications at the base engine due to an increase of the injection pressure. Therefore, only the injection pressure itself is the differential being compared.

The injection system can be divided into low- and high-pressure portions **(Figure D-3)**:

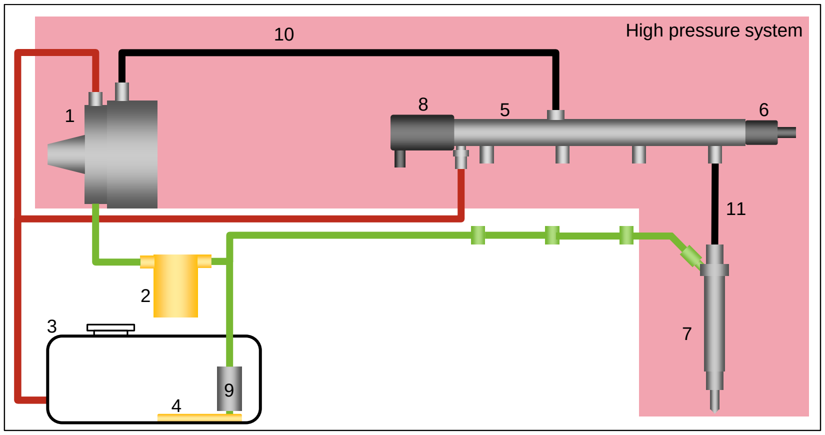


Figure D-3: Low-Pressure and High-Pressure Part of the Injection System

The low-pressure part of the system (e.g., fuel tank, fuel transfer pump, filters, and fuel return lines) is considered independent from the injection pressure. There is no difference assumed for low pressure, which is caused by an increase of the injection pressure. Therefore the components were not evaluated.

FEV purchased only the high-pressure components for the two injection systems, shown in **Figure D-4**.

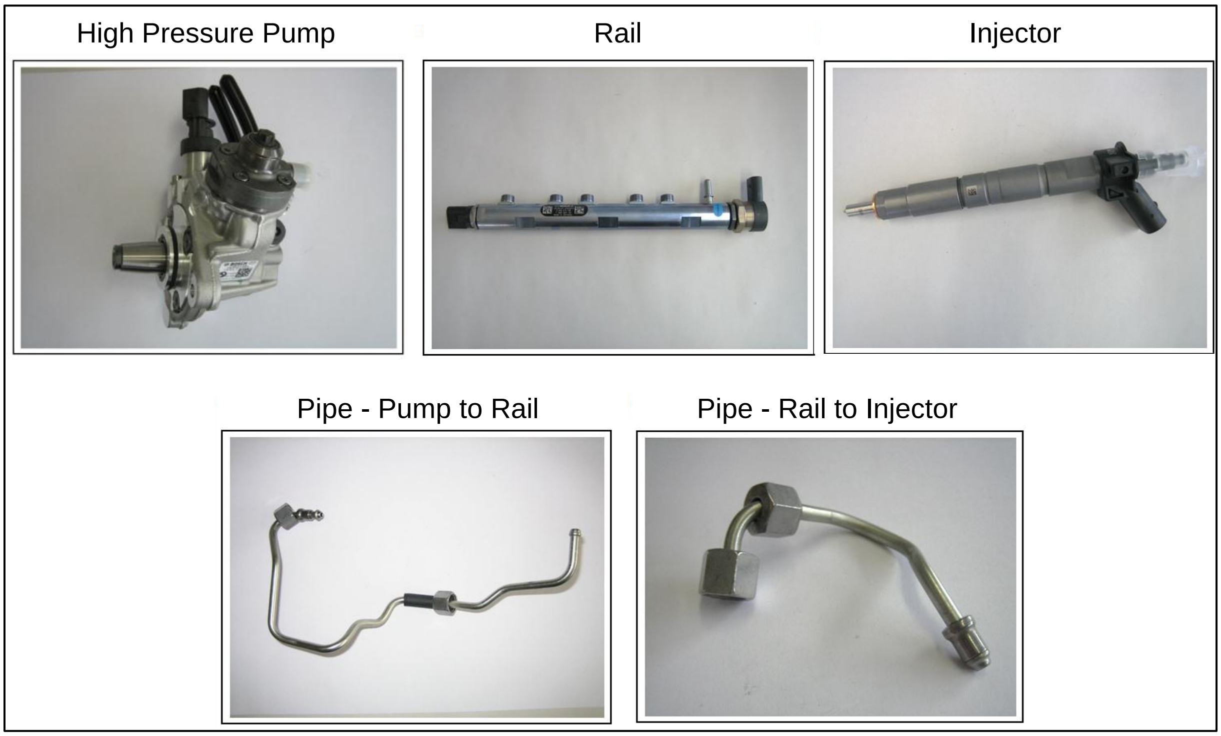


Figure D-4: High-Pressure Components of Common Rail System

D.2.4 Components Evaluated in the Analysis

To find out the differences between 1800 and 2000 bar subsystems, both were disassembled to a level where accurate assessments could be made; reference **Figure D-5**, **Figure D-6**, and **Figure D-7**.

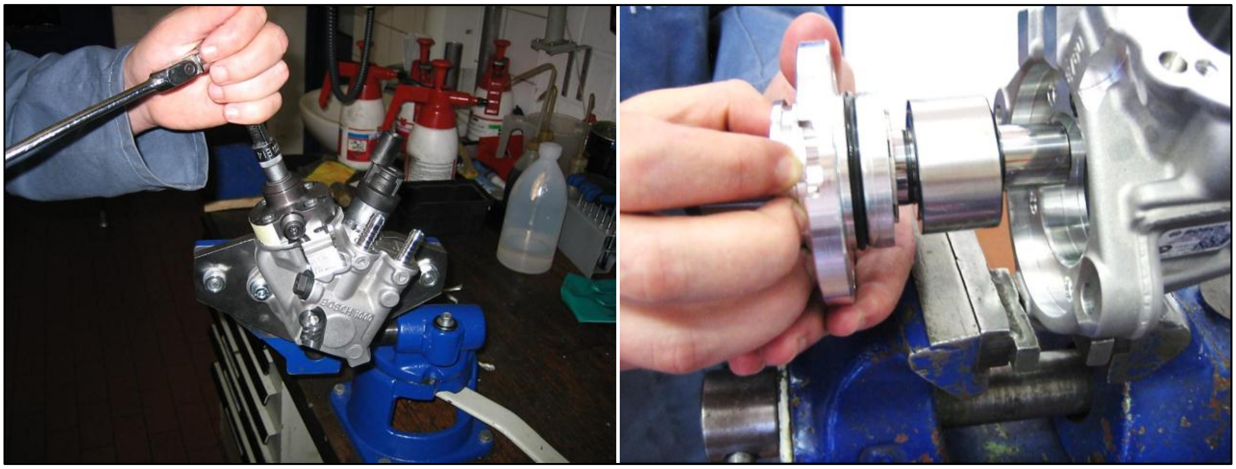
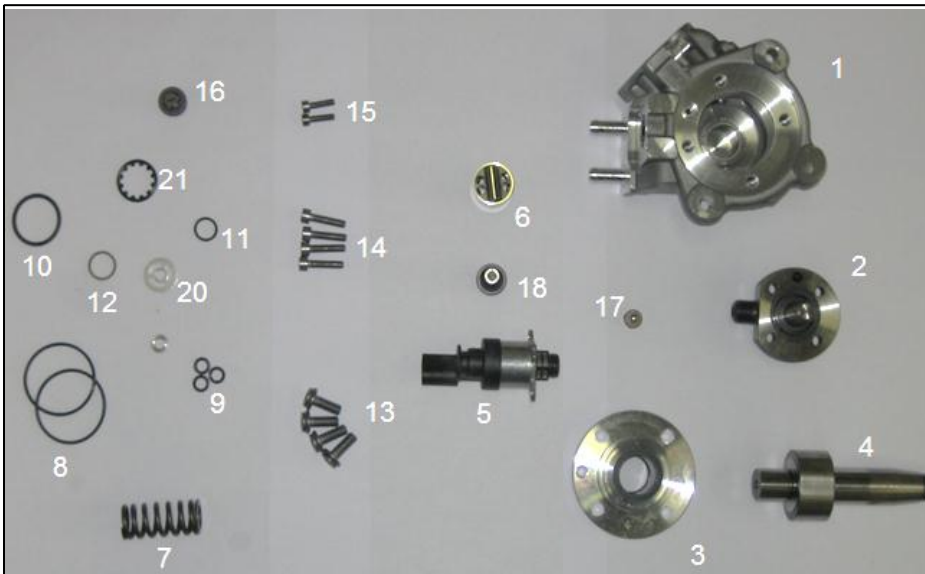


Figure D-5: Tear Down of High Pressure Pump



Nr.	Component
1	Pump housing
2	Cylinder head
3	Cover
4	Camshaft
5	Metering unit
6	Valve lifter
7	Coil spring
8	O-ring (cover)
9	O-ring (sealing surface of cylinder head and cover)
10	O-ring (cylinder head)
11	O-ring (pressure retention valve)
12	O-ring (screw check valve)
13	Screw (cylinder head)
14	Screw (cover)
15	Screw (metering unit)
16	Screw (check valve)
17	Check valve (cylinder head)
18	Plunger
19	Pressure retention valve
20	Disc
21	Disc

Figure D-6: Disassembled high pressure pump in detail

Nr.	Component
	Nozzle module incl.:
1	- Nozzle body
2	- Nozzle needle
3	- Supporting
4	- Needle bushing
5	- Nozzle spring
	Servo valve plate incl.:
6	- Plate
7	- Servo valve
8	- Servo valve spring
9	Adapter plate
10	- Positioning pins
	Coupler Module incl.:
11	- Tube Spring
12	- Driving piston
13	- Driven piston incl. spring
14	- Spring driven piston
15	- Adapter plate
16	- Coupler body
17	Clamping nut
18	Adjustment plate coupler
19	Injector body
20	Piezo module
21	Edgefilter
22	Seal ring
23	Connector body incl.:
24	- Return line connector
25	Thread seal

Figure D-7: Disassembled Fuel Injector

During the teardown process, the components shown below in **Figure D-8** were identified as subject for further investigation because of expected relevance to injection pressure or detected differences between the 1800 bar and 2000 bar systems.

Figure D-8: Components for Further Investigation

With most of the components, there were no visible differences between 1800 and 2000 bar. Therefore, FEV performed some material and microscope analyses at Aachen University (**Figure D-9**).

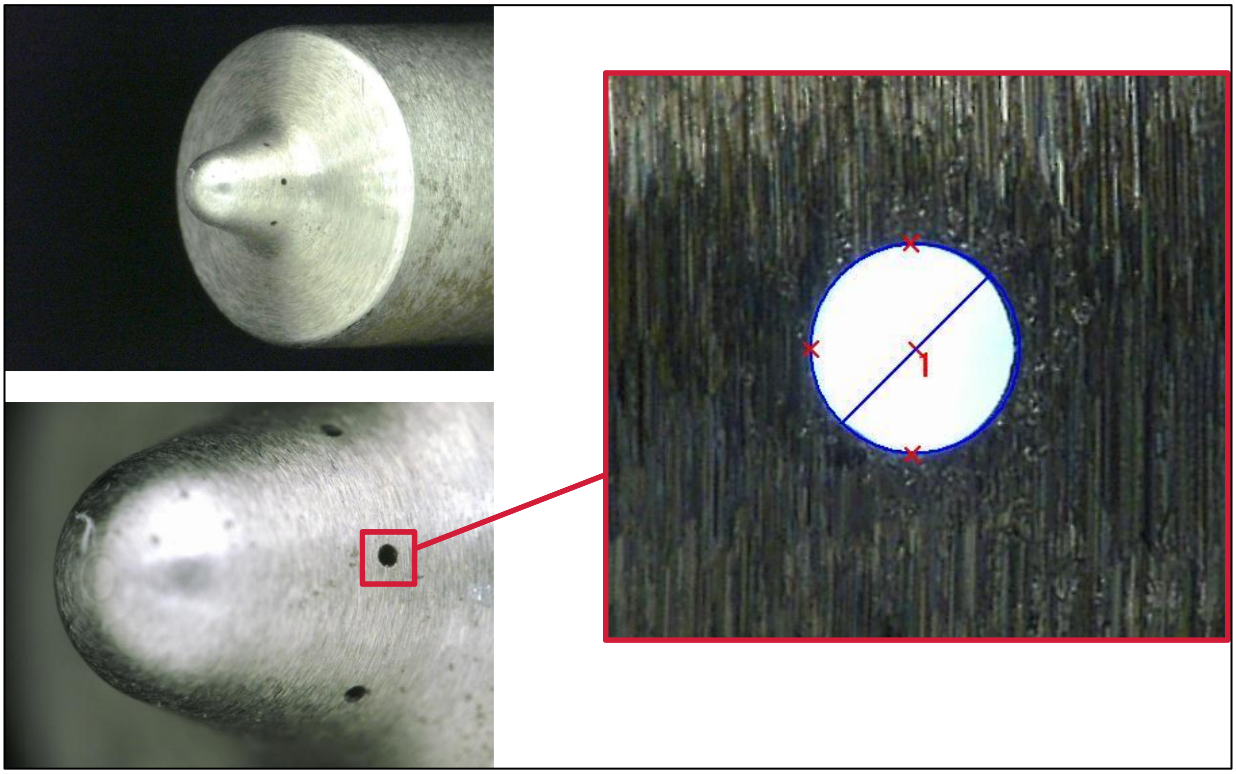
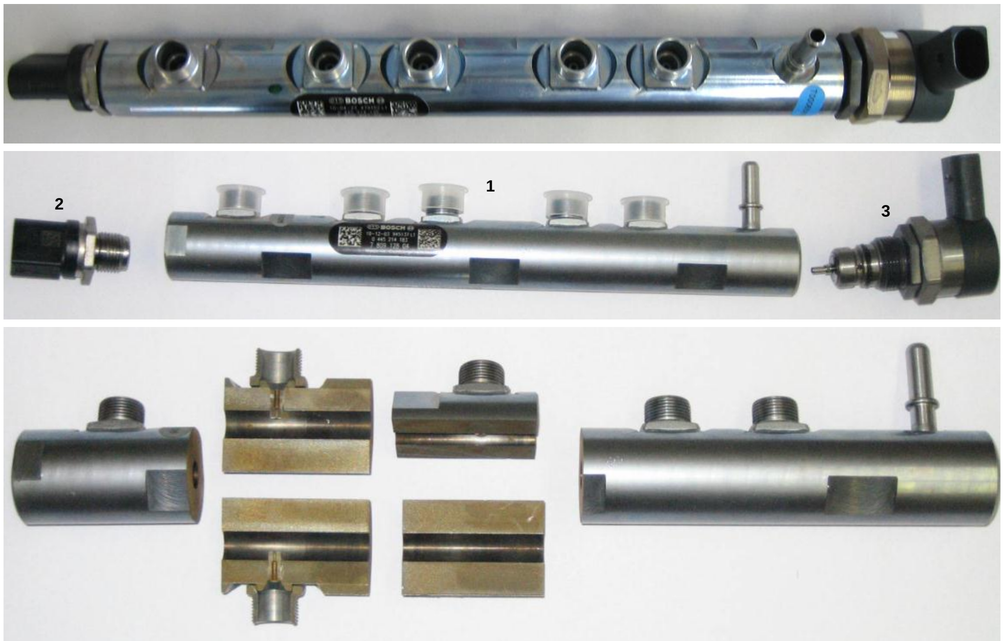


Figure D-9: Measuring of Nozzle Holes

The piezo element was actually disassembled to measure the dimension of the piezo stack (**Figure D-10**).

Figure D-10: Disassembled Piezo Module

Using electro-erosion machining, the fuel rail was sectioned permitting further investigation into key design and manufacturing features (**Figure D-11**).



Nr.	Component
1	Rail
2	Pressure sensor
3	Pressure regulator valve

Figure D-11: Sectioned Fuel Rail

Based on discussions with FEV´s technical experts, different institutes within Aachen University, and various manufacturers, the final results on the design and manufacturing differences, between the 1800 and 2000 bar injectors, as well as assumed modifications for 2500 bar systems were defined. **Figure D-12** identifies the high pressure fuel system components and required modifications for the 2500 bar injection system.

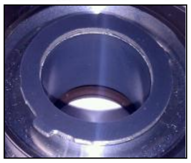
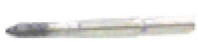
	Component	Result of comparison 1800 bar ←→ 2000 bar	Assumption for 2500 bar
	Pump housing	Weight difference 30g Same material: AlSi12CuNiMg	No modification assumed, Pressure in housing is ca. 3 bar
	Pump bushing	No difference	higher surface pressure at 2500bar on the bushing surface → Bushing has to be bigger
	Rail	Material: 20MnCr5 No visible differences	Autofrettage process required to dynamic durability Assumption after workshop with autofrettage specialists: Autofrettage is required for all rails and pipes with pressure over 1800 bar → Elastic stiffness is sufficient for 2500 bar
	Pipes	Material: Q 345 No visible differences	
	Injector nozzle	Diameter nozzle holes 1800 bar, 130 kW: 140 µm 2000 bar, 150 kW: 147 µm	■ Hole diameter 2500 bar, 130 kW: 130 µm ■ Increase of nozzle depth
	Nozzle Needle	No visible differences	Other coating process and/or coating material required
	Piezo stack	No difference in hardware. Length: 32,4 mm Assumption: higher voltage at 2000 bar system	■ No further voltage increasing ■ Increasing length of piezo stack proportional to increasing pressure (2000 → 2500 bar = +25%) ■ Piezo stack has to be 8,1mm longer

Figure D-12: Assumptions for High Pressure Fuel System Modifications (1800 bar to 2500 bar)

After all the investigations were performed, there were five (5) aspects remaining for the cost evaluation. For the injector needle, a different coating material and/or coating process was identified. New coating is assumed to avoid/reduce abrasion at higher running pressures.

Under the assumption of same power for both the basic and the advanced engines, the nozzle hole diameters had to be reduced in order to allow the same fuel mass flow at higher pressure. Furthermore, an increase of nozzle depth was assumed to offer greater material strength at higher pressures.

Because of the higher fuel pressure, higher forces at the fuel pump to camshaft interface will exist. The fuel pump bushing has to resist these forces and for this reason a larger bushing was assumed.

The most significant modification was with the piezo stack. This component has to work against the fuel pressure to open the needle. With higher fuel pressure, the piezo stack has to generate a higher force. This is possible by increase of voltage or length. Between 1,800 and 2,000 bar there were no differences in the dimension of the piezo stack. Therefore, it is assumed, the higher force for 2,000 bar is realized by voltage increase. For the 2,500 bar system it is assumed that the voltage will not be increased anymore, but the length. According to the pressure difference between 2,000 and 2,500 bar (+25%), the piezo stack is assumed to be 25% longer.

D.2.5 Cost Strategy Overview on Lead Case Study

Table D-13 shows the costing methodology for each of the evaluated aspects. Because it was not possible to make a clear definition for some of the modifications (e.g., the coating of the needle), an estimate was used to evaluate the delta costs.

Table D-13: Costing Methodology for Injection System Modifications

Component	Evaluated modification	Costing method
Injector needle	different coating material / different coating process	Estimation due to the fact, that an exact definition of the coating is not possible
Injector nozzle	Increase of nozzle depth	Estimation based on longer process time
Injector piezo stack	elongation of piezo stack 32,4mm --> 40,5 mm	Commodity - purchase part
Pump bushing	bigger bushing bearing (due to higher forces) --> more material at camshaft --> longer machining time at camshaft and pump housing	Estimation based on longer process times and additional material

D.2.6 Vehicle Segment Scaling Methodology Overview

The components that are assumed to be modified for the 2500 bar system are the injectors and the high-pressure pump (specifically the pump bushing).

For scaling the delta costs to other vehicle classes that have different engine displacements, power requirements, and number of cylinders, it is important to determine which parameter has an influence on the modifications. The only influence to the modification at the injectors is the injection pressure. There was no change in the engine displacement or power. So for scaling to other vehicle classes, the number of cylinders gives the base to multiply the delta costs.

The modification at the high-pressure pump is related to the force between the camshaft and the pump plunger. For vehicles with more power and more cylinders, a higher fuel mass flow will be required. Based on a one-plunger pump, it is possible to switch to a dual-plunger pump in this case. The dual-plunger pump would also be driven by a single camshaft; since the two plungers are actuated one after another and not at the same time, the force to the camshaft and the bushing will not be higher than at the one-plunger-pump. For that reason, the estimated delta-cost for the pump modification will not differ among the vehicle classes.

Table D-14 shows the scaling factors referring to the estimated delta costs:

Table D-14: Scaling Factors for Injection System Components

Modification		I3 engine		I4 engine		I6 engine		V6 engine		V8 engine	
		Units per engine	Scaling factor	Units per engine	Scaling factor	Units per engine	Scaling factor	Units per engine	Scaling factor	Units per engine	Scaling factor
Injector needle	different coating material / different coating process	3	75%	4	100%	6	150%	6	150%	8	200%
Injector nozzle	Increase of nozzle depth	3	75%	4	100%	6	150%	6	150%	8	200%
Injector piezo stack	elongation of piezo stack 32,4mm --> 40,5 mm	3	75%	4	100%	6	150%	6	150%	8	200%
Pump bushing	bigger bushing bearing camshaft and pump housing	1	100%	1	100%	1	100%	1	100%	1	100%

D.2.7 Cost Analysis Results Summary

Presented in **Table D-15** and **Table D-16** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for changing to a 2500 bar diesel fuel injection system from an 1800 bar fuel injection system.

Table D-15: Net Incremental Direct Manufacturing Costs for a 2500 Bar Fuel Injection System Compared to an 1800 Bar System

ICCT Europe Analysis
Diesel ICE High Pressure Fuel Injection Technnology Configuration
(Rev 6/04/2012)

		Calculated Incremental Direct Manufacturing Cost - High Presure Fuel Injection								
System Description		Subcompact Passenger Vehicle	Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle	Large Sport Utility Vehicle
System Analysis ID		2100A	2100B	2101	2102	2103A	2103B	2105	2106A	2106B
	Vehicle Example	VW Polo, Ford Fiesta	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4		1.6	2.0	2.0		2.0-3.0	3.0-4.2	
	Typical Engine Configuration	I3	I4	I4	I4	I4	I6	I4	I6	V8
	Ave. Power "kW" (hp)	62.5 (85)		78.6 (107)	104 (141)	148.5 (202)		117.6 (160)	213 (290)	
	Ave. Torque "N*m" (lb*ft)	201 (148)		246 (181)	321 (237)	416 (307)		336 (248)	623 (460)	
	Typical Transmission Type	5-Speed MT		5 & 6-Speed MT or DCT	6-Speed MT or 8-Speed AT	6-Speed MT or DCT, 8-Speed AT		6-Speed MT or 8-Speed AT	8-Speed AT	
	Ave. Curb Weight "kg" (lb)	1084 (2390)		1271 (2803)	1496 (3299)	1700 (3749)		1590 (3506)	2207 (4866)	
	Weight-to-Power Ratio "kg/kW" (lb/hp)	17.3 (28.1)		16.2 (26.2)	14.4 (23.4)	11.4 (18.6)		13.5 (21.9)	10.4 (16.8)	
Technology Configuration Comparison	New Technology Configuration	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System	2500 Bar Injection System
	Baseline Technology Configuration	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System	1800 Bar Injection System
A	**Assembly of Fuel Induction Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
B	**Fuel Rail High Pressure Delivery Sub-Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
C	**Fuel Rail Low Pressure Delivery Sub-Subsystem**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**	**€ 0.00**
D	**Fuel Injector Sub-Subsystem**	**€ 8.10**	**€ 10.80**	**€ 10.80**	**€ 10.80**	**€ 10.80**	**€ 16.20**	**€ 10.80**	**€ 16.20**	**€ 21.60**
D.1	Injector	€ 8.10	€ 10.80	€ 10.80	€ 10.80	€ 10.80	€ 16.20	€ 10.80	€ 16.20	€ 21.60
D.2	Injector Mounting and Miscalleous Hardware (e.g. O-ring, Gasket Ring, Clamping Jaw, Mount Screw)	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
D.3	Electrical Distribution and Controls	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
E	**Fuel Injection Pump Sub-Subsystem**	**€ 0.50**	**€ 0.50**	**€ 0.50**	**€ 0.50**	**€ 0.50**	**€ 0.50**	**€ 0.50**	**€ 0.50**	**€ 0.50**
E.1	High Pressure Pump Assembly	€ 0.50	€ 0.50	€ 0.50	€ 0.50	€ 0.50	€ 0.50	€ 0.50	€ 0.50	€ 0.50
E.2	Fuel Metering Device	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
E.3	Bracket - High Pressure Pump Mounitng	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
E.4	Sproket Assembly - High Pressure Pump Drive	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
E.5	Mounting and Miscellaneous Hardware (e.g. O-Ring, Fillister Head Screw, Hex Bolt, ASA Bolt)	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
E.6	Electrical Distribution and Controls	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	Net Incremental Direct Manufacturing Cost	**€ 8.60**	**€ 11.30**	**€ 11.30**	**€ 11.30**	**€ 11.30**	**€ 16.70**	**€ 11.30**	**€ 16.70**	**€ 22.10**

Table D-16: Net Incremental Technology Costs for 2500 Bar Fuel Injection System Compared to an 1800 Bar System

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
										ICM - Warranty		ICM - Other Direct Costs					
						2012	2016	2020	2025	Short Term 2012 thru $2018_{(1)}$	Long Term 2019 thru $2025_{(2)}$	Short Term 2012 thru $2018_{(1)}$	Long Term 2019 thru $2025_{(2)}$	2012	2016	2020	2025
High Pressure Fuel Injection, Diesel Engine	1	2100A	**Diesel I3 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I3 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 9	€ 12	€ 11	€ 9	€ 9	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	2	2100B	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 1.2-1.4L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 11	€ 16	€ 14	€ 12	€ 12	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	3	2101	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 11	€ 16	€ 14	€ 12	€ 12	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	4	2102	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 11	€ 16	€ 14	€ 12	€ 12	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	6	2103B	**Diesel I6 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I6 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 17	€ 23	€ 21	€ 18	€ 17	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	7	2105	**Diesel I4 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Diesel I4 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 11	€ 16	€ 14	€ 12	€ 12	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	9	2106B	**Diesel V8 ICE** **1800 Bar Fuel Injection System** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Diesel V8 ICE Upgraded to 2500 Bar Fuel Injection System**	€ 22	€ 31	€ 28	€ 24	€ 23	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74

D.3 Variable Valve Timing and Lift Valvetrain (VVTL) Analysis, Diesel Engines

D.3.1 Technology Overview

Variable valve timing and lift (VVTL) is a term used to describe the mechanism or method that can alter the shape or timing of a valve lift event within an internal combustion engine. While the engine is in operation, the VVTL allows the lift, duration, or timing (in various combinations) of the intake and/or exhaust valves to be changed.

