Plug-In Hybrid Electric Sprinter Van—Final System Design Specification

Phase 1 Prototype Vehicles

Technical Report

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Phase 1 Prototype Vehicles

1008761

Final Report, March 2005

EPRI Project Manager
M. Duvall

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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CITATIONS

This report was prepared by

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

Principal Investigator
M. Duvall

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Plug-In Hybrid Electric Sprinter Van – Final System Design Specification: Phase 1 Prototype Vehicles, EPRI, Palo Alto, CA: 2005. 1008761.

REPORT SUMMARY

In an effort to reduce the emissions, fuel consumption, and operating costs of the DaimlerChrysler Sprinter commercial van while maintaining its functionality and performance, EPRI and DaimlerChrysler have developed a Plug-in Hybrid Electric Vehicle (PHEV) concept for the Sprinter. This report presents the final architecture and system design for vehicles capable of achieving 20 miles (32 km) of operating range in pure electric mode with extended operation between recharging in a charge-sustaining hybrid operating mode that can provide up to 50% higher fuel economy than a conventional Sprinter.

Background
Plug-in hybrid electric vehicles (PHEVs) are “full” hybrids with the additional capability to power the vehicle, either partly or exclusively, from onboard battery energy. At rest, the battery is recharged by plugging the vehicle into a standard electrical outlet. PHEVs have a number of benefits: improved energy efficiency, reduction in the use of petroleum-based fuels, zero-emissions capability in congested or polluted areas, and significant potential for CO_2 reduction. As a result of this operational strategy, the battery for a PHEV experiences a duty cycle that is different from both electric vehicles and power-assist hybrid vehicles.

Objective
To describe the final architecture and system design for a series of prototype plug-in hybrid electric vans based on the DaimlerChrysler Sprinter van.

Approach
The project team prepared specifications for the PHEV Sprinter van including the power train and energy storage systems. Phase 1 of the PHEV Sprinter program will ultimately design and build six prototype vehicles for testing, demonstration, and engineering development. Four of these vehicles will be sent to program participants in the United States for three-year periods of field-testing and fleet demonstration. Two of the vehicles will remain in Germany and be used as developmental prototypes.

Results
The PHEV Sprinter concept is a parallel, pre-transmission hybrid configuration based upon current production Sprinter power train components. The first phase of PHEV Sprinter prototypes will use two different advanced battery chemistries, Nickel Metal Hydride (NiMH) and Lithium Ion (Li Ion). The four Sprinters delivered to the United States will use one of two engines—a 2.3L gasoline engine or a 2.7L diesel engine. All prototype Sprinters will use the same electric drive system, consisting of an electric motor and motor control unit (power inverter and controller). All hybrid Sprinter vehicles will use the same five-speed automatic transmission used in the production Sprinter.

In all, the report describes the specifications for six prototype vehicles. The diversity in the vehicles and power train components—almost every combination of engine and battery choice appears among the first six vehicles—represents a significant engineering challenge but will ultimately provide an extremely important data set for the next phases of development.

EPRI Perspective

It is projected that the utilization of grid electricity combined with the improved efficiency will significantly reduce the greenhouse gas emissions and criteria pollutants produced by the vehicle, especially in dense urban areas. The primary objective of this project is to demonstrate the capability of the PHEV Sprinter concept to provide these environmental benefits while reducing life-cycle operating costs in a typical commercial setting.

Keywords

Plug-in hybrid electric vehicle
Sprinter van
Lithium Ion
Nickel Metal Hydride
Parallel hybrid
System specification

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1 INTRODUCTION AND HYBRID SYSTEM DESCRIPTION

The Dodge Sprinter Van, by DaimlerChrysler, is a multipurpose commercial van designed for a number of diverse tasks. The vehicle is available in a number of configurations for work, cargo, or people transport capabilities, including the panel van shown in Figure 1-1. The Sprinter Van is available in wheelbases of 3,000 mm, 3,550 mm, and 4,025 mm. In the North American market, there are two series of Sprinter Vans, a 2500 with a gross vehicle weight (GVW) rating of 8,550 lbs. and a 3500 with a GVW of 9,900 lbs.

