# LIFE-CYCLE ENVIRONMENTAL EVALUATION OF ALUMINUM AND COMPOSITE INTENSIVE VEHICLES

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## Acronyms and Abbreviations

| | |
|---|---|
| ASR | Automobile Shredder Residue |
| $C_2F_6$ | Perfluoroethane |
| CCPCT | The Center for Clean Products and Clean Technologies |
| $CF_4$ | Perfluoromethane |
| $CH_4$ | Methane |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| DIATA | Direct Injection, Aluminum, Through-bolt Assembly |
| DOE | Department of Energy |
| EGR | Exhaust Gas Recirculation |
| EPA | Environmental Protection Agency |
| GWP | Global Warming Potential |
| ICE | Internal Combustion Engine |
| LCA | Life-Cycle Assessment |
| LCI | Life-Cycle Inventory |
| LCIA | Life-Cycle Impact Assessment |
| MIC | Molded-in-Color |
| MPG | Miles per Gallon |
| $N_2O$ | Nitrous Oxide |
| NGV | New Generation Vehicle |
| $NO_X$ | Nitrogen Oxides |
| ORNL | Oak Ridge National Laboratory |
| PET | Polyethylene Terephthalate |
| PFC | Perfluorocarbon |
| PM | Particulate Matter |
| PNGV | Partnership for a New Generation of Vehicles |
| $SF_6$ | Sulfur Hexafluoride |

## EXECUTIVE SUMMARY

This life-cycle-based environmental evaluation of New Generation Vehicles (NGVs) was conducted by The University of Tennessee Center for Clean Products and Clean Technologies (CCPCT) as part of research being done by the Oak Ridge National Laboratory (ORNL) under the Partnership for a New Generation of Vehicles (PNGV) initiative.

The two diesel-electric hybrid vehicles evaluated, which are currently under development, were the Ford P2000 and the Chrysler ESX2. They were compared against a generic U.S.-built 1994 vehicle (in the same class as the Ford Taurus and Chrysler Concorde).

Due to the limited timeframe of the study, it was not possible to conduct a complete Life-Cycle Assessment (LCA). Instead, using readily available data or previously conducted studies, estimates were made of the energy consumed, solid wastes generated and air emissions produced from the following life-cycle stages:

- Extraction and Materials Processing;
- Manufacturing;
- Use; and
- End-of-Life.

The major findings of this evaluation indicate that the New Generation Vehicles (NGVs) evaluated would result in:

- Significantly reduced lifetime energy consumption;
- Significantly reduced lifetime global warming emissions;
- Decreased CO emissions;
- Higher $NO_x$ and PM emissions from the assumed use of conventional diesel engines; and
- Increased solid waste generation due to materials extraction and processing for new materials.

The results reveal that the life-cycle energy consumption of the NGVs is considerably lower than that of the 1994 vehicle (by about 55%), attributable primarily to the reduced fuel requirement during the Use stage. Energy use in other stages is relatively insignificant, so that its increase in the Extraction and Materials Processing stage (from the newer, more energy-intensive materials in the NGVs) is overshadowed by the savings achieved during Use.

One life-cycle stage dominates in solid waste generation: Extraction and Materials Processing, which includes solid wastes from mining and refining of materials. The use of new materials in the NGVs clearly results in higher solid waste generation during this stage as compared to the baseline. The End-of-Life stage shows an increase in solid waste generation for the composite vehicle (ESX2) as

compared to the baseline, which can be somewhat offset by switching to molded-in-color (MIC) plastic body panels, since this eliminates much of the painting facility's waste in the Manufacturing stage, and by recycling the panels in the End-of-Life stage.

The lifetime GWP calculated for the NGVs is much lower than that of the 1994 vehicle (on the order of about 50% less), with the following global warming gases included in the analysis: $CO_2$, $CH_4$, nitrous oxide ($N_2O$), sulfur hexafluoride ($SF_6$), perfluoromethane ($CF_4$), and perfluoroethane ($C_2F_6$). This reduction is clearly due to reduced emissions of $CO_2$ and $CH_4$ during the Use life-cycle stage. There are increases in GWP in the Extraction and Materials Processing and Manufacturing stages for the NGVs, which are easily overcome by decreases during the Use stage. Of the other air emissions, CO emissions are also considerably reduced, while both PM and $NO_x$ emissions increase, compared to the baseline, due mostly to the combustion of diesel fuel (Use stage). In the Extraction and Materials Processing life-cycle stage, the increases in PM and $NO_x$ emissions are due to the use of more energy-intensive materials in the NGVs.

Future work to address the remaining issues in the switch to the NGVs would include exploration of modifications to hybrid-vehicle diesel engines for reducing emissions, improvements in diesel fuel properties, and the use of alternative fuels, alternative (less energy-intensive) materials, and alternative power sources (e.g., fuel cells). Further assessment is needed for the Extraction and Materials Processing stages of new materials to determine the sources and types of solid wastes generated and to ascertain the impact of using recycled materials. Additionally, further research is needed to evaluate the life-cycle impacts of new materials (such as carbon fiber composites) and advanced battery technologies, and to assess the recyclability of composites.

# 1. INTRODUCTION

The environmental impacts associated with a new vehicle design can be accurately assessed only if all the life-cycle stages are considered. For instance, the use of certain materials that seem benevolent to the environment in a particular life-cycle stage might require huge amounts of energy to produce in one of the upstream stages, rendering their selection unjustifiable. Furthermore, a seemingly large reduction in emissions during one stage might be rendered inconsequential by a hefty increase in another stage.

Since the environmental consequences are greatly dependent upon the materials and manufacturing processes chosen for the production of a particular vehicle, it is important to incorporate life-cycle considerations into the design process. Life-cycle design, therefore, is a proactive approach that prevents the imposition of unforeseen burdens on the environment by providing information on potential impacts at the design stage itself.

## 1.1 Goal and Scope of the Study

The *goal* of this study is to conduct a life-cycle-based environmental evaluation of two concept vehicles, comparing them against the generic 1994 mid-size, North American-built passenger car, which is the baseline vehicle for the study. The two vehicles of the future that have been evaluated are the aluminum-intensive Ford P2000 and the plastic composite-intensive Chrysler ESX2. Both these vehicles strive to meet the goals set by the PNGV, an initiative launched in 1993 involving the “Big 3" US automakers (General Motors, Ford and Chrysler), seven government agencies, and twenty national research laboratories [1]. The 1994 *baseline* vehicle is a passenger car in the same class as the Ford Taurus, Chevrolet Lumina, Dodge Intrepid, and Chrysler Concorde.

One of the major goals of the PNGV is up to 40% reduction in curb weight, in the quest of achieving the targeted fuel efficiency of 80 miles per gallon (MPG). The Energy Division of ORNL, a Department of Energy (DOE) participant in the PNGV initiative, has been researching various issues concerning the production, use and disposal of the New Generation Vehicles (NGVs). These include possible infrastructural impacts, environmental impacts, and market acceptance issues. This life-cycle-based environmental assessment, conducted by the University of Tennessee CCPCT, forms part of the ORNL research.

The *functional unit* for the purpose of this study is the U.S.-built passenger car (as defined above), driven for 120,000 miles.

Typical Life-Cycle Assessments (LCAs) can take on the order of one-to-several years to complete, and are highly dependent on the complexity of the product of interest. The LCA will usually include developing the goals and scoping of the project, obtaining all the necessary data for the Life-Cycle Inventory (LCI), performing a Life-Cycle Impact Assessment (LCIA), and lastly, assessing the results of the LCI and LCIA, or performing the Life-Cycle Improvement Analysis. Because of the short time frame over which this project was to be completed, it was deemed a life-cycle *evaluation*, which simply means that the work would focus on a complete-as-possible LCI and include a limited amount of LCIA work as considered feasible. With a simple product as the focus of an LCA (e.g., paper clip, water bottle, concrete blocks), it is possible to complete an assessment in a relatively small amount of time. However, with a complex product like an automobile that contains on the order of several thousand parts, it was possible to perform only a life-cycle based environmental evaluation, given the constraints of this project.

For this evaluation, four life-cycle stages spanning the entire life of the vehicles were chosen for analysis, and include:

***Extraction and Materials Processing***
Activities related to the acquisition of natural resources from the Earth, and their subsequent processing to yield usable materials for the manufacturing stage.

***Manufacturing***
Production of automobile parts and assemblies by manufacturers and their suppliers; assembly of automobiles by automakers.

***Use***
Use of vehicles for the intended purpose (safe and comfortable on-road transportation for up to five occupants per vehicle), over the expected life span of 120,000 miles.

***End-of-Life***
Disposition of vehicle parts and components at the end of its useful life, including the recycling of the majority of each vehicle and landfilling of the residuals.

The assumptions and analytical results for each life-cycle stage are discussed separately in latter sections of this report.

## 1.2 Material Composition Scenarios

In order to meet the PNGV goals, it is necessary to develop new lightweight materials for use in NGVs, resulting in increased fuel economy without sacrificing safety and performance. The PNGV has identified “lightweight materials” as one of the four key areas in which to focus its research and technology development efforts [2].

The material composition scenarios obtained from ORNL, upon which this evaluation is based, are outlined below:

Table 1. Material Composition Scenarios (lbs)

| *Material* | *1994 Vehicle* | *P2000* | *ESX2* |
|---|---|---|---|
| PET (glass reinforced) | 0 | 0 | 400 |
| Other Plastics | 223 | 251 | 145 |
| Wrought Aluminum | 47 | 462 | 330 |
| Cast Aluminum | 159 | 271 | 120 |
| Magnesium | 6 | 86 | 122 |
| Titanium | 0 | 11 | 40 |
| Ferrous | 2168 | 490 | 528 |
| Rubber | 138.5 | 123 | 148 |
| Glass | 96.5 | 36 | 70 |
| Lexan | 0 | 30 | 20 |
| Glass Fiber | 19 | 19 | 0 |
| Carbon Fiber | 0 | 8 | 24 |
| Other | 391 | 223 | 303 |
| **Total Weight** | **3,248** | **2,010** | **2,250** |

In the case of the “composite-intensive” ESX2, the body panels are made of a composite material, glass fiber-reinforced Polyethylene Terephthalate (PET). The glass fiber content is 15%. The ESX2 also contains more carbon-fiber composite than the other vehicles. The P2000 contains the largest quantity of aluminum and is, therefore, termed “aluminum intensive.” The ferrous content in both the P2000 and the ESX2 is considerably less than in the 1994 vehicle. Moreover, it is observed from Table 1 that the NGVs use more of the newer materials, titanium and magnesium.

## 2. METHODOLOGY AND ASSUMPTIONS

The methodology for performing the life-cycle evaluation and the major assumptions made are outlined below.

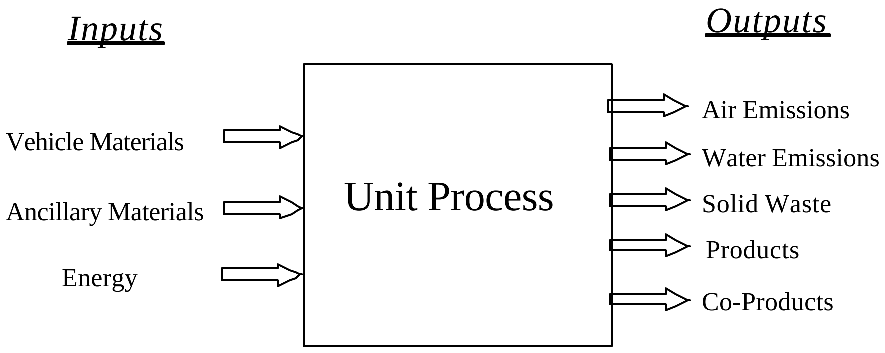


**Figure 1. Typical Life-Cycle Inventory Data Categories**

For each unit process considered, typical LCAs will focus on either all the input and output types shown in Figure 1, or select the ones in which the largest environmental burdens are found and focus on those alone. Again, due primarily to time limitations, we focused on five specific input and output types for this life-cycle evaluation: the primary (or vehicle) materials and energy consumed on the input side, and the products, air emissions, and total solid waste generated on the output side. For the air emissions, only the primary pollutants of PM, $NO_x$, CO, $CO_2$ and $CH_4$ were included, primarily due to the lack of other speciated pollutants information for all of the life-cycle stages. In addition, only those ancillary materials that had substantial environmental burdens were considered.

The major *assumptions* made in consultation with ORNL were:

- NGVs use a hybrid power plant that is a combination of a conventional direct-injection diesel engine and an electric motor powered by a lithium-ion battery; and
- NGVs achieve a fuel efficiency of 70 MPG (slightly less than the PNGV goal of 80 MPG).

The methodology and assumptions made for each individual life-cycle stage included in this evaluation are detailed in the following four sub-sections. It should be mentioned that in this evaluation the inputs and outputs for transportation of materials and parts were included within each process within each life-cycle stage, and not relegated to one particular “transportation” life-cycle stage (as done in some LCAs).

## 2.1 Extraction and Materials Processing

The Extraction and Materials Processing life-cycle stage encompasses the removal of true 'raw' materials (e.g., iron ore, bauxite, rutile) from the earth and their subsequent initial processing to yield materials that are usable in various manufacturing processes (e.g., iron, steel, aluminum, titanium, plastic resin). For this life-cycle stage, the data utilized were a proprietary, in-house set of environmental profiles for the extraction and materials processing of various materials.

The data for this life-cycle stage are of medium quality, mainly because:

- All processing, transportation, and energy use during the extraction and initial processing stages is included;
- Data on energy and primary and secondary material inputs as well as on air, water and land releases as outputs is included; and
- Emissions are somewhat speciated into specific compounds.

The drawbacks of the data used for this stage are:

- Most of the data are of European origin;
- A dataset for secondary (containing recycled materials) processes was excluded; and
- A profile for lithium production (for the battery) was not available.

To begin the inventory for this life-cycle stage, a materials breakdown for the three vehicles was obtained from ORNL (shown previously in Table 1). The breakdown includes all of the materials distinguishable for each vehicle with an "Other" category that includes those materials not able to be broken out (usually includes such items as car stereos). Due to the way each vehicle was broken down in the materials breakdown information, some of the inventories contained in the proprietary data had to be edited and modified to create inventories that represented the materials as they were listed in the breakdown. To that end, several edited processes were created.

Table 2 presents the material inventories that were utilized in this study split into three categories: unedited processes, source-merged processes and material-merged processes. The source-merged processes are those that required the blending of primary (virgin) and secondary (recycled) production information, to yield process environmental data that more closely resembles the actual inputs and outputs of those processes used in the automotive industry today. Additionally, the material-merged processes were those processes that required blending multiple unedited material inventories. For example, the edited 'PET with glass fiber' process was a combination of the unedited processes of PET production and glass fiber production, using the reported 15% glass fiber found in that particular plastic composite to create the edited process.

**Table 2. Material Profiles Included in Inventory**

| ***Unedited Processes*** | ***Source-Merged Processes*** | ***Material-Merged Processes*** |
|---|---|---|
| Titanium | Aluminum, Wrought | Ferrous |
| Lexan (Polycarbonate) | Aluminum, Cast | PET with Glass Fiber |
| Glass | Magnesium | Other plastics |
| Glass Fiber | | |
| Gasoline/Diesel | | |

In some cases, several processes were augmented with some additional emissions information for particularly environmentally burdensome emissions. These included adding emissions data on two perfluorocarbons (PFCs) generated during the production of primary aluminum (emitted as by-products of the smelting process), and adding data on $SF_6$ emissions during the production of primary and secondary magnesium (used as a protective covergas during casting of molten magnesium in both primary production processes and the subsequent downstream manufacturing processes). Each of these compounds is a potent greenhouse gas.

For this life-cycle stage, inputs and outputs associated with electricity generation were already included in each profile. Because the electricity inputs and outputs could not be separated from these profiles, it was not feasible to substitute U.S. electric grid data for the predominantly European grid data contained in these profiles.

## 2.2 Manufacturing

In this project, the Manufacturing life-cycle stage includes the final assembly of the automobile and the manufacturing processes from one to two tiers upstream of vehicle assembly (e.g., powertrain production, body frame, panels fabrication). Due to time and resource constraints, as well as the lack of available data on the manufacturing of these prototype car designs, the CCPCT used existing data from a previous study to represent the Manufacturing stage.

The CCPCT had already performed a detailed LCI for a vehicle manufacturing facility located in the U.S. Data from this LCI were scaled on the basis of total vehicle weight to obtain Manufacturing life-cycle stage data for the three vehicles of interest in this study. This method did not bring to light the true manufacturing differences that are inherent in the different materials used in each of these vehicles. However, the impacts of the Manufacturing stage as a whole and the differences in manufacturing impacts for the three car designs are generally much less than those in the other life-cycle stages. Furthermore, using generic manufacturing processes data would have almost certainly brought as much, if not more, error into the NGV input and output values, due to the use of different age, size and efficiency machines in manufacturing facilities, as well as the variations that exist in specific facility process efficiencies (e.g., extent of automation, human factors).

The original vehicle manufacturing LCI data quality was high in that facility-specific information was obtained, including the use of much directly measured information about plant operations. Though quality was reduced somewhat by scaling it to the NGVs by total vehicle weight, overall data quality should be considered to be about as high as can be attained outside of direct 1994 vehicle and NGV facility inventorying. It should be kept in mind that the two NGVs are not production level vehicles yet, and although there have been discussions about the newer technologies and processes that are to be used to produce various components of these two vehicles, there is currently little available data on the inputs and outputs for these technologies and processes.

In addition to the three profiles that were generated in this life-cycle stage, a fourth profile was generated to include an analysis that encompassed molding the ESX2's body panels in color (in lieu of painting them). The CCPCT had previously conducted an environmental analysis on molding specific automotive body parts in color [3], and this study was used to show the energy and environmental benefits of reducing the use of a big contributor to the automobile's environmental profile: the painting process.

The use of electricity during the Manufacturing life-cycle stage was also included, utilizing a U.S. electric grid environmental profile developed by the CCPCT.

## 2.3 Use

The Use life-cycle stage begins with the initial post-manufacturing operation of the vehicle and ends with the vehicle attaining 120,000 miles of service (the mileage assumed for this project). This stage includes the energy consumed in driving the vehicle and the production of fuel. The fuel production profile used had electricity generation environmental impacts already included, thus, the use of the U.S. electric grid was not needed for analysis of this life-cycle stage. The limited time frame of this project required reducing the scope to exclude vehicle maintenance and repair during the Use stage.

