Light-Duty Technology Cost Analysis, Report on Additional Case Studies

Revised Final Report

United States
Environmental Protection
Agency

Light-Duty Technology Cost Analysis, Report on Additional Case Studies

Revised Final Report

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
FEV, Inc.
EPA Contract No. EP-C-07-069
Work Assignment No. 2-3

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

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Environmental Protection
Agency

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Light-Duty Technology Cost Analysis
- Report on Additional Case Studies

Contract No. EP-C-07-069

Work Assignment 2-3

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Updates to "Light-Dutry Vehicle Technology Cost Analysis, Report on Additional Case Studies"

The overall goal of this study was to provide accurate technology assessments through highly detailed and transparent cost analysis methodologies that compare and contrast differences and similarities between these transmission systems. Based on that goal, FEV is hereby issuing an update to the previously released report dated 3/26/10. Minor revisions have been made to some of the electronic hardware and controls to more accurately account for all components as well as including required communication and feedback loops between these components with both high-side and low-side electronic drivers. These updates are described below and are comprised of refinements in cost analysis results obtained as well as detailing the electronic control system differentials between the compared transmissions. This is done in an added table detailing the various solenoids, valves, sensors, wiring and various drivers that differentiate each unit.

- Revision to List of Figures on page iii due to inclusion of new Figure 2-4 in report body.

Electronic Hardware Comparison

- This is done with the addition of a detailed paragraph on page 2-16 and Figure 2-4 on page 2-17 that detail a direct side-by-side comparison of the two transmission variations being studied.

Updates to Previous Text Descriptions and Tables in the Report Body

- Update Table ES-0-1 on page 2 due to the revision of the 6-Speed DCT vs. AT cost differential.
- Revision to text at the top of page 2-16 describing the cost differential to the net incremental direct manufacturing cost.
- Update Figure 2-5 on page 2-18 due to the insertion of electronic controls costs.

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Light-Duty Technology Cost Analysis – Report on Additional Case Studies

Executive Summary

The United States Environmental Protection Agency (EPA) contracted with FEV, Inc. to determine the incremental direct manufacturing costs for a set of advanced, light-duty vehicle technologies. The technologies selected are on the leading edge for reducing emissions of greenhouse gases in the future, primarily in the form of tailpipe carbon dioxide (CO_2).

This report, the second in a series of reports, addresses the direct incremental manufacturing cost of four (4) new powertrain configurations, relative to four (4) existing baseline configurations, with comparable driver performance metrics. The complete costing methodology used in the analysis of these configurations, as well as the pilot case study, is described in "Light-Duty Technology Cost Analysis Pilot Study (EPA-420-R-09-020)".

The four (4) new powertrain technology configurations analyzed are:

- 2.0L, I4, 4-valve, dual overhead cam (DOHC), dual variable valve timing (d-VVT), turbocharged, gasoline direct injection (GDI) engine, compared to an equivalent conventional 3.0L, V6, 4-valve, DOHC, d-VVT, naturally aspirated (NA), port fuel injected (PFI) engine.
- 3.5L, V6, 4-valve, dual overhead cam (DOHC), d-VVT, turbocharged, GDI engine, compared to an equivalent conventional 5.4L, V8, 3-valve, single overhead cam (SOHC), VVT, NA, PFI engine.
- A 6-speed automatic transmission, compared to an equivalent 5-speed automatic transmission
- A 6-speed wet dual clutch transmission (DCT), compared to an equivalent 6-speed automatic transmission

The results for the four (4) case studies are shown in Table ES-0-1 along the results previously published for case study #0101.

Table ES-0-1: Increment Unit Cost Impact – Five (5) New Technology Configurations

Case Study Reference	Technology Definition	Vehicle Class	Base Technology	New Technology	Incremental Unit Cost
0101	Downsized Turbocharged Gasoline Direct Injection (Engine)	Compact/ Budget/ Economy Car, Passenger. 2-4	CS# B0101 2.4L, I4, 4-V DOHC, d-VVT NA, PFI,	CS# N0101 1.6L, I4, 4-V DOHC, d-VVT, Turbo, GDI	$531.57
0102	Downsized Turbocharged Gasoline Direct Injection (Engine)	Mid to Large Size Car, Passenger 4-6	CS# B0102 3.0L, V6, 4-V, DOHC, d-VVT, NA, PFI	CS# N0102 2.0L, I4, 4-V, DOHC, d-VVT Turbo, GDI	$68.68
0104	Downsized Turbocharged Gasoline Direct Injection (Engine)	Passenger + Midsize Towing Capabilities Truck & SUV	CS# B0104 5.4L V8, 3-V, SOHC, VVT, NA, PFI	CS# N0104 3.5L V6, 4-V, DOHC, d-VVT Turbo, GDI	$846.26
0902	6-Speed Dual Clutch Transmission Replacing a 6-Speed Automatic Transmission	Mid to Large Size Car, Passenger 4-6	CS# B0801 6-Speed Automatic Transmission	CS# N0801 6-Speed Wet Dual Clutch Transmission	($97.34)
0802	6-Speed replacing a 5-Speed Automatic Transmission	Mid to Large Size Car, Passenger 4-6	CS# B0802 5-Speed Automatic Transmission	CS# N0802 6-Speed Automatic Transmission	($105.53)(1)

(1) The 6-speed automatic transmission evaluated incorporated a Ravigneaux gear set design, a major factor in the reduction of hardware and complexity in the 6-speed design over the 5-speed design. As such the 6-speed transmission was calculated to be less costly to manufacture than the 5-speed automatic transmission.

1 Introduction

1.1 Objectives

The objective of this work assignment was to determine the incremental direct manufacturing costs for four (4) new advanced light-duty vehicle technology configurations using the costing methodology, databases, and supporting worksheets developed in the previously concluded pilot study (Light-Duty Technology Cost Analysis Pilot Study [EPA-420-R-09-020]).

For the downsized, turbocharged, stoichiometric GDI engine case studies, careful consideration was given to the selection of vehicle classes analyzed to ensure that the developed costing models, at any analysis level (component, sub-subsystem, or subsystem) could be interpolated or extrapolated to other classes, configurations and/or content levels.
Table 1-1 exhibits the five (5) vehicle classes considered in this work assignment and identifies those vehicles classes with actual teardown-based cost studies.

Table 1-1: Vehicle Class and Corresponding Downsized, Turbocharged, Stoichiometric, GDI Engine Case Study Evaluated

Vehicle Class	Vehicle Class Description	Completed Analysis
Small Car	subcompact or compact car typically powered by an in-line 4 cylinder engine	Case Study #0101 (2.4L I4 » 1.6L I4) (≈175 hp) (Pilot Study)
Midsize Car	midsize or large passenger car typically powered by a V6 engine	Case Study #0102 (3.0 V6 » 2.0L I4) (≈225 hp)
Large Multipurpose Vehicle	minivan or large cross-over vehicle with a large frontal area, typically powered by a V6 engine, capable of carrying ~ 6 or more passengers	(Large V6»Small V6) Potential to scale costs from #0102 & #0104
Small Truck	small or mid-sized sports-utility or cross-over vehicle, or a small pickup truck, powered by a V6 or V8 engine	Case Study #0104 (5.4L V8 » 3.5L V6) (≈330 hp)
Large Truck	large sports-utility vehicles and large pickup trucks, typically powered by a V8 engine	(Large V8»Small V8) Potential to scale costs from #0104

1.2 Study Methodology

The first report published, “Light-Duty Technology Cost Analysis Pilot Study (EPA-420-R-09-020)”, covers in great detail the overall costing methodology used to calculate an incremental cost delta between various technology configurations. In summary, the costing methodology is heavily based on teardowns of both new and baseline technology configurations having similar driver 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. Information on how additional associated manufacturing fixed and variable cost elements (e.g. shipping, tooling, OEM indirect costs) are accounted for within the cost analysis is also discussed in the initial report (EPA-420-R-09-020).

