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ABSTRACT

Federal standards that mandate improved fuel economy have resulted in the increased use of lightweight materials in automotive applications. However, the environmental burdens associated with a product extend well beyond the use phase. Life cycle assessment is the science of determining the environmental burdens associated with the entire life cycle of a given product from cradle-to-grave. This report documents the environmental burdens associated with every phase of the life cycle of two fuel tanks utilized in full-sized 1996 GM vans. These vans are manufactured in two configurations, one which utilizes a steel fuel tank, and the other a multi-layered plastic fuel tank consisting primarily of high density polyethylene (HDPE). This study was a collaborative effort between GM and the University of Michigan's National Pollution Prevention Center, which received funding from EPA's National Risk Management Research Laboratory. Findings from this study include:

- Material production phase solid waste production for steel greatly exceeds that for HDPE, however, material production phase energy consumption is much higher for HDPE than steel.
- The use phase dominates the consumption of energy, the gas phase emissions of CO, CO_2, NO_x, and HC, and the generation of liquid phase dissolved solids. In each of these categories, the HDPE system is environmentally advantageous over the steel system.
- The manufacturing phase contributes the largest fractions of airborne particulate matter, liquid phase suspended solids, waterborne oil and grease, and waterborne metals. In each of these, except waterborne metals, the HDPE system is environmentally advantageous over the steel system.
- The end-of-life phase dominates the generation of solid waste. In this category, the steel system is environmentally advantageous over HDPE. This conclusion assumes there is no recycling of the HDPE system.

Keywords: Life cycle inventory, product system design, materials selection, automotive components, fuel tank, HDPE, steel, energy, solid waste

INTRODUCTION

Plastic fuel tanks date back to the early 1950's. The success of Volkswagen's use of high molecular weight polyethylene (HDPE) tanks in the early 1970's has considerably influenced the growth of HDPE fuel tanks in North America [Wood, 1991]. 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 (Office for the Study of Automotive Transportation 1996).

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 able to meet the current stringent US and California evaporative emissions standards, whereas monolayer tanks are not.

The total life cycle environmental burdens associated with plastic and steel fuel tanks have not previously been fully characterized. Yamato and Mituhara, 1997 analyzed the environmental burdens of steel and plastic tanks for material production, manufacturing and end-of-life stages. They concluded that the steel fuel tank posed a greater burden in energy consumption and CO_2 and NO_x emissions. While Yamato and Mituhara recognized the importance of the use phase contributions to the total life cycle burdens, they did not measure the use phase environmental burdens related to the fuel tank. Fussler and

Krummenacher, 1991 compiled the life cycle energies for a variety of automotive components. They reported that a 3.4 kg HDPE tank consumed 1135 MJ less energy compared to a 6.7 kg steel tank.

The purpose of this paper is to present the methodology and results of a full life cycle inventory analysis performed on a steel and an HDPE fuel tank system. The tanks investigated were designed and installed on 1996 General Motors full sized vans.

METHODOLOGY AND SYSTEM DESCRIPTIONS

The scope of the analysis includes all tank system components that are unique to each system. For the steel tank, this included a nickel-zinc coated, plain carbon steel tank, a plastic (HDPE) stone shield, and hot dipped galvanized steel straps coated with epoxy based paint. For the plastic tank, unique system components included the multilayer plastic tank, a steel heat shield and PVC coated straps. The six layers of the plastic tank from outer to inner layer include: virgin HDPE mixed with carbon black, an HDPE regrind layer, an adhesive layer, an ethyl vinyl alcohol (EVOH) copolymer permeation barrier, an adhesive layer, and finally a virgin HDPE inner layer. HDPE represents 99% of the material composition of the plastic tank. It should be noted that not all plastic fuel tank systems require a metal heat shield. The model tank studied in this report requires one because of its orientation on the vehicle frame. Plastic tanks systems for other vehicles have been used without a metal heat shield.

Table 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 (expected to be much less than 1% of the total system material mass) and lack of paint inventory data.	• 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	

Both fuel tanks went into production for 1996 full size GM vans (G-van model). The steel fuel tank has a volume of 31 gallons [117 l] while the HDPE tank is 34.5 gallons [131 l]. The HDPE tank weight was normalized to a 31-gallon capacity [117 l] so that the two tanks delivered equivalent functionality. The product composition by massfor each functionally equivalent tank system is shown in Figure 1. The total weight of the steel and HDPE tank systems (including shield and straps) are 21.92 kg and 14.07 g, respectively. The comparative analysis was conducted for a vehicle life of 110,000 miles [177,000 km]. The boundaries and major assumptions for this study are summarized in Table 1 (Keoliean, et al 1997d).

The major life cycle processes of the steel and plastic tank are illustrated in Figures 2 and 3, respectively. For both systems, the steel components are recycled whereas the HDPE components are disposed in a landfill as part of the automotive shredder residue (ASR).

The life cycle inventory analysis was conducted following EPA and SETAC guidelines (Vigon et al 1993, SETAC 1991). Environmental data evaluated were material and energy consumption, solid waste generation, and air and water pollutant releases.

