Updated Vehicle Specifications in the GREET Vehicle-Cycle Model

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Background

Alternative transportation fuels and advanced vehicle technologies are being promoted to help reduce local air pollution, greenhouse gas emissions, and the United States' dependence on imported oil. To more accurately and completely evaluate the energy and emissions effects of alternative fuels and vehicle technologies, researchers should consider emissions and energy use from vehicle operations, fuel production processes, and vehicle production processes. This research area is especially important for technologies that employ fuels and materials with distinctly different primary energy sources and production processes, i.e., those for which upstream emissions and energy use can be significantly different.

The GREET (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) model was originally developed to evaluate fuel-cycle (or well-to-wheels) energy use and emissions of various transportation technologies (Wang 1999). In 2006, the GREET vehicle-cycle model was released to examine energy use and emissions of vehicle production and disposal processes (Burnham et al. 2006). This document updates the key vehicle specifications in Burnham et al. (2006) for the latest publically available version, GREET2_2012, of the vehicle-cycle model. In addition to the parameters described in this document, GREET2_2012 includes updated data on production and recycling of lithium-ion batteries, material production of several key vehicle materials, and part manufacturing and vehicle assembly (Dunn et al. 2012; Keoleian et al. 2012; Sullivan et al. 2010).

Vehicle Specifications

The latest version of the Series 2 GREET vehicle-cycle model, GREET2_2012, has been updated to include three vehicle types: a mid-size passenger car, a mid-size sport utility vehicle (SUV), and a full-size pick-up truck (PUT) and five vehicle propulsion technologies: an internal combustion engine vehicle (ICEV) with a spark-ignition (SI) engine, a grid-independent hybrid electric vehicle (HEV) with a SI engine, a plug-in HEV (i.e. grid-connected HEV) with an SI engine, a battery electric vehicle (EV) and a fuel cell vehicle (FCV) with a hybrid configuration. A wide variety of data sources were used to characterize the various vehicle types and propulsion systems. These sources include vehicle tear-down data, various automotive models, personal communications, and literature reviews.

Total Vehicle Weight

The default total vehicle weights listed in Table 1 were estimated separately for conventional and lightweight (LW) vehicles. Selecting appropriate values is very important when comparing different vehicles in GREET 2 because these weights, along with assumptions about component material compositions, are used to determine how much of each material is in each vehicle. For consistency, the conventional vehicles were assumed to have the same total weight as the vehicles in Series 1 GREET fuel-cycle model. We followed this approach because we link the well-to-pump (feedstock and fuel production) and pump-to-wheels (vehicle operation) results of GREET 1 to those in GREET 2 so that the models can be used together. To allow users to accurately conduct life-cycle analysis using GREET 1 and 2, it is important to keep the simulation vehicle consistent across both models.

The weights are not specified explicitly in GREET 1; rather, simulations using Autonomie, which was developed at Argonne, were conducted to calculate the fuel economy of the vehicles included in the model (Moawad et al. 2011). For those simulations, the test vehicle weights are specified because they are crucial to a vehicle's fuel economy. The test vehicle weight is the curb weight plus 300 lb (which represents passengers and cargo). For GREET 2 simulations, vehicle fuel, which is accounted for in the curb weight, is not included in our total vehicle weight, nor is the 300 lb for passengers and cargo. GREET 1 does not include lightweight vehicles, so we used a bottom-up approach to calculate the total vehicle weights for these vehicles. As described in the following paragraph, we aggregated the weights of all vehicle parts to get a total weight, relying on data from several sources, including the Automotive System Cost Model (ASCM) developed by IBIS Associates and Oak Ridge National Laboratory (Das 2004). Then we scaled each conventional vehicle weight from Autonomie by the ratio of the ASCM lightweight vehicle weight to the ASCM conventional vehicle weight to calculate the total weight for the lightweight vehicles in GREET 2.

TABLE 1 Total Vehicle Weight Excluding Fuel (lb)

Vehicle Type	ICEV	HEV	PHEV10	PHEV20[a]	PHEV30	PHEV40	EV	FCV	LW ICEV	LW HEV	LW PHEV10	LW PHEV20[a]	LW PHEV30	LW PHEV40	LW EV	LW FCV
Passenger Car	2,980	3,220	3,240	3,310	3,740	3,850	4,270	3,630	1,820	2,030	2,070	2,120	2,390	2,460	2,680	2,400
Sport Utility Vehicle	3,620	3,960	4,010	4,110	4,630	4,770	5,520	4,590	2,220	2,580	2,660	2,730	3,080	3,170	3,650	3,140
Pick-Up Truck	4,170	4,560	4,640	4,760	5,350	5,510	6,510	5,360	2,750	3,220	3,080	3,430	3,550	3,660	4,800	4,120

[a] PHEV20 is default PHEV used in the model

The total weight of each vehicle is broken down into three major categories: vehicle components, battery, and fluids. The vehicle components category includes eight major systems: body, powertrain, transmission, chassis, electric traction motor, generator, electronic controller, and fuel cell auxiliaries. Each vehicle does not necessarily have all eight systems; an ICEV, for example, only has a body, powertrain, transmission, and chassis. The HEV, PHEV10 (10 mile all-electric range), and PHEV20 in our simulation were modeled as power-split (or series-parallel) hybrids and each has an electronic motor, generator, and controller in addition to an engine. While the PHEV30 and PHEV40 were modeled as series hybrids, they also have the same components as the power-split hybrids. Both the EV and FCV are powered by an electric motor; in addition the FCV was modeled as a hybrid, so it has a battery in conjunction with the fuel cell stack. The battery category includes a lead acid (Pb-Ac) battery to handle the startup and accessory load for each vehicle and, for the HEVs, PHEVs, EVs, and FCVs, the option to use either a nickel metal hydride (Ni-MH) or lithium-ion (Li-ion) battery in the electric-drive system. The fluid category includes engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives.

Depending on how one classifies the pieces of a vehicle, it can have thousands of parts; however, for this analysis, we studied the vehicle at an aggregate level, specifically looking at major systems and components. In order to examine the differences among ICEVs, HEVs, PHEVs, EVs, and FCVs, we broke the vehicle down into 10 major systems (Table 2) and calculated the weight and material composition of each system.

TABLE 2 Vehicle Systems Included in GREET2_2012

System	ICEV	HEV	PHEV	EV	FCV
Body system	✓	✓	✓	✓	✓
Powertrain system	✓	✓	✓	✓	✓
Transmission system	✓	✓	✓	✓	✓
Chassis system	✓	✓	✓	✓	✓
Traction motor		✓	✓	✓	✓
Generator		✓	✓		
Electronic controller		✓	✓	✓	✓
Fuel cell auxiliary system					✓
Batteries	✓	✓	✓	✓	✓
Fluids (excluding fuel)	✓	✓	✓	✓	✓

Definition of Vehicle Components

As stated previously, each vehicle does not necessarily have every system. When collecting data for various vehicles, the specific weights and material compositions often did not correspond perfectly to our definitions. Therefore, we needed a more detailed breakdown of each system in order to place part and subsystem data into the right component category; parts are aggregated into subsystems, and subsystems are aggregated into systems. In GREET2_2012, users do not see parts or subsystems — only systems. Tables 3 through 9 provide definitions, primarily based on the ASCM, for the major parts and subsystems in each component category (i.e., body, powertrain, transmission, chassis, electric-drive, battery, and fluid).

