PB98-117856

EPA 600/R-97-118

FEBRUARY 1998

Life Cycle Design of a Fuel Tank System

Gregory A. Keoleian, Sabrina Spatari, Robb Beal

Gregory A. Keoleian, Project Director

National Pollution Prevention Center
School of Natural Resources and Environment
University of Michigan
Dana Bldg. 430 E. University
Ann Arbor, MI 48109-1115

General Motors Demonstration Project

Project Leaders
Ronald L. Williams
Robert D. Stephens

General Motors
Research and Development
Warren, Michigan

Assistance Agreement # CR 822998-01-0

Project Officer
Kenneth Stone

National Risk Management Research Laboratory
Office of Research and Development
US Environmental Protection Agency
Cincinnati, OH 45268

I. NOTICE

The information in this document was funded wholly by the United States Environmental Protection Agency (EPA) under Cooperative Agreement number CR822998-01-0 to the University of Michigan. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. This approval does not necessarily signify that the contents reflect the views and policies of the US EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

II. FOREWARD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the abilities of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future. The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on the methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This work was sponsored by the National Risk Management Research Laboratory (NRMRL) of the U.S. Environmental Protection Agency. Since 1990, NRMRL has been at the forefront of development of Life Cycle Assessment as a methodology for environmental assessment. In 1994, NRMRL established an LCA team to organize individual efforts into a comprehensive research program. In addition to project reports, the LCA team has published guidance manuals, including "Life Cycle Assessment: Inventory Guidelines and Principles (EPA/600/R-92/245)" and "Life Cycle Design Framework and Demonstration Projects (EPA/600/R-95/107)."

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

III. Abstract

The design of automotive components is a challenging process due to the complex set of requirements that influence the automobile life cycle. This life cycle design project was a collaborative effort between the National Pollution Prevention Center at the University of Michigan, General Motors Research and Development, and the National Risk Management Research Laboratory of the U.S. Environmental Protection Agency. The primary objective of this project was to apply life cycle design tools to guide the improvement of fuel tank systems. Two alternative fuel tank systems used in the 1996 GMT 600 vehicle line were investigated: a multi-layer HDPE tank with a steel shield and PVC coated steel straps, and a steel tank with a HDPE shield and painted steel straps. The design analysis of a 31 gallon functionally equivalent fuel tank system included a life cycle inventory (LCI) analysis, performance analysis and preliminary life cycle cost analysis. The scope of the LCI study encompassed materials production, the manufacturing processes for each tank system, the contribution of each tank system to the use phase burdens of the vehicle, and end-of-life management processes based on the current vehicle retirement infrastructure.

The life cycle inventory analysis indicated lower energy burdens for the HDPE tank system and comparable solid waste burdens for both systems. The total life cycle energy consumption for the steel and HDPE tank systems were 4.9 GJ and 3.6 GJ per tank, respectively. The use phase was responsible for a majority of the energy consumption and most of the air pollutant emissions inventoried. In contrast, total solid waste burdens of 13 kg were concentrated in the material production stage for the steel tank system and the end-of-life management phase accounted for a majority of the 14 kg of total solid waste for the HDPE system. Based on results of the LCI, streamlined environmental metrics were proposed. While both systems meet basic performance requirements, the HDPE system offers design flexibility in meeting capacity requirements within defined spatial constraints. The HDPE system also provided a $10 fuel cost savings over 110,000 vehicle miles traveled.

The life cycle design framework was useful in evaluating environmental, performance, and cost tradeoffs among and between both fuel tank systems. Specific limitations of the study results and recommendations for additional research are provided in the full project report.

This report was submitted in partial fulfillment of Cooperative Agreement number CR822998-01-0 by the National Pollution Prevention Center at the University of Michigan under the sponsorship of the U.S. Environmental Protection Agency. This work covers a period from April 1, 1995 to July 31, 1997, and work was completed August 1, 1997.

IV. Contents

V. Acknowledgment

We wish to thank Dr. Ronald Williams, Principal Research Scientist and Mr. Robert Stephens, Staff Scientist at GM's Environmental Research Department for collaborating with us on this project. They were instrumental in conducting this project and both made many significant and valuable contributions during all phases of this research. Mr. Terry Cullum, Energy and Environmental Staff and Dr. Roger Heimbuch, Director of Materials and Fastening were very helpful in initiating this project and played an important role in the critical analysis and interpretation of results. Before joining the research team at the University of Michigan, Ms. Sabrina Spatari played a major role in this research at the Environmental Research Department of GM, Mr. Minoo Daroga of Truck Materials Engineering, Dr. Tom Ellis and Mr. John Laverty of the Polymers Department, Mr. Tom Olmin of Powertrain and Mr. Phil Yaccarino of the Chassis Center provided valuable input and data necessary for our research. In addition, Delphi Automotive and Walbro Automotive Corporation provided key environmental inventory data for steel tank and HDPE tank manufacturing, respectively.

1. Project Description

1.1 Introduction

Integration of environmental considerations into the design process represents a complex challenge to designers, managers and environmental professionals. A logical framework including definitions, objectives, principles and tools is essential to guide the development of more ecologically and economically sustainable product systems. In 1991, the US Environmental Protection Agency collaborated with the University of Michigan to develop the life cycle design framework [1][2][3]. This framework is documented in two publications: *Life Cycle Design Guidance Manual* [1] and the *Life Cycle Design Framework and Demonstration Projects* [3].

Two demonstration projects evaluating the practical application of this framework have been conducted with Allied-Signal and AT&T. AT&T applied the life cycle design framework to a business phone [4] and Allied-Signal investigated heavy duty truck oil filters [5]. In these projects environmental, performance, cost, and legal criteria were specified and used to investigate design alternatives. A series of new demonstration projects with Dow Chemical Company, Ford Motor Company, General Motors Corporation, United Solar and 3M Corporation have been initiated with Cleaner Products through Life Cycle Design Research Cooperative Agreement CR822998-01-0. Life cycle assessment and life cycle costing methods are applied in these demonstration projects in addition to establishing key design requirements and metrics. This report provides a description of the General Motors Corporation project that investigated the design of fuel tank systems. An overview of the life cycle design framework is provided in Appendix C of this document.

1.2 Project Description

This pilot project with General Motors Corporation applied the life cycle design (LCD) framework and tools to the design of fuel handling and storage systems used in the 1996 GMT600 vehicle line. A key component of this project was the evaluation of environmental burdens along with the life cycle costs and performance of two fuel tank designs. The project began on June 12, 1995. A cross-functional core team from General Motors Corporation, Delphi Automotive Systems, a GM subsidiary, and Walbro Automotive Corporation, a GM supplier, participated with University of Michigan project team members. GM team members included:

Division	Team Member
General Motors	
Health and Environment (R & D)	Ronald Williams
Health and Environment (R & D)	Robert Stephens
Health and Environment (R & D)	Sabrina Spatari
Environmental and Energy Staff	Terry Cullum
Materials and Fastening Center	Roger Heimbuch
Truck Materials Engineering	Minoo Daroga
Truck Materials Engineering	Bill Ptashnik
Truck Materials Engineering	Carol Lung
Truck Materials Engineering	Brad Rogers
Polymers Department (R & D)	Tom Ellis
Polymers Department (R & D)	John Laverty
Powertrain	Tom Olmin
Chassis Center	Phil Yaccarino
GM Subsidiary/Suppliers	
Delphi Automotive	Daryl Smith
Delphi Automotive	Neil McGuire
Delphi Automotive	Matt Malott
Delphi Automotive	Mark Matthews
Walbro Automotive Corporation	Christopher Quick
Walbro Automotive Corporation	Dan Wishart
Walbro Automotive Corporation	Ron Parent
Walbro Automotive Corporation	Dan Arbou
Other	
Modern Engineering	Leonard Jones
Modern Engineering	Pat Alexander

Walbro and Delphi are the manufacturers of plastic and steel fuel tanks respectively. They each supply fuel tanks that meet the design requirements specified by GM. Modern Engineering is a contract company that participated in the design and development of the GMT600 vehicle line.

From the University of Michigan, core team members from the National Pollution Prevention Center (NPPC) included

National Pollution Prevention Center, University of Michigan	
Assistant Research Scientist	Gregory Keoleian
Research Assistant	Robb Beal
Research Assistant	Mike Hicks
Research Assistant	Michelle Manion
Research Assistant	Sabrina Spatari

In addition to the GM and NPPC team, Ken Stone from the US EPA, National Risk Management Research Laboratory served as the project officer and coordinated the external review of this report.

Steel fuel tanks, which are manufactured by stamping and welding processes, have traditionally been used on motor vehicles. However, as with many automotive components, weight reduction goals are driving a trend toward lighter weight materials which are equivalent in performance to traditional materials. For example, with the G cutaway van, blow molded, coextruded multi-layer (HDPE) fuel tanks are being introduced for automotive applications.

The boundary of this project encompasses life cycle stages from material processing, manufacturing, use, and retirement. The data regarding material processing and retirement stages were gathered and assimilated by the NPPC, while data regarding the manufacturing and use stages were gathered by General Motors. A spreadsheet database was developed for the environmental, cost, and performance metrics based on available data. The results of the comparative assessment will be used to develop practical tools for engineering product design.

1.3 Product Selection

Two fuel tank systems used on the 1996 GMT600 vehicle line were analyzed by the project team members: a multi-layer high density polyethylene (HDPE) tank system and a steel tank system. Currently, GM's passenger G Van (curb weight 6100 lb.), equipped with a 5.7 l central point injection engine uses a 31 gallon steel tank. A 34.5 gallon multi-layer plastic tank is used on the cutaway version of the cargo van. To establish functional equivalency with the steel tank, the HDPE tank volume was set to 31 gallons. The HDPE fuel tank weight was scaled down accordingly. A discussion of this weight and volume adjustment is provided in Appendix A, along with appropriate calculations.

The GMT600 vehicle line falls under General Motors Truck platform. G van models include the Chevy Express/Savana passenger van, and the Chevy Commercial, Savana Special, Chevy RV/Savana, and Camper Special cutaway vans. Cutaway vans are modified versions of the G cargo van. They are assembled with the G Van chassis and front cabin, but are then sent to after-market assembly plants where they are fitted with application-specific attachments such as ambulance cabins and campers.

The steel fuel tank system, which is used on the passenger van, is produced in large volume at the Delphi manufacturing plant in Flint. This plant manufactures fuel tanks for an average of 171,000 passenger G vans per year in addition to approximately 3.7 million fuel tanks for other model vehicles. On the other hand, the multi-layer plastic tank is used on the low production cutaway van, requiring a production volume of 20,000 tanks per year. Ideally, the production rates for both plants should be comparable to minimize economy scale effects on the results. However, using actual plant data provides a more accurate characterization of each system than engineering model data. HDPE tank manufacturing burdens are based in part on multiple data sources and model sensitivity to production rates is difficult to assess.

Plastic tanks date back to the early 1950's. The success of Volkswagen's use of high molecular weight polyethylene tanks in the early 1970's has considerably influenced the growth of HDPE fuel tanks in North America [6]. During the late 1980's and early 1990's, American companies began experimenting with using plastic fuel tanks. Delphi studies forecast that by the year 2000, 40% of all North American-produced passenger cars and light trucks will have plastic fuel tanks and 60% will have steel tanks. By the year 2005, they forecast that 60% of fuel tanks will be made of plastic and 40% will be made of steel [7].

Earlier versions of the HDPE fuel tank used fluorination to reduce fuel permeation. With the invention of the coextrusion blow molding process by Krupp-Kautex, plastic fuel tanks are now more permeation-resistant than their predecessors. Multi-layer plastic tanks are now better able to meet automobile emissions requirements as guided by the EPA and CARB than previous monolayer tanks.

1.4 Objectives

The overall purpose of this project is to apply LCD methods to better integrate environmental considerations into product system design and management. This project focuses on material selection analysis and decision-making for the design of fuel tanks. The project seeks to identify specific tools and develop environmental metrics that can be used in the GM product development process. The scope of the study is to perform a comparative evaluation of the HDPE and steel fuel tanks used on the 1996 GMT600 cutaway van and passenger van. Specific objectives include:

- Compare steel and multi-layer HDPE fuel tanks and auxiliary components that are not common between the two systems for the 1996 GMT600 passenger and cutaway vans using the following LCD methods: multicriteria matrices, life cycle inventory analysis, and life cycle cost analysis
- Evaluate key criteria and develop environmental metrics for material selection
- Facilitate cross-functional team interaction and networking to effectively use GM's internal resources
- Demonstrate the value and barriers associated with the use of LCD as an engineering design method to management

GM's environmental principles recognize the importance of the entire product life cycle in environmental management. This project is one GM initiative to operationalize this principle through product design. The fuel tank was selected for a pilot study to test LCD approaches. GM's goal is to gather an objective and quantitative database of environmental, energy, and cost impacts covering the entire life cycle of a plastic and steel fuel tank. This cradle-to-grave approach will allow GM to fully assess the benefits and corresponding data needs for selecting one fuel system over another. For example, if materials are primarily selected because of weight savings issues during the use phase of the vehicle's life, end-of-life management issues might be ignored. Similarly, if material selection focuses on issues of recyclability and end-of-life management, weight savings and fuel economy issues might be ignored. For these reasons, such a study must consider all potential environmental impacts a materials choice will have over the entire life of the fuel tank and vehicle. The results of this study have the potential to influence the future selection of fuel tank materials at GM.

2. Systems Analysis

2.1 Scope

This study considers the entire life cycle of vehicle fuel tank systems from materials production, which includes raw material acquisition and materials processing, through end-of-life management. Specific flows which are either estimated or not inventoried are described in Section 2.3 Boundaries and Assumptions. The system also includes the contribution of the fuel tank to the environmental burdens related to vehicle use. Consequently, the effect of the tank weight on fuel consumption and the concomitant emissions are also evaluated. The design life of each fuel tank is eleven years or 110,000 miles, which is based on an average of 10,000 miles of vehicle travel per year.

2.2 Product Composition

For each tank system, the scope of the analysis includes all tank system components that are unique to that system. For example, the steel tank requires a plastic shield to protect it from environmental exposure, which includes humidity, salt, stones, and many other factors, whereas the plastic tank is inherently more resistant to corrosion and damage due to environmental exposure. On the other hand, for this particular design application, because of component layout, the plastic tank requires a metal (steel) heat shield, whereas the steel tank does not. Furthermore, the straps, which secure the tank to the frame, are different for each fuel system; therefore, they have been included in the study. Other auxiliary components of the fuel system include the sending unit, fuel lines, and fuel filter. These have not been included in the scope because they are common between the two systems.

Each fuel tank system consists of three components: the tank which contains the fuel, straps which secure the tank to the frame, and a shield which has a unique function for each fuel tank system. It should be noted however, that not all plastic fuel tank systems require a metal heat shield. The GMT600 tank requires one because of its orientation on the vehicle frame. Plastic fuel tank systems for other vehicle designs have been designed without a metal heat shield.

For the steel tank system, the fuel tank is plain carbon steel (1008-1010), with a nickel-zinc coating and an aluminum epoxy paint coat. The straps are made of hot dipped galvanized steel with a painted finish. The tank shield is made of HDPE.

For the HDPE tank system, the fuel tank is a six-layer plastic structure which consists primarily of HDPE. The six layers of the plastic tank include from outer to inner layer: virgin HDPE mixed with carbon black, a regrind layer which incorporates flash and scrapped tanks, an adhesive layer, an ethyl vinyl alcohol (EVOH) copolymer permeation barrier, an adhesive layer, and finally a virgin HDPE inner layer. The straps for this tank system are also hot-dipped galvanized steel with a PVC coating. The tank shield is plain carbon steel.

The steel fuel tank has a volume of 31 gallons while the HDPE tank is 34.5 gallons. The HDPE tank weight was normalized to 31 gallons so that the two tanks delivered equivalent functionality. The procedure for normalization is provided in Appendix A.

The product composition by mass for each tank system is shown in Figure 2-1. The total weight of the steel and HDPE tank systems (including shield and straps) are 21.92 kg and 14.07 kg, respectively.

2.3 Boundaries and Assumptions

The boundaries and major assumptions for this study are given in Table 2-1. A more detailed discussion about the assumptions made is given in Section 3: Data Collection and Analysis.

2.4 Product System for Steel Fuel Tank Systems

Material production	Production of Steel • Raw materials acquisition and production by BOF process Production of HDPE • Raw materials acquisition, ethylene production and polymerization of virgin HDPE
Manufacturing & Assembly	• Stamping and welding to manufacture steel tank • Injection molding to manufacture HDPE shield
Use	• Use of the Tank System
End Of Life	• Shredding of tank system to recover scrap steel • Disposal of HDPE ASR in landfill

The life cycle of the steel fuel tank system is illustrated in Figure 2-2. The figure shows the flow of materials beginning with extraction of minerals and proceeds through manufacture and ends with various waste management options.

2.5 Product System for HDPE Fuel Tank Systems

Material production	Production of HDPE • Raw materials acquisition, ethylene production and polymerization of virgin HDPE Production of Steel • Raw materials acquisition and production by BOF process Production of PVC • Raw materials acquisition, vinyl chloride production and polymerization of virgin HDPE
Manufacturing & Assembly	• Blow molding, machining, welding of HDPE tank • Stamping to manufacture steel strap
Use	• Use of the Tank System
End Of Life	• Shredding of tank system to recover scrap steel • Disposal of HDPE ASR in landfill

The life cycle of the HDPE fuel tank system is illustrated in Figure 2-3. The figure shows the flow of materials beginning with extraction of minerals and proceeds through manufacture and ends with various waste management options.

The steel shield and straps are recycled in the end-of-life phase whereas the HDPE tank is currently disposed in a landfill as part of the automotive shredder residue (ASR).

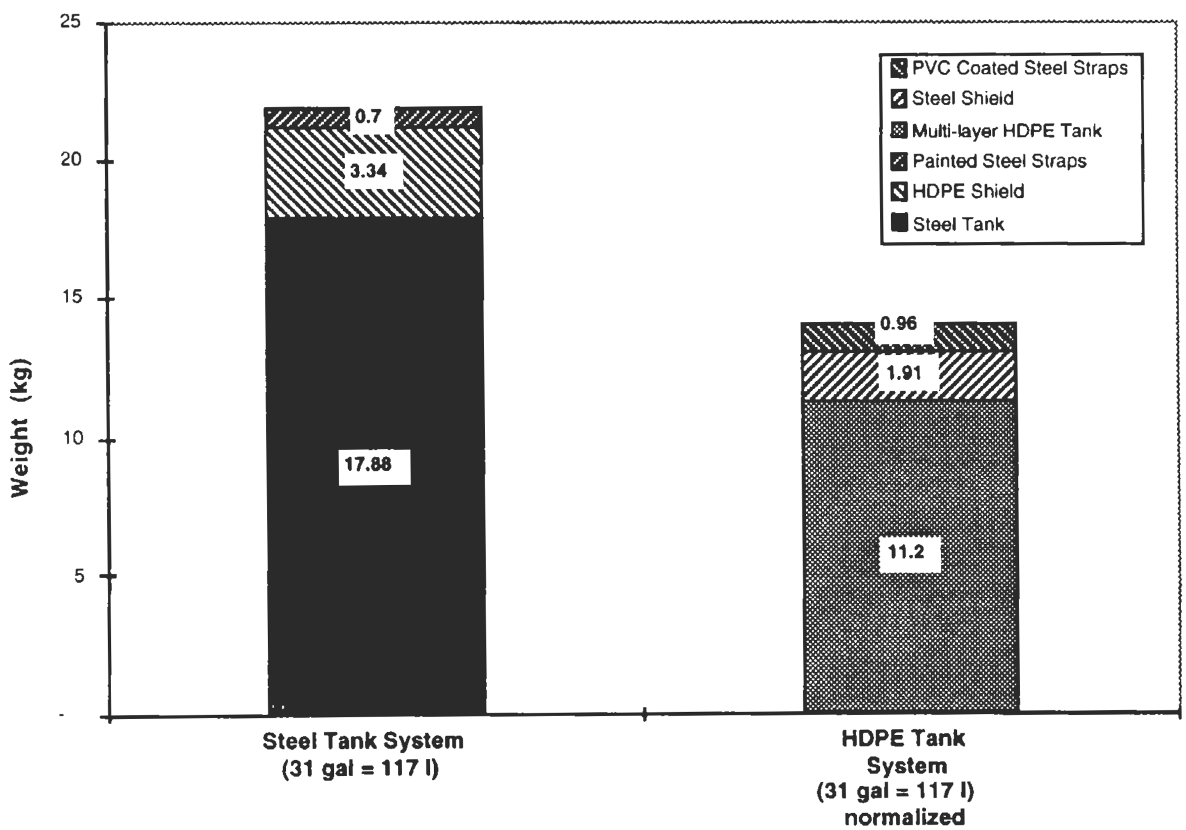


Figure 2-1 Composition of Fuel Tank Systems

Table 2-1 Boundaries and Major Assumptions for Fuel Tank Systems

LC Stage	Steel Tank	HDPE Tank
Material Production	• The paint applied to the steel straps was modeled as steel because of the lack of data on the amount of paint applied	• HDPE was substituted for the following components of the multi-layer tank: Carbon Black PE-based Adhesive EVOH • PVC applied to straps was assumed to be emulsion PVC
Manufacturing	• None of life cycle burdens of process materials were inventoried due to data availability • Scrap rate of 2% was estimated for HDPE injection molding process based on generic scrap rate data • No scrap was considered to be generated in steel strap fabrication • Zinc-Nickel coating and soap lubrication were not included due to data availability • Copper is used as a process material in steel tank fabrication. Copper recycling was not inventoried due to data availability • Foam pads used for tank distribution were excluded based on mass	• None of life cycle burdens of process materials were inventoried due to data availability • No scrap was considered to be generated in steel strap fabrication • The energy consumption for tank blow molding was based on generic blow molding/injection molding energy data.
Use	• Contribution of tank system weight to use phase energy consumption is calculated by assuming that weight is linearly proportional to fuel consumption. No secondary weight savings were estimated. • Vehicle use phase emissions are the sum of US EPA in-use emission standards for light trucks plus off-cycle emissions. • Tank system contribution to vehicle emissions is obtained by assuming that emissions are proportional to total vehicle fuel consumption allocated to the fuel tank system; the allocation rule is accurate for CO_2 but for other gases the relationship is non-linear.	
End Of Life	• All components are considered to be shredded. Shredding fuel requirements were considered independent of the type of material shredded or shape of the part • Steel is assumed to be recovered at 100% within each system • All HDPE is assumed to be landfilled • Preliminary analysis indicated that steel recovered at end of life generated (at least) the amount of scrap steel needed for steel making. No credit was given to the system for any steel recovered in excess of the amount needed for steel making	