Listed below, with the aid of Figure 1-1, is a high level summary of the ten (10) major steps taken during the cost analysis process. For additional information concerning the terminology used within the ten (10) steps, please reference the glossary of terms found at the end of this report.

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

Step 2: Existing vehicle models are identified for teardown to provide the basis for detailed incremental cost calculations.

Step 3: Pre-teardown ***Comparison Bills of Materials (CBOM)*** are developed, covering hardware that exists in the new and base technology configurations. These high level CBOM’s 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 is conducted for all subsystems identified in Step 3 and the assemblies that comprise them. Using ***Design Profit® software***, all high level processes (e.g. assembly process of the high pressure fuel pump onto the cylinder head assembly) are mapped during the disassembly.

<u>Step 5</u>: 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.

<u>Step 6</u>: Phase 2 (component/assembly level) teardowns are initiated, based on the updated CBOM's. Components and assemblies are disassembled, and processes and operations are mapped in full detail. The process mapping generates key process information for the quote worksheets. Several ***databases*** containing critical costing information provide support to the mapping process.

<u>Step 7</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.

<u>Step 8</u>: 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.

<u>Step 9</u>: 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. 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.

<u>Step 10</u>: The final step in the process is creating the ***System CMAT*** which 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. Within the scope of this cost analysis, the System CMAT provides the bottom line incremental unit cost between the base and new technology configurations under evaluation

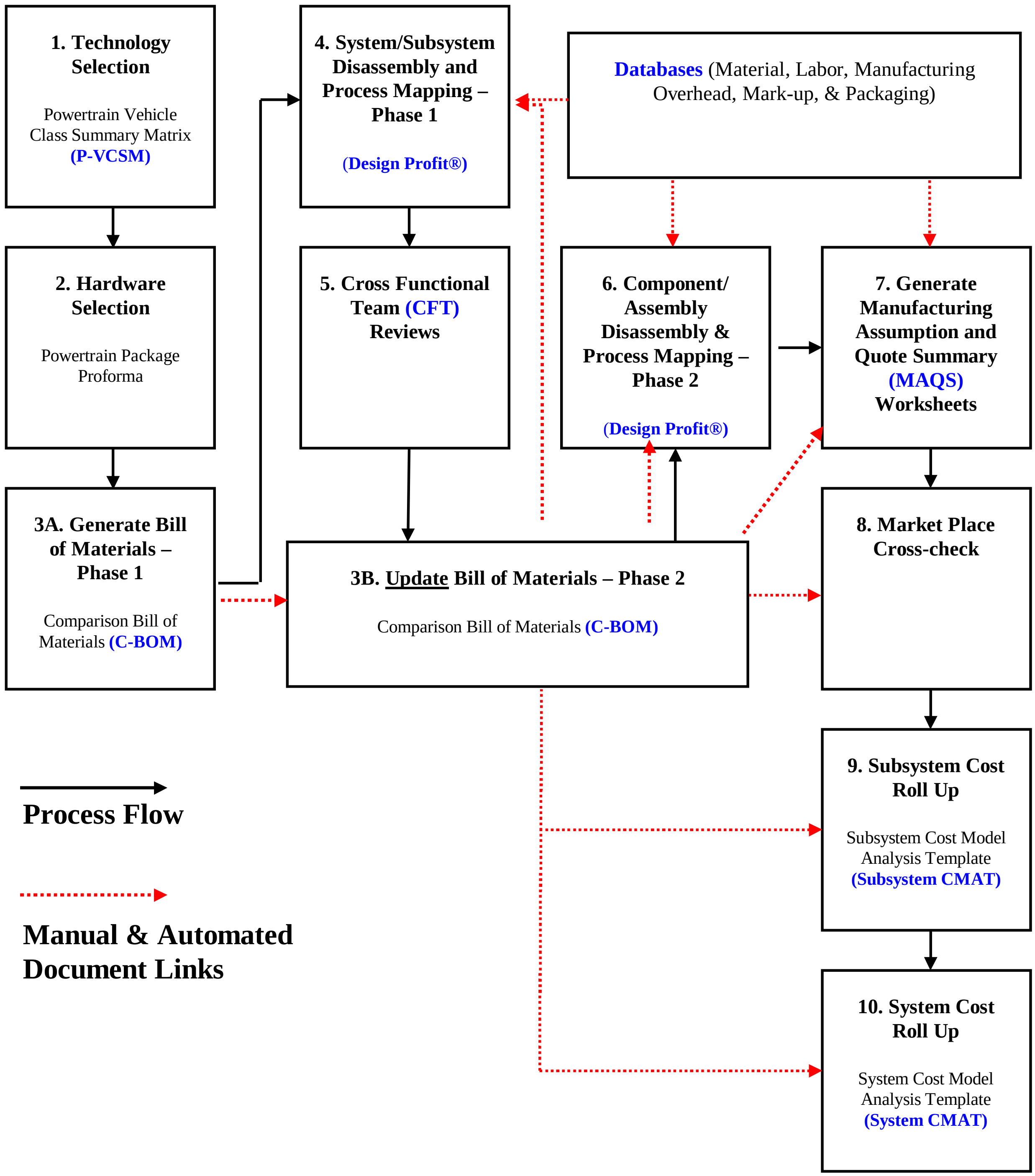

Figure 1-1: Cost Analysis Process Flow Steps and Document Interaction

1.3 Manufacturing Assumptions

When conducting the cost analysis for the various technology configurations, a number of assumptions are made in order to establish a consistent framework for all costing. The manufacturing assumptions can be broken into generic and specific case study assumptions.

The generic manufacturing assumptions apply to all technology configurations under analysis and are carry-over from the pilot study. Listed below are the fundamental assumptions:

1) Manufacturing rates are considered high volume (>450K Units/Year) and maintained throughout the product life. In the four (4) case studies which follow, a yearly capacity planning volume (CPV) of 450,000 units was assumed.

2) All OEM and supplier manufacturing locations are in North America, unless otherwise stated. This serves to make the resulting costs conservative to the extent that OEMs use offshore suppliers to reduce costs.

3) OEMs and suppliers have manufacturing equipment and facilities capable of handling required manufacturing processes and capacities unless otherwise stated.

4) All manufacturing processes and operations are based on standard/mainstream industrial practices.

5) Supplier and OEM manufacturing costs (material costs, labor rates, manufacturing overhead/burden rates) are based on 2008/2009 economics.

6) Supplier mark-up rates (end-item scrap, SG&A, profit, and ED&T) are based on mature technology and manufacturing methods (e.g. mature product designs, high production volumes, significant marketplace competition, and established manufacturing processes) unless otherwise specified.

7) All OEM mark-up will be applied using indirect cost (IC) multipliers. These are not within the scope of this analysis but should be separately determined and applied to the results of this analysis to obtain total (direct + indirect) manufacturing costs.

The specific case study assumptions are those unique to a given technology and hardware configuration. Listed below are some of the case study specific considerations:

1) Manufacturing site for defined operation or process; OEM, Tier 1 or Tier 2/3.

2) Intellectual property expense.

3) Neighboring system costs as a result of new technology adaptation.

4) A new or modified, maintenance and/or end-of-life expense.

5) Availability of significant material cost reductions (MCRs).

6) Performance and/or cost implications of alternative new technology advances (NTAs).