RESULTS

MATERIAL PRODUCTION PHASE

<u>Steel</u> – Environmental data for the material production of nickel-zinc coated, plain carbon steel were approximated using data for tin-plate steel from a European environmental database of packaging materials (FOEFL 1991) and are summarized in Table 2 (Keoleian et al 1997c). 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 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. The total transportation energy requirement, however, is only 5.5% of the total material production energy for steel (FOEFL 1991). Consequently, this factor would not significantly impact the final results. The emissions related specifically to the application of aluminum epoxy paint to the straps were excluded from the scope due to insufficient data.

<u>HDPE</u> – 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 (Boustead 1993). The data is for virgin HDPE and is summarized in Table 3 (Keoleian et al 1997c). Based on data availability, the multi-layer tank was modeled as 100 percent HDPE. The tank adhesive layers and EVOH barrier material constitute less than 1% of the total tank material on a volume basis.

Table 2. Environmental Data for Material Production for Tin-Plate Steel (source: [8] [19])

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/Sulphates	0.0004

* Carbon dioxide data point from McDaniel

Table 3. Environmental Data for Material Production for HDPE (source: [9])

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/Sulphates	4

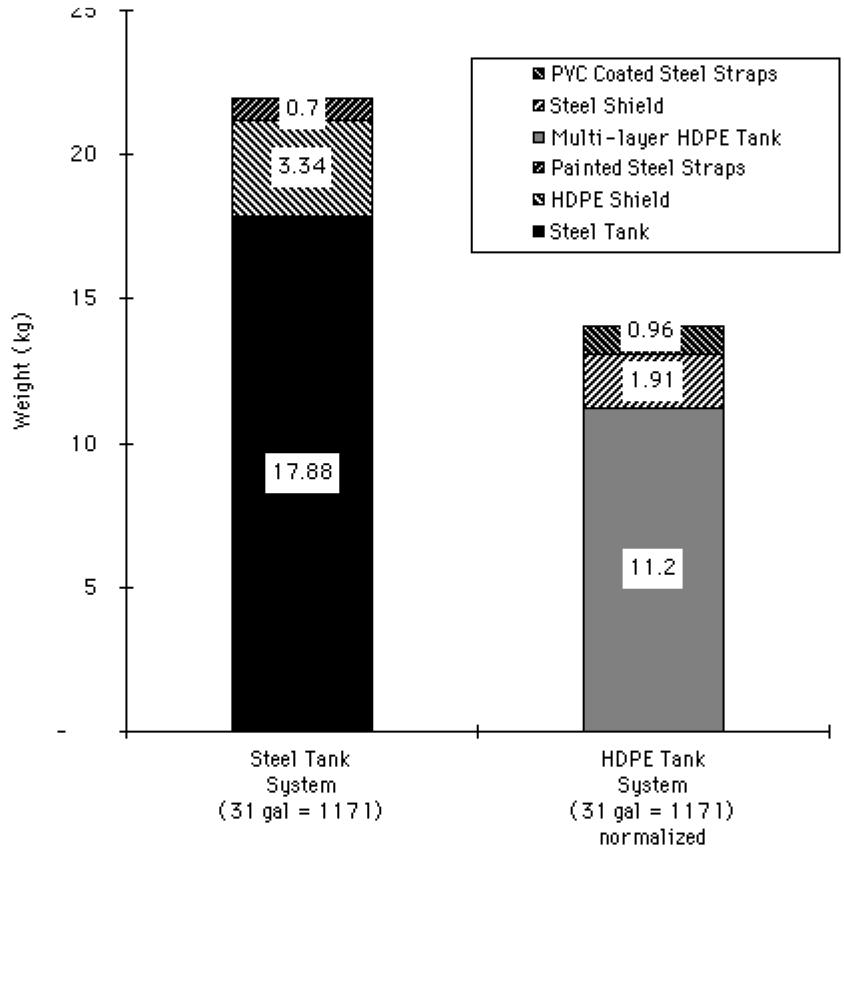

Figure 1. Composition of Fuel Tank Systems

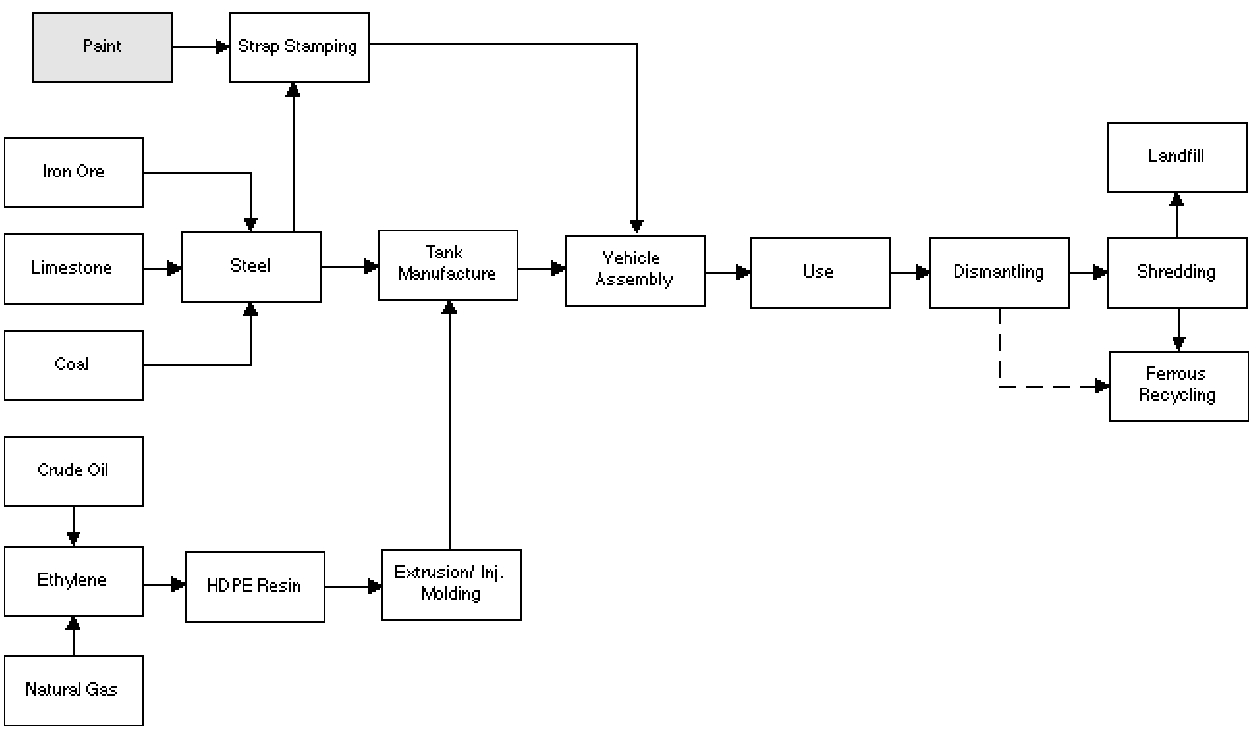

Figure 2. Steel Fuel Tank System Life Cycle

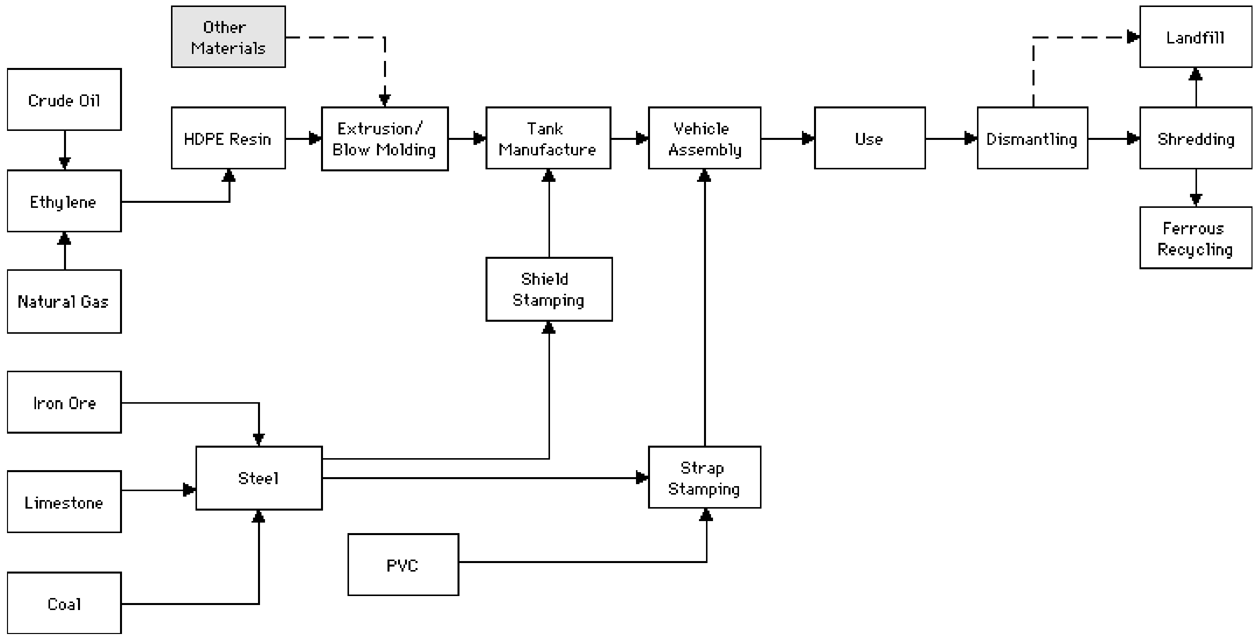

Figure 3. Plastic Fuel Tank System Life Cycle

PVC – Environmental data for the material production of PVC were obtained from APME (Boustead, 1994), summarized in Table 4 (Keoleian et al 1997c). The data is based on emulsion polymerization since this type of PVC is used in dipping applications.

Table 4. Environmental Data for Material Production for PVC (source: [10])

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/Sulphates	4

MANUFACTURING PHASE

Steel Tank – Environmental data for steel tank manufacturing were obtained from GM. The main manufacturing operations include stamping, trimming and piercing, washing, welding, quality control testing, and component assembly. The manufacturing process begins with the stamping of pre-cut, cold rolled steel, which has been pre-coated with a soap lubricant to improve stamping. The top and bottom halves of the tank are separately stamped, then joined together via resistance welding.

