



Analysis Report BAV 10-683-001_4

P2 Hybrid Electrification System Cost Reduction Potential Constructed on Original Cost Assessment

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

Submitted by:
Paul Lefief
FEV, Inc.
4554 Glenmeade Lane
Auburn Hills, MI 48326

February 10, 2014

Table of Contents

A.	Transmission System and Cost Summary Overview	3
A.1	Original Transmission Hardware Overview	3
A.2	Original P2 System	4
A.3	Comparison of the Original P2 and the Modified P2 Transmissions	6
A.3.1	Case	6
A.3.2	Launch Clutch	7
A.3.3	Oil Pump and Filter	9
A.3.4	Motor	10
	P2 Hybrid Transmission	10
A.3.5	Transmission Cooling System	12
A.4	Summary	13

Figures

NUMBER	PAGE
FIGURE 1: P2 HEV SYSTEM DIAGRAM ILLUSTRATING BASIC CONCEPT EVALUATED	4

Tables

Number	Page
TABLE 1: NET INCREMENTAL, DIRECT MANUFACTURING COSTS FOR ADDING P2 HEV TECHNOLOGY TO A RANGE OF VEHICLE SEGMENTS	5
TABLE 2: LIGHT-DUTY TECHNOLOGY COST ANALYSIS, P2 HEV AND P2 HEV MODIFIED	7
TABLE 3: LIGHT-DUTY TECHNOLOGY COST ANALYSIS, P2 HEV AND P2 HEV MODIFIED – LAUNCH CLUTCH SYSTEM	9
TABLE 4: LIGHT-DUTY TECHNOLOGY COST ANALYSIS P2 HEV AND P2 HEV MODIFIED – OIL PUMP AND FILTER	10
TABLE 5: LIGHT-DUTY TECHNOLOGY COST ANALYSIS P2 HEV AND P2 HEV MODIFIED – MOTOR	11
TABLE 6: LIGHT-DUTY TECHNOLOGY COST ANALYSIS P2 HEV AND P2 HEV MODIFIED – COOLING SYSTEM	12
TABLE 7: NET INCREMENTAL, DIRECT MANUFACTURING COSTS DEFERENCE BETWEEN P2 HEV AND MOD P2 HEV	14

Images

Number	Page
IMAGE 1: AISIN 6-SPEED (LEFT) AND FUSION ECVT (RIGHT)	3
IMAGE 2: ZF 9-SPEED AUTOMATIC TRANSMISSION FOR CHRYSLER AND DODGE CARS	7
IMAGE 3: FWD P2 HYBRID TRANSMISSION DEVELOPMENT	8
IMAGE 4: CHEVY MALIBU AUXILIARY PUMP	9
IMAGE 5: ZF OIL ACCUMULATOR	9
IMAGE 6 (LEFT): BMW ACTIVE HYBRID 7	11
IMAGE 7 (RIGHT): HONDA INSIGHT IMA	11
IMAGE 8: BMW 528 I	12

A. Transmission System and Cost Summary Overview

A.1 Original Transmission Hardware Overview

For this report the Ford Fusion electronic continuous variable transmission (eCVT) was being used, the P2 was a collaboration of multiple designs and our engineering estimate of what was going to be needed to generate an accurate cost model for a P2 system. The P2 transmission model or individual OEM design have little consequence in the study: only the material, component and technology cost. This comparison has homed in on the technology available today compared to when the original study was done (**Image 1**).

