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A Life-Cycle-Based Environmental Evaluation: Materials in New Generation Vehicles

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ABSTRACT

This project team conducted a life-cycle-based environmental evaluation of new, lightweight materials (e.g., titanium, magnesium) used in two concept 3XVs -- i.e., automobiles that are three times more fuel efficient than today's automobiles -- that are being designed and developed in support of the Partnership for a New Generation of Vehicles (PNGV) program. The two concept vehicles studied were the DaimlerChrysler ESX2 and the Ford P2000. Data for this research were drawn from a wide range of sources, including: the two automobile manufacturers; automobile industry reports; government and proprietary databases; past life-cycle assessments; interviews with industry experts; and models.

The major findings of this materials research project were:

- 3XVs are predicted to yield significant overall reductions in carbon monoxide and greenhouse gases, although emissions of sulfur hexafluoride (SF_6) and two perfluorocarbons (CF_4 and C_2F_6), gases with very high global warming potentials, will increase because of their current use in the production of magnesium and aluminum, respectively;
- there will likely be increases in the emissions of NO_x and particulate matter due to the use of diesel engines in the 3XVs; however, it appears that it will be feasible for the 3XVs to meet proposed regulations for these pollutants through the use of pre- and post-combustion technologies;
- the lifetime energy consumption is reduced by over 50%, where the savings from fuel use easily overcome the increases noted in the extraction and materials processing life-cycle stage from the use of aluminum, magnesium, and titanium; and
- lifetime solid waste generation may increase slightly due to increased quantities of solid wastes generated during the extraction and materials processing of aluminum, magnesium, and titanium;

INTRODUCTION

A fair assessment of the environmental impacts associated with a new vehicle design can be made only if a life-cycle approach is adopted. 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.

PNGV is an initiative launched in 1993 involving the “Big 3" US automakers (General Motors, Ford and DaimlerChrysler), seven government agencies, and twenty national research laboratories [1]. 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 Oak Ridge National Laboratory (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 (3XVs). These include possible infrastructural impacts, environmental impacts, and market acceptance issues. This life-cycle-based environmental assessment, conducted by the University of Tennessee Center for Clean Products and Clean Technologies (CCPCT), forms a part of the ORNL research.

GOAL AND SCOPE OF THE STUDY

The *goal* of the study was 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 was the baseline vehicle for the study. The two vehicles of the future that were evaluated are the aluminum-intensive Ford P2000 and the plastic composite-intensive DaimlerChrysler ESX2. Both these vehicles strive to meet the goals set by the PNGV. The 1994 *baseline* vehicle was a passenger car in the same class as the Ford Taurus, Chevrolet Lumina, Dodge Intrepid, and DaimlerChrysler Concorde.

The *functional unit* for the purpose of this study was 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, and the fact that the automobile is a complex product containing on the order of several thousand parts, 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.

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

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

<u>Manufacturing</u> – Production of automobile parts and assemblies by manufacturers and their suppliers; assembly of automobiles by automakers.

<u>Use</u> – 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.

<u>End-of-Life</u> – 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.

MATERIAL COMPOSITION SCENARIOS – In order to meet the PNGV goals, it is necessary to develop new lightweight materials for use in 3XVs, 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 in Table 1.

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 3XVs use more of the relatively newer lightweight materials, titanium and magnesium.

METHODOLOGY AND ASSUMPTIONS

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

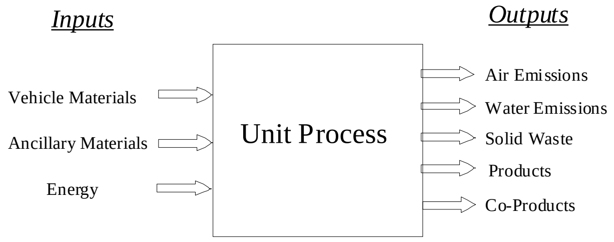

Figure 1. Typical Life-Cycle Inventory Data Categories

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 - PM, NO_x, CO, CO_2 and CH_4 - were included, mainly due to lack of information on other speciated pollutants for all the life-cycle stages. In addition, only those ancillary materials that had substantial environmental burdens were considered.

The major *assumptions* made were:

- 3XVs 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
- 3XVs 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 in each life-cycle stage, and not relegated to one particular “transportation” life-cycle stage (as done in some LCAs).

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.

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.

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 3XV 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).

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.

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 3XVs and 26.6 MPG for the 1994 vehicle. Though the PNGV goal for 3XVs is 80 MPG, it was considered 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 3XVs. However, the 3XVs 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.

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.

RESULTS

The following three sub-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.

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 3XVs 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 3XVs as compared to the 1994 vehicle, this increase only increases total 3XV lifetime energy consumption by 5%.