Eighty percent of the water used in this manufacturing process is consumed during soap lubricant washing with additional wastewater coming mainly from cooling water for the welding operation. The wastewater used in the washing operation is sent to a water treatment facility within the manufacturer's industrial complex, and is combined with wastewater from four other plants making it impossible to accurately attribute waste water emissions directly to fuel tank manufacturing. 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 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 5 (Keoleian et al 1997d) is based on the monthly average concentrations measured in 1995.

Table 5. Upper Limits for Waterborne Emissions for Steel Tank Manufacturing (Source: [GM, 1996])

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

† based on emissions data from multiple plants

The primary air emissions from steel tank manufacturing come from the welding operation. These 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 6 (Keoleian et al 1997d). Copper used as a welding aid is recycled and not consumed to any appreciable degree.

Table 6. Atmospheric Emissions for Steel Tank Manufacturing (Source: [GM 1996])

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

The total amount of scrap generated in steel tank manufacturing is 580 metric tons per 171,000 tanks per year. This scrap includes tank trimmings, tanks that fail quality control tests, and assembly plant returns. The overall scrap rate is 18.9% and the total primary energy consumption for steel tank manufacturing is 2.7 MJ/kg (GM 1996).

For steel strap manufacturing, the data scope includes steel stamping. Steel stamping energy data were obtained from the International Iron and Steel Institute (IISI 1994). No scrap was assumed generated in producing the straps. For HDPE shield manufacturing, the data scope includes injection molding. HDPE injection molding energy requirements were estimated from generic data for blow molding/injection molding of polyolefins (Wythe 1996). No scrap was assumed generated.

Upon completion of the manufacturing process, the tanks are shipped to the assembly plant via rail.

HDPE Tank – Environmental data for HDPE tank manufacturing were obtained from GM sources and the Steven's Institute of Technology (Wythe 1996). The main manufacturing stages for the plastic tank include extrusion and blow molding, regrind recycling, cooling, machining, component attachment, and quality and safety testing. The total primary energy consumption for plastic tank manufacturing is 14.0 MJ/kg. (Franklin Associates 1992) Energy requirements for HDPE tank manufacturing were based on HDPE blow molding/injection molding energy requirements obtained from the Steven's Institute of Technology (Wythe 1996). Particulate and hydrocarbon air emissions were estimated from Barlow (Barlow and Contos 1996).

The overall scrap rate for HDPE tank manufacturing is 1.7%. 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. A large portion of shut-down waste consists of low density polyethylene (LDPE). Residual amounts of LDPE are also 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. Tank scrappage rates for the multi-layer tank were not available from the manufacturer so data from monolayer tank manufacturing was used as a rough estimate. The multilayer tank manufacturer estimates that approximately 249.5 kg of waste material is generated during each start-up of a production run. 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. On a percentage basis, these solid waste generation rates would decrease for higher production volumes, which were quite low for this system. Table 7 summarizes the main sources of plastic waste and the amount generated per tank during manufacturing.

Table 7. 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

Process materials for tank manufacturing 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 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 (IISI 1994). No scrap was assumed generated. The steel straps are coated with 30 grams of PVC per strap. The mass of PVC coating was estimated from the strap geometry.

USE PHASE – The use phase environmental data were calculated for an assumed tank life of 110,000 miles [177,000 km]. The weight and fuel economy data for a 1996 G Passenger Van are indicated in Table 8 (Keoleian et al 1997d).

The lifetime fuel consumption for the two tank systems are given in Table 9 (Keoleian et al 1997d). Table 9 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 (Kar and Keoleian 1996).

The contribution of the tank system to vehicle fuel consumption, (F) was obtained using the following correlation:

$$\mathrm{F} = M_T \, x L x \left[\frac{FE}{M_v} \right] x \frac{\Delta f}{\Delta M} \qquad \text{(Eq. 1)}$$

where,

F=fuel (liters) consumed over the life of fuel tank system
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=fuel economy (liters/km)L =life of tank system (km)

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 (Ross and Goodwin 1995). Table 10 (Keoleian et al 1997d) shows these values for the G van equipped with a steel tank. The values in Table 10 do not include pre-combustion emissions. The Tier 0 emissions standards require that exhaust emissions not exceed the standards for 120,000 miles [193,000 km] of vehicle life.

CO_2 emissions are estimated at 2.338 kg per liter of gasoline combusted (Kar and Keoleian 1996). The tank contribution to total vehicle air emissions is based on the total fuel consumption allocated to the tank using the following relationship:

$$m_e = m_e' \text{ x } F \div FE \qquad \text{(Eq. 2)}$$

where,

m_e = life cycle emission per fuel tank system
m_e' = emission factor (g/km)

Table 8. Weight and Fuel Economy Data for 1996 G Passenger Van

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

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

Table 9. Fuel Consumption and Use Phase Energy Contribution of Fuel Tanks Systems

Fuel Tank System	Weight (kg)	Allocated Fuel Consumption		Energy (GJ)
		F (liter)	F (gallons)	
Steel	21.92	88.18	23.30	3.71
HDPE	14.07	56.60	14.95	2.38

Table 10. In Use Emissions (Tailpipe and Evaporative) Estimates for 1996 G Van (Equipped with a Steel Tank) (Source: [CFR, 1994], [Ross and Goodwin, 1995])