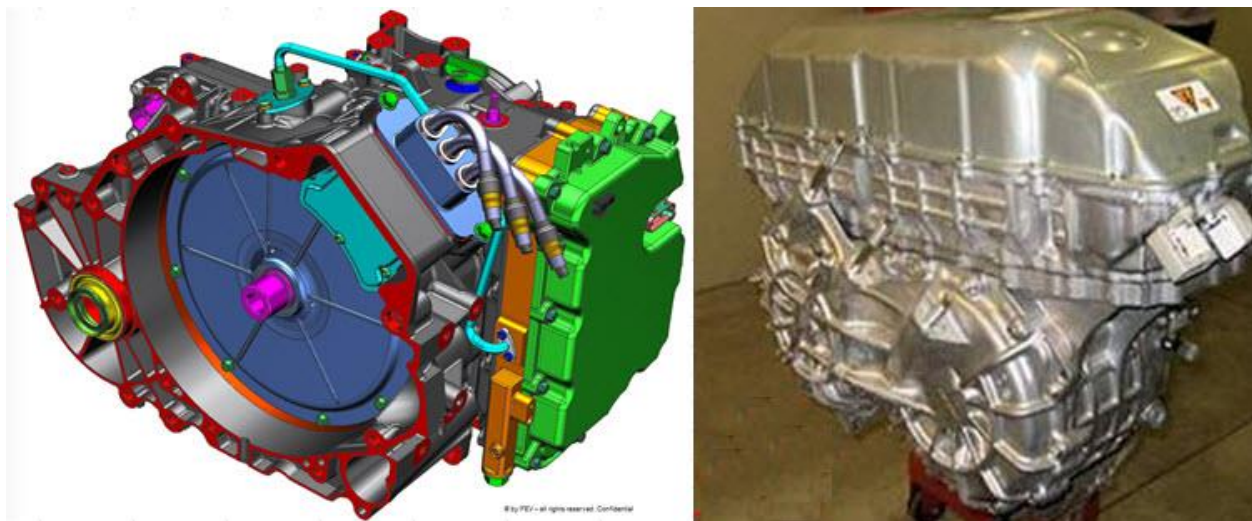


Image 1: P2 Hybrid design FEV (left) and Fusion eCVT (right)

The Fusion hybrid transaxle assembly, also shown in **Image 1**, is an electronic continuous variable transmission (eCVT). The eCVT utilizes the input from an ICE, an electric traction motor, and electric generator. The three (3) inputs are controlled by electronics packaged within the transaxle. Power is synchronized through a singular planetary using the sun gear, controlled by the generator, to control the variability. The hybrid transmission has a separate cooling system with a pump, heat exchanger, coolant, and reservoir that the (AT) does not have.

A.2 Original P2 System

The P2 hybrid design configuration (**Figure 1**) consisted of an integrated electric motor/generator and hydraulic clutch module positioned between a downsized internal combustion engine (ICE) and transmission. The electrical power supply/storage system consisted of high-voltage lithium polymer battery pack; voltage and capacity matched to the electric motor/generator size and vehicle mass. The P2 HEV technology configuration in this analysis was not considered to have a significant all-electric range (AER) capability.