In estimating the lifetime fuel requirement during Use, the only variable was the fuel efficiency, which was assumed to be 70 MPG for the NGVs and 26.6 MPG for the 1994 vehicle. Though the PNGV goal for NGVs is 80 MPG, the ORNL considered it prudent to utilize a (currently) more realistic fuel efficiency of 70 MPG. The 26.6 MPG used for the 1994 vehicle is consistent with the value specified for the baseline vehicle in the PNGV document stating the goals of the partnership [4].

The emissions for the 1994 vehicle have been estimated using available Environmental Protection Agency (EPA) data [5] on certification testing of 1994 Taurus and Intrepid vehicles, and averaging the emissions provided. As PM and $CH_4$ emissions were not provided in the EPA data for the 1994 Taurus and Intrepid vehicles, they were calculated from relationships obtained using Tier 0 Emission Certification standards.

The approach utilized for estimating the emissions for the P2000 and the ESX2, however, is not quite as straightforward, as actual test data were not available for these vehicles. Thus, a vehicle with a small-sized diesel engine (1998 Volkswagen Passat diesel) was chosen to simulate the emissions from NGVs. However, the NGVs are powered by a hybrid power plant, which is a combination of a diesel engine and an electric motor powered by a battery. The diesel engine, therefore, gets help from the battery at different times during vehicle operation, resulting in increased fuel efficiency and lower emissions.

Since the fuel efficiency of the 1998 Passat [6] was much lower (43 MPG) than that chosen for the P2000 and ESX2, the emissions were adjusted accordingly by reducing them in the same ratio as the fuel efficiency (i.e., multiplied by 43/70). Also, since $CO_2$ emissions were not provided in the EPA data for the 1998 Passat, they were estimated by establishing a relationship between the CO emissions from the Passat and those from another similar-sized Fiat diesel engine [7]. Assuming that $CO_2$ emissions vary proportionately to CO emissions, the CO relationship was then applied to the $CO_2$ emissions from the Fiat, in order to calculate the $CO_2$ emissions for the Passat. Additionally, the resulting $CO_2$ emission value was checked against some other emission values and was within the range found in other data.

## 2.4 End-of-Life

The last life-cycle stage, End-of-Life, was defined in this project to encompass the processing of a vehicle after its useful life into reusable components, recycled materials and landfilled automobile residuals, known as Automobile Shredder Residue (ASR).

Data for the End-of-Life stage are based on a study conducted previously by the CCPCT, involving visits to and collection of data from vehicle end-of-life processing facilities. For this life-cycle stage, the ESX2 has been evaluated using two scenarios - one assuming that the PET body panels are not recycled (being landfilled, along with the other plastics), and the other assuming that they are recycled. These two scenarios are termed “ESX2" and “ESX2 with PET Recycling,” respectively. Whether or not the PET body panels are recycled depends upon two things: how easy it is to dismantle them, making it economical, and whether the presence of glass fiber in the material hinders their recyclability. In this stage, the “Mold-in Color” scenario for the ESX2 is assumed to have no effect and is therefore left out of the comparisons.

At the end of their useful lives, automobiles are usually sold to automotive dismantlers who remove the still useable parts for reuse or remanufacture, and dispose of the hazardous materials (usually consisting of vehicle fluids) in an appropriate manner. The remaining hulks, often flattened to facilitate transportation, are sent to automobile shredders, who use hammermills to break them into fist-sized fragments. Most of the ferrous metals are recovered by magnetic separation, while the lightweight waste material or “fluff” (ASR), comprised mainly of foam, textiles, plastics and dirt, is removed by air cyclone separation. The ferrous metal scrap is sent to steel mills for recycling, and the fluff is landfilled. The remaining mixture of high density, non-magnetic materials is rich in nonferrous metals. It is usually sent to nonferrous metal separators for the recovery of metals such as aluminum, zinc, copper, brass, magnesium, and stainless steel. The processes employed by the nonferrous separators are water elutriation, eddy current separation, and heavy media separation. The waste material that remains, consisting mainly of dirt and fines, is landfilled.

Through discussions with professionals [8] in the automotive recycling field, it was determined that the following parts are commonly removed at dismantling, either for safety reasons or because they can be easily dismantled and have a resale/salvage value:

- Tires and wheels;
- Battery;
- Powertrain (Engine + Transmission);
- Fuel tank;
- Fluids;
- Air bags;
- Radiator; and
- Catalytic converter.

Of the hulk that is transported to the shredding operation, it is assumed that all the ferrous metals are recovered for recycling, while the subsequent non-ferrous metal separation processes result in the recovery of the following constituent weight fractions:

| | |
|---|---|
| Aluminum: | 70.0% |
| Zinc: | 18.5% |
| Copper and Brass: | 10.0% |
| Stainless Steel: | 1.5% |

The environmental issues of concern in the End-of-Life stage are:

- Solid waste generated (ASR), which is landfilled; and
- Energy consumed in operating the machinery used in the end-of-life processes.

Additionally, in order to accurately assess the impact of electricity used in the end-of-life processes, the inputs and outputs associated with electricity generation have been included via the CCPCT’s in-house electric grid process.

# 3. RESULTS

## 3.1 The Big Picture

The following three sections discuss in detail the results from the life-cycle evaluation broken down by the major types of inputs and outputs considered: energy consumption, total solid waste generation and major air emissions. Following this section will be a discussion of the major and minor impacts within each life-cycle stage.

### 3.1.1 Energy

Figure 2 shows the lifetime energy use for each vehicle arranged by life-cycle stage. In general, a reduction of almost 55% can be seen in the NGVs over the 1994 vehicle, primarily due to higher fuel efficiency in the Use stage. The life-cycle stages of Manufacturing and End-of-Life are relatively insignificant, and the Extraction and Materials Processing energy use is relatively small compared to the Use stage. While Extraction and Materials Processing energy use is twice as much for the NGVs as compared to the 1994 vehicle, this increase only increases total NGV lifetime energy consumption by 5%.

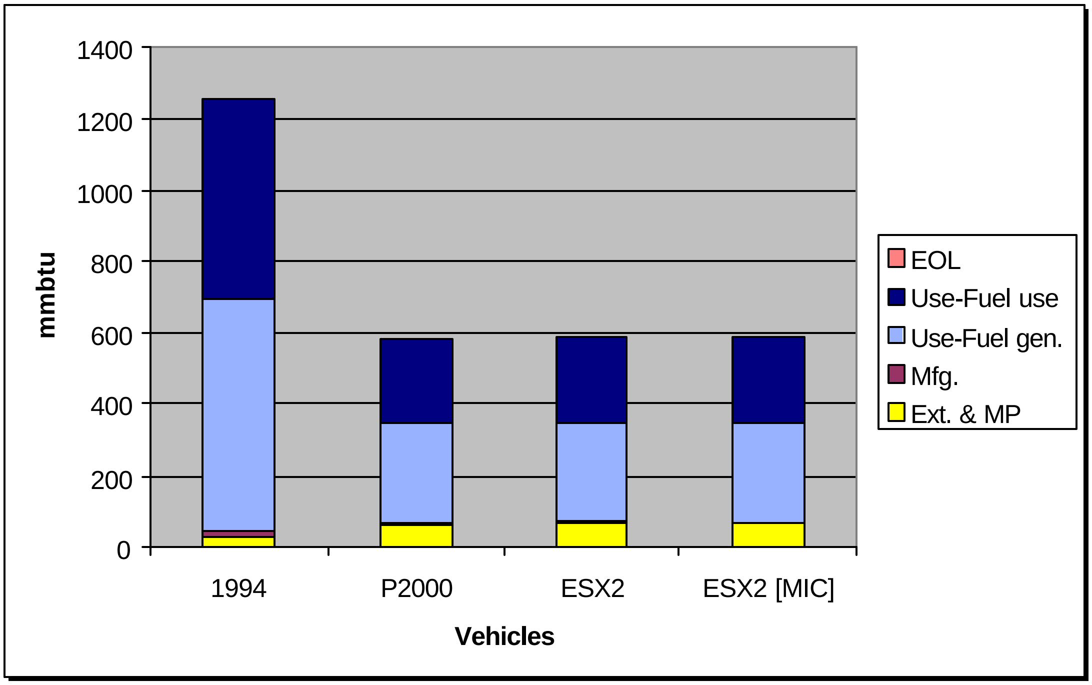


Figure 2. Lifetime Energy Consumption

The savings realized in this impact category can be almost completely attributed to the higher fuel efficiency of 70 MPG for the NGVs in the Use stage, which the prototype version of the ESX2 has supposedly already achieved. When the NGVs reach the PNGV goal of 80 MPG fuel efficiency, almost another 13% savings will be realized over the 1994 vehicle, including additional savings from the fuel generation and use facets of the Use life-cycle stage. The potential savings to be realized in this life-cycle stage will be a big step toward achieving the PNGV goals.

### 3.1.2 Solid Waste

The second impact category analyzed in this evaluation was that of solid waste generation. Figure 3 shows the impacts from solid waste generation for each vehicle broken down by life-cycle stage. Clearly, the Extraction and Materials Processing life-cycle stage dominates, with small increases seen in each NGV as compared to the 1994 vehicle. The P2000 represents a reduction in all life-cycle stages except for Extraction and Materials Processing, where the increase overshadows the savings achieved elsewhere. For the ESX2 with molded-in-color body panels and subsequent recycling of those panels at the vehicle's end-of-life, the solid waste reductions achieved in Manufacturing and End-of-Life are basically negated by the increase in solid waste generated in Extraction and Materials Processing.

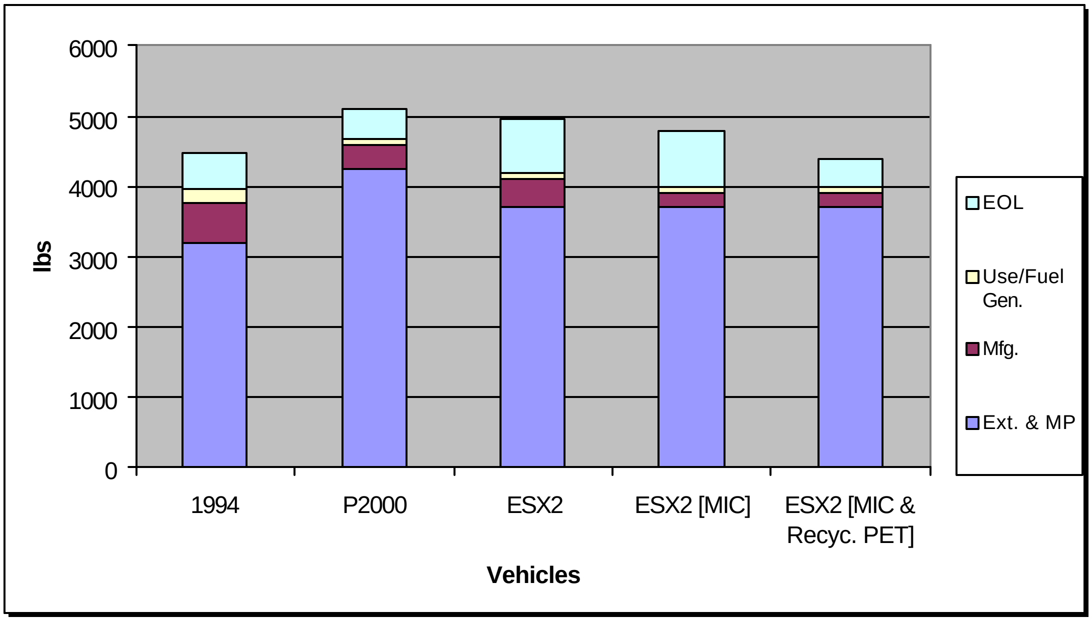


Figure 3. Lifetime Solid Waste Generation

Thus, it appears that there is definitely room for work in the solid waste generation impact category, and that work needs to be focused on either reducing solid wastes produced during upstream processes, using more recycled material as a raw material (thereby reducing upstream impacts significantly), or attempting to find materials that have less upstream solid waste impacts.

### 3.1.3 Air Emissions

The remaining pollutants evaluated all fall under the output type of air emissions: $CO_2$, $CH_4$, $N_2O$, $SF_6$, $CF_4$ and $C_2F_6$, which are all greenhouse gases, and PM, $NO_x$ and CO, which are criteria air pollutants. All of these are of the utmost importance to the PNGV goals considering that this is the primary output type in which government regulations currently exist for automobiles, and that these pollutants have effects within some of the most potentially damaging impact categories: acute and chronic human health effects and global warming.

Greenhouse Gases

Figure 4 reveals the life-cycle global warming potential (GWP) of the emissions of the above-mentioned six gases expressed as $CO_2$ equivalents. The mold-in-color and recycled PET options have been left out due to an insignificant effect on GWP (as they are for the remaining air emissions for the same reason). In short, the NGVs would reduce GWP for the automobile by almost 50% on average. The use of newer materials to help achieve weight reduction, however, causes notable increases in the GWP of emissions from the Extraction and Materials Processing (due specifically to $SF_6$, $CF_4$ and $C_2F_6$) and Manufacturing (due to $SF_6$) life-cycles stages. However, the greater gains realized from the large decrease in the Use stage GWP more than compensate for those increases. If the industries that utilize and generate these fluoride emissions can find ways to better control them, then even greater improvement should be realized in the GWP for the NGVs.

Particulate Matter

For PM emissions, the results are negative. Figure 5 shows the lifetime PM emissions for each vehicle broken down by life-cycle stage. Although small reductions can be seen in the Manufacturing and Use/fuel generation life-cycle stages, the increases from Extraction and Materials Processing and Use/fuel use are substantial, and increase the total PM generated by the two NGVs by an average 110% as compared to the 1994 vehicle.

For the Use/fuel use stage, the PM increase can be directly correlated to the switch to diesel fuel from gasoline. Diesel engines have traditionally had increased PM and $NO_x$ emissions, and those emissions are created by way of the different method the diesel engine utilizes to ignite the fuel: compression in lieu of a spark as in gasoline engines. With the acknowledgment of these emissions issues, much time and effort has been put into investigating ways in which these emissions can be reduced. For instance, PM emissions and their subsequent impacts can be reduced by several

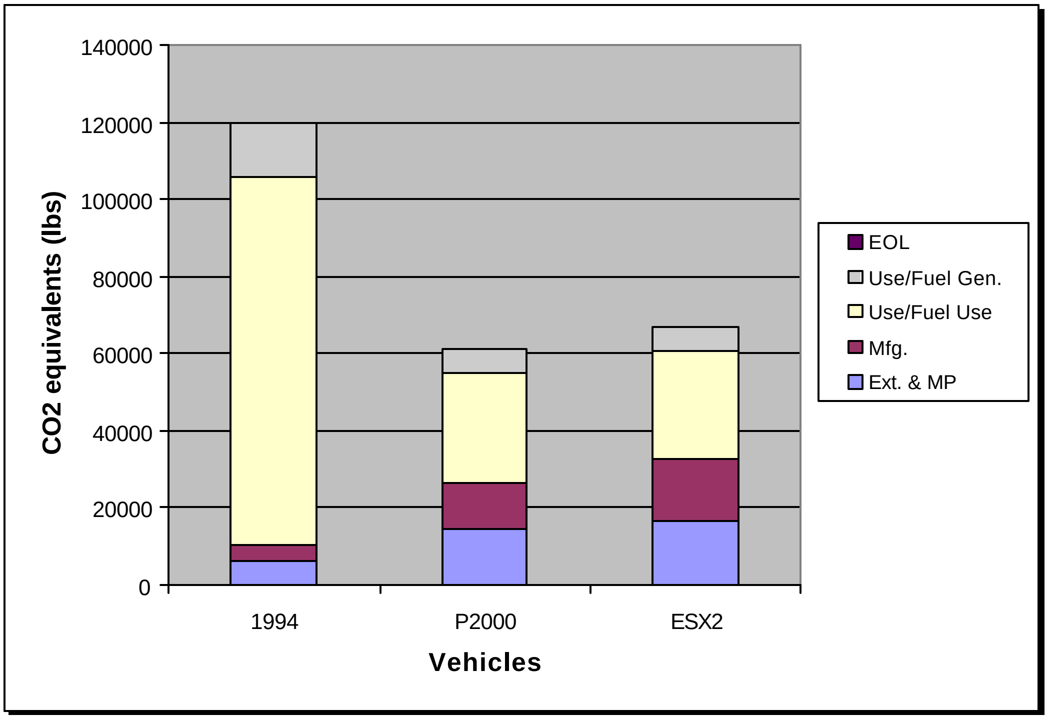


Figure 4. Lifetime Global Warming Potential

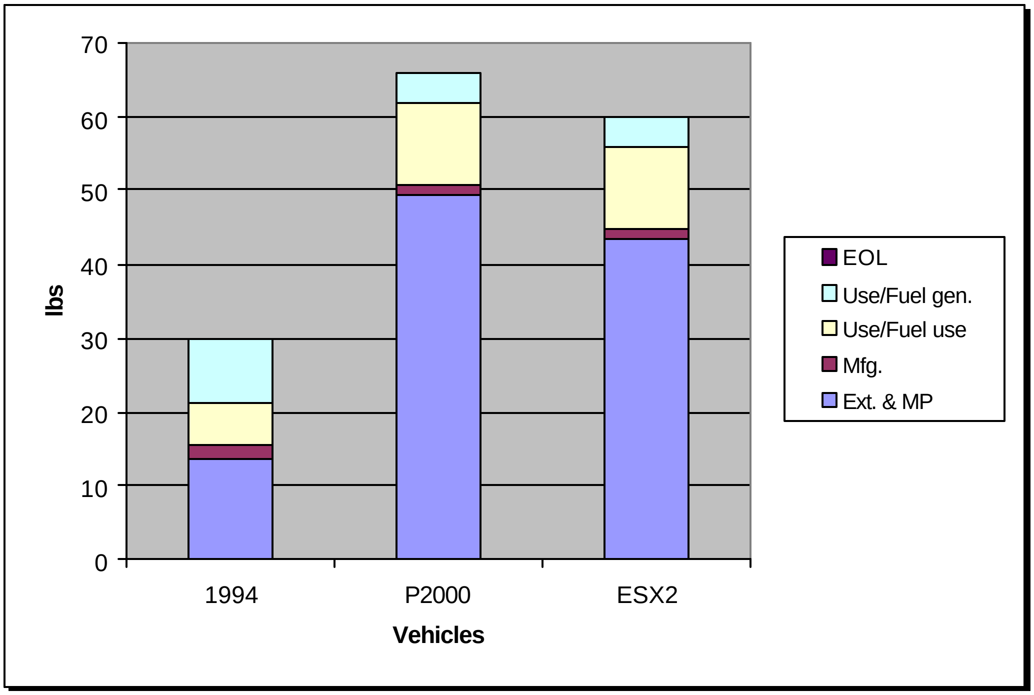


Figure 5. Lifetime Particulate Emissions

methods, with the following two aftertreatment technologies offered as examples: traps and catalysts. Traps can be used to capture and eventually burn PM emissions. Catalysts for diesel engines attempt to reduce PM emissions by converting them to less harmful compounds [9].