TABLE 3 Body System

Body-in-white	Primary vehicle structure, usually a single-body assembly to which other major components are attached
Body panels	Closure panels and hang-on panels, such as the hood, roof, decklid, doors, quarter panels, and fenders
Front/rear bumpers	Impact bars, energy absorbers, and mounting hardware
Body hardware	Miscellaneous body components
Glass	Front windshield, rear windshield, and door windows
Paint	E-coat, priming, base coats, and clear coats
Exterior trim	Molding, ornaments, bumper cover, air deflectors, ground effects, side trim, mirror assemblies, and nameplates
Body sealers/deadeners	All rubber trim
Exterior lighting	Head lamps, fog lamps, turn signals, side markers, and tail light assemblies
Instrument panel module	Panel structure, knee bolsters and brackets, instrument cluster, exterior surface, console storage, glove box panels, glove box assembly and exterior, and top cover
Trim and insulation	Emergency brake cover, switch panels, ash trays, arm rests, cup holders, headliner assemblies, overhead console assemblies, assist handles, coat hooks, small item overhead storage, pillar trim, sun visors, carpet, padding, insulation, and accessory mats
Door module	Door insulation, trim assemblies, speaker grills, switch panels and handles (door panels are considered as part of the body panels category)
Seating and restraint system	Seat tracks, seat frames, foam, trim, restraints, anchors, head restraints, arm rests, seat belts, tensioners, clips, air bags, and sensor assemblies
Heating, ventilation, air conditioning (HVAC) module	Air flow system, heating system, and air conditioning system (which includes a condenser, fan, heater, ducting, and controls)
Interior electronics	Wiring and controls for interior lighting, instrumentation, and power accessories

TABLE 4 Powertrain System

Engine unit	Engine block, cylinder heads, fuel injection, engine air system, ignition system, alternator, and containers and pumps for the lubrication system
Fuel cell stack	Membrane electrode assembly, bipolar plates, gaskets, current collector, insulator, outer wrap, and tie bolts
Engine fuel storage system	Fuel tank, tank mounting straps, tank shield, insulation, filling piping, and supply piping
Powertrain thermal system	Water pump, radiator, and fan
Exhaust system	Catalytic converter, muffler, heat shields, and exhaust piping
Powertrain electrical system	Control wiring, sensors, switches, and processors
Emission control electronics	Sensors, processors, and engine emission feedback equipment

TABLE 5 Transmission System

Transmission unit	Gearbox, torque converter, and controls
ICEV	Uses an automatic transmission and therefore a torque converter
HEV/PHEV	Uses a type of continuously variable transmission with a planetary gear set and therefore does not have a torque converter
EV/FCV	Weighs approximately one-third less than the HEV transmission and consists of a single-ratio gearbox and no torque converter (Bohn 2005)

TABLE 6 Chassis System

Cradle	Frame assembly, front rails, and underbody extensions, cab and body brackets (the cradle bolts to the BIW and supports the mounting of the engine/fuel cell)
Driveshaft/axle	A propeller shaft, halfshaft, front axle and rear axle (the propeller shaft connects the gearbox to a differential, while the halfshaft connects the wheels to a differential)
Differential	A gear set that transmits energy from the driveshaft to the axles and allows for each of the driving wheels to rotate at different speeds, while supplying them with an equal amount of torque
Corner suspension	Upper and lower control arms, ball joints, springs, shock absorbers, steering knuckle, and stabilizer shaft
Braking system	Hub, disc, bearings, splash shield, and calipers
Wheels	Four main wheels and one spare
Tires	Four main tires and one spare
Steering system	Steering wheel, column, joints, linkages, bushes, housings, and hydraulic-assist equipment
Chassis electrical system	Signals; switches; horn wiring; and the anti-lock braking system wiring, sensors, and processors

TABLE 7 Electric-Drive System

Generator	Power converter that takes mechanical energy from the engine and produces electrical energy to recharge the batteries and power the electric motor for HEVs and PHEVs
Motor	Electric motor used to drive the wheels
Electronic controller (controller/converter)	Power controller/phase inverter system that converts power between the batteries and motor/generators for electric-drive vehicles
Fuel cell auxiliaries	Compressed hydrogen tank system, water supply system, air supply system, cooling system, and piping system

TABLE 8 Battery System

ICEV	Pb-Ac battery to handle the startup and accessory load
HEV/PHEV/EV/FCV	Pb-Ac battery to handle the startup and accessory load and either an Ni-MH or Li-ion battery for use in the electric-drive system

TABLE 9 Fluid System

ICEV/HEV/PHEV	Engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives
EV/FCV	Power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives

Vehicle Component Material Composition and Weight

Our goal was to try to make a fair comparison among the vehicles without compromising the simulated performance of any vehicle. Component sizing calculations completed by Argonne for the ASCM were used to keep the vehicles' simulated performance consistent. ASCM allows users to select various options at a system level, and at a more detailed component level, to build a vehicle. The purpose of the model is to compare the cost of vehicles at the system level. For example, users can determine the cost of replacing a conventional engine system with a fuel cell system in an otherwise identical vehicle or the cost of using lightweight components versus conventional components throughout an ICEV. Our research interest in the ASCM was not for cost analysis, but rather the component weights and materials needed to calculate system costs.

For each component, the ASCM offers various options; for example, users can select bumpers made of sheet steel, roll formed steel, sheet aluminum, extruded aluminum, glass fiber composite, or carbon fiber composite. A weight is associated with each of these components, and the material composition is generally obvious from the name. However, for some components that contain more than one material (e.g., engine, transmission, and motor), the description was not useful in determining the material composition. Therefore, the material compositions of these components were estimated on the basis of (1) personal communications with Roy Muir (U.S Council for Automotive Research/Vehicle Recycling Partnership [USCAR/VRP]), Roy Cuenca (Argonne), and Eric Carlson (TIAX) (Muir 2005; Cuenca 2005; Carlson 2004); (2) vehicle dismantling reports; (3) literature review; and (4) our assumptions. Table 10 lists the material compositions for the vehicle components. The information on battery material composition (Table 11) was collected from three sources: a literature review for Pb-Ac; vehicle dismantling reports for Ni-MH; and Argonne researchers for Li-ion (Dunn et al. 2012).

For the conventional material vehicles the weight of components such as the engine, fuel cell system, and transmission were scaled so that all would meet the same performance requirements. For the lightweight material vehicles, additional components (such as the BIW and various chassis components) were also scaled. In addition, chassis components for the lightweight vehicles were assigned a 25% mass savings for reductions in the weight of other, non-chassis components. For example, a reduction of 100 lb in BIW mass would result in 25 lb of chassis mass reduction; we made this adjustment to compensate for the fact that the chassis needs less mass to support the other components if their mass is reduced. However, because the fuel storage systems are the same in both the conventional and lightweight models, the lightweight models will have a longer driving range; this is also true for the HEVs and PHEVs compared with the ICEVs. Tables 12 through 14 list the weights for the vehicle components of a passenger car, sport utility vehicle, and pick-up truck.

The weight of each component was aggregated with the weights of those in its corresponding system (e.g., body, powertrain, and chassis); this number was then divided by the total weight of all the systems to obtain the percentage weight associated with each system. Those results are listed in Tables 15 through 17. In the GREET 2 model, when a user changes the total vehicle weight, these percentages are used (along with material composition percentages) to determine the weight of each material in the vehicle components category.