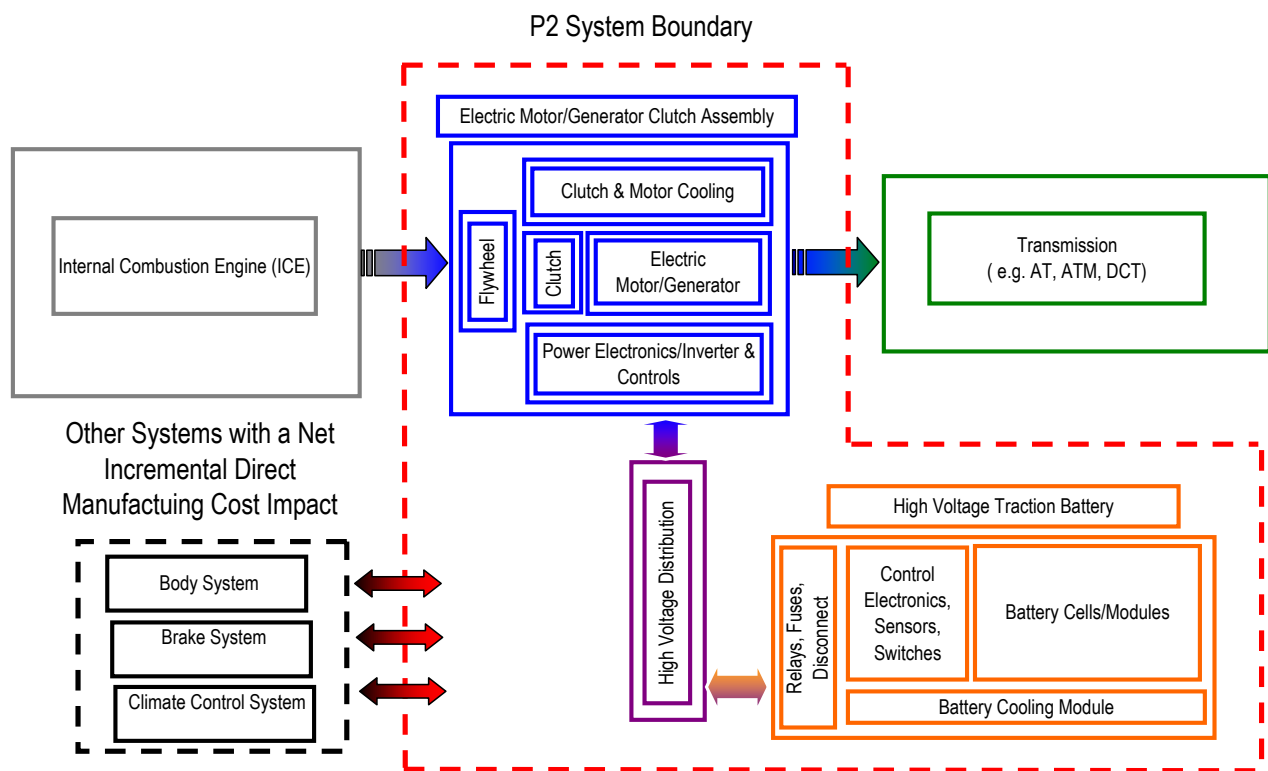


Figure 1: P2 HEV System Diagram Illustrating Basic Concept Evaluated

These estimates were generated by FEV for ICCT as part of an earlier study – “*Light-Duty Technology Cost Analysis of the Power-Split and P2 HEV*” (Ref: Case Study #0902) – of hybrid costs for EU. The net incremental direct manufacturing costs (**Table 1**) for each system and vehicle segment evaluated are representative of adding a P2 HEV system to a conventional powertrain configuration already downsized per the assumptions outlined above (i.e., vehicle mass reduction + assumption an ICE can be further reduced as result of electric motor addition).

Table 1: Net Incremental, Direct Manufacturing Costs for Adding P2 HEV Technology to a Range of Vehicle Segments