1.4 Subsystem Categorization

As with the first case study analysis, a design based classification system was used to group the various components and assemblies making up the technology configurations. In general, every vehicle system (e.g. engine system, transmission system, etc.) is made up of several subsystems levels (e.g. the engine system includes a crank drive subsystem, cylinder head subsystem, lubrication subsystem, air induction subsystem, etc.), which in-turn, is made up of several sub-subsystem levels (e.g. the air induction subsystem may include the following sub-subsystems: turbocharger, heat exchanger, pipes, hoses, and ducting). The sub-subsystem is the smallest classification level in which all components and assemblies are binned.

Adding new technology to a system will also affect the primary subsystem(s). Also impacted are the neighboring subsystems which require additions and/or modification for successful integration of the new technology into the system. For example, to add a turbocharged air induction subsystem to a naturally aspirated engine, as many as ten (10) additional subsystems may be affected relative to cost, some in the positive direction (added cost), others in the negative direction (cost savings). Table 1-2 and Table 1-3 provide an overview of the major subsystems and sub-subsystems included for each system (e.g. engine and transmission) evaluated within this analysis. In Section 2, Case Study Results, costs are presented for both the engine and transmission evaluations using these design subsystem categorizations.

Table 1-2: Engine System, Subsystem and Sub-Subsystem Classification

Subsystem	Sub-Subsystem
Engine Frames, Mountings & Brackets	Engine Frames, Engine Mountings, Hanging Hardware
Crank Drive	Crankshaft, Flywheels/Flexplates, Connecting Rods, Pistons, Bearing Elements
Counter Balance	Dynamic Parts, Static Parts, Drives
Cylinder Block	Cylinder Block, Crankshaft Bearing Caps, Bedplate, Piston Cooling
Cylinder Head	Cylinder Head, Valve Guides & Seats, Guides for Valvetrain, Camshaft Bearing Housing, Camshaft Sensors, Camshaft Carrier, Cylinder Head Covers.
Valvetrain	Camshaft, Intake Valves, Exhaust Valves, Valve Springs, Spring Retainers & Keepers & Seats,
Timing Drives	Timing Wheels, Tensioners, Guides, Belts, Chains
Accessory Drives	Pulleys, Tensioners, Guides, Belts
Intake	Intake Manifold, Air Filter Box, Air Filters, Throttle Housing Assembly & Supplies, Pipes/Hoses/Ducting
Fuel Induction	Fuel Rails, Fuel Injectors, Pressure Regulators & Sensors, Fuel Injection Pumps, Pipes/Hoses, Brackets
Exhaust	Exhaust Manifold, Collector Pipes, Catalysts, Silencers (Mufflers), Oxygen Sensors, Pipes/Hoses, Brackets
Lubrication	Oil Pans, Oil pumps, Pressure Regulators& Sensors, Oil Filters, Pipes/Hoses, Sealing Elements, Heat Exchangers
Cooling	Water Pumps, Thermostat Housing, Heat Exchangers, Pressure Regulators, Pipes/Hoses/Ducting, Brackets
Induction Air Charging	Turbochargers, Heat Exchangers, Pipes/Hoses/Ducting, Brackets
Breather	Oil/Air Separator, Valves, Adapters, Pipes/Hoses/Ducting
Electronic and Electrical	Engine Management, Engine Electronic, Engine Electrical (e.g. Wiring, Ignition, Plugs, Coils, Powertrain Control Module)
Accessory	Starter Motors, Alternators, Power Steering Pumps, Air Conditioning Compressors

Table 1-3: Transmission System, Subsystem and Sub-Subsystem Classification

Subsystem	Sub-Subsystem
Externally Mounted Component	Lift Eye, Vent Cap, Bracket, Bolting
Case(s)	Transaxle Case, Transaxle Housing, Covers, Bearing Race, Plug, Actuator
Gear Train	Input Shaft, Output Shaft, Transfer Shaft, Sun Gear, Planetary Gear, Ring Gear, Counter Gear, Differential Gear, Bearing (Roller, Needle)
Internal Clutch	Sprag Clutch, Clutch & Brake Hub, Disc and Plate, Piston, Snap Ring, Bearing (Roller, Needle), Synchronizer
Launch Clutch	Torque Converter, Clutch Assembly, Flexplate, Flywheel
Oil Pump and Filter	Oil pump, Cover, Oil Filter, Oil Cooler, Oil Squirter, Pipes/Tubes
Mechanical Control	Valve Body Assembly, Mechanical Controls (e.g. Shift Forks), Sealing Elements, Bearing Elements, Plugs & Cups
Electrical Control	Controller, Solenoid, Sensor, Switches, Wiring Harness
Park Mechanism	Rod/Shaft/Pin, Spring, Pawl, Bracket, Bolt

2 Case Study Results

The results for the four (4) case studies analyzed within this work assignment. For each case study, a brief description of the technology and its associated hardware is provided. Additional general specifications for each case study can also be found in the Powetrain Packaging Specification Proformas in Appendix A. A scaled-down version of the System Cost Model Analysis Template (CMAT) is provided, summarizing the incremental direct manufacturing costs for each major subsystem that was affected by adaptation of the new technology.

The full System CMATs for each case study can be found in Appendix B. The supporting Subsystem CMATs for each case study, which roll-up all the component and assembly costs for each subsystem, can be found in Appendix C. Table 2-1 provides a cross reference between each case study and the associated system and subsystem CMATs.

Because each case study consists of a large quantity of component and assembly Manufacturing and Assumption Quote Summary (MAQS) worksheets, approximately 200 pages per case study, hard copies were not included as part of this report. However, electronic copies of the MAQS worksheets, as well as all other supporting case study documents (e.g. CBOMs, Subsystem CMATs, System CMATs), can be accessed at **http://www.epa.gov/otaq/**.

Table 2-1: Location of System and Subsystem CMATs within Appendix

Case Study Numbers	Case Study Description	System CMAT Appendix Section	Subsystem CMAT Appendix Section
N0102 B0102	2.0L, I4, 4-valve, dual overhead cam (DOHC), dual variable valve timing (d-VVT), turbocharged, gasoline direct injection (GDI) engine, compared to an equivalent conventional 3.0L, V6, 4-valve, DOHC, d-VVT, naturally aspirated (NA), port fuel injected (PFI) engine.[a]	B1	C1
N0104 B0104	3.5L, V6, 4-valve, dual overhead cam (DOHC), d-VVT, turbocharged, GDI engine, compared to an equivalent conventional 5.4L, V8, 3-valve, single overhead cam (SOHC), VVT, NA, PFI engine.	B2	C2
N0802 B0802	A 6-speed automatic transmission, compared to an equivalent 5-speed automatic transmission	B3	C3
N0902 B0902	A 6-speed wet dual clutch transmission (DCT), compared to an equivalent 6-speed automatic transmission.	B4	C4

a For the purpose of these case studies, "equivalent" means similar performance and/or capability

2.1 Case Study #0102 Results
(V6 Downsizing to I4)

Case Study #0102 analyzed the direct incremental manufacturing cost for downsizing from a conventional 3.0L, V6, 4-V, DOHC, d-VVT, NA, PFI engine to a 2.0L, I4, 4-V, DOHC, d-VVT, turbocharged, GDI engine. The performance specifications for both engine configurations were considered to be equivalent with a maximum power output of approximately 225 hp and maximum torque of approximately 210 lb-ft.

Note that in this analysis, neither the new or base engine actual hardware had d-VVT. Both sets of hardware only consisted of intake-VVT. However, as part of the overall study assumptions, both technologies were assumed to have d-VVT.