After calculating the weight of each component, the data on the material composition of each component can be used to examine aggregate material composition (Tables 18 through 20). These tables show that conventional vehicles contain about 59% to 68% steel, while the lightweight vehicles contain significantly less, 19% to 33%. The lightweight vehicles contain a higher percentage of both aluminum and plastic compared with their conventional counterparts; automakers use these materials primarily to reduce the total weight of the vehicle. The conventional FCV contains advanced composites, which are used in the bipolar plates of the fuel cell stack, while the other conventional vehicles do not. Each lightweight vehicle has an advanced composite body made up of 70% liquid epoxy resin and 30% carbon fiber, while the lightweight FCV again contains additional composites in its fuel cell stack.

TABLE 10 Material Composition of Components

Component	Conventional	Lightweight	Source(s)
Body			
Body-in-white	100% steel	100% carbon fiber composite	ASCM
Body panels	100% steel	100% carbon fiber composite	ASCM
Front/rear bumpers	100% steel	100% carbon fiber composite	ASCM
Body hardware	89.8% plastic 5.3% steel 2.3% rubber 2% copper 0.6% glass	89.8% plastic 5.3% steel 2.3% rubber 2% copper 0.6% glass	Dismantling reports
Weld blanks and fasteners (electronics to body)	50% steel 50% plastic	50% wrought Al 50% plastic	Dismantling reports and our assumptions
Weld blanks and fasteners (other systems to body)	50% steel 50% plastic	50% wrought Al 50% plastic	Dismantling reports and our assumptions
Glass	100% glass	100% glass	ASCM
Exterior			
Paint	100% paint	100% paint	ASCM
Exterior trim	93.6% plastic 4.3% steel 1.5% rubber 0.6% organic	93.6% plastic 4.3% steel 1.5% rubber 0.6% organic	Dismantling reports
Sealers/deadeners	100% rubber	100% rubber	ASCM
Exterior electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Interior			
Instrument panel	46% steel 47% plastic 4% organic 1% wrought Al 1% rubber 1% magnesium	47% plastic 29% steel 19% magnesium 4% organic 1% wrought Al	Dismantling reports
Trim & insulation	67.2% plastic 29.5% steel 3.2% organic 0.1% wrought Al	67.2% plastic 29.6% wrought Al 3.2% organic	Dismantling reports

TABLE 10 (Cont.)

Component	Conventional	Lightweight	Source(s)
Interiors (Cont.)			
Door modules	65.3% plastic 32.6% organic 1.8% steel 0.3% glass	65.3% plastic 32.6% organic 1.8% steel 0.3% glass	Dismantling reports
Seating & restraint	58% steel 39% plastic 3% organic	42% steel 39% plastic 16% wrought Al 3% organic	Dismantling reports
HVAC	56.2% steel 21.5% wrought Al 16.7% copper 2.4% plastic 2% rubber 0.5% zinc 0.7% other	56.2% steel 21.5% wrought Al 16.7% copper 2.4% plastic 2% rubber 0.5% zinc 0.7% other	Dismantling reports
Interior electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Weld blanks and fasteners (interior to body)	50% steel 50% plastic	50% wrought Al 50% Plastic	Dismantling reports and our assumptions
Powertrain			
Engine	50% cast iron 30% cast Al 10% steel 4.5% plastic 4.5% rubber 1% copper	42% cast Al 27.3% steel 12.6% cast iron 8.4% stainless steel 4.2% rubber 4.2% plastic 1.3% copper	Conventional: Muir 2005 and our assumptions Lightweight: Cuenca 2005 and our assumptions
Fuel cell stack	62.8% carbon fiber composite 23.2% wrought Al 5.4% PFSA[a] 5.0% carbon paper 1.5% steel 1.4% PTFE[a] 0.6% carbon/PFSA[a] suspension 0.1% platinum	62.8% carbon fiber composite 23.2% wrought Al 5.4% PFSA[a] 5.0% carbon paper 1.5% steel 1.4% PTFE[a] 0.6% carbon/PFSA[a] suspension 0.1% platinum	Cooper 2004
Engine fuel storage system	100% steel	100% steel	Cuenca 2005
Powertrain thermal	50% steel 50% plastic	50% steel 50% plastic	Dismantling reports and our assumptions

TABLE 10 (Cont.)

Component	Conventional	Lightweight	Source(s)
Powertrain (Cont.)			
Exhaust	99.985% steel 0.015% platinum	99.985% steel 0.015% platinum	Cuenca 2005 and our assumptions
Powertrain electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Emission control electronics	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Weld blanks and fasteners (powertrain to body)	100% steel	100% wrought Al	Dismantling reports and our assumptions
Transmission (ICEV)	30% steel 30% wrought Al 30% cast iron 5% plastic 5% rubber	30% steel 30% wrought Al 30% cast Al 5% plastic 5% rubber	Muir 2005 and our assumptions
Transmission (HEV/FCV)	60.5% steel 20% wrought Al 19% copper 0.3% organic 0.2% plastic	60.5% steel 20% wrought Al 19% copper 0.3% organic 0.2% plastic	Dismantling reports
Chassis			
Cradle	100% steel	100% glass fiber composite	ASCM
Driveshaft/axle	100% steel	100% cast Al	ASCM
Differential	100% steel	100% steel	ASCM
Corner suspension	100% steel	100% cast Al	ASCM
Braking system	60% iron 35% steel 5% friction material	60% iron 35% steel 5% friction material	Cuenca 2005
Wheels	100% steel	100% cast Al	ASCM
Tires	67% rubber 33% steel	67% rubber 33% steel	Muir 2005 and our assumptions
Steering system	80% steel 15% wrought Al 5% rubber	80% steel 15% wrought Al 5% rubber	Cuenca 2005
Chassis electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Weld blanks and fasteners (chassis to body)	100% steel	100% wrought Al	Dismantling reports and our assumptions

TABLE 10 (Cont.)

Component	Conventional	Lightweight	Source(s)
Chassis (Cont.)			
Generator	36.1% steel 36.1% cast Al 27.3% copper	36.1% steel 36.1% cast Al 27.3% copper	Dismantling reports
Motor	36.1% steel 36.1% cast Al 27.8% copper	36.1% steel 36.1% cast Al 27.8% copper	Dismantling reports
Controller/inverter	5.0% steel 47.0% cast Al 8.2% copper 3.7% rubber 23.8% plastic 12.3% organic	5.0% steel 47.0% cast Al 8.2% copper 3.7% rubber 23.8% plastic 12.3% organic	Dismantling reports
Fuel cell auxiliaries (includes H_2 fuel storage)	36.8% steel 25.7% carbon fiber composite 16.7% wrought Al 9.6% copper 8.7% plastic 1.5% rubber 0.5% nickel 0.5% other	36.8% steel 25.7% carbon fiber composite 16.7% wrought Al 9.6% copper 8.7% plastic 1.5% rubber 0.5% nickel 0.5% other	Cooper 2004 and Carlson 2004

[a] PFSA = perfluorosulfonic acid; PTFE = polytetrafluoroethylene.