With respect to the Extraction and Materials Processing life-cycle stage, the bulk of the PM generation is due to the use of aluminum, magnesium and titanium. In the NGVs, 90% of the PM emissions generated in this life-cycle stage are a result of utilizing those three materials.

### Nitrogen Oxides

Similar to the PM emissions, the $NO_x$ emissions increase in the NGVs. Figure 6 depicts the lifetime $NO_x$ emissions for the three vehicles. The $NO_x$ emissions generated from the fuel generation portion of the Use life-cycle stage can be seen to decrease significantly, due specifically to the increased fuel efficiency and consequent need for less fuel over the lifetime. However, significant increases occur in the Extraction and Materials Processing and Use/fuel use stages. In the Extraction and Materials Processing stage, as in the case of PM emissions, the increases are due to the use of new materials, while those in the Use/fuel use stage are solely due to the switch from gasoline to diesel fuel. However, these emissions may not be indicative of what it may look like in the future if advanced diesel engines and cleaner fuel are employed in NGVs.

“Diesel particulates and nitrogen oxides, the two most troublesome components of diesel exhaust emissions, have a dramatic, damaging impact on the environment and on our health” states the front page of DieselNet’s website in discussing the diesel engine’s opportunity to become a “major candidate” for the power plant of the future [10]. Over the last several years, as the diesel engine has been looked at more and more for future use, $NO_x$ emissions and their control have been one of the primary concerns of diesel engine and diesel fuel manufacturers, and much research has been done in attempts to find ways to reduce these emissions. This evaluation does not include estimates of how these emissions might change in the near future due to the use of one or more of the multiple opportunities that exist to reduce diesel $NO_x$ emissions. However, Appendix A offers a comparison between the emissions used in this study and automobile manufacturers’ predicted emissions achievable through the use of multiple pollutant control measures. Some examples include:

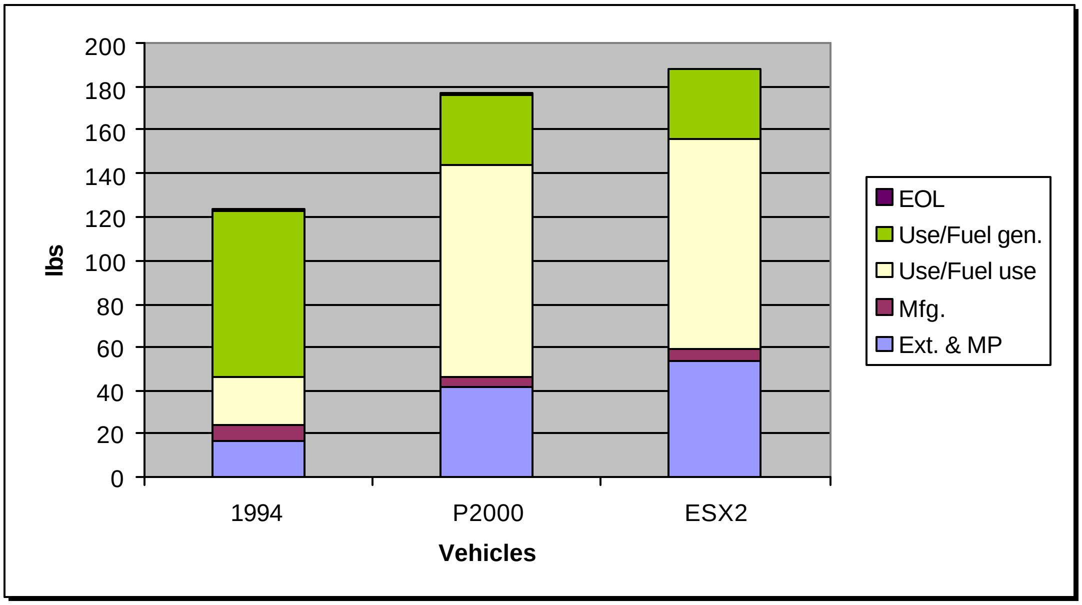


**Figure 6. Lifetime $NO_x$ Emissions**

- The reduction of the sulfur content of diesel fuel, which subsequently allows catalytic converters to operate more effectively;
- Altering other diesel fuel parameters like increasing the cetane number or decreasing the aromatics content which may allow engine manufacturers to utilize new emissions control technologies to reduce emissions;
- The alteration of fuel delivery systems to optimize the combination of injection pressure, injection timing and spray location to burn diesel more efficiently (thereby reducing the occurrence of temperature spikes that cause increased $NO_x$ emissions);
- The use of newer diesel engine catalysts that employ more complex technologies than typical gasoline vehicle catalysts; and
- Utilizing Exhaust Gas Recirculation (EGR) (already a proven diesel engine emissions control technology) [9].

Thus, there exists great opportunity for the reduction of $NO_x$ emissions from the Use/fuel use life-cycle stage, which can at least bring $NO_x$ emissions into the same range as those of the 1994 vehicle and balance out increases from the Extraction and Materials Processing stage.

Carbon Monoxide

Figure 7 shows the lifetime CO emissions for the three vehicles. Reductions can be seen in each life-cycle stage, for the ones that have significant emissions associated with them. The reduction in the Extraction and Materials Processing life-cycle stage can be attributed to the choice of the newer

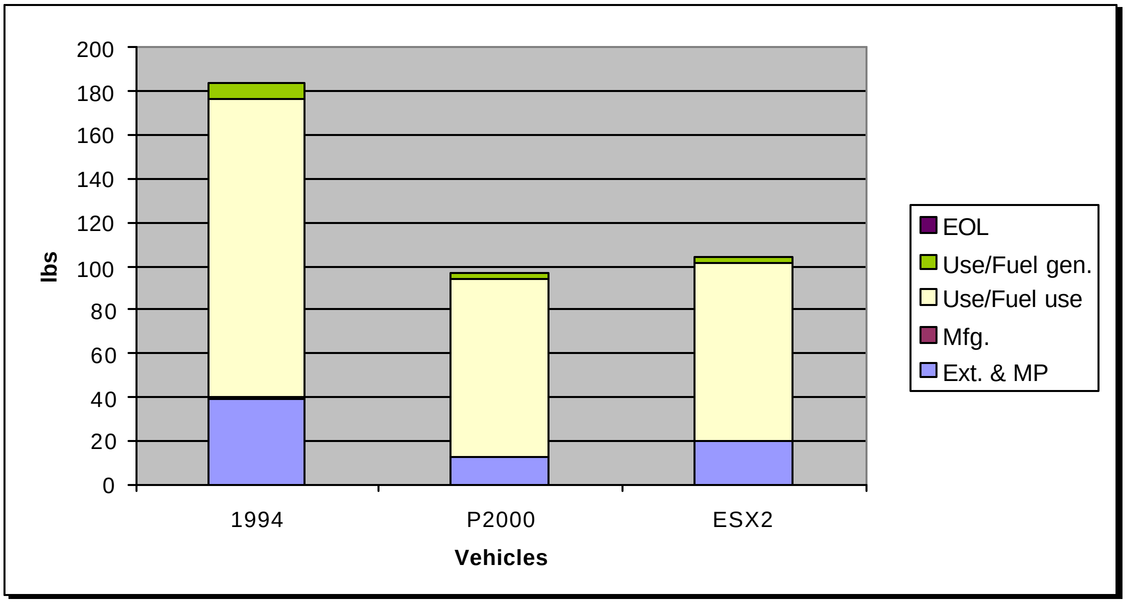


Figure 7. Lifetime CO Emissions

materials - aluminum, titanium and magnesium, and the reduction in the Use/fuel use life-cycle stage can be attributed to the switch to diesel fuel.

## 3.2 Results By Life-Cycle Stages

### 3.2.1 Extraction and Materials Processing

Table 3 shows the inputs and outputs for the Extraction and Materials Processing stage for the three vehicles. There are no results shown for the consideration of molding the ESX2's PET body panels in color, or for the recycling of those panels, because the upstream differences in Extraction and Materials Processing for molding of those panels in color were not evaluated, and the recycling of PET body panels was assumed to impact only the End-of-Life stage (i.e., there was no direct displacement of virgin PET by PET recycled from End-of-Life body panels).

An important thing to note from Table 3 is that almost all the values increase from the 1994 vehicle values, with the exception of CO. This life-cycle stage is one of the worst for the NGVs, due almost completely to the use of new, more energy intensive, materials and the increased use of aluminum, which is also energy intensive. In general, the energy use doubles, the solid waste generated increases on the order of 1,000 and 500 lbs (P2000 and ESX2, respectively), and the PM, $NO_x$ and total $CO_2$ equivalents all increase by approximately 100 - 200%. The effect of the use of newer materials on this life-cycle stage can be seen as shown in the chart in Figure 8. Although this chart

**Table 3. Inputs and Outputs from Extraction and Materials Processing**
**(all units are lbs/lifetime unless otherwise noted)**

| | 1994 Vehicle | P2000 | ESX2 |
|---|---|---|---|
| Energy (mmbtu/lifetime) | 31.81 | 62.20 | 65.71 |
| Solid Waste | 3192.47 | 4243.75 | 3703.44 |
| PM | 13.52 | 49.41 | 43.37 |
| $NO_x$ | 16.44 | 41.78 | 53.14 |
| CO | 38.87 | 12.44 | 19.33 |
| GWP - Total $CO_2$ equivalents | 6,267 | 14,798 | 16,535 |

represents only one of the impact categories (energy), it is indicative of the graphs for the remaining categories in Extraction and Materials Processing in its revelation of the impacts from the newer materials. The other charts can be found in Appendix B.

Figure 8 reveals the energy requirements for the extraction and initial processing of materials utilized to construct the 1994 vehicle and the two NGVs, broken down by individual energy of materials. The large increase in the use of aluminum and its associated energy use clearly predominates this graph, with increases in the use of magnesium and titanium also showing significant contributions. These are specifically due to material unit energy intensities, and those intensity values for the primary vehicle materials are shown in Table 4. If the feedstock energy of plastics were included, as is the convention in some LCAs, the plastic unit energy intensity would increase by up to 100%.

**Table 4. Material Unit Energy Intensities (MJ/kg)**
**Excludes Feedstock Energy**

| | Intensity |
|---|---|
| Titanium | 590.8 |
| Magnesium | 379.3 |
| Wrought Aluminum | 169.0 |
| Cast Aluminum | 32.8 |
| Ferrous | 19.3 |
| PET with Glass | 40.0 |
| Other Plastics | 69.3 |

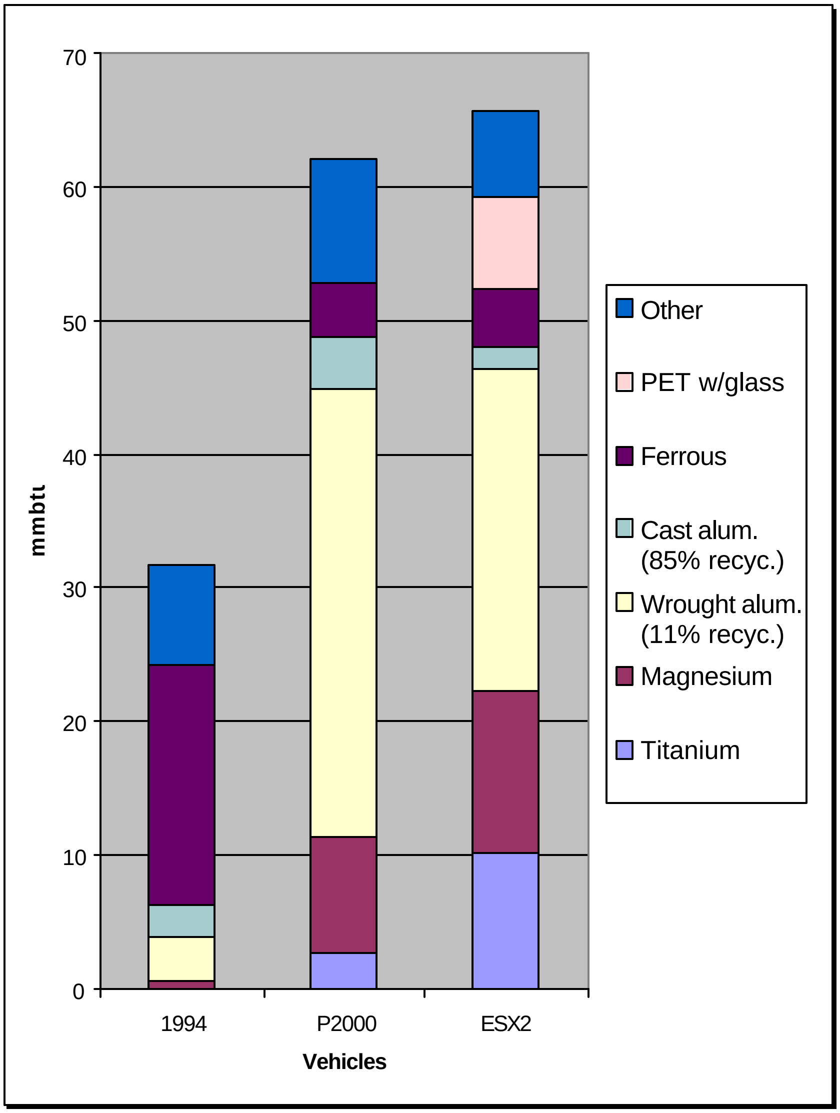


Figure 8. Extraction and Materials Processing Energy Consumption

Another important issue of concern in this life-cycle stage is the emissions of greenhouse gases as indicated by global warming potential (GWP). Observation of Table 5 below reveals the breakdown of the contributions to GWP from the Extraction and Materials Processing life-cycle stage by individual gases. The $SF_6$ emissions are solely associated with the use of magnesium; the $CF_4$ and $C_2F_6$ emissions (both of which are PFCs) are solely associated with the use of aluminum. Even with the elimination of the $SF_6$ and PFC emissions, both the P2000 and the ESX2 would still realize an increase in GWP in this life-cycle stage due to the substantial increase in $CO_2$ emissions.

**Table 5. Gases that Contribute to GWP in the Extraction and Materials Processing Life-Cycle Stage (lbs of $CO_2$ equivalents)**

| | *1994 Vehicle* | *P2000* | *ESX2* |
|---|---:|---:|---:|
| $CO_2$ | 5,568 | 8,610 | 9,310 |
| $CH_4$ | 155 | 600 | 790 |
| $SF_6$ | 247 | 3,541 | 5,023 |
| $CF_4$ | 248 | 1,708 | 1,178 |
| $C_2F_6$ | 49 | 339 | 234 |
| Total $CO_2$ Equivalents | 6,267 | 14,798 | 16,535 |

Even though the Extraction and Materials Processing life-cycle stage does not shine brightly for the NGVs, it should be noted that throughout these three vehicles' lifetimes, the energy use and generation of CO, $NO_x$ and $CO_2$ equivalent air emissions in the Extraction and Materials Processing life-cycle stage are only on the order of 10 - 40% of the lifetime totals (i.e., 90 - 60% of these impacts are generated in other life-cycle stages). Only in the particulate air emissions and solid waste generation categories do the Extraction and Materials Processing percentages of the lifetime total exceed 50%, reaching 72% and 83%, respectively.

### 3.2.2 Manufacturing

Table 6 shows the inputs and outputs (excluding greenhouse gases) for the Manufacturing stage of the three vehicles, plus an option of the ESX2 with molded-in color panels. In reviewing the results of the evaluation for this life-cycle stage, it should be kept in mind that all the results have been scaled to each vehicle's total weight, thus they have the same ratio with respect to one another. The best use of the data comes in the comparison across life-cycle stages. This holds true for all the data except for the GWP calculations, due to the addition of emissions associated with the use of $SF_6$ (as discussed in the Extraction and Materials Processing Methodology section). $SF_6$ is used as a covergas in the process of casting magnesium during primary production, as well as further downstream in the life cycle during the production of individual components. Table 7 shows the increase in the quantity of magnesium used in manufacturing the three vehicles, as well as the GWP effects. With a GWP of 24,900 times that

**Table 6. Mold-in-Color Savings**
**(all units are lbs unless otherwise noted)**

| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
|---|---|---|---|---|
| Energy consumption (mmbtu) | 11.12 | 6.88 | 7.71 | 4.48 |
| Solid waste generation | 571.33 | 353.57 | 395.78 | 216.58 |
| Air emissions - Particulates | 1.94 | 1.20 | 1.34 | 1.07 |
| Air emissions - CO | 0.61 | 0.38 | 0.43 | 0.29 |
| Air emissions - $NO_x$ | 7.80 | 4.82 | 5.40 | 2.99 |

**Table 7. Global Warming Potential Effects of Sulfur Hexafluoride**
**(all units are lbs of $CO_2$ equivalents unless otherwise noted)**

| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
|---|---|---|---|---|
| Quantity of magnesium used in vehicle production (lbs) | 6 | 86 | 122 | 122 |
| Mfg. - $SF_6$ alone | 675 | 9,677 | 13,728 | 13,728 |
| Mfg. - Total $CO_2$ equiv. | 3,988 | 11,727 | 16,023 | 15,015 |
| Lifetime $CO_2$ equiv. | 119,903 | 60,943 | 66,976 | 65,968 |

of $CO_2$, $SF_6$ is one of the most potent greenhouse gases known.

