APPENDIX D

Life-cycle Assessment Studies

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Anair, D., and A. Mahmassani. 2012. State of Charge: Electric Vehicles' Global Warming Emissions and Fuel-Cost Savings across the United States. Union of Concerned Scientists.	EVs and PHEVs.	Not applicable.	GHG emissions.
Bandivadekar, A., K. Bodek, L. Cheah, C. Evans, T. Groode, J. Heywood, E. Kasseris, M. Kromer, and M. Weiss. 2008. On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions. Massachusetts Institute of Technology.	Lightweighting, vehicle design, engine downsizing, BEVs, fuel-cell vehicles, HSS, and aluminum.	Cradle to grave.	Energy requirements and GHG emissions.
Baptista, P., J. Ribau, J. Bravo, C. Silva, P. Adcock, and A. Kells. 2011. Fuel Cell Hybrid Taxi Life Cycle Analysis.	Hydrogen fuel cell, HEVs, fuel cell PHEVs, and EVs.	Well to tank, tank to wheels, and cradle to grave.	GHG emissions.
Baptista, P., C. Silva, G. Gonçalves, and T. Farias. 2009. Full life cycle analysis of market penetration of electricity based vehicles. EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium.	PHEVs, EVs, hydrogen fuel-cell hybrids, and hydrogen fuel-cell plug-in hybrids.	Cradle to grave.	Energy requirements, GHG emissions, criteria pollutants, and PM emissions.
Bertram, M., K. Buxmann, and P. Furrer. 2009. Analysis of greenhouse gas emissions related to aluminium transport applications. *International Journal of Life Cycle Assessment*.	Aluminum, steel, and cast iron.	Cradle to grave.	GHG emissions.
Birat, J.P., L. Rocchia, V. Guerin, and M. Tuchman. 2003. Ecodesign of the Automobile, based on steel sustainability. SAE International.	Aluminum, steel, and recycling.	Cradle to grave.	CO_2 emissions.
Blawert, C., N. Hort, and K.U. Kainer. 2004. Automotive Applications of Magnesium and its Alloys. *Transactions of the Indian Institute of Metals.*	Magnesium used in vehicle manufacturing, including interior applications, body, chassis, and drivetrain.	Not applicable.	Recycling and fuel efficiency are mentioned but not explored.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Boncourt, M. 2011. The Electric Vehicle in the Climate Change Race: Tortoise, Hare, or Both?	Batteries (NiMH, Li-ion, lead-acid, NiCd, Zebra), electric vehicles, and drive trains.	Not applicable.	CO_2 emissions.
Brylawski, M.M., and A.B. Lovins. 1998. Advanced Composites: The Car Is At The Crossroads.	Advanced composites.	Not applicable.	Energy requirements and fuel use.
Caceres, C.H. 2009. Transient environmental effects of light alloy substitutions in transport vehicles. *Materials & Design*.	Magnesium and aluminum.	Alloy production.	Recycled materials.
California Air Resources Board. 2012. Staff Report: Initial Statement Of Reasons, Advanced Clean Cars. 2012 Proposed Amendments To The California Zero Emission Vehicle Program Regulations. California Air Resources Board.	Zero emission vehicles, including BEVs, hydrogen fuel-cell vehicles, and transitional zero emission vehicles, PHEVs, and hydrogen internal combustion engine vehicles). Environmental impacts are compared for gasoline vehicles at three different levels of minimum average fuel efficiency (2010, 2020, and 2025), plug-in hybrid vehicles, electric vehicles, and fuel cell vehicles.	Well to wheels.	Health impacts, emissions impacts (NO_x, PM, ROS, and GHGs), and energy requirements.
California Air Resources Board. 2012. Advanced Clean Cars: the Zero Emission Vehicle (ZEV) Regulation, Fact Sheet. California Air Resources Board.	Gasoline vehicles (2010, 2020, and 2025 emissions standards), plug-in hybrid vehicles, fuel-cell vehicles, electric vehicles.	Well to wheels.	Smog-forming pollution emissions (NO_x plus ROS), and GHG emissions.
Cheah, L. 2010. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. Massachusetts Institute of Technology.	Magnesium, aluminum, HSS, and polymer composites.	Cradle to grave.	Recycled materials.