TABLE 11 Material Composition of Batteries

Battery Type					
Pb-Ac	Ni-MH	Li-Ion (HEV)	Li-Ion (PHEV)	Li-Ion (EV)	Sources
69.0% lead	28.2% nickel	27.0% $LiMn_2O_4$	27.8% $LiMn_2O_4$	33.4% $LiMn_2O_4$	Argonne National Laboratory et al. 1998, dismantling reports, Dunn et al. 2012 and our assumptions
14.1% water	23.7% steel	23.7% wrought Al	22.9% wrought Al	19.1% wrought Al	
7.9% sulfuric acid	22.5% plastic	13.2% copper	14.8% copper	14.6% graphite/carbon	
6.1% plastic	12.0% iron	12.2% graphite/carbon	12.2% graphite/carbon	10.9% copper	
2.1% fiberglass	6.3% rare earth metals	4.5% plastic	4.9% ethylene carbonate	5.3% ethylene carbonate	
0.8% other	3.9% copper	4.4% ethylene carbonate	4.9% dimethyl carbonate	5.3% dimethyl carbonate	
	1.8% cobalt	4.4% dimethyl carbonate	4.3% plastic	3.2% plastic	
	1.0% magnesium	2.8% steel	2.1% binder	2.5% binder	
	0.5% wrought Al	2.3% glycol	1.9% steel	1.8% $LiPF_6$	
	0.1% rubber	2.1% binder	1.7% $LiPF_6$	1.4% steel	
		1.5% $LiPF_6$	1.3% glycol	1.2% electronic parts	
		1.5% electronic parts	0.9% electronic parts	1.0% glycol	
		0.4% thermal insulation	0.3% thermal insulation	0.3% thermal insulation	

TABLE 12 Passenger Car Component Weights (lb)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Body											
BIW	551	551	551	551	551	185	205	223	242	238	ASCM
Body panels	176	176	176	176	176	88	88	88	88	88	ASCM
Front/rear bumpers	22	22	22	22	22	5	5	5	5	5	ASCM
Body hardware	22	22	22	22	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (electronics to body)	22	22	22	22	22	10	10	10	10	10	ASCM
Weld blanks and fasteners (other systems to body)	22	22	22	22	22	10	10	10	10	10	ASCM
Glass	88	88	88	88	88	56	56	56	56	56	ASCM
Exterior											
Paint	26	26	26	26	26	13	13	13	13	13	ASCM
Exterior trim	22	22	22	22	22	9	9	9	9	9	ASCM
Sealers/deadeners	4	4	4	4	4	4	4	4	4	4	ASCM
Exterior electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Interior											
Instrument panel	53	53	53	53	53	35	35	35	35	35	ASCM
Trim & insulation	49	49	49	49	49	36	36	36	36	36	ASCM
Door modules	55	55	55	55	55	55	55	55	55	55	ASCM
Seating & restraint	132	132	132	132	132	103	103	103	103	103	ASCM
HVAC	44	44	44	44	44	44	44	44	44	44	ASCM
Interior electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (interior to body)	22	22	22	22	22	10	10	10	10	10	ASCM

TABLE 12 Passenger Car Component Weights (lb) (Cont.)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Powertrain											
Engine	450	243	209			240	151	130			ASCM and Moawad et al. 2011
Fuel cell stack					226					174	ASCM and Cooper 2004
Engine fuel storage system	119	119	119			119	119	119			ASCM
Powertrain thermal	53	32	27			53	32	27			ASCM
Exhaust	99	64	55			99	64	55			ASCM
Powertrain electrical	22	22	22	22		22	22	22	22		ASCM
Emission control electronics	22	4	4			22	4	4			ASCM
Weld blanks and fasteners (powertrain to body)	22	22	22	22		10	10	10	10		ASCM
Transmission	193	214	214	83	83	123	146	146	59	59	ASCM

TABLE 12 Passenger Car Component Weights (lb) (Cont.)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Chassis											
Cradle	66	66	66	66	66	33	36	38	41	41	ASCM
Driveshaft/axle	163	163	163	163	163	49	65	73	79	78	ASCM
Differential	55	55	55	55	55	54	55	55	55	55	ASCM
Corner suspension	90	90	90	90	90	41	44	48	51	50	ASCM
Braking system	84	84	84	84	84	61	66	71	76	75	ASCM
Wheels (4.5); spare = 0.5	91	91	91	91	91	38	38	38	38	38	ASCM
Tires (4.5); spare = 0.5	90	90	90	90	90	90	90	90	90	90	ASCM
Steering system	49	49	49	49	49	25	29	33	37	36	ASCM
Chassis electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (chassis to body)	22	22	22	22	22	10	10	10	10	10	ASCM
Generator		61	61				37	37			ASCM and dismantling reports
Motor		61	61	169	122		37	37	120	81	ASCM, dismantling reports, and Moawad et al. 2011
Controller/inverter		54	54	149	107		33	33	106	71	ASCM, dismantling reports, and Moawad et al. 2011
Fuel cell auxiliaries					546					421	ASCM, Carlson 2004, and Cooper 2004

[a] PHEV20 is default PHEV used in the model

TABLE 13 Sport Utility Vehicle Component Weights (lb)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Body											
BIW	860	860	860	860	860	301	344	379	412	387	ASCM
Body panels	192	192	192	192	192	96	96	96	96	96	ASCM
Front/rear bumpers	31	31	31	31	31	8	8	8	8	8	ASCM
Body hardware	36	36	36	36	36	36	36	36	36	36	ASCM
Weld blanks and fasteners (electronics to body)	29	29	29	29	29	15	15	15	15	15	ASCM
Weld blanks and fasteners (other systems to body)	29	29	29	29	29	15	15	15	15	15	ASCM
Glass	146	146	146	146	146	97	97	97	97	97	ASCM
Exterior											
Paint	32	32	32	32	32	16	16	16	16	16	ASCM
Exterior trim	27	27	27	27	27	12	12	12	12	12	ASCM
Sealers/deadeners	26	26	26	26	26	26	26	26	26	26	ASCM
Exterior electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Interior											
Instrument panel	53	53	53	53	53	35	35	35	35	35	ASCM
Trim & insulation	70	70	70	70	70	53	53	53	53	53	ASCM
Door modules	73	73	73	73	73	73	73	73	73	73	ASCM
Seating & restraint	159	159	159	159	159	127	127	127	127	127	ASCM
HVAC	51	51	51	51	51	51	51	51	51	51	ASCM
Interior electrical	26	26	26	26	26	26	26	26	26	26	ASCM
Weld blanks and fasteners (interior to body)	29	29	29	29	29	15	15	15	15	15	ASCM

TABLE 13 Sport Utility Vehicle Component Weights (lb) (Cont.)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Powertrain											
Engine	713	378	306			362	220	178			ASCM and Moawad et al. 2011
Fuel cell stack					326					255	ASCM and Cooper 2004
Engine fuel storage system	212	212	212			212	212	212			ASCM
Powertrain thermal	86	49	41			86	49	41			ASCM
Exhaust	119	75	66			119	75	66			ASCM
Powertrain electrical	33	33	33	33		33	33	33	33		ASCM
Emission control electronics	35	4	4			35	4	4			ASCM
Weld blanks and fasteners (powertrain to body)	29	29	29	29		15	15	15	15		ASCM
Transmission	240	321	321	124	124	158	223	223	90	90	ASCM