Figure 1-1
DaimlerChrysler Sprinter Van

EPRI and DaimlerChrysler have developed a Plug-in Hybrid Electric Vehicle (PHEV) concept for the Sprinter in an effort to reduce the emissions, fuel consumption, and operating costs of the vehicle while maintaining equivalent or superior functionality and performance. Plug-in hybrid electric vehicles (PHEVs) are “full” hybrids with the additional capability to power the vehicle, either partly or exclusively, from onboard battery energy. At rest, the battery is recharged by plugging the vehicle into a standard electrical outlet. PHEVs have a number of benefits: improved energy efficiency, reduction in the use of petroleum-based fuels, zero-emissions capability in congested or polluted areas, and significant potential for CO_2 reduction. As a result of this operational strategy, the battery for a PHEV experiences a duty cycle that is different from both electric vehicles and power-assist hybrid vehicles.

EPRI and DaimlerChrysler have finalized a hybrid architecture and system design for the Sprinter with the goal of achieving 20 miles (32 km) of operating range in its pure electric mode. The vehicle is also capable of extended operation between recharging by featuring a charge-sustaining hybrid operating mode with up to 50% higher fuel economy than the conventional Sprinter vehicle.

It is projected that the utilization of grid electricity combined with the improved efficiency will significantly reduce the greenhouse gas emissions and criteria pollutants produced by the vehicle, especially in dense urban areas. The primary objective of this project is to demonstrate the capability of the PHEV Sprinter concept to provide these environmental benefits while reducing lifecycle operating costs in a typical commercial setting.

Hybrid Powertrain Design

The PHEV Sprinter concept is a parallel, pre-transmission hybrid configuration based upon current production Sprinter powertrain components. The powertrain layout is shown in Figure 1-2. The combustion engine output shaft (engine crankshaft) is connected to an integrated clutch and electric motor system. The automated clutch engages and disengages the engine as determined by the hybrid control strategy. When engaged, engine output power flows through the electric motor into the input shaft of a five-speed automatic transmission. The electric motor is capable of powering the vehicle in a pure electric mode, but is always active in hybrid mode to provide regenerative braking and power assist. A hybrid system controller schedules engine operation, motor torque, and transmission shifting to optimize performance and efficiency.

Figure 1-3 shows the underbody of the Sprinter Van with the hybrid powertrain installed. The layout is very similar to the production Sprinter, with a slight adjustment of the transmission to the rear of the vehicle to accommodate the electric motor and clutch system. An important design driver for future iterations of electric motor development is to reduce motor length as much as possible to minimize the difference in overall powertrain length and transmission position between conventional and hybrid Sprinters.