Within an internal combustion engine, the flow of the intake and exhaust gases into and out of the combustion chamber is controlled by the valves. The timing, duration and lift of these valve events have a significant impact on engine performance. In a standard engine, the valve events are fixed, so performance at different loads and speeds is always a compromise between drivability (power and torque), fuel economy and emissions. An engine equipped with a VVTL system is free of this constraint, allowing improved performance over the entire engine operating range.

The desire to vary the valve opening duration to match an engine's rotational speed began in the 1920s when maximum allowable RPM limits were rising. Until then, an engine's idle RPM and its operating RPM were very similar, meaning that there was little need for variable valve duration.

The target of this case study is an analysis of delta-costs between a diesel engine with standard, non-variable valve train and a diesel engine with variable cam timing and variable valve lift were compared. The baseline technology covers a mainstream diesel engine, while the advanced system should be representative for the future.

D.3.2 Study Assumptions – Case Study Specific

For the VVTL analysis, the FEV High Efficient Combustion System (HECS) was chosen. The FEV HECS design has two functionalities and the following benefit:

1. **Variable Valve Lift on Intake Valves**

In combination with seat swirl chamfer, the VVL acts similar to a port deactivation (increased swirl level); however, the swirl is much more homogeneous and thus less particulates.

2. **Cam Phaser on Exhaust Camshaft**

An advanced exhaust valve opening allows internal EGR, which causes higher charge temperature, than uncooled externally, in the combustion chamber. Thus, at cold engine operation (especially at low load and during start of emission test cycle), HC and CO emissions can be reduced.

The complete FEV HECS cylinder head is shown below in **Figure D-13**.

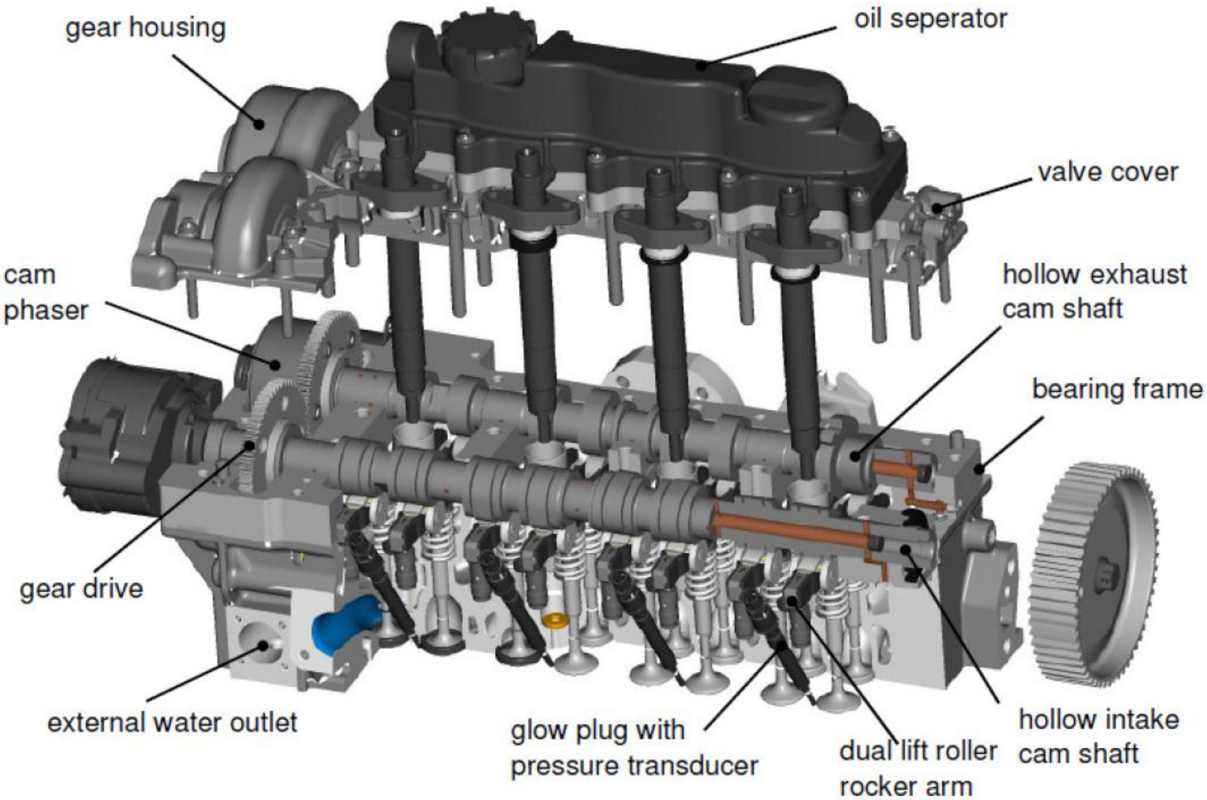


Figure D-13: FEV HECS Cylinder Head

The FEV HECS design is not available in a mass production yet. However, since FEV developed this system, all 3D models and manufacturing drawings for prototyping parts are available and utilized as base for the cost analysis.

D.3.3 Study Assumption Hardware Boundary Conditions

Before calculating component costs, FEV´s costing team discussed with FEV´s diesel design experts which parts should be taken into account. Three engine subsystems, (Valvetrain Subsystem, Cylinder Head Subsystem, and Engine Management, Electronic and Electrical Subsystem) were identified as impacted by the addition of the VVTL hardware. The team also selected what engine specifications should be used for the lead case study (**Table D-17**).

Table D-17: Engine Specifications

Engine specifications	
Displacement	2L
Power Output	150 kW
Max. Torque	400 Nm
Bore	84 mm
Stroke	90 mm
Stroke-Bore-Ratio	1,071
Compression Ratio	16
Peak Firing Pressure	180 bar
Valve Diameter Intake	27,2 mm
Valve Diameter Exhaust	24,6 mm
Crankcase	Aluminum
Camshafts	Composite

FEV examined and evaluated all components, within the three (3) key subsystems, which were potentially related to, or affected by, the functionality of the variable valve lift and the variable cam timing.

D.3.4 Components Evaluated in the Analysis

The VVTL's main components are the dual lift rocker arms and the triple cam profiles on the intake camshaft (**Figure D-14** and **Figure D-15**). The roller rocker arm incorporates the dual lift function. The compact, lightweight design of the rocker arm evaluated allows it to fit securely inside the cylinder of this modern engine, in this sense it represents another step forward in terms of compactness and weight. The rocker arm body also supports the slider pivoted. It also contains the latching group, which is comprised of a latch-pin that provides locking of the slider during high lift, by the return spring, with retainers; and the clip for pin orientation. Two side rollers run on an axis that is also used as stopping for the slider, and are kept in position by two compact torsion springs (LMS). This configuration makes it possible to have cam base radius in contact only with the rollers, allowing the cam lash compensation to occur through the hydraulic lash adjuster (HLA).

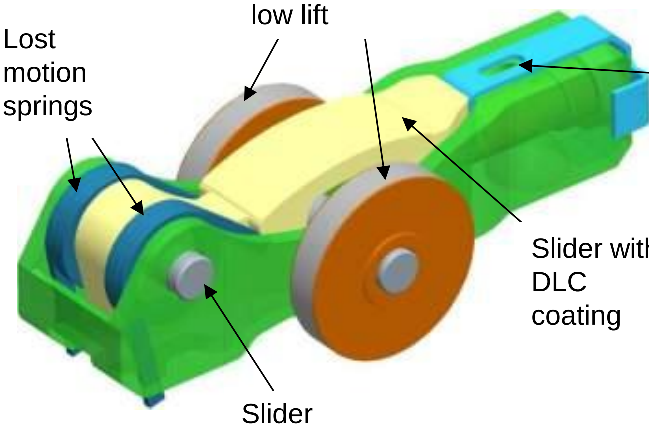


Figure D-14: Dual Lift Rocker Arm

The dual lift rocker arm uses a three-lobed camshaft intake. The main valve lift is controlled by the central cam while the secondary valve is controlled by two external cams acting on two rollers. For friction reduction, it was considered the use of DLC coating on the slider and using of an oil spray on cam/slider contact.

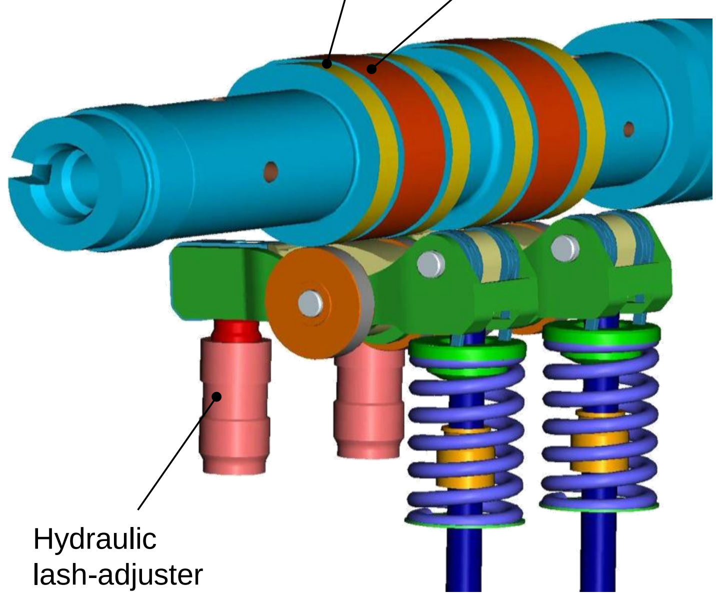


Figure D-15: Functional Principles of Dual Lift Rocker Arm with Triple Cam Profiles

The main components for the variable cam timing are the cam phaser, the control valve, and the oil supply for the cam phaser in the exhaust camshaft (**Figure D-16**).

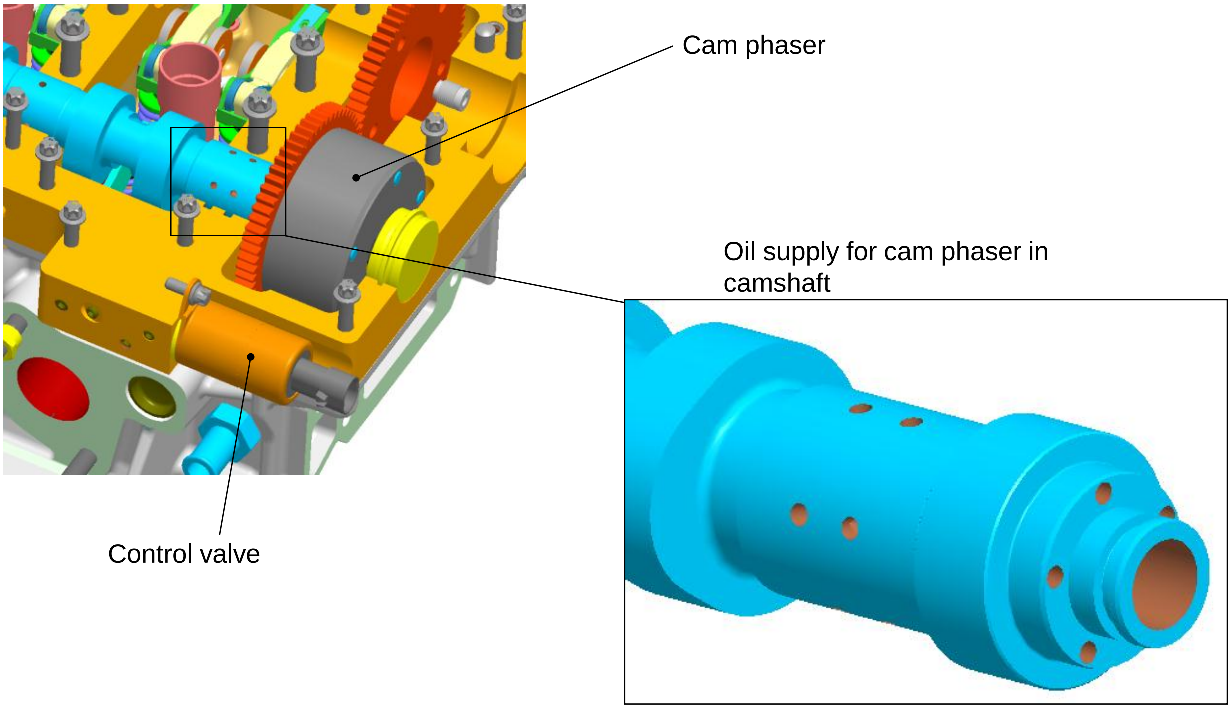


Figure D-16: Main Components for the Variable Cam Timing

In addition to the main components of the variable valve lift and variable cam timing, further parts were considered by FEV´s costing team and diesel design experts. The result was a list (**Table D-18**) of all components that should be added, substituted, deleted, or modified for integration of the VVTL technology in contrast to the conventional valvetrain technology.

Table D-18: Required updates to add VVTL Technology to a Diesel Engine with Conventional Valvetrain Technology

	Variable valve lift	Variable cam timing
Additional components	■ Control valve ■ Wiring for control valve	■ Cam phaser ■ Control valve ■ Camshaft position sensor ■ Wiring for new electrical components
Substitution of components	Dual lift rocker arm instead of "standard" rocker arm	
Design modifications	■ Camshaft with triple cams ■ Flange for control valve ■ Additional oil gallery ■ Oil supply for control valve	■ Extension of cylinder head on front end for cam phaser package ■ Sensor trigger wheel at camshaft ■ Flange for position sensor ■ Flange for control valve ■ Oil supply for cam phaser in camshaft

D.3.5 Cost Strategy Overview on Lead Case Study

Table D-19 and **Table D-20** provide the costing methodologies utilized on assessing the components impacted by the addition of variable valve timing and lift.

Table D-19: Costing Methodology for Components of the Variable Valve Lift

Variable valve lift	Costing level	Costing type
Control valve	Commodity	Purchase Parts
Wiring for control valve	Commodity	Purchase Parts
Dual lift rocker arm instead of “standard” rocker arm	Calculated	Modification Analysis
Camshaft with triple cams	Calculated	Modification Analysis
Flange for control valve	Calculated	Differential Analysis
Additional oil gallery	Calculated	Differential Analysis
Oil supply for control valve	Calculated	Differential Analysis

Table D-20: Costing Methodology for Components of the Variable Cam Timing

Variable cam timing	Costing level	Costing type
Cam phaser	Commodity	Purchase Parts
Control valve	Commodity	Purchase Parts
Camshaft position sensor	Commodity	Purchase Parts
Wiring for new electrical components	Commodity	Purchase Parts
Extension of cylinder head on front end for cam phaser package	Calculated	Differential Analysis
Sensor trigger wheel at camshaft	Calculated	Differential Analysis
Flange for position sensor	Calculated	Differential Analysis
Flange for control valve	Calculated	Differential Analysis
Oil supply for cam phaser in camshaft	Calculated	Differential Analysis

D.3.6 Vehicle Segment Scaling Methodology Overview

The lead case study vehicle segment evaluated in the VVTL analysis was vehicle segment three (3) with an I4 engine configuration. For the variable cam timing, the component scaling was directly proportional to the number of exhaust camshafts (**Table D-21)**. This means that for the vehicle segments with in-line engines the differences of the results in contrast to the lead case study was estimated to be the same (100%). For a V-engine (i.e., two exhaust camshafts) the scaling ratio was twice as high as for the lead case study (i.e., 200%).

Table D-21 : Scaling Methodology for the Variable Cam Timing

Variable cam timing			
	I4 engine	**I6 engine**	**V8 engine**
Cam phaser	100%	100%	200%
Control Valve	100%	100%	200%
Camshaft position sensor	100%	100%	200%
Cylinder head extension	100%	100%	200%
Flange for control valve	100%	100%	200%
Flange for camshaft position sensor	100%	100%	200%
Miscellaneous	100%	100%	200%

For the variable valve lift, most of the components were scaled in the same way as the parts of the variable cam timing. Only the modification of the intake camshaft and the substitution of the standard rocker arms by the dual lift rocker arms, were scaled by the number of cylinders (**Table D-22)**.

Table D-22: Scaling Methodology for the Variable Valve Lift

Variable valve lift			
	I4 engine	**I6 engine**	**V8 engine**
Control valve	100%	100%	200%
Flange for control valve	100%	100%	200%
Camshaft intake	100%	150%	200%
Substitutions of rocker arms	100%	150%	200%
Miscellaneous	100%	100%	200%

D.3.7 Cost Analysis Results Summary

Presented in **Table D-23** and **Table D-24** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for replacing a conventional valvetrain subsystem on a diesel engine to a VVTL subsystem. Note in the phase 2 analysis work, for 6 cylinder engine technologies, I6 versus V6 engine configurations were evaluated. In the case of the VVTL evaluation, there would be a difference in the Net Incremental Direct Manufacturing Costs (NIDMCs) between the I6 and V6 configuration. A good approximation of the impact for adding the VVTL technology to a V6 ICE configuration is to double the I3 results. For example, the NIDMCs for adding the VVTL technology configuration to an I3, as shown in **Table D-23**, is €89.35. For a V6 application, a good approximation of the cost impact would be €178.70 (2*€89.35). In comparison, the I6 NIDMC cost impact for adding VVTL is €112.27. The same methodology (i.e., V6 = 2*I3) can be applied to the values in Net Incremental Technology Cost table (**Table D-24)**.

Table D-23: Incremental Direct Manufacturing Costs for Replacing a Conventional Valvetrain Subsystem with a VVTL Valvetrain Subsystem

ICCT Europe Analysis Variable Valve Timing and Lift Technnology Configuration (Rev 6/4/2012)								
		Calculated Incremental Direct Manufacturing Cost - VVT:						
System Description		Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle
System Analysis ID		2200A	2201	2202	2203A	2203B	2205	2206B
	Vehicle Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4	1.6	2.0	2.0		2.0-3.0	3.0-4.2
	Typical Engine Configuration	I3	I4	I4	I4	I6	I4	V8
	Ave. Power "kW" (hp)	62.5 (85)	78.6 (107)	104 (141)	148.5 (202)		117.6 (160)	213 (290)
	Ave. Torque "N*m" (lb*ft)	201 (148)	246 (181)	321 (237)	416 (307)		336 (248)	623 (460)
	Typical Transmission Type	5-Speed MT	5 & 6-Speed MT or DCT	6-Speed MT or 8-Speed AT	6-Speed MT or DCT, 8-Speed AT		6-Speed MT or 8-Speed AT	8-Speed AT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)		1590 (3506)	2207 (4866)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	17.3 (28.1)	16.2 (26.2)	14.4 (23.4)	11.4 (18.6)		13.5 (21.9)	10.4 (16.8)
Technology Configuration Comparison	New Technology Configuration	VVTL	VVTL	VVTL	VVTL	VVTL	VVTL	VVTL
	Baseline Technology Configuration	Conventional Valvetrain (No VVTL)	Conventional Valvetrain (No VVTL)	Conventional Valvetrain (No VVTL)	Conventional Valvetrain (No VVTL)	Conventional Valvetrain (No VVTL)	Conventional Valvetrain (No VVTL)	Conventional Valvetrain (No VVTL)
A	**Cylinder Head Subsystem Modifications**	**€ 15.17**	**€ 15.17**	**€ 15.17**	**€ 15.17**	**€ 15.17**	**€ 15.17**	**€ 30.34**
A.1	Cylinder Head Sub-Subsystem	€ 7.02	€ 7.02	€ 7.02	€ 7.02	€ 7.02	€ 7.02	€ 14.05
A.2	Cam Shaft Speed Sensor Sub-Subsystem	€ 6.74	€ 6.74	€ 6.74	€ 6.74	€ 6.74	€ 6.74	€ 13.48
A.3	Cylinder Head Cover Sub-Subsystem	€ 0.11	€ 0.11	€ 0.11	€ 0.11	€ 0.11	€ 0.11	€ 0.23
A.4	Bolting Sub-Subsystem	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.03	€ 0.07
A.5	Power Distribution and Control Sub-Subsystem	€ 1.26	€ 1.26	€ 1.26	€ 1.26	€ 1.26	€ 1.26	€ 2.51
B	**Valvetrain Subsystem**	**€ 74.18**	**€ 81.01**	**€ 81.01**	**€ 81.01**	**€ 97.10**	**€ 81.01**	**€ 162.02**
B.1	Valve Actuation Sub-Subsystem	€ 20.48	€ 27.30	€ 27.30	€ 27.30	€ 40.95	€ 27.30	€ 54.60
B.2	Camshaft Sub-Subsystem	€ 8.38	€ 8.38	€ 8.38	€ 8.38	€ 10.81	€ 8.38	€ 16.75
B.3	Camshaft Phaser and/or Cam Sprocket Sub-Subsystem	€ 41.36	€ 41.36	€ 41.36	€ 41.36	€ 41.36	€ 41.36	€ 82.71
B.4	Bolting Sub-Subsystem	€ 1.46	€ 1.46	€ 1.46	€ 1.46	€ 1.46	€ 1.46	€ 2.92
B.5	Power Distribution and Control Sub-Subsystem	€ 2.51	€ 2.51	€ 2.51	€ 2.51	€ 2.51	€ 2.51	€ 5.03
	Net Incremental Direct Manufacturing Cost	**€ 89.35**	**€ 96.18**	**€ 96.18**	**€ 96.18**	**€ 112.27**	**€ 96.18**	**€ 192.35**

Table D-24: Net Incremental Technology Costs for Replacing a Conventional Valvetrain Subsystem with a VVTL Valvetrain Subsystem

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
						2012	2016	2020	2025	ICM - Warranty		ICM - Other Direct Costs		2012	2016	2020	2025
										Short Term 2012 thru 2018[1]	Long Term 2019 thru 2025[2]	Short Term 2012 thru 2018[1]	Long Term 2019 thru 2025[2]				
Variable Valve Timing and Lift	1	2200A	**Diesel I3 ICE** **Conventional Valvetrain** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I3 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 89	€ 133	€ 121	€ 106	€ 98	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81
Variable Valve Timing and Lift	3	2201	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 96	€ 143	€ 130	€ 114	€ 105	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81
Variable Valve Timing and Lift	4	2202	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 96	€ 143	€ 130	€ 114	€ 105	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81
Variable Valve Timing and Lift	5	2203A	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 96	€ 143	€ 130	€ 114	€ 105	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81
Variable Valve Timing and Lift	6	2203B	**Diesel I6 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I6 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 112	€ 167	€ 152	€ 133	€ 123	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81
Variable Valve Timing and Lift	7	2205	**Diesel I4 ICE** **Conventional Valvetrain** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Diesel I4 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 96	€ 143	€ 130	€ 114	€ 105	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81
Variable Valve Timing and Lift	9	2206B	**Diesel V8 ICE** Conventional Valvetrain Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Diesel V8 ICE Upgraded with Discrete Variable Valve Timing and Lift**	€ 192	€ 286	€ 261	€ 227	€ 210	0.045	0.031	0.343	0.259	1.10	0.97	0.89	0.81

D.4 High-Pressure, Low-Pressure Cooled Exhaust Gas Recirculation (EGR) Analysis, Diesel Engines

D.4.1 Technology Overview

The most effective method of achieving engine-based reductions of NO_x emissions is to maintain the highest possible exhaust gas recirculation (EGR) rates with simultaneously high cylinder fill rates. Ideally, this is done across the entire engine map at the lowest possible gas mixture temperatures in the intake manifold. To achieve this, it is necessary to technically enhance, in part with a coolant, the high pressure exhaust gas recirculation (HP-EGR) system. HP-EGR cycles are widely used in many applications today. A schematic of a cooled HP-EGR system is shown in **Figure D-17**.