For the conventional/baseline engine configuration, a 2008 Ford Cyclone Duratec 35 (i.e. 3.5L V6) engine was used in combination with a 2008 Ford Mondeo Duratec 30 (i.e., 3.0L V6) engine. The 3.5L Duratec engine was the principal hardware referenced in this analysis, with the 3.0L Duratec engine primarily used to support size and weight scaling of the 3.5L V6 engine to a 3.0L V6 equivalent. This approach was taken for two main reasons: 1) the 3.5L Duratec is a relative new engine (launched in 2007 timeframe, winner of 2007 Ward's Top 10 Best Engines) and, as such, is considered to contain some of the latest design and manufacturing advances for conventional V6 engines; and 2) much of this same base engine cost analysis could be reused in Case Study #0104 (5.4L V8, NA, PFI downsized to a 3.5L V6, Turbo, GDI engine), reducing analysis time.

For the new technology configuration, the 2007 BMW/PSA Peugeot Citroën Prince 1.6L I4, Turbo, GDI engine (used in the 2008 Mini Cooper, S) was selected as the lead hardware, scaled up to a 2.0L I4, Turbo, GDI equivalent. Both the Chrysler GEMA 2.4L, I4, NA, PFI engine and GM Family II, Ecotec, 2.0L, I4, Turbocharged, GDI engine were used for size and weight scaling (e.g. pistons, connecting rods, cylinder head), feature counts (e.g. valve cover fasteners, oil sump fasteners), as well as for costing selected items not captured within the 1.6L I4 BOM (e.g. balance shaft). Because the 1.6L I4, Prince engine was used in a previous study (i.e. case study #0101), selected cost models for this previously completed work could be reprocessed with updated function and performance specifications, reducing analysis time.

Features of the 2.0L I4, Turbo, GDI fuel induction subsystem include a direct rotary drive, swash plate, high pressure fuel pump assembly servicing four (4) side-mounted solenoid injectors (7-hole type) with a maximum operating pressure of 150 bar. The air induction subsystem includes a twin-scroll turbocharger assembly, featuring a vacuum-actuated waste gate actuator, electronically-actuated anti-surge valve, along with a water-cooled, pressure-lubricated bearing housing. The maximum exhaust gas temperature permitted at the turbine inlet is 950°C. Compressed air leaving the turbocharger assembly is cooled via an air-to-air heat exchanger prior to reaching the intake manifold.

In this cost analysis, as well as in the V8 to V6 Turbo, GDI, engine downsizing analysis, no additional intellectual property expenses were identified beyond the typical contribution included in the selling, general and administrative (SG&A) expense. It is acknowledged that each supplier currently manufacturing air induction components (e.g. Honeywell-Garret, BorgWarner, Cummins) and/or high pressure fuel system components (e.g. Bosch, Continental, Delphi) will have a large number of patents to protect their intellectual property. Because of these patents, market-leading suppliers can recover some of their development costs in the short term. However the approach of this cost analysis assumes that a competitive supplier base will develop similar components (which do not infringe on the original developer's patents), and that the value of the originator's intellectual property will diminish, resulting in more modest intellectual property allowances as the technology matures. This allowance is captured by the assigned SG&A rate.

As with the first pilot case study (#0101), new technology advances (NTAs) were identified as possible performance upgrades to the physical hardware of the turbocharged engines. These NTAs included the following: variable geometry turbochargers, water-to-air charge air coolers, electric water pump (replacing the conventional mechanical water pump) paired with a smaller auxiliary after-run pump. At this time, these alternative technologies are recorded and identified (and may be evaluated at a later date when representative hardware is available), but are not included in the cost analysis.

Many material cost reduction (MCR) ideas were identified in case study #0102, and these MCRs were incorporated at the beginning of this analysis. For example, certain manufacturing processes are sometimes better suited to lower-volume products due to lower tooling costs. An example of this would be a part manufactured using a powdered metal process; at low production volumes, this may result in the lowest cost, but at high production volumes, a fine blanking process may make better financial sense. Generally, anywhere a component design or manufacturing method was originally adopted based on low volume production, a revised design assumption and/or process suitable for high volume mass production was selected. A second example of where MCRs were directly implemented into the analysis was in the selection of "best practice" or "upward trending" manufacturing processes. An example of this is the replacement of a sandcast aluminum cylinder block with a diecast cylinder block. In this particular case study, the actual block for the 3.0L, V6, Ford Duratec block was sandcast, whereas the 3.5L block was diecast. For this reason, the 3.5L, V6, Ford Duratec diecast cylinder block was evaluated for cost and scaled down to a 3.0L V6 equivalent.

In all of the turbo, GDI, engine downsizing studies (case studies #0101, #0102, and #0104), this same approach to NTAs and MCRs was utilized.

Figure 2-1 shows the net incremental direct manufacturing cost of $68.68 for downsizing from a 3.0L V6, NA, PFI conventional engine to a 2.0L I4, Turbo, GDI engine. In addition to the subsystem cost breakdowns showing their net contribution to costs, the contribution from each cost element is also captured. Major incremental cost factors for the new technology were the fuel induction subsystem ($84.76) and air induction subsystem ($280.70). Major incremental cost savings for the new technology due to downsizing were the cylinder head subsystem ($158.70) and the valvetrain ($122.71).

Technology Level: 01-Downsized, Turbocharged, Gasoline Direct Inject (GDI) Engine
Vehicle Class: 02-Mid to Large Size Passenger Vehicle, 4-6 Passengers
Study Case#: 0102 (N0102 New Technology Configuration)
(B0102 Baseline Technology Configuration)

INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

NEW TECHNOLOGY PACKAGE COST INFORMATION
2.0L I4, DOHC, Turbo DI

BASE TECHNOLOGY PACKAGE COST INFORMATION
3.0L V6, DOHC, NA, PFI

SYSTEM & SUBSYSTEM DESCRIPTION			Manufacturing				Markup						
Item	Subsystem	Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
0100		ENGINE SYSTEM											
1	02	Engine Frames, Mountings & Brackets Subsystem	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
2	03	Crank Drive Subsystem	$ (5.88)	$ (7.87)	$ (24.93)	$ (38.68)	$ 0.38	$ (1.64)	$ (1.60)	$ (0.56)	$ (3.41)	$ (0.31)	$ (42.40)
3	04	Counter Balance Subsystem	$ 10.37	$ 6.22	$ 10.89	$ 27.47	$ 0.84	$ 3.16	$ 2.92	$ 0.91	$ 7.83	$ 0.05	$ 35.36
4	05	Cylinder Block Subsystem	$ (15.80)	$ 4.82	$ 16.04	$ 5.06	$ 0.88	$ 0.69	$ 0.57	$ (0.09)	$ 2.04	$ 0.40	$ 7.51
5	06	Cylinder Head Subsystem	$ (57.68)	$ (13.65)	$ (74.52)	$ (145.85)	$ (2.28)	$ (4.26)	$ (4.60)	$ (1.34)	$ (12.48)	$ (0.37)	$ (158.70)
6	07	Valvetrain Subsystem	$ (36.81)	$ (15.43)	$ (56.25)	$ (108.49)	$ (0.47)	$ (5.72)	$ (5.53)	$ (2.24)	$ (13.96)	$ (0.26)	$ (122.71)
7	08	Timing Drive Subsystem	$ (39.24)	$ (5.99)	$ (11.58)	$ (56.80)	$ (0.59)	$ (1.56)	$ (1.04)	$ (0.24)	$ (3.43)	$ (0.38)	$ (60.61)
8	09	Accessory Drive Subsystem	$ 7.00	$ -	$ -	$ 7.00	$ -	$ -	$ -	$ -	$ -	$ -	$ 7.00
9	10	Intake Subsystem	$ (10.69)	$ (3.38)	$ (9.89)	$ (23.96)	$ (0.11)	$ (1.45)	$ (1.34)	$ (0.56)	$ (3.46)	$ (0.24)	$ (27.66)
10	11	Fuel Subsystem	$ 29.35	$ 9.28	$ 27.31	$ 65.94	$ 0.81	$ 7.62	$ 7.53	$ 2.75	$ 18.71	$ 0.10	$ 84.76
11	12	Exhaust Subsystem	$ 9.22	$ (11.62)	$ (23.67)	$ (26.06)	$ 3.43	$ (1.57)	$ (1.80)	$ (0.91)	$ (0.85)	$ (0.39)	$ (27.30)
12	13	Lubrication Subsystem	$ (2.86)	$ 3.56	$ (5.40)	$ (4.69)	$ (0.04)	$ (0.20)	$ (0.38)	$ (0.37)	$ (0.99)	$ 0.02	$ (5.66)
13	14	Cooling Subsystem	$ 18.49	$ 6.29	$ 10.55	$ 35.33	$ 0.20	$ 2.40	$ 2.48	$ 1.06	$ 6.15	$ 0.11	$ 41.59
14	15	Induction Air Charging Subsystem	$ 98.15	$ 51.97	$ 73.38	$ 223.50	$ 7.36	$ 20.61	$ 20.71	$ 7.75	$ 56.44	$ 0.76	$ 280.70
15	16	Exhaust Gas Re-Circulation Subsystem- Not Applicable In Analysis	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
16	17	Breather Subsystem	$ 7.93	$ 1.99	$ 6.80	$ 16.71	$ 0.06	$ 1.14	$ 0.76	$ 0.19	$ 2.15	$ 0.03	$ 18.89
17	60	Engine Management, Engine Electronic and Electrical Subsystems	$ 11.16	$ (1.22)	$ 6.09	$ 16.03	$ 0.21	$ 1.76	$ 2.31	$ 1.25	$ 5.53	$ 0.01	$ 21.57
18	70	Accessories Subsystem (Starter Motors, Alternators, Power Steering Pumps, etc)	$ 3.44	$ 2.55	$ 7.45	$ 13.45	$ 0.09	$ 1.35	$ 1.10	$ 0.30	$ 2.84	$ 0.09	$ 16.38
19			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
20			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
		SUBSYSTEM ROLL-UP	$ 26.67	$ 27.51	$ (48.19)	$ 5.99	$ 10.77	$ 22.33	$ 22.08	$ 7.91	$ 63.08	$ (0.39)	$ 68.68