	CO gpm, (g/km)	HC gpm, (g/km)	NO_x gpm, (g/km)
Tier 0 Standards	10.0 (6.2)	.8 (5)	1.7 (1.1)
Off-cycle Emissions	7.9 (4.9)	.12 (07)	.3 (.2)
Total Average Lifetime Emission Rate	17.9 (11.1)	.92 (.57)	2.0 (1.2)
Total Emissions for 110,000 miles (177,000 km) in kg	1969.0	101.2	220.0

END OF LIFE PHASE – For the purposes of this study all components of both tank systems are assumed to be shredded, all steel is recovered and subsequently recycled at 100%, and all plastic is landfilled. This represents current industry practice. Although HDPE is technically recyclable, future efforts to recycle HDPE fuel tanks will require the development of techniques to remove fuel that permeates into the inner layers of the tank. Studies have demonstrated that absorbed gasoline degrades the performance of HDPE (Ellis et al 1998). Energy requirements (108 kJ/kg) for shredding were obtained from (Kar and Keoleian 1996), (Sullivan and Hu 1995). The shredding data was assumed to be independent of material or part geometry.

TRANSPORT – Transport distance data for the linkages between manufacturing operations were obtained from the GM project team and estimates for end-of-life management were obtained from the American Plastics Council (American Plastics Council 1994). Transportation fuel efficiency and emissions data were obtained from Franklin Associates (Franklin 1992). The transportation energy for manufacturing operations was 31.7 MJ per steel tank and 54.1 MJ per plastic tank. For end-of-life management, the transportation energy was 6.4 MJ per steel tank and 8.2 MJ per plastic tank. Plastic tank transport energies are higher than for steel tanks due to the greater reliance upon trucks for shipping as opposed to the use of rail for the steel tanks. A detailed analysis of each transportation step is provided elsewhere by the authors (Keoleian et al. 1997a).

LIFE CYCLE ENERGY – Figure 4 shows the life cycle energy in GJ/tank for each fuel tank based on a vehicle life of 110,000 miles [177,000 km]. For both tank systems, the use phase accounts for the majority of the energy consumed. Over the 110,000 miles [177,000 km] 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 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 HDPE blow molding compared to steel stamping. End-of-life management energy is relatively negligible. The current practice of landfill disposal of HDPE tanks, however, results in a significant loss of energy in the form of the embodied energy of the material.

LIFE CYCLE SOLID WASTE – The solid waste generated across each stage of the fuel tank life cycle is shown in Figure 5. 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 is associated with end-of-life management.

The Swiss Ecobalance study (FOEFL 1991), which was used to estimate solid waste generation from steel production, 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 (FOEFL 1991).

LIFE CYCLE AIR EMISSIONS – The cumulative life cycle air emissions of carbon monoxide, NO_x, particulate matter (PM), hydrocarbons (HC) and SO_2 are presented in Figure 6. In all cases, emissions were higher for the steel tank system than with the HDPE tank system. In general, the use phase dominated the life cycle air emissions of these pollutants. Particulate matter is an exception in that material production contributed the largest fraction for the steel fuel tank system. The use phase PM and SO_2 emissions result from upstream processes in the total gasoline fuel cycle (precombustion). For SO_2, about half of the life cycle emissions occurred in the use phase while most of the balance occurred in material production and manufacturing stages for both tank systems.

Total carbon dioxide emissions correlate well with total life cycle energy consumption; 295 kg of CO_2 is released for the steel fuel tank system compared with 191 kg of CO_2 for the HDPE fuel tank system. This correlation is expected because of the large fraction of energy originating from carbon based fossil fuels.

LIFE CYCLE WATER EFFLUENTS – The cumulative life cycle waterborne emissions of suspended solids, oil & grease, and metals are presented in Figures 7. The total life cycle dissolved solids emissions were 890 g for the steel fuel tank system compared to 560 g for the HDPE fuel tank system. The results show greater waterborne releases for the steel fuel tank system than for the HDPE fuel tank system for all pollutants except metals.

For dissolved solids, emissions occur primarily in the use phase. These emissions are derived from the refineries which produce the gasoline used by 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 responsible for a significant source of emissions. These emissions can be traced back primarily to electricity production for steel stamping and HDPE blow molding. In the steel tank system, steel stamping plant releases represent a very small portion of the total manufacturing releases.

DISCUSSION

The vehicle air pollutant emissions in the use phase dominated the total life cycle burdens, therefore, the methodology for evaluating these emissions was very significant. Tier 0 standards were supplemented with off-cycle emissions not captured in EPA test procedures. The Tier 0 standards represent a maximum emissions level and therefore the use phase emission results should be an upper limit to the expected in-use vehicle emissions. The in-use emissions modeling did not account for differences in the evaporative emissions contributed by the HDPE and steel fuel tanks. A more precise model would distinguish between tailpipe emissions, evaporative emissions from the total vehicle excluding the fuel tank and evaporative emissions related to the fuel tank.

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 evaporative emissions and 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 (Keoleian et al. 1997b).