ICCT Europe Analysis P2 HEV Technnnology Configuration							
System ID	System Description	Calculated Incremental Manufacturing Cost - P2 HEV Technology					
		Subcompact Segment, Passenger Seating: 2-4	Compact or Small Segment, Passenger Seating: 2-5	Mid Size Segment, Passenger Seating: 4-5	Mid to Large Size Segment, Passenger Seating: 4-7	Small to Mid Size Sports Utility and Cross Over Segment, Passenger Seating: 4-5	Large Sports Utility Segment, Passenger Seating: 4-7
	Vehicle Example	VW Polo	VW Golf	VW Passat	VW Sharan	VW Tiguan	VW Touareg
Basic Powertrain Parameters	Curb Weight Average "lb" (% Mass Reduction)	2390 (0%)	2803 (0%)	3299 (0%)	3749 (0%)	3513 (0%)	4867 (0%)
	System Power "kW" (hp) (100% Conventional Powertrain)	74.7 (100.2)	90 (120.7)	117 (156.9)	174.8 (234.4)	132.6 (177.7)	271.8 (364.3)
	ICE Power "kW" (hp) (80% System Power w/ exception of Large SUV - No Reduction)	59.8 (80.1)	72 (96.6)	93.6 (125.5)	139.9 (187.5)	106.1 (142.2)	271.8 (364.3)
	Traction Motor Power "kW" (hp) (20% System Power)	14.9 (20)	18 (24.1)	23.4 (31.4)	35.0 (46.9)	26.5 (35.5)	54.3 (72.9)
	High Voltage Battery Capacity "V, kWh"	140, 0.743	162, 0.857	188, 0.994	211, 1.118	199, 1.053	269, 1.427
A	Internal Combustion Engine (ICE) System	(€ 136)	(€ 61)	(€ 61)	(€ 384)	(€ 61)	€ 0
B	Transmission System (Integrated Electric Motor/Generator and Clutch Assemby System + Baseline Transmission System Credit)	€ 568	€ 600	€ 642	€ 726	€ 670	€ 878
C	Body System	€ 6	€ 6	€ 6	€ 6	€ 5	€ 6
D	Brake System	€ 163	€ 167	€ 171	€ 174	€ 172	€ 183
E	Steering System	n/a	n/a	n/a	n/a	n/a	n/a
F	Climate Control System	€ 138	€ 144	€ 152	€ 156	€ 160	€ 184
G	Electric Power Supply System	€ 816	€ 908	€ 1,017	€ 1,109	€ 1,063	€ 1,345
H	Power Distribution and Control System	€ 148	€ 152	€ 155	€ 159	€ 154	€ 160
	Net Incremental Direct Manufacturing Cost	€ 1,704	€ 1,915	€ 2,080	€ 1,947	€ 2,164	€ 2,756

A.3 Comparison of the Original P2 and the Modified P2 Transmissions

This study investigates the assumptions that were made on the P2 transmission at the time of the first study and compares those with known transmission technical advancements over the last three years. No attempt was made to forecast future cost reductions beyond currently known technologies. In this analysis only efficiency, mass, and cost opportunities, associated with the Integrated Electric Motor/Generator and Clutch Assembly System were investigated. Cost reduction opportunities on other vehicle system such as the electric power supply (i.e., high voltage battery), brake-by-wire, and climate control (i.e., electric air-conditioning compressor) were not considered in the analysis.

Further, the cost reduction opportunities calculated in this analysis are based on the “Mid to Large Size Segment, Passenger Vehicle Seating 4-7 people (Reference Table 1). The developed costs would scale up or down for the remaining vehicle segments based upon vehicle and powertrain size.

Lastly the costs reduction opportunities developed in this analysis are considered net incremental direct manufacturing costs. They are not the complete component/assembly costs, rather only the incremental costs for upgrading a baseline vehicle (i.e., vehicle with a conventional internal combustion engine and automatic transmission) into a P2 hybrid electric vehicle (HEV) with similar performance characteristics. In tables two (2) through six (6) the original net incremental direct manufacturing costs developed for the P2 HEV are presented under the “P2” label. Below the “P2 Mod” label are the updated net incremental direct manufacturing costs with adjustments made for the cost reduction opportunities.

A.3.1 Case

In the initial study, the case was identified as a component requiring up-sizing in order to accommodate the additional size of the electric motor over a typical torque converter configuration. Looking at today’s modular designed units, the functional areas of the transmission (i.e., gear and clutch packages, torque converter, clutch and electric motor/generator packages and optional accessory output drives) are small and compact systems that can be matched as the vehicle platform dictates. Using this design philosophy, a more compact overall transmission package can be made. With this assumption, material volume could be reduced incrementally with the size of the system.

The standard inside dimensional clearance for most torque converters is approximately 320 mm. The ZF HP 948 TE used in the new Jeep Cherokee and other Chrysler and Dodge vehicles (**Image 2**) has approximately 430 mm clearance. The ZF HP 948 TE utilizes this package space for stop-start in that case module. Four (4) individual gearsets

and six (6) shifting elements made it possible to have nine speeds; yet the transmission is compact since the gearsets are transversely nested instead of distributed along the longitudinal axis.