Cheah, L., and J. Heywood. 2011. Meeting U.S. passenger vehicle fuel economy standards in 2016 and beyond. *Energy Policy*.	Lightweighting, HEVs, PHEVs, and advanced diesel.	Not applicable.	None.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Cheah, L., J. Heywood, and R. Kirchain. 2009. Aluminum Stock and Flows in U.S. Passenger Vehicles and Implications for Energy Use. *Journal of Industrial Ecology.*	Aluminum.	Not applicable.	Energy requirements.
Cheah, L., J. Heywood, and R. Kirchain. 2010. The Energy Impact of U.S. Passenger Vehicle Fuel Economy Standards. Massachusetts Institute of Technology.	Batteries (NiMH and Li-ion).	Not applicable.	Rare earth elements.
Chester, M., and A. Horvath. 2009. Environmental Assessment of Passenger Transportation Should Include Infrastructure and Supply Chains. *Environmental Research Letters.*	Conventional gasoline vehicles.	Infrastructure, fuel production, supply chains, and vehicle production.	GHG emissions, selected criteria air pollutants emissions, and life-cycle energy.
Chester, M., and A. Horvath. 2011. Vehicle Manufacturing Futures in Transportation Life-cycle Assessment. Institute of Transportation Studies, University of California at Berkeley.	Lightweighting, HEVs, EVs, PHEVs, and Batteries (Li-ion and NiMH).	Manufacturing.	GHG emissions and energy requirements.
Das, S. 2011. Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites. *International Journal of Life Cycle Assessment.*	Steel and carbon-fiber composites.	Cradle to grave.	Energy and CO_2 emissions.
Dhingra, R., J.G. Overly, G.A. Davis, S. Das, S. Hadley, and B. Tonn. 2000. A Life-Cycle-Based Environmental Evaluation: Materials in New Generation Vehicles. SAE International.	Magnesium, aluminum, and titanium.	Cradle to grave.	Energy requirements, GHG emissions, criteria pollutants, and solid waste generation.
Dubreuil, A., L. Bushi, S. Das, A. Tharumarajah, and G. Xianzheng. 2010. A Comparative Life Cycle Assessment of Magnesium Front End Autoparts. SAE International.	Magnesium, aluminum, and steel.	Cradle to grave.	Energy requirements, GHG emissions, and criteria pollutants.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Edwards, K.L. 2003. Strategic Substitution of New Materials for Old: Applications in Automotive Product Development. *Materials and Design.*	Tires, wheels, seating, heating and ventilation systems, bumpers, lighting, vehicle interior, drive train and suspension systems, brakes, exterior body panels, under bonnet applications.	Not an LCA; mostly focused on the design and manufacturing stages, although some discussion of use and end of life.	Mentions that the desire to reduce emissions will drive materials and design advances, but does not quantify them.
Elgowainy, A., J. Han, L. Poch, M. Wang, A. Vyas, M. Mahalik, and A. Rousseau. 2010. Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles. Argonne National Laboratory.	PHEVs.	Cradle to grave.	Energy requirements and GHG emissions.
Fox, J.W., and D.R. Cramer. 1997. Hypercars: A Market-Oriented Approach to Meeting Lifecycle Environmental Goals.	Lightweighting and HEVs.	Not applicable.	Energy requirements, CO_2 emissions, criteria pollutants, PM emissions, and recyclability of materials.
Gaines, L., J. Sullivan, A. Burnham, and I. Belharouak. 2011. Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling. Argonne National Laboratory.	Batteries (Li-ion).	Cradle to gate.	Energy requirements and GHG emissions.
Gaines, L., and M. Singh. 1995. Energy and Environmental Impacts of Electric Vehicle Battery Production and Recycling. Argonne National Laboratory.	Batteries (Pb-acid, Na-S, NiCd, and NiMH).	Not applicable.	Energy requirements, CO_2 emissions, and non-GHG emissions.
Gaines, L., and P. Nelson. 2009. Lithium-Ion Batteries: Possible Materials Issues. Argonne National Laboratory.	Batteries (NCA-G, LFP-G, LMO-TiO, LMO-G).	Not applicable.	Recycled materials.
Gaines, L., and R. Cuencas. 2000. Operation of an Aluminum-Intensive Vehicle: Report on a Six-Year Project. Center for Transportation Research, Argonne National Laboratory.	Lightweighting.	Manufacturing and use.	GHG emissions and energy requirements.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Gaustad, G., E. Olivetti, and R. Kirchain 2012. Improving aluminum recycling: A survey of sorting and impurity removal technologies. Resources, Conservation and Recycling.	Lightweighting.	Not Applicable.	None.