The mold-in-color savings on the global warming front are small, however, these savings become more noticeable upon review of the energy consumption, air emissions, and solid waste generation values, as seen in Table 6. Comparing only the ESX2 with painted body panels (ESX2) and the ESX2 MIC (ESX2 [MIC]), an energy savings of 42% is realized, air emissions are reduced by 20 - 45%, and solid waste decreases by 45%. These results reflect not only the savings attained in-plant, but also those savings associated with a reduction in electricity use.

### 3.2.3 Use

The Use stage is concerned with the environmental implications of driving the vehicle over its expected life of 120,000 miles. This life-cycle stage deals with the fuel consumed by the vehicle during its useful life and the tailpipe emissions produced as a result. The energy and materials required to produce the fuel and the emissions from its production are also dealt with in this stage. Being based on the same kind of diesel engine, the two NGVs being evaluated (Ford P2000 and Chrysler ESX2) are both assumed to have identical fuel efficiencies and, therefore, show identical results in the Use stage. Moreover, the “Mold-in Color” scenario for the ESX2 does not affect this life-cycle stage.

Based on fuel efficiencies of 26.6 MPG for the 1994 vehicle and 70 MPG for the NGVs, their lifetime fuel requirement is shown in Table 8.

**Table 8. Lifetime Fuel Requirement (gallons)**

| | *1994 Vehicle* | *P2000/ESX2* |
|---|---|---|
| Gasoline | 4,511 | - |
| Diesel | - | 1,714 |

For the NGVs, this represents a saving of 2,797 gallons (or 62%) over the lifetime of the vehicle. The significantly reduced fuel consumption results in reduced air emissions during Use for some types of emissions. However, the change from gasoline to diesel fuel causes some categories of emissions to increase, particularly PM and $NO_x$ .

The energy consumption during the Use stage is made up of the heat value of the fuel used and the energy required to produce the lifetime quantity of fuel. The total energy is reduced by about 57% from the baseline 1994 vehicle, as is seen in Table 9.

**Table 9. Energy Consumption in the Use Stage (mmbtu)**

| *Energy Consumption* | *1994 Vehicle* | *P2000/ESX2* |
|---|---|---|
| Fuel use | 559 | 238 |
| Fuel generation | 654 | 278 |
| **Use-Stage Total** | **1,213** | **516** |

The air emissions estimated from EPA test results on 1994 Taurus and Intrepid vehicles for the 1994 vehicle, and from a 1998 Passat for the NGVs, as described earlier in the methodology, are provided in Table 10.

**Table 10. Estimated Use-Stage Emissions (lbs/lifetime)**

| | *1994 Vehicle* | | | *P2000/ESX2* | | |
|---|---|---|---|---|---|---|
| | Fuel gen. | Fuel use | Total | Fuel gen. | Fuel use | Total |
| CO | 7.36 | 136.80 | 144.16 | 3.13 | 81.27 | 84.4 |
| $NO_x$ | 76.53 | 22.49 | 99.02 | 32.54 | 97.52 | 130.06 |
| PM | 8.96 | 5.56 | 14.52 | 3.81 | 11.38 | 15.19 |
| $CH_4$ | 23.71 | 3.44 | 27.15 | 10.08 | 1.63 | 11.71 |
| $CO_2$ | 13,756 | 95,225 | 108,981 | 5,849 | 28,322 | 34,171 |

As may be observed from the above, the NGVs score better in the CO, $CH_4$, and $CO_2$ emission categories, all of which show a reduction. The other emissions, namely $NO_x$ and PM, go up considerably, on account of using diesel fuel instead of gasoline.

The inputs and outputs associated with the generation of gasoline and diesel fuel needed for the driving the vehicles were obtained from the same proprietary, in-house data set used for the major primary materials. The energy required, solid waste generated, and air emissions from the production of gasoline and diesel are as shown below:

**Table 11. Inputs and Outputs from Gasoline/Diesel Production (all units are lbs/lifetime unless otherwise noted)**

| | *1994 Vehicle* | *P2000/ESX2* |
|---|---|---|
| Energy (mmbtu/lifetime) | 653.67 | 277.93 |
| Solid Waste | 188.97 | 80.35 |
| PM | 8.95 | 3.81 |
| $NO_x$ | 76.53 | 32.54 |
| CO | 7.36 | 3.13 |
| $CO_2$ | 13756.75 | 5849.13 |
| $CH_4$ | 23.71 | 10.08 |

Based on the estimated $CO_2$ and $CH_4$ emissions (the two global warming gases), the GWP in terms of $CO_2$ equivalents was evaluated, and is depicted in Figure 9.

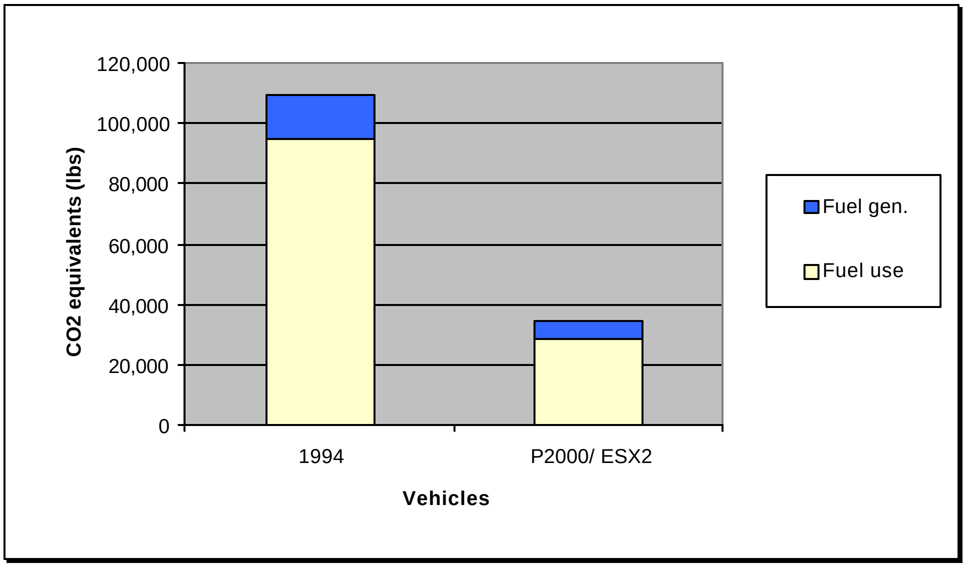


**Figure 9. Global Warming Potential - Use Stage**

Figure 9 shows that the contribution of the P2000 and ESX2 to the GWP is significantly lower than that of the 1994 vehicle, and that fuel production plays a minor role, compared to fuel use.

Overall, in the Use stage, it may be noted that the use of NGVs results in significant reduction in energy, solid waste and certain air emissions, particularly those that contribute to GWP. The categories in which there is an increase over the 1994 vehicle are $NO_x$ and PM.

Researchers at Argonne National Laboratory (ANL) have come up with a different set of emission values for the Use stage, based on an average of Low Emission Vehicle (LEV) and Ultra Low Emission Vehicle (ULEV) standards in the future. These values have been used in place of the Passat-derived values to illustrate another scenario for the Use stage, as shown in Appendix C.

### 3.2.4 End-of-Life

Figure 10 shows the End-of-Life Solid Waste generated. The P2000 reduces ASR generated as compared to the 1994 vehicle. However, the ESX2 turns out to be better than the 1994 car only if the PET body panels can be recycled. It may be noted that the solid waste quantities shown include the waste produced during the electricity generation process. However, the waste from electricity generation is only 2% of the total or less, in each case.

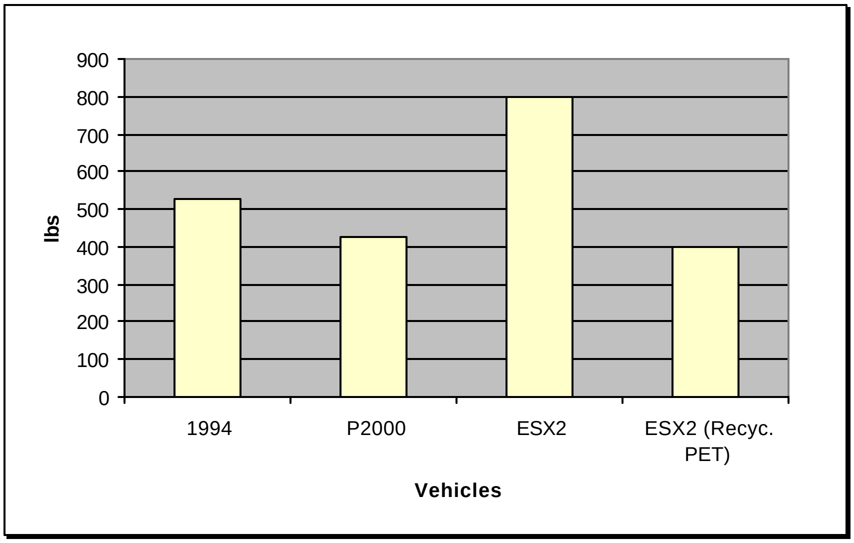


**Figure 10. End-of-Life Solid Waste Generation**

The energy consumed in this stage is almost all electricity, and is compared for the different vehicles in Table 12:

**Table 12. End-of-Life Energy Consumption (mmbtu)**

| Vehicle | Energy |
|---|---:|
| 1994 | 0.1062 |
| P2000 | 0.0873 |
| ESX2 | 0.1003 |

The air emissions considered in the End-of-Life stage are entirely those from electricity generation and, therefore, follow the same comparative pattern as Table 12. The breakdown of the air emissions is shown in Table 13.

**Table 13. Air Emissions from Electricity Generation - End-of-Life Stage (lbs)**

| | 1994 | P2000 | ESX2 |
|---|---:|---:|---:|
| Particulates | 0.01336 | 0.00826 | 0.009252 |
| CO | 0.00574 | 0.00355 | 0.003978 |
| $NO_x$ | 0.11633 | 0.07199 | 0.080584 |
| $CO_2$ equivalents | 44.0413 | 27.2546 | 30.50892 |

The table shows that the global warming gases, expressed in $CO_2$ equivalents, are the most significant of all air emissions from electricity generation. Nevertheless, the air emissions in the End-of-Life stage are a minuscule fraction of the total lifetime emissions.

# 4. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In summation, it appears that both the P2000 and ESX2 hold promise for becoming more efficient and less environmentally burdensome modes of transportation for the new century. This evaluation specifically results in the key conclusions listed below.

- In the areas of energy consumption, GWP, and CO generation, considerable gains will be realized through the propagation and use of the NGVs, where reductions of over 50% are seen in each category.
- With the important and positive work being done on the solid waste front to reduce as much as possible the quantity generated from Manufacturing through End-of-Life, the gains are notable. However, with over 90% of the quantity generated throughout the life-cycle coming from Extraction and Materials Processing, there is still much room for improvement through the use of recycled materials, wiser choices of NGV primary materials, or better waste management practices in the upstream processes.
- Though this evaluation indicates increased PM and $NO_x$ emissions, there are multiple opportunities for reductions of both pollutants. For PM emissions, even though there are options that would allow for reductions in PM generation during fuel use, the most concerted effort will have to be applied to finding ways to reduce PM generated during Extraction and Materials Processing. The most obvious way is to utilize more recycled materials than are currently used. For $NO_x$ emissions, where more opportunities exist for reduction in the Use stage and less significant increases are found in the Extraction and Materials Processing stage, there are better chances that the NGVs will achieve $NO_x$ emission levels close to or below that of the 1994 vehicle.

From these conclusions, the following recommendations for future work are made to help the NGVs in becoming less environmentally burdensome in all aspects of their life cycle. There are many ways to improve the environmental footprint of the NGVs, and the options available are discussed below.

### Reductions in hybrid-vehicle diesel engine emissions

Much work is currently being done to improve diesel engine performance. Fuel delivery is one way emissions can be reduced through improving the process of injection of the fuel into the compression chamber. Changing the air intake dynamics can also have the effect of reducing emissions, with Exhaust Gas Recirculation (EGR) reducing $NO_x$ emissions specifically. Aftertreatment is also providing several different ways to reduce tailpipe emissions from the NGVs by using technologies like particulate filters to collect PM and lean $NO_x$ catalysts to convert $NO_x$ to more benign compounds.

### Improvements to existing diesel fuel

There are several changes that fuel manufacturers can make during the fuel production processes to decrease pollution generated during fuel burning. Of these, significant sulfur-content reduction and increase in the cetane number appear to be the most attractive ways to reduce the generation of all pollutants, including PM and $NO_x$.

### Use of alternative fuels

Over the last ten years, many different fuels have been tested in attempts to reduce emissions, sometimes increasing the sustainability of the fuel generation process itself. Good examples include ethanol and biodiesel, which both utilize raw materials coming from renewable sources, decreasing the portion of nonrenewable petroleum required. Methanol, which may be obtained either from natural gas, coal or biomass, costs less than gasoline or diesel and results in fewer emissions. Additionally, compressed natural gas, dimethyl ether and Fischer-Tropsch (a natural gas-derived fuel) have been tested and improved for use as fuels, however some limitations exist in using these fuels, primarily cost.

### Research on hybrid vehicle batteries

Of the available battery technologies that have been further developed for use in electric vehicles, the most promising appears to be the lithium-ion battery, due to its higher energy density - greater power in a lighter package. However, it appears that these developing technologies will require further life-cycle evaluation to ensure that the benefits they offer do not produce more environmentally damaging effects in other life-cycle stages.

### Use of alternative power sources

Alternative power sources seem to be the greatest “leapfrog technologies” [11] available to move the NGVs significantly further in their fuel efficiency. The brightest technology currently being developed and refined is fuel cells, which generate almost no pollutants during Use. Fuel cells utilize hydrogen as the basic raw material which can be obtained from several different sources, including, but not limited, to gasoline and pure hydrogen, allowing for greater flexibility in bringing fuel cell-powered vehicles to the market. Additionally, newer power source technologies like gas turbines, flywheels, ultracapacitors, and hydropneumatics are maturing into usable technologies that can increase even further the operating efficiency of NGVs.

### Use of recycled/alternative materials

This evaluation found that the use of lighter-weight materials, including primarily aluminum, titanium and magnesium, has a trade-off. As environmental burdens are reduced in the Use stage, burdens are increased significantly in the Extraction and Materials Processing life-cycle stage. The increased fuel efficiency gained through the use of these lighter-weight materials is offset by a much greater energy demand per unit mass of product produced and a substantially greater quantity of air emissions and solid wastes generated. There are several options available to improve the situation, including primarily using the same materials but with a higher recycled content (which reduces the need for virgin ore while significantly decreasing the required production energy), finding ways to reduce the impacts from production of these materials, or using different materials (like carbon fiber composites).

Further evaluation of the life-cycle impacts of these materials or other materials chosen for use in the NGVs will be necessary to evaluate these trade-offs.

### Solid waste reduction

Solid waste reduction can be achieved in several ways including the following:

- Evaluate recyclability of glass-reinforced PET plastics;
- Use materials with more recycled content; and
- Develop technologies to recover and recycle plastics in a more cost-effective manner.

In general, the NGVs are expected to make significant strides toward improving the automobile's environmental footprint. However, to continue to move in that direction, automakers will have to work more closely with their supply chains. Through these partnerships, the automobile industry should be able to meet the PNGV goals and thereby move another step forward in coming closer to a more sustainable future for the automobile.

## References

1. Technology Administration’s PNGV website.
http://www.ta.doc.gov/pngv/introduction/intro.htm

2. USCAR website.
http://www.uscar.org/techno/tsp.htm

3. Kelly, K.E., J.G. Overly, M.L. Socolof, and G.A. Davis. “Environmental Evaluation of Molding Body Panels in Color.” *SAE Southern Automotive Manufacturing Conference & Exposition*, 1998.

4. Technology Administration’s PNGV website.
http://www.ta.doc.gov/pngv/introduction/intro.htm#baseline

5. EPA website.
http://www.epa.gov/OMSWWW/gopher/Cert/Veh-cert/Cert-Tst/

6. EPA website.
http://www.epa.gov/OMSWWW/gopher/Cert/MPG/98guide.txt

7. Raffelsberger, et. al. “Fuel System for the Future High Speed Long Life DI Diesel Engines with the Suitable Electronic Control.” *Total Life Cycle Conference*, SAE, 1995.

8. Personal communications with Terry Lindell of Automotive Computers Inc., a member of the Automotive Recyclers Association, April 1998.

9. EPA - OMS Fact Sheet.
http://www.epa.gov/reg3artd/vehic/noxfact2.htm

10. DieselNet Website.
http://www.dieselnet.com

11. EPA - Environmental Fact Sheet. “Partnership for a New Generation of Vehicles and the Environment.” *Office of Mobile Sources*. Publication number EPA420-F-98-007, April 1998.

## Appendix A

## Manufacturers' diesel emission goals

The major drawbacks of using diesel fuel to power the NGVs, as shown by this study, are increases in $NO_x$ and PM emissions. According to U.S. automobile manufacturers, the following series of measures, if implemented, are likely to result in a several-fold decrease in these emissions:

- The use of a Direct Injection, Aluminum, Through-bolt Assembly (DIATA) engine;
- The use of sulfur-free diesel fuel;
- Cooled EGR and advanced fuel systems;
- The use of a catalyzed soot filter; and
- The use of a 90% absorption $NO_x$ catalyst.

If all the above actions are taken, the manufacturers feel that the emissions could be brought down to a level much lower than currently feasible. Table A1 compares the Use-stage emissions values actually used in this study to those considered achievable (obtained from ORNL).

**Table A1. Reduced $NO_x$ and PM emissions (g/mile)**

| | *Used in Study* | *Achievable* |
|---|---|---|
| $NO_x$ | .369 | .030 |
| PM | .043 | .010 |

It is observed from Figure A1 that lifetime PM emissions are somewhat reduced by using the new values. However, the emissions still remain much higher for the NGVs than those associated with the 1994 vehicle, due to Extraction and Materials Processing being the dominant life-cycle stage for PM emissions.