Using a modular design strategy, sizing the torque converter/electric motor and/or start-stop packages will allow them to fit in the same housing. For future transmissions this will provide flexibility to dial-in the approach to powering a hybrid vehicle.



Image 2: ZF 9-Speed Automatic Transmission for Chrysler and Dodge Cars
(Source: <http://www.allpar.com/mopar>)

Table 2: Light-Duty Technology Incremental Cost Analysis, P2 HEV and P2 HEV Case Subsystem (VW Sharan)

01 Transmission System				P2				P2 Mod			
B.1	Case Subsystem				Original Case	€ 94	C	New Case	€ 75		
				B.1.01	Assembly of Case Subsystem	3	C.1.01	Assembly of Case Subsystem	3		
				B.1.02	Transaxle Case	35	C.1.02	Transaxle Case	27		
				B.1.03	Transaxle Housing	46	C.1.03	Transaxle Housing	37		
				B.1.04	Covers	10	C.1.04	Covers	8		

A.3.2 Launch Clutch

The initial P2 transmission had a torque converter as its launch clutch and motor decouple. It was a cost hit to the P2 over the Power-Split. In the reference study, both scenarios' (P2 & P2 Modified) clutches were integrated into the system. As **Image 3** shows, the packaging constraints are visible. Getting a drive plate, clutch pack, and a

motor/generator all in this area is a challenge. It is apparent, however, that both FEV and Bosch have accomplished this task without compromising the package parameters.

Smoothing the transition between electric and gas engine hybrid modes, the clutch that replaced the torque converter was found to be the cause for poor launch. However, by working with the interval time of the clutch, satisfactory launch and shift results can be obtained. Both BorgWarner and Getrag have fully functional wet and dry applications for this system. A cost saver shown in **Table 3** is the dry clutch. Bosch's (IMG) package has been used by the Volkswagen Group for the hybrid versions of the VW Touareg and Porsche Cayenne. Bosch provides the electric motor, the power electronics, dry clutch pack, and the special Motronic control unit, which governs both the electric and the internal combustion engine. The goal is to achieve good response without unpleasant delays or bumpy transitions. Outside of the mechanical issues between dry and wet clutches the fact is that a dry clutch is generally a cost reduction over a conventional wet clutch system. For the P2 cost reduction analysis it was estimated the dry clutch configuration would save an additional 10 euros relative to a wet clutch configuration.