Geyer, R. 2007. Life Cycle Greenhouse Gas Emission Assessments of Automotive Materials: The Example of Mild Steel, Advanced High Strength Steel and Aluminum in Body in White Applications, Methodology Report. University of California–Santa Barbara.	Aluminium, AHSS, and steel.	Cradle to gate.	GHG emissions.
Geyer, R. 2008. Parametric Assessment of Climate Change Impacts of Automotive Material Substitution. *Environmental Science Technology*.	Lightweighting, aluminum, HSS, and steel.	Material production and vehicle use stages only.	GHG emissions.
Ghassemieh, E. 2011. Materials in Automotive Application, State of the Art and Prospects. *New Trends and Developments in Automotive Industry.*	Steel, aluminum, magnesium, plastics and composites, thermoplastic/ thermoset polymers.	Not an LCA, although it does look at the impact of lightweighting and recycling and other life-cycle considerations, but only in a general sense rather than specific to one type of material substitution.	Some discussion of the impacts of materials on fuel efficiency and recyclability. More detailed discussion of the impacts of different materials on vehicle weight.
Gibson, T. 2000. Life Cycle Assessment of Advanced Materials for Automotive Applications. *Society of Automotive Engineers, Inc.* 109(6):1932–1941.	Nine advanced and conventional materials including graphite, titanium, steel, aluminum, and carbon composites.	Cradle to grave.	Energy use; GHG emissions; air emissions, including, SO_x and NO_x; water emissions; solid waste; and hydrogen fluoride.
Glennan, T.B. 2007. Strategies for Managing Vehicle Mass throughout the Development Process and Vehicle Life Cycle. SAE International.	Lightweighting.	Not an LCA; mostly focused on the design and manufacturing stages.	Fuel savings are mentioned but not quantified in detail.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Granly, B., T. Welo, and S. Støren. 2010. Adaptive Processing: A Knowledge-Based Approach for Achieving Sustainability. Proceedings from the IMS 2020 Summer School on Sustainable Manufacturing.	Aluminum extrusions, likely but not necessary for vehicles.	Not an LCA, although there is a discussion of the impacts of producing aluminum components for vehicles using adaptive bending technology across the material production, manufacturing, use, and disposal/recycling phases.	Mentions that producing aluminum components for vehicles (rather than steel) using adaptive bending technology will lead to reduced energy consumption during manufacturing, reduced fuel consumption during use, reduced impacts from paint production, and higher recyclability.
Gruber, P.W., P.A. Medina, G.A. Keoleian, S.E. Kesler, M.P. Everson, and T.J. Wallington. 2011. Global Lithium Availability: A Constraint for Electric Vehicles? *Journal of Industrial Ecology.*	Batteries (Li-ion).	Not applicable.	Not discussed.
Hadley, S., and A. Tsvetkova. 2008. Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation. Prepared for the U.S. Department of Energy under contract No. DE-AC05-00OR22725, Oak Ridge National Laboratory, Oak Ridge, Tennessee.	PHEVs and HEVs.	Not applicable.	Energy use; GHG emissions; air emissions, including SO_x and NO_x; and generating capacity.
Hakamada, M., T. Furuta, Y. Chino, Y. Chen, H. Kusuda, and M. Mabuchi. 2007. Life cycle inventory study on magnesium alloy substitution in vehicles. *Energy.*	Magnesium, steel, and aluminum.	Cradle to grave.	Energy requirements and CO_2 emissions.
Hearron, J.D., M. McDonough, A. Ranjbar, W. Wang, C. Lin, P. Shamsi, S. Manohar, and B. Fahimi. 2011. The Sustainability of New Technologies in Vehicular Transportation. University of Texas–Dallas.	Biofuels (E85), PHEVs, and batteries (NiMH).	Cradle to grave.	GHG emissions and waste generation.