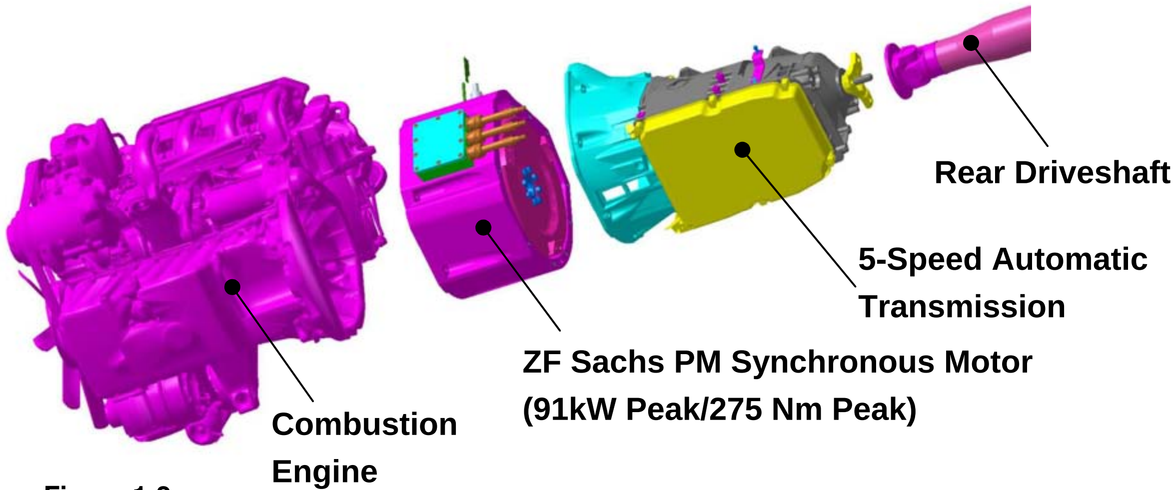

Figure 1-2
Close-Up View of Integrated Parallel Hybrid Powertrain

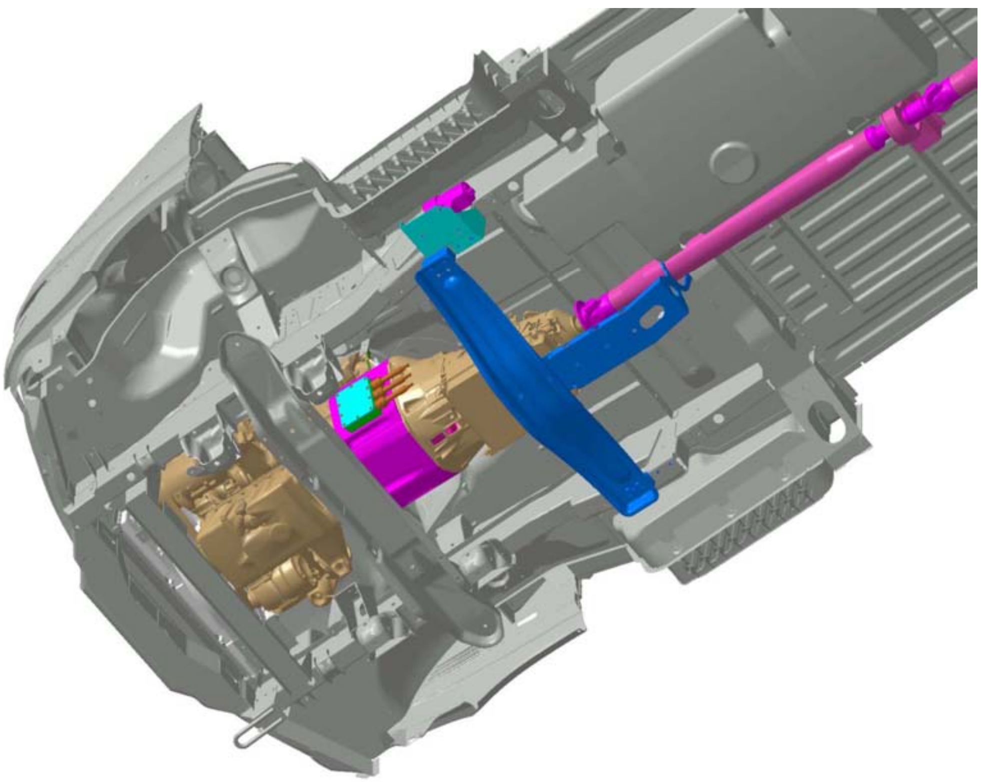

Figure 1-3
Underbody of Sprinter Van with Hybrid Powertrain System Installed

Figure 1-4
ZF Sachs High-Voltage, Permanent Magnet, Synchronous Drive Motor and Motor Control Unit (MCU)

Electric Motor

ZF Sachs developed the electric motor drive system for the Sprinter (Figure 1-5). The motor is a permanent magnet, synchronous machine with a peak power rating of 98 kW and a continuous power rating of 75 kW. The motor is extremely compact to minimize dislocation of other powertrain components. The design has a number of advanced features, including an outer rotor design with a high pole count to produce high torque and smooth operation.

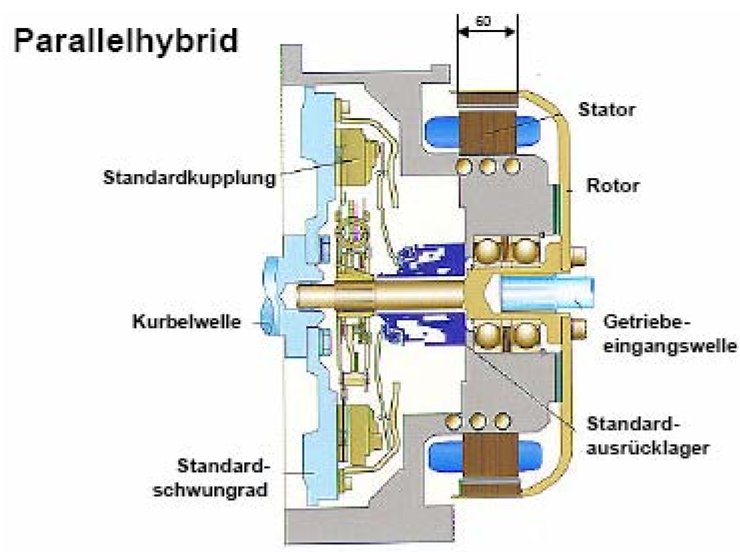

Figure 1-5
Sample Illustration of Electric Motor with Integrated Clutching System

An automatic clutch system is integrated between the combustion engine and electric motor to control the operation of the combustion engine. This clutch can be opened to allow for operation in electric mode or closed to engage the engine for hybrid mode. Figure 1-5 illustrates this concept, and shows the approximate location of the clutch relative to the electric motor.