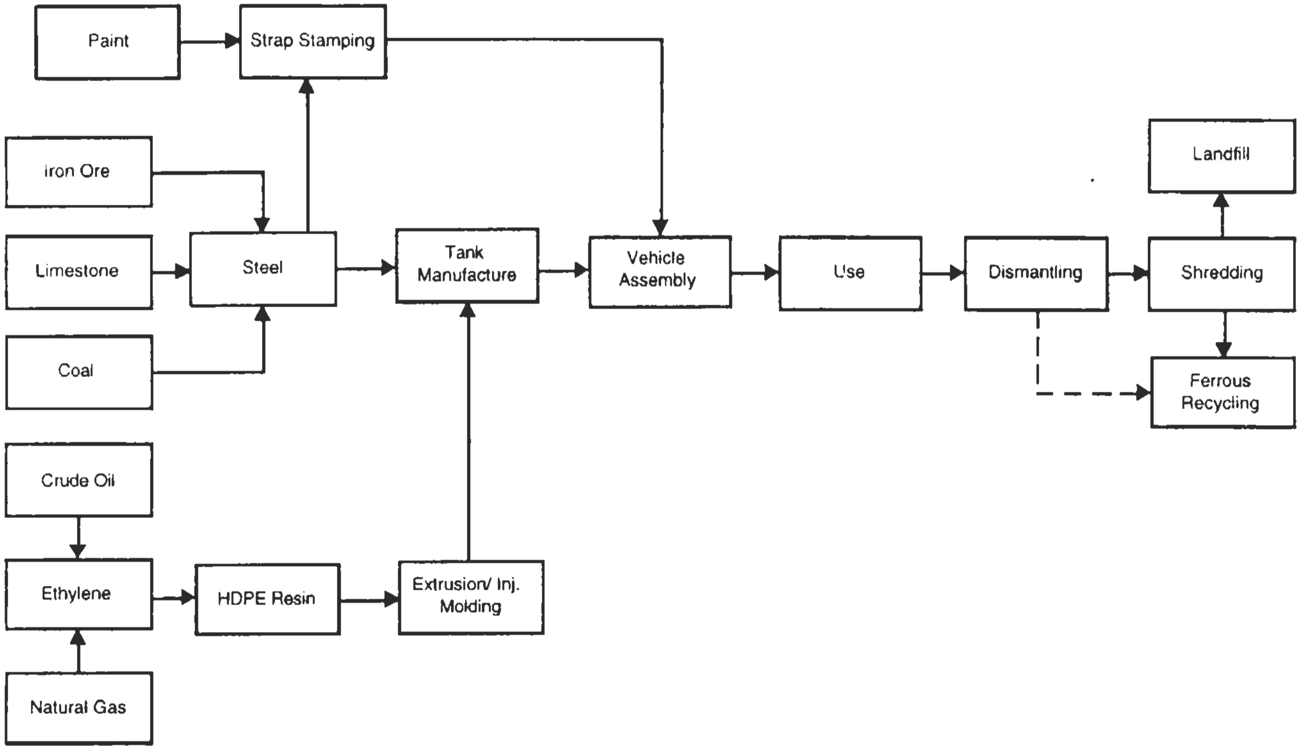


Figure 2-2. Steel Fuel Tank System

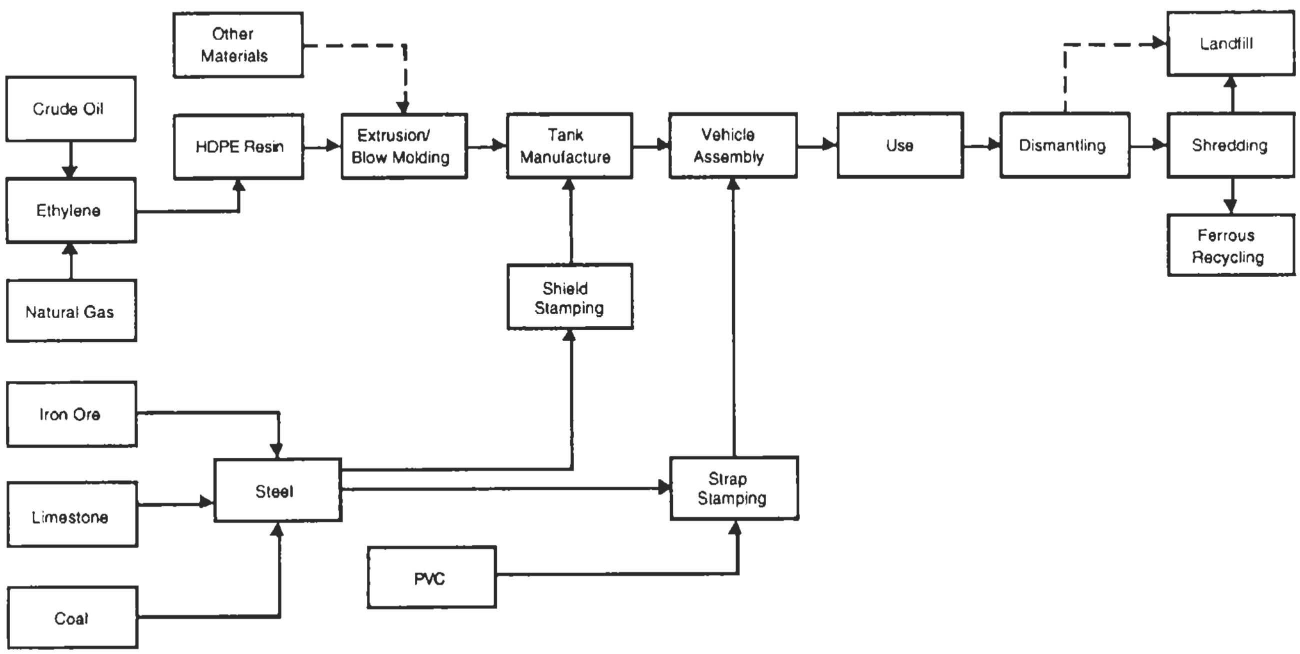


Figure 2-3. HDPE Fuel Tank System

3. Data Collection and Analysis

3.1 Methodology

This chapter describes environmental, cost and performance analyses for two fuel tank designs. A life cycle inventory analysis was conducted following EPA and SETAC guidelines. A life cycle cost analysis was conducted following conventional practices. This analysis did not include external costs that are not reflected in market prices.

Environmental data evaluated were material and energy consumption, solid waste generation, and air and water pollutant releases. Environmental data in the material production stage were obtained from published sources [8], [9], [10], [11]. Environmental data in the manufacturing stage were obtained from GM facilities and supplemented with data from external [12] and published sources, [13], [14]. In the use phase, fuel efficiency data was provided by GM and emissions standards for light duty trucks were obtained from the USEPA and supplemented with off-cycle emissions data from Ross [15]. In the retirement phase, shredding data was also obtained from published results [16], [17].

Emissions and wastes for different life cycle stages were obtained as the sum of process and fuel-related emissions and wastes. A discussion of the approach used to aggregate emission categories from disparate data sources is given in Appendix B.

Fuel related burdens can be separated into combustion and precombustion categories. All precombustion burden data, except in the material production phase, were obtained from published data [11].

Transportation requirements throughout the life cycle are summarized in Section 3.2.5.

Cost data evaluated include material cost, after-market replacement cost, use cost, and retirement cost. The cost of materials were evaluated from unit cost data from published sources [18]. A cost assessment for the manufacturing of each fuel tank was excluded from the study because such information is proprietary, and hence data is not available for publishing. However, after-market costs were obtained from a GMC Truck dealership in Saginaw, MI. The after-market price of each fuel tank system should reflect manufacturing and material costs. Use phase costs were calculated from the price of consumed fuel over the useful life of the vehicle, but this cost was not corrected for potential inflation. Finally, retirement costs were evaluated using techniques from Kar and Keoleian (1996) [16] which incorporate a retirement spreadsheet model of the American Plastics Council (APC) [19]. Transportation and disposal costs were calculated using data from Franklin Associates [11] and the National Solid Waste Management Association (NSWMA) (1995) [20].

3.2 Life Cycle Inventory Analysis

3.2.1 Material Production

Material production energy data and emissions factors were used to evaluate the environmental burdens for the steel and HDPE tank systems.

Steel

Environmental data for the material production of plain carbon steel were approximated using data for tin-plate steel from a European environmental database of packaging materials [8]. The data represents Western European technology of production. The data includes hot and cold rolling of the steel to produce sheet. The nickel-zinc coating was not included in the scope because of data availability. The emissions related specifically to the aluminum epoxy paint application were excluded from the scope due to insufficient data. The data include the burdens associated with the tinning of steel (which could not be disaggregated from the inventory data set) and the reprocessing of scrap steel. The steel had a tin content of 0.4 percent for this data set.

Additionally, the data assumes a transport distance of 7500 kilometers for iron ore transport to Germany. This distance would be considerably shorter for steel produced in the US.

Table 3-1 summarizes the cumulative environmental data for rolled steel.

Table 3-1 Environmental Data for Material Production for Tin-Plate Steel

Primary Energy (MJ / kg)		33.5
Waste (g / kg)		
Air emissions		
	Carbon Dioxide*	1571
	Carbon Monoxide	1.3814
	Hydrocarbons	16.52
	Nitrogen Oxides	2.73
	Sulfur Oxides	8.45
	Particulates	26.96
	Other Organics	0.0169
Solid waste		398.6
Water effluents		
	Dissolved Solids	0.9516
	Suspended Solids	0.318
	BOD	0.0052
	COD	0.0013
	Oils	0.5142
	Chlorides	0.0
	Metals	.1002
	Sulfides/Sulfates	0.0004

source: [8] [21]

* Carbon dioxide data point from McDaniel

The material production energy for the steel tank is computed using the equation:

$$E_{matl.prod.} = E_{steel} \times m_{steel} \tag{3-1}$$

where,

E_{steel} = the specific energy required to produce one kilogram of steel (MJ/kg)
m_{steel} = the mass of rolled steel required to produce one fuel tank

HDPE

Environmental data for the material production of HDPE were obtained from the European Center for Plastics in the Environment now known as the Association of Plastic Manufacturers in Europe's (APME) Technical and Environmental Center [9]. The data represents Western European technology of production. The data is for virgin HDPE. Based on the multi-layer tank composition and data availability, the tank was modeled as 100 percent HDPE. Minor consistuents of the tank by weight include the carbon-mixed HDPE outer layer, polyethylene-based adhesive, and EVOH barrier material. The adhesive and EVOH material constitute less than 1% of the total tank material on a volume basis.

Table 3-2 summarizes the cumulative environmental data for HDPE.

PVC

Environmental data for the material production of PVC were obtained from APME [10]. The data represents Western European technology of production and is based on emulsion polymerization since this type of PVC is used in dipping applications.

Table 3-3 summarizes the cumulative environmental data for PVC.

Table 3-2 Environmental Data for Material Production for HDPE

Primary Energy (MJ / kg)		80.98
Waste (g / kg)		
Air emissions		
	Carbon Dioxide	940
	Carbon Monoxide	0.6
	Hydrocarbons	21.1
	Nitrogen Oxides	10.1
	Sulfur Oxides	6
	Particulates	2
	Other Organics	0.005
Solid waste		32.04
Water effluents		
	Dissolved Solids	0.5
	Suspended Solids	0.2
	BOD	0.1
	COD	0.2
	Oils	0.03
	Chlorides	.8
	Metals	0.3
	Sulfides/Sulfates	4

source: [9]

Table 3-3 **Environmental Data for Material Production for PVC**

Primary Energy (MJ / kg)		74.88
Waste (g / kg)		
Air emissions		
	Carbon Dioxide	2741
	Carbon Monoxide	1.6
	Hydrocarbons	26
	Nitrogen Oxides	19
	Sulfur Oxides	18
	Particulates	5.4
	Other Organics	1.389
Solid waste		335.8
Water effluents		
	Dissolved Solids	.76
	Suspended Solids	4.2
	BOD	.06
	COD	1.2
	Oils	.05
	Chlorides	39
	Metals	2.22
	Sulfides/Sulfates	4

source: [10]

3.2.2 Manufacturing

Steel Tank

Environmental data for steel tank manufacturing were obtained from GM. The data scope includes stamping/trimming, washing, welding, and auxiliary component attachment. The copper used as a welding aid is recycled and not consumed to any appreciable degree.

Both electricity and natural gas are consumed in manufacturing. Electricity used for steel sheet stamping accounts for a major portion of the energy consumed in steel tank manufacturing.

A detailed illustration of steel fuel tank manufacturing is provided in Figure 3-1. The manufacturing process begins with the stamping of pre-cut cold rolled steel. The stamped steel is trimmed and appropriate holes are pierced for installing components such as the sending unit and rollover valves. Each tank half is then washed to remove soap lubricant. Eighty percent of the water used in this manufacturing process is consumed during soap lubricant washing. Additional wastewater comes mainly from the cooling and chilling system from the welding operation. The wastewater used in this washing operation is sent to a water treatment facility within the Delphi industrial complex, and is combined with wastewater from four other plants.

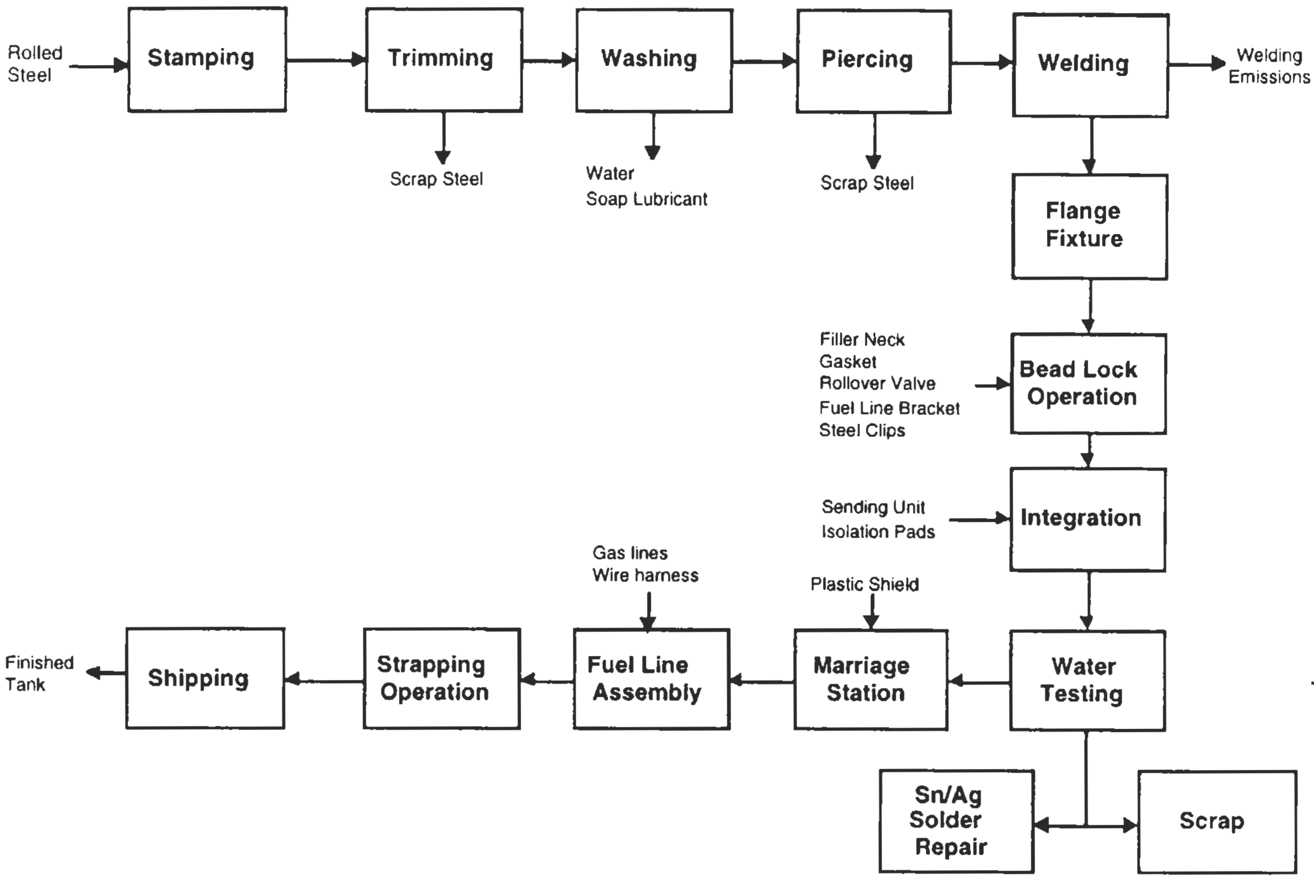


Figure 3-1 Steel Tank Manufacture

Once the top and bottom halves are stamped, trimmed, washed and pierced, they are welded together. Resistance welding is used. Air emissions from welding consist of manganese, nickel, chromium, zinc, particulates and hydrocarbons from the aluminum-based epoxy paint coat. Emission factors for these air pollutants based on plant data are provided in Table 3-4. Emission factors for various processes are available from EPA based on the material specifications for the steel and the area being welded; however, currently there are no EPA emission factors for soudronic welding.

Table 3-4. Atmospheric Emissions for Steel Tank Manufacturing

Emission	Amount (g/tank)
Mn	0.0868
Ni	0.0658
Cr	0.0500
Zn	0.0605
Particulate	1.841
Hydrocarbon	0.684

source: [22]

After the two tank halves are welded together, auxiliary components are attached, including the filler neck, gasket, rollover valve assembly, steel clips, and the plastic fuel line bracket. The tank is then sent for leak testing.

Each tank is water tested for leaks as a quality control mechanism. There are two possible failure modes. One failure mode is known as a seam leak due to hot welding. It is repaired by soldering the leaking area with a 99%Sn/1%Ag-based solder. The other possible failure mode is an edge leak which is due to cold welding. Only 10% of edge leaks are repairable, the remaining 90% of edge leaking tanks are scrapped. 100% of tanks that are rejected because of edge leak failure are recycled.

The tanks that pass leak testing are sent to a shield tank marriage station, where the HDPE stone shield is attached, and the fuel filter, filter strap, canister and canister strap are installed. Next the fuel line assembly, which includes two gas lines, a wiring harness, a wiring harness locking clip, and a plastic gas line bracket is attached to the fuel tank.

Finally, the tanks are prepared for shipping. They are stacked onto shipping racks and sent to the shipping docks. They are transported to the Wentzville, MO G van assembly plant via rail.

Steel scrap is generated in the stamping process. Approximately, 3.3 kilograms per tank of scrap steel is generated from trimming and piercing operations and approximately 5.6×10^5 kilograms total for the production of 171,000 tanks per year. Furthermore, 0.43 percent of all steel tanks produced are scrapped because they have unrepairable edge leaks, yielding an additional 1.3×10^4 kilograms of scrap per year. This steel scrap is transported to a steel mill and used to produce more steel products. The transport of this scrap steel is not included in the scope. Additional sources of scrapped tanks include those that fail quality control tests and a portion of tanks returned from the Wentzville, MO G van assembly plant. Thus, the total amount of scrap generated in association with the GMT600 steel tank manufacturing which includes tank trimmings, and scrapped tanks due to edge leaks, quality control failure, and assembly plant returns is 5.8×10^5 kilograms.

Waterborne emissions result primarily from tank washing to remove lubricant. As previously stated, the wastewater from this washing step is combined with wastewater from four other plants and is treated in a wastewater treatment plant. Eighty percent of the treated wastewater originates at the fuel tank manufacturing plant. Emissions include oil and grease, zinc, nickel, tin, silver, and copper. Table 3-5 summarizes the levels of these emissions after treatment. One hundred percent of the emissions from this wastewater treatment plant were allocated to the tank system, despite the fact that the wastewater analysis includes emissions from four other plants. Hence these emissions represent the upper limit of waterborne releases.

The water emissions data shown in Table 3-5 is based on the monthly average concentrations measured in 1995. Production of the 1996 GMT600 began in November 1995, and will continue through much of 1996. It should be noted that heavy metal concentrations have steadily decreased over the years in which measurements have been taken. Delphi expects this to be the case for 1996, while the GMT600 is in production. Hence, the upper limits indicated in Table 3-5 are expected to be lower for the steel tank studied.

Table 3-5. Upper Limits for Waterborne Emissions for Steel Tank Manufacturing

Emission†	Amount (mg/tank)
Copper	.029
Nickel	.944
Zinc	15.90
Oil and Grease	170.8

source: [22]

† based on emissions data from multiple plants

Table 3-6 summarizes the key parameters for steel tank manufacture.

Table 3-6. Steel Tank Manufacturing Data

Parameter	Value
Overall Scrap Rate	18.9%
Total Energy Consumption (Precomb+Comb)	2.658 MJ/kg

source: [22]

For steel strap manufacture, the data scope includes steel stamping. Steel stamping energy data were obtained from the International Iron and Steel Institute [14]. No scrap was assumed to be generated in producing the straps.

For the HDPE shield manufacture, the data scope includes injection molding. HDPE injection molding energy requirements were estimated from generic data for polyolefins blow molding/injection molding [12]. No scrap was assumed to be generated.

HDPE Tank

Environmental data for HDPE tank manufacturing were obtained from GM sources and the Steven's Institute of Technology [12]. The data scope includes tank blow molding, machining, and auxiliary component attachment.

Energy requirements for HDPE tank manufacturing were based on HDPE blow molding/injection molding energy requirements obtained from the Steven's Institute of Technology [12].

Particulate and hydrocarbon air emissions were estimated from Barlow [13].

A detailed process flow diagram of plastic fuel tank manufacturing is illustrated in Figure 3-2. This manufacturing process begins with the mixing of resin with appropriate additives in six individual mixing vessels. Each of the six polymer layers is fed through six individual extruders prior to entering the blow molder. The fuel tank is then molded. Flash is removed, sent to a regrinder and re-incorporated into the extruding and molding stages. The molded tank is cooled to retain its shape, then sent to a piercing and machining station. Auxiliary components such as rollover valves and clips are then welded onto the tank, while other components such as the sending unit and fuel lines are assembled onto the tank. Each tank is leak tested in a water bath. One tank per shift of production is filled with ethylene glycol and drop tested in a testing chamber. The ethylene glycol used in this test is drained from the tank and reused. All finished tanks are placed on shipping racks and are sent to the assembly plant by truck.