Huo, H., Y. Wu, and M. Wang. 2009. Total versus urban: Well-to-wheels assessment of criteria pollutant emissions from various vehicle/fuel systems. *Atmospheric Environment*.	Vehicle fuel systems (conventional gasoline, conventional diesel, E85 [with corn-based and switchgrass-based ethanol], hybrid electric, all-electric, hydrogen fuel cell).	Cradle to grave.	Criteria pollutants.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Jung, K. 2004. Substitute Products in the Automotive Steel Sheets Market According to Sustainable Innovations in Technology. *International Journal of Product Development.*	Steel.	Not applicable.	Does not discuss environmental impacts or mass reduction.
Kaierle, S., M. Dahmen, and O. Güdükkurt. 2012. Eco-Efficiency of Laser Welding Applications. Invited Paper, Fraunhofer-Institut for Laser Technology.	Laser welding.	Use phase.	Energy and mass.
Kendall, A., and L. Price. 2012. Incorporating Time-Corrected Life Cycle GHG Emissions in Vehicle Regulations. *Environmental Science and Technology.*	Lightweighting.	Cradle to grave.	GHG emissions.
Keoleian G.A., J. Kelly, J. MacDonald, A. Camere, C. Monasterio, and A. Schafer. 2011. Environmental Assessment of Plug-In Hybrid Electric Vehicles in Michigan: Greenhouse Gas Emissions, Criteria Air Pollutants, and Petroleum Displacement. University of Michigan Center for Sustainable Systems.	PHEVs.	Not applicable.	GHG emissions, criteria air pollutants (also net energy usage and fuel displacement).
Keoleian, G.A., and J. Staudinger. 2001. Management of End-of-Life Vehicles (ELVs) in the US. University of Michigan Center for Sustainable Systems.	Lightweighting and HSS.	End of life.	Energy use, mercury contamination, and landfill disposal of automotive shredder residue (contains plastics and some potentially toxic materials).

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Keoleian, G.A., and K. Kar. 1999. Life Cycle Design of Air Intake Manifolds: Phase I: 2.0 L Ford Contour Air Intake Manifold. University of Michigan Center for Sustainable Systems.	1995 Ford Contour with three different air intake manifolds: (1) a 2.74 kilogram composite manifold currently used in 2.0 liter 1995 Ford Contours, (2) a 6.5 kilogram sand-cast aluminum backup (used as a prototype for the composite manifold), and (3) a 3.43 kilogram multi-tube brazed aluminum manifold currently used in the 1.9 liter Escort engine. (For uniform baseline comparison, the 1.9 liter Escort manifold is converted to a 2.0 liter equivalent by multiplying the weight ratio of the two engines [1.05]; the converted 2.0 liter multi-tube brazed manifold weights 3.62 kilograms [p. 4]).	Cradle to grave.	Energy requirements, solid waste, air pollutant emissions, GHG emissions, water pollution.
Keoleian, G.A., and K. Kar. 2003. Elucidating Complex Design and Management Tradeoffs Through Life Cycle Design: Air Intake Manifold Demonstration Project. *Journal of Cleaner Production.*	1995 Ford Contour with three different air intake manifolds: (1) a 2.74 kilogram glass reinforced nylon composite, (2) a 6.5 kilogram sand-cast aluminum, and (3) a 3.62 kilogram multi-tube brazed aluminum (p. 63).	Cradle to grave.	Energy requirements, solid waste, air pollutant emissions, GHG emissions, water pollution.
Khanna, V., and B.R. Bakshi. 2009. Carbon Nanofiber Polymer Composites: Evaluation of Life Cycle Energy Use. *Environmental Science Technology.*	PNC, CNF and CNF-GF hybrid polymer, CNF PNC, CNF-GF hybrid PNCs, and steel.	Cradle to gate and use stage.	Energy requirements.
Kim, H.J., C. McMillan, G.A. Keoleian, and S.J. Skerlos. 2010. Greenhouse Gas Emissions Payback for Lightweighted Vehicles Using Aluminum and High-Strength Steel. *Journal of Industrial Ecology*.	Lightweighting, aluminum, and HSS.	Cradle to grave.	GHG emissions.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Kim, H.C., M.H. Ross, and G.A. Keoleian. 2003. Optimal Fleet Conversion Policy from a Life Cycle Perspective. *Transportation Research Part D: Transport and Environment* 9(3):229–249.	U.S. passenger car fleet at the time this report was written.	Cradle to grave.	Energy requirements and emissions (CO, non-methane hydrocarbons, NO_x, and CO_2).
Knittel, C.R. 2009. Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector.	None.	Not applicable.	None.