Energy Storage System

The first phase of PHEV Sprinter prototypes will use two different advanced battery chemistries, Nickel Metal Hydride (NiMH) and Lithium Ion (Li Ion). In addition to the laboratory testing outlined in this document, both battery technologies will be evaluated as part of the Sprinter demonstration program.

Nickel Metal Hydride Battery System

The first battery chosen for the Sprinter was an advanced NiMH system from VARTA. The VARTA battery is packaged in a series of “blocks” containing 40 cells with integrated air cooling and battery management system (BMS). Phase 1 Sprinter prototypes using the VARTA battery will use this modular design for ease of packaging and operation.

The Sprinter NiMH will consist of seven 40-cell blocks for a total of 280 cells and a nominal voltage of 336 VDC. Pack energy is rated at 14.0 kWh with peak power of approximately 70 kW.

The VARTA battery system will be located inside the vehicle for Phase 1, occupying the rear load floor behind the second seating position. The batteries will be covered to allow for use of the cargo area with a slight loss of cargo volume capacity. Future use of this battery in the Sprinter program will require an integrated battery design to reduce this intrusion into the cargo or passenger compartment of the vehicle and to minimize overall battery pack mass and volume burden[1]. In addition, the current VARTA prototypes are metal-cased cells that will be replaced with plastic-case, 4-cell monoblocks after the initial packs are delivered.

VARTA NiMH batteries have been independently tested to 5000 deep cycles to 80% depth-of-discharge (DOD). VARTA has provided a warranty on the prototype cells for between 2000 to 4000 deep cycles, depending on operating temperature. VARTA provides an integrated battery monitoring system (BMS) that tracks pack health and provides instantaneous operating data (available energy and power, battery state-of-charge, etc) via CANbus to the hybrid controller.

[1] Mass burden and volume burden are terms used to characterize the added mass and volume from battery enclosure hardware and structure.

Figure 1-6
VARTA 4-Cell, Plastic-Case, 40 amp-Hour NiMH Module (Below) and Modular Pack System (Above) Based on 32-40 Cell “Blocks”

Lithium Ion Battery System

The second battery for the Sprinter prototypes is a liquid-cooled, medium power lithium ion battery from SAFT. The battery consists of 102 VL41 M cells (17 six-cell modules) integrated into an environmentally sealed underfloor pack located behind the rear axle of the Sprinter. The nominal voltage of lithium ion batteries is much higher the NiMH, at 3.6 to 3.7 VDC, leading to a significantly reduced cell count. Each Li Ion pack has an integrated BMS system to control the battery, including cell equalization and overcharge protection.