Carbon monoxide is primarily a mobile source pollutant originating from vehicle exhaust. In the United States, two serious, and 39 moderate carbon monoxide non-attainment zones were reported by EPA in 1995. NO_x emissions and hydrocarbon emissions 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. However, it should be noted that CO and ozone non-attainment is largely a regional issue. The total life cycle air emissions of CO and ozone precursors are distributed over a large geographical area and time frame. Hence, direct relationships between these emissions and the problems of regional smog are difficult to define.

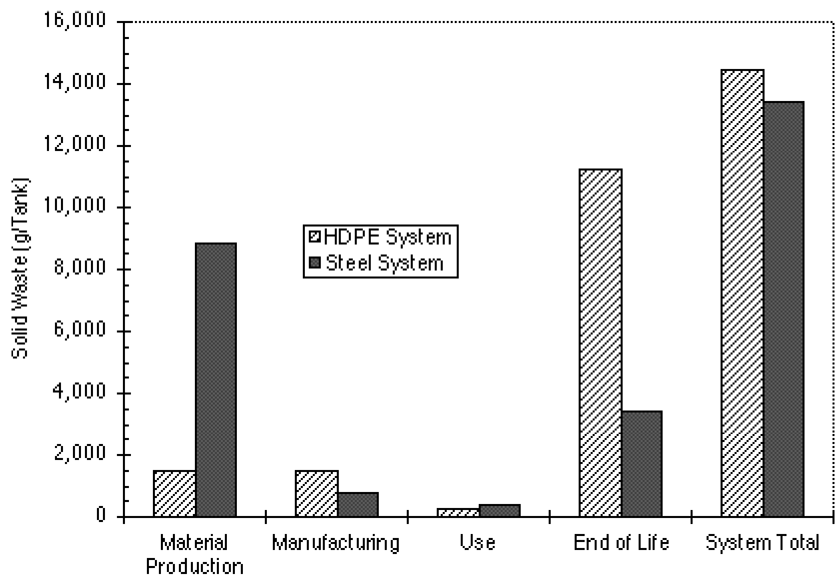

Figure 4. Life Cycle Energy Consumption for HDPE and Steel Fuel Tank Systems

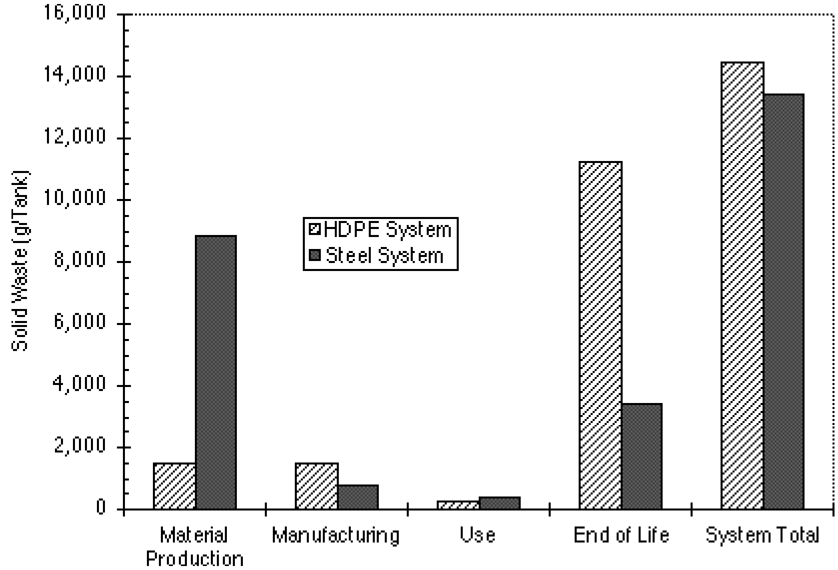

Figure 5. Life Cycle Solid Waste Generation for HDPE and Steel Fuel Tanks

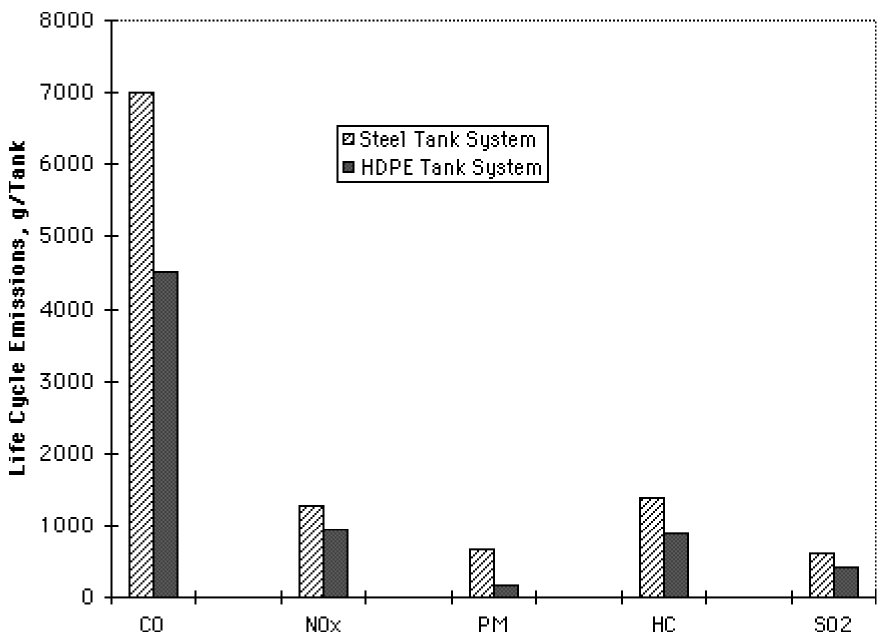

Figure 6. Cumulative Life Cycle Air Emissions

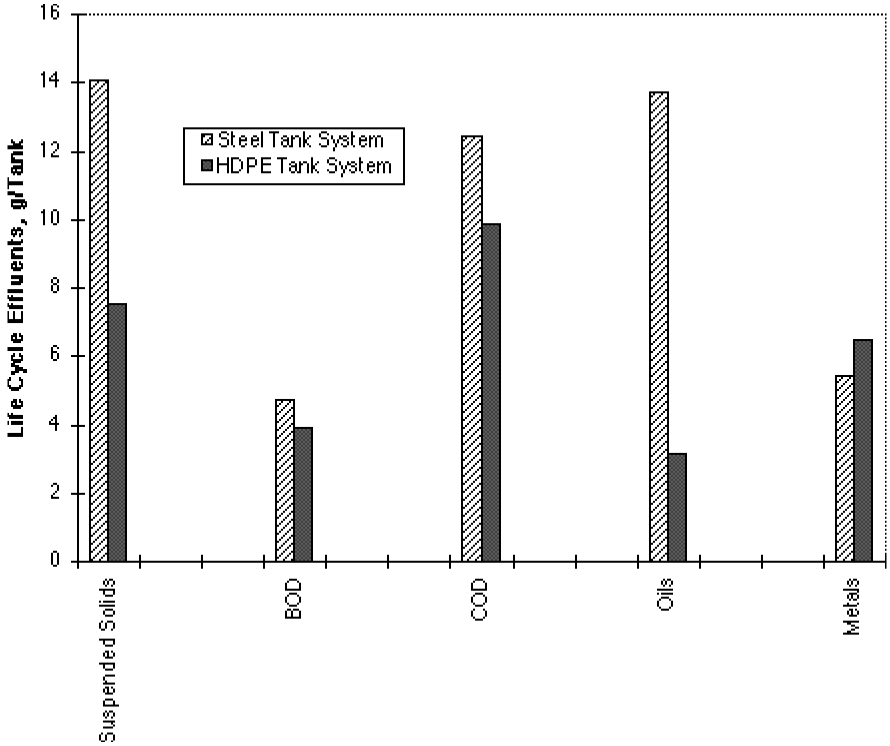

Figure 7. Cumulative Life Cycle Water Emissions

This investigation relied heavily on European material production data because these data are not yet publicly available from US sources. Production processes are not expected to differ significantly between Europe and the US for the materials investigated herein. Environmental releases could, however, differ significantly due in part to differences in environmental regulations controlling these material industries. Electricity production efficiencies for Europe and the US are very comparable; hence this factor may not strongly affect the representativeness of the European inventory data for US conditions. For example, the electricity production efficiency for the national grid in the US has been reported as 0.32 (Franklin Associates, 1991) whereas the efficiency for the UCPTE (Union for the Connection of Production and Transportation of Electricity) was found to be 0.378 (FOEFL 1991). Regional differences in electricity production within the US and Europe, however, are much greater than this difference and could be significant. However, differences in electricity production efficiency is probably not significant because electricity accounts for less than twenty-five percent of the total material production energies for steel and HDPE (FOEFL 1991)((Boustead 1993).