Kocanda, A., and H. Sadlowska. 2008. Automotive Component Development by Means of Hydroforming. *Archives of Civil and Mechanical Engineering.*	Hydroforming.	Not an LCA, but focuses on manufacturing and design, with some attention to use.	Some discussion of fuel efficiency savings, but not quantified.
Koffler C., and K. Rohde-Brandenburger. 2009. On the Calculation of Fuel Savings through Lightweight Design in Automotive Life Cycle Assessments. *International Journal of Life Cycle Assessment.*	Lightweighting.	Not an LCA.	Fuel saving methodology, not specific to any certain technology.
Kulekci, M.L. 2008. Magnesium and its Alloys Applications in Automotive Industry. *International Journal of Advanced Manufacturing Technology.*	Magnesium used in vehicle manufacturing, including interior applications, body, chassis, and drivetrain.	Not an LCA, but discusses manufacturing and use phases.	Mentions improvements in fuel efficiency but does not quantify the fuel efficiency or other environmental benefits of weight reduction.
Kushnir, D., and B.A. Sandén. 2011. Multi-Level Energy Analysis of Emerging Technologies: A Case Study in New Materials for Lithium Ion Batteries. *Journal of Cleaner Production.*	Nanomaterials used in Li-ion batteries, namely, lithium iron phosphate and lithium titanate.	Cradle to gate.	Energy requirements.
Lloyd, S.M., and L.B. Lave. 2003. Life Cycle Economic and Environmental Implications of Using Nanocomposites in Automobiles. *Environmental Science Technology.*	Steel, aluminum, and clay-polypropylene nanocomposite.	Cradle to gate.	Energy requirements, GHG emissions, criteria air pollutants, fuel/electricity use, resource depletion, water use, hazardous waste generation, and toxic releases.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Lotus Engineering. 2010. An Assessment of Mass Reduction Opportunities for a 2017 - 2020 Model Year Vehicle Program. International Council on Clean Transportation.	Vehicle design.	Not applicable.	None.
Ma, H., F. Balthasar, N. Tait, X. Riera-Palou, and A. Harrison. 2012. A New Comparison Between the Life Cycle Greenhouse Gas emissions of Battery Electric Vehicles and Internal Combustion Vehicles. *Energy Policy.*	BEVs.	Well to wheels (fuel), cradle to grave (vehicle).	GHG emissions.
Maclean, H.L., and L.B. Lave. 2003. Life Cycle Assessment of Automobile/Fuel Options. *Environmental Science Technology*.	Gasoline ICEs, diesel ICEs, BEVs, HEVs, ethanol ICEs, and hydrogen fuel-cell ICEs.	Cradle to gate and use stage for vehicle; cradle to grave for fuels.	Energy requirements and GHG emissions.
Majeau-Bettez, G., T.R. Hawkins, and A.H. Strømman. 2011. Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. *Environmental Science and Technology.*	Batteries (NiMH and Li-ion).	Cradle to gate.	Global warming potential, fuel use, resource depletion, freshwater and marine ecotoxicity, freshwater and marine eutrophication, ozone depletion, metal depletion, PM emissions, terrestrial acidification, and human toxicity.
Markel, T., K. Smith, and A. Pesaran. 2008. PHEV Energy Storage Performance/Life/Cost Trade-off Analysis. National Renewable Energy Laboratory.	PHEV batteries.	Not applicable.	None.
Mayyas, A.T., A. Qattawi, A.R. Mayyas, and M.A. Omar. 2012. Life Cycle Assessment-Based Selection for a Sustainable Lightweight Body-in-White Design. *Energy*.	Carbon fiber/epoxy composite, high strength glass fiber, advanced high-strength steel, aluminum, and magnesium.	Cradle to grave.	GHG emissions and energy requirements.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
McMillan, C.A., and G.A. Keoleian. 2008. Not All Primary Aluminum Is Created Equal: Life Cycle Greenhouse Gas Emissions from 1990 to 2005. *Environmental Science and Technology.*	Aluminum.	Cradle to gate.	GHG emissions.
Michalek, J.J., M. Chester, P. Jaramillo, C. Samaras, C.N. Shiau, and L.B. Lave. 2011. Valuation of Plug-In Vehicle Life-Cycle Air Emissions and Oil Displacement Benefits. *Proceedings of the National Academy of Science.*	HEVs and Batteries (Li-ion).	Cradle to grave.	GHG emissions and criteria air pollutants.