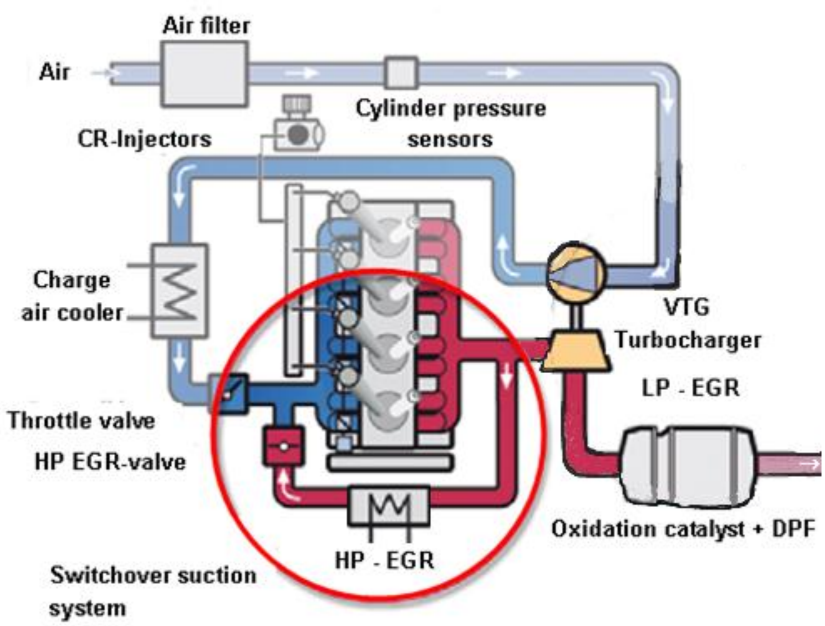


Figure D-17: Diesel HP-EGR System

A viable technical solution is presented by combining a cooled low pressure exhaust gas recirculation (LP-EGR) system with an uncooled HP-EGR system.

The fundamental advantages of adding the cooled LP-EGR include:

- Nearly engine map-wide possibility of NO_x emission reductions through exhaust gas recirculation.
- EGR rates can be regulated independently of drops in charge air pressure.
- Low, homogeneously distributed NO_x concentrations across the engine map.

- Low loss of exhaust gas enthalpy through extraction of exhaust gas energy after the turbocharger or particulate filter with simultaneous high air ratios.
- Nearly ideal equal distribution during exhaust gas recirculation through mixing in the diffuser in the compressor and in the charge air cooler.
- Improved boost pressure build-up with partial load and high EGR rates.

D.4.2 Study Assumptions – Case Study Specific

To evaluate the benefits of the HP-/LP-EGR system it is necessary to conduct an analysis of cost differences between a high/low-pressure EGR and a high-pressure EGR in a charge air cooling system. For this project the US Jetta (HP-/LP-EGR system) is contrasted to the European Jetta (HP-EGR system). Both vehicles use the same base engine which helps simplify the analysis. The primary technical data for the engine is found below in **Table D-25.**

Table D-25: Technical Data of Jetta Engine

	VW Jetta
Displacement	2 l
Power Output	103 kW
Power Output per liter	51,5 kW/l
Numbers of cylinders / valves per cylinder	4/4
Bore	81 mm
Stroke	95,5 mm
Max. Torque	320 Nm
Compression ratio	16,5

D.4.3 Study Assumption Hardware Boundary Conditions

In the LP-EGR system, the exhaust gas is first extracted behind the diesel particulate filter (DPF) near the engine (**Figure D-18**). The catalytically cleaned and particulate-free exhaust gas is first circulated to a stainless steel EGR cooler with more than 8 kW of cooling performance. When the electrically-controlled EGR valve is activated, the exhaust gas is channeled via a short connecting pipe in a mixing unit directly upstream of the exhaust gas turbo charger compressor into the intake air stream. The pressure gradient can be raised when using an electrically-controlled exhaust valve. This valve is positioned in the exhaust stream behind the NO_x storage catalytic converter (NSC) and is operated together with the LP-EGR valve in an integrated control loop.

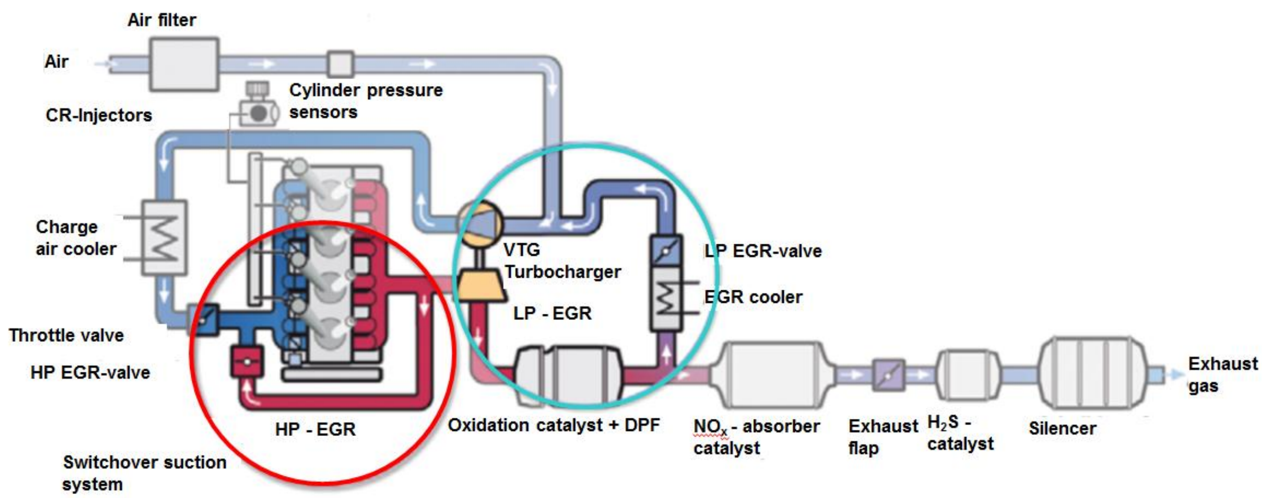


Figure D-18: HP-/LP-EGR System

In addition to the LP-EGR system, the 2.0 l 4V TDI Bin5 engine also features a traditional high pressure EGR system (**Figure D-18**). This dual-circuit EGR system makes it possible to set almost any exhaust gas recirculation rate and selectable quantity ratio of high- and low-pressure EGR in any engine operating state. This also makes it possible to manipulate the intake manifold temperature. Thus, it is possible, for example, to increase the proportion of high-pressure EGR when external temperatures are very low in order to improve combustion stability. In case of fast changes to the load state, exhaust intake must be adjusted as nearly simultaneously as possible. In this case, the high-pressure EGR control loop can compensate for delays in the low-pressure system resulting from the increased gas circulation time through the charge air cooler.

The boundary conditions for comparison of the two (2) diesel EGR analysis system starts at the charge air cooler and ends after the exhaust flap for the HP-EGR, Cooled LP-EGR system (**Figure D-18**). All components added, deleted, or modified that were required to convert the Cooled HP-EGR system to a HP-EGR, Cooled LP-EGR system, where evaluated.

D.4.4 Components Evaluated in the Analysis

As mentioned above, the considered system starts at the charge air cooler and ends after the exhaust flap. The following hardware components were selected and purchased:

- All different components of the high-pressure EGR cycles
- Additional components of the low-pressure EGR cycle

Table D-26 lists the main components which were investigated.

Table D-26: Differences of Diesel EGR components

Component	Remarks
Charge air cooler	Same in both systems
Throttle Valve	Different in both systems
EGR-cooler	Different in both systems
HP-EGR-valve	Same in both systems
HP-EGR-pipes	Different in both systems
Turbocharger	Same in both systems
LP-EGR-valve	Additional for the new technology
LP-EGR-pipes	Additional for the new technology

D.4.5 Cost Strategy Overview on Base Analysis

The main parts of both EGR systems are divided into three costing levels. **Figure D-19**, **Figure D-20**, and **Figure D-21** illustrate the components included and the cost level employed at each level.

Component	Costing Level	Costing Type
Cooler (HP)	Calculated	Full
Cooler (HLP)	Calculated	Full
Regulator Valve (HP)	Calculated	Full
Regulator Valve (HLP)	Calculated	Full
Exhaust Valve (HLP)	Calculated	Full
Exhaust pipe with catalytic converter and particulate filter (HP)	Calculated	Differential Analysis

Figure D-19: EGR Calculated Part Costs

Component	Costing Level	Costing Type
Oil pipe 1 (HP)	Commodity	Low Impact
Connection pipe 1 (HP)	Commodity	Low Impact
Oil pipe 2 (HP)	Commodity	Low Impact
Connection pipe 2 (HP)	Commodity	Low Impact
Connection pipe 1 (HLP)	Commodity	Low Impact
Control Line (HLP)	Commodity	Low Impact
….	…	…

Figure D-20: EGR Commodity Costs – Low Impact Parts

Component	Costing Level	Costing Type
Exhaust gas temperature sensor (HLP)	Commodity	Purchase Parts
Pressure sensor (HLP)	Commodity	Purchase Parts
Temperature sensor (HLP)	Commodity	Purchase Parts
Clamp (HLP)	Commodity	Purchase Parts
Seal (HLP)	Commodity	Purchase Parts
Pressure hose (HLP)	Commodity	Purchase Parts
Pressure hose (LP)	Commodity	Purchase Parts
Seal (LP)	Commodity	Purchase Parts
….	…	…

Figure D-21: EGR Commodity Costs – Purchased Parts

D.4.6 Vehicle Segment Scaling Methodology Overview

The lead case study vehicle segment for the diesel EGR analysis was vehicle segment two (2). To calculate incremental costs for alternative vehicle segments, engine horsepower was used to develop scaling factors between the lead case study and alternative vehicle segments. **Table D-27** shows the scaling factors used in the analysis. For the majority of components evaluated, the Net Incremental Direct Manufacturing Costs for the lead case study remained the same (100%) for the other vehicle segments evaluated. The cooling element and element tubes were scaled according to engine horsepower; however, because the incremental costs for these components between the new and baseline technology configurations were very small, there was minimal effect to the overall NIDMCs (i.e., the NIDMC impact was approximately the same for all vehicle segments).

Table D-27: Scaling Factors for Diesel EGR Analysis

Scaling methodology						
	Vehicle segments					
	0	**1**	**2**	**3**	**5**	**6**
Engine type	I4	I4	I4	I4-I6	I4	I6
Average power [hp]	85	107	141	202	160	290
Cooling element housing	60%	76%	100%	143%	113%	206%
Cooling element tubes system	60%	76%	100%	143%	113%	206%
Rest	100%	100%	100%	100%	100%	100%

D.4.7 Cost Analysis Results Summary

Presented in **Table D-28** and **Table D-29** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for Replacing a Cooled HP-EGR Subsystem with a HP, Cooled LP-EGR Subsystem.

Table D-28: Net Incremental Direct Manufacturing Costs for Replacing a Cooled HP-EGR Subsystem with a HP, Cooled LP-EGR Subsystem

ICCT Europe Analysis
Diesel Exhaust Gas Recirculation (EGR) Technnology Configuration
(Rev 6/4/2012)

		Calculated Incremental Direct Manufacturing Cost - EGR:						
	System Description	**Subcompact Passenger Vehicle**	**Compact or Small Passenger Vehicle**	**A Midsize Passenger Vehicle**	**Midsize or Large Passenger Vehicle**	**Midsize or Large Passenger Vehicle**	**Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van**	**Large Sport Utility Vehicle**
	System Analysis ID	**2300A**	**2301**	**2302**	**2303A**	**2303B**	**2305**	**2306B**
	Vehicle Example	**VW Polo, Ford Fiesta**	**VW Golf Ford Focus**	**VW Passat BMW 3 Series Audi A4**	**VW Sharan BMW 5 Series Audi A6**	**VW Sharan BMW 5 Series Audi A6**	**VW Tiguan BMW X1/X3 Audi Q5**	**VW Touareg BMW X5/X6 Audi Q7**
Vehicle Segment Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4	1.6	2.0	2.0		2.0-3.0	3.0-4.2
	Typical Engine Configuration	I3	I4	I4	I4	I6	I4	V8
	Ave. Power "kW" (hp)	62.5 (85)	78.6 (107)	104 (141)	148.5 (202)		117.6 (160)	213 (290)
	Ave. Torque "N*m" (lb*ft)	201 (148)	246 (181)	321 (237)	416 (307)		336 (248)	623 (460)
	Typical Transmission Type	5-Speed MT	5 & 6-Speed MT or DCT	6-Speed MT or 8-Speed AT	6-Speed MT or DCT, 8-Speed AT		6-Speed MT or 8-Speed AT	8-Speed AT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)		1590 (3506)	2207 (4866)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	17.3 (28.1)	16.2 (26.2)	14.4 (23.4)	11.4 (18.6)		13.5 (21.9)	10.4 (16.8)
Technology Configuration Comparison	New Technology Configuration	High Pressure, Cooled Low Pressure EGR	High Pressure, Cooled Low Pressure EGR	High Pressure, Cooled Low Pressure EGR	High Pressure, Cooled Low Pressure EGR	High Pressure, Cooled Low Pressure EGR	High Pressure, Cooled Low Pressure EGR	High Pressure, Cooled Low Pressure EGR
	Baseline Technology Configuration	Cooled High Pressure EGR	Cooled High Pressure EGR	Cooled High Pressure EGR	Cooled High Pressure EGR	Cooled High Pressure EGR	Cooled High Pressure EGR	Cooled High Pressure EGR
A	**Exhaust Gas Recirculation Subsystem**	**€ 88.55**	**€ 88.54**	**€ 88.52**	**€ 88.50**	**€ 88.50**	**€ 88.52**	**€ 88.47**
A.1	Exhaust Diesel Recirculation Sub-Subsystem	€ 39.59	€ 39.58	€ 39.56	€ 39.54	€ 39.54	€ 39.56	€ 39.51
A.2	Intercooling Sub-Subsystem	(€ 0.40)	(€ 0.40)	(€ 0.40)	(€ 0.40)	(€ 0.40)	(€ 0.40)	(€ 0.40)
A.3	Exhaust Manifold with Turbocharger Sub-Subsystem	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08	€ 0.08
A.4	Exhaust Pipe Sub-Subsystem	€ 49.28	€ 49.28	€ 49.28	€ 49.28	€ 49.28	€ 49.28	€ 49.28
	Net Incremental Direct Manufacturing Cost	**€ 88.55**	**€ 88.54**	**€ 88.52**	**€ 88.50**	**€ 88.50**	**€ 88.52**	**€ 88.47**

Table D-29: Net Incremental Technology Costs for Replacing a Cooled HP-EGR Subsystem with a HP, Cooled LP-EGR Subsystem

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
										ICM - Warranty		ICM - Other Direct Costs					
						2012	2016	2020	2025	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	2012	2016	2020	2025
High Pressure, Cooled Low Pressure EGR	1	2300A	**Diesel I3 ICE** **Cooled High Pressure EGR** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: 5-Speet MT Curb Weight: 1084kg (2390lb)	**Diesel I3 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 89	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	3	2301	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: 5 or 6 speed MT or DCT Curb Weight: 1271kg (2803lb)	**Diesel I4 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 89	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	4	2302	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1496kg (3299lb)	**Diesel I4 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 89	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	5	2303A	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I4 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 89	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	6	2303B	**Diesel I6 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: 6-Speed MT or DCT, or 8-Speed AT Curb Weight: 1700kg (3749lb)	**Diesel I6 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 89	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	7	2305	**Diesel I4 ICE** **Cooled High Pressure EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: 6-Speed MT or 8-Speed AT Curb Weight: 1590kg (3505lb)	**Diesel I4 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 89	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	9	2306B	**Diesel V8 ICE** **Cooled High Pressure EGR** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: 8-Speed AT Curb Weight: 2207kg (4866lb)	**Diesel V8 ICE Upgrade with High Pressure, Cooled Low Pressure EGR**	€ 88	€ 123	€ 112	€ 97	€ 90	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74

D.5 Cooled, Low Pressure EGR Compared to Uncooled, Low Pressure EGR Analysis, Gasoline Engines

D.5.1 Technology Overview

The motivation for EGR usage on turbocharged gasoline engines with homogeneous combustion systems is primarily a fuel consumption benefit. Different EGR system layouts have different “working areas” concerning the engine load, differentiating between part-load (**Figure D-22**) and high-load (**Figure D-24**).

Part load EGR

The fuel consumption benefit at part load is primarily the effect of pumping loss reduction via de-throttling. EGR cooling is not necessarily required for this concept: uncooled EGR can lead to even higher de-throttling due to higher intake manifold temperatures. Although cooled EGR could lead to better efficiency at higher part load due to knock suppression.

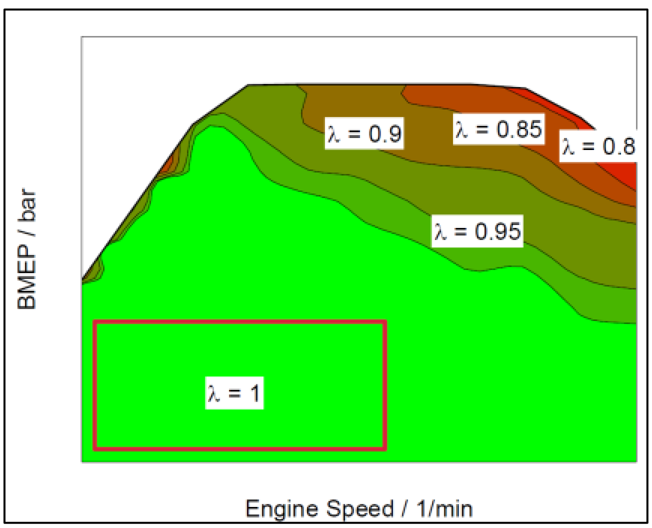


Figure D-22: Part Load Area (red frame)

The fuel consumption benefit of the external part load EGR (**Figure D-23**) is similar to the level that can be achieved with variable cam timing. Variable cam timing is state-of-the-art, therefore part load EGR is typically not used on modern turbocharged direct injection engines.

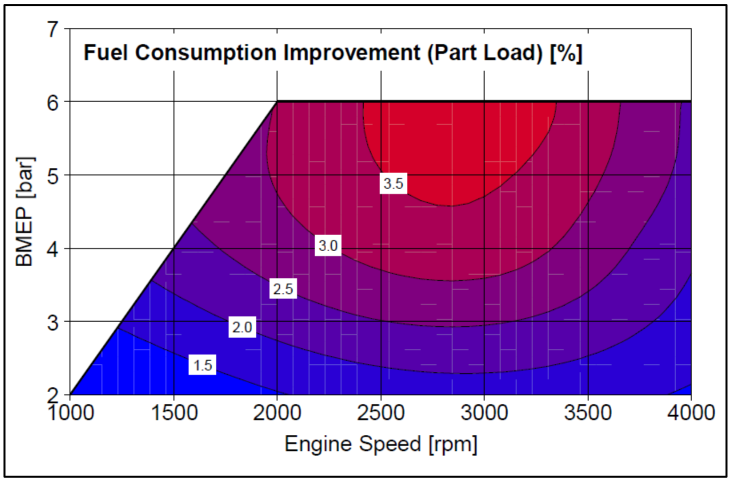


Figure D-23: Fuel Consumption Improvement with Part Load EGR

High-load EGR

The main effects of high-load EGR (**Figure D-24**) are reduced knock sensitivity and reduced exhaust gas temperatures. These effects lead to an advanced combustion phasing and offer the possibility of reducing the enrichment for turbine protection. Such a system requires EGR cooling as well as an improved charge air cooling.

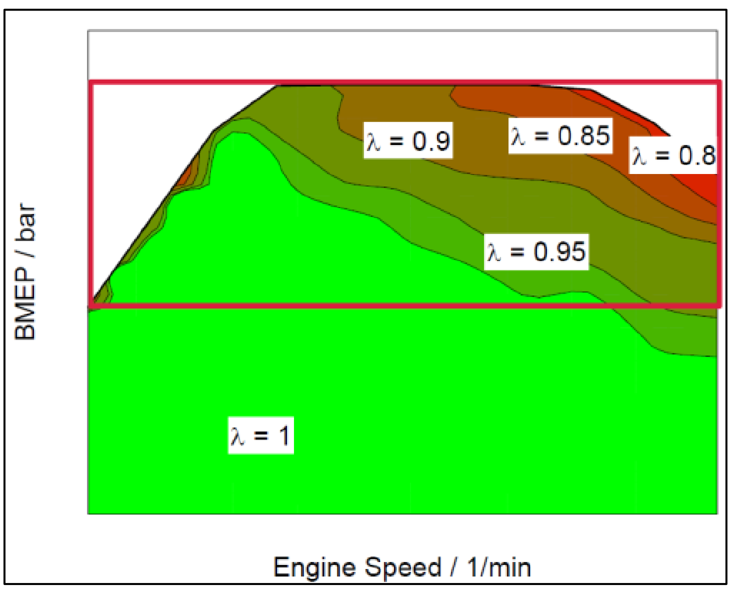


Figure D-24: High-Load Area with Enrichment (red frame)

Advanced combustion phasing and reduced enrichment for turbine protection result in efficiency benefits of up to ≈15% in the high-speed, high-load area where the baseline enrichment is typically the highest.

The cooled external high-load EGR fuel consumption benefit depends significantly on the resulting manifold air temperature and thus on the cooling capacity. Approximately 50% of the possible fuel consumption benefit is lost if the intake manifold increases by ≈20°C.

Independent from the targeted engine load, both low- and high-pressure EGR systems are plausible options for achieving fuel economy benefits.

Low-Pressure EGR

Low-pressure EGR enables the use of EGR in the entire high load area for the following routing options:

- “Upstream three-way catalyst” to “upstream TC compressor”
- “Downstream three-way catalyst” to “upstream TC compressor”

The possibility to use a low-pressure EGR at part load using these routings without additional throttling devices depends on the engine’s individual pressure drop in the low-load, low-speed region.

The standard routings for usage of low-pressure EGR for part load are:

- “Upstream three-way catalyst” to “downstream throttle body”
- “Downstream three-way catalyst” to “downstream throttle body”

High-Pressure EGR

High-pressure EGR can only be utilized in the high-load area, only at higher engine speeds, where a pressure difference is sufficient. Possible routings here:

- “Upstream turbine” to “upstream intercooler”
- “Upstream turbine” to “upstream throttle body” (unlikely)
- “Upstream turbine” to “downstream throttle body”

The possibility to use high-pressure EGR at part load is only given for the routing “upstream turbine” to “downstream throttle body.”

The water content in gasoline engine exhaust gas is higher than that in diesel engine exhaust gas. Therefore, in order to avoid condensation and damage of the turbocharger compressor wheel, a higher EGR temperature has to be ensured at the EGR cooler outlet in case of low-pressure EGR with routing to “upstream compressor.”

This limits the potential to use cooled LP-EGR in the emission test cycle due to the required time for the coolant temperature to reach ~55 °C. The solution in this case is to use an EGR-cooler bypass.

D.5.2 Study Assumptions – Case Study Specific

High- and low-pressure EGR systems do not interact in the same way on turbocharged gasoline engines as on turbocharged diesel engines. Moreover, the base technology of the diesel EGR study (i.e., cooled high-pressure EGR) is not state-of-the-art on turbocharged gasoline engines.

Considering cooled high-pressure EGR as the base technology on gasoline engines assumes that significant component modifications (i.e., increased cooling capacity) are already state-of-the-art which is not the case.