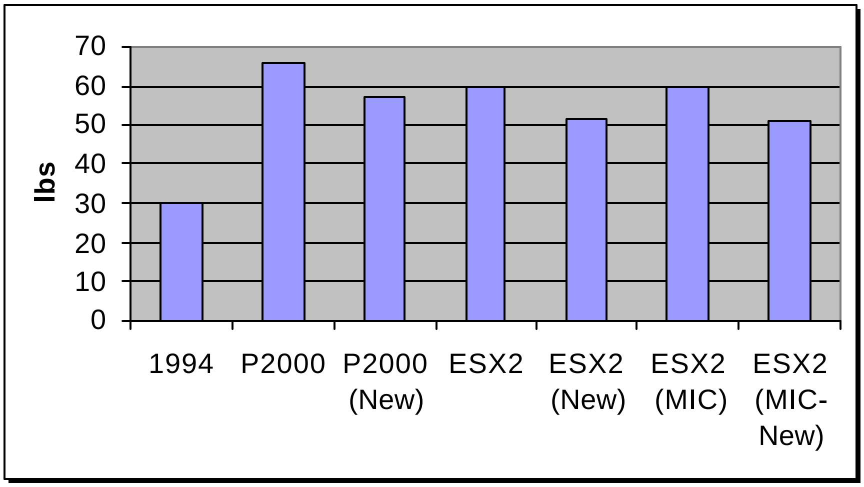


**Figure A1. Particulate Emissions Comparison**

In the case of $NO_x$ emissions, on the other hand, substantial improvements are seen for the NGVs when the new values are used. $NO_x$ emissions cease to be a problem and are, in fact, lower than the 1994 vehicle for all the scenarios modeled. It should be noted, however, that automobile manufacturers have not yet been able to achieve the lower emission values used in this comparison for hybrid diesel engines, but only anticipate the likelihood of attaining them if all presently known techniques are used make the vehicles more efficient.

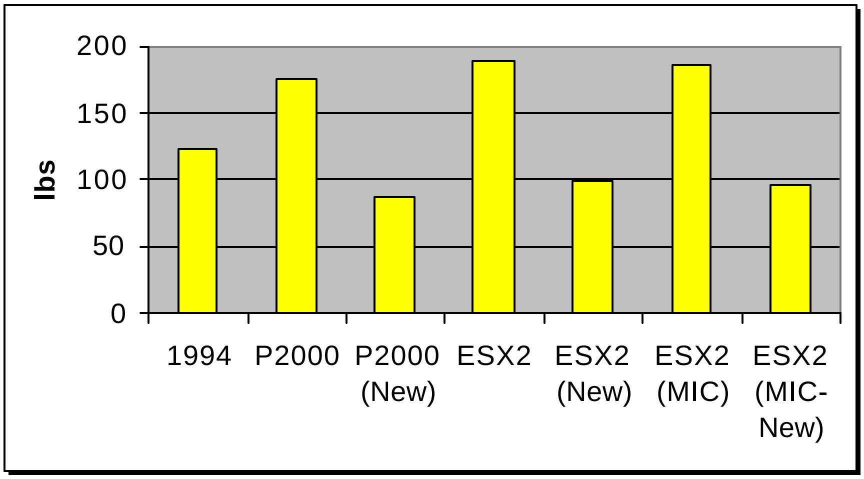


**Figure A2. $NO_X$ Emissions Comparison**

# Appendix B

## Table B1. Breakdown of Material Contributions to Environmental Burdens in the Extraction & Materials Life-cycle Stage

| | **Titanium** | **Magnesium*** | **Auto Alum. Wrought^** | **Auto Alum. Cast**** | **Ferrous^^** | **Fiberglass** | **PET w/ fiberglass***** | **Other Plastics^^^** | **Glass** | **PC (Lexan)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Energy** | (thousands of btus of energy / lb of material) | | | | | | | | | |
| Total | 263.435 | 165.442 | 83.688 | 16.441 | 8.327 | 17.369 | 34.249 | 47.423 | 5.894 | 50.200 |
| | (percentage of total energy value) | | | | | | | | | |
| *% electricity* | *53.95%* | *47.63%* | *63.07%* | *64.60%* | *16.12%* | *29.76%* | *10.75%* | *21.69%* | *13.75%* | *12.72%* |
| *% feedstocks* | *3.57%* | *1.42%* | *13.18%* | *14.32%* | *0.11%* | *5.29%* | *49.77%* | *37.15%* | *0.09%* | *32.50%* |
| **Solid Waste** | (lbs of waste / lb of material) | | | | | | | | | |
| Total | 9.530 | 3.453 | 5.880 | 1.235 | 1.133 | 0.714 | 0.143 | 0.776 | 0.570 | 0.192 |
| **Air Emissions** | (lbs of pollutant / lb of material) | | | | | | | | | |
| PM | 1.20E-01 | 4.42E-02 | 8.51E-02 | 4.45E-03 | 3.04E-03 | 6.17E-03 | 3.98E-03 | 7.43E-03 | 1.86E-03 | 6.69E-03 |
| CO | 2.20E-02 | 8.40E-03 | 4.15E-03 | 7.95E-04 | 1.75E-02 | 8.78E-04 | 1.56E-02 | 2.59E-03 | 3.38E-04 | 3.61E-03 |
| CO2 | 3.90E+01 | 1.50E+01 | 9.12E+00 | 1.75E+00 | 1.66E+00 | 2.22E+00 | 2.48E+00 | 4.65E+00 | 8.38E-01 | 4.96E+00 |
| NOX | 2.70E-01 | 1.13E-01 | 4.15E-02 | 7.26E-03 | 3.01E-03 | 2.03E-02 | 2.05E-02 | 2.02E-02 | 1.30E-02 | 1.93E-02 |
| N2O | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.67E-04 | 0.00E+00 | 1.02E-07 |
| CH4 | 2.30E-01 | 1.06E-01 | 1.98E-02 | 2.66E-03 | 1.07E-03 | 2.05E-02 | 3.12E-03 | 5.46E-03 | 4.18E-03 | 1.83E-02 |

*This profile is a combination of 60% primary production (using virgin materials) and 40% secondary production (recycled materials).

^This profile is a combination of 89% primary production (using virgin materials) and 11% secondary production (recycled materials).

**This profile is a combination of 15% primary production (using virgin materials) and 85% secondary production (recycled materials).

^^This profile is a combination of three other profiles from the in-house proprietary data set: iron production (21%), hot-rolled steel production (67%) and cold-rolled steel (12%).

***This profile is a combination of 85% PET with 15% fiberglass.

^^^This profile is primarily a combination of PU foam, PP, ABS and PE and includes smaller quantities of PVC, nylon and PC.

## Table B2. Calculation of Vehicle Emission Values for 1994 Vehicle

| | **Emission Values^** | | | | (all are grams/mile except for fuel efficiencies in miles/gallon) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *City* | | | | *Highway* | | | | |
| **Vehicle** | CO | CO2 | NOx | MPG | CO | CO2 | NOx | MPG | Avg. MPG |
| Taurus #1 | 0.64 | 419 | 0.17 | 21.1 | 0.04 | 242 | 0.04 | 36.6 | 26.1 |
| Taurus #2 | 0.88 | 413 | 0.05 | 21.5 | 0.11 | 247 | 0.03 | 36.1 | 26.4 |
| Taurus #3 | 1.08 | 409 | 0.05 | 21.7 | 0.06 | 247 | 0.03 | 36.1 | 26.4 |
| Taurus average | 0.867 | 413.667 | 0.090 | 21.433 | 0.070 | 245.333 | 0.033 | 36.267 | 26.300 |
| Intrepid #1 | 0.49 | 405 | 0.1 | 21.9 | 0.08 | 249 | 0.09 | 35.8 | 26.5 |
| Intrepid #2 | 0.71 | 423 | 0.14 | 21 | 0.15 | 257 | 0.03 | 34.6 | 25.7 |
| Intrepid #3 | 0.53 | 417 | 0.13 | 21.3 | 0.17 | 254 | 0.03 | 35 | 25.7 |
| Intrepid average | 0.577 | 415.000 | 0.123 | 21.400 | 0.133 | 253.333 | 0.050 | 35.133 | 25.967 |
| Taurus/Intrepid average | 0.722 | 414.333 | 0.107 | 21.417 | 0.102 | 249.333 | 0.042 | 35.7 | **26.133** |

| **Final Emission Factors** | | | | |
|---|---|---|---|---|
| Assumed driving type split: | **City -** | 67% | **Highway -** | 33% |
| | CO | CO2 | NOx | MPG |
| 1994 Vehicle | 0.517 | 359.883 | 0.085 | 26.133 |

| CH4* | PM* |
|---|---|
| 0.013 | 0.021 |

^These emissions values are from the EPA's "1994 Light-Duty Vehicle & Truck Annual Certification Test Results Report."

*These two emissions were not included in EPA's Certification Report, and thus were estimated using a scaled relationship between those found in the Certification Report and EPA's "Exhaust Emission Certification Standards (Tier 0)."

## Table B3. Calculation of Vehicle Emission Values for the New Generation Vehicles

| | **Emission Values^^** | | | (all are grams/mile except for fuel efficiencies in miles/gallon) | | | |
|---|---|---|---|---|---|---|---|
| | *City & Highway Combined* | | | | | | |
| **Vehicle** | CO | NOx | PM | CH4** | HC-total | HC-NM | **MPG** |
| VW Passat M5 diesel | 0.5 | 0.6 | 0.07 | 0.01 | 0.22 | 0.21 | **43** |
| PNGV Vehicle emissions | 0.307 | 0.369 | 0.043 | 0.006 | ---- | ---- | **70** |

| CO2^^^ |
|---|
| 174 |
| 107 |

^^These emission values are from the EPA's "1998 Annual Certification Test Results" for light-duty vehicles and light-duty trucks.

**Derived from the difference of the two HC categories shown shaded in gray.

^^^Estimated using Fiat diesel engine emissions data from "Fuel Systems for the Future: High Speed Long Life DI Diesel Engines with the Suitable Electronic Control," Total Life Cycle Conference, SAE, 1995.

## Life-Cycle Energy Consumption Data

MIC = Mold-in-color

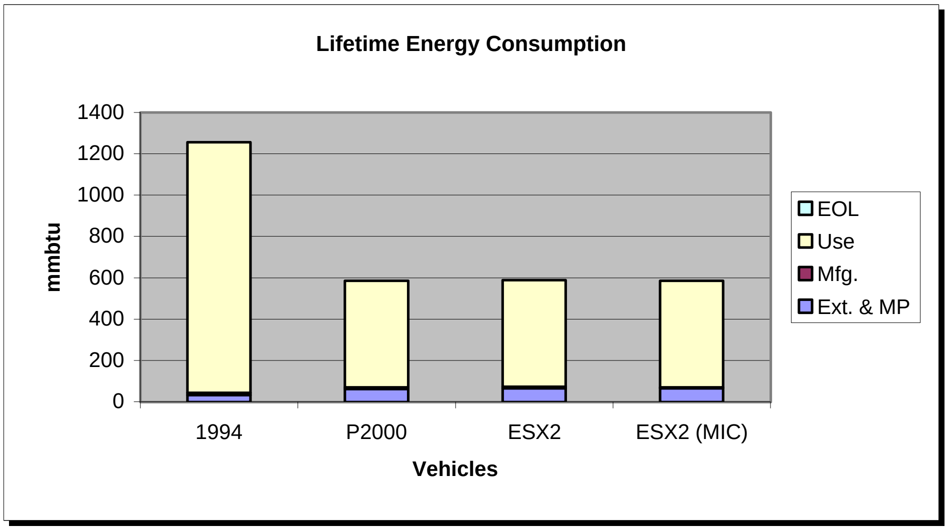
0.00094778 mmbtu = 1 MJ

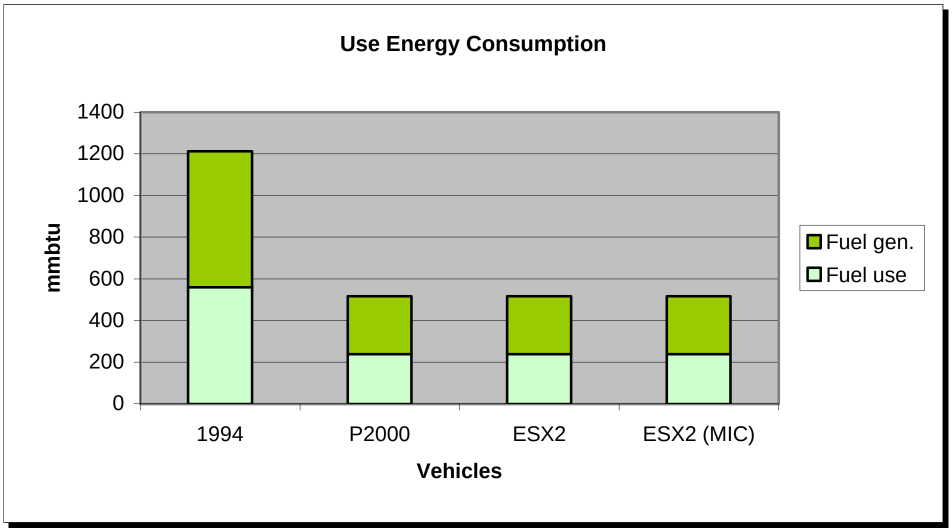
| **Life Cycle Stage** | **1994** | **P2000** | **ESX2** | **ESX2 (MIC)** |
|---|---|---|---|---|
| | (all units are mmbtu) | | | |
| Extraction & Matl. Proc. | 31.81218364 | 62.19965486 | 65.71058532 | 65.71058532 |
| Manufacturing | 11.1249946 | 6.88461796 | 7.70666189 | 4.482383193 |
| Use | 1212.853917 | 515.6840529 | 515.6840529 | 515.6840529 |
| *Fuel Use* | 559.18 | 237.7542857 | 237.7542857 | 237.7542857 |
| *Fuel Generation* | 653.6719624 | 277.9297672 | 277.9297672 | 277.9297672 |
| End-of-Life | 0.1062 | 0.0873 | 0.1003 | 0.1003 |
| Total | 1255.897296 | 584.8556257 | 589.2016001 | 585.9773214 |

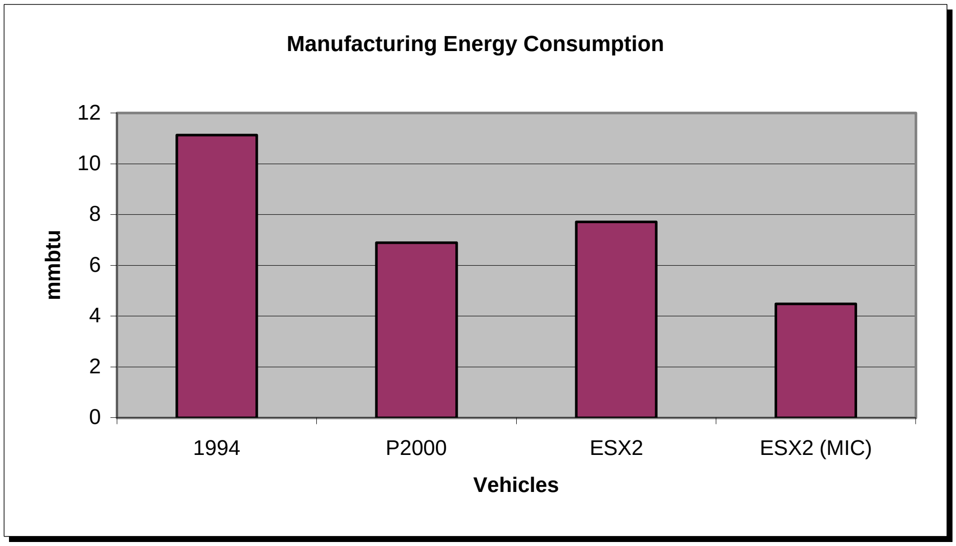
| **Extraction & Matl. Proc. (units of MJ)** | | | |
|---|---|---|---|
| Titanium | 0 | 2947.905576 | 10719.65664 |
| Magnesium | 631.8513225 | 9056.535623 | 12847.64356 |
| Wrought alum. | 3602.863868 | 35415.38526 | 25296.70376 |
| Cast alum. | 2363.078995 | 4027.637784 | 1783.455845 |
| Ferrous | 19025.00465 | 4299.931862 | 4633.395966 |
| Glass fiber | 329.7610622 | 329.7610622 | 0 |
| PET w/glass | 0 | 0 | 7260.238026 |
| Other Plastics | 7012.855133 | 7893.392998 | 4559.928226 |
| Glass | 599.5300455 | 223.6588771 | 434.892261 |
| Lexan | 0 | 1072.403374 | 714.935583 |
| Carbon fiber | 0 | 360.06768 | 1080.20304 |
| Totals | 33564.94508 | 65626.6801 | 69331.0529 |

| **Extraction & Matl. Proc. (units of mmbtu)** | | | |
|---|---|---|---|
| Titanium | 0 | 2.793965947 | 10.15987617 |
| Magnesium | 0.598856046 | 8.583603332 | 12.17673961 |
| Wrought alum. | 3.414722317 | 33.56599384 | 23.97570989 |
| Cast alum. | 2.23967901 | 3.817314539 | 1.690323781 |
| Ferrous | 18.03151891 | 4.075389421 | 4.391440029 |
| Glass fiber | 0.31254094 | 0.31254094 | 0 |
| PET w/glass | 0 | 0 | 6.881108397 |
| Other Plastics | 6.646643838 | 7.481200015 | 4.321808774 |
| Glass | 0.568222587 | 0.211979411 | 0.412182187 |
| Lexan | 0 | 1.01640247 | 0.677601647 |
| Carbon fiber | 0 | 0.341264946 | 1.023794837 |
| Totals | 31.81218364 | 62.19965486 | 65.71058532 |

| **Extraction & Matl. Proc. (units of mmbtu)** | | | |
|---|---|---|---|
| Titanium | 0 | 2.793965947 | 10.15987617 |
| Magnesium | 0.598856046 | 8.583603332 | 12.17673961 |
| Wrought alum. | 3.414722317 | 33.56599384 | 23.97570989 |
| Cast alum. | 2.23967901 | 3.817314539 | 1.690323781 |
| Ferrous | 18.03151891 | 4.075389421 | 4.391440029 |
| PET with fiberglass | 0 | 0 | 6.881108397 |
| Other | 7.527407364 | 9.363387782 | 6.435387445 |
| Totals | 31.81218364 | 62.19965486 | 65.71058532 |