Mitropoulos, K., and P. Prevedouros. 2011. Sustainability Framework for the Life Cycle Assessment of Light-Duty Vehicles. *Renewable and Sustainable Energy Reviews*.	HEVs, fuel-cell vehicles, EVs, and PHEVs.	Cradle to grave.	GHG, VOC, CO, NO_x, PM, SO_x emissions.
National Academy of Engineering and National Research Council. 2010. America's Energy Future Energy Efficiency Technologies Subcommittee; National Academy of Sciences. Real Prospects for Energy Efficiency in the United States. The National Academic Press.	Lightweighting and vehicle design.	Not applicable.	Energy requirements and GHG emissions.
Nitta, S., and Y. Moriguchi. 2011. New Methodology of Life Cycle Assessment for Clean Energy Vehicle and New Car Model. SAE International.	Hydrogen fuel cells.	Cradle to grave.	GHG emissions, waste generation, and energy requirements.
Notter, D.A., M. Gauch, R. Widmer, P. Wager, A. Stamp, R. Zah, and H.J. Althaus. 2010. Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. *Environmental Science Technology.*	Batteries (Li-ion).	Cradle to grave.	Energy requirements, GHG emissions/global warming potential, criteria air pollutants, resource depletion, and Ecoindicator 99.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Offer, G.J., D. Howey, M. Contestabile, R. Clague, and N.P. Brandon. 2009. Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System. *Energy Policy.*	BEVs, hydrogen fuel cells, and HEVs.	Manufacturing and use.	GHG emissions and criteria air pollutants.
Opbroek, E. 2011. Reinventing Automotive Steel. Presented at the Green Steel Summit.	High-strength steel.	Cradle to grave.	GHG emissions.
Overly, J.G., R. Dhingra, G.A. Davis, and S. Das. 2002. Environmental Evaluation of Lightweight Exterior Body Panels in New Generation Vehicles. SAE International.	Aluminum, carbon-fiber-reinforced polymer, and glass-fiber-reinforced polymer.	Cradle to grave.	CO_2 emissions, PM emissions, eutrophication, photochemical smog, solid and hazardous waste generation, and water quality.
Patterson, J., M. Alexander, and A. Gurr. 2011. Preparing for a Life Cycle CO_2 Measure. Ricardo Low Carbon Vehicle Partnership.	Gasoline vehicles, diesel vehicles, PHEVs, EREVs, EVs, and fuel-cell vehicles.	Not applicable.	GHG emissions.
Peterson, P.T. 2002. Environment for Green Vehicles, Efficient is Better. Society of Automotive Engineers.	High-strength steel.	Not an LCA, but does mention all life-cycle phases without going into particular detail.	Describes the mass reduction and fuel efficiency of the Ultra Light Steel Auto Body - Advanced Vehicle Concepts but does not go into detail about the specific substitutions/technologies that enable improved fuel efficiency compared to a baseline vehicle.
Rooijen, J. 2006. A Life Cycle Assessment of the PureCell Stationary Fuel Cell System: Providing a Guide for Environmental Improvement. University of Michigan Center for Sustainable Systems.	Fuel cells.	Manufacturing, use, end of life.	GHG emissions, human health impacts, ecotoxicity, acidification/eutrophication, and land use.
Samaras, C., and K. Meisterling. 2008. Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. *Environmental Science Technology.*	Batteries (NiMH and Li-ion).	Cradle to gate.	Energy requirements and GHG emissions.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Schexnayder, S.M., S. Das, R. Dhingra, J.G. Overly, B.E. Tonn, J.H. Peretz, G. Waidley, and G.A. Davis. 2001. Environmental Evaluation of New Generation Vehicles and Vehicle Components. Oak Ridge National Laboratory.	Batteries (NiMH and Li-ion), and hydrogen fuel-cell vehicles.	Cradle to grave.	Energy requirements, GHG emissions, solid and hazardous waste generation, and water quality.
Schlosser, R., F. Klocke, B. Döbbeler, B. Riemer, K. Hameyer, T. Herold, W. Zimmermann, O. Nuding, B.A. Schindler, and M. Niemczyk. 2011. Assessment of Energy and Resource Consumption of Processes and Process Chains within the Automotive Sector. Proceedings of the 18th CIRP International Conference on Life Cycle Engineering.	Not applicable.	Cradle to grave.	Energy requirements.