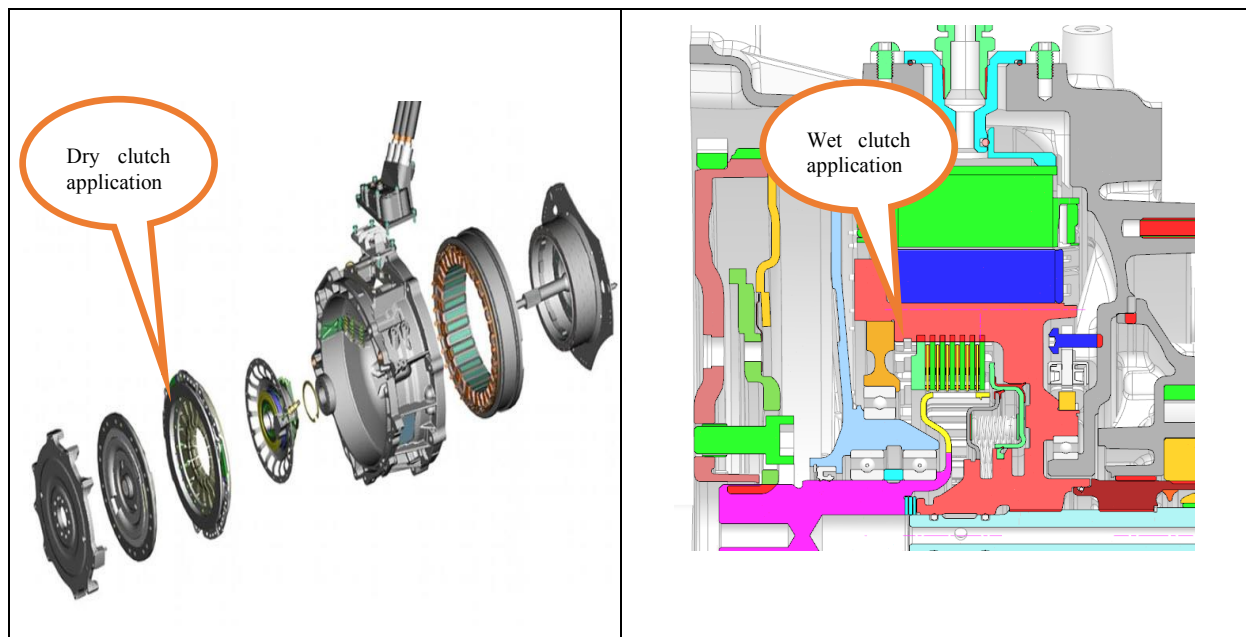


Image 3: FWD P2 Hybrid Transmission Development

(Sources: Bosch IMG [left]; FEV Project [right])

Table 3: Light-Duty Technology Incremental Cost Analysis, P2 HEV and P2 HEV Modified – Launch Clutch System (VW Sharan)

01 Transmission System				P2				P2 Mod			
	B.2	Launch Clutch Subsystem			Wet clutch application	€ 57		Dry clutch application	€ 47		
				B.2.01	Clutch Assembly	18		C.2.01	Clutch Assembly	8	
				B.2.02	Fly Wheel/Flex Plate/Starter Ring	37		C.2.02	Fly Wheel/Flex Plate/Starter Ring	37	
				B.2.03	Snap Rings and Retainers	1		C.2.03	Snap Rings and Retainers	1	
				B.2.08	Sealing Elements	0		C.2.08	Sealing Elements		
				B.2.09	Bearing Elements	0		C.2.09	Bearing Elements	0	
				B.2.10	Trans Assembly of Launch Clutche	1		C.2.10	Trans Assembly of Launch Clutche	1	

A.3.3 Oil Pump and Filter

Most start-stop vehicles in the market today, such as the 2013 Chevy Malibu Eco, have a secondary electric oil pump on the P2 to ensure efficient transmission function. The new ZF 9-speed automatic transmission has no auxiliary oil pump: an accumulator is substituted. Only one (1) friction shift element needs to be closed for restarting, and response times are very fast. The ZF HP 948 TE is a stop-start capable transmission that can be used as a hybrid transmission by replacing the torque converter module with an electric motor module.

Looking at P2s in the marketplace today, it is not necessary to have an auxiliary oil pump (**Image 4**). The use of an accumulator will suffice as in the ZF HP8 (**Image 5**) with less cost. This is a cost reduction for the new P2 design.



Image 4 (Left): Chevy Malibu auxiliary pump
(Source: FEV Library)



Image 5 (Right): ZF Oil Accumulator
(Source: greencarcongress.com)

Table 4: Light-Duty Technology Incremental Cost Analysis P2 HEV and P2 HEV Modified – Oil Pump and Filter (VW Sharan)

01 Transmission System				P2				P2 Mod			
B.3	Oil Pump and Filter Subsystem			Auxiliary Pump System			€ 34	Oil Accumulator System			€ 15
				B.3.01	Oil Pump Assembly		28	C.3.01	Accumulator		13
				B.3.02	Covers		6	C.3.02	Regulator		2
				B.3.03				C.3.03	O-rings		0