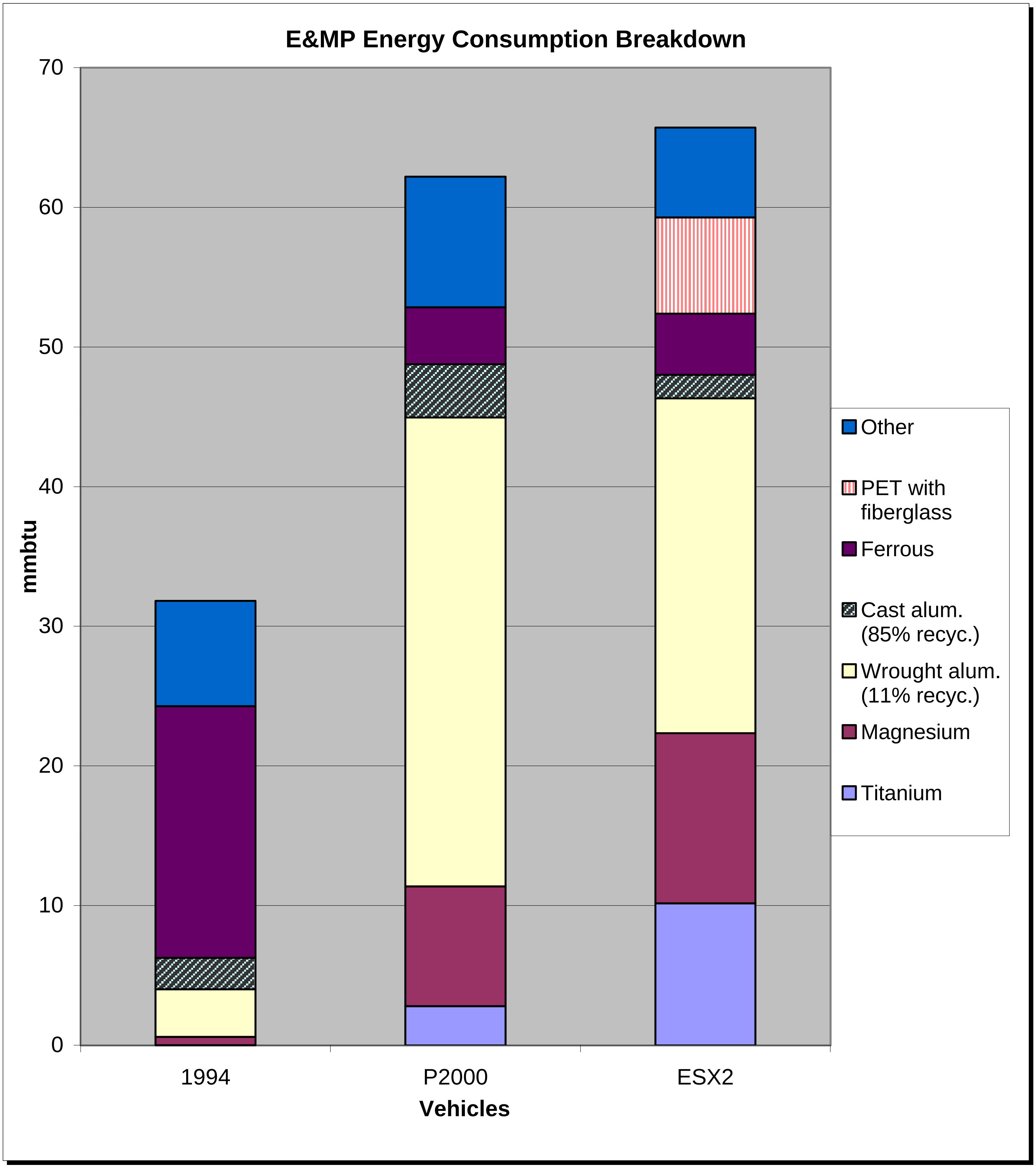






- Vehicle manufacturing data scaled from conventional compact car manufacturing data by total vehicle weight.

- Primary purpose of this graph is to show the savings obtained through MIC option.



- Other category includes plastics other than glass-reinforced PET, glass fiber, glass, lexan and carbon fiber.

## Life Cycle Solid Waste Generation Data

MIC = Mold-in-color

| Life Cycle Stage | 1994 | P2000 | ESX2 | ESX2 [Recyc. PET] | ESX2 [MIC] |
|---|---|---|---|---|---|
| | (all units are lbs) | | | | |
| Extraction & Matl. Proc. | 3192.47 | 4243.75 | 3703.44 | 3703.44 | 3703.44 |
| Manufacturing | 571.33 | 353.57 | 395.78 | 395.78 | 216.23 |
| Use/Fuel Generation | 188.968922 | 80.34624629 | 80.34624629 | 80.34624629 | 80.34624629 |
| End-of-Life | 524.64 | 424.81 | 800.64 | 400.64 | 800.64 |
| Total | 4477.42 | 5102.47 | 4980.22 | 4580.22 | 4800.67 |

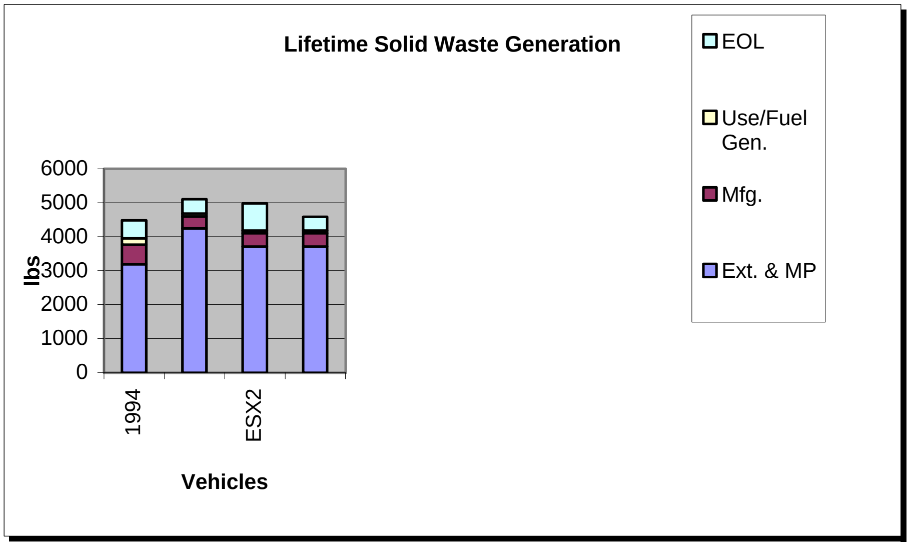
| | | | | | |
|---|---|---|---|---|---|
| Manufacturing | 43.74 | 27.07 | 30.30 | 30.30 | 18.23 |
| Mfg.- Elec. Gen. | 527.5984892 | 326.5002966 | 365.4854066 | 365.49 | 198.00 |

| | | | | | |
|---|---|---|---|---|---|
| End-of-Life | 516.16 | 419.56 | 794.77 | 394.77 | 794.77 |
| EOL - Elec. Gen. | 8.480786606 | 5.248270036 | 5.874929145 | 5.874929145 | 5.87 |

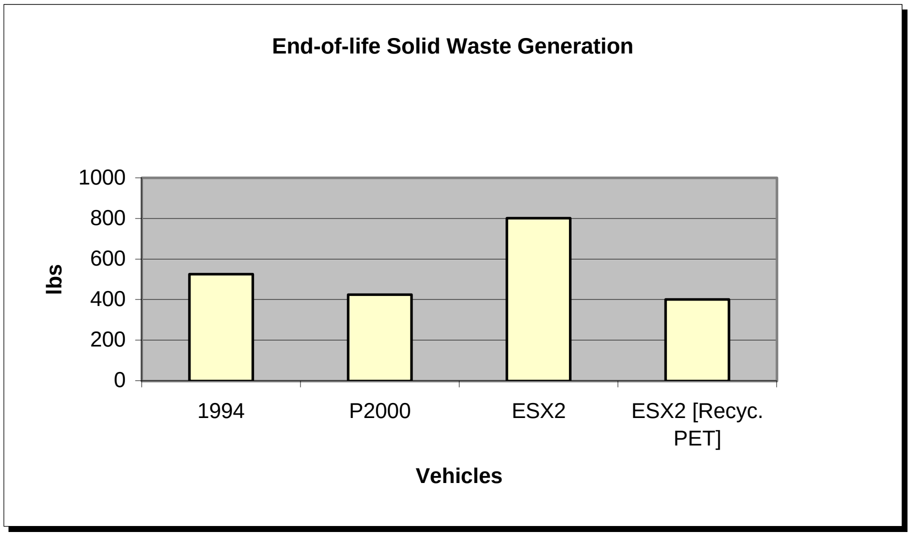
NOTE: Electricity generation-related solid wastes are not added to the E&MP and Use/Fuel Gen. life-cycle stages due to those wastes already being included in the numbers reported in the first table above.

| **Extraction & Matl. Proc. (units of lbs)** | | | |
|---|---|---|---|
| Titanium | 0 | 104.8497741 | 381.2719056 |
| Magnesium | 20.72175828 | 297.0118687 | 421.3424184 |
| Wrought alum. | 276.4071222 | 2717.023201 | 1940.730858 |
| Cast alum. | 196.3802379 | 334.7109716 | 148.2115003 |
| Ferrous | 2457.177476 | 555.358378 | 598.4269869 |
| Glass fiber | 13.57159028 | 13.57159028 | 0 |
| PET w/glass | 0 | 0 | 57.08317467 |
| Other Plastics | 173.1780476 | 194.9223764 | 112.6045601 |
| Glass | 55.03553675 | 20.53139195 | 39.92215101 |
| Lexan | 0 | 5.773917295 | 3.849278196 |
| Carbon fiber | 0 | 0 | 0 |
| Totals | 3192.471769 | 4243.753469 | 3703.442833 |

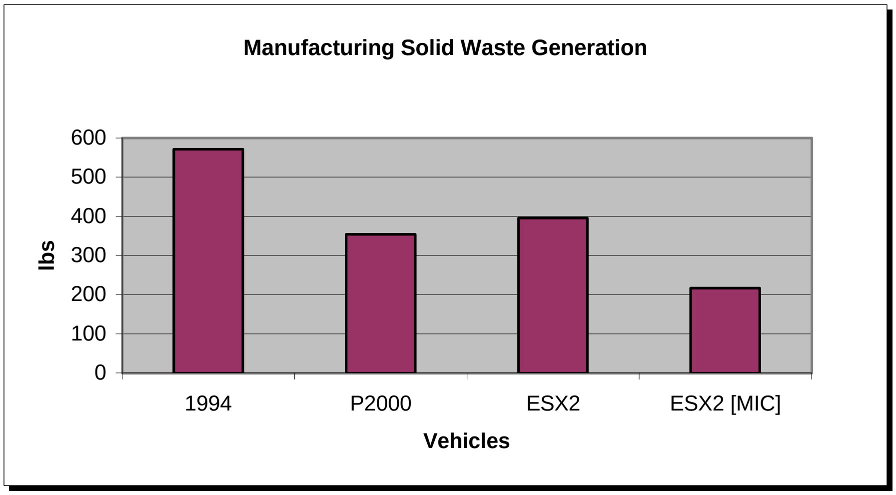
| **Extraction & Matl. Proc. (units of lbs)** | | | |
|---|---|---|---|
| Titanium | 0 | 104.8497741 | 381.2719056 |
| Magnesium | 20.72175828 | 297.0118687 | 421.3424184 |
| Wrought alum. | 276.4071222 | 2717.023201 | 1940.730858 |
| Cast alum. | 196.3802379 | 334.7109716 | 148.2115003 |
| Ferrous | 2457.177476 | 555.358378 | 598.4269869 |
| PET w/glass | 0 | 0 | 57.08317467 |
| Other | 241.7851746 | 234.799276 | 156.3759893 |
| Totals | 3192.471769 | 4243.753469 | 3703.442833 |



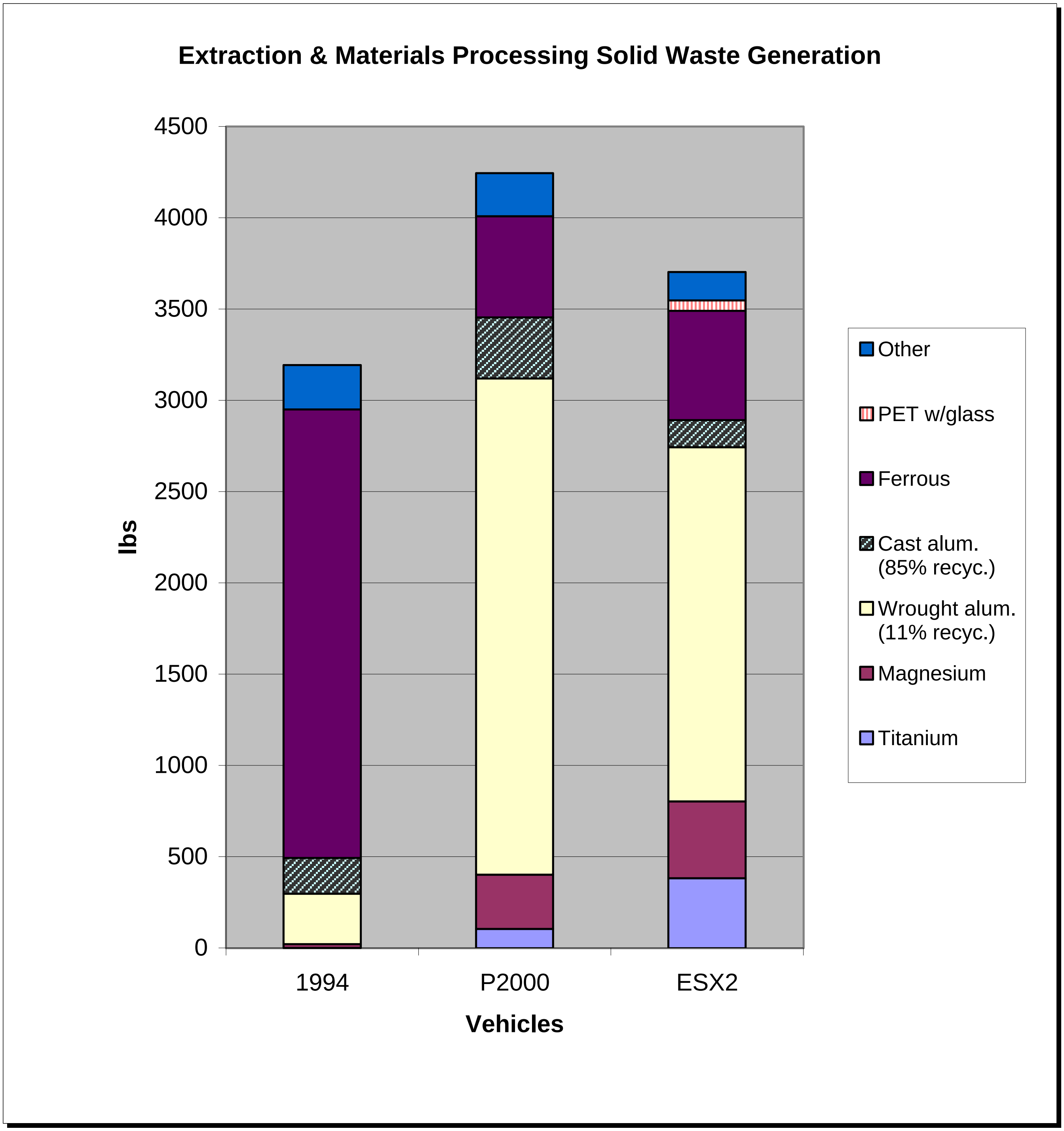
- MIC savings not shown due to scale of graph being inadequate to show manufacturing stage details (see below).
- Extraction and Materials Processing wastes include mineral wastes, mixed industrial wastes, slags and ash, inert chemicals and regulated chemicals.



- Note that ESX2's total solid waste generation in this life-cycle stage is reduced to below that of the 1994 vehicle when glass-reinforced PET is recycled.



- Vehicle manufacturing data scaled from conventional compact vehicle manufacturing data by total vehicle weight.
- Primary purpose of this graph is to show the savings obtained through MIC option.



- Other category includes plastics other than glass-reinforced PET, glass fiber, glass, lexan and carbon fiber.