For a gasoline engine, a state-of-the-art EGR usage approach is uncooled EGR with one of the three routings:

- “Upstream three-way catalyst” to “downstream throttle body” (LP-EGR)
- “Downstream three-way catalyst” to “downstream throttle body” (LP-EGR)
- “Upstream turbine” to “downstream throttle body” (HP-EGR)

An LP-EGR with an EGR cooler bypass and one of the following two routings should be evaluated for a system upgrade:

- “Upstream three-way catalyst” to “upstream TC compressor”
- “Downstream three-way catalyst” to “upstream TC compressor”

The base system allows utilizing EGR at part load in order to slightly improve the fuel consumption compared to a gasoline engine without external EGR. The upgraded system enables lower fuel consumption at high engine loads and an equal, if not even a higher, part load benefit as the base system.

D.5.3 Study Hardware Boundary Conditions

FEV’s technical experts defined the engine specifications for the primary gasoline EGR analysis (**Table D-30**). The same engine specifications are assumed for both technology configurations. The basic layout schematics for the baseline and advance configurations are shown in **Figure D-25** and **Figure D-26**, respectively. For the base EGR system, the routing “upstream three-way catalyst” to “downstream throttle body” is used (uncooled low-pressure EGR). In this case, there is no cooler and the EGR valve is located after the throttle body. For the upgraded EGR system the “downstream three-way catalyst” to “upstream TC compressor” routing including an EGR cooler with bypass was selected.

Table D-30: Gasoline EGR Engine Specifications

Engine Specifications	
Displacement	2.0 l
Specific Power	90 kW/l
Number of cylinders	4
Injection System	Direct Injection
Turbocharged	
Variable Cam Timing	

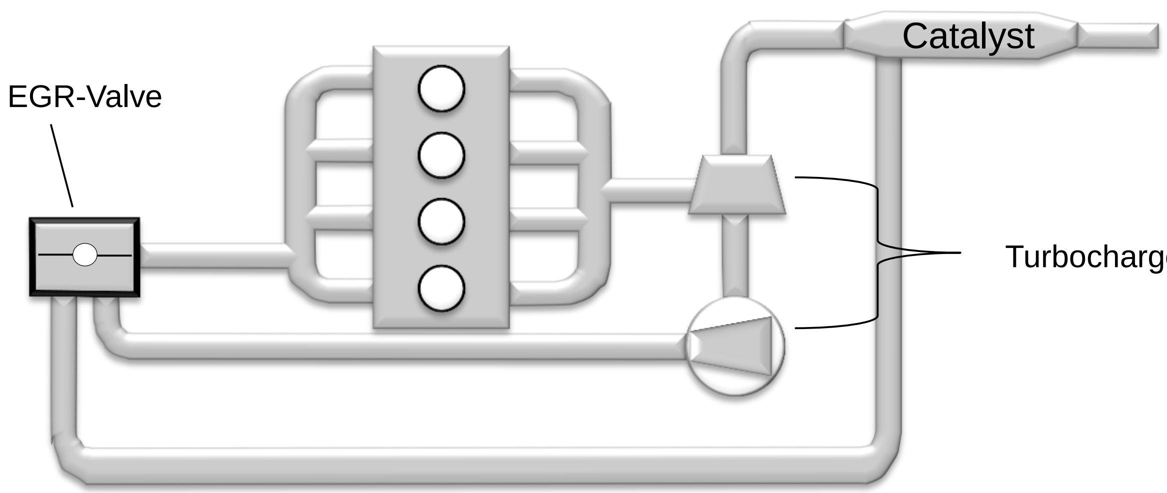


Figure D-25: Base-EGR-System (uncooled LP-EGR)

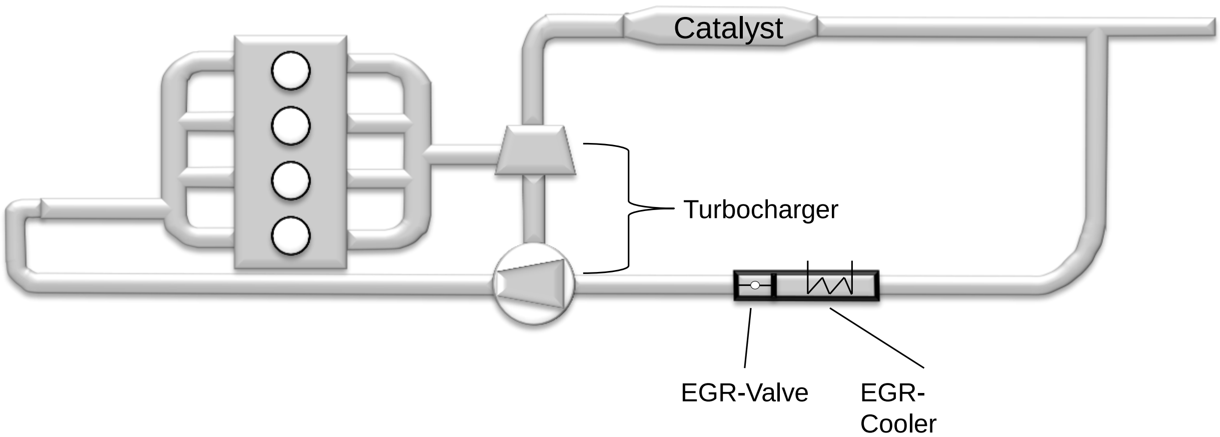


Figure D-26: Upgraded EGR System (cooled LP EGR)

FEV’s costing group worked with a mixture of available hardware components and technical data provided by its gasoline technical team. Before calculating the components, FEV´s costing team discussed with FEV´s gasoline design experts which parts should be taken into account.

The system boundary for both technologies is defined from the throttle body up to and including the catalyst (**Figure D-25** and **Figure D-26**). In addition to these components, the following parts are also taken into account:

- Water pump
- Water cooler
- Intercooler

D.5.4 Components Evaluated in the Analysis

As a result of the previous discussion, following is a list showing all relevant components and what has to be done with each part, if a cooled low-pressure EGR is used instead of an uncooled low-pressure EGR (**Table D-31**).

Table D-31: Component Modifications for Updating from Uncooled Low-Pressure EGR to Cooled Low-Pressure EGR, Gasoline Engine Application

	Components
Reduced number of components	-
Design modifications	■ Water pump ■ Water cooler ■ Intercooler ■ Modifications for crankcase
Substituted components	■ EGR-pipes
Additional components	■ EGR-cooler (incl. bypass system)

Additional assumptions for the cost analysis were made: the "advanced" (upgraded) system included the following specifications:

- High-pressure EGR valve is the same as for the low-pressure EGR
- Flange connections for the connecting pipes (EGR pipes) are welded instead of brazed as for the diesel EGR
- Baseline system will have no EGR cooler
- Upgraded system will use the diesel low-pressure EGR cooler including the bypass system of the diesel high-pressure EGR cooler
- Increase of the effective cooler length by 50% in contrast to the diesel project
- Water pump of the upgraded system needs 20% more flow capacity than that of the baseline technology
- Depth of the water cooler for the upgraded system will increase by 50%
- Intercooler size of the upgraded system will increase by 32%
- Crankcase of the upgraded system needs one additional water channel and one additional flange (to get the cooling water from the water pump near to the EGR cooler)

D.5.5 Cost Strategy Overview on Base Analysis

For this project, FEV used two different costing levels: calculated and commodity parts. The commodity components are divided into low-impact items and purchase parts. For the calculated costing level the full incremental analysis is used. For the commodity parts

FEV has utilized its own database or has requested a quotation, **Table D-32**, **Table D-33**, and **Table D-34** show the costing methodologies for the gasoline EGR project.

Table D-32: Costing Methodology for "Design Modifications"

Design modifications	Costing level	Costing type
Water pump	Commodity	Purchase Parts
Water cooler	Commodity	Purchase Parts
Intercooler	Commodity	Purchase Parts
Modifications for crankcase	Commodity	Purchase Parts

Table D-33: Costing Methodology for "Substituted Components"

Substituted components	Costing level	Costing type
EGR-pipes	Commodity	Low Impact

Table D-34: Costing Methodology for "Additional Components"

Additional components	Costing level	Costing type
Cooler housing	Calculated	Full
Cooling element flange	Commodity	Low Impact
Cooling element housing	Commodity	Low Impact
Cooling element tubes system	Commodity	Low Impact
Cooling element holder	Commodity	Low Impact
Bypass system	Commodity	Purchase Parts

D.5.6 Vehicle Segment Scaling Methodology Overview

The midsize to large vehicle segment (i.e., vehicle segment 3) was chosen as the lead case study for the gasoline EGR analysis. The components are scaled by average ICE power, relative to the lead analysis, for each additional vehicle segment. **Table D-35** shows the scaling factors referring to the estimated delta costs:

Table D-35: Scaling methodology for Gasoline EGR Analysis

Gasoline EGR						
	Vehicle segments					
	0	**1**	**2**	**3**	**5**	**6**
Engine type	I4	I4	I4	I4-I6	I4	I6
Average Power (hp)	100	121	157	234	178	364
Cooler Housing (EGR-cooler)	100%	100%	100%	100%	100%	100%
Cooling element flange (EGR-cooler)	100%	100%	100%	100%	100%	100%
Cooling element housing (EGR-cooler)	43%	52%	67%	100%	76%	156%
Cooling element tubes system (EGR-cooler)	43%	52%	67%	100%	76%	156%
Cooling element holder (EGR-cooler)	100%	100%	100%	100%	100%	100%
Seal (EGR-cooler)	100%	100%	100%	100%	100%	100%
Bypass System (EGR-cooler)	100%	100%	100%	100%	100%	100%
EGR-Pipes	100%	100%	100%	100%	100%	100%
Water pump	43%	52%	67%	100%	76%	156%
Water cooler	43%	52%	67%	100%	76%	156%
Intercooler	43%	52%	67%	100%	76%	156%
Addtitional Water Channel (Crankcase)	100%	100%	100%	100%	100%	100%
Additional Flange (Crankcase)	100%	100%	100%	100%	100%	100%
Hose (Crankcase)	100%	100%	100%	100%	100%	100%
Clamp (Crankcase)	100%	100%	100%	100%	100%	100%
Connector (Crankcase)	100%	100%	100%	100%	100%	100%

D.5.7 Cost Analysis Results Summary

Presented below in **Table D-36** and **Table D-37** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for replacing an uncooled LP EGR subsystem with a Cooled LP EGR subsystem in various gasoline ICE applications.

Table D-36: Net Incremental Direct Manufacturing Costs for Replacing an Uncooled LP EGR Subsystem with a Cooled LP EGR Subsystem (Gasoline ICE)

ICCT Europe Analysis Gasoline Exhaust Gas Recirculation (EGR) Technology Configuration (Rev 7/23/2012)								
		Calculated Incremental Direct Manufacturing Cost - EGR						
	System Description	Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle
	System Analysis ID	3100A	3101	3102	3103A	3103B	3105	3106B
	Vehicle Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment 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	3.0-4.2
	Typical Engine Configuration	I3	I4	I4	I4, I6, V6		I4	V8
	Ave. Power "kW" (hp)	74 (100)	89 (121)	115 (157)	172 (234)		131 (178)	268 (364)
	Ave. Torque "N*m" (lb*ft)	146 (108)	179 (132)	236 (174)	321 (237)		264 (195)	491 (362)
	Typical Transmission Type	5-Speed MT	5 or 6-Speed MT	6-Speed MT	6-Speed MT		6-Speed MT	6-Speed MT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)		1590 (3505)	2207 (4867)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	14.7 (23.9)	14.3 (23.2)	13.0 (21.0)	9.9 (16.0)		12.1 (19.7)	8.2 (13.4)
Technology Configuration Comparison	New Technology Configuration	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR
	Baseline Technology Configuration	UnCooled Low Pressure EGR	UnCooled Low Pressure EGR	UnCooled Low Pressure EGR	UnCooled Low Pressure EGR	UnCooled Low Pressure EGR	UnCooled Low Pressure EGR	UnCooled High Pressure EGR
A	**Exhaust Gas Recirculation Subsystem**	**€ 43.21**	**€ 46.66**	**€ 52.42**	**€ 65.08**	**€ 65.08**	**€ 55.87**	**€ 86.58**
A.1	Crankcase Sub-Susbsystem	€ 5.59	€ 5.59	€ 5.59	€ 5.59	€ 5.59	€ 5.59	€ 5.59
A.2	Cooler Sub-Subsystem	€ 23.20	€ 23.56	€ 24.16	€ 25.49	€ 25.49	€ 24.52	€ 27.73
A.3	Pumps & Intercooler Sub-Subsystem	€ 14.42	€ 17.51	€ 22.66	€ 34.01	€ 34.01	€ 25.76	€ 53.25
	Net Incremental Direct Manufacturing Cost	**€ 43.21**	**€ 46.66**	**€ 52.42**	**€ 65.08**	**€ 65.08**	**€ 55.87**	**€ 86.58**

Table D-37: Net Incremental Technology Costs for Replacing an Uncooled LP EGR Subsystem with a Cooled LP EGR Subsystem (Gasoline ICE)

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
										ICM - Warranty		ICM - Other Direct Costs					
						2012	2016	2020	2025	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	2012	2016	2020	2025
Gasoline, Cooled Low Pressure EGR (Compared to Uncooled Low Pressure EGR)	1	3100A	**Gasoline I3 ICE** **Uncooled Low Pressure EGR** Ave. Displacement = 1.2-1.4L Ave. Power = 74kW (100HP) Ave. Torque = 146N*m (108lb*ft) Typical Transmission Type: 5-Speed MT Curb Weight: 1084kg (2390lb)	**Gasoline I3 ICE Upgraded with Cooled Low Pressure EGR System**	€ 43	€ 60	€ 55	€ 52	€ 44	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	3	3101	**Gasoline I4 ICE** **Uncooled Low Pressure EGR** Ave. Displacement = 1.4-1.6L Ave. Power = 89kW (121HP) Ave. Torque = 179N*m (132lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1271kg (2803lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 47	€ 65	€ 59	€ 56	€ 48	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	4	3102	**Gasoline I4 ICE** **Uncooled Low Pressure EGR** Ave. Displacement = 1.6-2.0L Ave. Power = 115kW (157HP) Ave. Torque = 236N*m (174lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1496kg (3299lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 52	€ 73	€ 66	€ 63	€ 53	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	5	3103A	Gasoline I4 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 65	€ 90	€ 82	€ 78	€ 66	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	6	3103B	Gasoline I6 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I6 ICE Upgraded with Cooled Low Pressure EGR System**	€ 65	€ 90	€ 82	€ 78	€ 66	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	7	3105	Gasoline I4 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 1.2-3.0L Ave. Power = 131 kW (178HP) Ave. Torque = 264N*m (195lb*ft) Typical Transmission Type: 6_Speed MT Curb Weight: 1590kg (3505lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 56	€ 78	€ 71	€ 67	€ 57	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	9	3106B	Gasoline V8 ICE **Uncooled Low Pressure EGR** Ave. Displacement = 3.0-5.5 Ave. Power = 268 kW (364HP) Ave. Torque = 491N*m (362lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 2207kg (4867lb)	**Gasoline V8 ICE Upgraded with Cooled Low Pressure EGR System**	€ 87	€ 120	€ 110	€ 104	€ 88	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74

D.6 Addition of Cooled Low Pressure EGR Compared to a Conventional ICE with no Existing EGR Subsystem.

D.6.1 Technology Overview

A second gasoline EGR study was conducted to understand the incremental cost impact of adding a cooled low-pressure EGR subsystem to a conventional gasoline combustion engine without an existing EGR system. For this analysis, the same core case study assumptions for the cooled low-pressure EGR subsystem were maintained as define in **Section D.5**.

D.6.2 Study Hardware Boundary Conditions

The same engine specifications are assumed for both technology configurations (**Table D-30**). The basic layout schematics for the baseline and advance configurations are shown in **Figure D-27** and **Figure D-28**, respectively. As stated above, the base system has no EGR. For the upgraded EGR system, the “downstream three-way catalyst” to “upstream TC compressor” routing including an EGR cooler with bypass was selected.

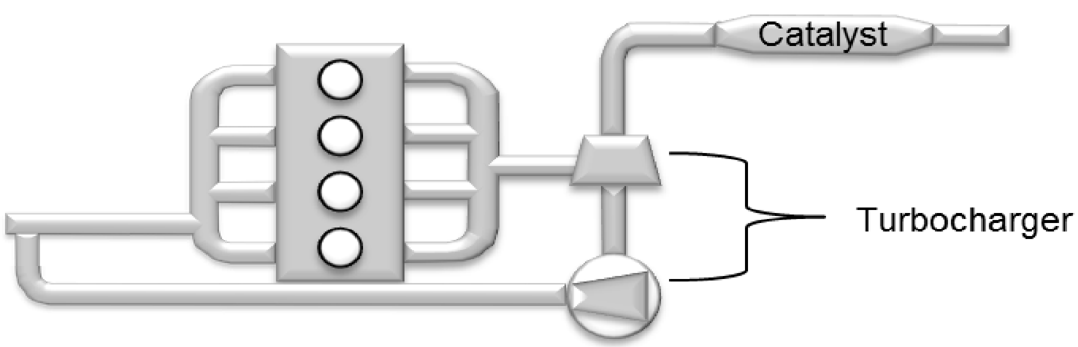


Figure D-27: Base System (No EGR)

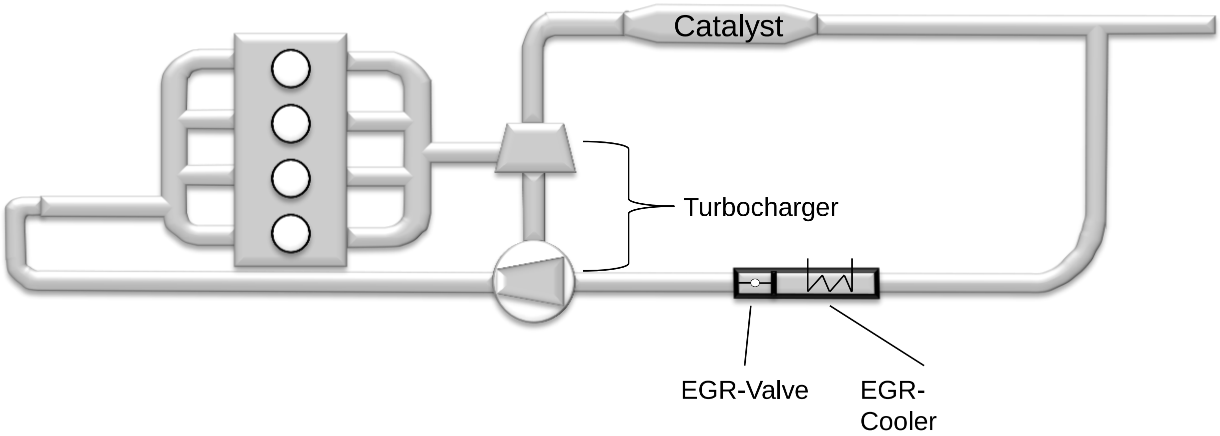


Figure D-28: Upgraded EGR System (cooled LP EGR)

D.6.3 Components Evaluated in the Analysis

Table D-38 below provides a summary of the required component modifications, substitutions, and additions for adding a cooled low-pressure EGR system to a gasoline ICE.

Table D-38: Required Components and Modifications for Updating a Baseline ICE (No EGR) with Cooled Low-Pressure EGR, Gasoline Engine Application

	Components
Reduced number of components	-
Design modifications	▪ Water pump ▪ Water cooler ▪ Intercooler ▪ Modifications for crankcase
Substituted components	-
Additional components	▪ EGR-pipes ▪ EGR-Valve ▪ EGR-cooler (incl. bypass system)

As with the first gasoline EGR analysis (**Section D.5**), components and costs developed as part of the diesel EGR analysis were used as the foundation for costs. Listed following are some of the component assumptions made to transfer the diesel EGR component costs into applicable gasoline EGR costs.

- The flange connections for the connecting pipes (EGR-pipes) are welded instead of brazed as they were for the diesel EGR
- The upgraded system will use the Diesel low-pressure EGR-cooler including the bypass system of the Diesel high-pressure EGR-cooler
- Increase of the effective cooler length by 50% in contrast to the Diesel project
- The water pump of the upgraded system needs 20% more flow capacity than the one of the baseline technology
- The depth of the water cooler of the upgraded system will increase by 50%
- The intercooler size of the upgraded system will increase by 32%
- The crankcase of the upgraded system needs one additional water channel and one additional flange (to get the cooling water from the water pump near to the EGR-cooler)

D.6.4 Cost Strategy Overview on Base Analysis

For this project, FEV used two different costing levels: calculated and commodity parts. The commodity components are divided into low-impact items and purchase parts. For the calculated costing level, the full incremental analysis is used; for the commodity parts, FEV utilized its own database or requested a quotation. **Table D-39** and **Table D-40** show the costing methodologies for the gasoline EGR project.

Table D-39: Costing Methodology for Design Modifications

Design modifications	Costing level	Costing type
Water pump	Commodity	Purchase Parts
Water cooler	Commodity	Purchase Parts
Intercooler	Commodity	Purchase Parts
Modifications for crankcase	Commodity	Purchase Parts

Table D-40: Costing Methodology for Additional Components

Additional components	Costing level	Costing type
EGR-Valve	Commodity	Purchase Parts
EGR-Pipes	Commodity	Low Impact
Cooler housing	Calculated	Full
Cooling element flange	Commodity	Low Impact
Cooling element housing	Commodity	Low Impact
Cooling element tubes system	Commodity	Low Impact
Cooling element holder	Commodity	Low Impact
Bypass system	Commodity	Purchase Parts

D.6.5 Vehicle Segment Scaling Methodology Overview

The midsize to large vehicle segment (i.e., vehicle segment 3) was chosen as the lead case study for the gasoline EGR analysis. The components are scaled by average ICE power, relative to the lead analysis, for each additional vehicle segment. **Table D-41** shows the scaling factors referring to the estimated delta costs:

Table D-41: Scaling Methodology for Gasoline EGR Analysis

Gasoline EGR						
	Vehicle segments					
	0	1	2	3	5	6
Engine type	I4	I4	I4	I4-I6	I4	I6
Average Power (hp)	100	121	157	234	178	364
Cooler Housing (EGR-cooler)	100%	100%	100%	100%	100%	100%
Cooling element flange (EGR-cooler)	100%	100%	100%	100%	100%	100%
Cooling element housing (EGR-cooler)	43%	52%	67%	100%	76%	156%
Cooling element tubes system (EGR-cooler)	43%	52%	67%	100%	76%	156%
Cooling element holder (EGR-cooler)	100%	100%	100%	100%	100%	100%
Seal (EGR-cooler)	100%	100%	100%	100%	100%	100%
Bypass System (EGR-cooler)	100%	100%	100%	100%	100%	100%
EGR-Pipes	100%	100%	100%	100%	100%	100%
EGR-Valve	100%	100%	100%	100%	100%	100%
Water pump	43%	52%	67%	100%	76%	156%
Water cooler	43%	52%	67%	100%	76%	156%
Intercooler	43%	52%	67%	100%	76%	156%
Addtitional Water Channel (Crankcase)	100%	100%	100%	100%	100%	100%
Additional Flange (Crankcase)	100%	100%	100%	100%	100%	100%
Hose (Crankcase)	100%	100%	100%	100%	100%	100%
Clamp (Crankcase)	100%	100%	100%	100%	100%	100%
Connector (Crankcase)	100%	100%	100%	100%	100%	100%

D.6.6 Cost Analysis Results Summary

Presented in **Table D-42** and **Table D-43** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for adding cooled LP EGR subsystems to selected gasoline ICE applications.