TABLE 13 Sport Utility Vehicle Component Weights (lb) (Cont.)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Chassis											
Cradle	66	66	66	66	66	49	55	60	64	61	ASCM
Driveshaft/axle	307	307	307	307	307	102	153	157	164	159	ASCM
Differential	61	61	61	61	61	67	73	74	73	73	ASCM
Corner suspension	262	262	262	262	262	146	165	181	194	184	ASCM
Braking system	164	164	164	164	164	110	123	133	142	135	ASCM
Wheels (4.5); spare = 0.5	136	136	136	136	136	57	57	57	57	57	ASCM
Tires (4.5); spare = 0.5	135	135	135	135	135	135	135	135	135	135	ASCM
Steering system	82	82	82	82	82	40	50	58	64	60	ASCM
Chassis electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (chassis to body)	29	29	29	29	29	15	15	15	15	15	ASCM
Generator		94	94				60	60			ASCM and dismantling reports
Motor		94	94	272	188		60	60	200	136	ASCM, dismantling reports, and Moawad et al. 2011
Controller/inverter		83	83	240	165		53	53	177	119	ASCM, dismantling reports, and Moawad et al. 2011
Fuel cell auxiliaries					788					616	ASCM, Carlson 2004, and Cooper 2004

TABLE 14 Pick-Up Truck Component Weights (lb)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Body											
BIW	741	741	741	741	741	259	296	326	356	333	ASCM
Body panels	134	134	134	134	134	67	67	67	67	67	ASCM
Front/rear bumpers	44	44	44	44	44	11	11	11	11	11	ASCM
Body hardware	29	29	29	29	29	29	29	29	29	29	ASCM
Weld blanks and fasteners (electronics to body)	23	23	23	23	23	11	11	11	11	11	ASCM
Weld blanks and fasteners (other systems to body)	23	23	23	23	23	11	11	11	11	11	ASCM
Glass	115	115	115	115	115	76	76	76	76	76	ASCM
Exterior											
Paint	32	32	32	32	32	16	16	16	16	16	ASCM
Exterior trim	26	26	26	26	26	12	12	12	12	12	ASCM
Sealers/deadeners	22	22	22	22	22	22	22	22	22	22	ASCM
Exterior electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Interior											
Instrument panel	53	53	53	53	53	35	35	35	35	35	ASCM
Trim & insulation	63	63	63	63	63	47	47	47	47	47	ASCM
Door modules	49	49	49	49	49	49	49	49	49	49	ASCM
Seating & restraint	90	90	90	90	90	72	72	72	72	72	ASCM
HVAC	34	34	34	34	34	34	34	34	34	34	ASCM
Interior electrical	17	17	17	17	17	17	17	17	17	17	ASCM
Weld blanks and fasteners (interior to body)	23	23	23	23	23	11	11	11	11	11	ASCM

TABLE 14 Pick-Up Truck Component Weights (lb) (Cont.)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Powertrain											
Engine	699	378	302			277	170	136			ASCM and Moawad et al. 2011
Fuel cell stack					323					278	ASCM and Cooper 2004
Engine fuel storage system	251	251	251			251	251	251			ASCM
Powertrain thermal	107	79	64			107	79	64			ASCM
Exhaust	154	115	95			154	115	95			ASCM
Powertrain electrical	30	30	30	30		30	30	30	30		ASCM
Emission control electronics	35	4	4			35	4	4			ASCM
Weld blanks and fasteners (powertrain to body)	23	23	23	23		15	15	15	15		ASCM
Transmission	294	312	312	119	119	211	237	237	97	97	ASCM

TABLE 14 Pick-Up Truck Component Weights (lb) (Cont.)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV	Source(s)
Chassis											
Cradle	66	66	66	66	66	49	55	60	64	61	ASCM
Driveshaft/axle	307	307	307	307	307	102	153	157	164	159	ASCM
Differential	61	61	61	61	61	67	73	74	73	73	ASCM
Corner suspension	262	262	262	262	262	146	165	181	194	184	ASCM
Braking system	164	164	164	164	164	110	123	133	142	135	ASCM
Wheels (4.5); spare = 0.5	136	136	136	136	136	57	57	57	57	57	ASCM
Tires (4.5); spare = 0.5	135	135	135	135	135	135	135	135	135	135	ASCM
Steering system	82	82	82	82	82	40	50	58	64	60	ASCM
Chassis electrical	22	22	22	22	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (chassis to body)	29	29	29	29	29	15	15	15	15	15	ASCM
Generator		94	94				60	60			ASCM and dismantling reports
Motor		94	94	272	188		60	60	200	136	ASCM, dismantling reports, and Moawad et al. 2011
Controller/inverter		83	83	240	165		53	53	177	119	ASCM, dismantling reports, and Moawad et al. 2011
Fuel cell auxiliaries					788					616	ASCM, Carlson 2004, and Cooper 2004

TABLE 15 Passenger Car Component Weight Breakdown (%)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV
Body	44.1	45.3	46.2	53.5	44.7	39.6	40.3	41.2	49.1	40.0
Powertrain	25.7	17.0	15.6	1.7	6.5	30.7	21.6	19.7	2.0	7.7
Transmission	6.3	7.2	7.3	3.3	2.6	6.7	7.8	7.8	3.6	2.8
Chassis	23.9	24.5	24.9	28.9	23.1	23.0	24.5	25.6	31.2	23.7
Traction motor	0.0	2.1	2.1	6.7	3.9	0.0	2.0	2.0	7.5	3.0
Generator	0.0	2.1	2.1	0.0	0.0	0.0	2.0	2.0	0.0	0.0
Controller/inverter	0.0	1.8	1.8	5.9	3.4	0.0	1.8	1.7	6.6	3.4
Fuel cell auxiliaries	0.0	0.0	0.0	0.0	15.8	0.0	0.0	0.0	0.0	18.5

TABLE 16 Sport Utility Vehicle Component Weight Breakdown (%)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV
Body	40.9	41.8	42.6	49.1	37.8	36.8	36.5	37.6	44.0	32.1
Powertrain	26.5	17.2	15.6	1.6	7.5	30.9	20.8	18.7	1.8	8.6
Transmission	5.2	7.1	7.2	3.2	2.6	5.7	7.6	7.6	3.5	2.8
Chassis	27.4	27.9	28.5	32.8	26.6	26.6	29.1	30.3	36.1	27.9
Traction motor	0.0	2.1	2.1	7.1	4.0	0.0	2.1	2.0	7.8	4.2
Generator	0.0	2.1	2.1	0.0	0.0	0.0	2.1	2.0	0.0	0.0
Controller/inverter	0.0	1.8	1.9	6.2	3.5	0.0	1.8	1.8	6.8	3.7
Fuel cell auxiliaries	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	0.0	20.7

TABLE 17 Pick-Up Truck Component Weight Breakdown (%)

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV
Body	35.1	36.3	37.3	44.7	39.3	28.2	28.3	29.3	34.1	30.6
Powertrain	29.7	20.8	18.6	1.5	6.3	30.5	22.4	20.0	1.7	7.1
Transmission	6.7	7.4	7.5	3.5	2.7	7.4	8.0	8.0	3.7	2.9
Chassis	28.5	29.5	30.3	36.3	28.8	33.9	35.2	36.7	45.0	33.2
Traction motor	0.0	2.1	2.2	7.4	4.1	0.0	2.1	2.1	8.3	4.9
Generator	0.0	2.1	2.2	0.0	0.0	0.0	2.1	2.1	0.0	0.0
Controller/inverter	0.0	1.8	1.9	6.6	3.6	0.0	1.9	1.8	7.2	4.3
Fuel cell auxiliaries	0.0	0.0	0.0	0.0	15.2	0.0	0.0	0.0	0.0	17.0

TABLE 18 Passenger Car Material Composition Aggregated by Component (% by weight)[a]