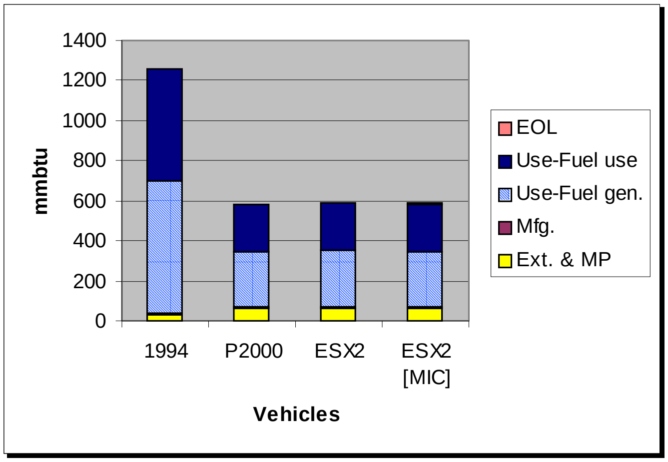

Figure 2. Lifetime Energy Consumption

The savings realized in this impact category can be almost completely attributed to the higher fuel efficiency of 70 MPG for the 3XVs in the Use stage, which the prototype version of the ESX2 has supposedly already achieved. When the 3XVs 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.

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 3XV 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.

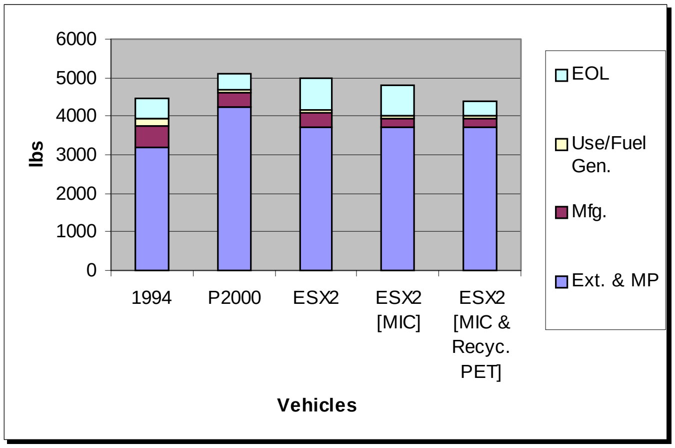

Figure 3. Lifetime Solid waste Generation

Thus, it appears that there is definitely room for improvement in the solid waste generation impact category, and that research 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.

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 3XVs 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 3XVs.

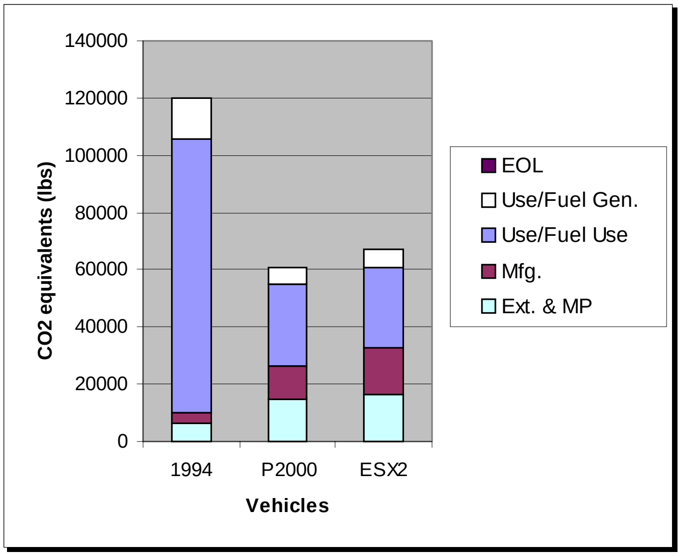

Figure 4. Lifetime Global Warming Potential

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 3XVs by an average 110% as compared to the 1994 vehicle.

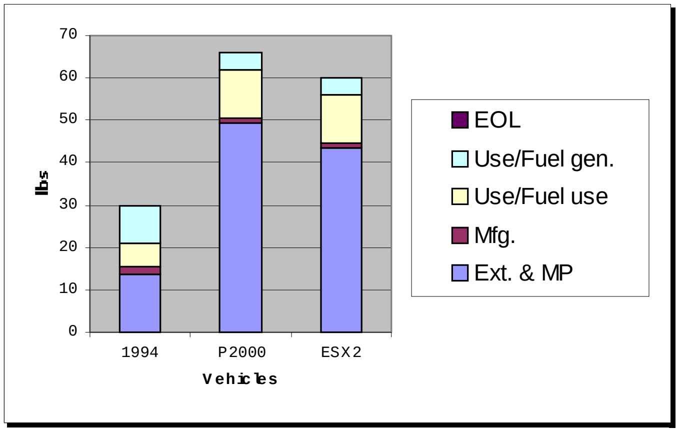

Figure 5. Lifetime Particulate Emissions

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 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 3XVs, 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 3XVs. 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 3XVs.