Table D-42: Net Incremental Direct Manufacturing Costs for Adding a Cooled LP EGR Subsystem to a Gasoline ICE

ICCT Europe Analysis
Gasoline Exhaust Gas Recirculation (EGR) Technnology Configuration
(Rev 7/19/2012)

	System Description	Calculated Incremental Direct Manufacturing Cost - EGR						
		Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle
	System Analysis ID	3200A	3201	3202	3203A	3203B	3205	3206B
	Vehicle Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment 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	3.0-4.2
	Typical Engine Configuration	I3	I4	I4	I4, I6, V6		I4	V8
	Ave. Power "kW" (hp)	74 (100)	89 (121)	115 (157)	172 (234)		131 (178)	268 (364)
	Ave. Torque "N*m" (lb*ft)	146 (108)	179 (132)	236 (174)	321 (237)		264 (195)	491 (362)
	Typical Transmission Type	5-Speed MT	5 or 6-Speed MT	6-Speed MT	6-Speed MT		6-Speed MT	6-Speed MT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)		1590 (3505)	2207 (4867)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	14.7 (23.9)	14.3 (23.2)	13.0 (21.0)	9.9 (16.0)		12.1 (19.7)	8.2 (13.4)
Technology Configuration Comparison	New Technology Configuration	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR	Cooled Low Pressure Cooled EGR
	Baseline Technology Configuration	No EGR	No EGR	No EGR	No EGR	No EGR	No EGR	No EGR
A	**Exhaust Gas Recirculation Subsystem**	**€ 73.87**	**€ 77.32**	**€ 83.08**	**€ 95.74**	**€ 95.74**	**€ 86.53**	**€ 117.23**
A.1	Crankcase Sub-Susbsystem	€ 5.59	€ 5.59	€ 5.59	€ 5.59	€ 5.59	€ 5.59	€ 5.59
A.2	Cooler Sub-Subsystem	€ 28.65	€ 29.01	€ 29.61	€ 30.94	€ 30.94	€ 29.97	€ 33.18
A.3	Pumps & Intercooler Sub-Subsystem	€ 39.62	€ 42.72	€ 47.87	€ 59.21	€ 59.21	€ 50.96	€ 78.46
	Net Incremental Direct Manufacturing Cost	**€ 73.87**	**€ 77.32**	**€ 83.08**	**€ 95.74**	**€ 95.74**	**€ 86.53**	**€ 117.23**

Table D-43: Net Incremental Technology Costs for Adding a Cooled LP EGR Subsystem to a Gasoline ICE

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
										ICM - Warranty		ICM - Other Direct Costs					
						2012	2016	2020	2025	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	2012	2016	2020	2025
Gasoline, Cooled Low Pressure EGR (Compare to ICE with no EGR)	1	3200A	**Gasoline I3 ICE** **No EGR** Ave. Displacement = 1.2-1.4L Ave. Power = 74kW (100HP) Ave. Torque = 146N*m (108lb*ft) Typical Transmission Type: 5-Speed MT Curb Weight: 1084kg (2390lb)	**Gasoline I3 ICE Upgraded with Cooled Low Pressure EGR System**	€ 74	€ 102	€ 94	€ 88	€ 75	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	3	3201	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 1.4-1.6L Ave. Power = 89kW (121HP) Ave. Torque = 179N*m (132lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1271kg (2803lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 77	€ 107	€ 98	€ 92	€ 79	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	4	3202	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 1.6-2.0L Ave. Power = 115kW (157HP) Ave. Torque = 236N*m (174lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1496kg (3299lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 83	€ 115	€ 105	€ 99	€ 85	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	5	3203A	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 96	€ 133	€ 121	€ 114	€ 98	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	6	3203B	**Gasoline I6 ICE** **No EGR** Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I6 ICE Upgraded with Cooled Low Pressure EGR System**	€ 96	€ 133	€ 121	€ 114	€ 98	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	7	3205	**Gasoline I4 ICE** **No EGR** Ave. Displacement = 1.2-3.0L Ave. Power = 131 kW (178HP) Ave. Torque = 264N*m (195lb*ft) Typical Transmission Type: 6_Speed MT Curb Weight: 1590kg (3505lb)	**Gasoline I4 ICE Upgraded with Cooled Low Pressure EGR System**	€ 87	€ 120	€ 110	€ 103	€ 88	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	9	3206B	**Gasoline V8 ICE** **No EGR** Ave. Displacement = 3.0-5.5 Ave. Power = 268 kW (364HP) Ave. Torque = 491N*m (362lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 2207kg (4867lb)	**Gasoline V8 ICE Upgraded with Cooled Low Pressure EGR System**	€ 117	€ 163	€ 149	€ 140	€ 120	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74

D.7 6-Speed, Dry, Dual Clutch Transmission Analysis

D.7.1 Technology Overview

A transmission links the engine, the vehicle, and the driver. It acts as an interface which has to optimize the power flow to the wheels according to the driver's request. The European automotive market tends to favor the Manual Transmissions (MT) for its high efficiency, low cost, and the full control it provides the driver. Conversely, the conventional Automatic Transmission (AT) is favored in the U.S. and Japanese markets where comfort and ergonomics are preferred, at the expense of lower efficiency and higher costs. The Dual Clutch Transmission (DCT) can be considered as a hybrid of the manual and automatic transmission. The DCT design architecture, more representative of a manual transmission, delivers similar efficiencies to that of manual transmission. The automated shifting aspect of a DCT offers similar comfort and convenience found in an automated transmission; the price somewhere in-between a manual and automatic transmission. Debatable in the industry, the current performance and shift quality differences which exist between DCTs and automatic transmissions. Currently two types of DCTs are available in the market, Wet-DCTs and Dry-DCTs. Based on unit sales, Wet-DCTs are the current market leader.

Table D-44 provides a high level comparison of the two (2) types of DCT transmissions. As shown in the table, a current advantage of the Wet-DCT systems over the Dry-DCT is the ability to handle higher torque requirements. Although for the smaller vehicles, where the torque requirements are lower, the Dry-DCT provides a good fit at a reduced cost over the Wet-DCT.

For this project, a cost comparison was initially developed between a 6-Speed Dry-DCT and 6-Speed MT (max input torque 350 N*m). The applicable vehicle segments include Midsize (02) and Midsize to Large Passenger (03) Vehicle segments. The technology was scaled to other vehicle segments with the acknowledgement that for the larger vehicle segments, shift quality would most likely be jeopardized without advances in the technology.

Table D-44: Dual Clutch Transmissions – Wet vs. Dry

Wet Clutch	Dry Clutch
Clutches are cooled and lubricated by oil	Clutches are not lubricated
May have a combined (single) sump for the clutch and gearbox, or separate sumps for the clutch and gearbox	Single sump for the gearbox
Customised DCT fluid is needed for the clutches in a single sump application – this needs to provide for both the frictional requirements of the clutches and the load-carrying and synchromesh performance of the gearbox	No lubricant is required for the clutches
Gearbox lubricated either by DCT fluid (in single sump application) or MTF (in separate sump application)	Gearbox lubricated with MTF
Can be used in higher, as well as lower, torque applications due to the cooling effect of the lubricant on the clutches under high loads	Restricted to lower torque applications due to the lack of oil to cool the clutches under high loads
Incurs parasitic losses when pumping the DCT fluid	Improved efficiencies due to reduced parasitic losses for fluid pumping, reduced weight and fluid quantity

(Source: http://www.dctfacts.com/Wet-vs-Dry/default.aspx)

D.7.2 Study Assumptions – Case Study Specific

The selected manual and dual clutch transmissions (
Figure D-29) were developed and produced by FIAT Powertrain Technologies (FPT). The C635 transmissions are transversal front-wheel drive and are characterized by a compact, three-shaft architecture with a maximum input torque of 350 Nm. The primary applications of this transmission are B- and C-segment vehicles powered by turbocharged gasoline and Diesel engines. The Dual Dry Clutch Transmission of the C635 family features an electro-hydraulic actuation system and is characterized by compactness, speed, and efficiency. Both transmissions, the Manual and Dual Dry Clutch, are sharing the maximum possible number of common mechanical components and the same production line (FPT Verrone Plant, Biella, Italy).

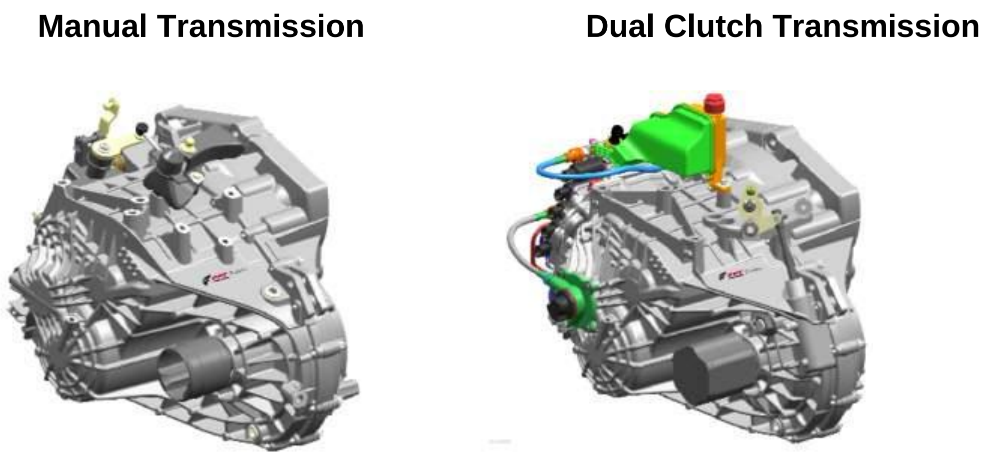


Figure D-29: C635 MT and DCT Versions

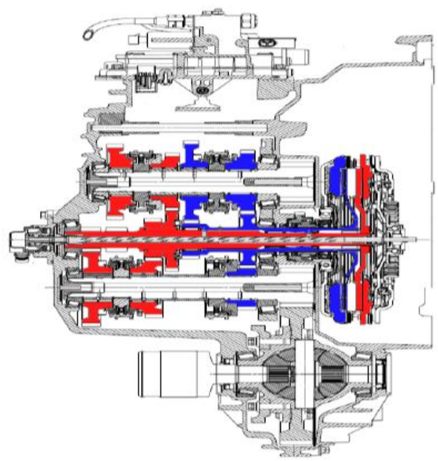
D.7.2.1 DCT Technology Details

As shown in **Figure D-30** below, the 3-shaft DCT transmission architecture is contained in a two (2)-piece aluminum housing with an intermediate support plate for the shaft bearings. This solution allowed the positioning of the differential group closer to the engine Rear Face of Block (RFOB) and renders the transmission compatible with the packaging requirements in the B-Segment target vehicles. Also illustrated by **Figure D-30**, (i.e., highlights red and blue components) is the component commonality between the manual and dual clutch transmissions.

The gear set housing is characterized by reduced upper secondary shaft length, a feature which was also necessary in order to ensure packaging in the lower segment vehicles where the longitudinal crash beam imposes serious installation constrains. The 6th gear is shared with the 4th while an eventual, non-power shift 7th gear would be shared with the 5th, with either increased or equal overall gear spread compared to the 6-speed version. The most important feature of this transmission in terms of packaging characteristics is the adoption of a coaxial pull-rod for the actuation of the odd-gear clutch (K1), while the even-gear clutch (K2) is actuated with a rather conventional hydraulic Concentric Slave Cylinder (CSC). This pull-rod is connected to a hydraulic piston actuator located on the rear face of the transmission housing.

Finally, all synchronizer groups share the same base elements and are identical to those of the MT version. Logistics and economic considerations favored this solution which may not be necessary in a DCT transmission which doesn't share components. The four (4) forks are guided on two (2) rods. The MT and DCT forks differ only in terms of prong shape. Further, a specific form of the rods allows production of a single part number.

Table D-45 provides some basic mechanical characteristics of the 6-speed Dry-DCT.



(Source: Vafidis, C.: FPT's high torque density dual dry clutch transmission (HTD-DDCT), 8th International CTI-Symposium Innovative Automotive Transmissions, 2009)

Figure D-30: Cross-Section of C635 Dry-DCT

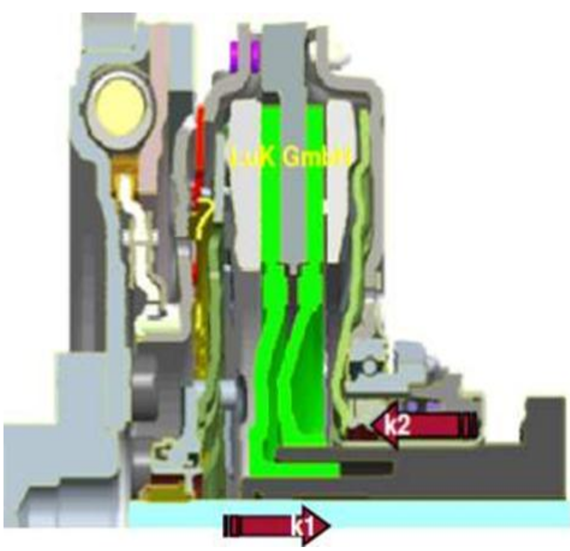
Table D-45: Mechanical Characteristic of C635 Dry-DCT

Layout	3-Shaft plus Reverse Gear Idler
Number of Speeds	6 (7 Possible)
Housing	2-Piece with Intermediate Support Plate
Shaft Center Distance	197mm
Input Torque	350 N*m Max
Output Torque	4200 N*m Max
Gear Ratios in Production	1st = 3.9-4.154 2nd = 2.269 3rd = 1.435-1.522 4th = 0.978-1.116 5th= 0.755 -0.915 6th = 0.622-0.767 RG =4.00
Synchronizers	1st, 2nd, 3rd → 3-cone 4th, RG → 2-cone 5th, 6th → 1-cone
Weight	81kg (with hydraulic and lubrication oil)

(Source: Vafidis, C.: FPT's high torque density dual dry clutch transmission (HTD-DDCT), 8th International CTI-Symposium Innovative Automotive Transmissions, 2009)

The Dual Clutch Unit

The dual clutch unit (**Figure D-31**) of the C635 DCT is a very compact design. This, together with the K1 actuator solution described previously, are the main contributors to the transmission's compactness. The K1 clutch is normally closed (as in conventional manual transmissions) and features an integrated wear compensation mechanism. The adoption of a normally closed 5th gear was primarily dictated by energy-saving considerations. Since odd-gear driving exceeds 50% of the vehicle mission, the operation of the hydraulic power unit to maintain the odd-clutch closed is considered inefficient. Furthermore, this configuration results in a more compact Dual Clutch Unit (DCU) and, eventually, can be exploited in motorway driving if the 7th gear is adopted. Although not contemplated at this stage, the adoption of a normally closed launch clutch would effectively eliminate the need for a parking brake; which, in the C635 case, is integrated in the differential block. However, given the current regulations, this parking concept seems rather difficult to implement in a DCT transmission.



Dual Clutch Unit Characteristics

- Extremely compact
- Supported by one bearing on clutch housing
- Coupled through spline to the DMF
- Odd Gear Clutch
    - normally closed
    - actuated through coaxial pull-rod
    - position controlled
    - Wear compensation
- Even Gear Clutch
    - normally open
    - actuated through concentric slave cylinder
    - force controlled
- Actuated through CSC
- Force controlled

(Source: Vafidis, C.: FPT's high torque density dual dry clutch transmission (HTD-DDCT), 8th International CTI-Symposium Innovative Automotive Transmissions, 2009)

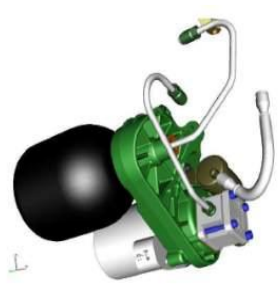
Figure D-31: Dual Clutch Unit C635 Dry DCT

The K1 clutch is position-controlled by means of a contact-less linear position sensor integrated in the rear hydraulic piston actuator. Given the space available and the less hostile environment outside the clutch housing, this solution was rather straightforward and allowed the implementation of launch control strategies nearly identical to those of the well-established automated manual transmission (AMT) products of the FPT portfolio.

The even-gear K2 clutch is normally open and is controlled in force (i.e., hydraulic pressure) by means of a CSC. The two (2) clutches act on a center plate which, together with the two (2) pressure plates, has been dimensioned according to the thermal dissipation characteristics required for the most critical vehicle/engine applications foreseen. This model resides in the control algorithms of the Transmission Control Unit (TCU) and forms the basis of the torque transmissibility and thermal protection strategies. The entire DCU is mounted on the clutch housing by means of a single main support bearing. The DCU is linked through a splined connection to a dual mass flywheel mounted on the engine crankshaft.

The Clutch- and Gear-Actuation System

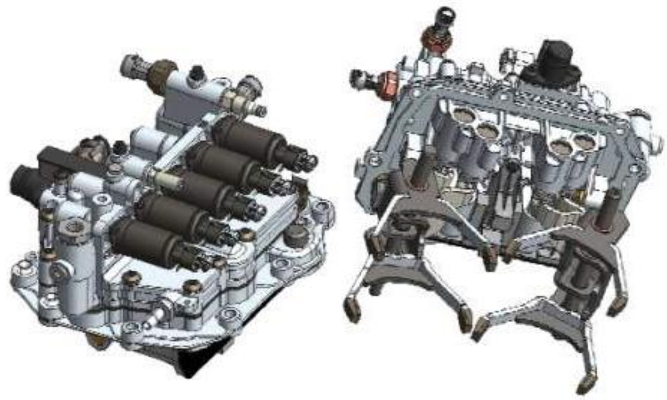
The C635 DCT clutches and gear shifting mechanisms are electro-hydraulically actuated through a dedicated, sealed, hydraulic oil circuit. The system is composed of a hydraulic power unit **(Figure D-32),** consisting of an electrically driven high pressure pump and accumulator, and an Actuation Module (**Figure D-33)** which includes the control solenoid valves, gear shift actuators and sensors. The hydraulic oil used is the same one used in FPT's current AMTs. The actuation pressure of the system under normal driving conditions does not exceed 20 bar, although the hydraulic power unit is capable of delivering pressure between 40 and 50 bar. The electric oil pump is driven by a Smart Drive Unit (SDU), controlled using Pulse Width Modulation (PWM) signals, thus allowing the pump speed regulation for noise control and efficiency optimization. The pump's duty cycle in urban driving rarely exceeds 25%, evidence of the system's efficiency when compared to alternative concepts which require continuous operation of a mechanically driven hydraulic pump. This also allows the use of a brushed motor for the pump electric drive.



Hydraulic Power Unit (HPU)

- Electrically Driven
- Smart driver actuated
- Low duty cycle (efficiency)
- Stop & Start compatibility

Figure D-32: The hydraulic Power Unit (HPU)

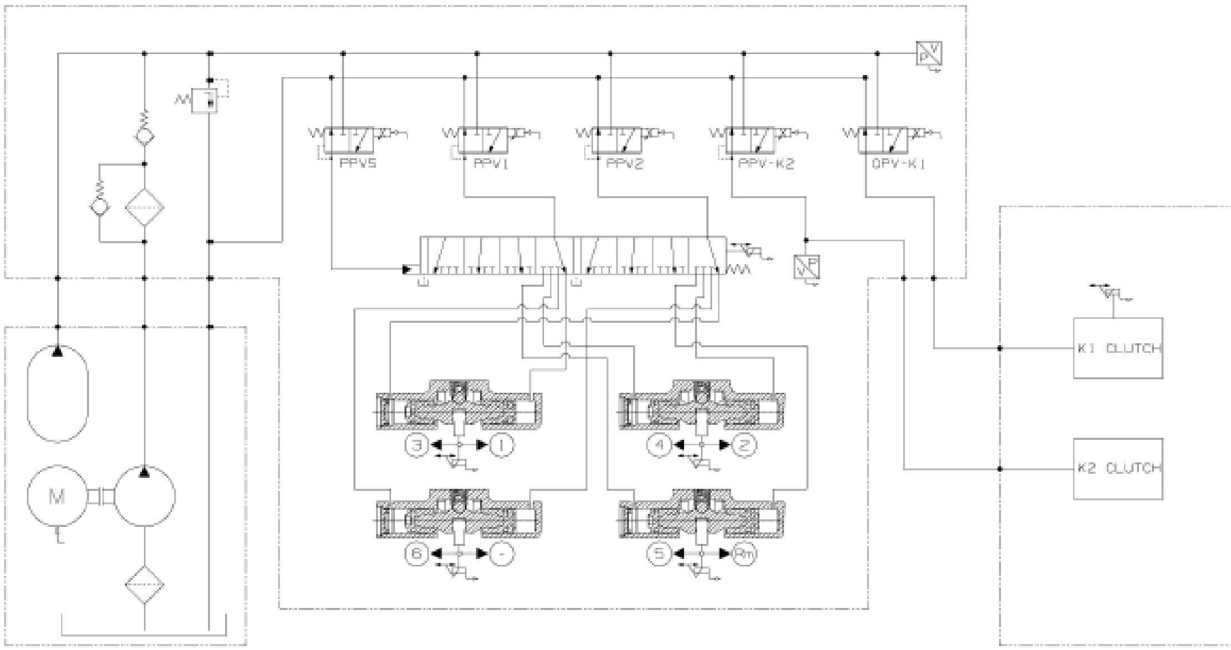


Clutch Actuation module (CAM)

- 5 pressure/flow control valves
- Integrated:
    - contact-less position sensors
    - speed sensors
    - pressure sensors

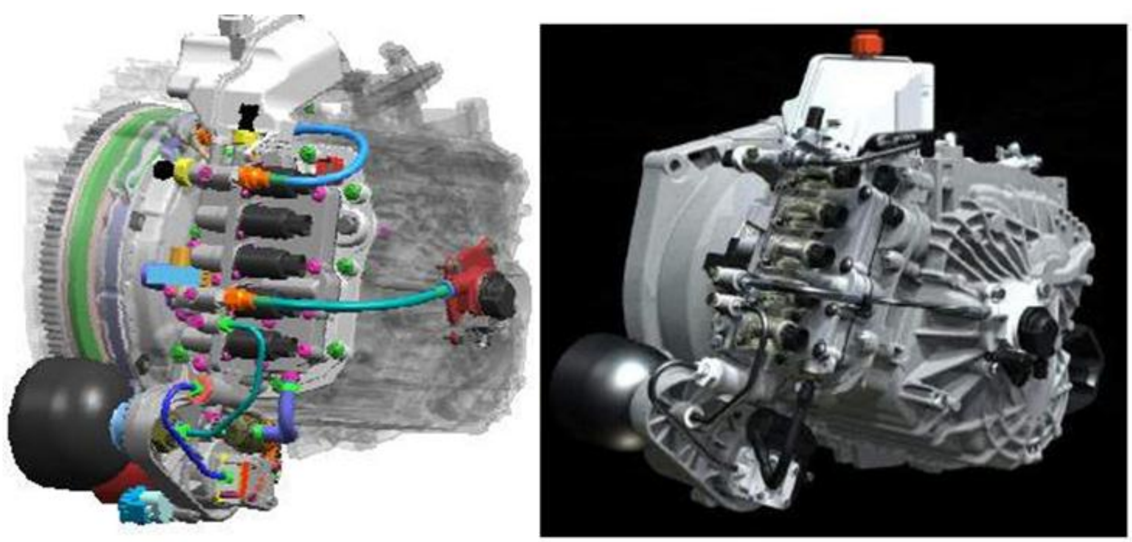
Figure D-33 : The complete Clutch Actuation Module (CAM) (upper and lower view)

The clutch and gear actuation module, consists of 4 distinct double action pistons operating the gear engagement forks, one "shifter" spool which selects the piston to be actuated and 5 solenoid valves of which 4 are pressure proportional (PPV) and one flow proportional (QPV). Two of the PPVs actuate the gear engagement piston which is selected by the spool valve operated by the third PPV. The fourth PPV is used for the control of the K2 concentric slave cylinder (CSC). The QPV is used for the position control of the K1 clutch. All solenoid valves are direct derivatives of those currently used in FPT's AMT systems and, therefore, employ well proven technology and guarantee robustness. The Actuation Module also comprises of five (5) non-contact linear position sensors, one for each shifting piston and one for the shifter spool, as well as two speed sensors reading the speed of the two primary shafts. Finally, one pressure sensor is used for the control of the K2 clutch and one for the system pressure monitoring and control. The K1 clutch position sensor, as mentioned before, is integrated in the clutch piston actuator located at the rear of the transmission**. Figure D-34** below represents the hydraulic circuit of the complete actuation system. **Figure D-35** presents the corresponding physical layout complete with the hydraulic oil tank.



(Source: Vafidis, C.: FPT's high torque density dual dry clutch transmission (HTD-DDCT), 8th International CTI-Symposium Innovative Automotive Transmissions, 2009)

Figure D-34: Complete Actuation System Hydraulic Circuit



(Source: Vafidis, C.: FPT's high torque density dual dry clutch transmission (HTD-DDCT), 8th International CTI-Symposium Innovative Automotive Transmissions, 2009)

Figure D-35: Layout of the Complete Actuation System and Installation on the C635 DDCT

D.7.3 Study Hardware Boundary Conditions

For the transmission analysis the majority of the changes were associated with components in the transmission system. The illustration below provides a simple representation of the key components found in each technology configuration.