Shiau, C., and J. Michalek. 2011. Global Optimization of Plug-In Hybrid Vehicle Design and Allocation to Minimize Life Cycle Greenhouse Gas Emissions. *Journal of Mechanical Design*.	Fleet optimization, HEVs, and PHEVs.	Not applicable.	GHG emissions.
Shiau, C., C. Samaras, R. Hauffe, and J.J. Michalek. 2009. Impact of Battery Weight and Charging Patterns on the Economic and Environmental Benefits of Plug-In Hybrid Vehicles. *Energy Policy.*	Batteries (Li-ion).	Cradle to gate.	GHG emissions.
Shulock, C., E. Pike., A. Lloyd, and R. Rose. 2011. Vehicle Electrification Policy Study. Task 1 Report: Technology Status. ICCT (International Council on Clean Transportation): Brussels, Belgium; Washington, DC and San Francisco, California, USA.	BEVs and FCEVs.	Well to wheels and well to tank.	GHG emissions, criteria air pollutant emissions, water pollution, water consumption, and waste.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Sivertsen, L.K., J.O. Haagensen, and D. Albright. 2003. A Review of the Life Cycle Environmental Performance of Automotive Magnesium. SAE International.	Magnesium and aluminum.	Cradle to grave.	Recycled materials.
Smith, V.M., D.L. Gard, and G.A. Keoleian. 2002. Ultra Light Steel Auto Body - Advanced Vehicle Concepts Life Cycle Inventory Study, Final Report. University of Michigan Center for Sustainable Systems.	Lightweighting, steel, and ultra-light steel.	Cradle to grave.	Energy requirements, GHG emissions, criteria air pollutants, and solid waste generation.
Smith, V.M., R.A. Williams, and S.T. Chubbs. 2003. Life Cycle Inventory Study of the UltraLight Steel Auto Body - Advanced Vehicle Concepts Vehicle Product System. University of Michigan Center for Sustainable Systems. SAE International.	Steel, iron, non-ferrous metals, and fluids.	Cradle to gate and use stage.	Energy requirements, GHG emissions; criteria air pollutants, resource depletion, and solid waste generation.
Spitzley, D.V., D.E. Grande, G.A. Keoleian, and H.C. Kim. 2005. Life Cycle Optimization of Ownership Costs and Emissions Reduction in US Vehicle Retirement Decisions. *Transportation Research Part D.*	Not applicable.	Materials production, manufacturing, use, maintenance, and end of life.	GHG emissions and criteria air pollutants.
Spitzley, D.V., and G.A. Keoleian. 2001. Life Cycle Design of Air Intake Manifolds: Phase II: Lower Plenum of the 5.4 L F-250 Air Intake Manifold, Including Recycling Scenarios. University of Michigan Center for Sustainable Systems.	5.4 liter Ford F-250 with three different air intake manifolds: (1) a 2.89 kilogram lost-core composite used in most of the 5.4 liter engines, (2) a 5.58 kilogram sand-cast aluminum manifold currently used in Ford's 5.4 liter natural gas vehicles, and (3) a 2.89 kilogram vibration welded composite (pp. 3–5).	Cradle to grave.	Energy, solid waste, air pollutant emissions, GHG emissions, and water pollution discharges.
Stodolsky, F., A. Vyas, R. Cuenca, and L. Gaines. 1995. Life-cycle Energy Savings Potential from Aluminum-Intensive Vehicles. Argonne National Laboratory.	Lightweighting, aluminum, and recycling technology.	Cradle to grave.	Energy requirements and fuel use.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Streimikiene, D., and J. Sliogeriene. 2011. Comparative assessment of future motor vehicles under various climate change mitigation scenarios. *Renewable and Sustainable Energy Reviews.* October 2011.	Biofuels, PHEVs, and HEVs.	Cradle to gate (vehicle life cycle) and well to wheels (fuels).	GHG emissions.
Sullivan, J., A. Burnham, and M. Wang. 2010. Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing. Argonne National Laboratory.	Aluminum, steel, iron, plastics, polymer, brass, copper, and lead.	Gate to gate.	None.