The exclusion of burdens associated with nickel/zinc coating of steel, due to the lack of available data, suggests that the steel fuel tank burdens were understated. This condition strengthens the conclusion that the HDPE tank is environmentally preferable to the steel tank. Steel stamping water effluents were characterized using an upper limit to the actual plant releases. The upper limit was used because effluent data for several facilities could not be disaggregated. In this case, waterborne metal and oil/grease manufacturing emissions were overstated. For oil and grease, however, the manufacturing emissions for the steel tank system were insignificant relative to material production and use phase emissions.

The lack of available inventory data for US production of steel and HDPE is a potential limitation. European data were the best available data at the time of this study. While the use of European data introduces additional uncertainty in the results, the relative distribution of environmental burdens across the life cycle for each tank system could not be characterized without these data. Material databases are currently being developed in the US which will be available for future LCAs. The discrepancy between US and European databases can then be evaluated and their implications on these life cycle inventory results can be ascertained.

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 and thereby further improve the performance of the HDPE tank relative to that of the steel tank.

CONCLUSIONS AND RECOMMENDATIONS

The environmental profiles of the steel and HDPE fuel tank systems differ significantly. Overall, the HDPE fuel tank system is environmentally preferable to the steel tank system based on the inventory results from this investigation.

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 major fraction of this energy was consumed during the use phase, hence the weight savings associated with the HDPE system is an advantage.

The solid waste burdens associated with the fuel tank systems were concentrated in the material production phase for the steel system and the end-of-life phase for the HDPE system. 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.

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.