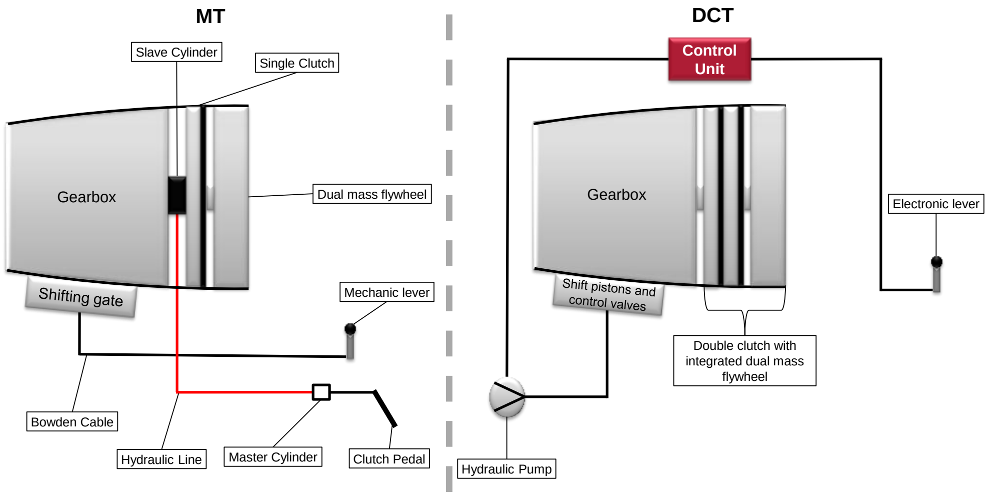


Figure D-36: Layout Difference between MT and DCT

D.7.4 Components Evaluated in the Analysis

The target for this project was to calculate both transmission configurations completely to arrive at a differential cost. Both transmissions along with the necessary periphery components were purchased for the analysis. **Table D-46** provides high level summary of the transmission subsystem components evaluated.

Table D-46: Evaluated components of DCT and MT

Subsystem	DCT	MT
Housing	2 piece aluminum	2 piece aluminum
Gear Train	4 shafts	3 shafts
	9 single gears	10 single gears
Clutch	Double clutch with integrated dual mass flywheel	Single clutch
		Dual mass flywheel
Actuation system	Electronic lever	Mechanic lever
	Control unit	Clutch pedal
	Hydraulic pump	Master cylinder
	Control valves	Hydraulic line
	Shift pistons	Bowden cable
	Shift forks	Shift forks
	2 slave cylinders	1 slave cylinder

D.7.5 Cost Strategy Overview on Lead Case Study

The components of both transmissions are divided into three costing levels. **Table D-47**, **Table** D-47, and **Table** D-49 illustrate the components included, and the cost level employed, at each level.

Table D-47: Transmission Components Evaluated Using Full Costing Type Methodology

Component	Costing Level	Costing Type
Gear wheels	Calculated	Full
Input shafts	Calculated	Full
Gear ring	Calculated	Full

Table D-48: Transmission Components Evaluated Using Low Impact Costing Type Methodology

Component	Costing Level	Costing Type
Housing	Commodity	Low Impact
Carrier Differential + Annulus	Commodity	Low Impact
Pinion differential	Commodity	Low Impact

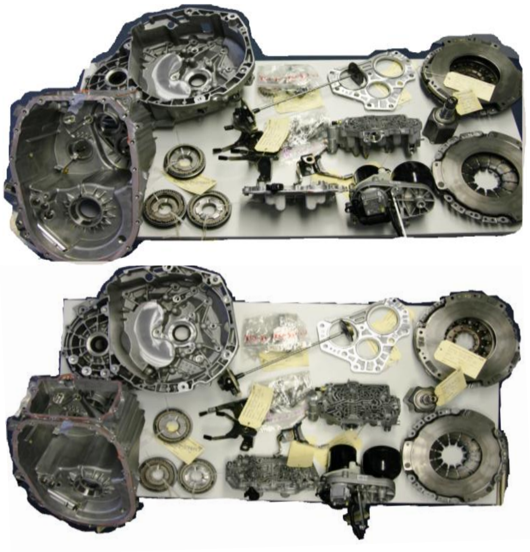


Table D-49: Transmission Components Evaluated Using Purchased Part Costing Type Methodology

Component	Costing Level	Costing Type
Shaft seal	Commodity	Purchase Parts
Screws/Bolts	Commodity	Purchase Parts
Sensors	Commodity	Purchase Parts
Valves	Commodity	Purchase Parts
Bearings	Commodity	Purchase Parts
Bushings	Commodity	Purchase Parts
Clutch	Commodity	Purchase Parts
Pipes	Commodity	Purchase Parts
Actuation system	Commodity	Purchase Parts
Lever	Commodity	Purchase Parts
Flywheel	Commodity	Purchase Parts
Parking lock	Commodity	Purchase Parts
…	…	…

D.7.6 Vehicle Segment Scaling Methodology Overview

The lead case study for this analysis was the midsize passenger vehicle segment (vehicle segment 2). The transmission cost scaling analysis was founded on average diesel engine output torque for each vehicle segment. For each vehicle segment, based on average transmission maximum input torque, a transmission weight was calculated using **Figure D-37**. Based on weight, scaling ratios were developed to scale the net incremental direct manufacturing costs from the lead case study to other vehicle segments. **Table D-50** summarizes the scaling factors utilized for the scaling analysis.

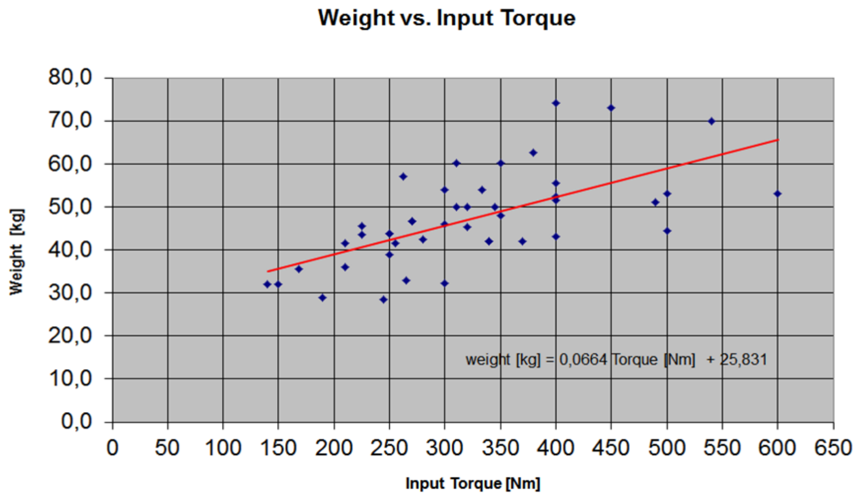


Figure D-37: Weight in dependence on input torque (Manual Transmissions)

Table D-50: Transmission Scaling Methodology

Scaling methodology												
	Vehicle segments											
	0	0	1	1	2	2	3	3	5	5	6	6
Engine type	I3-I4	I3-I4	I4	I4	I4	I4	I4-I6	I4-I6	I4	I4	I6-V8	I6-V8
Transmission type	MT	DCT	MT	DCT	MT	DCT	MT	DCT	MT	DCT	MT	DCT
Torque [Nm]	201	201	246	246	321	321	416	416	336	336	623	623
~ Weight [kg]	39	39	42	42	47	47	53	53	48	48	67	67
Transmission without mecatronic/actuation system	83%	83%	89%	89%	100%	100%	113%	113%	102%	102%	143%	143%
Transmission mechatronic/actuation system	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

D.7.7 Cost Analysis Results Summary

Presented below in **Table D-51** and **Table D-52** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for replacing a 6-Speed Manual Transmission with a 6-Speed Dry Dual Clutch Transmission.

As a point of reference the calculated net incremental direct manufacturing cost difference between a 6-Speed Dry DCT and 6-Speed Wet DCT (maximum input torque approximately 350N*m) is approximately +€39 ($54/1.4 US to Euro Exchange Rate). That is the Wet DCT was calculated to be approximately €39 more in cost than the Dry DCT. The cost calculation was based on converting VW's Wet DCT (Model DQ250) into a Dry DCT using their 7-Speed DQ200 (250N*m) transmission as reference for the differences.

Table D-51: Net Incremental Direct Manufacturing Costs for Replacing an 6-Speed Manual Transmission with a Dry, Dual Clutch Transmission (DCT)

ICCT Europe Analysis
Dry Dual Clutch Transmission Technnology Configuration
(Rev 6/4/2012)

		Calculated Incremental Direct Manufacturing Cost - Dry DCT								
System Description		Subcompact Passenger Vehicle	Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle	Large Sport Utility Vehicle
System Analysis ID		2600A	2600B	2601	2602	2603A	2603B	2605	2606A	2606B
	Vehicle Example	VW Polo, Ford Fiesta	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment Powertrain Parameters	Typical Engine Size Range (Liters)	1.2-1.4		1.6	2.0	2.0		2.0-3.0	3.0-4.2	
	Typical Engine Configuration	I3	I4	I4	I4	I4	I6	I4	I6	V8
	Ave. Power "kW" (hp)	62.5 (85)		78.6 (107)	104 (141)	148.5 (202)		117.6 (160)	213 (290)	
	Ave. Torque "N*m" (lb*ft)	201 (148)		246 (181)	321 (237)	416 (307)		336 (248)	623 (460)	
	Typical Transmission Type	5-Speed MT		5 & 6-Speed MT or DCT	6-Speed MT or 8-Speed AT	6-Speed MT or DCT, 8-Speed AT		6-Speed MT or 8-Speed AT	8-Speed AT	
	Ave. Curb Weight "kg" (lb)	1084 (2390)		1271 (2803)	1496 (3299)	1700 (3749)		1590 (3506)	2207 (4866)	
	Weight-to-Power Ratio "kg/kW" (lb/hp)	17.3 (28.1)		16.2 (26.2)	14.4 (23.4)	11.4 (18.6)		13.5 (21.9)	10.4 (16.8)	
Technology Configuration Comparison	New Technology Configuration	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT	6-Speed Dry DCT
	Baseline Technology Configuration	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission	6-Speed Manual Transmission
A	Mechanical and Electrical Actuation and Control Subsystem	€ 208.21	€ 208.21	€ 208.26	€ 208.36	€ 208.47	€ 208.47	€ 208.38	€ 208.73	€ 208.73
B	Case Subsystem	€ 1.92	€ 1.92	€ 2.01	€ 2.17	€ 2.37	€ 2.37	€ 2.20	€ 2.82	€ 2.82
C	Gear Train Subsystem	(€ 2.14)	(€ 2.14)	(€ 2.60)	(€ 3.46)	(€ 4.47)	(€ 4.47)	(€ 3.61)	(€ 6.80)	(€ 6.80)
D	Launch Clutch Subsystem	€ 50.88	€ 50.88	€ 54.36	€ 60.74	€ 68.28	€ 68.28	€ 61.90	€ 85.68	€ 85.68
E	Parking Mechanism Subsystem	€ 5.96	€ 5.96	€ 5.96	€ 5.96	€ 5.96	€ 5.96	€ 5.96	€ 5.96	€ 5.96
F	Assembly & Test	€ 23.30	€ 23.30	€ 23.30	€ 23.30	€ 23.30	€ 23.30	€ 23.30	€ 23.30	€ 23.30
	Net Incremental Direct Manufacturing Cost	€ 288.12	€ 288.12	€ 291.28	€ 297.07	€ 303.90	€ 303.90	€ 298.12	€ 319.68	€ 319.68

Table D-52: Net Incremental Technology Costs for Replacing an 6-Speed Manual Transmission with a Dry, Dual Clutch Transmission (DCT)

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied: 2012	2016	2020	2025	ICM Factor: ICM - Warranty: Short Term 2012 thru 2018(1)	ICM - Warranty: Long Term 2019 thru 2025(2)	ICM - Other Direct Costs: Short Term 2012 thru 2018(1)	ICM - Other Direct Costs: Long Term 2019 thru 2025(2)	Learning Factor: 2012	2016	2020	2025
Dry Dual Clutch Transmission	1	2600A	**Diesel I3 ICE** Ave. Displacement = 1.0L Ave. Power = 62.5kW (85HP) Ave. Torque = 201N*m (148lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1084kg (2390lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	€ 288	€ 400	€ 365	€ 317	€ 294	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	3	2601	**Diesel I4 ICE** Ave. Displacement = 1.6L Ave. Power = 78.6kW (107HP) Ave. Torque = 246N*m (181lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1271kg (2803lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	€ 291	€ 404	€ 369	€ 321	€ 297	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	4	2602	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 104kW (141HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1496kg (3299lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	€ 297	€ 412	€ 377	€ 327	€ 303	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	5	2603A	**Diesel I4 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1700kg (3749lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	€ 304	€ 422	€ 385	€ 334	€ 310	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	6	2603B	**Diesel I6 ICE** Ave. Displacement = 2.0L Ave. Power = 148.5W (202HP) Ave. Torque = 416N*m (306lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1700kg (3749lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission (Ave. Max. Input Torque 592 N*m)**	€ 304	€ 422	€ 385	€ 334	€ 310	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	7	2605	**Diesel I4 ICE** Ave. Displacement = 2.0-3.0L Ave. Power = 117.6W (160HP) Ave. Torque = 336N*m (248lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 1590kg (3505lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	€ 298	€ 414	€ 378	€ 328	€ 304	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74
	9	2606B	**Diesel V8 ICE** Ave. Displacement = 3.0 -4.2L Ave. Power = 213kW (290HP) Ave. Torque = 623N*m (460lb*ft) Typical Transmission Type: **6-Speed MT** Curb Weight: 2207kg (4866lb)	**Upgrade with 6-Speed Dry Dual Clutch Tranmission**	€ 320	€ 443	€ 405	€ 352	€ 326	0.045	0.031	0.343	0.259	1.00	0.89	0.82	0.74

D.8 Belt-Driven Starter-Generator (BSG), Stop-Start Hybrid Electric Vehicle Analysis – Gasoline Engine, Manual Transmission

D.8.1 Stop-Start Technology Overview

Today's vehicle manufacturers continue to explore and adopt new technologies in order to reduce fuel consumption and emissions within their fleets. Among this array of automotive expertise are stop-start system technologies. A stop-start system, used in conjunction with other fuel-saving technologies, can be a key to attaining the stringent carbon-emission standards set for 2020.

Stop-start technology, simply stated, is the automatic switch-off of the engine when such an equipped vehicle stops, or the re-start after idling as needed. This saves fuel when the vehicle is at a lengthy stop – such as when at a traffic light or in a traffic jam – and then restarting instantly when the driver accelerates. Fuel otherwise consumed dramatically in heavy traffic conditions is conserved and CO_2 emissions are reduced.

The European market is currently dominated by stop-start systems such as belt-driven starter generator (BSG). Stop-start systems cost a fraction of competing hybrid technologies (e.g., full hybrid, plug-in, pure electric vehicle), which carry significant prices for returns in fuel economy improvement. It is estimated that stop-start vehicles yield fuel economy improvements in the range of 10-15%.

It is estimated that more than 50% of new registered vehicles after 2013 will include stop-start technology as standard. Even though the technology is more widely utilized among the small- and mid-size car segments in Europe, it is seen to have high potential among future compact and luxury car segments.

Engine stop-start capability while driving (i.e., during coast down) will soon be implemented in many vehicle systems. Different stop-start technologies have been adopted by various vehicle manufacturers. The most common stop-start systems currently found in the European market are:

1. Belt-driven starter generator (BSG)
2. Enhanced starter
3. Direct starter
4. Integrated/Crankshaft starter generator (ISG/CSG)

D.8.1.1 Belt-Driven Starter Generator (BSG)

A conventional starter motor and alternator can be replaced by a belt starter generator system. The BSG minimizes engine start-up time, as well as charges the vehicle battery by recuperating energy. The BSG is integrated into the belt drive system of a conventional combustion engine, much the same way as a normal alternator. It has the same fixing points as a normal alternator, so it may be used as a flexible replacement solution.

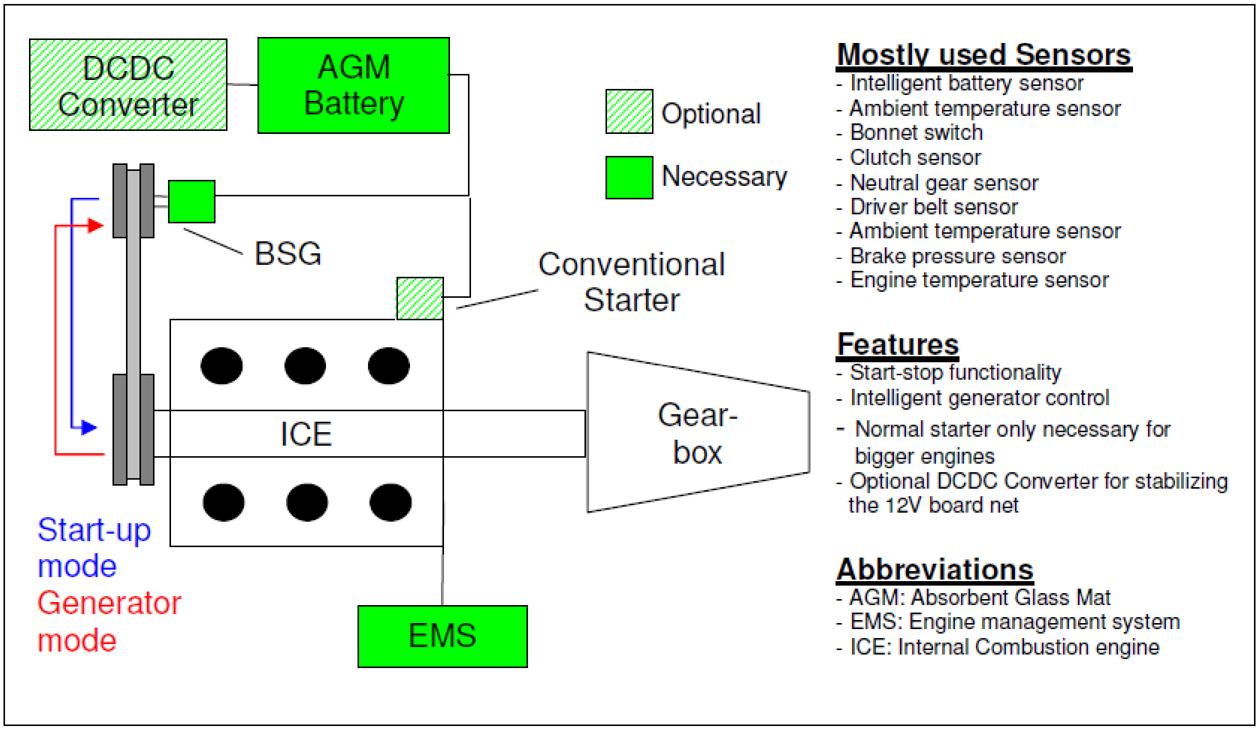


Figure D-38: System Layout of Belt-driven Starter Generator (BSG)

A major modification on the belt-drive system is the reinforcement of the belt tensioning system. This is necessary because a normal alternator is using the force of the belt power transfer in only one direction, while the BSG movement is bi-directional on the belt to speed up the combustion engine during start-up (**Figure D-38**). Higher forces and wear must be taken into account for the new belt system with a BSG concept. The larger forces requires a redesign of the belt drive system (i.e., with a wider belt, the tension roller has to increase the belt tension, the deflection puller has to be adapted regarding higher bearing force, and the bearings have to be reinforced). Changes on the belt drive system lead to a different loading on the crankshaft driving pulley damper assembly modifications.

Positive features of the BSG style system include integration ease into exiting conventional powertrain systems, elimination of conventional starter for smaller engines, and smoothness of restart. Conversely the BSG system requires higher service frequency on the belt drive system components and the need for a conventional starter on larger engines to handle the higher cold start loading.

Current suppliers offering BSG systems include Valeo, INA, Bosch, and Denso.

D.8.1.2 Enhanced Starter System

The enhanced starter stop-start system (**Figure D-39**) consists of a modified starter to meet the requirement of multiple starts as compared to conventional starter. The system also consists of a modified generator for energy recuperation.

The enhance starter system is a very economical solution. However the restarts are not as smooth as with other available systems. In addition, not until recently, have systems been offered with the potential for restart at various vehicle speeds.

Current suppliers of enhance starter systems include Bosch and Denso.

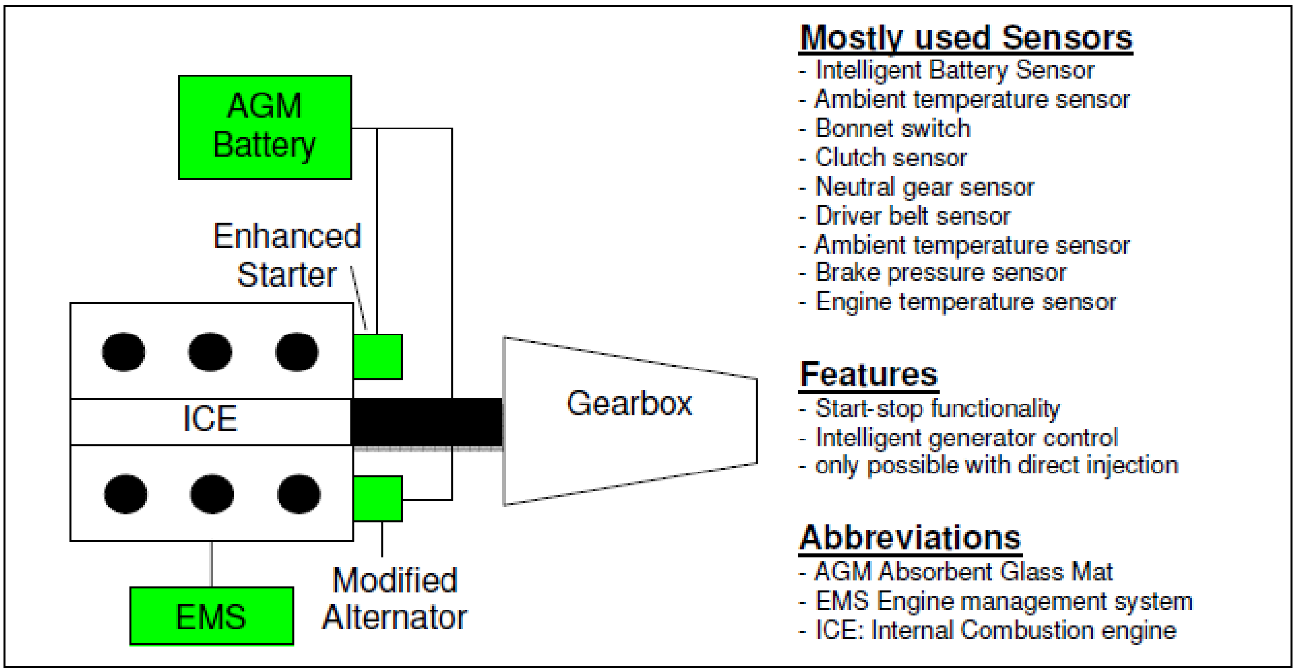


Figure D-39: System Layout – Enhanced Starter

D.8.1.3 Direct Starter

A direct starter system (**Figure D-40**) uses direct injection and combustion to instantly restart the engine, rather than requiring replacement alternator and starter as in case of other stop-start systems. The principle of this system is to position the piston in an optimal position during the vehicle stop, so as to instantly restart the vehicle by injecting fuel into the cylinder. This system can be capable of generating a quick restart. Challenges with the direct starter system include emissions and NVH control at start-up.

The Mazda i-Stop system is an example of a direct starter system in the market.

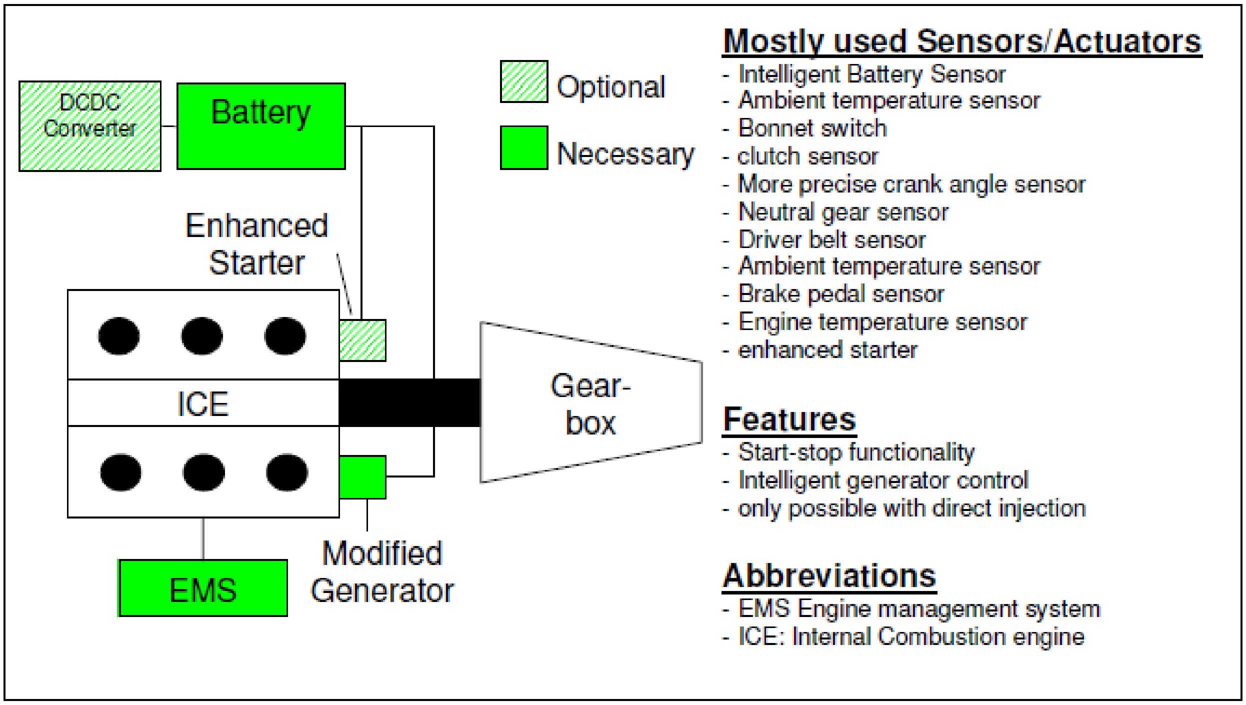


Figure D-40: System Layout – Direct Starter

D.8.1.4 Integrated/Crankshaft Starter Generator (ISG/CSG)

The typical ISG layout (**Figure D-41**) includes a short axis, large-diameter, permanent magnet synchronous motor mounted directly on the end of the engine crankshaft between the engine and the clutch in the gearbox bell housing. This system is also known as a crankshaft starter generator (CSG). Vehicles with such a system are usually termed as mild-hybrid, as they not only provide functions as stop-start and recuperation but also additional boost during acceleration.