# Life Cycle Air Emissions Data

MIC = Mold-in-color

| % primary - | wrought: | 89% |
|---|---|---|
| | cast: | 15% |
| Methane GWP = | | 24.5 |

**Extraction & Materials Processing**

| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
|---|---|---|---|---|
| | (all units are lbs) | | | |
| Particulates | 13.51713 | 49.408453 | 43.36886 | 43.3688602 |
| CO | 38.866465 | 12.442955 | 19.325197 | 19.3251973 |
| CO2 | 5567.9783 | 8610.0144 | 9310.0294 | 9310.02942 |
| NOX | 16.44068 | 41.780388 | 53.14062 | 53.14062 |
| Hydrocarbons | 3.6226436 | 5.9346519 | 17.954883 | 17.954883 |
| Methane | 6.3135029 | 24.484802 | 32.235901 | 32.2359009 |
| Methane (CO2 equiv.) | 155 | 600 | 790 | 790 |
| SF6 (CO2 equiv.) | 247 | 3,541 | 5,023 | 5023.30608 |
| CF4 (CO2 equiv.) | 248 | 1,708 | 1,178 | 1178.23 |
| C2F6 (CO2 equiv.) | 49 | 339 | 234 | 233.775 |
| PFC total (CO2 equiv.) | 298 | 2,047 | 1,412 | 1,412 |
| Total CO2 equiv. | 6,267 | 14,798 | 16,535 | 16,535 |

**Extraction & Materials Processing**

| Material | 1994 | P2000 | ESX2 |
|---|---|---|---|
| ***GWP values only!*** | | | |
| Titanium | 0 | 491.077305 | 1785.73566 |
| Magnesium | 353 | 5,053 | 7,168 |
| Wrought alun | 640.816259 | 6299.0865 | 4499.3475 |
| Cast alum. | 396.734193 | 676.195608 | 299.422409 |
| Ferrous | 3666.8251 | 828.756595 | 893.027515 |
| PET w/glass | 0 | 0 | 1021.36554 |
| Other | 1210.35154 | 1449.9431 | 868.516172 |
| Totals: | 6267.23699 | 14797.701 | 16535.1161 |

PFC contributions to aluminum production utilized in above calculations:

| | | | |
|---|---|---|---|
| Wrought: | 189.49 | 1862.6454 | 1330.461 |
| Cast: | 108.04 | 184.1445 | 81.54 |
| Totals: | 297.53 | 2046.7899 | 1412.001 |

**Manufacturing (Summary table)**

| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
|---|---|---|---|---|
| Particulates | 1.9380368 | 1.1993393 | 1.342544 | 1.06548752 |
| CO | 0.6149051 | 0.3805293 | 0.4259657 | 0.28833899 |
| CO2 | 3304.2304 | 2044.7977 | 2288.9527 | 1283.69291 |
| NOX | 7.7964565 | 4.8247776 | 5.4008704 | 2.99195731 |
| N2O (CO2 equiv.) | 6.8025305 | 4.209694 | 4.7123441 | 2.55743544 |
| Methane | | | | |
| Methane (CO2 equiv.) | 2.2599065 | 1.3985259 | 1.565514 | 1.29682247 |
| SF6 (CO2 equiv.) | 675.1386 | 9676.9866 | 13727.818 | 13727.8182 |
| Total CO2 equiv. | 3988.4314 | 11727.393 | 16023.049 | 15015.3654 |

**Extraction & Materials Processing**

| Material | 1994 | P2000 | ESX2 |
|---|---|---|---|
| ***Particulate values only!*** | | | |
| Titanium | 0 | 1.32024816 | 4.8009024 |
| Magnesium | 0.26543439 | 3.80455962 | 5.39716597 |
| Wrought alun | 4.00198704 | 39.3386811 | 28.099058 |
| Cast alum. | 0.70788616 | 1.20652295 | 0.5342537 |
| Ferrous | 6.58878022 | 1.48916158 | 1.60464758 |
| PET w/glass | 0 | 0 | 1.59173928 |
| Other | 1.95304233 | 2.24927932 | 1.34109327 |
| Totals: | 13.5171301 | 49.4084528 | 43.3688602 |

| | **Use/Fuel Use** | | | | **Use/Fuel Generation** | | | |
|---|---|---|---|---|---|---|---|---|
| | 1994 | P2000 | ESX2 | ESX2 (MIC) | 1994 | P2000 | ESX2 | ESX2 (MIC) |
| Particulates | 5.5566 | 11.3778 | 11.3778 | 11.3778 | 8.95468987 | 3.80737589 | 3.80737589 | 3.80737589 |
| CO | 136.7982 | 81.27 | 81.27 | 81.27 | 7.36123498 | 3.12986703 | 3.12986703 | 3.12986703 |
| CO2 | 95225.042 | 28281.96 | 28281.96 | 28281.96 | 13756.752 | 5849.12783 | 5849.12783 | 5849.12783 |
| NOX | 22.491 | 97.524 | 97.524 | 97.524 | 76.5265148 | 32.5377217 | 32.5377217 | 32.5377217 |
| Hydrocarbons | 16.9344 | 34.1334 | 34.1334 | 34.1334 | 0 | 0 | 0 | 0 |
| Methane | 3.4398 | 1.6254 | 1.6254 | 1.6254 | 23.7126276 | 10.0821902 | 10.0821902 | 10.0821902 |
| Methane (CO2 equiv.) | 84.2751 | 39.8223 | 39.8223 | 39.8223 | 580.959377 | 247.013661 | 247.013661 | 247.013661 |
| Total CO2 equiv. | 95,309 | 28,322 | 28,322 | 28,322 | 14,338 | 6,096 | 6,096 | 6,096 |
| | | | | CO2 total: | 108,982 | 34,131 | 34,131 | 34,131 |
| | | | | CH4 total: | 665.234477 | 286.835961 | 286.835961 | 286.835961 |
| | | | | | 109,647 | 34,418 | 34,418 | 34,418 |

**Total Lifetime Air Emissions**

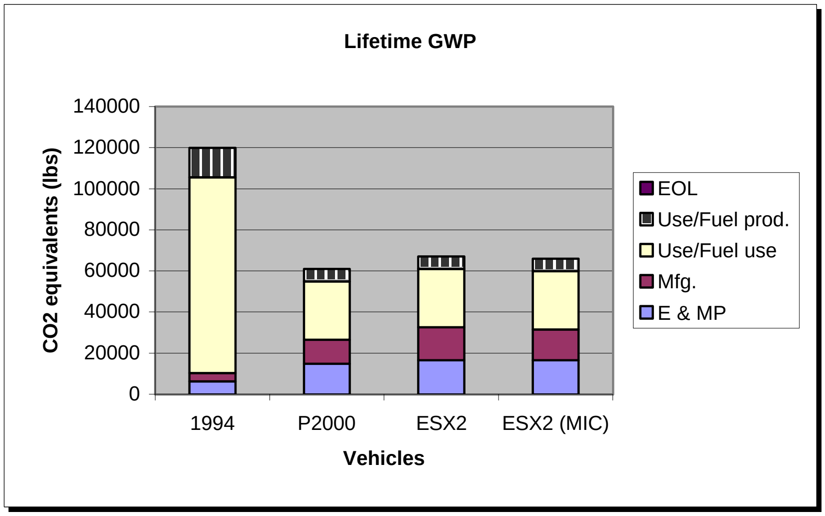
| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
|---|---|---|---|---|
| Particulates | 29.966457 | 65.792968 | 59.89658 | 59.6195236 |
| CO | 183.64081 | 97.223351 | 104.15103 | 104.013403 |
| NOX | 123.25465 | 176.66689 | 188.60321 | 186.194299 |
| Total CO2 equiv. | 119,903 | 60,943 | 66,976 | 65,968 |

| | Manufacturing (Main table) | | | |
|---|---|---|---|---|
| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
| Particulates | 1.1071731 | 0.6851656 | 0.7669764 | 0.75312134 |
| Particulates-EG | 0.8308638 | 0.5141737 | 0.5755676 | 0.31236618 |
| CO | 0.2576337 | 0.1594346 | 0.1784716 | 0.15402154 |
| CO-EG | 0.3572714 | 0.2210947 | 0.2474941 | 0.13431746 |
| NOX | 0.5596331 | 0.3463247 | 0.3876769 | 0.27124791 |
| NOX-EG | 7.2368234 | 4.4784529 | 5.0131935 | 2.7207094 |
| CO2 | 571.91205 | 353.9234 | 396.18291 | 256.468143 |
| CO2-EG | 2732.3183 | 1690.8743 | 1892.7698 | 1027.22476 |
| Methane (CO2E) | 1.6832931 | 1.0416931 | 1.1660743 | 1.08004263 |
| Methane-EG (CO2E) | 0.5766134 | 0.3568328 | 0.3994397 | 0.21677985 |
| SF6 (CO2E) | 675.1386 | 9676.9866 | 13727.818 | 13727.8182 |
| SF6-EG (CO2E) | 0 | 0 | 0 | 0 |
| N2O (CO2E) | 0 | 0 | 0 | 0 |
| N2O-EG (CO2E) | 6.8025305 | 4.209694 | 4.7123441 | 2.55743544 |
| Tot. CO2 equiv. | 1248.7339 | 10031.952 | 14125.167 | 13985.3664 |
| Tot. CO2 equiv-EG | 2739.6975 | 1695.4409 | 1897.8816 | 1029.99898 |

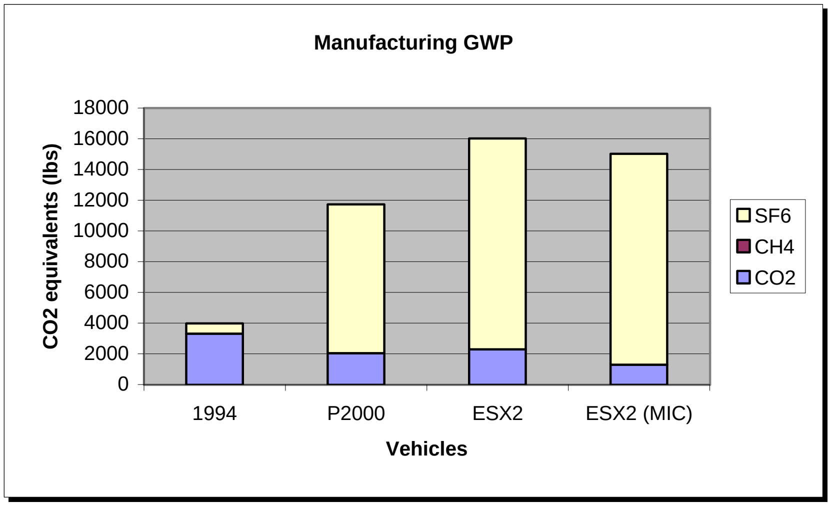
EG --> Electricity Generation

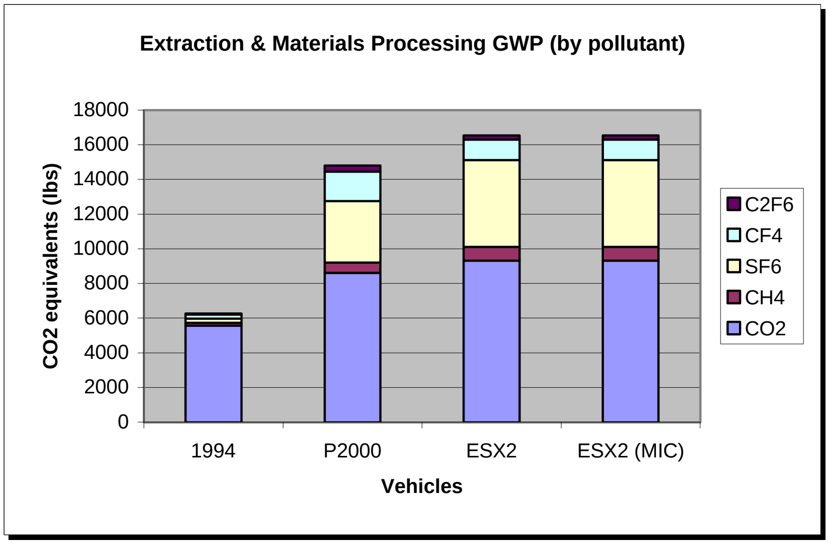
CO2E --> CO2 equivalents

| | End-of-Life | | | |
|---|---|---|---|---|
| | 1994 | P2000 | ESX2 | ESX2 (MIC) |
| Particulates-Elec. Gen. | 0.0133556 | 0.008265 | 0.0092519 | 0.00925186 |
| CO-Elec. Gen. | 0.0057429 | 0.0035539 | 0.0039783 | 0.0039783 |
| NOX-Elec. Gen. | 0.116327 | 0.0719881 | 0.0805837 | 0.08058367 |
| CO2 equiv-Elec. Gen. | 44.041316 | 27.254632 | 30.508917 | 30.5089169 |

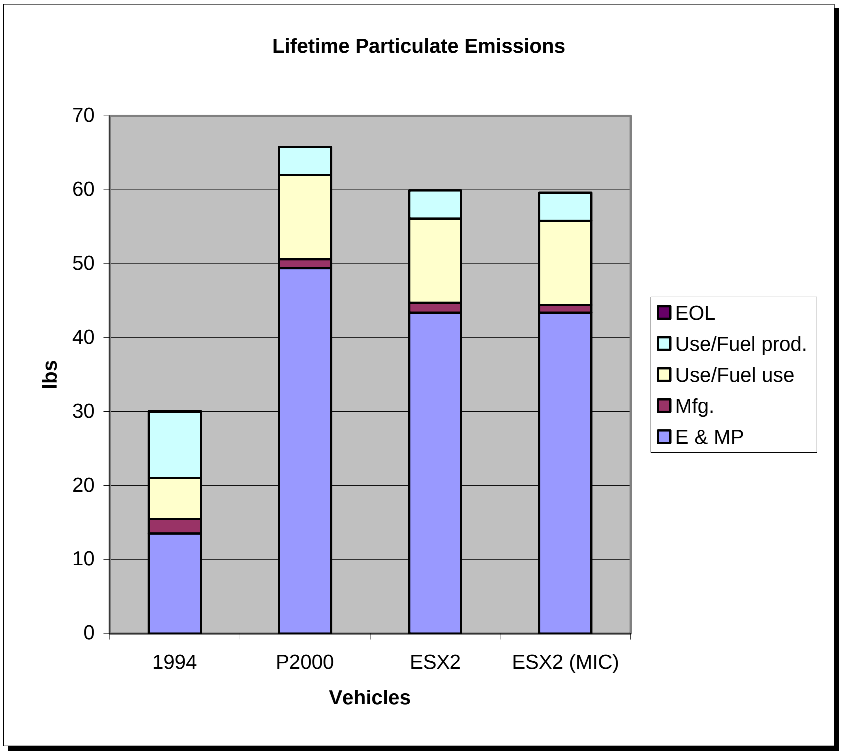


- Fuel use savings are partially offset by Materials Processing global warming emissions.



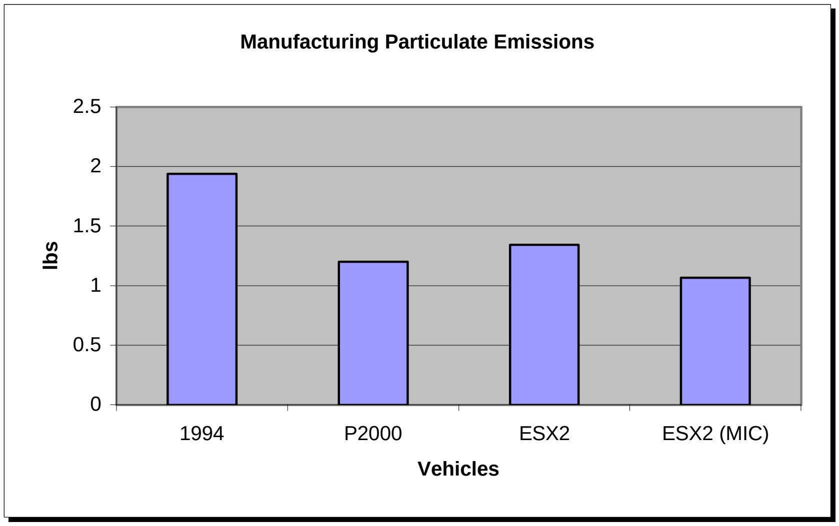


- CO2 and SF6 predominate.

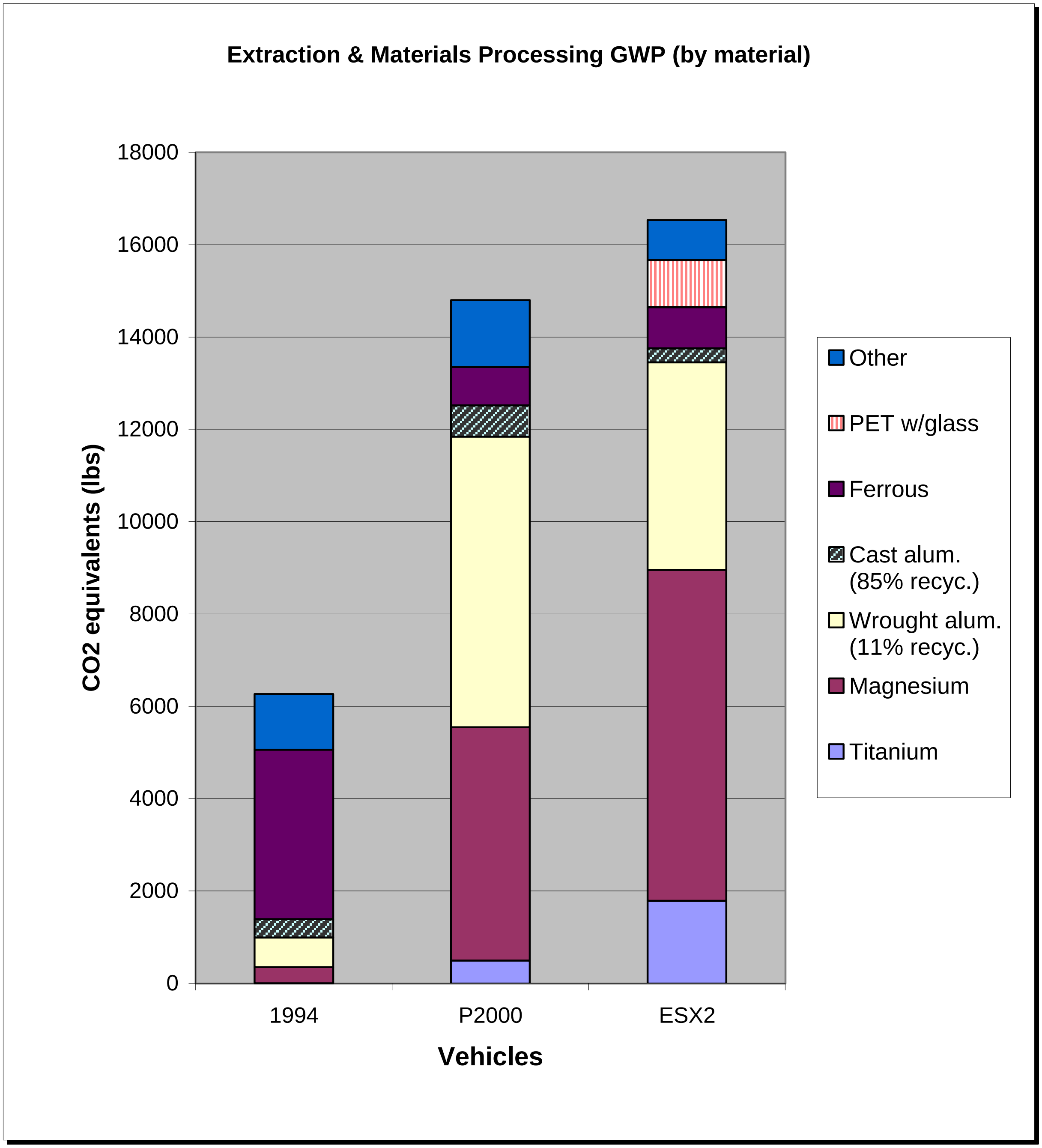


- Slight increase in particulate emissions from fuel use can be seen in P2000 and ESX2 columns, as expected.

- Decrease in particulate emissions from fuel generation visible; from reduction in fuel needs over lifetime of vehicles.