Process materials for this operation include water for cooling machinery and leak testing, machining and lubricating fluids, ethylene glycol for drop testing, and LDPE for purging the EVOH extruder. According to the manufacturer, water is sent directly to the drain without any pre-treatment. The manufacturer did not provide any data on the quantity or composition of water sent to the drain. The ethylene glycol is recycled and reused. The LDPE used to purge the EVOH extruder is landfilled because it cannot be incorporated into the product.

For steel straps and shield manufacture, the data scope includes steel stamping. Steel stamping energy data was obtained from the International Iron and Steel Institute [14]. No scrap was assumed to be generated.

The steel straps are coated with 29.75 grams of PVC per strap. The mass of PVC coating was estimated from the strap geometry.

Table 3-7 summarizes the key parameters for HDPE tank manufacturing.

Table 3-7. Plastic Tank Manufacturing Data

Parameter	Value
Overall Scrap Rate	1.7 %
Total Energy Consumption (Precomb+Comb)	13.96 MJ/kg

source: [22], [11]

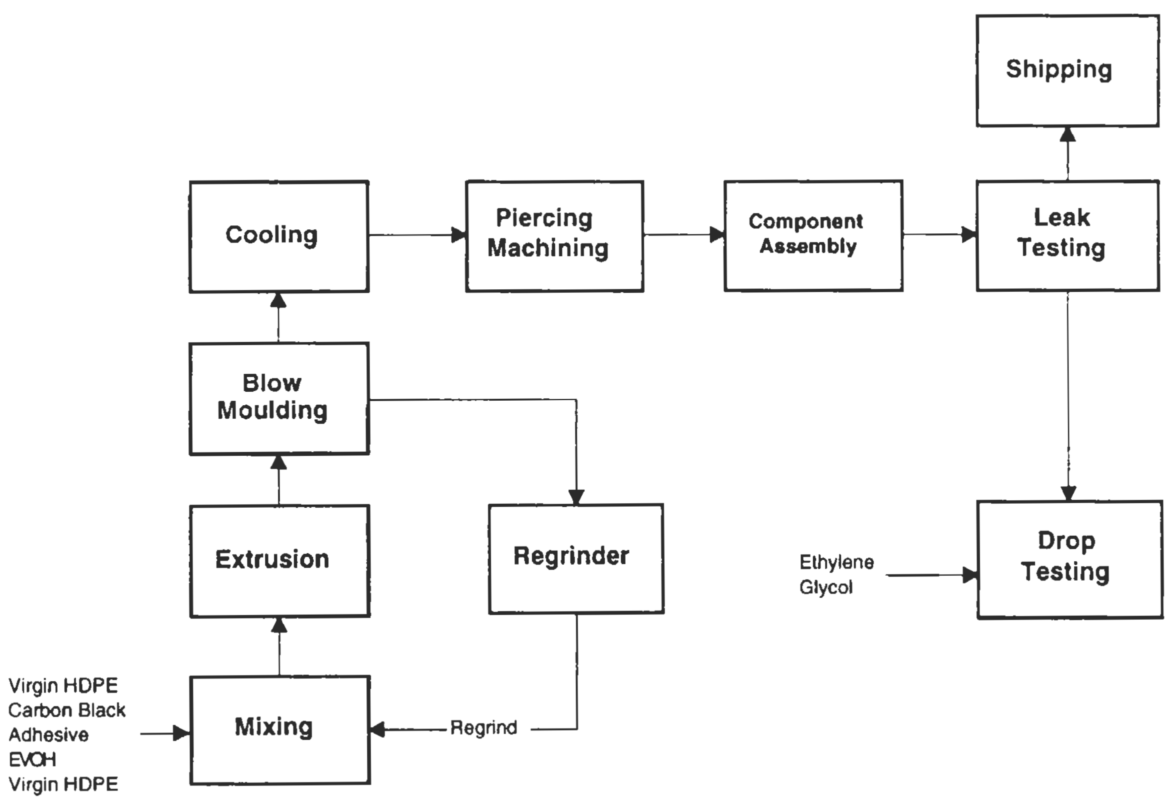


Figure 3-2 Multilayer Plastic Fuel Tank Manufacture

Three sources of scrap formation exist during the manufacture of plastic fuel tanks, including: 1) flash, i.e. excess blow-molded material, 2) scrapped fuel tanks, i.e. tanks that fail to meet quality specifications, and 3) waste material generated during start-up and shut-down. This scrap consists of the components of the multi-layer fuel tank, i.e., HDPE, EVOH, and the polyethylene-based adhesive. A large portion of shut-down waste consists of LDPE. Residual amounts of LDPE are present during start-up; therefore, these molds cannot be incorporated as regrind and must be landfilled.

The multilayer tank manufacturer estimates that flash represents 30% of fuel tank weight. Flash is reground and does not contribute significantly to solid waste leaving the manufacturing facility. However, approximately 1.5% of all reground material is landfilled. Assuming a plastic fuel tank weight of 11.2 kg, flash contributes 0.05 kg of solid waste per tank.

Tank scrappage rates for the multilayer tank were not available from the manufacturer so data from monolayer tank manufacturing was used as a rough estimate. A monolayer tank manufacturer indicated that approximately 9.3% of all low production volume tanks do not meet quality specifications. This scrappage rate was assumed for the multi-layer tank used in the GMT600 cutaway van. All scrapped tanks were assumed to be re-incorporated into the regrind layer of the multi-layer fuel tank. Therefore, only the 1.5% of regrind to which the scrapped tanks contribute, will actually be landfilled. Thus, of the 21,860 tanks manufactured in a year, 1,860 will be reincorporated as regrind.

The multilayer tank manufacturer estimates that approximately 249.5 kg of waste material is generated during each start-up of a production run. This start-up material is landfilled. At full G van tank production rates, approximately 2100 tanks will be manufactured per production run. This represents 0.119 kg of waste material per tank, or 2744 kg of landfilled material per year, assuming there are eleven start-up cycles per year.

Table 3-8 summarizes the main sources of plastic waste and the amount generated per tank during manufacturing.

Table 3-8 Solid Waste Summary

Source of scrap	Mass (kg per tank)
Flash	0.05
Scrapped tanks	0.016
Start-up wastes	0.119
Shut-down	NA

The overall scrap rate shown in Table 3-7 includes plastic waste generated in production start-up and regrind waste. Shut-down waste, a significant waste source, was not included in the overall scrap rate because this data was not available.

3.2.3 Use

The use phase environmental data were calculated for an assumed tank life of 110,000 miles for a 1996 G Passenger Van with the weight and fuel economy data indicated in Table 3-9. Functional equivalency was defined as:

A tank required to provide sufficient fuel to propel the model truck 450 to 600 highway kilometers between refueling over an eleven year expected life of the vehicle.

Table 3-9. Weight and Fuel Economy Data for 1996 G Passenger Van

Parameter	Metrics
Test weight	2766 kg (6100 lb)
Fuel economy	Steel Tank 14.34 L/100 km (16.40 mpg)
	HDPE Tank 14.32 L/100 km (16.42 mpg)
Weight to fuel economy correlation	10% weight reduction ≡ 4.38% fuel consumption reduction‡

source: [22]

‡ Derived from fuel economy data and the differential fuel tank weights

The contribution of the tank system to vehicle fuel consumption ($F_{(l)}$) was obtained using the following correlation:

$$F_{(l)} = M_T \times L \times \left[\frac{FE_{(l)}}{M_v}\right] \times \frac{\Delta f}{\Delta M} \qquad (3\text{-}2)$$

where,

$F_{(l)}$	=	fuel (liters) consumed over the life of fuel tank system (L)
M_T	=	mass of the fuel tank system
M_V	=	test weight (mass) of vehicle
$\frac{\Delta f}{\Delta M}$	=	fuel consumption correlation with mass
$FE_{(l)}$	=	fuel economy (liters/km)
L	=	life of tank system (km)

The lifetime fuel consumption for the two tank systems are given in Table 3-10. These data represent the total vehicle fuel consumption over 110,000 miles that was allocated to each fuel tank system. It is the fuel required to transport each tank system a distance of 110,000 miles. Table 3-10 reports primary energy consumption in GJ which includes precombustion and combustion energies associated with the total fuel cycle of gasoline. The primary energy factor for gasoline is 42.03 MJ/l [16].

Table 3-10. Fuel Consumption and Use Phase Energy Contribution of Fuel Tanks Systems

Fuel Tank System	Weight (kg)	$F_{(l)}$, (liter)‡	Energy (GJ)
Steel	21.92	88.18	3.71
HDPE	14.07	56.60	2.38

‡ 88.18 l is equivalent to 23.30 gallons; and 56.60 l is equivalent to 14.95 gallons

Emissions

The vehicle emissions analyzed in this study include in-use emissions (tailpipe and evaporative) and precombustion emissions associated with the gasoline fuel cycle. With the exception of carbon dioxide, air emissions data for vehicle fuel combustion are based on a combination of Tier 0 emission standards for light duty trucks and off-cycle emissions (i.e., emissions that occur from driving at high power) as reported by Ross [15]. Table 3-11 shows these values for the G van equipped with a steel tank. The values do not include pre-combustion emissions. The Tier 0 emissions standards require that exhaust emissions not exceed the standards for 120,000 miles of vehicle life.

Table 3-11 Use Phase Emissions Estimates for 1996 G Van (Equipped with a Steel Tank)

	CO (gpm)	HC (gpm)	NOx (gpm)
Tier 0 Standards	10.0	.8	1.7
Off-cycle Emissions	7.9	.12	.3
Total Average Lifetime Emission Rate	17.9	.92	2.0
Total Emissions for 110,000 miles (kg)	1969.0	101.2	220.0

source: [23], [15]

CO_2 emissions are estimated at 2.338 kg per liter of gasoline combusted [16]. The fuel tank's contribution to total vehicle air emissions is based on the total fuel consumption allocated to the tank using the following relationship:

$$m_e = m_e^{'} \times F_{(l)} \times FE_{(l)} \qquad (3\text{-}3)$$

where,

m_e = life cycle emission per fuel tank system

$m_e^{'}$ = emission factor (gpm)

3.2.4 End-of-Life Management

The nature of the vehicle recycling industry and the relative scarcity of data regarding its practice make it difficult to model accurately.

For the purposes of this study all components of both tank systems are assumed to be shredded, any steel is recovered and subsequently recycled at 100%, and all plastic is landfilled.

Energy requirements for shredding were obtained from [16], [17]. The shredding data was assumed to be independent of material or part geometry.

3.2.5 Transport

Transport distance data for the linkages between manufacturing operations were obtained from the GM project team. Transportation fuel efficiency and emissions data were obtained from Franklin Associates [11]. Within the scope of manufacturing, two modes of transport were identified: rail and combination truck. Both of these modes of transport consume diesel fuel.

The steel straps for both tank systems were assumed to be transported by truck to the vehicle assembly plant the same distance that the tank and shield are transported. The racks used to transport both tanks were included in the transportation scope. Transport of auxiliary components was not included.

Table 3-12 summarizes the manufacturing transportation data for both tank systems.

Table 3-12 Transportation Description, Distance, and Efficiency for Tank Systems Manufacturing

Description	Type	Distance* (ton-miles)	Efficiency (gallons/ ton-mile)	Fuel Consumption* (gallons)
Steel Tank System				
Rolled Steel to ZnNi Coating	Combination Truck (Diesel)	223.3	1.18E-02	2.63
Coated Steel to Soap Lube	Combination Truck (Diesel)	168.3	1.18E-02	1.99
Lubed Steel to Tank Manuf.	Combination Truck (Diesel)	99	1.18E-02	1.17
Finished Tank to Assembly	Rail (Diesel)	627	3.10E-03	1.94
Off-spec. Tanks to Tank Manuf.	Rail (Diesel)	627	3.10E-03	1.94
HDPE Tank System				
HDPE Resin to Tank Manuf.	Combination Truck (Diesel)	40.7	1.18E-02	0.48
Finished Tank to Assembly	Combination Truck (Diesel)	451	1.18E-02	5.32
Off-spec. Tanks to Tank Manuf.	Combination Truck (Diesel)	451	1.18E-02	5.32

* Per 1000 kg transported

source: [22],[11]

Transport distance estimates for end-of-life management were obtained from the American Plastics Council [19]. The transport from the vehicle dismantler to the shredder was estimated as 100 miles. The transport of the ASR from the shredder to the landfill was estimated as 100 miles. All end of life transport was assumed to be by combination truck.

Table 3-13 summarizes the transportation data for end-of-life management for both systems.

Table 3-13 Transportation Description, Distance, and Efficiency for End of Life

Description	Type	Distance* (ton-miles)	Efficiency (gallons/ ton-mile)	Fuel Consumption* (gallons)
Steel Tank System				
Dismantler to Shredder	Combination Truck (Diesel)	110	1.18E-02	1.298
Shredder Residue to Landfill	Combination Truck (Diesel)	110	1.18E-02	1.298
HDPE Tank System				
Dismantler to Shredder	Combination Truck (Diesel)	110	1.18E-02	1.298
Shredder Residue to Landfill	Combination Truck (Diesel)	110	1.18E-02	1.298

* Per 1000 kg transported

source: [19],[11]

3.3 Life Cycle Cost Analysis

A life cycle cost analysis was performed which accounted for explicit costs to manufacturers, customers, and end-of-life managers. Externalities were not identified. In addition, the project team did not attempt to uncover hidden environmental costs associated with the fuel tank system, which were not allocated by the manufacturer.

3.3.1 Material Production

The material cost for each fuel tank system component was obtained by summing up the cost of each material in the system using the following formula:

$$C_{matl} = \sum_{i=1}^{n} C_i \times M_i \tag{3-4}$$

where,

C_i = cost per unit of mass of i^{th} material purchased
M_i = mass of i^{th} material purchased
n = total number of different material in the fuel tank system

Steel Fuel Tank System

The steel fuel tank system consists of three main components: a tank, straps and a shield. The material composition of this system is steel (18.58 kg), which includes the tank and straps, and HDPE (3.34 kg) for the shield. The quantity of zinc, nickel and paint used to coat the steel was not available and therefore these materials were not included in the cost analysis. Thus, for the steel fuel tanks system, Equation 3-4 reduces to:

$$C_{matl,sfs} = C_{CS} \times M_{CS} + C_{HDPE} \times M_{HDPE} \tag{3-5}$$

where,

$C_{matl,sfs}$ = material cost of the steel fuel tank system
C_{CS} = material cost of plain carbon steel = \$0.738
M_{CS} = mass of carbon steel purchased = 22.01 kg
C_{HDPE} = material cost of HDPE = \$0.914/ kg
M_{HDPE} = mass of HDPE purchased = 3.407 kg

Thus, $C_{matl,sfs} = \$19.38$

Plastic Fuel Tank System

The plastic fuel tank system also consists of three main components: a multilayer plastic tank, PVC coated steel straps, and a shield. The material composition of this system is HDPE (10.864 kg), EVOH (0.336 kg), PVC (0.095 kg), and steel (2.81 kg). Equation 3-4 then, reduces to:

$$C_{matl,pfs} = C_{HDPE} \times M_{HDPE} + C_{EVOH} \times M_{EVOH} + C_{PVC} \times M_{PVC} + C_{CS} \times M_{CS} \quad (3\text{-}6)$$

where,

$C_{matl,pfs}$	=	material cost of the plastic fuel tank system
C_{HDPE}	=	material cost of HDPE = $0.948/kg
M_{HDPE}	=	mass of HDPE = 10.864 kg
C_{PVC}	=	material cost of PVC = $0.871/kg
M_{PVC}	=	mass of PVC = 0.095 kg
C_{EVOH}	=	material cost of EVOH = $5.314/kg
M_{EVOH}	=	mass of EVOH = 0.336 kg
C_{CS}	=	material cost of carbon steel = $0.738/kg
M_{CS}	=	mass of carbon steel = 2.81 kg

Thus, $C_{matl,pfs} = \$14.25$

3.3.2 Manufacturing

The manufacturing costs for each fuel tank system are proprietary information, and hence were not available to be included in this report. After-market replacement prices were used to approximate the manufacturing costs. A study of an air intake manifold by Kar and Keoleian [16] reported a six times mark up of the replacement price over the manufacturing cost of the manifold. This factor of six mark up was used to provide a rough estimate of the fuel tank manufacturing costs. Replacement prices were obtained from a GM dealership and are reported in Table 3-14. Applying the estimated mark up factor yields manufacturing costs of $71 for the steel fuel tank system. The manufacturing cost of the plastic fuel tank system was estimated to be about $6 less than the steel tank system [22]. Thus, the derived manufacturing cost of the plastic fuel tank system is $65. It must be recognized that the derived manufacturing costs are very crude estimates of the actual costs. They serve as rough estimates so that manufacturing costs can be compared with other life cycle costs.

Table 3-14 Replacement Costs of Steel Tank System Components

Steel Fuel Tank System	
Component	Purchase Price ($)
Tank (steel)	369.00
Straps	18.00
Shield (HDPE)	37.25
Total	424.25

3.3.3 Use

Use phase costs are separated into two categories: purchase costs and operating costs. Purchase costs represent the initial cost of all components in each fuel tank system to the consumer. The manufacturing costs for the fuel tank systems were used as a surrogate for the price of the fuel tank system (its portion of the sticker price of the total vehicle). Operating costs represent the gasoline costs for vehicle use that are attributed to the fuel tank system weight according to equation 3-2.

It was assumed that both fuel tank systems perform without maintenance for 110,000 miles. Thus, the only cost to the user is purchasing gasoline. The national average cost of gasoline (C_f) was obtained from the American Petroleum Association [24] as $1.17/gallon. Lifetime use phase fuel cost (C_{use}) of each tank system was obtained from the lifetime fuel consumption ($F_{(gal)}$) as:

$$C_{use} = C_f \times F_{(gal)} \qquad (3\text{-}7)$$

Lifetime fuel consumption was taken from Table 3-10. Thus, the estimated lifetime fuel costs were $27.26 for the steel fuel tank system, and $17.50 for the plastic fuel tank system.

3.3.4 End-of-Life Management

A cost analysis was conducted for each stage of the retirement process. It was assumed that used tanks are not sold for used parts. Therefore, no credit for used parts was given in the life cycle cost analysis.

Typically steel fuel tanks are removed from the vehicle, punctured and flattened in order to avoid explosion hazards. This cost analysis does not take into account the labor costs of removing the tank from the vehicle.

Fuel tanks are transported from dismantlers to shredders as part of the retired vehicle. The transportation cost from dismantlers to shredders, assuming a 100 mile average distance [11] is $0.362 for the steel tank system, and $0.233 for the plastic tank system. This cost assumes a 50% split between flattened and unflattened hulks. The average of the two costs was used in the analysis.

Total costs and credits to shredder operators were obtained from the APC retirement spreadsheet model [19] as $116.64/hulk and $125.21/hulk, respectively. Shredding cost (C_{sh}) can be calculated as shown in Equation 3-8:

$$C_{sh} = C_h + C_t + C_d + C_{pr} \qquad (3\text{-}8)$$

where,

C_h = hulk sale value
C_t = transportation cost
C_d = disposal cost
C_{pr} = processing cost

The processing cost was estimated using Equation 3-8 along with data from the APC spreadsheet and assuming a 1992 average automobile. The average weight of a 1992 vehicle was 1425.22 kg [25]. The material composition of this automobile includes 953.41 kg of ferrous material, 136.82 kg of nonferrous metals, 254.54 kg of nonmetals and 80.45 kg of fluids [25]. Assuming the dismantler drains all fluids and transports the remaining materials to the shredder, the weight of each hulk sold to the shredder is 1344.77 kg. The APC study assumed a hulk sales value (C_h) to the shredder to be $30.00

and a transportation cost of $0.12 / ton-mile [19]. In this model, the metal portion (1090.23 kg) of the hulk was assumed to be transported from shredders to metal recyclers an average distance of 200 miles and the nonmetal portion (254.54 kg) was assumed to be transported from shredders to landfills an average distance of 100 miles. Thus the total cost for transportation (C_t) was calculated to be $32.14. The APC study assumed a disposal fee for non hazardous waste of $75.00/ton. Because automotive shredder residue (ASR) in the US is classified as non hazardous, the total cost for disposing (C_d) 254.54 kg of nonmetal ASR was calculated to be $21.00. Hence, from Equation 3-8, the processing cost (C_{pr}) for the hulk was estimated to be $33.50.

Table 3-15 itemizes the end-of-life costs for each fuel tank system.

Table 3-15. Itemized Cost (US Dollars) Description for Different ELV Managers per Fuel Tank System

ELV Managers	Cost Descriptors	Steel Fuel Tank System, $	Plastic Fuel Tank System, $
Dismantler	• transportation (a)	0.362	0.233
Shredder	• transportation to metal recycler (b)	0.614	0.033
	• transportation to landfill (c)	0.055	0.187
	• disposal (d)	0.276	0.934
	• processing (e)	0.546	0.351
Total cost	sum: (a) through (e)	1.854	1.738
Scrap value	(f)	2.867	0.434

A scrap value for shredded auto scrap steel of $ 0.15 per kg was obtained from *American Metal Market* [18].

Retirement cost information for end-of-life (ELV) vehicle management as described above were converted to cost per tank system as shown in Table 3-15. The disposal cost was calculated using a national average tipping fee of $30.25/ton [20]. Total retirement costs for the steel and plastic fuel tank system are $1.85 and $1.74 respectively. The scrap value of the steel and plastic fuel tank system is $2.87 and $0.43 respectively.

3.4 Performance Analysis

Performance requirements predominate the material selection, design, manufacturing, and assembly of any vehicle component. The engineering properties of these fuel tank materials and the mechanics of the design will dictate how the tank performs in terms of vapor permeation, thermal expansion, crack resistance, impact and tensile strength, corrosion resistance, flammability, crash worthiness, and many other factors, over the useful life of the vehicle.