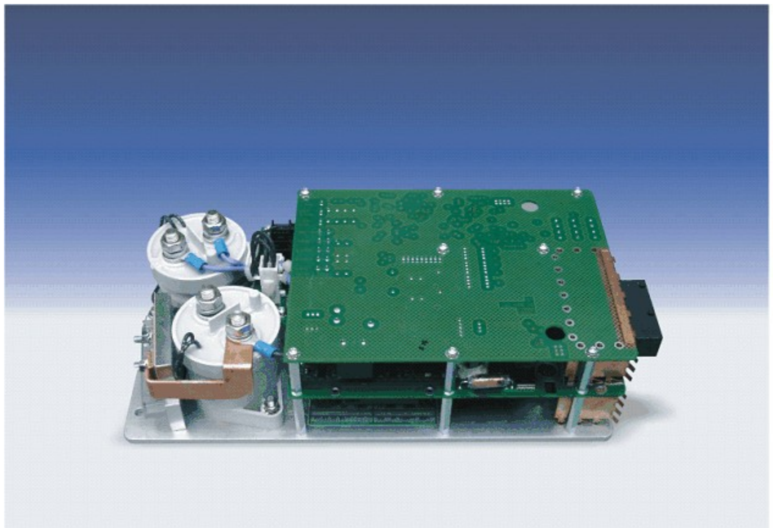

Figure 1-7
Battery Management System for SAFT Li Ion Battery Pack

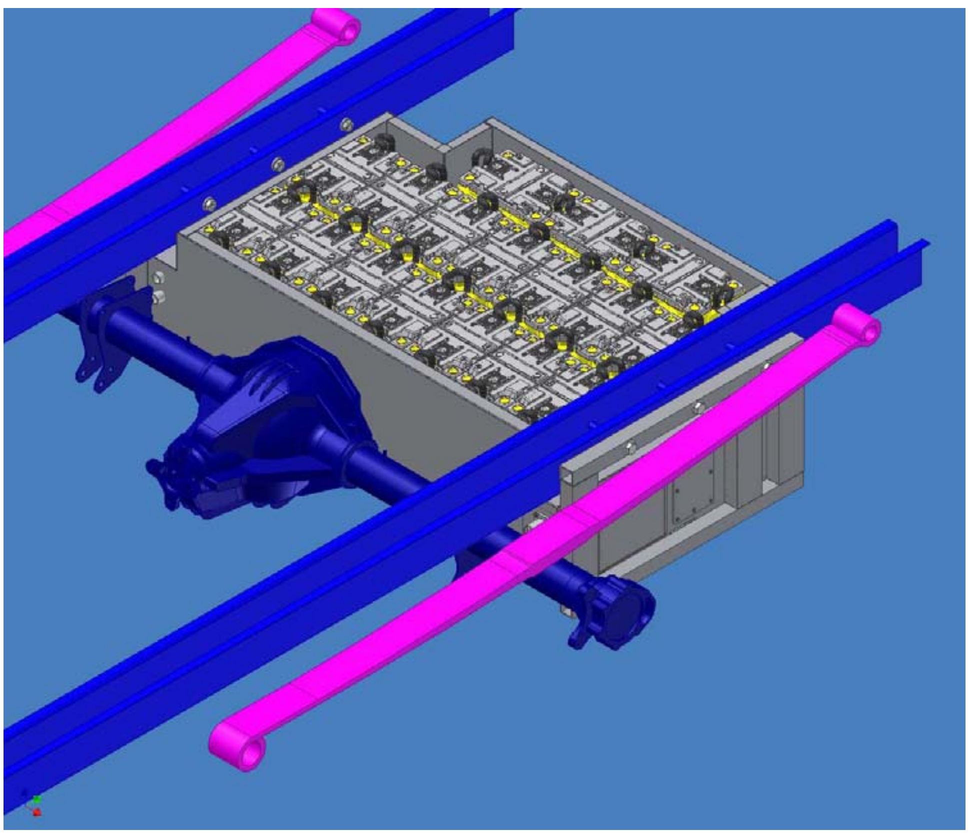

Figure 1-8
SAFT Li Ion Battery Mounted to the Sprinter Frame Behind the Rear Axle

Battery Charger and Charge Station

The charging system for the Sprinter has two components, an on-board charger and an off-board charge station or power supply. The on-board charger is a 3.3 kW Brusa NLG5 that converts an AC input voltage supply to DC power for battery charging. The off-board charge station can be any conductive EVSE (electric vehicle supply equipment) with input voltage range of 100-240 VAC.

The PHEV Sprinter is therefore capable of charging with the most frequent voltages available in the United States, including 120 VAC, 208 VAC, and 240 VAC. It should be noted that power is reduced at lower voltages, and output at 120 VAC is estimated at 1.2 kW.

The first phase of vehicles will be equipped with inlet ports compatible with the AVCON conductive charge coupler. Choice of charge connector is widely considered to be a customer choice and other connectors are under serious consideration.

2
HYBRID SYSTEM SPECIFICATION

Powertrain Component Specifications

The following tables contain the specifications for each major component of the hybrid system for the PHEV Sprinter. The specifications are the result of several months of collaborative design work between the project partners, including EPRI, DaimlerChrysler, and suppliers ZF Sachs, VARTA, and SAFT. These specifications are for the Phase 1 prototype vehicles only, and are subject to alterations or changes over the course of developing these vehicles.

Combustion Engine

The four Sprinters delivered to the United States will use one of two engines—a 2.3L gasoline engine or a 2.7L diesel engine. The diesel engine is currently the only engine certified for use in the Sprinter for the North American market. The gasoline engine, available in Europe, was added by customer request for these experimental vehicles. Two of the first prototypes will remain in Germany as engineering prototypes—these two vehicles will use a 2.2L, four-cylinder diesel engine (OM611) that will not be described in this report.