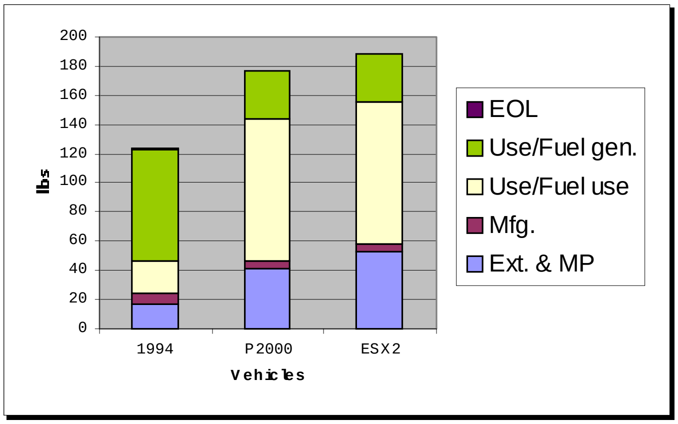

Figure 6. Lifetime NO_x Emissions

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 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.

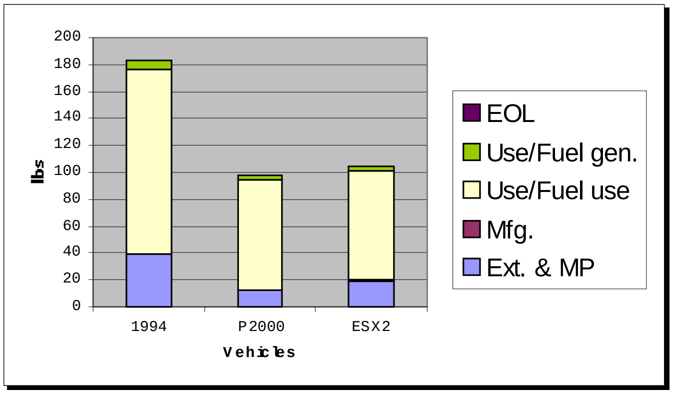

Figure 7. Lifetime CO Emissions

MANUFACTURERS' DIESEL EMISSION GOALS

"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 among 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.

Some examples of multiple opportunities that exist to reduce diesel NO_x and PM emissions include:

- The use of a Direct Injection, Aluminum, Through-bolt Assembly (DIATA) engine (planned for the P2000);
- The use of sulfur-free diesel fuel;
- Exhaust Gas Recirculation (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 3 compares the Use-stage emissions values actually used in this study to those considered achievable (obtained from ORNL).

Table 3. Reduced NO_x and PM emissions (g/mile)

	Used in Study	***Achievable (New)***
NO_x	.369	.030
PM	.043	.010

It is observed from Figure 8 that lifetime PM emissions are somewhat reduced by using the new values. However, the emissions still remain much higher for the 3XVs than those associated with the 1994 vehicle, due to Extraction and Materials Processing being the dominant life-cycle stage for PM emissions.

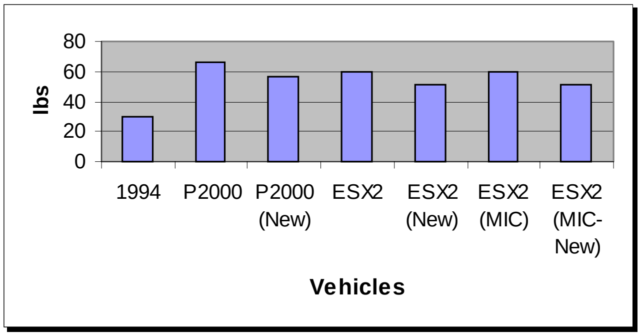

Figure 8. Particulate Emissions Comparison

In the case of NO_x emissions, on the other hand, substantial improvements are seen for the 3XVs 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.

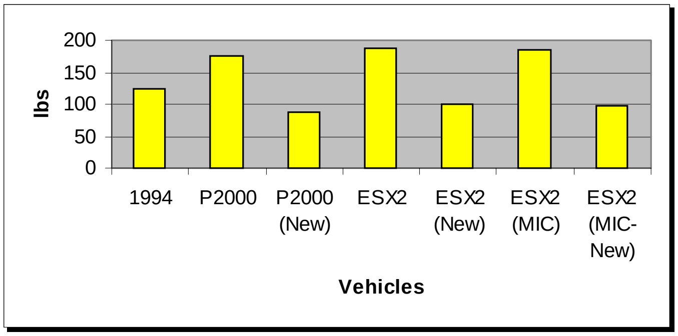

Figure 9. NO_x Emissions Comparison

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 3XVs, 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 3XV 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 3XVs 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 3XVs in becoming less environmentally burdensome in all aspects of their life cycle. There are many ways to improve the environmental footprint of the 3XVs, 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 3XVs 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 3XVs 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 3XVs.

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 3XVs 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 3XVs 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.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

3XV: New generation vehicle, 3 times more fuel-efficient than the average vehicle of today
ASR: Automobile Shredder Residue
C_2F_6: Perfluoroethane
CCPCT: 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
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
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