When comparing environmental burdens of alternative materials, tradeoffs between burdens are often necessary. In this case, the weight savings associated with HDPE, and the consequent reductions in use-phase energy consumption and emissions is a distinct advantage. However, the non-recyclability of HDPE is a distinct disadvantage relative to steel. This is a potentially serious disadvantage given mandates to increase the recyclability of end-of-life vehicles. For example, a European union draft directive (Official Journal of the European Communities, 1998) calls for minimum material recovery (re-use or energy recovery) of 85% by 2005 and 95% by 2015. However, it is possible that methodology for recycling end of life HDPE fuel tanks will be developed in time to meet these proposed mandates.

The sensitivity of the results with respect to the steel material production energy was tested previously (Keoleian et al. 1997a). A 20% improvement in the material production energy to 26.7 MJ/kg would reduce the total life cycle energy for the steel tank system by only 2.9% to 4.7 GJ. A significant reduction of the steel tank mass (approximately one-third) is required to achieve a lower total life cycle energy relative to the HDPE tank system energy. Performance requirements probably prohibit mass reductions of these magnitudes.

Although a comprehensive set of life cycle inventory data is often not available, modeling techniques demonstrated in this investigation provide a useful approach towards characterizing the relative environmental performance of two different product systems. The project team experienced difficulties in collecting inventory data from the Tier 1 supplier of plastic fuel tanks. In contrast, manufacturing data for steel tanks was readily forthcoming from a GM facility. One possible strategy for facilitating data collection is to seek the commitment of key stakeholders to participate in the initial phase of the project. Furthermore, the results of this study provide a framework for OEM's to develop a simplified set of metrics for comparing multilayer HDPE and steel fuel tank systems for other vehicle platforms. Many of these metrics can be computed using energy, emissions, and waste factors evaluated in this investigation. These metrics would address major burdens in the fuel tank life cycle and would reduce resource requirements for data collection and analysis.

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REFERENCES

1. American Plastics Council. Economics of Recovery and Recycling 1994.
2. 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 (1996).
3. Boustead, Ian. Eco-Profiles of the European Plastics Industry - Polyethylene and Polypropylene: Report 3. The European Centre for Plastics in the Environment, Brussels, 1 1993.
4. Eco-Profiles of the European Plastics Industry, Report 6: Polyvinyl Chloride (PVC). The European Centre for Plastics in the Environment, Brussels, 1994.
5. CFR. 40 CFR Part 81 Section 86.094-8, 1994.
6. Ellis, Thomas S., John L. Laverty and Michele M. Lesinski. Recyclability and Characterization of Co-Extruded Multilayer Fuel Tanks, SAE980096, 1998.
7. (FOEFL) Swiss Federal Office of Environment, Forests, and Landscape, Ecobalance of Packaging Materials State of 1990. Bernes , Switzerland, 1991.
8. Franklin Associates. Appendix A: Energy Requirements and Environmental Emissions for Fuel Consumption. Franklin Associates, Prairie Village, KS, 1992.
9. Fussler, C.R., B. Krummenacher. Ecobalances: A Key to Better Environmental Material Choices in Automotive Design. Materials and Design 12 (3): 123-128 (1991)
10. General MotorsCorporate Data 1996.
11. International Iron and Steel Institute, Competition Between Steel and Aluminum for the Passenger Car Brussels, 1994.
12. 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.

13. Keoleian, G.A., K. Kar, M.M. Manion, and J.W. Bulkley. Industrial Ecology of the Automobile: A Life Cycle Perspective, Society of Automotive Engineers (SAE): Warrendale, PA, 1997b, 148 pages.
14. 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.
15. Keoleian, Gregory A., Sabrina Spatari, and Robb T. Beal. Life Cycle Design of Fuel Tank Systems. US Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, OH, 1997a.
16. Keoleian, Gregory A, Sabrina Spatari, Robb T. Beal, Robert D. Stephens, and Ronald L. Williams. Application of Life Cycle Inventory Analysis to Fuel Tank System Design. International Journal of Life Cycle Assessment 3 (1), 1998.
17. 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: The University of Michigan, 1996.
18. Office for the Study of Automotive Transportation, Delphi VIII: Forecast and Analysis of the North American Automotive Industry: Volume 3 Materials. University of Michigan Transportation Research Institute, Ann Arbor, MI UMTRI-96-01-03, 1996.
19. Official Journal of the European Communities, “Proposal for a Council Directive on End of Life Vehicles”, 97/C337/02, 9 July 1998.
20. Ross, Marc, Rob Goodwin, Rick Watkins, Michael Q. Wang, and Tom Wenzel. Real-World Emissions from Model Year 1993, 2000 and 2010 Passenger Cars. American Council for an Energy-Efficient Economy, Washington DC, 1995.
21. 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.
22. 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.
23. 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. US Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH EPA/600/R-92/245, 1993.
24. Wood, Richard. Automotive Engineering Plastics. London: Pentech, 1991.
25. Wythe, Steve. Stevens Institute of Technology, personal communication, 1996.
26. Yamato, Masako, Yoshihito Mituhara. Life Cycle Inventory Study of Automotive Fuel Tank. Life Cycle Inventory Study of Automotive Fuel Tank, Proceedings of the 1997 Total Life Cycle Conference - Life Cycle Management and Assessment (Part 1). Warrendale, PA: Society of Automotive Engineers, SAE Paper 971177, 1997.