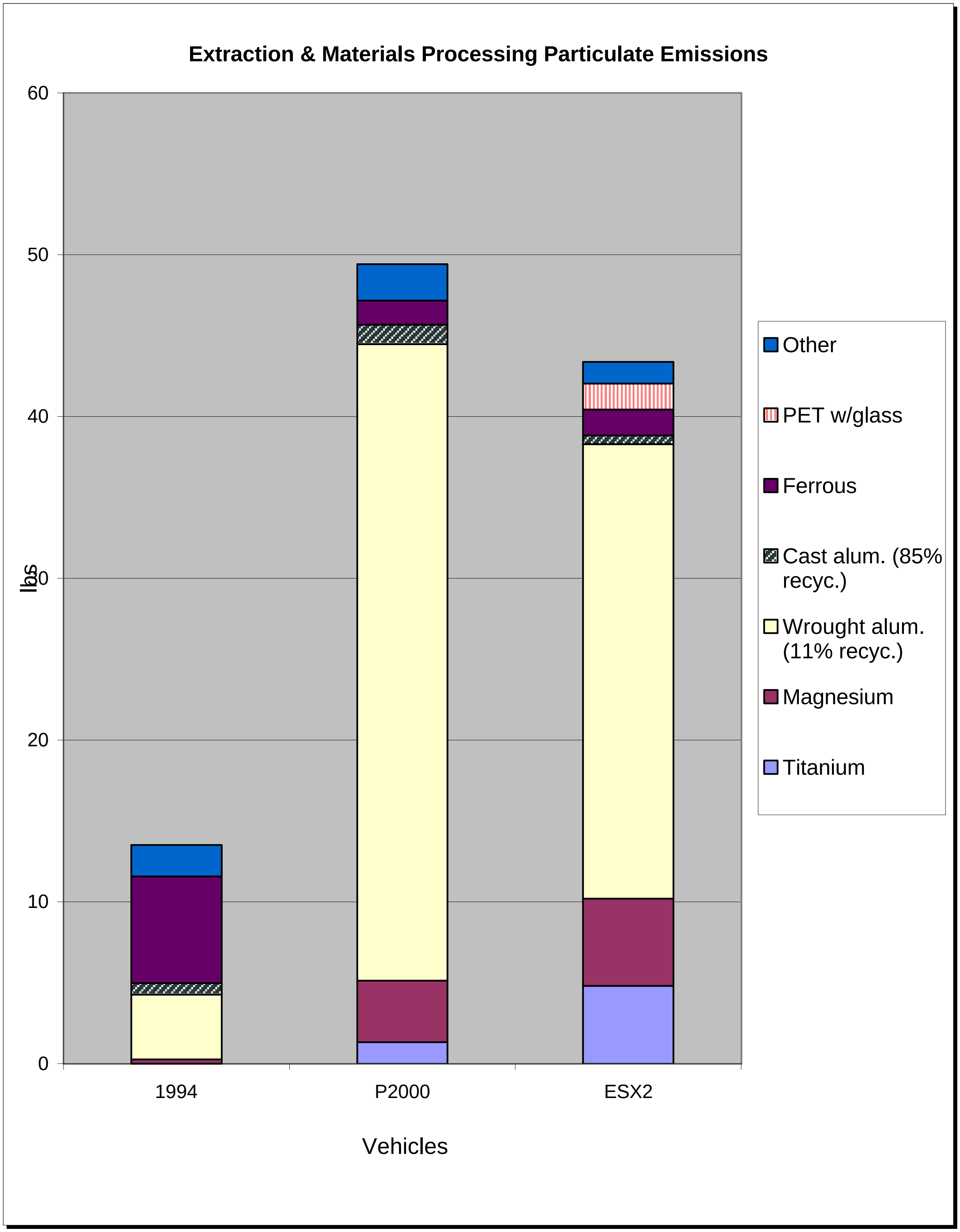


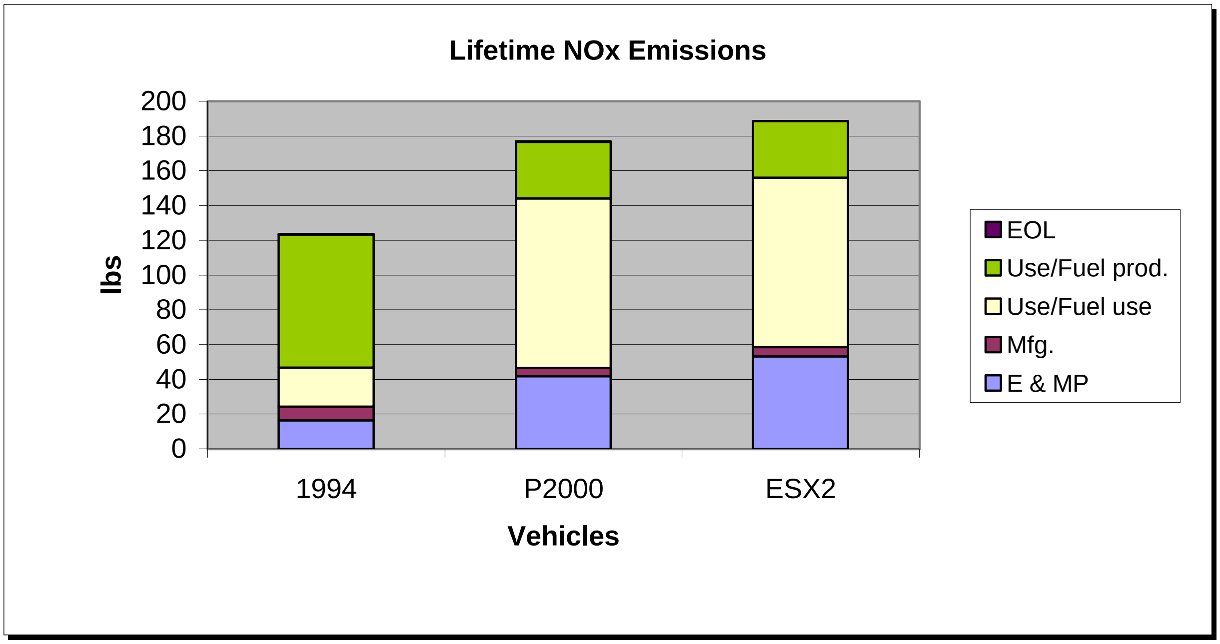
- Vehicle manufacturing data scaled from conventional compact vehicle manufacturing data by total vehicle weight.



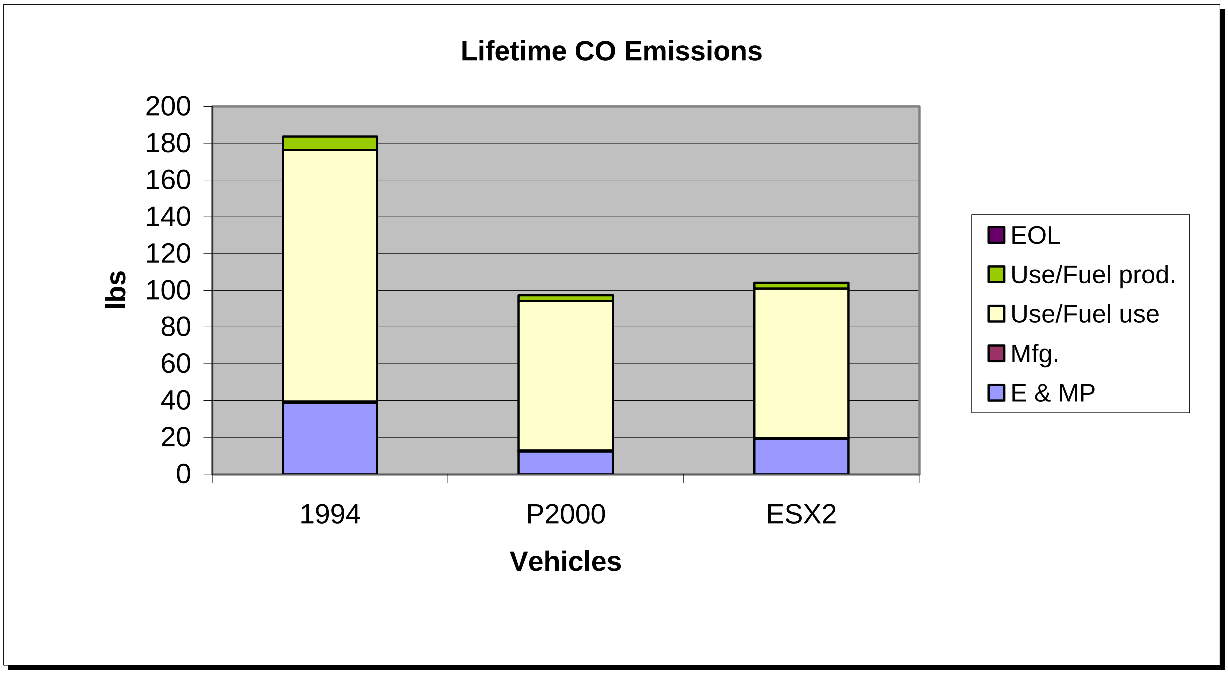
- Without magnesium-related global warming emissions, vehicles are very similar in GWP in Extraction and Materials Processing life cycle stage.

- 80% of magnesium-related emissions are from SF6.


Extraction & Materials Processing Particulate Emissions
60
50
40
30
20
10
0
lbs
1994
P2000
ESX2
Vehicles
Other
PET w/glass
Ferrous
Cast alum. (85% recyc.)
Wrought alum. (11% recyc.)
Magnesium
Titanium



- Consistent with the fact that diesel NOx emissions are significantly worse than gasoline NOx emissions.



**Appendix C**

## Lifetime Air Emissions Based on ANL Estimates

In this study, the Use-stage air emissions for NGVs have been estimated on the basis of emissions from a Volkswagen Passat diesel engine. However, another way of estimating them could be to assume that they are in conformance with future emissions standards. Researchers at Argonne National Laboratory (ANL) have come up with estimates of emissions based on an average of LEV and ULEV standards (which emphasize reduction of NOx and PM emissions), for both near-term and long-term baseline vehicles. The emission rates estimated by ANL for the DI Diesel Car (long term) are shown alongside the Passat-derived values in Table C-1 below:

**Table C-1. Use-Stage Emission Rates (grams/mile)**

| | ***Passat-derived Values*** | ***ANL estimates*** |
|---|---|---|
| $NO_x$ | .369 | .073 |
| PM | .043 | .010 |
| CO | .307 | 2.15 |

The ANL values have been taken and substituted for the original Passat-derived Use-stage emission values. Also, ANL estimates for emissions from fuel production (provided below in Table C-2) have been used in place of the previous values.

**Table C-2. Fuel Production Emissions Estimated by ANL**

| | ***Emissions* (g/mile)*** |
|---|---|
| $NO_x$ | .128 |
| PM | .013 |
| CO | .089 |

** Includes Feedstock and Fuel values*

As a result of these modifications, the lifetime NOx emissions for NGVs are now lower than the 1994 vehicle, instead of having gone up. Though the particulate emissions for NGVs are still higher than the 1994 vehicle, as in the earlier case, the total increase is lower than that associated with the Passat values.

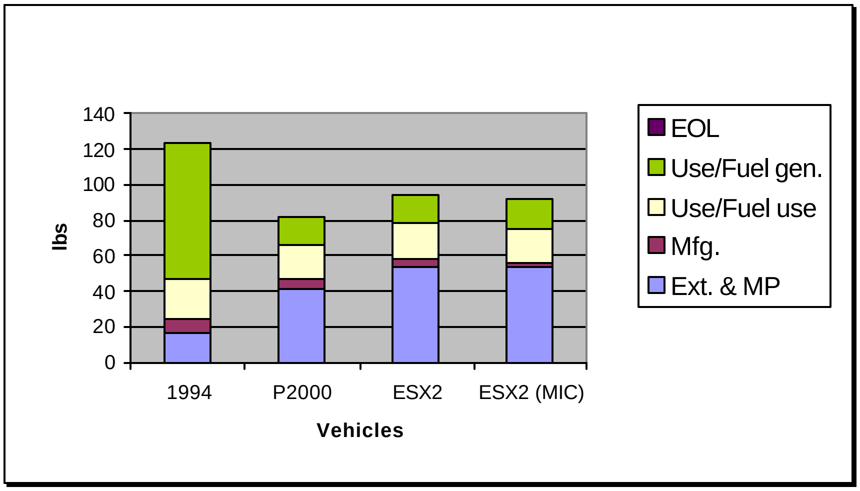


Figure C-1. Lifetime NOx Emissions using ANL Estimates

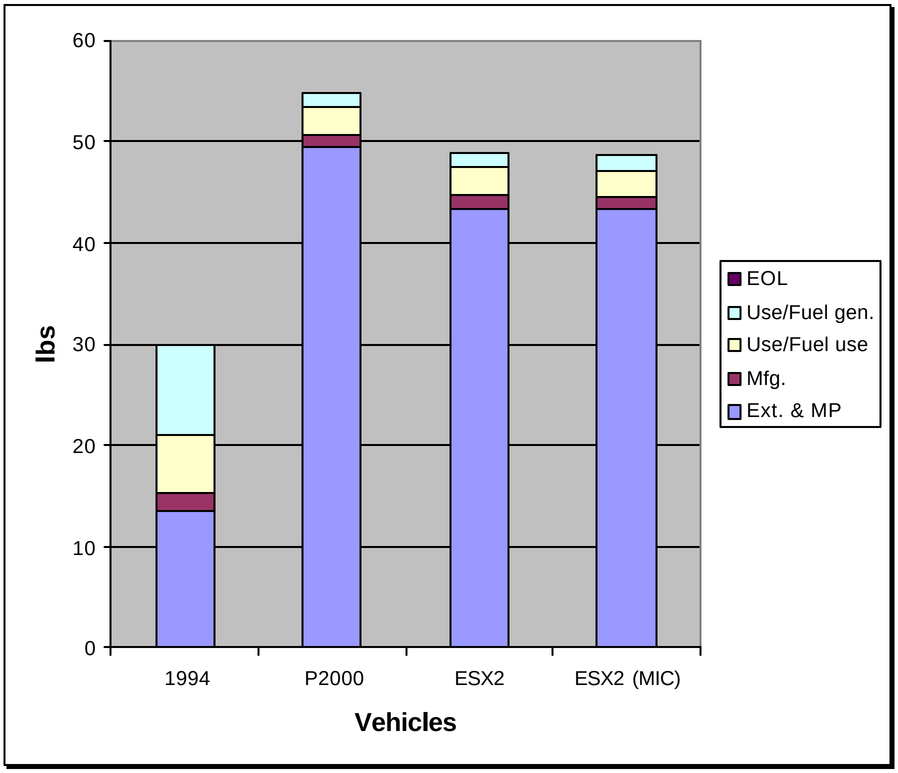


Figure C-2. Lifetime PM Emissions using ANL Estimates

The carbon monoxide emissions, however, go up considerably. The reason for this increase is that standards that emphasize NOx and PM reduction are now being used in place of the actual 1998 Passat data. It is believed that the actual CO emission values will be much lower than shown below for the NGVs.

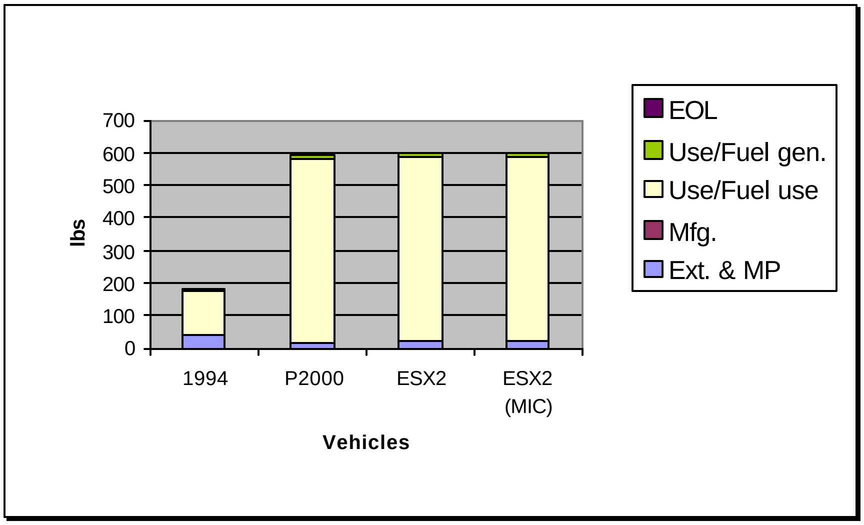


**Figure C-3. Lifetime CO Emissions using ANL Estimates**

## Rural/Urban Air Emissions Split

The lifetime air emissions arrived at using ANL estimates have been further split into rural and urban emissions (Table C-3), based on the following assumptions:

- Extraction and Materials Processing takes place predominantly in rural areas (emissions assumed to be 100% rural).
- Manufacturing takes place predominantly in urban areas (emissions assumed to be 100% urban).
- For the Use stage:
  - The air emissions from fuel use (driving the car) are 33% rural (highway driving) and 67% urban (city driving);
  - The air emissions from fuel production are 50% rural and 50% urban.
- For the End-of-Life stage, in which the only significant air emissions are from electricity generation, it is assumed that 50% are rural and 50% urban.

## Table C-3. Lifetime Air Emissions - Rural/Urban

| Emission Categories | 1994 | | | P2000 | | | ESX2 | | | ESX2 (MIC) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rural | Urban | Total | Rural | Urban | Total | Rural | Urban | Total | Rural | Urban | Total |
| Particulates | 19.85 | 10.13 | 29.98 | 51.09 | 3.76 | 54.85 | 45.05 | 3.91 | 48.96 | 45.05 | 3.63 | 48.68 |
| CO | 88.15 | 95.50 | 183.65 | 207.51 | 385.11 | 592.62 | 214.39 | 385.16 | 599.55 | 214.39 | 385.02 | 599.41 |
| NOx | 62.26 | 61.11 | 123.37 | 56.09 | 25.58 | 81.67 | 67.45 | 26.16 | 93.61 | 67.46 | 23.75 | 91.21 |
| Total CO2 equiv. | 45,225 | 74,722 | 119947 | 27,299 | 33,671 | 60970 | 29,038 | 37,969 | 67,007 | 29,038 | 36,961 | 65,999 |