Figure 2-1: System Cost Model Analysis Template Illustrating the Incremental Subsystem Costs Roll Up for V6 to I4, Turbo, GDI Downsizing, Case Study #0102

An alternative method of binning component and assembly incremental costs is based on their contribution to cost relative to downsizing, GDI, or turbocharging categories. In Table 2-2, the incremental subsystems costs are broken out into these three (3) alternative categories. The combined subsystems cost of adding GDI to a 2.0L I4 over a conventional PFI subsystem is $213. The combined subsystems cost for adding turbocharging to an I4 engine over a conventional NA subsystem is $403. Lastly, the credit for downsizing from a conventional V6 to a conventional I4 is $547.

Table 2-2: Cost for Adding Turbocharging and GDI to a 2.0L, I4, NA, PFI engine and the Estimated Credit for Downsizing from a Conventional 3.0L V6 to 2.0L I4.

	Combine Subsystem Incremental Impact	Direct Subsystem Incremental Contribution	Indirect Subsystem Incremental Contribution
GDI	$213	$85	$128
Turbo	$403	$281	$122
Downsizing	(-$547)		
Net Incremental Cost	$69		

2.2 Case Study #0104 Results
(V8 Downsizing to V6)

Case Study #0104 analyzed the direct incremental manufacturing cost for downsizing from a conventional 5.4L, V8, 3-V, SOHC, VVT, NA, PFI engine to a 3.5L V6, 4-V, DOHC, d-VVT, turbocharged, GDI engine.

For the conventional/baseline engine configuration, a 2008 Ford Modular 5.4L V8 engine was selected. Standard features of this engine include a cast iron block, forged crankshaft, aluminum heads, variable valve timing and hydraulic, roller finger valve lifters. The maximum power output rating is 300 hp @ 5000 rpm with a maximum torque of 365 lb.-ft. @ 3750 rpm.

For the new technology configuration, a 2008 Ford Cyclone Duratec 35 (i.e. 3.5L V6) base engine was selected for the foundation of the analysis. Utilizing the project team's expertise, published data on Turbo, GDI, V6 engine architectures, surrogate component data from existing benchmarking evaluations, and previously completed cost studies (i.e., case study #0101 and #0102), the project team developed a 3.5L V6, Turbo, GDI engine Bill of Materials (BOM). In regards to a target performance specification, the Ford EcoBoost engine (3.5L V6, 4-V, DOHC, i-VVT, Turbo, GDI, engine) specification was used as a surrogate; maximum 355 hp @ 5000 rpm and 350 lb.-ft. @ 3500 rpm.

Features of the 3.5L V6, Turbo, GDI fuel induction subsystem include a direct rotary drive, swash plate design, high-pressure fuel pump servicing six (6) side-mounted solenoid injectors (7-hole type), with a maximum operating pressure of 150 bar. The air induction subsystem features twin, single-scroll turbocharger assemblies. Each turbocharger assembly has a vacuum-actuated waste gate, an electronically-actuated anti-surge valve, and a water-cooled, pressure-lubricated bearing housing. The maximum exhaust gas inlet temperature permitted at the turbine inlet is 950°C. Compressed air leaving the turbocharger assemblies is cooled prior to reaching the intake manifold via an air-to-air heat exchanger.

Figure 2-2 shows the net incremental direct manufacturing cost of $846.26 for downsizing from a 5.4L V8, NA, PFI conventional engine to a 3.5L V6, Turbo, GDI engine. Major incremental cost factors for the new technology were the fuel induction subsystem ($124.59) and air induction subsystem ($448.79). The downsizing of many subsystems (e.g. intake, crank drive, cylinder block) resulted in a cost savings of $155.

Technology Level: 01-Downsized, Turbocharged, Gasoline Direct Inject (GDI) Engine
Vehicle Class: 04-Small to Midsize Truck, Passenger + Midsize Towing Capability
Study Case#: 0104 (N0104 New Technology Configuration)
(B0104 Baseline Technology Configuration)

INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

NEW TECHNOLOGY PACKAGE COST INFORMATION
3.5L,V6 DOHC, Turbo DI

BASE TECHNOLOGY PACKAGE COST INFORMATION
5.4L V8, SOHC, NA, PFI

SYSTEM & SUBSYSTEM DESCRIPTION			Manufacturing				Markup						
Item	Subsystem	Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
0100		ENGINE SYSTEM											
1	02	Engine Frames, Mountings & Brackets Subsystem	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
2	03	Crank Drive Subsystem	$ (5.10)	$ (5.29)	$ (12.50)	$ (22.89)	$ 0.79	$ (1.45)	$ (1.43)	$ (0.49)	$ (2.58)	$ (0.23)	$ (25.70)
3	04	Counter Balance Subsystem	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
4	05	Cylinder Block Subsystem	$ 9.55	$ 1.91	$ (36.13)	$ (24.67)	$ 0.01	$ 1.02	$ 0.31	$ (0.25)	$ 1.09	$ (0.66)	$ (24.24)
5	06	Cylinder Head Subsystem	$ (8.66)	$ 2.31	$ 16.07	$ 9.71	$ (0.67)	$ (1.18)	$ (1.29)	$ (0.36)	$ (3.49)	$ (0.01)	$ 6.21
6	07	Valvetrain Subsystem	$ (62.89)	$ 12.60	$ 45.66	$ (4.63)	$ 0.35	$ 4.20	$ 4.12	$ 1.81	$ 10.48	$ 0.26	$ 6.11
7	08	Timing Drive Subsystem	$ (11.10)	$ -	$ -	$ (11.10)	$ (0.11)	$ (0.13)	$ (0.08)	$ (0.02)	$ (0.34)	$ -	$ (11.44)
8	09	Accessory Drive Subsystem	$ 11.00	$ -	$ -	$ 11.00	$ -	$ -	$ -	$ -	$ -	$ -	$ 11.00
9	10	Intake Subsystem	$ (19.56)	$ (2.70)	$ (4.96)	$ (27.23)	$ (0.18)	$ (1.85)	$ (2.11)	$ (0.53)	$ (4.67)	$ (0.03)	$ (31.94)
10	11	Fuel Subsystem	$ 41.04	$ 14.52	$ 42.50	$ 98.06	$ 1.11	$ 10.78	$ 10.58	$ 3.85	$ 26.32	$ 0.21	$ 124.59
11	12	Exhaust Subsystem	$ 54.98	$ 0.70	$ 0.80	$ 56.49	$ 2.80	$ 3.86	$ 4.84	$ 2.50	$ 14.00	$ (0.06)	$ 70.43
12	13	Lubrication Subsystem	$ 36.55	$ 15.16	$ 33.00	$ 84.71	$ 0.30	$ 4.09	$ 3.65	$ 1.38	$ 9.43	$ 1.08	$ 95.22
13	14	Cooling Subsystem	$ 24.98	$ 7.54	$ 12.56	$ 45.08	$ 0.25	$ 3.07	$ 3.14	$ 1.31	$ 7.78	$ 0.18	$ 53.04
14	15	Induction Air Charging Subsystem	$ 146.26	$ 76.44	$ 106.36	$ 329.41	$ 17.87	$ 38.21	$ 40.86	$ 16.27	$ 113.21	$ 6.17	$ 448.79
15	16	Exhaust Gas Re-Circulation Subsystem- Not Applicable In Analysis	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
16	17	Breather Subsystem	$ 14.78	$ 3.80	$ 12.33	$ 30.91	$ 0.10	$ 2.06	$ 1.38	$ 0.34	$ 3.88	$ 0.03	$ 34.83
17	60	Engine Management, Engine Electronic and Electrical Subsystems	$ 32.70	$ 8.88	$ 16.15	$ 57.73	$ 0.43	$ 4.69	$ 4.98	$ 2.35	$ 12.46	$ (0.04)	$ 70.15
18	70	Accessories Subsystem (Starter Motors, Alternators, Power Steering Pumps, etc)	$ 4.11	$ 2.92	$ 8.67	$ 15.69	$ 0.11	$ 1.62	$ 1.32	$ 0.37	$ 3.41	$ 0.11	$ 19.22
19			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
20			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
		SUBSYSTEM ROLL-UP	$ 268.64	$ 138.78	$ 240.51	$ 648.28	$ 23.16	$ 69.00	$ 70.27	$ 28.54	$ 190.97	$ 7.02	$ 846.27

Figure 2-2: System Cost Model Analysis Template Illustrating the Incremental Subsystem Costs Roll Up for V8 to V6, Turbo, GDI Downsizing, Case Study #0104

Similar to the V6 to I4 downsizing analysis, Table 2-3 breaks down the incremental component and subsystems costs into downsizing, GDI, and turbocharging categories. As shown in the table, the combined subsystem cost for adding GDI to a V6 (over a conventional PFI subsystem) is $321. The combined subsystem costs for adding turbocharging to a V6 engine over a conventional NA subsystem is $681. Lastly, the credit for downsizing from a conventional V8 to a conventional V6 is $155.

Table 2-3: Cost for Adding Turbocharging and GDI to a 3.5L, V6, NA, PFI engine and the Estimated Credit for Downsizing from a Conventional 5.4L V8 to 3.5L V4.

	Combine Subsystem Incremental Impact	Direct Subsystem Incremental Contribution	Indirect Subsystem Incremental Contribution
GDI	$321	$125	$196
Turbo	$681	$449	$232
Downsizing	(-$155)		
Net Incremental Cost	$846		

2.3 Case Study #0802 Results
(6-Speed versus 5-Speed Automatic Transmission)

Case Study #0802 analyzed the direct incremental manufacturing cost for updating from a conventional 5-speed automatic transmission to a next generation 6-speed automatic transmission.

The 5-speed automatic transmission selected for the analysis was the Toyota U151E FWD transmission. This transmission was used in various applications including the Toyota Camry through the 2005-2006 timeframe. The main construction of the transmission includes three (3) full planetary gear sets. The front and rear planetary gear sets are positioned in series along a common intermediate shaft assembly. Adjacent to the front and rear planetary sets, and mounted in series to the counter shaft assembly, is a third underdrive planetary set. The transmission contains a total of nine (9) shift elements, four (4) disc clutches, three (3) disc brakes, and two (2) one-way-clutches. The hydraulic valve body assembly, containing a total of seven (7) shift solenoid valves is controlled directly by the engine control module (ECM). The total weight of the transmission, including Automatic Transmission Fluid (ATF), is approximately 221 lbs. The maximum output torque rating for the U151E is 258 lb-ft.

The 6-speed automatic transmission selected for the analysis was the replacement transmission to the Toyota 5-speed. The Toyota 6-speed FWD transmission (U660E) was a complete redesign of the existing U151E transmission, which launched in the 2007 timeframe. Employing a Ravigneaux and underdrive planetary gear set, positioned along a common intermediate shaft assembly, the U660E gear driveline is much simpler compared to its predecessor. Only six (6) shift elements are required for operation of the transmission; two (2) disc clutches, three (3) disc brakes, and one (1) one-way-clutch. The U660E valve body assembly also contains a total of seven (7) shift solenoid valves interfacing with an exterior-mount transmission control module (TCM), which in-turn communicates with the engine control module (ECM). The total weight of the transmission, including ATF, is 208 lbs. The maximum output torque rating for the U660E is 295 lb.-ft.

As discussed in the initial report (EPA-420-R-09-020), the costing methodology employs an exclusion approach to costing. Following completion of the comparison bill of materials (CBOMs), the cross functional team began the process of rationalizing similarities and differences between hardware on the five (5) and six (6) speed transmissions. A combination of component function and content exclusion analysis was conducted, eliminating the majority of components which required costing. Since the 5-speed transmission contained more hardware (i.e., approximately 150 more parts), and was generally more complex, the 6-speed established a zero cost baseline from which an incremental cost for the 5-speed was established. The majority of incremental cost increase of the five 5-speed over the 6-speed was associated with the two (2) additional clutch packs, the need for a counter shaft assembly, and some additional gearing.

According to the SAE Technical Paper 2006-01-0847 ("Toyota's New 6-Speed Automatic Transaxle U660E for FWD Vehicles"), the U660E's transmission geartrain structure, consisting of a Ravigneaux gear set and simpler planetary set, was Toyota's original invention. As such, there was no patent royalty fee penalization assessed against the 6-speed design. The patent rights for similar 6-speed transmission designs (e.g. Lepelletier) are due to expire in 2010. Therefore we do not expect royalty fees to be a significant part of the cost for 6-speed transmissions.

For the 6-speed automatic transmission, there were no NTA or MCR ideas identified as part of the cost analysis. It was obvious from the transmission teardown assessment that in addition to Toyota's goal for improving overall performance with their new 6-speed automatic transmission relative to the 5-speed predecessor, keeping costs at or below the existing manufacturing cost was a key metric. In regard to the 5-speed automatic transmission, many of innovative ideas implemented into the 6-speed automatic could have been incorporated into a new 5-speed if it were to be redesigned). The most obvious NTA would be adopting a similar Ravigneaux geartrain design, which could conceivably have the same financial benefit recognized by the 6-speed automatic. As part of this analysis, no additional work was conducted to determine what the financial impact would be on the 5-speed automatic by employing some of these NTA and MCRs concepts. As such, the net incremental direct manufacturing cost shown below is solely based on the physical hardware evaluated.