The electronically controlled ISG combines the conventional automotive starter and alternator (generator) into a single machine. The conventional starter is a low-speed, high-current DC machine, while the alternator is a variable-speed, 3-phase AC machine.

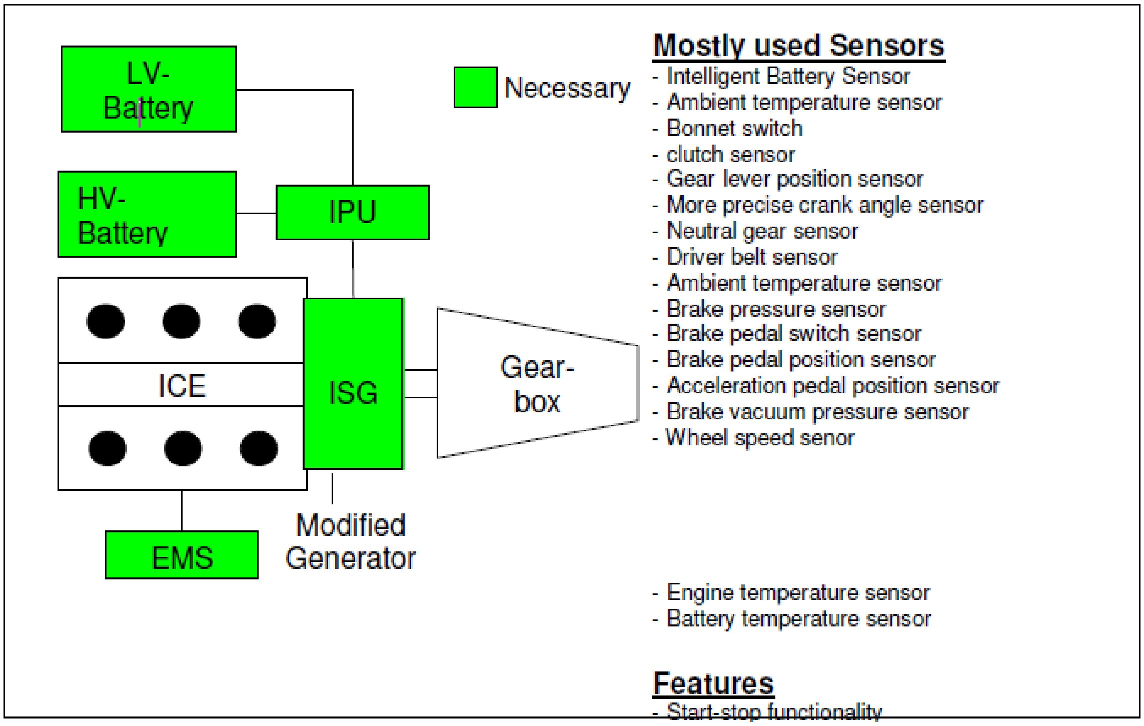


Figure D-41: System layout of Integrated Starter Generator (ISG)

Among the primary advantages an ISG system provides is that it is crank-mounted, thus avoiding the complexities and costs associated with belt-drive systems. This benefit transfers torque directly to the shaft and has the ability to reach high power levels (42V limited to 10 KW, but high voltage can reach 30+ KW). Costs and wear are restrained since components such as drive belts, starter ring gear, and pinion (which are subject to wear) are not necessary.

Conversely, the disadvantages of this system include required major modifications to the power train and limitations to increase powertrain length. With the power assist feature, a high-voltage system is needed. Ultimately, this presents higher costs compared to those of other solutions.

The newly developed stop-start systems provide the potential for decreasing losses of energy during braking (thermal energy) by using a secondary energy storage system with higher voltage level and the possibility to store higher density of energy within secondary storage systems (e.g., ultra capacitors). The regenerated energy can be used in different ways: the 12-volt electrical system can be supported, reducing the alternator load on the combustion engine; or there is the possibility for using the recuperated energy to boost the combustion engine under certain driving situations. From this, a mild hybrid seems a promising solution for future applications with bigger engines.

Examples of current systems in the market place include the Integrated Starter Alternator Damper (ISAD) from Continental, DynaStart from ZF-Sachs, Integrated Motor Generator (IMG) from Bosch, and Integrated Motor Assist (IMA) from Honda.

D.8.1.5 Comparison of Four Stop-start Systems

To further compare the four different stop-start systems evaluated, a decision matrix based on a spider diagram helps explain the complex dependencies (**Figure D-42**). The diagram is based on FEV´s experience in past and ongoing projects.

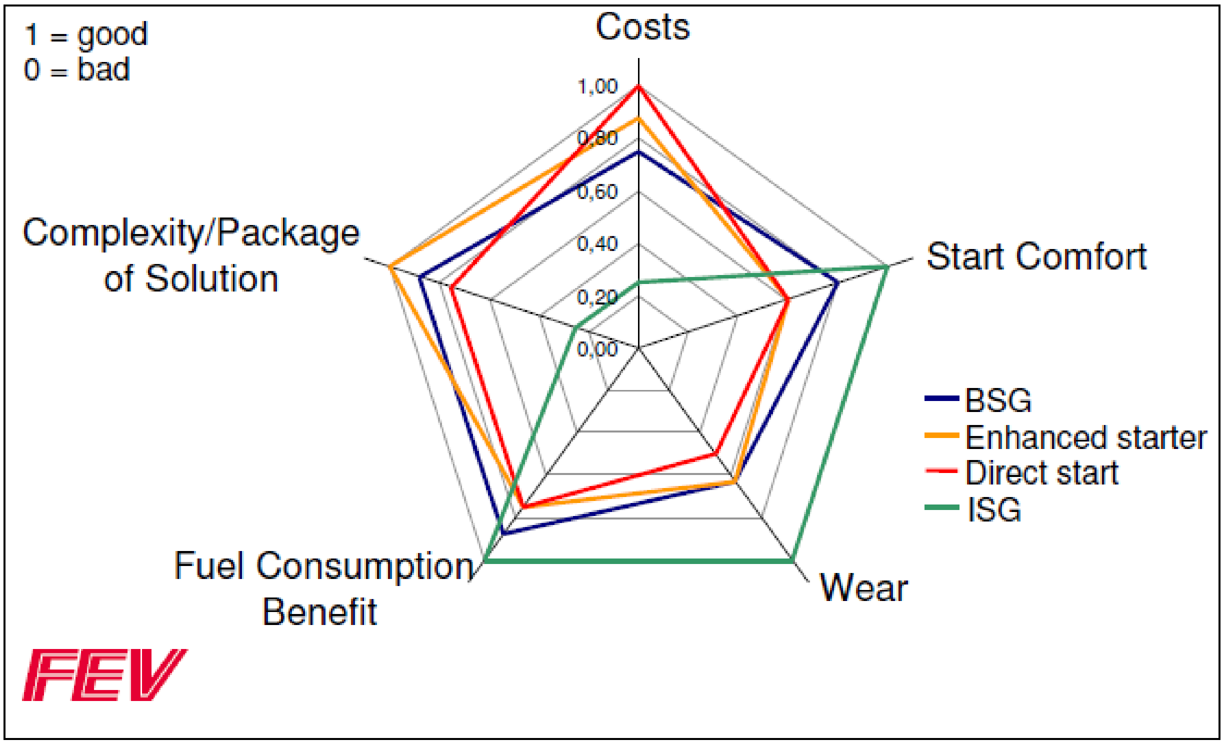


Figure D-42: Stop-start System Comparison

The two most competitive stop-start systems in the near future are the BSG and the enhanced starter combined with an enhanced alternator for regenerative braking. As indicated in **Figure D-42,** both systems have similar advantages and benefits, such as packaging, fuel consumption, and comparable costs. Compared to these systems the ISG is a high-cost solution but provides much more possibilities for hybrid functionalities.

Another BSG advantage is the possibility to omit the conventional starter in small engine applications: Keeping the existing system layout, while incurring comparable additional costs for stop-start integration, a belt-driven starter-generator with the ability to boost might be the solution.

Regarding start comfort, which is also a big issue for customers, the ISG is the best solution followed by the BSG. The advantage of ISG is the possibility to ramp up the speed of the combustion engine and then start injection and ignition. Therefore, almost no vibration occurs during restart. The BSG has similar advantages over the enhanced starter and the direct start, but cannot reach the high engine speeds.

Cost is, of course, a very important factor for manufacturers. Therefore, all systems which are based on the existing system are less cost intensive than the hybrid version. The complexity of the stop-start system is also important for manufacturers; the more complex the integration, the more costs may be incurred during the development phase.

Hence, the enhanced starter is the less complex system. The BSG needs further adaptations of the belt drive system and the direct start requires the most complex adaptations inside of the engine control unit. Most complex of the solutions is the ISG, as the complete drive train has to be adapted.

For all the above mentioned systems, a new layout of the electrical system appears necessary. A second energy storage system with a higher voltage than 12V electrical system (e.g., 48V) would have impact on recuperation performance. The second energy storage system is needed because higher power during recuperation cannot be stored inside of a normal 12V battery or an Absorbed Glass Mat (AGM) battery.

Only storage systems like Lithium-Ion batteries or capacitor-based storage systems are capable of backing high recuperative power demands. Energy consumers of the vehicle with higher power demand might also be sourced by the higher electrical system voltage (e.g., electric power steering). A DC/DC-converter should be included between the 48V electrical system and the 12V electrical system, with the possibility to store the recuperated energy from high-voltage electrical system toward the 12V electrical system and to recharge the 12V battery. An intelligent electrical system management should be used that controls energy flow between the two electrical systems and also controls the regenerative/boosting energy flow.

The boost function of the BSG is restricted by the power transfer limitations of the belt system. With the currently available systems, only limited power can be transferred to the belt and toward the crankshaft of the combustion engine. Further development of these systems, however, may make it possible to reach a relevant power that has additional influence on fuel consumption.

In case the challenges of the belt power transfer cannot be accomplished, the next step in hybridization points toward the ISG, which has major cost impacts relative to competitive systems. While it provides additional hybrid drive functionalities to the stop-start system, this gives it higher system complexity.

D.8.2 Study Assumptions – Case Study Specific

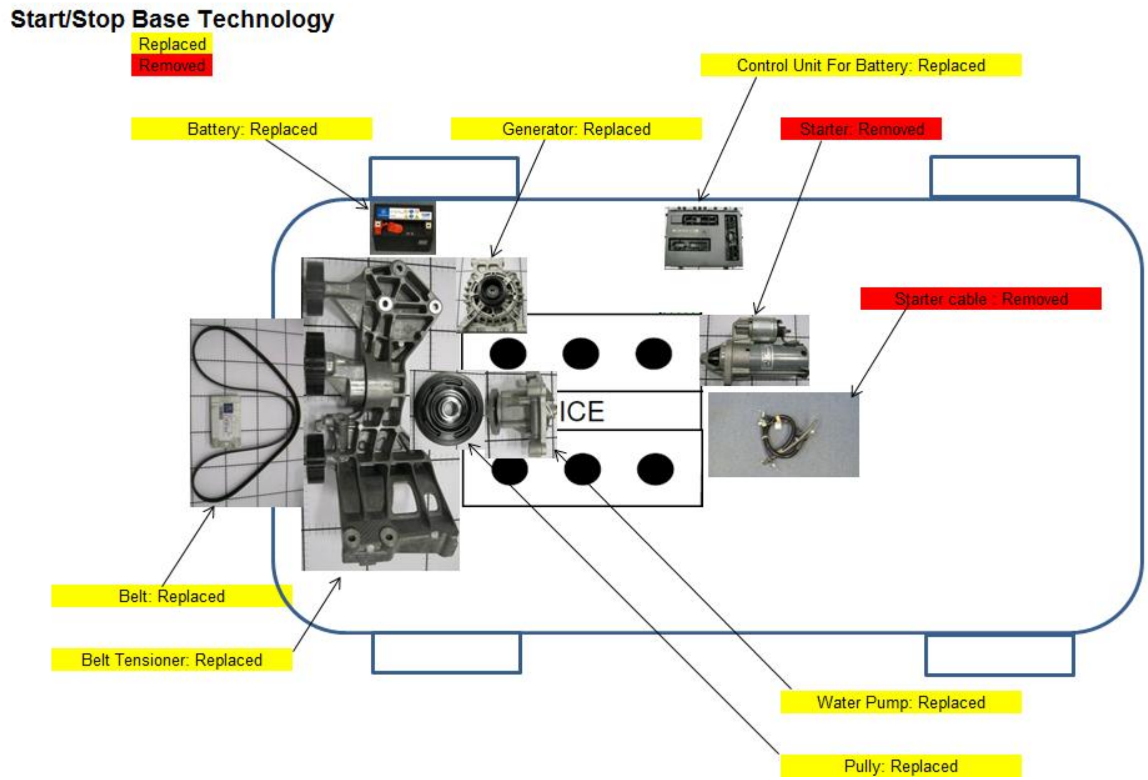
For the lead case study the Mercedes A-160 Blue Efficiency, 1.5L I4 Gasoline ICE, 5-speed manual transmission was selected. The stop-start system packaged in the Mercedes A-160 is the Valeo Starter Alternator Reversible System (StARS). A starter-generator (14V, 130A) replaces the traditional generator and delivers power to, and receives power from, an upgraded service battery. The premium AGM (Absorbed Glass Mat) lead acid service battery is a 12V, 70Ah battery. In addition a smaller 12V, 12Ah back-up/auxiliary lead acid battery is packaged in the truck of the vehicle. The Mercedes A-class vehicle was selected as the lead case study since it had the highest BSG system sales in Germany (43,542) during production year 2011. According to published information from Valeo, the potential fuel savings can reach 6-8% on the New European Drive Cycle (NED) cycle, and up to 25% in heavy city traffic, when cars are at idle for around 35% of the time (reference http://www.valeo.com/en/press-releases/details.html?id=115).

The baseline technology configuration was the same primary powertrain system (1.5L, I4 ICE with a 5-Speed MT) minus the BSG stop-start hardware and component modifications for the addition of the stop-start technology configuration. It has a standard electrical power supply subsystem comprising of a generator (14V 90A) and lead acid battery (12V 62Ah).

D.8.3 Study Hardware Boundary Conditions

For the cost analysis all BSG components added to the vehicle, as well as baseline powertrain components modified or deleted from the vehicle, for the integration of the BSG system were evaluated. The FEV technical team, with the access to vehicles, vehicle hardware, and service publications were able to support this portion of the analysis.

The primary vehicle system effect by the addition of the stop-start technology included the Engine System, Electrical Power Supply System, and Electrical Distribution and Control System. **Figure D-43** provides an overview of the base ICE engine and components replaced or removed and the new stop-start technology items replaced or added new.



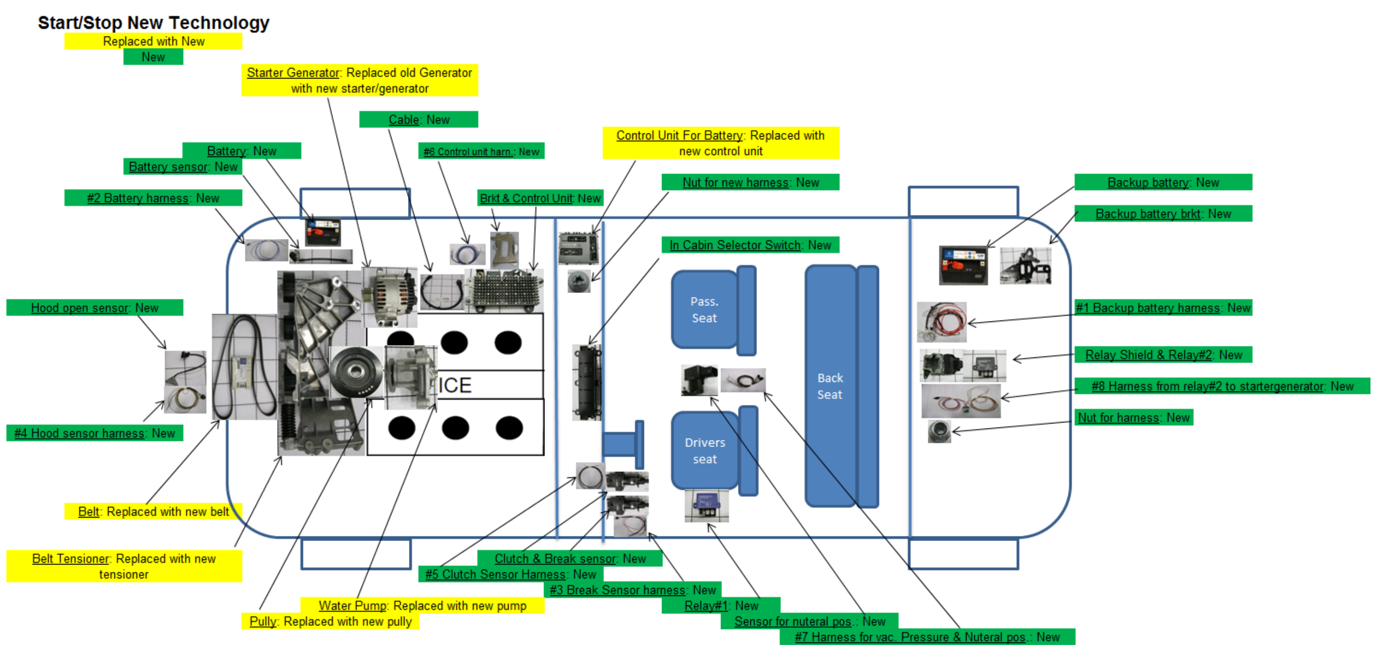
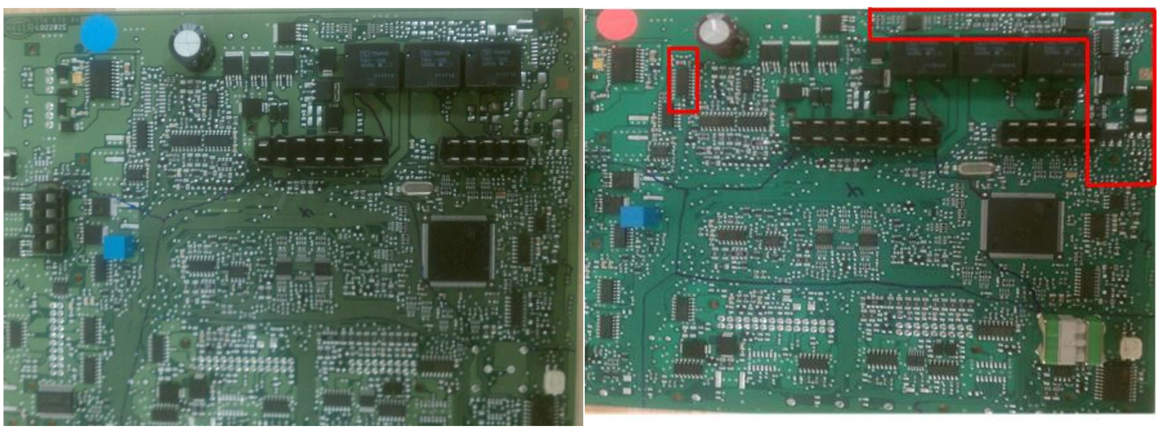


Figure D-43: Conventional Powertrain Technology Configuration (Top); Stop-start BSG Technology Configuration (Bottom)

D.8.4 Components Evaluated

The cost analysis was performed as an incremental cost evaluation. That is, if components were found identical from the base to the new technology, then those items would be considered cost neutral in the analysis costing. For example, the electronic control unit casing was identical from the base to the new technology: The unit had a common housing module configuration; the only difference was in the circuit board. Therefore, no cost was associated to the housing portion of the control module.

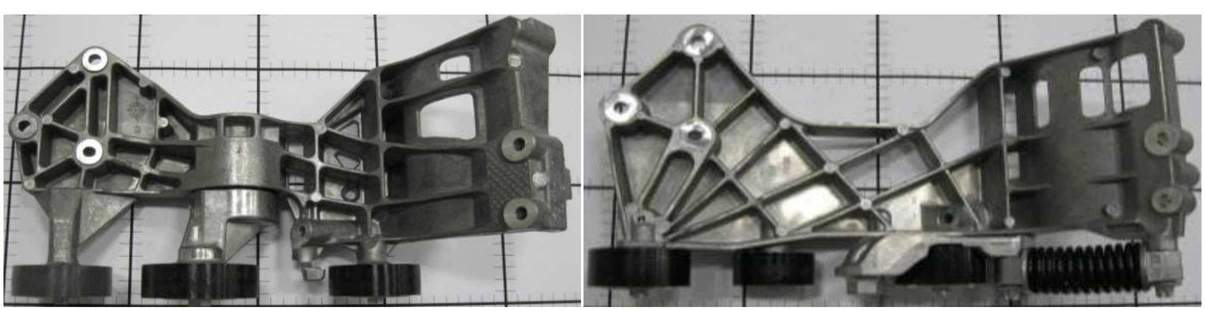
The control unit circuit board, as indicated, had some modifications made to the circuit board for operating the stop-start system. The outlines in red (**Figure D-44**) were the items costed; the rest of the control board was considered cost neutral.



Base Technology Circuit Board **New Technology Circuit Board**

Figure D-44: Control Unit Circuit Board

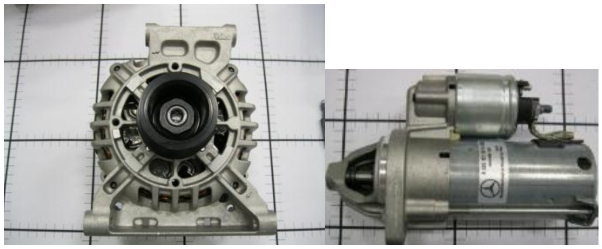
Other items were costed complete due to all parts being different. For example, the baseline technology belt tensioner was replaced with a BSG dual-action tensioner assembly capable of handling bi-directional loading (**Figure D-45**).



Baseline Technology Belt Tensioner **BSG Technology Belt Tensioner**

Figure D-45: Belt Tensioner Assemblies

The conventional generator assembly and starter assembly were replaced by a starter-generator assembly (≈2.2-2.5kW).



Baseline Technology Configuration,
Generator Assembly and Starter Assembly

New Technology Start-Generator Assembly

Figure D-46: Starter, Generator and Starter-Generator Assemblies

Valeo claims the StARS BSG stop-start system can be applied to diesel and gasoline engines, capable of starting gasoline engines with displacements as high as 3.0L, and even up to 4.5L in previously conducted Valeo tests. In diesel applications, engines up to 2.0L displacement can be started using the StARS BSG system. For the large sport utility vehicle segment (displacement 3.0-4.2L), the standard start motor was <u>not</u> deleted from the analysis protecting for cold starts.

Power supply items added for the stop-start technology were the secondary battery, relays, sensors and wiring. The relays and sensors were considered commodity items for costing purposes; the wiring was costed complete. The added battery included a mounting bracket and wiring harness (**Figure D-47**) as well as a new relay (**Figure D-48**) with wiring harness. All components were added in the trunk area.