Sullivan, J.L., and L. Gaines. 2010. A Review of Battery Life-cycle Analysis: State of Knowledge and Critical Needs. Argonne National Laboratory.	Batteries (lead-acid, NiMH, NiCd, Na-S, and Li-ion).	Cradle to gate.	Energy requirements, GHG emissions, criteria air pollutants, other emissions, and solid waste generation.
Taub, A.I. 2006. Automotive Materials: Technology Trends and Challenges in the 21st Century. MRS Bulletin.	Magnesium, steel, aluminum, HSS, and plastics.	Not applicable.	GHG emissions.
Tempelman, E. 2011. Multi-Parametric Study of the Effect of Materials Substitution on Life Cycle Energy Use and Waste Generation of Passenger Car Structures.	Carbon-fiber reinforced thermosets, glass-fiber reinforced thermosets, HSS, and aluminum.	Cradle to grave.	GHG emissions, resource consumption, and waste generation.
Tharumarajah, A., and P. Koltun. 2007. Is there an environmental advantage of using magnesium components for light-weighting cars? *Journal of Cleaner Production.*	Lightweighting, magnesium, aluminum, and magnesium casting.	Cradle to grave.	GHG emissions.
Ungurean, C.A., and S. Das. 2007. Development of a sustainability scoring method for manufactured automotive products: a case study of auto body panels. ASME International Mechanical Engineering Congress and Exposition.	Aluminum and steel alloy.	Not applicable.	CO_2 emissions.

Table D-1. Studies Analyzed in Chapter 6, Life-cycle Assessment Literature Synthesis (continued)

Study Analyzed	Technologies/Materials Covered[a]	Life-cycle Boundaries[b]	Environmental Impacts Estimated[c]
Ungureanu, C.A., S. Das, and I.S. Jawahir. 2007. Life-cycle Cost Analysis: Aluminum versus Steel in Passenger Cars. The Minerals, Metals and Materials Society.	Lightweighting.	Pre-manufacturing, manufacturing, use, and end of life.	GHG emissions and energy requirements.
Weiss, M.A., J.B. Heywood, E.M. Drake, A. Schafer, and F.F. AuYeung. 2000. On the Road in 2020: A life-cycle analysis of new automobile technologies. Massachusetts Institute of Technology.	Lightweighting, HEVs, BEVs, fuel cells, HSS, aluminum, plastics, and alternative fuels.	Cradle to grave.	Energy requirements and GHG emissions.
Zackrisson, M., L. Avellán, and J. Orlenus. 2010. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. *Journal of Cleaner Production.*	Batteries (Li-ion).	Cradle to gate; also battery recycling.	Global warming potential, eutrophication, ozone depletion, acidification, and photochemical smog.

a. AHHS = advanced high-strength steel; BEV = battery electric vehicle; CNF = carbon nanofiber; CNF-GF = carbon nanofiber-glass fiber; E85 = an ethanol fuel blend of up to 85 percent denatured ethanol fuel and gasoline or other hydrocarbon by volume; EREV = extended range electric vehicle; EV = electric vehicle; FCEV = fuel-cell electric vehicle; HEV = hybrid electric vehicle; HSS = high-strength steel; ICE = internal combustion engine; LFP-G = phosphate-graphite; Li-ion = lithium-ion; LMO-G = lithium, manganese, and oxygen-graphite; LMO-TiO = lithium, manganese, and oxygen-titanium and oxygen; Na-S = sodium-sulfur; NCA-G = nickel, cobalt, and aluminum-graphite; NiCd = nickel-cadmium; NiMH = nickel-metal hydride; Pb-acid = lead-acid; PHEV = plug-in hybrid electric vehicle; PNC = polymer nanocomposites.

b. Cradle to gate = assessment of a partial product life cycle that includes the raw material extraction and manufacturing stages, and transportation between these stages; cradle to grave = life-cycle assessment that includes all five stages of a product's life cycle (i.e., raw material extraction, manufacturing, vehicle use, end-of-life management, and transportation between the various stages); gate to gate = assessment of a partial product life-cycle that includes only the manufacturing stage; LCA = life-cycle assessment.

c. CO = carbon monoxide; CO_2 = carbon dioxide; GHG = greenhouse gas; NO_x = nitrogen oxide; PM = particulate matter; ROS = reactive organic gas; SO_x = sulfur oxide; VOC = volatile organic compound.