Figure 2-3 shows the net incremental direct manufacturing cost between the six (6) and five (5) speed automatic transmissions. In evaluating the physical hardware, the 6-speed automatic was analyzed to be less expensive to manufacture by approximately $105. Note that when the 6-speed transmission was redesigned, several other functional and performance updates not driven by the added 6th-gear ratio were incorporated (e.g. modified hydraulic control strategy, spool valve material, and friction discs, as well as a newly-developed torque converter). These modifications were not costed in the analysis since they are independent of the gear ratio addition and modifications.

Technology Level: 08 - 6 Speed Automatic versus 5 Speed Automatic Transmission
Vehicle Class: 02 - Mid to Large Size Passenger Vehicle, 4-6 Passengers
Study Case#: 0802 (N0802 New Technology Configuration)
(B0802 Baseline Technology Configuration)

INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

NEW TECHNOLOGY PACKAGE COST INFORMATION
6 Speed Automatic Transmission: 2007-2009 Toyota Camry

BASE TECHNOLOGY PACKAGE COST INFORMATION
5 Speed Automatic Transmission: 2004-2006 Toyota Camry

SYSTEM & SUBSYSTEM DESCRIPTION			Manufacturing				Markup						
Item	Subsystem	Subsystem Description	Material	Labor	Burden	Total Manufacturing Cost (Component/ Assembly)	End Item Scrap	SG&A	Profit	ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
0200		**TRANSMISSION SYSTEM**											
1	01	EXTERNAL COMPONENTS: Consists of installation of oil coolers, lift eyes, vent caps.	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
2	02	CASE(S): Includes pressed in components (i.e., bearing races), plugs, and associated hardware.	$ (0.83)	$ (0.53)	$ (4.68)	$ (6.03)	$ -	$ -	$ -	$ -	$ -	$ -	$ (6.03)
3	03	GEAR TRAIN: Includes Input Shafts, Output Shafts, Differential and all associated gears and bearings on the shaft.	$ (1.83)	$ (4.69)	$ (13.67)	$ (20.19)	$ (0.14)	$ (1.45)	$ (1.64)	$ (0.81)	$ (4.05)	$ -	$ (24.24)
4	04	INTERNAL CLUTCHES: Internal for Gears, Synchronizers, Bands, etc.	$ (19.46)	$ (8.87)	$ (34.46)	$ (62.80)	$ (0.47)	$ (4.27)	$ (4.28)	$ (1.90)	$ (10.91)	$ (0.26)	$ (73.98)
5	05	LAUNCH CLUTCHES: Torque Converter	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
6	06	OIL PUMP & FILTER: Includes Pump, Pump Shaft/Drive Mechanism, Oil Filters (Internal or External), Pick-up Tube, and Oil Baffles.	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
7	07	MECHANICAL CONTROLS	$ (0.17)	$ (0.52)	$ (0.50)	$ (1.19)	$ (0.00)	$ (0.04)	$ (0.03)	$ (0.01)	$ (0.07)	$ (0.02)	$ (1.28)
8	08	ELECTRICAL CONTROLS	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
9	09	PARK MECHANISM: Includes Park & Lock Pawl Mechanism and Actuating Levers	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
10	10	MISCELLANEOUS:	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
11													
12													
		SUBSYSTEM ROLL-UP	$ (22.29)	$ (14.61)	$ (53.32)	$ (90.22)	$ (0.61)	$ (5.76)	$ (5.95)	$ (2.71)	$ (15.04)	$ (0.28)	$ (105.53)

Figure 2-3: System Cost Model Analysis Template Illustrating the Incremental Subsystem Costs Roll Up for a 6-Speed Automatic Transmission compared to a 5-Speed Automatic Transmission

2.4 Case Study #0902 Results
(6-Speed Wet Dual Clutch Transmission versus 6-Speed Automatic Transmission)

Case Study #0902 analyzed the direct incremental manufacturing cost for updating from a conventional 6-speed automatic transmission to a 6-speed, wet, dual clutch transmission.

The baseline technology configuration selected for the analysis was the Toyota 6-speed automatic transmission (U660E) of case study #0802. General design parameters of the U660E transmission can be found in section 2.3 of this report.

The new technology configuration selected for the analysis was the Volkswagen (VW) six 6-speed, wet, dual clutch transmission (DCT); model number DQ250. Other industry naming conventions for this technology configuration include twin-clutch gearbox or dual shift gearbox (DSG). The basic components of the DCT include a twin clutch pack assembly driving two (2) coaxial input shafts. Power from the engine is transmitted to the input shafts through a dual-mass flywheel which is connected in series to the twin-clutch pack. Each input shaft, dependent on the selected gear, is designed to mesh with one (1) of two (2) output shafts. Upon reverse gear selection, there is an intermediate shaft which engages with both input shaft one (1) and output shaft two (2). There are four (4) shift forks, two (2) on each output shaft, hydraulically activated into one of two positions from their neutral home position. The controls for the DCT, which include the hydraulic controls, electronic controls, and various sensors and actuators, are integrated into a single module VW refers to as a Mechatronic unit. The total weight of the transmission module, including the dual-mass flywheel, is approximately 207 lbs. The maximum output torque rating for the DQ250 transmission is 258 lb.-ft.

Relative to intellectual property costs, no additional allowances were provided, outside the general allowance covered as part of the selling, general and administrative (SG&A) expense, for protecting intellectual property. It is acknowledged that each supplier currently making a version of a DCT (e.g. BorgWarner, Getrag, ZF, LuK) will have a large number of patents on their own technology. Because of these patents, suppliers who are considered to be market leaders in DCT technology will certainly recover some of their development costs in the short term. However, it is assumed that as the supplier base and associated technologies mature, the value (i.e. function/cost) each supplier provides will begin to equalize, resulting in a diminishing intellectual property cost allowance for each design.

As part of the hardware review and evaluation, no NTA or MCR ideas were considered in the final cost analysis. The evaluation team felt that in general, both transmissions were robustly designed, with each consisting of a high level of component and function integration, which resulted in two financially competitive solutions.

In this analysis, approximately seventy-five (75) percent of the components on both the 6-speed automatic transmission and 6-speed wet DCT were evaluated for cost. This level of analysis was required due to the inherent differences between the automatic versus DCT components. The only subsystems identified as common in function and cost between the two (2) transmissions were the oil pump, filter, park mechanism, and external components.

Figure 2-5 shows the net, incremental, direct manufacturing cost between the 6-speed wet DCT and 6-speed automatic transmissions. In evaluating the physical hardware, the 6-speed wet DCT was analyzed to be less expensive to manufacture by approximately $97. The major cost increment of the 6-speed wet DCT was the launch clutch system ($64.79), which included a dual-mass flywheel and twin clutch assembly. The major incremental cost savings for the new technology were the internal clutches ($132.35) and the geartrain ($38.04).

Also shown in Figure 2-5, a differential exist between the electronic hardware and controls in the two transmission systems. Differences including Gear Selecting Solenoids and Sensors and well as wiring harnesses and communication drivers can be clearly identified in Figure 2-4 below. These components and controls account for an additional cost differential of $46.99 contributing to the net incremental direct manufacturing cost of $-97.34.