Table 2-1
Internal Combustion Engine Specifications

Manufacturer	Mercedes-Benz	Mercedes-Benz
Engine Model	M111E	OM647
Fuel Type	Gasoline	Diesel
Engine Type	Spark-Ignition	Compression-Ignition
No. of Cylinders	4/in-line	4/in-line
Bore (mm)	90.9	88.0
Stroke (mm)	88.4	88.3
Displacement (cm^3)	2295	2686
No. of valves	4 per cylinder 2 intake/2 exhaust	4 per cylinder 2 intake/2 exhaust
Aspiration	Natural	VTG Turbocharger
Engine Management	Electronically-controlled fuel injection and ignition	Common Rail Direct Injection (CDI)
Output (kW/hp) at (rpm)	105/143 5000	115/154 3800
Maximum Torque (Nm) at (rpm)	215 3200-4700	330 1600-2400

Transmission

All hybrid Sprinter vehicles will use the same five-speed automatic transmission used in the production Sprinter. Due to the degree of powertrain integration necessary between the electric motor and transmission, development focused on this single transmission.

Table 2-2
Transmission Specifications

Manufacturer	Mercedes-Benz
Type	Automatic
Transmission Model	NAG1
Number of Speeds	5
Shift Control	Electronically-Controlled Shifting
Gear Ratios	3.595, 2.186, 1.405, 1.000, 0.831
Final Drive Ratio	3.72:1

Electric Drive System

All prototype Sprinters will use the same electric drive system, consisting of an electric motor and motor control unit (power inverter and controller). The real-world performance of this system and the operational strategy for the motor will depend on the battery and engine used in a specific vehicle.

Table 2-3
Electric Drive Motor Specifications

Manufacturer		ZF Sachs
Model		SG300D/L80
Type		3 Phase Synchronous Brushless Permanent Magnet
Continuous Power at	(kW) (rpm)	74 4000
Peak power at	(kW) (rpm)	98 (for 180 seconds) 2800
Continuous Torque at	(Nm) (rpm)	240 200
Peak Torque at	(Nm) (rpm)	380 200
Rated Voltage	(VDC)	350
Voltage Range	(VDC)	100 – 430
Maximum Efficiency		92.2%
Coolant		Water with glycol (70/30)
Max. Winding Temp.	(°C)	200 (Current limiting at T > 180°C)
Min. Coolant Flowrate	(L/min)	5
Max. Coolant Pressure	(bar)	3
Max. Inlet Temperature	(°C)	60
Cooling		Glycol/Water

Table 2-4
Electric Motor Control Unit (MCU)

Manufacturer		ZF Sachs
Model		MCU606
Mass	(kg)	20
Input Voltage	(VDC)	100 – 430
Input Current	(Amps)	200
Max. Phase Current	(Amps)	430 (AC RMS Current)
Coolant		Water with glycol (70/30)
Min. Coolant Flowrate	(L/min)	5
Max. Coolant Pressure	(bar)	1
Max. Inlet Temperature	(°C)	60

Battery System

Table 2-5
Battery System Specifications

Manufacturer		SAFT	VARTA Autobatterie GmbH
Battery Chemistry		Lithium Ion	Nickel Metal Hydride
Model		VL41 M	NP40
No. of Cells		102	280
Nominal Voltage	(VDC)	367	336
Cell Capacity	(Ahrs)	41	40
Energy Capacity	(kWh)	15.1	14.0
Peak Power	(kW)	100	70
Package		6-cell module	40-cell block (2 modules)
Module/Block Dimensions	(mm)	190x123x242	507x354x290
Total System Weight	(kg)	180	352
Estimated Cycle Life		2000 (80% DOD)	3000 (80% DOD at 35°C)
Cooling		Liquid	Air BMS-controlled individual electric fans
Battery Monitoring		DC BMS with voltage, current, and temperature sensing	VARTA BMS 5.P with voltage, current and temperature sensing
Charger		3.3 kW Conductive 208-240 VAC Input	3.3 kW Conductive 208-240 VAC Input

3
FINAL SPECIFICATION – PHASE 1 PROTOTYPE VEHICLES

Introduction

Phase 1 of the PHEV Sprinter program will ultimately design and build six prototype vehicles for testing, demonstration, and engineering development. Four of these vehicles will be sent to program participants in the United States for three-year periods of field testing and fleet demonstration. Two of the vehicles will remain in Germany and used as developmental prototypes—one at DaimlerChrysler and one at ZF Sachs, the electric motor supplier.

Table 3-1 describes the primary attributes of the first six prototype vehicles. The diversity in the vehicles and powertrain components—there is almost every combination of engine and battery choice among the first six vehicles—represents a significant engineering challenge but will ultimately provide an extremely important data set for the next phases of development.