In addition to the in-use performance of a part or component, vehicle manufacturers may be interested in components that can be manufactured flexibly and efficiently. We are therefore interested in the performance characteristics of both stamping and welding for the steel tank system and blow molding for the HDPE tank system. Items to consider include cycle time and tool life. How a particular design is oriented on the vehicle frame is directly related to the type of manufacturing. For example, the blow molding process allows for a flexible HDPE tank shape. This in turn, facilitates better use of vehicle frame space in the overall design of the vehicle.

Important performance parameters are identified for each life cycle stage and are presented in Table 3-16.

3.4.2 Manufacturing

Manufacturing performance issues, which include production rate, cycle time, and tool life among other factors, represent proprietary information and are not available for publishing. We can, however, include a qualitative discussion about the two manufacturing processes considered in this report.

One factor to consider when comparing the manufacturing processes for both the plastic and steel tank, is the number of process stages. Figures 3-1 and 3-2 illustrate the process steps in the manufacturing of the steel and plastic tank respectively. The steel tank manufacturing process has more processing steps than the plastic blow molding operation. Furthermore, steel tank manufacturing progresses in a series of linear stages, whereas plastic tank manufacturing has some material feedback with the incorporation of reground flash and scrapped tank materials into each tank.

Steel Fuel Tank

The process flow diagram shown in Figure 3-1 illustrates the number of processing stages required to manufacture a steel fuel tank. Based on the data provided by Delphi, fifteen processing stages, including quality control testing, repair and shipment, are required to manufacture one steel tank.

As discussed earlier, there are two possible failure types when welding. Hot welding gives rise to tanks with seam leaks. These can be repaired with a Sn/Ag-based solder. However, 5% of the tanks that fail leak testing are due to seam leaks. The remaining 95% of leaking tanks fail because of edge leaks caused by cold welding. Again, 10% of edge leaking tanks are repairable, the remaining 90% must be scrapped. In addition to the scrapped tanks that fail either by seam leak or by edge leak, overall approximately 240 tanks per year are scrapped after process control testing. Less than 1% of tanks are returned from the Wentzville assembly plant. For the production of 171,000 fuel tanks, approximately 82 are expected to be returned to the manufacturing plant from the assembly plant. Overall, the number of anticipated scrapped tanks is approximately 1053 for a required production volume of 171,000 tanks.

Table 3-16 Performance Parameters

Life Cycle Stage	Criteria	Plastic	Steel
Manufacturing and Assembly	Formability	• Easily molded into irregular shapes of various dimensions • Color is integrated into molding process	Requires several metal forming steps
	Manufacturability:		
	tool life	n.a.	n.a.
	cycle time	n.a.	n.a.
Use	Corrosion	Corrosion resistant	Requires coating to prevent corrosion
	Weight	Up to 30% lighter than steel tank	
	Fatigue	Fatigue failures rare for three reasons: 1. Walls of tank are generally thicker than those of steel 2. Increased damping keeps vibration amplitudes low 3. Resonance that occurs is decreased by softening of material due to heat generated by vibration	
	Permeability	Dependent upon barrier technology	Low permeability, however, permeation at welding seams of tank cannot be ignored
Retirement and Disposal	Reusability	Expected long tank life indicates high re-use potential for tank replacement	Recyclable
	Draining	Comparable	Comparable
	Tank Disassembly	Comparable	Comparable, but heavier

HDPE Fuel Tank

Little data was available from the multilayer plastic tank manufacturer concerning performance issues with their manufacturing process because such information is proprietary. However, there is much published information detailing the advantages of manufacturing a blow molded plastic fuel tank over a steel one. Figure 3-2 shows the relatively few stages required to produce one multilayer plastic fuel tank. In contrast to the steel tank manufacturing process, extrusion and blow molding is performed continuously with one machine. Ten steps are required for this manufacturing process. These steps include leak and drop testing.

According to the multilayer plastic tank manufacturer, the tank scrappage rate for the low volume production of the GMT600 fuel tank is 2%. For larger production volumes—an order of magnitude or greater than that of the GMT600, a lower percentage of tanks are anticipated to be scrapped. As well, a smaller start-up and shut-down waste generation rate is expected.

3.4.3 Use

Use phase performance characteristics, like use phase energy consumption, are extremely important design parameters when considering the entire life cycle of the fuel system and the vehicle. As stated earlier, impact and tensile strength, corrosion resistance, resistance to permeability—these qualities and many others related to legal and safety requirements dictate whether a fuel tank is considered or rejected.

Table 3-17 shows some performance data for HDPE and steel. Designers use this and other data when considering a given material for a fuel tank design.

Steel Fuel Tank

Being the traditional material of choice for fuel tanks, the steel tank exhibits excellent mechanical properties, such as tensile strength as evidenced in Table 3-17.

In terms of corrosion resistance, the plain carbon steel base does not sufficiently resist corrosion. Therefore, a coating is required. However, if the tank is designed for use with flex fuels (i.e., fuels that contain alcohol), the zinc-nickel and aluminum paint coating cannot sufficiently protect the tank from corrosion over the design life of the tank. The steel fuel tank studied in this report does not have adequate corrosion resistance for use with flex fuels. Auto makers could select stainless steel as a fuel tank material for use with flex fuels; however, stainless steel is considerably more expensive than low carbon steel.

HDPE Fuel Tank

As shown in Table 3-17, the HDPE system is less dense than the steel system and hence this leads to a light-weight component (fuel tank) and better fuel economy for the vehicle. Another advantage of the plastic fuel tank is the design flexibility that plastics offer. The shape of the plastic fuel tank can be designed to conform well to the available space in the rear compartment of the vehicle. This design flexibility enables greater gas tank capacity which results in a greater driving range for the vehicle. Larger size tanks, however, may lead to tradeoffs with respect to energy consumption. Significant energy is consumed over the lifetime of the vehicle in transporting the additional fuel contained in a larger tank.

3-17 Performance Data

	HDPE tank	Steel tank
Density (g/cm^3)	0.96	7.87
Strength:		
Impact (J/m)*	747	
Tensile (MPa)‡	20-37	290-400
Permeability	CARB, EPA	CARB, EPA
Fuel Economy (L per km)†	14.32	14.34
Corrosion Resistance	resistant	requires a zinc and paint coat

* Izod Impact test: 1 ft-lb/in = 53.38J/m [26]

‡ Source: [26]

† The fuel economy of the G passenger van equipped with a plastic tank system and a steel tank system

In terms of strength, both fuel tanks undergo a crash simulation drop test. The plastic tank is filled with ethylene glycol and dropped in a chamber at -40 C a distance of 20m. This test simulates the impact of a 5 to 15 mph collision. It also tests the tanks ability to withstand impact at the temperature at which the plastic material becomes brittle.

This particular multilayer plastic fuel tank, unlike many monolayer plastic designs used in the past has an EVOH permeation barrier which has enabled the tank to pass California Air Resources Board (CARB) evaporative emissions tests. CARB passed legislation that limits hydrocarbon evaporative emissions to no greater than two grams per day. In response to this, the Society of the Plastics Industry (SPI) designed a rigorous test protocol to simulate the hydrocarbon emissions in the multilayer plastic tank over its eleven year design life. The test is conducted over forty six weeks, and the multilayer fuel tank has succeeded in passing this test. In addition to the SPI protocol, entire vehicles are subjected to an evaporative emissions test. A complete vehicle equipped with a multilayer plastic tank typically gives rise to a 0.7g evaporative emission from the underhood, 0.7 g emission from the chassis, and 0.1 g emission from the fuel tank [22].

Designers strive to match the performance qualities of components with legal and safety requirements. All fuel storage and handling systems must follow a set of powertrain, steering, suspension, acoustic, display, and other guidelines. As well, all designs and materials undergo specific test procedures to ensure that the standards set by the automobile industry and government are met.

4. Results and Discussion

The life cycle inventory analysis and the life cycle cost analysis provide comprehensive environmental and cost data for evaluating the steel and HDPE fuel tank designs. The results are based on functionally equivalent fuel tank systems described in Section 2.2. The life cycle inventory analysis also serves to guide the development of environmental metrics.

4.1 Life Cycle Energy

The life cycle energy profile for each fuel tank based on a vehicle life of 110,000 miles is shown in Figure 4-1. (The primary energy consumed for each stage of life cycle is indicated in units of GJ/tank.) For both tank systems, the use phase accounts for the majority of the energy consumed. Over the 110,000 miles traveled, the steel and HDPE tanks (including shield and straps) are responsible for the consumption of 88.2 and 56.6 liters of gasoline, respectively. For comparison, the G passenger van consumes 25,390 liters when equipped with a steel fuel tank system; whereas when equipped with an HDPE fuel tank system, the G passenger van consumes 25,359 liters.

For the steel tank design, the use phase constitutes 76 percent of the total life cycle energy. For the HDPE tank, it is responsible for 66 percent of the total energy. Although less HDPE material is used in the fabrication of one tank relative to steel, the higher specific energy for HDPE (81 MJ/kg) compared to steel (33.5 MJ/kg) yields comparable total material production energies for each system. The manufacturing for the HDPE tank system requires 85 percent more energy than for steel which is a consequence of greater energy input for blow molding of HDPE compared to steel stamping. End-of-life management energy is relatively negligible. The current practice of landfill disposition for the HDPE tank, however, results in a significant loss of energy in the form of the embodied energy of the material.

4.2 Life Cycle Solid Waste

The solid waste generated across each stage of the fuel tank life cycle is shown in Figure 4-2. The material production and end-of-life management stages indicate opposite trends for the two systems. The relatively high solid waste from the production of steel is associated with precombustion processes (e.g. coal mining) and slag, whereas the high solid waste from the plastic system results from end-of-life management.

The Swiss Ecobalance study [8] did not account for wastes from mining iron ore. This study also reported that a significant fraction of the slag was reused in applications such as road construction [8]. Solid waste from the end-of-life management stage was evaluated using a model describing current practices. It is recognized that the infrastructure may change over the next decade when a majority of these tanks will be retired. Scenarios involving HDPE recycling, energy recovery, and tank reuse could significantly impact the results.

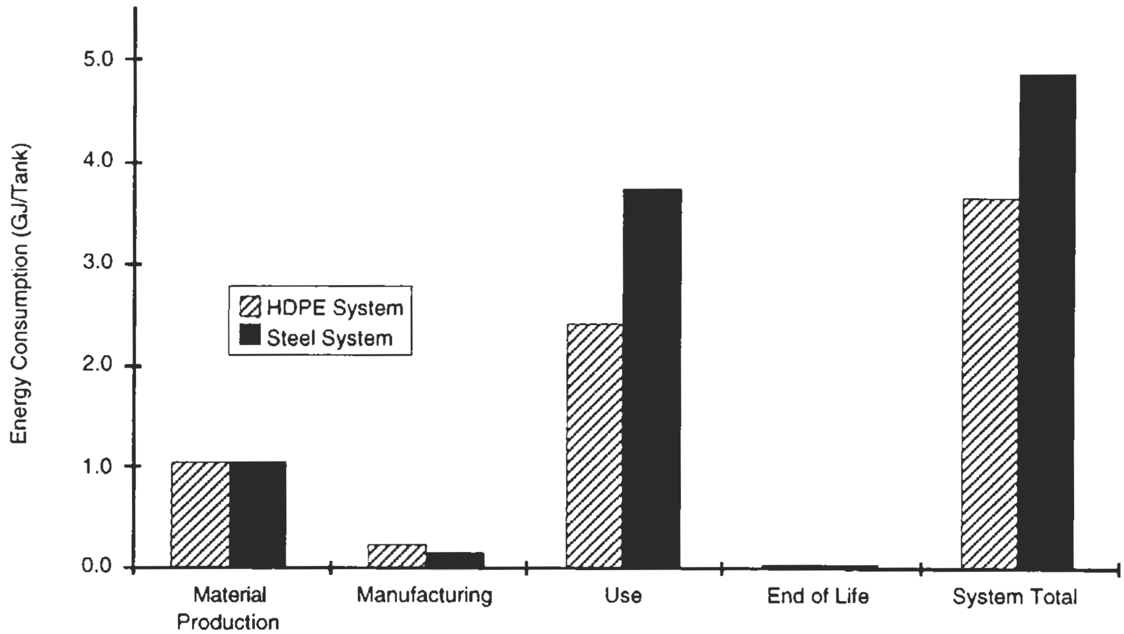


Figure 4-1. Life Cycle Energy Consumption for HDPE and Steel Tank Systems

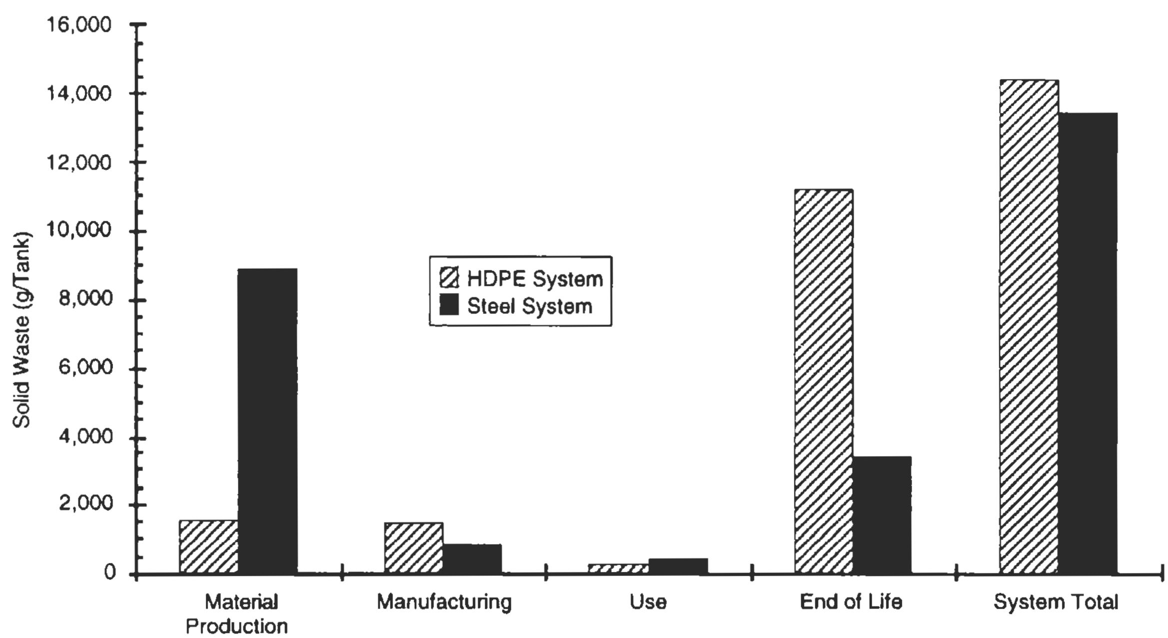


Figure 4-2. Life Cycle Solid Waste Generation for HDPE and Steel Tank Systems

4.3 Life Cycle Air Emissions

The life cycle air emissions of carbon dioxide, carbon monoxide, NOx, particulate matter (PM), and hydrocarbons are presented in Figures 4-3 through 4-7.

In general, the use phase dominates the life cycle air emissions of these pollutants. Particulate matter is an exception.

The carbon dioxide emissions shown in Figure 4-3 correlate well with energy consumption across the life cycle shown in Figure 4-1. This correlation is expected because of the large fraction of energy originating from carbon based fossil fuels. The carbon dioxide emissions account for a majority of the greenhouse gas emissions which have potentially catastrophic effects on climate.

The contribution of the fuel tank to the total vehicle use phase emissions was estimated assuming that these emissions are proportional to gasoline consumption. Although this relationship is valid for carbon dioxide, this allocation is probably not accurate for the other pollutants that are controlled by the catalytic converter. The use phase emission factors used in this study represent a significant increase over the EPA certified vehicle emissions for the new model G and cutaway vans. This difference has also been corroborated by EPA [27].

Carbon monoxide is primarily a mobile source pollutant originating from vehicle exhaust. Two serious and 39 moderate carbon monoxide non-attainment zones were reported by EPA in 1995.

NOx emissions (shown in Figure 4-5) and hydrocarbon emissions (shown in Figure 4-7) contribute to ozone formation which is a major urban air quality problem in several areas. Twenty-two serious ozone non-attainment zones were cited by EPA.

Relatively large amounts of PM emissions occurred in the material production phase of the steel tank system. The use phase PM emissions result from upstream processes in the total gasoline fuel cycle (precombustion).

The air emissions data for material production reported in the figures is expected to be highly uncertain and a comparison between the two systems is not recommended. The steel and HDPE material production data were taken from two different sources. A comparison of material production inventory data from two different sources showed a much greater variation in results for air and water emissions than was found for energy and solid waste [21].

4.4 Life Cycle Water Effluents

The life cycle waterborne emissions of dissolved solids, suspended solids, oil & grease, and metals are presented in Figures 4-8 through 4-11.

For dissolved solids, emissions occur primarily in the use phase. These emissions are derived from the refineries which produce the gasoline used in the vehicle. For suspended solids, oil & grease, and metal emissions, the material production phase is the largest source. The aggregate form of the data for both steel and HDPE do not allow us to determine the precise sources of these emissions. For waterborne metals, the manufacturing phase is also a significant source of emissions. These emissions can be traced back primarily to electricity production for steel stamping and HDPE blow