6-Speed DSG **Device Description**	**Device Captured In MAQS**	**6-Speed AT** **Device Description**	**Device Captured In MAQS**
Gearbox Input Speed Sensor (G182)	**Cost Neutral**	Counter Gear Speed Sensor	**Cost Neutral**
Multi Plate Clutch Oil Temperature Sender (G509)	**Cost Neutral**	AFT Temperature Sensor	**Cost Neutral**
Drive Shaft 1 Speed Sensor (G501)	**Cost Neutral**	Input Turbine Speed Sensor	**Cost Neutral**
Drive Shaft 2 Speed Sensor (G502)	**Cost**		
Gearbox Output Speed Sensor (G195)	**Cost**		
Gearbox Output Direction Sensor (G196)	**Cost**		
Automatic Gearbox Hydraulic Pressure Sender -1- (G193)	**Cost Neutral**	AFT Pressure Switch 1	**Cost Neutral**
Automatic Gearbox Hydraulic Pressure Sender -2- (G194)	**Cost Neutral**	AFT Pressure Switch 2	**Cost Neutral**
		AFT Pressure Switch 3	**Cost**
Solenoid Valve 1 (N88)	**Cost**	Shift Solenoid Valve SL1	**Cost**
Solenoid Valve 2 (N89)	**Cost**	Shift Solenoid Valve SL2	**Cost**
Solenoid Valve 3 (N90)	**Cost**	Shift Solenoid Valve SL3	**Cost**
Solenoid Valve 4 (N91)	**Cost**	Shift Solenoid Valve SL4	**Cost**
Solenoid Valve 5 (N92)	**Cost**	Shift Solenoid Valve SLU	**Cost**
		Shift Solenoid Valve SLT	**Cost**
		Shift Solenoid Valve SL	**Cost**
Electrical Pressure Control Valve 1 (N215)	**Cost**		
Electrical Pressure Control Valve 2 (N216)	**Cost**		
Electrical Pressure Control Valve 3 (N217)	**Cost**		
Electrical Pressure Control Valve 4 (N218)	**Cost**		
Electrical Pressure Control Valve 5 (N233)	**Cost**		
Electrical Pressure Control Valve 6 (N371)	**Cost**		
Gear Selector Travel Sensor -1- (G487)	**Cost**		
Gear Selector Travel Sensor -2- (G488)	**Cost**		
Gear Selector Travel Sensor -3- (G489)	**Cost**		
Gear Selector Travel Sensor -4- (G490)	**Cost**		
Mechatronic Control Unit	**Cost**	Mechatronic Control Unit	**Cost**
Mechatronic Control Unit - Wiring Harness	**Cost**	Mechatronic Control Unit - Wiring Harness	**Cost**

Figure 2-4: System Electronic Hardware & Controls Comparison Matrix for a 6-Speed DSG compared to a 6-Speed Automatic Transmission

Technology Level: 09 - 6 Speed Automatic versus 6 Speed Direct Shift Transmission
Vehicle Class: 02- Mid to Large Size Passenger Vehicle, 4-6 Passengers
Study Case#: 0902 (N0902 New Technology Configuration)
(B0902 Baseline Technology Configuration)

INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

NEW TECHNOLOGY PACKAGE COST INFORMATION
6 Speed Direct Shift Gearbox (dual clutch): 2007-2009 VW Jetta SportWagen

BASE TECHNOLOGY PACKAGE COST INFORMATION
6 Speed Automatic Transmission: 2007-2009 Toyota Camry

SYSTEM & SUBSYSTEM DESCRIPTION

Item	Subsystem	Subsystem Description	Manufacturing: Material	Manufacturing: Labor	Manufacturing: Burden	Total Manufacturing Cost (Component/ Assembly)	Markup: End Item Scrap	Markup: SG&A	Markup: Profit	Markup: ED&T-R&D	Total Markup Cost (Component/ Assembly)	Total Packaging Cost (Component/ Assembly)	Net Component/ Assembly Cost Impact to OEM
0200		TRANSMISSION SYSTEM											
1	01	EXTERNAL COMPONENTS: Consists of installation of oil coolers, lift eyes, vent caps.	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
2	02	CASE(S): Includes pressed in components (i.e., bearing races), plugs, and associated hardware.	$ 5.82	$ (3.19)	$ (32.86)	$ (30.24)	$ 3.49	$ (1.88)	$ (1.73)	$ (1.94)	$ (2.06)	$ 0.39	$ (31.91)
3	03	GEAR TRAIN: Includes Input Shafts, Output Shafts, Differential and all associated gears and bearings on the shaft.	$ 9.38	$ (17.50)	$ (16.25)	$ (24.37)	$ (1.99)	$ (7.08)	$ (4.20)	$ 0.31	$ (12.96)	$ 1.76	$ (35.57)
4	04	INTERNAL CLUTCHES: Internal for Gears, Synchronizers, Bands, etc.	$ (44.06)	$ (22.63)	$ (37.74)	$ (104.43)	$ (1.32)	$ (12.82)	$ (13.06)	$ (4.30)	$ (31.49)	$ (2.26)	$ (138.19)
5	05	LAUNCH CLUTCHES: Torque Converter	$ (42.83)	$ 28.06	$ 60.71	$ 45.94	$ 0.99	$ 7.94	$ 7.48	$ 1.31	$ 17.71	$ 0.72	$ 64.37
6	06	OIL PUMP & FILTER: Includes Pump, Pump Shaft/Drive Mechanism, Oil Filters (Internal or External), Pick-up Tube, and Oil Baffles.	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
7	07	MECHANICAL CONTROLS	$ 8.41	$ (7.79)	$ 1.21	$ 1.83	$ 0.37	$ (1.98)	$ (1.95)	$ (0.34)	$ (3.89)	$ 0.37	$ (1.69)
8	08	ELECTRICAL CONTROLS	$ 30.89	$ 2.79	$ 5.88	$ 39.56	$ 0.21	$ 2.68	$ 2.48	$ 1.06	$ 6.43	$ 0.00	$ 45.99
9	09	PARK MECHANISM: Includes Park & Lock Pawl Mechanism and Actuating Levers	$ (0.20)	$ (0.16)	$ 0.04	$ (0.32)	$ (0.00)	$ (0.01)	$ (0.01)	$ (0.01)	$ (0.03)	$ -	$ (0.34)
10	10	MISCELLANEOUS:	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
11													
12													
		SUBSYSTEM ROLL-UP	$ (32.59)	$ (20.42)	$ (19.01)	$ (72.03)	$ 1.75	$ (13.14)	$ (11.00)	$ (3.91)	$ (26.29)	$ 0.98	$ (97.34)

Figure 2-5: System Cost Model Analysis Template Illustrating the Incremental Subsystem Costs Roll Up for a 6-Speed Wet DCT compared to a 6-Speed Automatic Transmission

3 GLOSSARY OF TERMS

Assembly: generally refers to 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).

Buy: is the terminology used to identify those components or assemblies as ones in which a manufacturer would purchase versus manufacture. All parts designated as a “buy” part, within the analysis, only have a net component cost presented. Typically these types of parts are considered commodity purchase parts having industry established pricing.

CBOM (Comparison Bill of Materials): is 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 implications 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: is 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 act independently performing a function within a sub-subsystem or subsystem (e.g. exhaust manifold within the exhaust subsystem).

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

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, 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.

Make: is the terminology used to identify those components or assemblies as ones in which 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: is the 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): is 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.

Net Component/Assembly Cost Impact to OEM: is defined as 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): is 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.

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

Process Maps: are 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, 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: refers to the analytical process of establishing a cost for a component or assembly.

Sub-subsystem: refers to 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 the following: turbocharging, heat exchangers, and pipes, hoses and ducting.

Subsystem: refers to 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 the following: crank drive subsystem, cylinder block subsystem, cylinder head subsystem, fuel induction subsystem, and air induction subsystem.

Subsystem CMAT (Cost Model Analysis Templates): is 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: refers to a part similar in fit, form and function as the part required for the cost analysis. Surrogate parts are sometimes used in the cost analysis when actual parts are unavailable. The cost of a surrogate part is considered equivalent to the cost of the actual part.

System: refers to 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): is 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.