Table 3-1
Summary of Primary Vehicle Attributes

Prototype Vehicle	Vehicle Type	Wheelbase	Engine	Battery
ZF Sachs Sprinter	Cargo Van	3,550 mm	4-cyl Diesel	NiMH
California 1 Sprinter	Utility Van	3,550 mm	4-cyl Gasoline	NiMH
California 2 Sprinter	Cargo Van	3,550 mm	4-cyl Gasoline	Li Ion
Kansas City Sprinter	Paratransit Van	4,000 mm	5-cyl Diesel	Li Ion
New York Sprinter	Cargo Van	3,550 mm	5-cyl Diesel	Li Ion
KEN Sprinter	Cargo Van	3,550 mm	4-cyl Diesel	Li Ion

Final Vehicle Specifications

Table 3-2 described the intended use of each vehicle at its demonstration location and the participants for each vehicle.

Table 3-2
Brief Description of Primary Vehicle Purpose

Prototype Vehicle	Intended Use	Participants
ZF Sachs Sprinter	Engineering prototype for second phase motor development at ZF Sachs	ZF Sachs, DaimlerChrysler
California 1 Sprinter	Utility work van for transporting people and equipment	South Coast AQMD, Southern California Edison, EPRI
California 2 Sprinter	Cargo van for delivery demonstrations and equipment transport	South Coast AQMD, Southern California Edison, EPRI
Kansas City Sprinter	Paratransit van operated in public transit revenue service by Kansas City Area Transit Authority	Metropolitan Energy Center, KCATA, Long Island Power Authority, EPRI
New York Sprinter	Cargo van for urban delivery	New York Power Authority, Consolidated Edison, EPRI
KEN Sprinter	Engineering prototype for continued development of hybrid Sprinter concept at DaimlerChrysler.	DaimlerChrysler

Table 3-3 through Table 3-6 list the individual specifications of each of the four PHEV Sprinter prototypes to be demonstrated in the United States. It is important to note that the vehicles are configured for a combination of engineering development and customer requirements. In general, each of the given powertrain options would be capable of serving in each of the applications. The hybrid system, as defined by the electric drive system and transmission is identical in each Sprinter, but there will be significant operational differences due to the variance of choice with regard to the combustion engine or battery.

Table 3-3
Vehicle Specification for California 1 Sprinter Van

Base Vehicle	Dodge Sprinter 2500 Van
Configuration	Utility Van (cargo van with second row bench seat)
Engine	M111E 2.3L Gasoline Engine
Transmission	NAG1-380 5-speed Automatic
Electric Motor	ZF Sachs SG300D, 98 kW
Battery	VARTA NP40 NiMH, 14.0 kWh
Charger	Brusa NLG5 Conductive, 3.3 kW
Wheelbase	3,550 mm[2]
Roof Height	Normal
Overall Length	5,630 mm
Overall Width	1,930 mm
Overall Height	2,360 mm
Interior Volume	9.1 m^3
Gross Vehicle Weight	3,880 kg
Payload (approximate)	1,500 kg
Seating	5 (driver and front passenger seats, second row bench seat)
Wheels	16 inch aluminum
Tires	P225/75 R16
Rear Axle Ratio	3.72
Air Conditioning	Electrically driven A/C compressor
Cabin Heating	Electric heater for EV mode operation
Electric Windows	Yes
Remote Controlled Power Locks	Yes
Auxiliary Components – Power Steering	Electrically-Driven Hydraulic Power Assist
Auxiliary Components – Brake Assist	Electric Vacuum Pump
Auxiliary Components – Low-Voltage Power Supply	DC-DC voltage converter

[2] This specification is different for the Kansas City proof-of-concept vehicle. This vehicle will be a 4,000 mm wheelbase paratransit vehicle with a custom body. The dimensions of this vehicle will be determined by the bodybuilder. All other specifications, as well as the hybrid powertrain system, are the same.