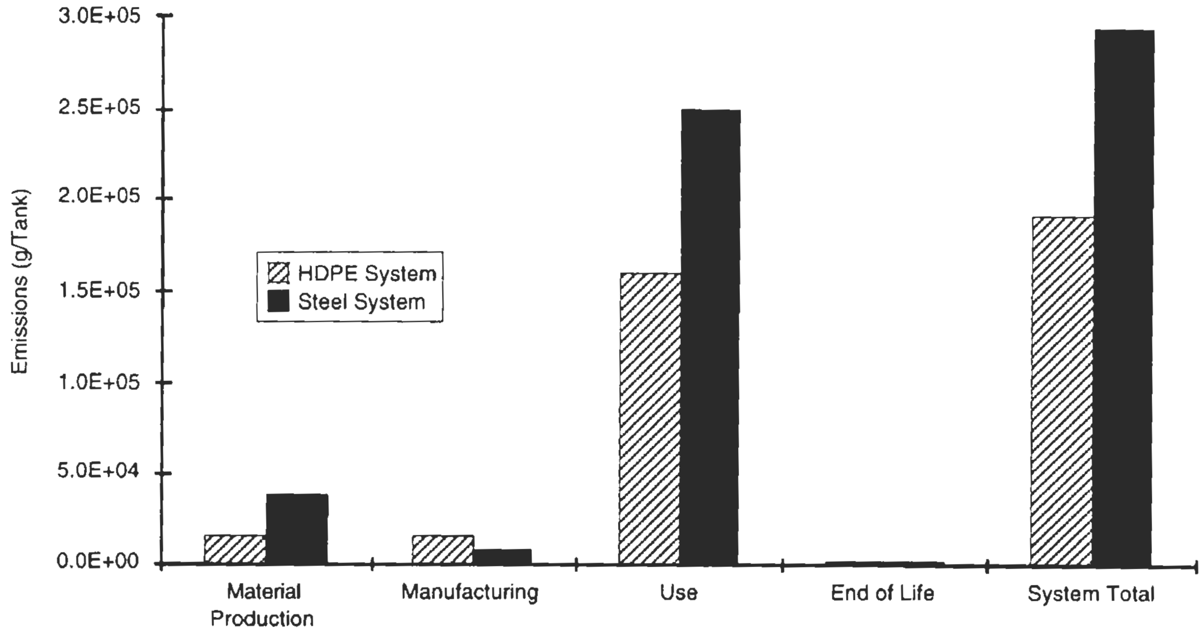


Figure 4-3. Life Cycle Carbon Dioxide Emissions for HDPE and Steel Tank Systems

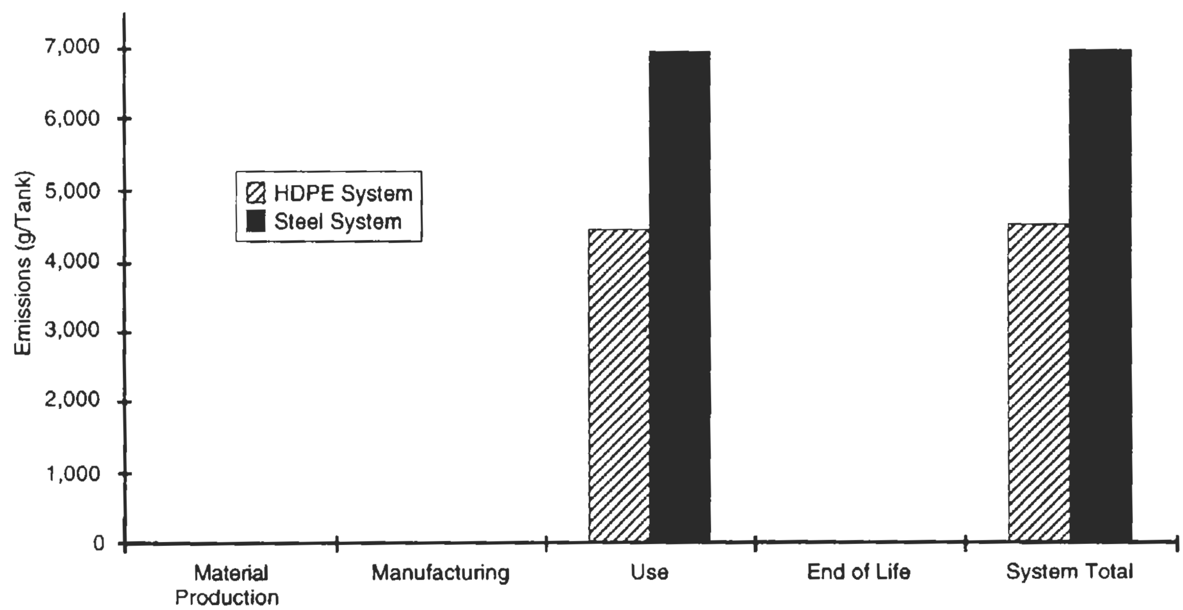


Figure 4-4. Life Cycle Carbon Monoxide Emissions for HDPE and Steel Tank Systems

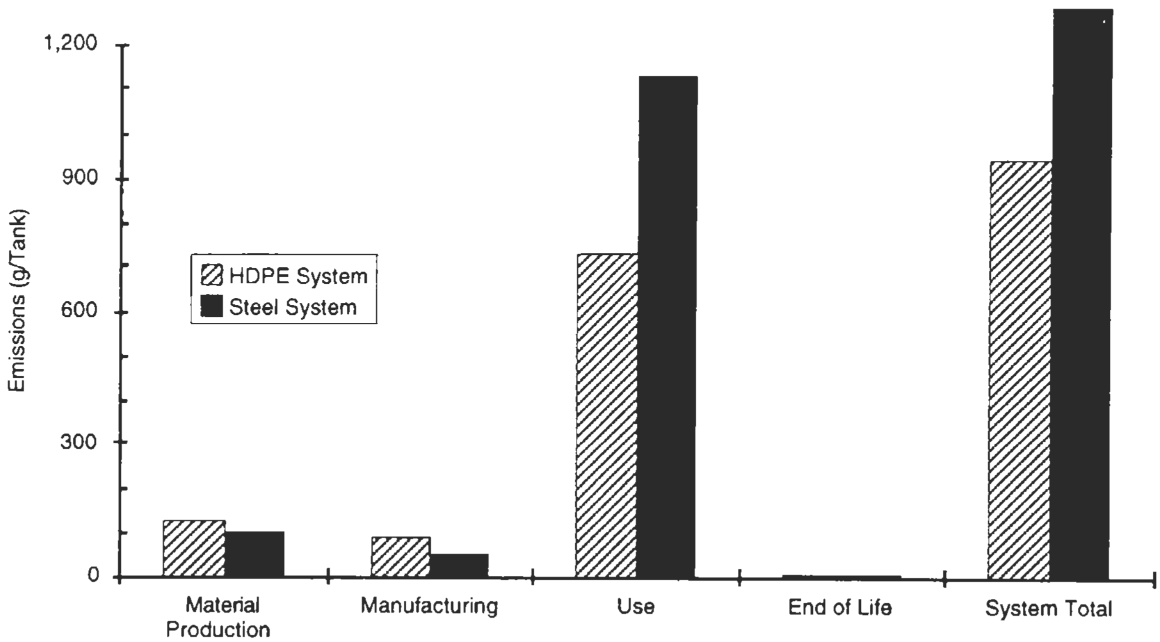


Figure 4-5. Life Cycle NOx Emissions for HDPE and Steel Tank Systems

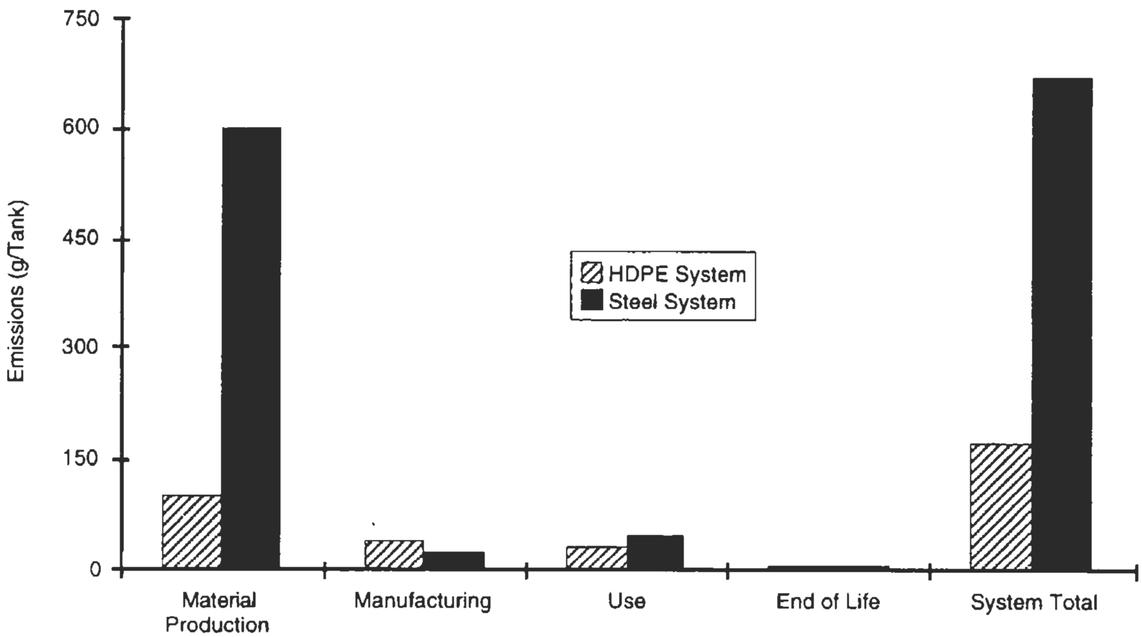
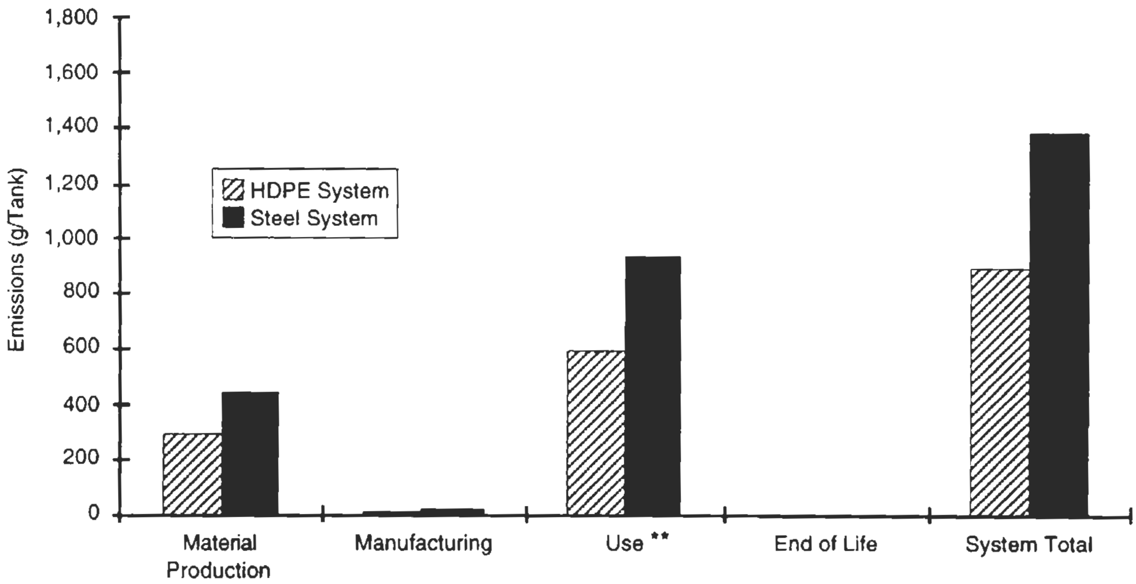


Figure 4-6. Life Cycle PM Emissions for HDPE and Steel Tank Systems



* Uncertainty of use phase lower than others

** Use phase based on certification standards and off-cycle emissions

Figure 4-7. Life Cycle Hydrocarbon Emissions for HDPE and Steel Tank Systems*

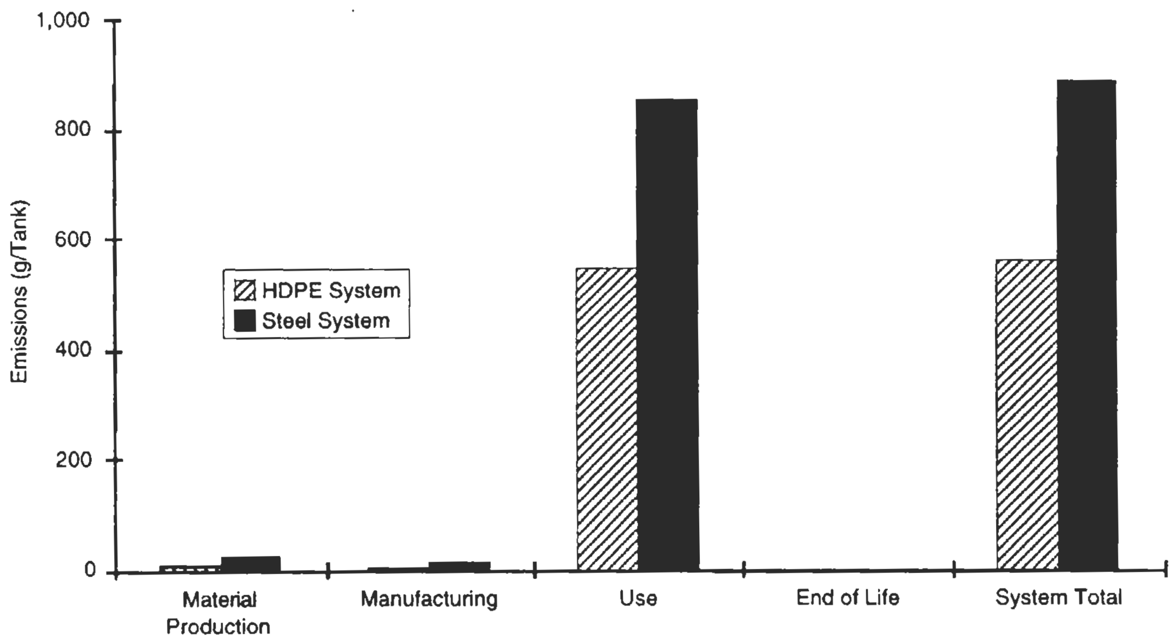


Figure 4-8. Life Cycle Dissolved Solids Emissions for HDPE and Steel Tank Systems

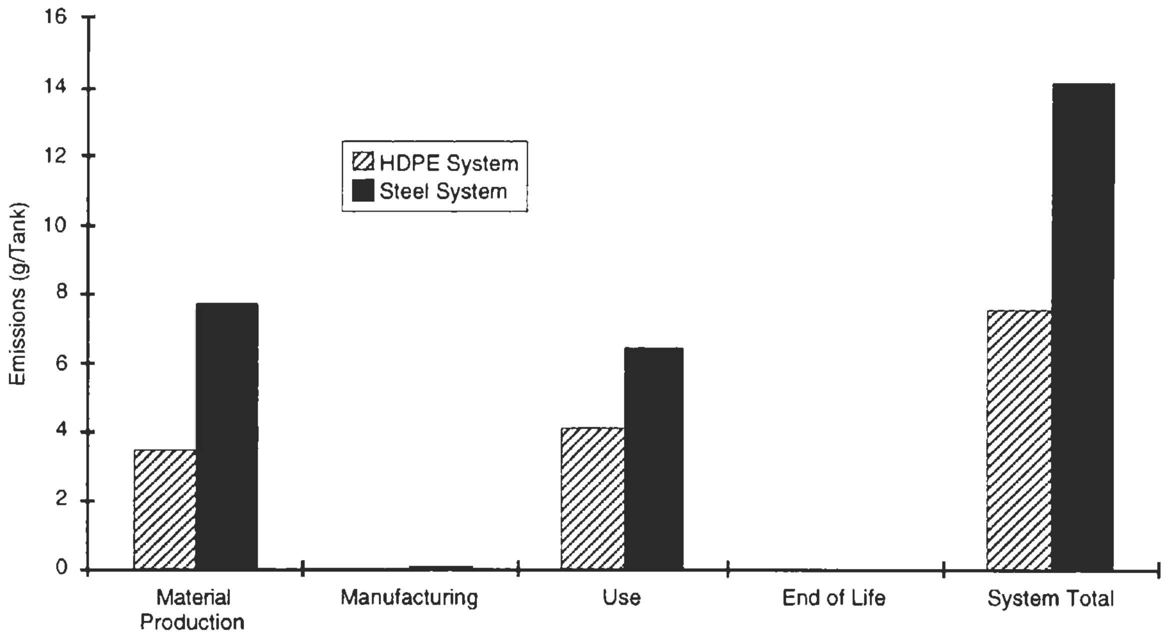


Figure 4-9. Life Cycle Suspended Solids Emissions for HDPE and Steel Tank Systems

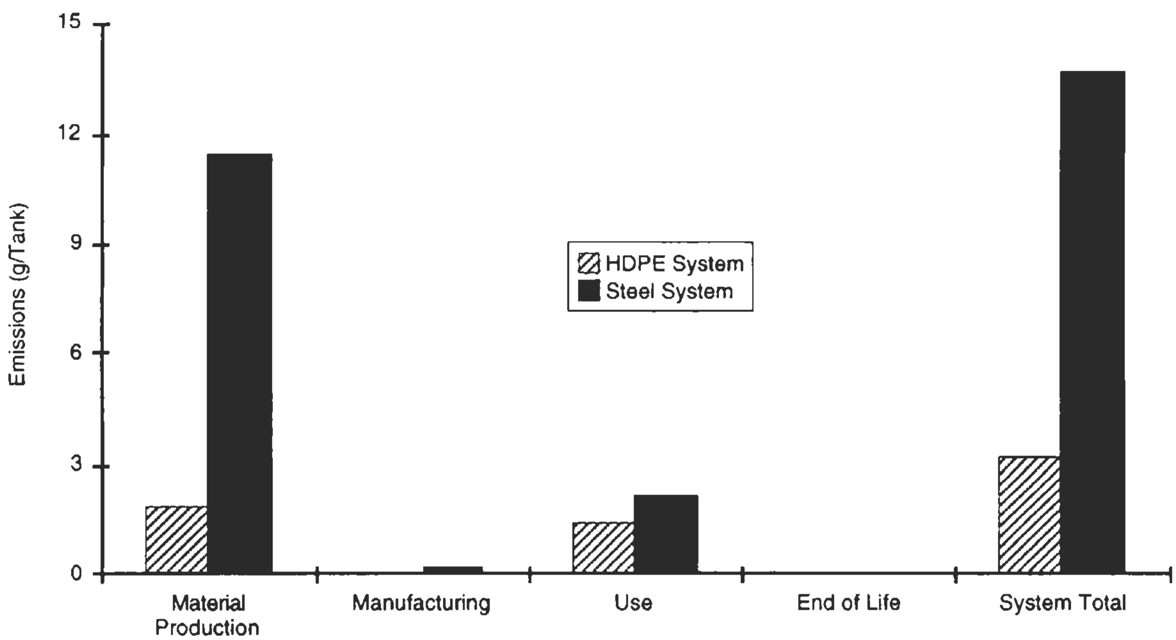


Figure 4-10. Life Cycle Waterborne Oil & Grease Emissions for HDPE and Steel Tank Systems

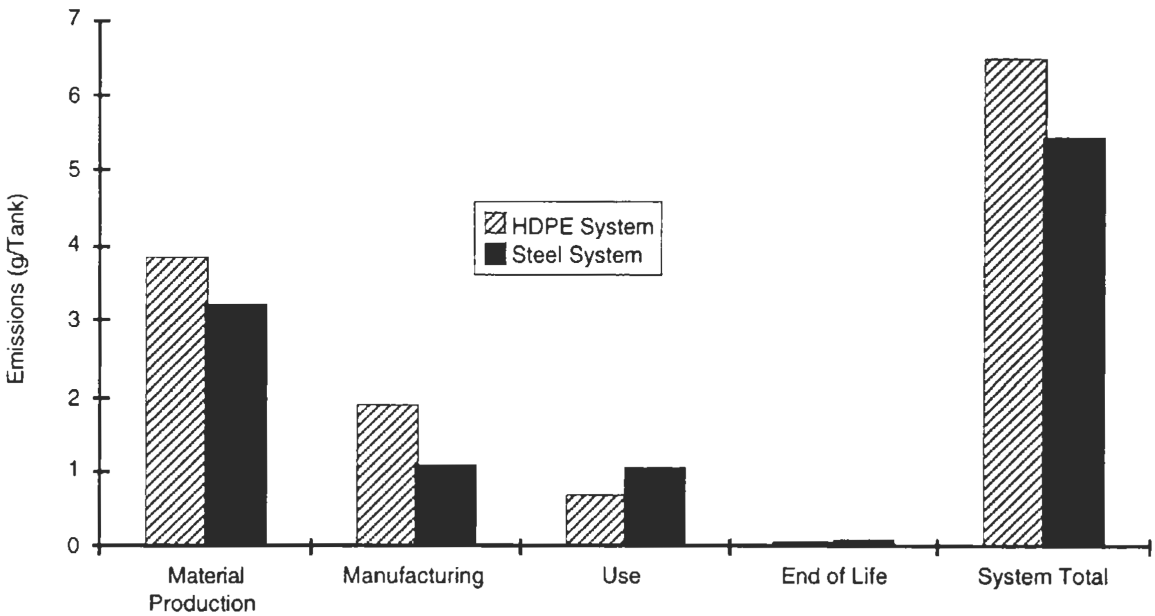


Figure 4-11. Life Cycle Waterborne Metals Emissions for HDPE and Steel Tank Systems

molding. In the steel tank system, steel stamping plant releases represent a very small portion of the total manufacturing releases.

The waterborne emissions data for material production reported in the figures is expected to be highly uncertain and a comparison between the two systems is not recommended.

4.5 Cost

Life cycle costs for each fuel tank system are presented in Figure 4-12. As indicated in the methodology section, this life cycle cost analysis does not account for externality costs or hidden environmental costs associated with manufacturing. Manufacturing costs which are estimated from after-market replacement prices dominate the life cycle cost of each vehicle fuel tank system. The HDPE tank system was approximately $5 cheaper to manufacture and saved the customer about $10 in gasoline costs over a distance of 110,000 vehicle miles traveled.

End-of-life management costs which account for shredding, ASR disposal, and related transportation costs are comparable. ASR disposal costs for the HDPE tank system represent over half of the total end of life costs. This cost was based on average US conditions and could be much higher within various European countries.

In the waste management stage, the scrap value associated with the steel tank system more than offsets the end-of-life management costs; whereas, the current scrap value for the plastic fuel tank system is not significant enough to cover the end-of-life management costs, resulting in a net cost for this life cycle phase.

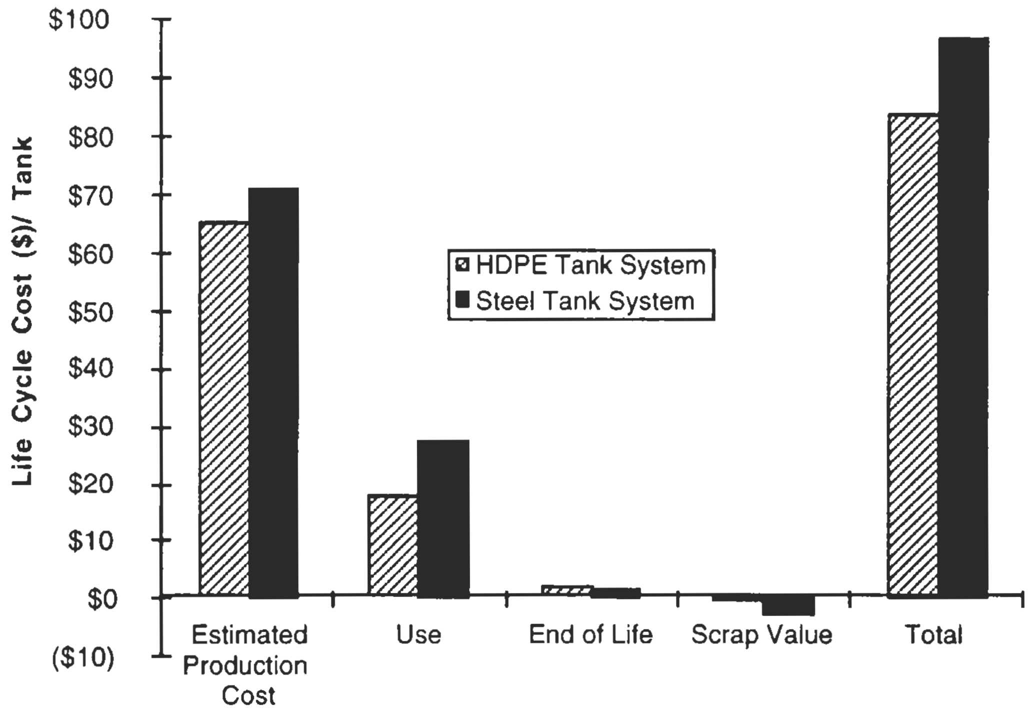


Figure 4-12. Life Cycle Costs of Fuel Tank Systems

4.6 Design Analysis and Integration

Consideration of the environmental profile of each fuel tank system is an important component in product design and planning. Several differences between environmental profiles appear to be significant. The lighter weight of the HDPE results in significant savings in use phase energy relative to the steel for this particular application. This contributes to an overall lower life cycle energy requirement for the HDPE tank system. The life cycle solid waste generation for both systems is comparable. Currently, the HDPE tank is not recyclable in the end-of-life management stage. On the other hand, in the material production phase, the steel tank system results in significantly more solid waste compared to the HDPE system according to the published data sources available for this study. Air and water release data is much less reliable, but in several pollutant categories, the use phase burdens associated with the full gasoline fuel cycle dominate. In these instances, the HDPE tank system has lower burdens.

Several other factors should be considered in an overall evaluation of both systems. The zinc coating of the steel tank can pose environmental concerns in the coating operation as well as steel recycling. Recent data from the Automotive Pollution Prevention Project indicated that significant zinc air emissions have been reported in the TRI from foundries, which process zinc coated steel [27]. Volatile zinc poses occupational health hazards. The useful life and durability of the tanks can also be an important issue in resource management. While both tanks are designed to last 110,000 miles, the HDPE tank is expected to have a longer life, beyond the design life of the vehicle. Data from dismantlers can be used to evaluate trends in the availability of and demand for reused tanks from retired vehicles. Steel tanks can corrode and may require replacement in older vehicles. Actual warranty data should be reviewed and inventory data adjusted accordingly to account for defective tanks. The issue of reparability for HDPE tanks should also be investigated. Finally, the gasoline absorbed by the HDPE tank wall poses a concern upon end-of-life management. These issues not withstanding, the HDPE tank overall appears to demonstrate less environmental burden relative to the steel tank system.

Design decisions are currently dominated by performance, cost, and regulatory requirements. Life cycle environmental considerations are being considered only in special pilot studies. Several performance and legal issues represent a set of "must" requirements that have to be addressed for a design to be successful.

U.S. EPA, OSHA, and the U.S. DOT (Federal Motor Vehicle Safety Standards) have promulgated regulations that affect multiple points in the fuel tank life cycle. At this time regulations are not specifically designed to minimize life cycle burdens; instead they address discrete phases of the life cycle. European targets for reducing auto shredder residue are a factor in assessing the future of the HDPE tank system.