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV
Steel	62.3	65.7	66.3	66.4	59.0	31.7	32.2	31.4	21.0	22.5
Stainless steel	0.0	0.0	0.0	0.0	0.0	1.1	0.7	0.6	0.0	0.0
Cast iron	10.9	5.8	5.3	2.0	1.6	3.6	3.1	3.1	2.9	2.2
Wrought aluminum	2.2	1.8	1.8	1.0	5.0	6.7	6.2	5.4	5.2	9.3
Cast aluminum	4.6	5.1	4.7	5.5	3.2	14.6	13.8	13.9	16.6	11.2
Copper/brass	1.9	4.3	4.3	4.7	4.5	3.1	5.3	5.3	6.1	5.4
Magnesium	0.02	0.02	0.02	0.02	0.02	0.4	0.4	0.4	0.4	0.4
Glass	2.9	2.9	3.0	3.5	2.9	3.0	3.0	3.0	3.5	2.9
Average plastic	11.1	10.5	10.6	12.1	10.7	13.8	12.4	13.0	14.9	11.8
Rubber	2.3	1.7	1.7	1.8	1.6	2.9	2.4	2.4	2.6	2.2
CFRP[b]	0.0	0.0	0.0	0.0	8.1	15.1	16.0	17.0	20.9	26.5
GFRP[b]	0.0	0.0	0.0	0.0	0.0	1.8	1.9	2.0	2.6	1.9
Nickel	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
PFSA[b]	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.4
Carbon paper	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.4
PTFE[b]	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
Carbon and PFSA suspension	0.0	0.0	0.0	0.0	0.04	0.0	0.0	0.0	0.0	0.05
Platinum	0.0005	0.0003	0.0003	0.0	0.006	0.0009	0.0004	0.0004	0.0	0.007
Others	1.9	2.2	2.2	3.0	2.4	2.1	2.4	2.5	3.3	2.6

[a] Batteries excluded.

[b] CFRP = carbon fiber-reinforced plastic; GFRP = glass fiber-reinforced plastic; PFSA = perfluorosulfonic acid; PTFE = polytetrafluoroethylene.

TABLE 19 Sport Utility Vehicle Material Composition Aggregated by Component (% by weight)[a]

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV
Steel	63.1	66.6	67.4	67.1	58.5	30.3	30.6	29.9	19.3	21.9
Stainless steel	0.0	0.0	0.0	0.0	0.0	1.1	0.6	0.5	0.0	0.0
Cast iron	11.4	6.3	5.8	2.6	2.1	4.0	3.5	3.5	3.3	2.5
Wrought aluminum	1.8	1.7	1.7	0.9	5.5	5.3	4.9	4.9	4.5	8.4
Cast aluminum	4.9	5.1	4.8	5.8	3.4	18.3	18.7	18.6	22.5	15.9
Copper/brass	1.6	3.9	3.9	4.4	4.4	2.5	4.7	4.6	5.4	5.1
Magnesium	0.01	0.01	0.01	0.01	0.01	0.3	0.2	0.2	0.3	0.2
Glass	3.1	3.2	3.3	3.8	2.9	3.5	3.4	3.3	3.8	2.8
Average plastic	9.8	9.0	9.0	10.4	8.9	13.0	11.2	10.9	12.3	10.2
Rubber	2.7	2.2	2.2	2.3	2.0	3.5	3.0	2.9	3.2	2.8
CFRP[b]	0.0	0.0	0.0	0.0	9.3	14.6	15.3	16.5	20.0	24.9
GFRP[b]	0.0	0.0	0.0	0.0	0.0	1.8	1.9	2.1	2.5	1.9
Nickel	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
PFSA[b]	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.5
Carbon paper	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.4
PTFE[b]	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
Carbon and PFSA suspension	0.0	0.0	0.0	0.0	0.04	0.0	0.0	0.0	0.0	0.05
Platinum	0.0003	0.0002	0.0002	0.0	0.007	0.0006	0.0004	0.0004	0.0	0.008
Others	1.6	1.9	1.9	2.7	2.0	1.9	2.1	2.1	2.9	2.2

[a] Batteries excluded.

[b] CFRP = carbon fiber-reinforced plastic; GFRP = glass fiber-reinforced plastic; PFSA = perfluorosulfonic acid; PTFE = polytetrafluoroethylene.

TABLE 20 Pick-Up Truck Material Composition Aggregated by Component (% by weight)[a]

Component	ICEV	HEV	PHEV	EV	FCV	LW ICEV	LW HEV	LW PHEV	LW EV	LW FCV
Steel	63.4	67.5	68.4	67.8	60.9	31.8	32.7	31.7	19.2	20.6
Stainless steel	0.0	0.0	0.0	0.0	0.0	0.8	0.5	0.4	0.0	0.0
Cast iron	12.3	6.8	6.0	2.9	2.3	3.9	3.6	3.7	4.1	2.9
Wrought aluminum	2.2	1.7	1.7	0.9	4.7	5.0	4.3	4.3	3.7	7.3
Cast aluminum	5.0	5.2	4.9	6.0	3.3	23.9	23.3	23.5	29.7	21.1
Copper/brass	1.5	3.9	4.0	4.5	4.2	2.2	4.4	4.4	5.3	4.9
Magnesium	0.01	0.01	0.01	0.01	0.01	0.2	0.2	0.2	0.3	0.2
Glass	2.6	2.7	2.8	3.4	2.9	2.7	2.6	2.6	2.9	2.7
Average plastic	9.0	8.2	8.2	9.5	8.6	11.0	9.4	9.1	9.9	9.4
Rubber	2.7	2.2	2.2	2.3	2.1	3.3	2.8	2.7	3.1	2.7
CFRP[b]	0.0	0.0	0.0	0.0	7.8	11.8	12.6	13.6	16.4	23.2
GFRP[b]	0.0	0.0	0.0	0.0	0.0	1.8	1.9	2.1	2.7	1.9
Nickel	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
PFSA[b]	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.4
Carbon paper	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.4
PTFE[b]	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
Carbon and PFSA suspension	0.0	0.0	0.0	0.0	0.04	0.0	0.0	0.0	0.0	0.04
Platinum	0.0006	0.0004	0.0004	0.0	0.006	0.0009	0.0007	0.0004	0.0	0.006
Others	1.5	1.8	1.8	2.7	2.1	1.5	1.7	1.7	2.6	2.2

[a] Batteries excluded.

[b] CFRP = carbon fiber-reinforced plastic; GFRP = glass fiber-reinforced plastic; PFSA = perfluorosulfonic acid; PTFE = polytetrafluoroethylene.

Fuel Cell and Battery Sizing

On the basis of Argonne component sizing calculations, the conventional vehicle fuel cell stack power was calculated to be 70 kW for the FCV passenger car, 101 kW for the FCV sport utility vehicle, and 100 kW for the FCV pick-up truck. The lightweight vehicle fuel cell stack power was calculated to be 54 kW for the FCV passenger car, 79 kW for the FCV sport utility vehicle, and 86 kW for the FCV pick-up truck. The lightweight pick-up truck stack power does not decrease as much as the SUV case due to less lightweighting potential of other PUT components. GREET2_2012 allows users to select their own stack power by using equations to calculate the resulting fuel cell stack and auxiliary weights. These equations, which use weights of 3.23 lb/kW for the stack and 7.8 lb/kW for the auxiliaries, are from a fuel cell component breakdown presented in a Society of Automotive Engineers (SAE) paper (Cooper 2004). If users want to change the stack power, they will likely also want to change the battery power. For the conventional FCVs, the default battery power was estimated to be 33 kW for a passenger car, 37 kW for a SUV, and 41 kW for a PUT (Moawad et al. 2011). For the lightweight FCVs, the Argonne component sizing equations were used to calculate a battery power of 20 kW for the passenger car, 24 kW for the SUV, 29 kW for the PUT.