Table 3-4
Vehicle Specification for California 2 Sprinter Van

Base Vehicle	Dodge Sprinter 2500 Van
Configuration	Cargo Van
Engine	M111E 2.3L Gasoline Engine
Transmission	NAG1-380 5-speed Automatic
Electric Motor	ZF Sachs SG300D, 98 kW
Battery	SAFT VL41 M, 15.1 kWh
Charger	Brusa NLG5 Conductive, 3.3 kW
Wheelbase	3,550 mm[3]
Roof Height	Normal
Overall Length	5,630 mm
Overall Width	1,930 mm
Overall Height	2,360 mm
Interior Volume	9.1 m^3
Gross Vehicle Weight	3,880 kg
Payload (approximate)	1,500 kg
Seating	2 (driver and front passenger)
Wheels	16 inch aluminum
Tires	P225/75 R16
Rear Axle Ratio	3.72
Air Conditioning	Electrically driven A/C compressor
Cabin Heating	Electric heater for EV mode operation
Electric Windows	Yes
Remote Controlled Power Locks	Yes
Auxiliary Components – Power Steering	Electrically-Driven Hydraulic Power Assist
Auxiliary Components – Brake Assist	Electric Vacuum Pump
Auxiliary Components – Low-Voltage Power Supply	DC-DC voltage converter

[3] This specification is different for the Kansas City proof-of-concept vehicle. This vehicle will be a 4,000 mm wheelbase paratransit vehicle with a custom body. The dimensions of this vehicle will be determined by the bodybuilder. All other specifications, as well as the hybrid powertrain system, are the same.

Table 3-5
Vehicle Specification for Kansas City Van

Base Vehicle	Dodge Sprinter 2500 Van
Configuration	Paratransit Van – Sprinter passenger van with Braun paratransit body conversion including wheelchair lift, access door, and seating positions
Engine	OM647 2.7L Diesel Engine
Transmission	NAG1-380 5-speed Automatic
Electric Motor	ZF Sachs SG300D, 98 kW
Battery	SAFT VL41 M, 15.1 kWh
Charger	Brusa NLG5 Conductive, 3.3 kW
Wheelbase	4,025 mm[4]
Roof Height	High
Overall Length	6,580 mm
Overall Width	1,930 mm
Overall Height	2,590 mm
Interior Volume	13.4 m^3
Gross Vehicle Weight	3,880 kg
Payload (approximate)	800 kg
Seating	6-10 (driver and front passenger, up to two wheelchair positions with fold-down bench seats when not in use, rear individual seats)
Wheels	16 inch aluminum
Tires	P225/75 R16
Rear Axle Ratio	3.72
Air Conditioning	Electrically driven A/C compressor
Cabin Heating	Electric heater for EV mode operation. Diesel-fired supplemental heater for cold weather
Electric Windows	Yes
Remote Controlled Power Locks	Yes
Auxiliary Components – Power Steering	Electrically-Driven Hydraulic Power Assist
Auxiliary Components – Brake Assist	Electric Vacuum Pump
Auxiliary Components – Low-Voltage Power Supply	DC-DC voltage converter

[4] This specification is different for the Kansas City proof-of-concept vehicle. This vehicle will be a 4,000 mm wheelbase paratransit vehicle with a custom body. The dimensions of this vehicle will be determined by the bodybuilder. All other specifications, as well as the hybrid powertrain system, are the same.

Table 3-6
Vehicle Specification for New York Sprinter

Base Vehicle	Dodge Sprinter 2500 Van
Configuration	Cargo Van
Engine	OM647 2.7L Diesel Engine
Transmission	NAG1-380 5-speed Automatic
Electric Motor	ZF Sachs SG300D, 98 kW
Battery	SAFT VL41 M, 15.1 kWh
Charger	Brusa NLG5 Conductive, 3.3 kW
Wheelbase	3,550 mm[5]
Roof Height	Normal
Overall Length	5,630 mm
Overall Width	1,930 mm
Overall Height	2,360 mm
Interior Volume	9.1 m^3
Gross Vehicle Weight	3,880 kg
Payload (approximate)	1,500 kg
Seating	2 (driver and front passenger)
Wheels	16 inch aluminum
Tires	P225/75 R16
Rear Axle Ratio	3.72
Air Conditioning	Electrically driven A/C compressor
Cabin Heating	Electric heater for EV mode operation. Diesel-fired supplemental heater for cold weather
Electric Windows	Yes
Remote Controlled Power Locks	Yes
Auxiliary Components – Power Steering	Electrically-Driven Hydraulic Power Assist
Auxiliary Components – Brake Assist	Electric Vacuum Pump
Auxiliary Components – Low-Voltage Power Supply	DC-DC voltage converter

[5] This specification is different for the Kansas City proof-of-concept vehicle. This vehicle will be a 4,000 mm wheelbase paratransit vehicle with a custom body. The dimensions of this vehicle will be determined by the bodybuilder. All other specifications, as well as the hybrid powertrain system, are the same.

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