Cost issues can be very difficult to resolve when considering the total life cycle of the fuel tank. The cost analysis conducted in this project estimates explicit costs in manufacturing, use, and end-of-life management. Externality costs associated with the life cycle inventory burdens of each fuel tank system were not estimated. Furthermore, hidden, liability, and other less tangible environmental costs in fuel tank manufacturing could not be identified, because only replacement tank cost data was available. Figure 4-12 showed that the use phase and end-of-life management costs are relatively small compared to the tank production costs as reflected in Section 3.3. Although use phase environmental burdens are high, unless the associated costs in the market system become more significant, it is unlikely that they will receive the same attention from corporate management that manufacturing costs currently receive.

4.7 Uncertainty Analysis

It was not possible to conduct an uncertainty analysis by propagating uncertainties in individual data points to estimate the overall uncertainties in the results. In most cases only single data points were available for parameters such as the material production energy and manufacturing solid waste. Thus, confidence intervals for these parameters could not be determined. A sensitivity analysis was conducted to examine the effects of changes in key parameters on life cycle energy and life cycle solid waste for each fuel tank system.

Parameters studied included tank manufacturing energy, scrap rate, material production energy, fuel economy, and vehicle and fuel tank life (miles). Tables 4-1 to 4-4 show the results of this analysis.

Table 4-1 shows the effects of changing these parameters by -20% to +20% on the life cycle energy of each fuel tank system. The life cycle energy is most sensitive to changes in fuel economy, which is expected since use phase dominates life cycle energy consumption. Vehicle/fuel tank life also has a strong influence on total life cycle energy for the same reason. Table 4-2 shows the percentage deviation of energy from the actual case (0% change) for each incremental change of the input parameters.

Similarly, Tables 4-3 and 4-4 show how life cycle solid waste of each fuel tank design is affected by -20% to +20% changes in four input parameters. The material production solid waste factor has the greatest impact on life cycle solid waste particularly for steel. For steel, material production solid waste accounts for a majority of the total life cycle solid waste. Changes in fuel economy and vehicle and fuel tank life (miles) have only marginal affects on life cycle solid waste generation.

Table 4-1
Sensitivity Analysis of Life Cycle Energy (MJ)

	Life Cycle Energy (MJ/Tank)								
	Change in Parameter Value								
Parameter	-20%	-15%	-10%	-5%	**0%**	5%	10%	15%	20%
Tank Manuf. Energy									
Steel Tank	4.851	4.853	4.856	4.858	**4.860**	4.863	4.865	4.867	4.870
HDPE Tank	3.600	3.607	3.615	3.623	**3.631**	3.639	3.647	3.654	3.662
Scrap Rate									
Steel Tank	4.837	4.843	4.849	4.855	**4.860**	4.866	4.872	4.878	4.883
HDPE Tank	3.628	3.629	3.629	3.630	**3.631**	3.632	3.632	3.633	3.634
Material Production Energy									
Steel Tank									
Steel (Tank and Straps)	4.718	4.753	4.789	4.825	**4.860**	4.896	4.932	4.967	5.003
HDPE	4.805	4.819	4.833	4.847	**4.860**	4.874	4.888	4.902	4.915
HDPE Tank									
Steel (Shield and Straps)	3.612	3.617	3.622	3.626	**3.631**	3.636	3.640	3.645	3.650
HDPE	3.447	3.493	3.539	3.585	**3.631**	3.677	3.723	3.769	3.815
Fuel Economy									
Steel Tank	5.787	5.514	5.272	5.055	**4.860**	4.684	4.523	4.377	4.243
HDPE Tank	4.226	4.051	3.895	3.756	**3.631**	3.518	3.415	3.321	3.234
Tank and Vehicle Life (miles)									
Steel Tank	4.119	4.304	4.490	4.675	**4.860**	5.046	5.231	5.416	5.602
HDPE Tank	3.155	3.274	3.393	3.512	**3.631**	3.750	3.869	3.988	4.107

Table 4-2
Sensitivity Analysis of Life Cycle Energy (% Difference)

	Percent Change in Life Cycle Energy								
	Change in Parameter Value								
Parameter	-20%	-15%	-10%	-5%	**0%**	5%	10%	15%	20%
Tank Manuf. Energy									
Steel Tank	-0.20%	-0.15%	-0.10%	-0.05%		0.05%	0.10%	0.15%	0.20%
HDPE Tank	-0.86%	-0.65%	-0.43%	-0.22%		0.22%	0.43%	0.65%	0.86%
Scrap Rate									
Steel Tank	-0.47%	-0.35%	-0.24%	-0.12%		0.12%	0.24%	0.35%	0.47%
HDPE Tank	-0.08%	-0.06%	-0.04%	-0.02%		0.02%	0.04%	0.06%	0.08%
Material Production Energy									
Steel Tank									
Steel (Tank and Straps)	-2.93%	-2.20%	-1.47%	-0.73%		0.73%	1.47%	2.20%	2.93%
HDPE	-1.14%	-0.85%	-0.57%	-0.28%		0.28%	0.57%	0.85%	1.14%
HDPE Tank									
Steel (Shield and Straps)	-0.52%	-0.39%	-0.26%	-0.13%		0.13%	0.26%	0.39%	0.52%
HDPE	-5.08%	-3.81%	-2.54%	-1.27%		1.27%	2.54%	3.81%	5.08%
Fuel Economy									
Steel Tank	19.07%	13.46%	8.47%	4.01%		-3.63%	-6.93%	-9.95%	-12.71%
HDPE Tank	16.38%	11.56%	7.28%	3.45%		-3.12%	-5.96%	-8.55%	-10.92%
Tank and Vehicle Life (miles)									
Steel Tank	-15.25%	-11.44%	-7.63%	-3.81%		3.81%	7.63%	11.44%	15.25%
HDPE Tank	-13.10%	-9.83%	-6.55%	-3.28%		3.28%	6.55%	9.83%	13.10%

Table 4-3
Sensitivity Analysis of Life Cycle Solid Waste (g)

Parameter	Life Cycle Solid Waste (g/Tank) Change in Parameter Value -20%	-15%	-10%	-5%	0%	5%	10%	15%	20%
Scrap Rate									
Steel Tank	13,140	13,208	13,275	13,342	**13,410**	13,477	13,544	13,612	13,679
HDPE Tank	14,407	14,417	14,426	14,436	**14,446**	14,455	14,465	14,474	14,484
Material Production Solid Waste									
Steel Tank									
Steel (Tank and Straps)	11,715	12,139	12,562	12,986	**13,410**	13,833	14,257	14,681	15,105
HDPE	13,388	13,393	13,399	13,404	**13,410**	13,415	13,421	13,426	13,432
HDPE Tank									
Steel (Shield and Straps)	14,222	14,278	14,334	14,390	**14,446**	14,502	14,558	14,614	14,670
HDPE	14,373	14,391	14,409	14,427	**14,446**	14,464	14,482	14,500	14,519
Fuel Economy									
Steel Tank	13,505	13,477	13,452	13,430	**13,410**	13,392	13,375	13,360	13,346
HDPE Tank	14,507	14,489	14,473	14,459	**14,446**	14,434	14,423	14,414	14,405
Tank and Vehicle Life (miles)									
Steel Tank	13,333	13,352	13,371	13,391	**13,410**	13,429	13,448	13,467	13,486
HDPE Tank	14,397	14,409	14,421	14,433	**14,446**	14,458	14,470	14,482	14,495

Table 4-4
Sensitivity Analysis of Life Cycle Solid Waste (% Difference)

Parameter	Percent Change in Life Cycle Solid Waste Change in Parameter Value -20%	-15%	-10%	-5%	0%	5%	10%	15%	20%
Scrap Rate									
Steel Tank	-2.01%	-1.51%	-1.00%	-0.50%		0.50%	1.00%	1.51%	2.01%
HDPE Tank	-0.27%	-0.20%	-0.13%	-0.07%		0.07%	0.13%	0.20%	0.27%
Material Production Solid Waste									
Steel Tank									
Steel (Tank and Straps)	-12.64%	-9.48%	-6.32%	-3.16%		3.16%	6.32%	9.48%	12.64%
HDPE	-0.16%	-0.12%	-0.08%	-0.04%		0.04%	0.08%	0.12%	0.16%
HDPE Tank									
Steel (Shield and Straps)	-1.55%	-1.16%	-0.78%	-0.39%		0.39%	0.78%	1.16%	1.55%
HDPE	-0.51%	-0.38%	-0.25%	-0.13%		0.13%	0.25%	0.38%	0.51%
Fuel Economy									
Steel Tank	0.71%	0.50%	0.32%	0.15%		-0.14%	-0.26%	-0.37%	-0.48%
HDPE Tank	0.42%	0.30%	0.19%	0.09%		-0.08%	-0.15%	-0.22%	-0.28%
Tank and Vehicle Life (miles)									
Steel Tank	-0.57%	-0.43%	-0.29%	-0.14%		0.14%	0.29%	0.43%	0.57%
HDPE Tank	-0.34%	-0.25%	-0.17%	-0.08%		0.08%	0.17%	0.25%	0.34%

4.8 Proposed Environmental Metrics

A primary objective of this project is to develop metrics to guide the environmental improvement of automotive parts and components. These environmental metrics are intended to complement the existing set of metrics and criteria that support design analysis and decision making. The life cycle inventory of the fuel tank can be used as a basis to propose a set of generic metrics for product design, although the distribution and magnitude of environmental burdens and impacts will vary according to the automotive part/component under development. Three factors influence the selection of metrics: reliability and accuracy in representing environmental burdens and impacts, ease of measurement and evaluation, and their applicability to a wide range of automotive parts and components. Based on these preconditions the project team decided to make recommendations for the following cases.

Case 1. A comprehensive set of metrics applicable to all automotive applications; unrestricted by data availability (i.e., the ideal case).

Case 2. Metrics that are specific to fuel tank design.

Case 3. A subset of the metrics defined in Case 1 but restricted by data availability.

Case 1 - Comprehensive set of metrics

The development of an ideal set of environmental metrics can draw on LCA methodology. The following four categories for metrics can be defined: product system definition, life cycle energy, life cycle materials, and life cycle waste. Table 4-5 presents specific metrics within each of these categories. A detailed life cycle process flow diagram is necessary to model the product system and evaluate environmental metrics.

The methodology for evaluating global warming potentials and ozone depletion potentials is relatively well established by the international community. Models for predicting climate change based on the emissions of greenhouse gases and ozone depleting substances are, however, much less certain. Human toxicity and ecotoxicity potentials are much more difficult to define compared to GWP and ODP. Model parameters for assessing toxicity have been developed by Leiden University and Pre Consultants. The human and ecosystem health effects depend on the various parameters affecting fate and transport of pollutants, and the duration, frequency, routes, and characteristics of the population exposed. Consequently, very detailed and accurate assessments require site specific modeling.

Table 4-5 Comprehensive set of environmental metrics

Product System Definition	additional parameters and data requirements
Composition of part/component(s): mass and materials	
Expected useful life of part, expected useful life of vehicle	
Life Cycle Energy	
Material Production Energy	specific material production energies, total mass of material input into manufacturing
Manufacturing Energy	part fabrication energies, mass of product and process used at each process step (or material efficiencies)
Use Energy	fuel consumption to mass reduction correlation, mass of vehicle
End-of-Life Management Energy	shredding energy
Distribution Energies	transportation and packaging energies, distances between stages/processing steps
(note that the distribution energy for transporting materials between stage i and i+1 would be included with the ith stage)	
Total Life Cycle Energy	
Life Cycle Materials	
Mass of Nonrenewable Resources Input into the ith stage	
Mass of Materials of Concern Input into the ith stage	
(note life cycle materials can be distinguished between product, process, and distribution components)	
Life Cycle Waste	
Solid Waste	
(distinguish hazardous and municipal/sanitary waste where possible)	
Mass of Material Production Solid Waste	material production solid waste factors
Mass of Manufacturing Solid Waste	part fabrication solid waste factors
Mass of Use Solid Waste	mass of solid waste associated with the service part, solid waste associated with the fuel cycle
Mass of End-of-Life Solid Waste	
Total Mass of Solid Waste	
Waterborne Effluents	
Ecosystem Effects	releases of waterborne pollutants, LCIA data and model parameters
Human Health Effects	releases of waterborne pollutants, LCIA data and model parameters
Air	*Emission factors for air pollutants*
GWP	GW emission factors, GW potentials
ODP	emission factors for ozone depleting substances, ODP
Acidification Potential	emission factors for acidifying gases, acidification potentials [28]
Smog Formation Potential	emission factors for smog forming gases, smog formation potentials [28]
Human Toxicity Potential †	releases of pollutants, LCIA data, and model parameters [28]
Ecotoxicity Potential †	releases of waterborne pollutants, LCIA data, and model parameters [28]

† methods for evaluating human toxicity and ecotoxicity potentials are not well established

Case 2 - Metrics for the Fuel Tank System

The metrics proposed in Table 4-6 for fuel tank system design are based on the life cycle inventory analysis conducted in this project. The metrics that are specific to the fuel tank system represent a streamlined set of the metrics presented in Table 4-5. The metrics presented in Table 4-6 are consistent with the assumption and boundary conditions indicated in Table 2-1. It should be recognized that although models can be established for future design analysis of fuel tank systems, material production and manufacturing processes undergo continuous improvement and model parameters must be adjusted accordingly.

Table 4-6 provides metrics for the fuel tank system which can be evaluated relatively easily using existing data sources. This investigation provides a basis for streamlining future fuel tank design analyses. Life cycle inventory results indicate which life cycle phases are responsible for a majority of the energy and material consumption, and waste burdens. Life cycle energy can be approximated by evaluating the material production, manufacturing, and use phase energy inputs. Transport energy and end-of-life management energy accounted only for approximately 1-2% of the total life cycle. In the case of solid waste, the use phase solid waste which is associated with gasoline production contributed only 2-3% of the total solid waste burden, and therefore, could be neglected.

Case 3 - Metrics based on current data restrictions

The entire set of metrics in Table 4-5 and Table 4-6 can not be evaluated easily because of the lack of specific published data such as part fabrication energies and emissions factors, and material production and manufacturing solid waste. Table 4-7 presents a "practical" set of metrics defined by existing data restrictions. Based on the judgment of the project team many of the metrics in Table 4-5 and Table 4-6 were excluded.

Table 4-6 Metrics for the fuel tank system

Product System Definition	additional parameters and data requirements
Composition of part/component(s)	mass and materials of part and auxiliary components
Expected useful life of part, expected useful life of vehicle	
Life Cycle Energy	
Material Production Energy	steel and HDPE material production energies
Manufacturing Energy	stamping and blow molding energies
Use Energy	fuel consumption to mass reduction correlation, vehicle mass
End-of-Life Management Energy	shredding energy
Transport Energy	distances between stages/processing steps
Life Cycle Materials	
Mass of Nonrenewable Resources Input (product material only)	
Mass of Materials of Concern (MOC) Input (entering GM gate only)	
(note life cycle materials can be distinguished between product, process, and distribution components)	
Life Cycle Waste	
Solid Waste	
(distinguish hazardous and municipal/sanitary waste where possible)	
Mass of Material Production Solid Waste	material production solid waste factors
Mass of Manufacturing Solid Waste	stamping and molding scrap rates
Mass of Use Solid Waste	solid waste associated with the fuel cycle
Mass of End-of-Life Management Solid Waste (ASR)	
Air	
Mass of CO2	CO2 emission factors for all stages
Mass of CO, NOx, HC, particulates	these air pollutant emission factors are available for the use phase but they are not complete for other stages
Water	waterborne pollutant emission factors are not complete

Table 4-7 Streamlined set of metrics based on data restrictions

Product System Definition	**additional parameters and data requirements**
Composition of part/component(s): mass and materials	
Expected useful life of part, expected useful life of vehicle	
Life Cycle Energy	
Material Production Energy	specific material production energies, total mass of material input into manufacturing
Use Energy	fuel consumption to mass reduction correlation, vehicle mass
End-of-Life Management Energy	shredding energy
Life Cycle Materials	
Mass of Nonrenewable Resources Input (product material only)	
Mass of Materials of Concern Input (entering GM gate only)(note life cycle materials can be distinguished between product, process, and distribution components)	
Life Cycle Waste	
Solid Waste	
Mass of End-of-Life Management Solid Waste (ASR)	
Air	
Mass of CO2, CO, NOx, HC, particulates (use phase)	CO2, CO, NOx, HC, particulate emission factors

Several investigations have shown that the use phase dominates the total life cycle energy consumption for an automobile. Approximately 90% of the life cycle energy is consumed in the use phase [27]. The energy profile for a particular part or component depends on its composition and design. Unfortunately, energy data for part fabrication steps in the manufacturing stage are not readily available and these energies vary considerably. Stamping and plastic molding processes are often less energy intensive compared with casting processes. Specific material production energies have been published in the literature and can serve to inform the design team about large differences between material types. For example, the energy for primary aluminum production is 178 MJ/kg compared to 18 MJ/kg for secondary aluminum [16].

The mass of material input into the manufacturing stage is needed to compute the material production energy of a part. These data are not always readily accessible. A first order approximation of the material production energy would be based on the mass of material in the part and the specific material production energy (MJ/kg). The error introduced with this approximation is directly related to the material losses in the manufacturing stage.

Mass of materials of concern (MOC) inputs were limited to materials procured by GM. The scope is restricted partially by GM's capability of tracking MOC use by suppliers. Solid waste from end-of-life management of the fuel tank accounts for only one portion of the total life cycle solid waste. Unfortunately, published data on solid waste from material production is limited. It should be recognized that the proposed metric tends to favor metallic parts over plastics and other non-metallic parts which are currently constituents of automotive shredder residue (ASR).

The goal of this project is to recommend reliable design metrics which will enhance the decision making capabilities of the design team. The limitations of these metrics should be made transparent and caution should be taken in using metrics which are not comprehensive. A comprehensive set of metrics would address all major input and output streams associated with each product, process and distribution component throughout the life cycle of the product system. As the level of comprehensiveness is reduced the accuracy of the design analysis in measuring environmental performance decreases. The complete set of environmental metrics can always be improved as more accurate data become available. Metrics are useful in highlighting discrete environmental issues and therefore can be useful in raising the awareness of the design team.

5. Conclusions

The life cycle design framework was applied to the GMT 600 fuel tank system to serve three basic functions: 1) demonstrate the effectiveness of life cycle design tools, 2) enhance the project teams understanding of environmental, performance, and cost factors related to the design of the fuel tank system, and 3) recommend environmental metrics for design analysis. Specific tools used in this demonstration project were life cycle inventory analysis and life cycle cost analysis.

Life cycle inventory analysis established environmental profiles for the 31 gallon steel fuel tank system which is used in the GMT 600 passenger van and the 34.5 gallon HDPE fuel tank system currently being used in a GMT 600 cutaway version of the cargo van. To facilitate a comparative assessment of these systems a functionally equivalent tank size of 31 gallons was defined. The total life cycle energy consumption for the steel and HDPE tank systems was 4.9 GJ and 3.6 GJ per tank, respectively. A majority of this energy was consumed during the use phase. Conversely, the solid waste burdens associated with the fuel tank systems were concentrated in the material production and end-of-life management phases. The steel tank system generated approximately 14 kg of total solid waste per tank while the HDPE system generated approximately 13 kg. These differences are not significant within the expected uncertainty of this analysis. The analysis indicates that most of the solid waste associated with steel is generated in the material production phase whereas the HDPE solid waste is generated in vehicle end-of-life management. Previous research conducted by the NPPC indicated that the data uncertainty associated with the air emissions and waterborne effluents is much greater than that for the energy and waste data. Considering these caveats the inventory analysis indicates that the environmental burden of the HDPE tank system is lower than that for the steel tank system for this particular vehicle platform and design. The next logical phase of research would involve conducting a comprehensive uncertainty analysis of the results. This uncertainty analysis would require material production data from other sources and additional manufacturing inventory data to assess its uncertainty.

A performance analysis addressing manufacturability and use phase performance requirements was conducted along with a life cycle cost analysis of manufacturing, gasoline costs, and end-of-life processing costs. Both tanks meet basic performance requirements. Evaporative emissions testing showed that the HDPE multilayer design, with an EVOH layer, served effectively as a permeation barrier to VOCs in gasoline. The major performance requirement that distinguished the two tank designs was design flexibility in meeting capacity requirements within defined spatial constraints.

In examining the distribution of costs among life cycle stages, the estimated production costs dominate for both tank systems. A total cost assessment for manufacturing the two tank systems, however, was not conducted and consequently, hidden environmental costs and liability costs could not be assessed. The difference in use phase costs between the two tank systems is significant—with the HDPE tank system providing a $10 fuel cost savings to consumers over 110,000 vehicle miles traveled. Although the savings related to the fuel tank may appear small, successful application of life cycle design to other vehicle components can result in a much greater total savings to the customer. In the waste management stage, the scrap value associated with the steel tank system more than offsets the end-of-life management costs; whereas, the current scrap value for the plastic fuel tank system is not significant enough to cover the end-of-life management costs, resulting in a net cost for this life cycle phase.

The project team discussed integration of environmental analysis into the product development process. It was recognized that the application of life cycle inventory analysis to fuel tank design is currently most useful in the product planning stage where material selection decisions are made. Results of this analysis, however, can be applied to future design analysis projects. The greatest challenge in inventory data collection was in gathering manufacturing plant data because of its proprietary nature and weaknesses in corporate environmental information management systems. It was particularly difficult for GM to obtain data from their HDPE tank supplier. In one case, waterborne wastes associated with metal forming operations of the steel tank could not be disaggregated from a waste stream which consisted of effluents from other manufacturing facilities. For this project no other special product allocation problems in the manufacturing stage were encountered. Modeling becomes difficult when examining manufacturing plants that involve a mix of process activities that produce multiple products. In this case, process specific data must be collected.

Environmental metrics for life cycle design were proposed based on the results of the life cycle inventory analysis. One objective of the project team was to develop a practical set of metrics for guiding environmental improvement of products. The most comprehensive set of metrics represents a complete life cycle inventory. Data availability and other resource constraints, however, limit the practical application of life cycle inventory analysis on a routine basis. Life cycle inventory metrics were developed in three categories: life cycle energy, materials and wastes. A critical need for implementing life cycle design is accurate sets of air emission factors (g of pollutant emissions/kg of product material), waste generation factors (g of solid waste/kg of product material), and energy factors (MJ of energy/kg of product material). These parameters were compiled for the fuel tank system from either primary plant data or previously published data. The inventory analysis also served to identify metrics that are associated with a majority of the environmental burden across the life cycle.