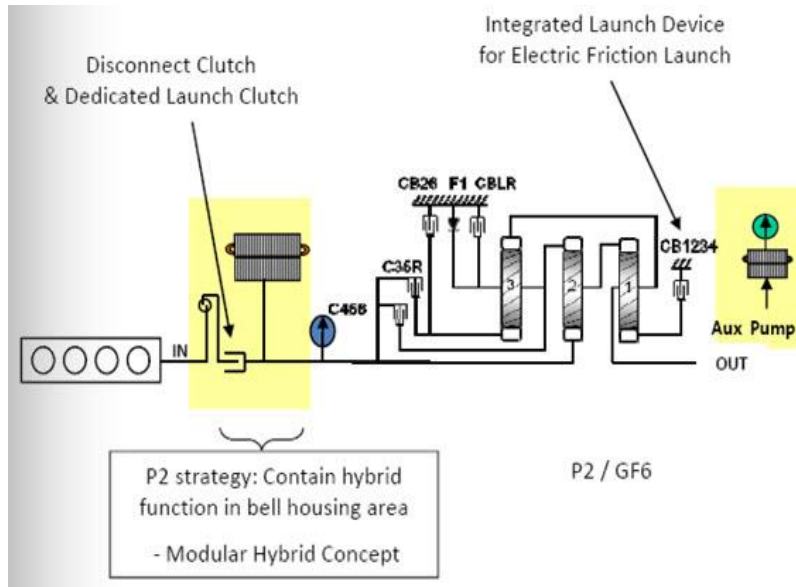
A.3.4 Motor

Motor cost was a developed value and is well within current market prices. Another consideration is that the size and efficiencies of the motors are better than when the initial study was performed. As shown in **Image 6**, the motor configurations are becoming more compact and able to fit into the narrowest of packages.

P2 Hybrid Transmission

This standard P2 arrangement shows an additional clutch integrated between the combustion engine and electric motor.

The hybrid transmission is based on the 6-speed automatic transmission, in which the clutch replaces the torque converter and allows some additional installation space for the integration of the hybrid motor drive system configuration.



(Source: PDL Library)

Motor cost will continue to decrease as hybrids become more popular, helping both scenarios.



Image 7 (Right): Honda Insight IMA
(Source: Wikipedia)

There are many factors driving motor design, size, shape, and material selection for the most efficient system. However, prices will decrease on the package which is used the most. Bosch has a package that is 300 mm in diameter and 145 mm long and delivers 46 hp with 300 Nm torque. This package is being used by Volkswagen Group for the hybrid versions of the VW Touareg and Porsche Cayenne to improve overall performance and economy.

Table 5: Light-Duty Technology Incremental Cost Analysis P2 HEV and P2 HEV Modified – Motor

01 Transmission System				P2 P2 Mod							
	B.3	Traction Motor - Generator Subsystem			Original P2 Motor Generator		€ 129		New P2 Motor Generator		€ 103
				B.4.01	Motor		129	C.4.01	Motor		103

01 Transmission System				P2 P2 Mod			
B.11 Electric Motor/Generator & Clutch Cooling Subsystem		Auxiliary Coolant System		€ 67	Expanded Main Coolant System		€ 37
		B.11.00	Assembly of Cooling Susystem	0	C.11.00	Assembly of Cooling Susystem	0
		B11.01	Water Pump	34	C.11.01	Water Pump addition sizing	34
		B.11.02	Heat Exchanger	25	C.11.02	Heat Exchanger	
		B.11.03	Expansion Tank	6	C.11.03	Expansion Tank	
		B11.04	Pipes, Hosees, Ducting	2	C.11.04	Pipes, Hosees, Ducting	3

A.4 Summary

Since the initial release of the *“Light-Duty Technology Cost Analysis of the Power-Split and P2 HEV”* (Ref: Case Study #0902), some changes that should be considered were found to have taken place.

The industry has adopted a modular design of transmission case systems that helps OEMs dial in the power configuration to their specific needs (i.e., torque convert, stop-start, electric motor, etc.). This design approach, in most scenarios, will help reduce the cost of the case.

Launch clutch systems have also been redesigned to fit smaller package. The efficiencies of dry versus wet clutches were analyzed and cost developed.

The assumption that an auxiliary oil pump is required for an HEV transmission is no longer valid. The use of an accumulator to replace the auxiliary pump reduces cost, improves space conservation, and helps the overall size of the transmission.