Similar to FCV stack and battery sizing in GREET2_2012, the HEV's battery is sized by power. For the conventional HEVs, the default battery power was estimated to be 28 kW for the passenger car, 33 kW for the SUV, and 37 kW for the PUT (Moawad et al. 2011). For the lightweight HEVs, the Argonne component sizing equations were used to calculate a battery power 17 kW for the passenger car, 21 kW for the SUV, and 26 kW for the PUT. However in GREET2_2012, the PHEV's and EV's battery is sized by energy. For the conventional PHEV20s, the default battery energy was estimated to be 7 kWh for the passenger car, 10 kWh for the SUV, and 12 kWh for the PUT (Moawad et al. 2011). For the lightweight PHEV20s, the Argonne component sizing equations were used to calculate a battery power 4 kWh for the passenger car, 6 kWh for the SUV, and 8 kWh for the PUT. For the conventional EVs, the default battery energy was estimated to be 63 kWh for the passenger car, 89 kWh for the SUV, and 108 kWh for the PUT (Moawad et al. 2011). For the lightweight EVs, the Argonne component sizing equations were used to calculate a battery power 38 kWh for the passenger car, 57 kWh for the SUV, and 76 kWh for the PUT.

The power of a startup Pb-Ac battery is about 6 kW for the conventional ICEV passenger car and 9 kW for the SUV and PUT. For the conventional HEV, PHEV, EV, and FCV the power is 4 kW for the passenger car and 6 kW for the SUV and PUT (Argonne National Laboratory et al. 1998 and ASCM). The startup Pb-Ac batteries for the lightweight vehicles were scaled down according to the Argonne component sizing calculations. The lightweight ICEV battery power is about 4 kW for the passenger car and 6 kW for the SUV and PUT, while the battery power for both the lightweight HEV, PHEV, EV and FCV is about 2 kW for the passenger car and 4 kW for SUV and PUT.

For HEV and FCV battery sizing, we assumed a specific power of 800 W/kg for the Ni-MH and 1,500 W/kg for the Li-ion battery (Moawad et al. 2011 and Dunn et al. 2012). In GREET2_2012 we differentiate between PHEV and EV specific energy for sizing purposes as a PHEV battery typically has a lower specific energy than pure EV battery due to design and cost considerations (Nelson et al. 2011). For PHEV battery sizing, we assumed a specific energy of 53 Wh/kg for the Ni-MH and 74 Wh/kg for the Li-ion battery (Kalhammer et al. 2007 and Moawad et al. 2011). For EV battery sizing, we assumed a specific energy of 65 Wh/kg for the Ni-MH and 102 Wh/kg for the Li-ion battery (Kalhammer et al. 2007 and Moawad et al. 2011). We assumed a specific energy of approximately 390 W/kg for the Pb-Ac battery on the basis of information in ASCM; however in GREET 2, the user directly inputs Pb-Ac battery weight. Tables 21 through 23 show the default battery weights in GREET2_2012.

TABLE 21 Passenger Car Battery Weights (lb)

Battery Type	ICEV	HEV	PHEV10	PHEV20[a]	PHEV30	PHEV40	EV	FCV	LW ICEV	LW HEV	LW PHEV10	LW PHEV20[a]	LW PHEV30	LW PHEV40	LW EV	LW FCV
Pb-Ac	36	22	22	22	22	22	22	22	23	14	14	14	14	14	14	14
Ni-MH		77	166	291	541	749	2137	91		47	83	166	333	458	1289	55
Li-ion		41	119	209	387	536	1362	49		25	60	119	238	328	821	29

[a] PHEV20 is default PHEV used in the model

TABLE 22 Sport Utility Vehicle Battery Weights (lb)

Battery Type	ICEV	HEV	PHEV10	PHEV20[a]	PHEV30	PHEV40	EV	FCV	LW ICEV	LW HEV	LW PHEV10	LW PHEV20[a]	LW PHEV30	LW PHEV40	LW EV	LW FCV
Pb-Ac	54	36	36	36	36	36	36	36	35	24	24	24	24	24	24	24
Ni-MH		91	208	416	749	998	3019	102		58	125	250	499	624	1933	66
Li-ion		49	149	298	536	715	1924	54		31	89	179	358	447	1232	35

[a] PHEV20 is default PHEV used in the model

TABLE 23 Pick-Up Truck Battery Weights (lb)

Battery Type	ICEV	HEV	PHEV10	PHEV20[a]	PHEV30	PHEV40	EV	FCV	LW ICEV	LW HEV	LW PHEV10	LW PHEV20[a]	LW PHEV30	LW PHEV40	LW EV	LW FCV
Pb-Ac	54	36	36	36	36	36	36	36	35	24	24	24	24	24	24	24
Ni-MH		102	208	499	915	1206	3663	113		72	166	333	624	832	2578	80
Li-ion		54	149	358	655	864	2334	60		38	119	238	447	596	1643	43

[a] PHEV20 is default PHEV used in the model

Battery Replacement

Another important factor when considering batteries is the number of times they will need to be replaced during the vehicle's lifetime. A key assumption used in determining the battery replacement interval is the distance traveled by the vehicles during their lifetimes. The VISION model developed at Argonne estimates an average lifetime distance of approximately 160,000 miles for a passenger car and 180,000 miles for a SUV and PUT; these values are used for our analysis (Argonne National Laboratory 2012). However, the various vehicle types might have a different expected lifetime due to variances in materials and components; these differences result from variations in rust resistance, the ability to repair a material after an accident, and other factors. We have built in the flexibility to change the lifetime total distance each vehicle is driven as more data become available.

There is also uncertainty regarding the life of advanced batteries, such as Ni-MH and Li-ion, during actual use in electric-drive vehicles. This is a concern for potential buyers because of the cost of replacement. Currently, the manufacturer's warranty for new 2012 Toyota HEVs and PHEVs, General Motors HEVs and PHEVs, Ford HEVs and EVs, and Nissan EVs covers the electric-drive (Ni-MH or Li-ion) battery and other electric drive-related components for 8 years or 100,000 miles, whichever comes first (Toyota Motor Corporation 2012; Ford Motor Company 2012; General Motors Company 2012; Nissan Motor Company 2012). For Honda's 2012 HEVs, the company states that the warranty may vary but the standard warranty has been 8 years or 80,000 miles (Honda Motor Company 2012 and Autos.com 2012). However, in states that adopted California's emission standards, the warranty for electric drive-related components of partial zero emission vehicles (e.g., HEVs and PHEVs) is 10 years or 150,000 miles (Ford Motor Company 2012). Warranty information provides some indication of battery life, but there is still some uncertainty.

A study examining the use of Ni-MH batteries in various electric-drive vehicles, including an HEV, a PHEV, and an EV states that it is highly probable that Ni-MH batteries can achieve 130,000 to 150,000 lifetime mileage (Duvall 2003). In 2008, first generation (model year 2001 through 2003 for the U.S. market) Toyota Prius Ni-MH batteries reportedly had about a one percent failure rate after the warranty expired; however, Toyota suggested that second generation batteries would last the life of the car, roughly 180,000 miles (Naughton 2008). Further anecdotal information suggest that the Ni-MH batteries can last even longer, with Consumer Reports finding that a model year 2002 Toyota Prius driven 208,000 miles had only slightly lower fuel economy and performance than a new 2001 Toyota Prius driven 2,000 miles that was tested when the vehicle was originally released in the U.S. (Fisher 2011).