GM recognized the importance of life cycle design and management as evidenced by their corporate environmental principle, which states: "We are committed to reducing waste and pollutants, conserving resources and recycling materials at every stage of the product life cycle." This demonstration project represents one initiative to implement this policy at an operational level within the company. Further refinement in the valuation component of life cycle impact assessment is required to guide decision makers in the interpretation of inventory data. Significant tradeoffs can exist within and between inventory categories. Integration of the full set of performance, cost, environmental, and regulatory requirements becomes even more complex. Policies and guidelines are in place that address vehicle recyclability, however, issues such as material production energy and waste are not specifically addressed. Design decisions are made in the context of internal and external policies. External policies and regulation do not treat environmental burdens consistently across the life cycle, which makes design analysis and decision making by OEMs more difficult. Inventory interpretation and impact assessment represents a logical extension of this project and another area for further research. As higher quality data for air emissions and water effluents become available, impact assessment techniques become necessary for characterizing human and ecological health impacts.

Despite the limitations of life cycle design, which were identified in this demonstration, the project team gained some important insights regarding the environmental profile of the steel and HDPE fuel tank systems. In addition, the analyses of performance, cost, and policy issues surrounding fuel tank design were valuable for all team members. One attribute of life cycle design is that it provides a framework for identifying and resolving critical design issues. This project provided an opportunity for product development team members that have different functional responsibilities to address the broad scope and complexity of life cycle design issues. This study expanded the scope of analysis beyond the system boundaries used previously by GM for fuel tank design. The overall hypothesis of life cycle design is that a more comprehensive analysis will ultimately create more economically and ecologically sustainable products. This hypothesis will be tested as more corporations begin to implement key elements of life cycle design and management.

References

1. Keoleian, Gregory A., and Dan Menerey. *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System*. US EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, Cincinnati, OH, 1993.

2. ---. "Sustainable development by design: Review of life cycle design and related approaches." *Journal of the Air and Waste Management Association* 44 (5): 645–668 (1994).

3. Keoleian, Gregory A., Jonathan Koch, and Dan Menerey. *Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal*. (EPA/600/R-95/107) Cincinnati: US Environmental Protection Agency, National Risk Management Research Laboratory, 1995.

4. Keoleian, Gregory A., Werner J. Glantschnig, and William McCann. "Life cycle design: AT&T demonstration project." IEEE International Symposium on Electronics and the Environment, San Francisco, 2 May. Piscataway, NJ: Institute of Electrical and Electronic Engineers, 1994.

5. Keoleian, Gregory A. "Pollution prevention through life cycle design." In *Pollution Prevention Handbook*. ed. Harry M. Freeman, 253–292. New York: McGraw-Hill, 1995.

6. Wood, Richard. *Automotive Engineering Plastics*. London: Pentech, 1991.

7. OSAT. *Delphi VIII: Forecast and Analysis of the North American Automotive Industry: Volume 3 Materials*. (UMTRI-96-01-03) Ann Arbor, MI: Office for the Study of Automotive Transportation, University of Michigan Transportation Research Institute, 1996.

8. *Ecobalance of Packaging Materials State of 1990*. Berne, Switzerland: Swiss Federal Office of Environment, Forests, and Landscape, 1991.

9. Boustead, Ian. *Eco-Profiles of the European Plastics Industry - Polyethylene and Polypropylene: Report 3*. Brussels: The European Centre for Plastics in the Environment, 1993.

10. ---. *Eco-Profiles of the European Plastics Industry, Report 6: Polyvinyl Chloride (PVC)*. Brussels: The European Centre for Plastics in the Environment, 1994.

11. *Appendix A: Energy Requirements and Environmental Emissions for Fuel Consumption*. Prairie Village, KS: Franklin Associates, 1992.

12. Wythe, Steve. Stevens Institute of Technology, personal communication, 1996.

13. Barlow, A., D. Contos, M. Holdren, P. Garrison, L. Harris, and B. Janke. "Development of Emission Factors for Polyethylene Processing." *Journal of the Air and Waste Management Association* 46 (June 1996): 569–580 .

14. *Competition Between Steel and Aluminum for the Passenger Car*. Brussels: International Iron and Steel Institute, 1994.

15. Ross, Marc, Rob Goodwin, Rick Watkins, Michael Q. Wang, and Tom Wenzel. *Real-World Emissions from Model Year 1993, 2000 and 2010 Passenger Cars*. Washington, DC: American Council for an Energy-Efficient Economy, 1995.

16. Kar, K., and G. A. Keoleian. "Application of life cycle design to aluminum intake manifolds." SAE International Congress and Exposition, Detroit, MI, 26 February. Warrendale, PA: Society of Automotive Engineers, 1996.

17. Sullivan, J. L., and J. Hu. "Life cycle energy analysis for automobiles." SAE Total Life Cycle Conference, Vienna, 16 October. Warrendale, PA: Society of Automotive Engineers, SAE Paper

951829, 1995.

18. *American Metals Market*, p. 6, (19 July 1996).

19. *Economics of Recovery and Recycling*. American Plastics Council, 1994.

20. NSWMA. National Solid Waste Management Association, personal communication, May 1995.

21. McDaniel, Jeff. *Application of Life Cycle Assessment and Design Tools to Instrument Panels: Analysis for Common Sense Initiative Pilot Project. Masters Thesis.* Ann Arbor, MI: University of Michigan, 1996.

22. *GM Corporate Data*. 1996.

23. 40 CFR Part 81 Section 86.094-8, 1994.

24. Lockhart, Jim. American Petroleum Association. Personal communication, April 1995.

25. *AAMA Motor Vehicle Facts & Figures*. American Automobile Manufacturers Association, Detroit, MI, 1994.

26. Smith, W. *Principles of Materials Science and Engineering, 2nd. Edition*. New York: McGraw Hill, 1990.

27. Keoleian, G. W., K. Kar, M. Manion, and J. Bulkley. *Industrial Ecology of the Automobile: A Life Cycle Perspective*. Warrendale, PA: SAE, 1997.

28. Heijungs, R., J. B. Guinée, G. Huppes, R. M. Lankreijer, H. A. Udo de Haes, A. Wegener Sleeswijk, A. M. M. Ansems, P. G. Eggels, R. van Duin, and H. P. de Goede. *Environmental Life Cycle Assessment of Products - Guide*. Leiden, Netherlands: Center of Environmental Science, 1992.

Appendix A HDPE Fuel Tank Weight and Volume Adjustment

In order to compare the environmental burdens of the two fuel tanks on an equivalent basis, that is, to examine two fuel tanks that perform equivalent functions, the volume of the HDPE fuel tank was reduced to match the volume of the steel tank. For these two fuel tank systems, functional equivalency is defined as: A tank size required to provide sufficient fuel to propel the model truck 450 to 600 highway kilometers between refueling over an 11 year expected life of the vehicle. The criteria for setting tank size is partly based on a requirement to propel the vehicle 450 to 600 highway kilometers between refueling. Therefore, large, heavy vehicles require larger fuel tanks than do small vehicles. For the two vehicles studied, the passenger and cutaway van, the latter is designed to carry heavier loads than the former; its weight falls in the range 9,500 to 12,300 lb. versus the 6,100 to 7,100 lb range of the passenger vehicle.

In order to conduct a meaningful results in the in-use comparison of energy consumption and vehicle emissions, the tanks were compared on the passenger G van. In other words, the actual passenger G van equipped with the steel tank is compared to a hypothetical passenger G van equipped with a plastic tank. Since the plastic tank is designed to carry 34.5 gallons of fuel on a cargo van, which falls within the weight range described above, it would correspondingly be designed to carry 31 gallons of fuel (or less[1] [1]) on the lighter passenger van. Since we are interested in comparing the two fuel tanks on the passenger van, the 31 gallon steel tank was set as the functional volume and the plastic tank volume was hypothetically reduced to 31 gallons. Correspondingly, the plastic fuel tank weight was also reduced. The methodology and calculations for this volume and weight reduction are described below:

Methodology for Reducing the HDPE Tank Volume

The plastic fuel tank is approximately shaped like a rectangular box with dimensions :

length, l = l
width, w = a
height, h = 0.8a

where,

a = 38.1 cm

these dimensions are based on tank measurement.

Note: Plastic density, $\rho = 0.949\ g/cm^3$
Original tank weight = 12 kg

The liquid filling capacity, V_{liq}, of this tank is 34.5 gallons, and the vapor space, V_{vap}, is 4% of the liquid volume.

Therefore, the total volume of the fuel tank, V_{total}, is,

---

[1] Since the plastic tank is lighter in weight than the steel tank, the vehicle's overall weight is lighter with a plastic tank. Some authors [1] have suggested that for each pound of weight reduction in the body panel, another 0.3 pounds can be ultimately reduced from other parts of the automobile while keeping performance constant.

Therefore, the total volume of the fuel tank, V_{total}, is,

$$V_{total} = V_{liq} + V_{vap} = 34.5 + 0.04 \times 34.5 = 35.88 \text{ gallons}$$

To approximate l, given the box configurationdescribed above:

$$V_{total} = h \times w \times l = 0.8 \times a^2 \times l$$
$$l = V_{total}/(0.8 \times a^2) = (35.88 \text{ gal} \times 3785 \text{ cm}^3/\text{gal})/(0.8 \times 38.1\text{cm} \times 38.1\text{cm})$$
$$l = 116.9 \text{ cm}$$

To adjust the liquid volume to 31 gallons (the functionally equivalent steel tank liquid capacity), the new total volume, V'_{total}, assuming that the vapor space is equally distributed along the top of the box configuration, will be:

$$V'_{total} = V'_{liq} + V'_{vap} = 31 + 0.04 \times 31 = 32.24 \text{ gallons}$$

Now adjusting the length (l') of the tank to meet the new volume, V'_{total}:

$$V'_{total} = h \times w \times l' = 0.8 \times a^2 \times l' = 32.24 \text{ gallons}$$

$$l' = (32.24 \text{ gal} \times 3785 \text{ cm}^3/\text{gal})/(0.8 \times 38.1\text{cm} \times 38.1\text{cm})$$
$$l' = 105.1 \text{ cm}$$

Therefore the change in length Δl is,

$$\Delta l = l - l' = 116.9 - 105.1$$
$$\Delta l = 11.8 \text{ cm}$$

To approximate the mass of material removed to shorten the tank length (trimming a cross-section) and thus decrease the liquid capacity:

$$m_R = V_R \times \rho$$

where

m_R = mass of material removed
V_R = volume of material removed
ρ = density of material removed

$$V_R = (2 \times 38.1 \text{ cm} + 2 \times 30.48 \text{ cm}) \times 11.8 \text{ cm} \times 0.5 \text{ cm}$$
$$V_R = 809.2 \text{ cm}^3$$

$$m_R = (809.2 \text{ cm}^3 \times 0.949 \text{ g/cm}^3)/(1000 \text{ g/kg})$$
$$m_R = 0.76 \text{ kg}$$

Therefore, the adjusted mass m', will be,

$$m' = m - m_R$$

where m = mass of 34.5 gallon tank

$$m' = 12 - 0.76 \text{ kg}$$
$$m' = 11.2 \text{ kg}$$

Therefore, the adjusted plastic fuel tank weight is approximately 11.2 kg. If instead of assuming that the vapor space is equally distributed along the top of the box, and we assume that the vapor space is left as a separate, unchanged space entity, leaving the liquid volume space alone as the adjusted variable, the following weight adjustment would result:

The liquid volume space would be reduced to 31 gallons from 34.5 gallons. Therefore, 3.5 gallons of liquid space would be removed.

Let l_R = length by which the plastic fuel tank is shortened
and V_{LR} = volume of liquid space removed = 3.5 gal = 13247.5 cm^3

$$V_{LR} = l_R \times w \times h = 13247.5 \text{ cm}^3$$
$$l_R = (13247.5 \text{ cm}^3)/(38.1 \text{ cm} \times 30.48 \text{ cm})$$
$$l_R = 11.4 \text{ cm}$$

thus the mass of material removed as a result of shortening the tank length is,

$$m_R = V_R \times r$$

Where V_R = Volume of material removed
Using $V_R = (2 \times a + 2 \times 0.8 \times a) \times Dl \times t$

Therefore, $m_R = (2 \times a + 2 \times 0.8 \times a) \times Dl \times t \times r$

$$m_R = (2 \times 38.1 \text{ cm} + 2 \times 30.48 \text{ cm}) \times (11.4 \text{ cm} \times 0.5 \text{ cm} \times 0.949 \text{ g/cm}^3)/1000 \text{ g/kg}$$
$$m_R = 0.74 \text{ kg}$$

$$m' = 12 - 0.74 = 11.3 \text{ kg}$$

Hence the difference between reducing the plastic tank weight by reducing the liquid volume space alone versus reducing both the liquid and vapor volume space is 0.1 kg.

Since in the design of the fuel tank, the vapor space is set to 4% of the liquid volume, the assumption that the total volume decreases is justified. Therefore, the new adjusted plastic fuel tank weight is 11.2 kg.

Appendix A References

1. Kusik, Charles L., Stanley E. Dale, Phillip G. Gott, and Krishna Parameswaran. Life cycle energy requirements for selected automotive sheet materials, Detroit, MI, 22 February. Warrendale, PA: Society of Automotive Engineers, Technical Paper 820148, 1982.

Table B-1

Gross Inputs and Outputs Associated with the Production of 1 kg of HDPE

Air Emissions	Dust	mg	2000
	Carbon Monoxide	mg	600
	Carbon Dioxide	mg	940000
	Sulphur Oxides	mg	6000
	Nitrogen Oxides	mg	10000
	Hydrogen Chloride	mg	50
	Hydrogen Fluoride	mg	1
	Hydrocarbons	mg	21000
	Other Organics	mg	5
	Metals	mg	1
	Hydrogen	mg	1
Water Emissions	COD	mg	200
	BOD	mg	100
	Acid as H+	mg	100
	Nitrates	mg	10
	Metals	mg	300
	Ammonium Ions	mg	10
	Chloride Ions	mg	800
	Dissolved Organics	mg	20
	Suspended Solids	mg	200
	Oil	mg	30
	Hydrocarbons	mg	150
	Dissolved Solids	mg	500
	Phosphate	mg	1
	Other Nitrogen	mg	5
Solid Waste	Industrial Waste	mg	3000
	Mineral Waste	mg	18000
	Slags and Ash	mg	5000
	Toxic Chemicals	mg	40
	Non-toxic Chemicals	mg	6000

source: [1]

Table B-2

Ecobalance of Tin Plate

		Units	0% Recycling
Atmospheric	Particles	g	26.9553
	CO	g	1.3814
	HC	g	16.527
	NOx	g	2.7329
	N2O	g	0.4172
	SO2	g	8.4503
	Aldehydes	g	0.0092
	F-	g	0
	HF	g	0.0005
	NH3	g	0.0735
	Other Organic Compounds	g	0.0169
	Tar	g	0.0001
Water	Dissolved Solids	g	0.9516
	Suspended Solids	g	0.318
	BOD	g	0.0052
	COD	g	0.0013
	Ammonia	g	0.0065
	Chlorides	g	0
	Cyanides	g	0.0001
	Fe-Ions	g	0.1
	Fluorides	g	0.0334
	Sulphides	g	0.0002
	HCl	g	2
	Na-Ions	g	0.0002
	Nitrates	g	0.0003
	Oils	g	0.5412
	Phenols	g	0.0003
	Sulfates	g	0.0002
	Tar	g	0

source: [2]

Table B-3

Gross Inputs and Outputs Associated with the Production of 1 kg of PVC

		Unit	Average
Air Emissions	Dust	mg	5400
	Carbon Monoxide	mg	1600
	Carbon Dioxide	mg	2741000
	Sulphur Oxides	mg	18000
	Nitrogen Oxides	mg	19000
	Chlorine	mg	4
	Hydrogen Chloride	mg	300
	Hydrocarbons	mg	26000
	Metals	mg	3
	Chlorinated Organics	mg	1389
Water Emissions	COD	mg	1200
	BOD	mg	60
	Acid as H+	mg	130
	Metals	mg	220
	Chloride Ions	mg	3900
	Dissolved Organics	mg	1000
	Suspended Solids	mg	4200
	Oil	mg	50
	Dissolved Solids	mg	760
	Other Nitrogen	mg	2
	Chlorinated Organics	mg	4
	Sulphate Ions	mg	4000
	Sodium Ions	mg	2000
Solid Waste	Industrial Waste	mg	1300
	Mineral Waste	mg	110000
	Slags and Ash	mg	210000
	Toxic Chemicals	mg	11000
	Non-toxic Chemicals	mg	3500

source: [3]

Table B-4

Air Emissions

- The hydrogen chloride emissions given in the HDPE and PVC data source were not inventoried because it was not included as a category in the steel data source.
- The metal emissions given in the HDPE and PVC data source were not inventoried because it was not included as a category in the steel data source.
- The hydrogen fluoride emissions given in the HDPE and steel data sources were not inventoried because: a) it was not included in as a category in the PVC data source and b) the amount of the emissions were small relative to the other categories inventoried.
- The chlorinated organics category for the PVC data set was renamed to other organics which is a category found in the HDPE and Steel data sets.
- Chlorine, hydrogen, tar, ammonia, and aldehyde emission categories were excluded because they appeared in only one of the three data sets.

Waterborne Emissions

- The sulfides category found in the steel data set was included with the sulphate category found in all three data sets. The category was named sulfides/sulphates.
- Metals were speciated in the steel and PVC data sets, but not in the HDPE data set. For the steel data set, the metal category was calculated as the sum of Na-Ions and Fe-Ions categories. For the PVC data set, the sodum ion category was summed with the metals category.
- The acid as H+ category for the HDPE and PVC data sets was not inventoried because the category was not included in the steel data set. A similar category existed (HCL), but detailed knowledge of the data prohibited it being inventoried with acid as H+.
- Ammonia, cyanides, fluorides, HCL, nitrates, phenols, tar, ammonium ions, dissolved organics, hydrocarbons, and other nitrogen emission categories were excluded because they did not appear in all three data sets.

Appendix B References

1. Boustead, Ian. *Eco-Profiles of the European Plastics Industry - Polyethylene and Polypropylene: Report 3*. Brussels: The European Centre for Plastics in the Environment, 1993.

2. *Ecobalance of Packaging Materials State of 1990*. Berne, Switzerland: Swiss Federal Office of Environment, Forests, and Landscape, 1991.

3. Boustead, Ian. *Eco-Profiles of the European Plastics Industry, Report 6: Polyvinyl Chloride (PVC)*. Brussels: The European Centre for Plastics in the Environment, 1994.

Appendix C. Life Cycle Design Framework

Primary elements of the life cycle design framework are [1]:

- Product life cycle system
- Goals
- Principles
- Life cycle management
- Development process

Product Life Cycle System

Life cycle design and management requires an accurate definition of the product system, including both spatial and temporal boundaries. The product system can be organized by life cycle stages and product system components. Life cycle stages include materials production, manufacturing and assembly, use and service, and end-of-life management as shown in Figure C-1.

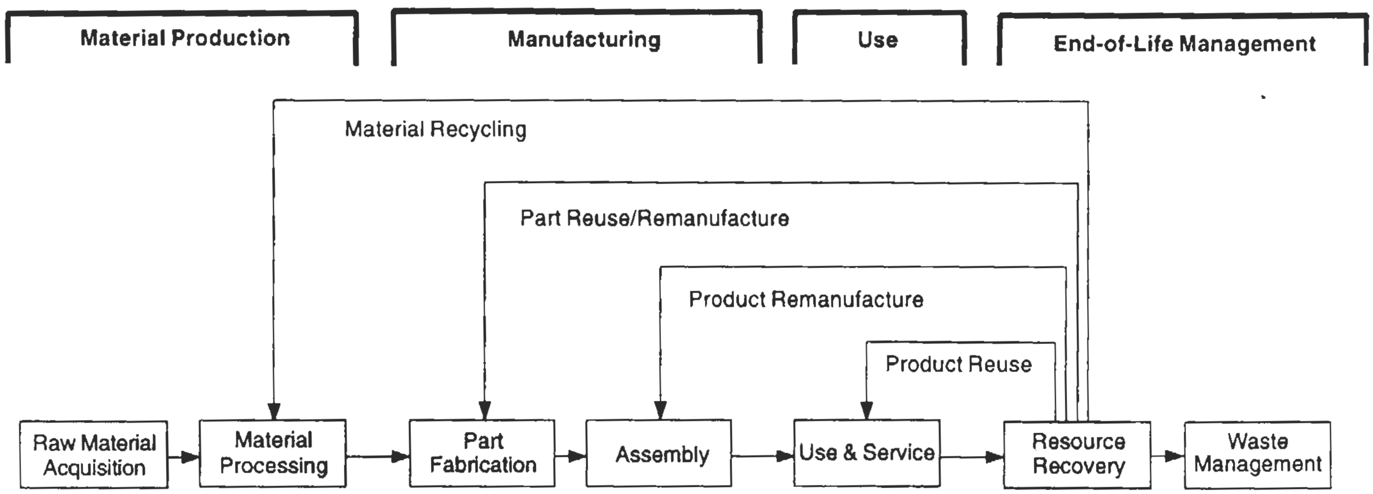


Figure C-1. Product Life Cycle System

Product, process and distribution components further characterize the product system for each life cycle stage as shown in Figures C-2 and C-3. This organization in contrast to LCA convention can better accommodate product and process design functions. The time frame for a design project ranges between a short term horizon that may emphasize incremental improvements in the product system and a long range view that explores next generation designs.