Motor packages will continue to get smaller and become more cost-efficient. Motors/generators for 2014 have already gone through a design revolution to fit into future P2 HEV systems.

Cooling systems that are being developed will become more efficient and integrated into the main engine cooling system, helping reduce vehicle weight and cost. Electric pump systems will be incorporated and will handle every need of a vehicle from front to back.

This report’s assumption is that the marketplace will increase the demand for more mileage-efficient automobiles. The number of parallel P2 full hybrids will also increase. All hybrid systems require power electronics and the special Motronic control units that govern both the electric and the internal combustion engine. These costs, however, are a wash between systems. This study found the only pure savings over the last study are the case, launch clutch, coolant motor, and oil pump system changes as previously discussed and shown in **Table 7**.

The calculated additional saving was estimated to be €105/vehicle, representing approximately a 5% (€105/€1947) reduction in net incremental direct manufacturing costs over the last three years from the original P2 analysis. These costs are for a Mid to Large Segment Passenger Vehicle - the developed costs would scale up or down for larger and smaller vehicles. As this analysis only investigated improvements to the Integrated Electric Motor/Generator and Clutch Assembly System, a savings of approximately 14% over the last three years was estimated within the analyzed system (€105/€726).

Table 7: Net Incremental, Direct Manufacturing Costs deference between P2 HEV and P2 Modified HEV

Vehicle Systems		P2				P2 Mod						Delta		
00	Engine System					€ 384						€ 384		
01	Transmission System	B	Integrated Electric Motor/Generator and Clutch Assembly System				€ 726	B	Integrated Electric Motor/Generator and Clutch Assembly System				€ 623	
		B.1	Case Subsystem				94	B.1	Case Subsystem				75	19
		B.2	Launch Clutch Subsystem				57	B.2	Launch Clutch Subsystem				47	9
		B.3	Oil Pump and Filter Subsystem				34	B.3	Oil Pump and Filter Subsystem				15	19
		B.4	Traction Motor - Generator Subsystem				129	B.4	Traction Motor - Generator Subsystem				103	26
		B.5	Passive Power Electronics Component Subsystem (Capacitors, Filters, etc)				64	B.5	Passive Power Electronics Component Subsystem (Capacitors, Filters, etc)				64	-
		B.6	Power Electronics/Inverter & Controls Subsystem				192	B.6	Power Electronics/Inverter & Controls Subsystem				192	-
		B.7	Traction Motor-Generator Sensor Subsystem				29	B.7	Traction Motor-Generator Sensor Subsystem				29	-
		B.8	Internal Electrical Connection Subsystem				33	B.8	Internal Electrical Connection Subsystem				33	-
		B.9	Switch Subsystem				2	B.9	Switch Subsystem				2	-
		B.10	Electrical Housing/Support Structure Subsystem				29	B.10	Electrical Housing/Support Structure Subsystem				29	-
		B.11	Electric Motor/Generator & Clutch Cooling Subsystem				67	B.11	Electric Motor/Generator & Clutch Cooling Subsystem				37	30
		B.12	Other Misc (e.g. brackets, sealing, etc)				3	B.12	Other Misc (e.g. brackets, sealing, etc)				3	-
		B.13	OE Electric Motor/Generator Clutch System Assembly				54	B.13	OE Electric Motor/Generator Clutch System Assembly				54	-
			Transmission - Baseline (Credit)				-60		Transmission - Baseline (Credit)				-60	-
02	Body System					€ 6						€ 6	-	
03	Brake System					€ 174						€ 174	-	
04	Climate Control System					€ 156						€ 156	-	
05	Power Supply System					€ 1,109						€ 1,109	-	
06	Electric Distribution System					€ 159						€ 159	-	
Total						€ 1,947						€ 1,842	€ 105	

(Reference <http://www.epa.gov/otaq/climate/420r10010.pdf>, Case Study #0902)