While Ni-MH batteries were typically used in the HEVs introduced in the past decade, Li-ion batteries are just now being deployed in PHEVs, such as the Chevrolet Volt and Toyota Plug-in Prius, and EVs, such as the Nissan Leaf and Ford Focus Electric. The United States

Advanced Battery Consortium goal is a 15-year calendar life for HEV and PHEV Li-ion batteries and 10-year calendar life for PHEV Li-ion batteries (Vehicle Technologies Program 2012). While lifetime goals have not been fully demonstrated, laboratory tests from Quallion, Johnson Controls Inc., A123 Systems, and Maxwell Technologies have shown that there are Li-ion battery technologies that should meet these goals (Vehicle Technologies Program 2012).

In GREET2_2012 we assume that both the Ni-MH and Li-ion batteries will last for the entire vehicle life. However, in order to accurately determine replacement intervals, further research and real-world data are needed. This will be especially important for Li-ion PHEV and EV batteries that may deteriorate faster due deep cycling. Also depending on the performance of the battery when the vehicle is scrapped, these batteries could potentially be reused in a secondary application (Neubauer et al. 2012).

In contrast, Pb-Ac battery life can be determined with more certainty because the technology is fairly mature. On the basis of data collected from a life-cycle inventory performed by USCAR, we assume that the Pb-Ac battery will require two replacements in the lifetime of the ICEV, HEV, and FCV (Sullivan et al. 1998). In addition, Pb-Ac batteries are the top recycled consumer product, at more than 97%; new batteries contain 60% to 80% recycled lead and plastic (Battery Council International 2012).

The recycling of Ni-MH and Li-ion batteries used in automotive applications is an important issue that has been getting more attention as the fleet of electric-drive vehicles grows. The United States already has a network to collect and recycle rechargeable consumer batteries (Call2Recycle 2012). For automotive Ni-MH batteries, INMETCO has a process to recover nickel, iron, manganese, and zinc to be used as alloying materials in the production of stainless steel. Toyota has partnered with Sumitomo Metal Mining and Primearth EV Energy to develop a process to recycle automotive Ni-MH batteries and use the nickel for new batteries (Toyota 2010). There are several approaches that have been developed to recycle Li-ion batteries, though only two processes are commercial today: pyrometallurgical and intermediate physical recycling (Dunn et al. 2012). These recycling processes have been primarily developed to recover cobalt; however each process can recover other resources. Umicore has a smelting process that is also able to capture copper, iron, and nickel but other materials like lithium and aluminum will be sent to the slag. Toxco has an intermediate recycling process that involves cryogenically freezing the batteries in liquid nitrogen to render them non-reactive, then shearing the batteries and separating the materials. The metals are collected and sold, while the lithium components are separated and converted to lithium carbonate for resale. Plastic casings and other miscellaneous components are separated for recycling or scrapping.

Tire and Fluid Replacement

Additional components also require replacement during a vehicle's lifetime. In GREET2_2012, we include tire and fluid replacement. Replacement of parts such as air filters, brake pads, spark plugs, and windshield wiper blades was not included because of the small weight of these parts and because the model aggregates these parts into larger components that are not completely replaced. Tires, which are composed of approximately two-thirds rubber and one-third steel (by weight) are replaced regularly; however, their life span varies depending on tire specifications (Muir 2005). In this analysis, we assume that the tires are replaced every 40,000 miles, so about three replacements are needed for a passenger car and four replacements for a SUV or PUT using our assumed vehicle lifetimes. The last set of tires will be scrapped when the rest of the vehicle is scrapped (Sullivan et al. 1998). Potentially, the tires could last slightly longer on average, but because of safety concerns, used tires are not reused on vehicles. In 2009, approximately 290 million scrap tires were generated; about 85% of those were consumed in a scrap market such as tire-derived fuel, ground rubber, and civil engineering applications (Rubber Manufacturers Association 2011).

The fluids in a vehicle are replaced during routine maintenance (e.g., oil changes and other maintenance intervals). We assumed that the engine oil is replaced, on average, every 4,000 miles, requiring 39 lifetime replacements for cars and 44 for SUVs and PUTs; most vehicle manufacturers recommend oil changes every 5,000 miles, while maintenance shops recommend changes every 3,000 miles. In addition, we assumed that the windshield wiper fluid, which is a 50%/50% mix of methanol and water, is completely consumed every 8,000 miles, requiring 19 lifetime refills for cars and 22 for SUVs and PUTs. This fluid is often filled during oil changes, when incremental amounts are added to fill the wiper fluid reservoir.

Power steering fluid, which is mineral based, is not replaced. In addition, makers of most new ICEVs and all electric-drive vehicles are transitioning to a fluidless electric power assist steering system because it requires fewer parts, no maintenance, and weighs less (Bohn 2005). Most HEVs combine their anti-lock braking system with the hybrid control system; regenerative brakes and conventional brakes are used together to slow the vehicle down, and the amount of braking from each is controlled electronically. However, because this is a controls modification, the amount of brake fluid used does not significantly change from one vehicle to another (Bohn 2005). We assumed that both the brake fluid and powertrain coolant, which is a 50%/50% mix of ethylene glycol and water, are replaced every 40,000 miles, each requiring three lifetime replacements for cars and four replacements for SUVs and PUTs (Sullivan et al. 1998).

Transmission fluid, a mineral-based lubricant, is used significantly less in electric-drive vehicles compared with ICEVs because of the differences in the gearboxes in these vehicles compared with the automatic transmission in ICEVs (which we assume to be used in our analysis) (Bohn 2005). We assume that each vehicle has one lifetime replacement and that, at a density of about 7 lb/gal, the passenger car ICEV requires about 24 lb of transmission fluid, while the HEV and FCV each needs about 2 lb (Royal Purple 2012). Finally passenger cars use about 30 lb of adhesives while SUVs and PUTs use about 40 lb; they are not replaced (Argonne National Laboratory et al. 1998). We assume that two-thirds of each fluid, except for the windshield wiper fluid, is combusted when it is replaced, while the remaining one-third is lost during operation; all of the wiper fluid is released to the atmosphere. The weights of the fluids were determined by using dismantling reports to calculate the volume required and density formulas to calculate the weights; the results are shown in Tables 24 through 26.

TABLE 24 Passenger Car Fluid Weights (lb)

Vehicle Type	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Wiper Fluid	Adhesives
ICEV	9	0	2	24	23	6	30
HEV	9	0	2	2	23	6	30
PHEV	9	0	2	2	23	6	30
EV	0	0	2	2	16	6	30
FCV	0	0	2	2	16	6	30

TABLE 25 Sport Utility Vehicle Fluid Weights (lb)

Vehicle Type	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Wiper Fluid	Adhesives
ICEV	11	0	2	32	29	11	40
HEV	11	0	2	2	29	11	40
PHEV	11	0	2	2	29	11	40
EV	0	0	2	2	20	11	40
FCV	0	0	2	2	20	11	40

TABLE 26 Pick-Up Truck Fluid Weights (lb)

Vehicle Type	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Wiper Fluid	Adhesives
ICEV	11	0	2	32	29	11	40
HEV	11	0	2	2	29	11	40
PHEV	11	0	2	2	29	11	40
EV	0	0	2	2	20	11	40
FCV	0	0	2	2	20	11	40

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