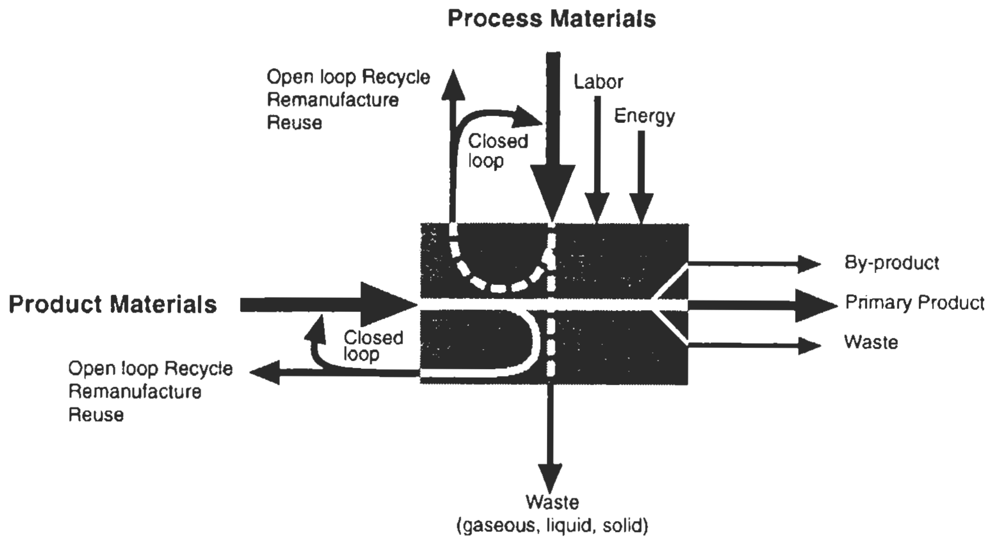


Figure C-2. Flow Diagram Template for Life Cycle Subsystem

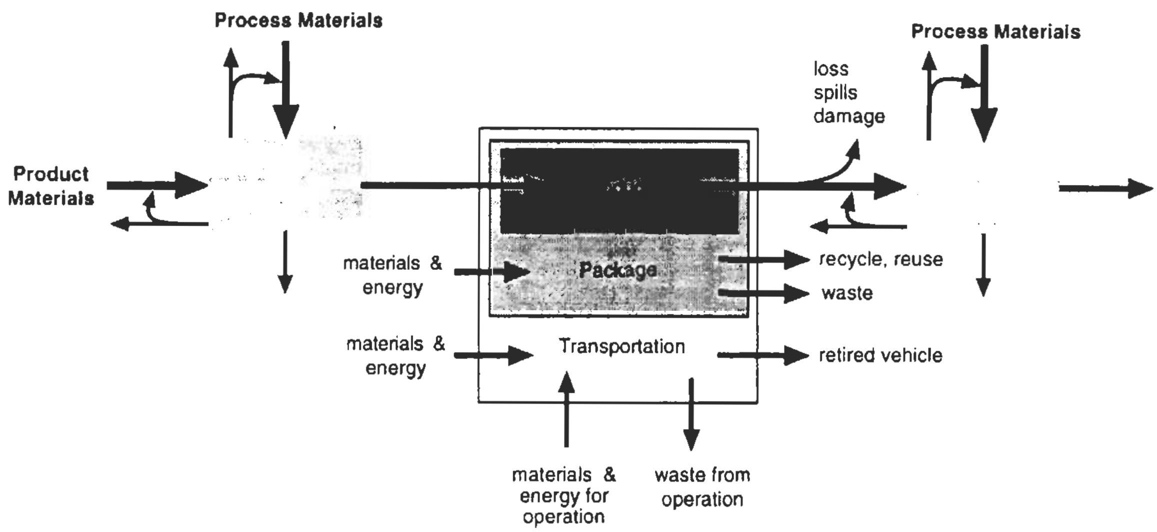


Figure C-3. Distribution Component Flow Diagram

Goals

The broad goal of life cycle design is the design and management of products that are ecologically and economically sustainable. Necessary conditions for sustainability include: sustainable resource use (conserve resources, minimize depletion of non-renewable resources, use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environmental equity. All of these conditions are interrelated and highly complementary. Economic sustainability requires that the product system meet basic cost, performance, legal and cultural criteria.

The specific environmental goal of life cycle design is to minimize the aggregate life cycle environmental burdens and impacts associated with a product system. Environmental burdens include resource inputs and waste outputs which can be classified into impact categories according to life cycle impact assessment methods. [2][3][4] General impact categories include resource depletion and ecological and human health effects. No universally accepted method for aggregating impacts is available.

Principles

There are three main themes for guiding environmental improvement of product systems in life cycle design: *systems analysis* of the product life cycle; *multicriteria analysis* of environmental, performance, cost, and legal requirements and issues (see specification of requirements section); and *multistakeholder participation and cross-functional teamwork* throughout the design process. The following principles relating to each of these themes have been derived from our empirical research. Many of these principles of life cycle design are already considered best design practice.

Systems Analysis

Systems analysis focuses on understanding the behavior of individual components of a system and the relationships between the collection of components that constitute the entire system. In addition the relationships between the system under study and higher order/larger scale systems should be analyzed. Both time and space dimensions must be addressed.

1. The product life cycle is a logical system for product management and design because it encompasses the total physical flow of product materials through the economy.
2. Successful design initiatives should establish clear system boundaries for analysis. The scope of a design activity can be restricted to smaller system boundaries such as individual life cycle stages or process steps, but this will inherently limit the opportunities for improvement.
3. Studying the relationship between product materials and related process/distribution components - systems that transform/transport the product material along the life cycle - is critical towards improving the product system design.
4. The breadth of system boundaries depends on the vision of the organization; less responsible firms do not address environmental issues much beyond the manufacturing domain whereas more ecologically responsible corporations will address the full product life cycle. The broader perspective may not yield immediate economic benefits but should lead to long term success.

Multiobjective Analysis

A successful design will satisfy multiple objectives including performance, cost, legal and environmental requirements. Many design requirements will overlap and reinforce each other while others conflict and limit design possibilities.

1. Specifying design requirements for both guiding improvement and evaluating alternatives is critical to efficient product design and management. Clearly defined requirements that are both internal and external to an organization reduce uncertainty in decision making.
2. Understanding the interactions and conflicts between performance, cost, legal, and environmental requirements serves to highlight opportunities as well as vulnerabilities. In some cases, environmentally preferable designs may not be adopted because they do not show a direct cost advantage to the manufacturer, are not supported by regulations, or do not demonstrate performance advantages.
3. Unless more specific guidance can be offered through well-established corporate environmental policies and goals or national environmental policies or goals design teams must rely on their personal knowledge and experience to make complex tradeoffs. Tradeoffs often exist among environmental criteria, such as minimizing waste, energy and emissions as well as between environmental, cost, performance and legal criteria. Judgment is ultimately required to weight and rank criteria.

Multistakeholder Participation

The stakeholders that control the life cycle of a product can be considered part of a virtual organization. Some stakeholders share a common goal for enhancing the overall economic success of the product, while maximizing their own individual profit. Minimizing life cycle burdens, however, may not be a priority. Identifying the actors that control the life cycle of a product and their interests is a first step in achieving better life cycle management of a product.

1. Harmonizing the often diverse interests of stakeholders (suppliers, manufacturers, customers, waste managers, regulators, investors) into a product design that is technically, economically, socially and ecologically feasible/optimal is a fundamental challenge of design.
2. Partnerships are helpful in implementing changes that affect more than one stage or activity in the life cycle.
3. Initiatives to reduce life cycle environmental burdens will be limited in their effectiveness by the degree to which stakeholders recognize this as a common goal for product design and management.

Life Cycle Management

Life cycle management includes all decisions and actions taken by multiple stakeholders which ultimately determine the environmental profile and sustainability of the product system. Key stakeholders are users and the public, policymakers/regulators, material and waste processors, suppliers, manufacturers, investors/shareholders, the service industry, and insurers. The design and management decisions made by the manufacturer of the end-use product may have the greatest influence over the life cycle environmental profile of a product system. It is useful to distinguish between environmental management by internal and external stakeholders. A major challenge for product manufacturers is responding to the diverse interests of external stakeholder groups.

The environmental management system (EMS) within a corporation is the organizations structure of responsibilities, policies, practices, and resources for addressing environmental issues. Several voluntary EMS standards and guidelines have been developed (BS7750, ISO 14,001, GEMI). Although EMS activities have emphasized proactive measures in addition to regulatory compliance, traditionally these systems have only addressed the manufacturing domain of the corporation [5] and have not covered end-of-life management or material acquisition processing stages.

Life Cycle Development Process

The product development process varies widely depending on the type of product and company and the design management organization within a company. In general, however, most development processes incorporate the key activities shown in Figure C-4. For life cycle design this process takes place within the context of sustainable development and life cycle management.

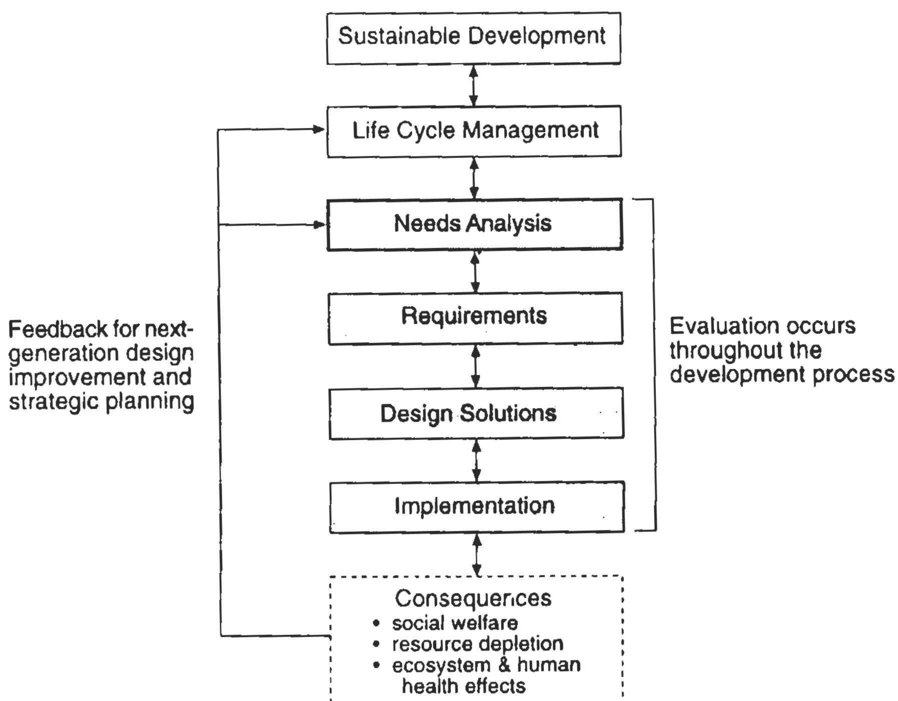


Figure C-4. Life Cycle Development Process

The life cycle design framework emphasizes three important design activities: specifying requirements to guide design improvements, selecting strategies for reducing environmental burden, and evaluating design alternatives.

The specification of requirements to guide design and management decisions is a fundamental activity for any design initiative [6]. Techniques for assisting development teams in establishing environmental design criteria have not been widely implemented. A multilayer requirements matrix has been developed as a tool to identify, organize, and evaluate environmental, cost, performance, legal and cultural design criteria [7][8][1]. DFX or Design for X strategies [9] such as design for recyclability, disassembly, and remanufacturability have been more widely promoted. Life cycle assessment tools for evaluating product systems [10][11][12][13][14] have probably received the most attention in the last two decades. The practical application of LCA tools by product development engineers, however, is currently limited [15][16]. It is the refinement and application of these three types of design and analysis tools that will lead to the most effective implementation of life cycle design and DFE.

Specification of Requirements

Specification of requirements is one of the most critical design functions. Requirements guide designers in translating needs and environmental objectives into successful designs. Environmental requirements should focus on minimizing natural resource consumption, energy consumption, waste generation, and human health risks as well as promoting the sustainability of ecosystems. A primary tool of life cycle design is the multicriteria matrices for specifying requirements shown in Figure C-5. Other tools for guiding designers include design checklists and guidelines.

The matrices shown in Figure C-5 allow product development teams to study the interactions and tradeoffs between environmental, cost, performance and legal requirements. Each matrix is organized by life cycle stages and product system components. Elements can then be described and tracked in as much detail as necessary. Requirements can include qualitative criteria as well as quantitative metrics.

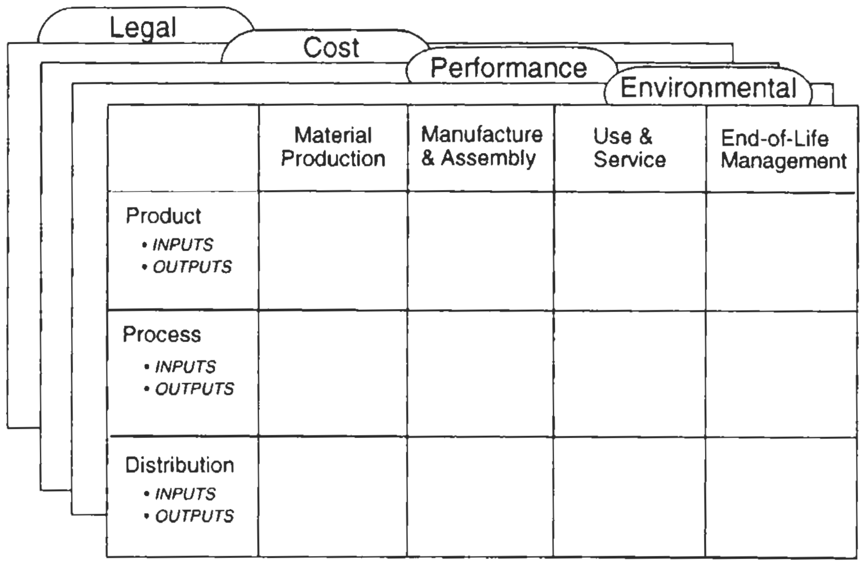


Figure C-5. Multicriteria Requirements Matrix

Design Strategies

Selecting and synthesizing design strategies for meeting the full spectrum of requirements is a major challenge of life cycle design and management. General strategies for fulfilling environmental requirements are product oriented (product life extension, remanufacturability, adaptability, serviceability, and reusability); material oriented (recycling, substitution, dematerialization); process oriented; and distribution oriented (optimize transportation and packaging). An explanation of each strategy is provided in the *Life Cycle Design Guidance Manual* [7].

Design Evaluation

Analysis and evaluation are required throughout the product development process as well as during strategic planning by management. Approaches for design evaluation range from comprehensive analysis tools such as life cycle assessment (LCA) to the use of single environmental metrics. LCA tools can be broadly classified as SETAC related methodologies [10][11][13], semi-quantitative matrix evaluation tools [17][18], and other techniques such as the Environmental Priority Strategies (EPS) system [19]. If environmental requirements for the product system are well specified, design alternatives can be checked directly against these requirements. Several tools for environmental accounting and cost analysis are also emerging [20] [21] [22] [23]. Cost analysis for product development is often the most influential tool guiding decision making. Key issues of environmental accounting are: measuring environmental costs, allocating environmental costs to specific cost centers, and internalizing environmental costs.

In principle, LCA represents the most accurate tool for design evaluation in life cycle design and DFE. Many methodological problems, however, currently limit LCA's applicability to design [15]. Costs to conduct a LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles [24] [16]. Although significant progress has been made towards standardizing life cycle inventory analysis, [13] [11] [10] [14] results can still vary significantly [25] [26]. Such discrepancies can be attributed to differences in system boundaries, rules for allocation of inputs and outputs between product systems, and data availability and quality issues.

Incommensurable data presents another major challenge to LCA and other environmental analysis tools. A large complex set of inventory data can be overwhelming to designers and managers who often lack environmental training and expertise. The problem of evaluating environmental data remains inherently complicated when impacts are expressed in different measuring units (e.g., kilojoules, cancer risks, or kilograms of solid waste). Furthermore, impact assessment models vary widely in complexity and uncertainty.

Even if much better assessment tools existed, LCA has inherent limitations in design and management, because the complete set of environmental effects associated with a product system can not be evaluated until a design has been specified in detail [15]. This limitation indicates the importance for requirements matrices, checklists and design guidelines which can be implemented during conceptual design phases.

Appendix C References

1. Keoleian, Gregory A., Jonathan Koch, and Dan Menerey. *Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal.* (EPA/600/R-95/107) Cincinnati: US Environmental Protection Agency, National Risk Management Research Laboratory, 1995.

2. Guinée, Jeroen B., Reinout Heijungs, Helias A. Udo de Haes, and Gjalt Huppes. "Quantitative life cycle assessment of products: Classification, valuation and improvement analysis." *Journal of Cleaner Production* 1, no. 2 (1993): 81–91.

3. SETAC. "Workshop Report - A Conceptual Framework for Life-Cycle Impact Assessment," Sandestin, FL, 1 February 1992. Pensacola, FL: Society of Environmental Toxicology and Chemistry, 1993.

4. Weitz, Keith A., and John L. Warren. *Life Cycle Impact Assessment: Framework Issues, Draft.* Research Triangle Park, NC: US EPA, Office of Air Quality, Planning and Standards, 1993.

5. Marguglio, B. W. *Environmental Management Systems.* New York: Marcel Dekker, 1991.

6. Gause, Donald G., and Gerald M. Weinberg. *Requirements: Quality Before Design.* New York: Dorset House, 1989.

7. Keoleian, Gregory A., and Dan Menerey. *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System.* Cincinnati: US EPA, Office of Research and Development, Risk Reduction Engineering Laboratory, 1993.

8. ---. "Sustainable development by design: Review of life cycle design and related approaches." *Journal of the Air and Waste Management Association* 44, no. 5 (1994): 645–668.

9. Gatenby, David A., and George Foo. Design for X (DFX): "Key to Competitive, Profitable Products." *AT&T Technical Journal* 69, no. 3 (1990): 2–11.

10. Vigon, B. W., D. A. Tolle, B. W. Cornary, H. C. Latham, C. L. Harrison, T. L. Bouguski, R. G. Hunt, and J. D. Sellers. *Life Cycle Assessment: Inventory Guidelines and Principles.* (EPA/600/R-92/245) Cincinnati: US EPA, Risk Reduction Engineering Laboratory, 1993.

11. Heijungs, R., J. B. Guinée, G. Huppes, R. M. Lankreijer, H. A. Udo de Haes, A. Wegener Sleeswijk, A. M. M. Ansems, P. G. Eggels, R. van Duin, and H. P. de Goede. *Environmental Life Cycle Assessment of Products - Guide.* Leiden, Netherlands: Center of Environmental Science,1992.

12. Guinée, J. B., H. A. Udo de Haes, and G. Huppes. "Quantitative life cycle assessment of products: Goal definition and inventory." *Journal of Cleaner Production* 1 (1993): 3-13 .

13. SETAC. Workshop Report - A Technical Framework for Life-Cycle Assessment, Smugglers Notch, VT, 18 August 1990. Washington, DC: Society of Environmental Toxicologists and Chemists, 1991.

14. ---. Workshop Report - Guidelines for Life-Cycle Assessment: A Code of Practice, Sesimbra, Portugal, 31 March. Pensacola, FL: Society of Environmental Toxicology and Chemistry, 1993.

15. Keoleian, Gregory A. "The application of life cycle assessment to design." *Journal of Cleaner Production* 3-4 (1994): 143-149.

16. White, Allen L., and Karen Shapiro. "Life cycle assessment: A second opinion." *Environmental Science & Technology* 27, no 6 (1993): 1016–1017.

17. Graedel, T. E., B. R. Allenby, and P. R. Comrie. "Matrix approaches to abridged life cycle assessment." *Environmental Science and Technology* 29, no. 3 (1995): 134-139.

18. Allenby, Braden R. "Design for environment: A tool whose time has come." *SSA Journal* (September 1991): 6–9 .

19. FSI. *The Product Ecology Report: Environmentally-Sound Product Development Based on the EPS System*. Stockholm: Federation of Swedish Industries, 1993.

20. US EPA. *Pollution Prevention Benefits Manual: Volume I The Manual.* Washington: US EPA, Office of Policy, Planning, and Evaluation & Office of Solid Waste, 1989.

21. White, Allen L., Monica Becker, and James Goldstein. *Total Cost Assessment: Accelerating Industrial Pollution Prevention Through Innovative Project Financial Analysis.* Washington, DC: US EPA, Office of Pollution Prevention and Toxics, 1992.

22. US EPA. *An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms*. Washington, DC: US Environmental Protection Agency, Office of Pollution Prevention and Toxics, 1995.

23. SNL. *Life Cycle Cost Assessment: Integrating Cost Information into LCA, Project Summary*. Albuquerque, NM: Sandia National Laboratories, 1993.

24. Sullivan, Michael S., and John R. Ehrenfeld. "Reducing life-cycle environmental impacts: An industry survey of emerging tools and programs." *Total Quality Environmental Management* 2, no. 2 (1992): 143–157.

25. Svensson, Göran. "Experience from the inventory phase of LCA studies." First NOH European Conference: Design for the Environment, 1.1.1, 1-8. Nunspeet, Netherlands, 21 September. 1992.

26. Curran, Mary Ann. "Broad-based environmental life cycle assessment." *Environmental Science and Technology* 27, no. 3 (1993): 430–436 .

Appendix D Acronyms

APC	American Plastics Council
APME	Association of Plastic Manufacturers in Europe
ASR	auto shredder residue
BOD	Biological Oxygen Demand
C	cost
CARB	California Air Resources Board
CO	carbon monoxide
CO2	carbon dioxide
COD	Chemical Oxygen Demand
CS	carbon steel
DFE	Design for Environment
DFX	Design for X
ELV	end-of-life vehicle
EMS	Environmental Management System
EPA	U.S. Environmental Protection Agency
EPS	Environmental Priority Strategy
EVOH	ethyl vinyl alcohol
F	volume of fuel
FE	fuel economy
g	gram
G	General Motors vehicle line (e.g., G-Van)
GJ	giga joule
GM	General Motors
GMT600	light duty truck line
GMC	General Motors vehicle Line (e.g., GMC truck)
GWP	Global Warming Potential
HC	hydrocarbon
HDPE	high density polyethylene
kg	kilogram
LCCA	Life Cycle Cost Analysis
LCD	Life Cycle Design
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LDPE	low density polyethylene
M, m	mass of emission
m′	emission factor
MJ	mega joule
MOC	Materials of Concern
NOx	nitrogen oxides
NPPC	National Pollution Prevention Center
NSWMA	National Solid Waste Management Association

ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
PE	polyethylene
PFS	plastic fuel tank system
PM	Particulate Matter
PVC	polyvinyl chloride
Sn/Ag	tin-silver
SFS	steel fuel tank system
SPI	Society of the Plastics Industry
USDOT	United States Department of Transportation
$\frac{\Delta f}{\Delta M}$	fuel consumption correlation with mass