Figure D-47: New Technology Battery, Mounting Bracket & Harness

Figure D-48: New Technology Relay, Relay Shield & Harness

Additional sensors and wiring for the stop-start system included the clutch, brake and neutral position sensors and associated wiring harness (**Figure D-49**)

Figure D-49: Stop-Start Clutch Sensor and Wire Harness (Left), Brake Sensor and Wire Harness (Center), and Neutral Position Sensor and Harness (Right)

The BSG high power control unit/electronic transformer is the shown below in **Figure D-50.** Next to the BSG assembly, the BSG control unit is an instrumental part of the BSG stop-start technology.

Figure D-50: BSG Control Unit (aka Electronic Transformer), Mounting Bracket and Associated Wire Harnesses

D.8.5 Cost Strategy Overview on Base Analysis

Table D-53 and **Table D-54** present a list of key components from the two technologies evaluated and the costing type used in the analysis.

Table D-53: Baseline Technology Configuration – Costing Type Methodology

Base technology pricing methodology	
COMPONENT	**COSTING TYPE**
Pulley	Detailed costing
Tensioner	Detailed costing
Belts	Commodity
Water pump	Cost neutral
Control unit cover	Cost neutral
Control unit circuit board	Differential
Starter motor	Commodity
Starter motor wiring harness	Detailed costing
Generator	Detailed costing
Battery	Commodity

Table D-54: BSG Stop-start – Costing Type Methodology

New Stop-start technology pricing methodology	
COMPONENT	**COSTING TYPE**
Pulley	Detailed costing
Tensioner	Detailed costing
Belts	Commodity
Water pump	Cost neutral
Control unit cover	Cost neutral
Control unit circuit board	Differential
Relay shield	Detailed costing
Control unit w/heat sink	Detailed costing
Starter/Generator	Detailed costing
Relays	Commodity
Sensors	Commodity
In-cabin switch	Differential
Battery	Commodity
All wire harness's	Detailed costing

D.8.6 Vehicle Segment Scaling Methodology Overview

In the consideration of scaling, torque was the primary consideration of the stop-start system. Scaling by torque was founded on the idea that a larger internal combustion engine (i.e., larger displacement) requires greater turn-over torque. The starter generator and associated components need to be sized to handle the larger input toque to turn the engine. No data was available regarding the average ICE start-up torque as a function of displacement and engine configuration. Therefore, the maximum ICE output torques was used as a means of scaling between the lead case study and alternative vehicle segments.

A good approximation of added cost as a function of torque differences is constructed on the one third power of the ratio of torque change. The one third power relationship is based on the assumption that, as torque increases, the primary rotating members will also increase in size/cost relative to the one third power of the torque relationship (i.e., Vehicle Segment "X" Cost = Lead Case Study Vehicle Segment Cost * [(Torque "X"/Torque Lead Case Study)^1/3]. **Table D-55** provides the scaling factors used to scale the lead case study costs to alternative vehicle segments.

Table D-55: Scaling Factors for Stop-start BSG Technology Configuration

Scaling methodology						
Component/Assembly	Vehicle segments					
	0	1	2	3	5	6
Engine Configuration	I3-I4	I4	I4	I4-I6	I4	I6-V8
Engine Displacement	1.2-1.4	1.4-1.6	1.6-2.0	2.0	1.2-3.0	3.0-5.5
Engine Max. Output Torque	146	179	236	321	264	491
Transmission Configuration	MT	MT	MT	MT	MT	MT
Crank Pulley	100%	107%	117%	130%	122%	150%
Tensioner	100%	107%	117%	130%	122%	150%
Belt	100%	107%	117%	130%	122%	150%
Water Pump	100%	100%	100%	100%	100%	100%
Control Unit	100%	100%	100%	100%	100%	100%
Shield Box	100%	100%	100%	100%	100%	100%
Control Unit with Heat Sink	100%	107%	117%	130%	122%	150%
Neutral Position Sensor	100%	100%	100%	100%	100%	100%
Hood Open Sensor	100%	100%	100%	100%	100%	100%
Brake Sensor	100%	100%	100%	100%	100%	100%
Clutch Sensor	100%	100%	100%	100%	100%	100%
Relay #1	100%	100%	100%	100%	100%	100%
Relay #2	100%	100%	100%	100%	100%	100%
In-cabin Switch	100%	100%	100%	100%	100%	100%
Battery Sensor	100%	100%	100%	100%	100%	100%
Brkt for Additional Battery	100%	107%	117%	130%	122%	150%
Additional Battery Cable	100%	107%	117%	130%	122%	150%
Generator	100%	107%	117%	130%	122%	150%
Assembly	100%	100%	100%	100%	100%	100%
Starter	100%	107%	117%	130%	122%	0%
Big Battery	100%	107%	117%	130%	122%	150%
Small Battery	100%	107%	117%	130%	122%	150%

D.8.7 Cost Analysis Results Summary

Presented below in **Table D-56** and **Table D-57** are the Net Incremental Direct Manufacturing Costs and Net Incremental Technology Costs for adding a BSG stop-start system to a conventional powertrain vehicle.

Table D-56: Net Incremental Direct Manufacturing Costs for Adding a BSG Stop-start System to a Conventional Powertrain Vehicle

ICCT Europe Analysis
Start-Stop Hybrid Vehicle {Belt-Driven, Starter-Generator (BSG) System} Technology Configuration (Rev 6/4/2012)

		Calculated Incremental Direct Manufacturing Cost - Start-Stop Micro Hybrid					
	System Description	Subcompact Passenger Vehicle	Compact or Small Passenger Vehicle	A Midsize Passenger Vehicle	Midsize or Large Passenger Vehicle	Small or Midsized Sport Utility or Cross-Over Vehicle, or Mini Van	Large Sport Utility Vehicle
	System Analysis ID	3000B	3001	3002	3003B	3005	3006B
	Vehicle Example	VW Polo, Ford Fiesta	VW Golf Ford Focus	VW Passat BMW 3 Series Audi A4	VW Sharan BMW 5 Series Audi A6	VW Tiguan BMW X1/X3 Audi Q5	VW Touareg BMW X5/X6 Audi Q7
Vehicle Segment 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	3.0-4.2
	Typical Engine Configuration	I4	I4	I4	I6 or V6	I4	V8
	Ave. Power "kW" (hp)	74 (100)	89 (121)	115 (157)	172 (234)	131 (178)	268 (364)
	Ave. Torque "N*m" (lb*ft)	146 (108)	179 (132)	236 (174)	321 (237)	264 (195)	491 (362)
	Typical Transmission Type	5-Speed MT	5 or 6-Speed MT	6-Speed MT	6-Speed MT	6-Speed MT	6-Speed MT
	Ave. Curb Weight "kg" (lb)	1084 (2390)	1271 (2803)	1496 (3299)	1700 (3749)	1590 (3505)	2207 (4867)
	Weight-to-Power Ratio "kg/kW" (lb/hp)	14.7 (23.9)	14.3 (23.2)	13.0 (21.0)	9.9 (16.0)	12.1 (19.7)	8.2 (13.4)
Technology Configuration Comparison	New Technology Configuration	Conventional Powertrain w/ addition of Belt-Driven, Starter-Generator (BSG)	Conventional Powertrain w/ addition of Belt-Driven, Starter-Generator (BSG)	Conventional Powertrain w/ addition of Belt-Driven, Starter-Generator (BSG)	Conventional Powertrain w/ addition of Belt-Driven, Starter-Generator (BSG)	Conventional Powertrain w/ addition of Belt-Driven, Starter-Generator (BSG)	Conventional Powertrain w/ addition of Belt-Driven, Starter-Generator (BSG)
	Baseline Technology Configuration	Conventional Powertrain	Conventional Powertrain	Conventional Powertrain	Conventional Powertrain	Conventional Powertrain	Conventional Powertrain
A	**Engine System**	**(€ 36.11)**	**(€ 38.64)**	**(€ 42.39)**	**(€ 47.01)**	**(€ 44.05)**	**€ 8.36**
A.1	Crank Pully Sub-Subsystem	€ 1.42	€ 1.52	€ 1.66	€ 1.84	€ 1.73	€ 2.12
A.2	Tensioner Sub-Subsystem	€ 3.58	€ 3.83	€ 4.20	€ 4.66	€ 4.36	€ 5.37
A.3	Belt Sub-Subsystem'	€ 0.58	€ 0.62	€ 0.68	€ 0.75	€ 0.70	€ 0.87
A.4	Water Pump Sub-Subsystem	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
A.5	Starter Sub-Subsystem	(€ 41.68)	(€ 44.60)	(€ 48.93)	(€ 54.27)	(€ 50.85)	€ 0.00
B	**Transmission System**	**€ 19.81**	**€ 19.81**	**€ 19.81**	**€ 19.81**	**€ 19.81**	**€ 19.81**
B.1	Clutch Sensor Sub-Subsystem	€ 2.07	€ 2.07	€ 2.07	€ 2.07	€ 2.07	€ 2.07
B.2	Nuteral Position Sensor Sub-Subsystem	€ 17.74	€ 17.74	€ 17.74	€ 17.74	€ 17.74	€ 17.74
C	**Body System**	**€ 19.68**	**€ 19.68**	**€ 19.68**	**€ 19.68**	**€ 19.68**	**€ 19.68**
C.1	Instrument Panel System On/Off Switch Sub-Subsystem	€ 12.00	€ 12.00	€ 12.00	€ 12.00	€ 12.00	€ 12.00
C.2	Hood Open Sensor Sub-Subsystem	€ 7.68	€ 7.68	€ 7.68	€ 7.68	€ 7.68	€ 7.68
D	**Brake System**	**€ 2.99**	**€ 2.99**	**€ 2.99**	**€ 2.99**	**€ 2.99**	**€ 2.99**
D.1	Brake Sensor Sub-Subsystem	€ 2.99	€ 2.99	€ 2.99	€ 2.99	€ 2.99	€ 2.99
F	**Electrical Power Supply System**	**€ 139.43**	**€ 145.82**	**€ 155.32**	**€ 167.00**	**€ 159.52**	**€ 185.08**
F.1	Battery Sensor Sub-Subsystem	€ 48.15	€ 48.15	€ 48.15	€ 48.15	€ 48.15	€ 48.15
F.2	Battery Mounting Bracket Sub-Subsystem	€ 6.74	€ 7.21	€ 7.91	€ 8.77	€ 8.22	€ 10.11
F.3	Battery Cable Sub-Subsystem	€ 32.02	€ 34.26	€ 37.59	€ 41.68	€ 39.06	€ 48.02
F.4	Generator Sub-Subsystem	€ 28.17	€ 30.14	€ 33.07	€ 36.67	€ 34.36	€ 42.25
F.5	Big Battery Sub-Subsystem	€ 11.08	€ 11.85	€ 13.00	€ 14.42	€ 13.51	€ 16.61
F.6	Small Battery Sub-Subsystem	€ 13.29	€ 14.22	€ 15.60	€ 17.31	€ 16.22	€ 19.94
G	**Electrical Distribution and Control System**	**€ 143.28**	**€ 151.83**	**€ 164.53**	**€ 180.16**	**€ 170.15**	**€ 204.34**
G.1	Control Unit Sub-Subsystem	€ 5.13	€ 5.13	€ 5.13	€ 5.13	€ 5.13	€ 5.13
G.2	Shield Box Sub-Subsystem	€ 0.82	€ 0.82	€ 0.82	€ 0.82	€ 0.82	€ 0.82
G.3	Control Unit with Heat Sink Sub-Subsystem	€ 122.11	€ 130.66	€ 143.36	€ 158.99	€ 148.98	€ 183.17
G.4	Relay #1 Sub-Subsystem	€ 5.31	€ 5.31	€ 5.31	€ 5.31	€ 5.31	€ 5.31
G.5	Relay #2 Sub-Subsystem	€ 9.91	€ 9.91	€ 9.91	€ 9.91	€ 9.91	€ 9.91
H	**Vehicle Assembly**	**€ 9.08**	**€ 9.08**	**€ 9.08**	**€ 9.08**	**€ 9.08**	**€ 9.08**
H.1	Vehicle Operations Assembly	€ 9.08	€ 9.08	€ 9.08	€ 9.08	€ 9.08	€ 9.08
	Net Incremental Direct Manufacturing Cost	**€ 298.17**	**€ 310.58**	**€ 329.02**	**€ 351.71**	**€ 337.17**	**€ 449.34**

Table D-57: Net Incremental Technology Costs for Costs for Adding a BSG Stop-start System to a Conventional Powertrain Vehicle

Technology	ID	Case Study #	Baseline Technology Configuration	New Technology Configuration	Calculated Incremental Direct Manufacturing Cost 2010/2011 Production Year	Net Incremental Manufacturing Costs (Direct and Indirect Costs) with Applicable Learning Applied				ICM Factor				Learning Factor			
										ICM - Warranty		ICM - Other Direct Costs					
						2012	2016	2020	2025	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	Short Term 2012 thru 2018(1)	Long Term 2019 thru 2025(2)	2012	2016	2020	2025
Start-Stop Hybrid Electric Vehicle Technology	2	3000B	**Gasoline I4 ICE** Conventional Powertrain Ave. Displacement = 1.2-1.4L Ave. Power = 74kW (100HP) Ave. Torque = 146N*m (108lb*ft) Typical Transmission Type: 5-Speed MT Curb Weight: 1084kg (2390lb)	**Gasoline I4 ICE, Manual Transmission, upgraded with Belt-Driven, Starter-Generator (BSG) System.**	€ 298	€ 589	€ 414	€ 349	€ 311	0.045	0.031	0.343	0.259	1.56	1.00	0.89	0.76
	3	3001	**Gasoline I4 ICE** Conventional Powertrain Ave. Displacement = 1.4-1.6L Ave. Power = 89kW (121HP) Ave. Torque = 179N*m (132lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1271kg (2803lb)	**Gasoline I4 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	€ 311	€ 613	€ 431	€ 364	€ 324	0.045	0.031	0.343	0.259	1.56	1.00	0.89	0.76
	4	3002	**Gasoline I4 ICE** Conventional Powertrain Ave. Displacement = 1.6-2.0L Ave. Power = 115kW (157HP) Ave. Torque = 236N*m (174lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1496kg (3299lb)	**Gasoline I4 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	€ 329	€ 650	€ 456	€ 385	€ 343	0.045	0.031	0.343	0.259	1.56	1.00	0.89	0.76
	6	3003B	**Gasoline I6 or V6 ICE** Conventional Powertrain Ave. Displacement = 2.0-3.0L Ave. Power = 172kW (234HP) Ave. Torque = 321N*m (237lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 1700kg (3749lb)	**Gasoline I6 or V6 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	€ 352	€ 695	€ 488	€ 412	€ 367	0.045	0.031	0.343	0.259	1.56	1.00	0.89	0.76
	7	3005	**Gasoline I4 ICE** Conventional Powertrain Ave. Displacement = 1.2-3.0L Ave. Power = 131 kW (178HP) Ave. Torque = 264N*m (195lb*ft) Typical Transmission Type: 6_Speed **MT** Curb Weight: 1590kg (3505lb)	**Gasoline I4 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	€ 337	€ 666	€ 468	€ 395	€ 351	0.045	0.031	0.343	0.259	1.56	1.00	0.89	0.76
	9	3006B	**Gasoline V8 ICE** Conventional Powertrain Ave. Displacement = 3.0-5.5 Ave. Power = 268 kW (364HP) Ave. Torque = 491N*m (362lb*ft) Typical Transmission Type: 6-Speed MT Curb Weight: 2207kg (4867lb)	**Gasoline V8 ICE, Manual Transmission, Upgraded with Belt-Driven, Starter-Generator (BSG) System.**	€ 449	€ 887	€ 623	€ 526	€ 468	0.045	0.031	0.343	0.259	1.56	1.00	0.89	0.76

E. Glossary of Terms

Assembly: a group of interdependent components joined together to perform a defined function (e.g., turbocharger assembly, high pressure fuel pump assembly, high pressure fuel injector assembly).

Automatic Transmission (AT): is one type of motor vehicle transmission that can automatically change gear ratios as the vehicle moves, freeing the driver from having to shift gears manually.

BAS (Belt Alternator Starter): is a system design to start/re-start an engine using a non-traditional internal combustion engine (ICE) starter motor. In a standard internal ICE the crankshaft drives an alternator, through a belt pulley arrangement, producing electrical power for the vehicle. In the BAS system, the alternator is replaced with a starter motor/generator assembly so that it can perform opposing duties. When the ICE is running, the starter motor/generator functions as a generator producing electricity for the vehicle. When the ICE is off, the starter motor/generator can function as a starter motor, turning the crankshaft to start the engine. In addition to starting the ICE, the starter motor can also provide vehicle launch assist and regenerative braking capabilities.

Buy: the components or assemblies a manufacturer would purchase versus manufacture. All designated “buy” parts, within the analysis, only have a net component cost presented. These types of parts are typically considered commodity purchase parts having industry established pricing.

CBOM (Comparison Bill of Materials): a system bill of materials, identifying all the subsystems, assemblies, and components associated with the technology configurations under evaluation. The CBOM records all the high-level details of the technology configurations under study, identifies those items which have cost implication as a result of the new versus base technology differences, documents the study assumptions, and is the primary document for capturing input from the cross-functional team.

Component: the lowest level part within the cost analysis. An assembly is typically made up of several components acting together to perform a function (e.g., the turbine wheel in a turbocharger assembly). However, in some cases, a component can independently perform a function within a sub-subsystem or subsystem (e.g., exhaust manifold within the exhaust subsystem).

Cost Estimating Models: cost estimating tools, external to the Design Profit® software, used to calculate operation and process parameters for primary manufacturing processes (e.g., injection molding, die casting, metal stamping, forging). Key information calculated from the costing estimating tools (e.g., cycle times, raw material usage, equipment size) is inputted into the Lean Design® process maps supporting the cost analysis. The Excel base cost estimating models are developed and validated by Munro & Associates.

Costing Databases: the five core databases that contain all the cost rates for the analysis. (1) The **material database** lists all the materials used throughout the analysis along with the estimated price/pound for each; (2) The **labor database** captures various automotive, direct labor, manufacturing jobs (supplier and OEM), along with the associated mean hourly labor rates; (3) The **manufacturing overhead rate database** contains the cost/hour for the various pieces of manufacturing equipment assumed in the analysis; (4) A **mark-up database** assigns a percentage of mark-up for each of the four main mark-up categories (i.e., end-item scrap, SG&A, profit, and ED&T), based on the industry, supplier size, and complexity classification; (5) The **packaging database** contains packaging options and costs for each case.

Cross Functional Team (CFT): is a group of people with different functional expertise working toward a common goal.

Direct Labor (DIR): is the mean manufacturing labor wage directly associated with fabricating, finishing, and/or assembling a physical component or assembly.

Dual Clutch Transmission (DCT): is a differing type of semi-automatic or automated manual automotive transmission. It utilizes two separate clutches for odd and even gear sets. It can fundamentally be described as two separate manual transmissions (with their respective clutches) contained within one housing, and working as one unit. They are usually operated in a fully automatic mode, and many also have the ability to allow the driver to manually shift gears, albeit still carried out by the transmission's electro-hydraulics.

ED&T (engineering, design, and testing): is an acronym used in accounting to refer to engineering, design, and testing expenses.

Fringe (FR): are all the additional expenses a company must pay for an employee above and beyond base wage.

Fully Variable Valve Actuation (FVVA): is a generalized term used to describe any mechanism or method that can alter the shape or timing of a valve lift event within an internal combustion engine.

Gasoline Direct Inject (GDI): is a variant of fuel injection employed in modern two-stroke and four-stroke gasoline engines. The gasoline is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that happens in the intake tract, or cylinder port.

Hybrid Electric Vehicle (HEV): is a type of hybrid vehicle and electric vehicle which combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system.

Indirect Cost Multipliers (ICM): is developed by EPA to address the OEM indirect costs associated with manufacturing new components and assemblies. The indirect costs,

costs associated with OEM research and development, corporate operations, dealership support, sales and marketing material, legal, and OEM owned tooling, are calculated by applying an ICM factor to the direct manufacturing cost.

Indirect Labor (IND): is the manufacturing labor indirectly associated with making a physical component or assembly.

Lean Design® (a module within the *Design Profit® software):* is used to create detailed process flow charts/process maps. Lean Design® uses a series of standardized symbols, with each base symbol representing a group of similar manufacturing procedures (e.g., fastening, material modifications, inspection). For each group, a Lean Design® library/database exists containing standardized operations along with the associated manufacturing information and specifications for each operation. The information and specifications are used to generate a net operation cycle time. Each operation on a process flow chart is represented by a base symbol, operation description, and operation time, all linked to a Lean Design® library/database.

Maintenance Repair (MRO): All actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions

Make: terminology used to identify those components or assemblies a manufacturer would produce internally versus purchase. All parts designated as a “make” part, within the analysis, are costed in full detail.

MAQS (Manufacturing Assumption and Quote Summary) worksheet: standardized template used in the analysis to calculate the mass production manufacturing cost, including supplier mark-up, for each system, subsystem, and assembly quoted in the analysis. Every component and assembly costed in the analysis will have a MAQS worksheet. The worksheet is based on a standard OEM (original equipment manufacturer) quote sheet modified for improved costing transparency and flexibility in sensitivity studies. The main feeder documents to the MAQS worksheets are **process maps** and the **costing databases**.

MCRs (Material Cost Reductions): a process employed to identify and capture potential design and/or manufacturing optimization ideas with the hardware under evaluation. These savings could potentially reduce or increase the differential costs between the new and base technology configurations, depending on whether an MCR idea is for the new or the base technology.

Naturally Aspirated (NA): is one common type of reciprocating piston internal combustion that depends solely on atmospheric pressure to counter the partial vacuum in the induction tract to draw in combustion air.

Net Component/Assembly Cost Impact to OEM: the net manufacturing cost impact per unit to the OEM for a defined component, assembly, subsystem, or system. For components produced by the supplier base, the net manufacturing cost impact to the OEM includes total manufacturing costs (material, labor, and manufacturing overhead), mark-up (end-item scrap costs, selling, general and administrative costs, profit, and engineering design and testing costs) and packaging costs. For OEM internally manufactured components, the net manufacturing cost impact to the OEM includes total manufacturing costs and packaging costs; mark-up costs are addressed through the application of an indirect cost multiplier.

NTAs (New Technology Advances): a process employed to identify and capture alternative advance technology ideas which could be substituted for some of the existing hardware under evaluation. These advanced technologies, through improved function and performance, and/or cost reductions, could help increase the overall value of the technology configuration.

Port Fuel Injected (PFI): is a method for admitting fuel into an internal combustion engine by fuel injector sprays into the port of the intake manifold.

Powertrain Package Proforma: a summary worksheet comparing the key physical and performance attributes of the technology under study with those of the corresponding base configuration.

Power-Split HEV: In a power-split hybrid electric drive train there are two motors: an electric motor and an internal combustion engine. The power from these two motors can be shared to drive the wheels via a power splitter, which is a simple planetary gear set.

Process Maps: detailed process flow charts used to capture the operations and processes and associated key manufacturing variables involved in manufacturing products at any level (e.g., vehicle, system, subsystem, assembly, and component).

P-VCSM (Powertrain–Vehicle Class Summary Matrix): records the technologies being evaluated, the applicable vehicle classes for each technology, and key parameters for vehicles or vehicle systems that have been selected to represent the new technology and baseline configurations in each vehicle class to be costed.

Quote: the analytical process of establishing a cost for a component or assembly.

SG&A (selling general and administrative): is an acronym used in accounting to refer to Selling, General and Administrative Expenses, which is a major non-production costs presented in an Income statement.

Sub-subsystem: a group of interdependent assemblies and/or components, required to create a functioning sub-subsystem. For example, the air induction subsystem contains several sub-subsystems including turbocharging, heat exchangers, pipes, hoses, and ducting.

Subsystem: a group of interdependent sub-subsystems, assemblies and/or components, required to create a functioning subsystem. For example, the engine system contains several subsystems including crank drive subsystem, cylinder block subsystem, cylinder head subsystem, fuel induction subsystem, and air induction subsystem.

Subsystem CMAT (Cost Model Analysis Templates): the document used to display and roll up all the sub-subsystem, assembly, and component incremental costs associated with a subsystem (e.g., fuel induction, air induction, exhaust), as defined by the Comparison Bill of Material (CBOM).

Surrogate part: a part similar in fit, form, and function as another part that is required for the cost analysis. Surrogate parts are sometimes used in the cost analysis when actual parts are unavailable. The surrogate part's cost is considered equivalent to the actual part's cost.

System: a group of interdependent subsystems, sub-subsystems, assemblies, and/or components working together to create a vehicle primary function (e.g., engine system, transmission system, brake system, fuel system, suspension system).

System CMAT (Cost Model Analysis Template): the document used to display and roll up all the subsystem incremental costs associated with a system (e.g., engine, transmission, steering) as defined by the CBOMs.