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**Supporting Infrastructure and
Acceptability Issues for Materials
Used in New Generation Vehicles**

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ENERGY DIVISION

**SUPPORTING INFRASTRUCTURE AND ACCEPTABILITY
ISSUES FOR MATERIALS USED IN
NEW GENERATION VEHICLES**

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TABLE OF CONTENTS

ABSTRACT	xi
1. INTRODUCTION	1
1.1 Scenarios	2
1.2 Introduction to the Analysis	5
2. MODELING 3X VEHICLES MATERIALS SUPPLY TRANSITIONAL ISSUES	7
2.1 Introduction	7
2.2 Materials Production Transitional Issues	7
2.3 Modeling the Transitional Path for 3X Vehicle Materials Production and Use	9
2.4 Factors Determining New Material Penetration	9
2.4.1 Demand for 3X Vehicles	10
2.4.2 Fixed and Variable Materials Production Costs, Scale Economies	10
2.4.3 Learning-by-Doing	11
2.5 Result Available from Analysis	14
2.6 Outstanding Issues to Address and Next Steps	15
3. ESTIMATING THE INDIRECT ECONOMIC IMPACTS OF 3X VEHICLE DEVELOPMENT	17
3.1 Introduction: The Input-Out Representation of the U.S. Production Sector	17
3.2 The Input-Output Representation of the Production Technology of 3X Vehicles	20
3.2.1 The Representation of Industrial Structure by the Make and Use Coefficients	21
3.2.2 The 3X Vehicle Technologies Added to the Input-Output Matrix	22
3.2.3 Method of Analysis	23
3.2.3.1 3X vehicle production formulated as additional industrial process	25
3.2.3.2 Capturing the primary automotive production technology	26
3.2.3.3 The baseline scenario	27
3.3 Results	29
3.3.1 Overview of Macro-economic Impacts	29
3.3.2 Industry Impacts	30
3.3.2.1 Industries with negative impacts	31

3.3.2.2	The composite 3X vehicle spurs growth in several materials-related industries	31
3.3.2.3	The aluminum 3X vehicle provides growth impetus to different set of industries	31
3.3.3	Summary.	33
3.4	Cautions, Caveats, Further Research	34
3.4.1	Cautions	34
3.4.2	Caveats	34
3.4.3	Further Research Issues Related to Infrastructure Development	35
4.	3X VEHICLES AND AUTOMOBILE RECYCLING	37
4.1	Recycling Infrastructure	37
4.2	Recycling Infrastructure Model	40
4.3	Results	41
4.3.1	Base Case	41
4.3.2	Aluminum	42
4.3.3	Composites	48
4.4	Conclusions	50
5.	PNGV INFRASTRUCTURE AND MARKET ACCEPTABILITY ISSUES	53
5.1	Introduction	53
5.2	Physical Infrastructure	53
5.2.1	Fueling	53
5.2.2	Constraints on Driving	55
5.3	Social and Institutional Infrastructure	55
5.3.1	Relationship of Vehicle Construction to Insurance Costs	55
5.3.2	Maintenance and Service	56
5.3.3	Training, Certification, and Licensing	57
5.3.4	Uniformity of Standards	58
5.4	Market Acceptance	58
5.4.1	Safety	58
5.4.2	Performance Uncertainties	60
5.4.3	Comfort, Accommodating Consumer Expectations, Costs	60
5.4.4	Market Niches	61
5.5	Summary	62

6.	CONCLUSIONS	65
7.	REFERENCES	69

LIST OF TABLES

1-1. Vehicle Mass Reduction Targets for 3X Vehicles	2
1-2. Material Composition Scenarios for PNGV Infrastructure: Maximum Substitution of Individual Materials	3
1-3. Lightweight Material Requirements, Given Maximum Potential Substitution for 3X Vehicles, 2007-2030	5
2-1. Empirical Evidence on Rates of Learning-by-Doing	13
3-1. Expected Major Changes at Various Production Life-cycle Stages	24
3-2. Use Matrix Adjustment Coefficients	25
3-3. New Industrial Complexes Are Added to the Input-output Model to Capture 3X Production	27
3-4. Direct and Indirect Impacts from an Increase of \$1 in Automobile Production	28
3-5. Economic Projections of Motor Vehicle Demand	28
3-6. Summary of Macro-economic Impacts in 2030	29
3-7. Comparison of 3X Vehicle Scenario Differences in 2030	30
3-8. I-O Industries with 2% or Greater Change in Output due to 3X Vehicle Penetration	30
3-9. Industries Adversely Affected by a 3X Vehicle Scenario	31
3-10. Industries That Experience $\geq$ \$1,000 Gains Under the Composite Scenario	32
3-11. Industries That Experience $\geq$ \$1,000 Gains Under the Aluminum Scenario	32
3-12. Industrial Impacts by Materials Life-cycle Stage	33
4-1. Current Composition of an Average Automobile along with Material Recovery/ Disposal Rates at Each Recycling State	38

LIST OF FIGURES

1-1. Projected 3X vehicles sales scenarios	4
2-1. Material supply and choice model, block diagram	10
2-2. Declining capital cost per vehicle as plant scale grows	11
2-3. Fixed variable cost per vehicle across plant scale	11
2-4. Declining total cost per vehicle for body production, as plant scales increases	12
2-5. 3X vehicle penetration depends on whether producers benefit from experiential learning and have accurate foresight	15
3-1. The circular flow of money	18
3-2. The social accounts matrix	19
3-3. Input-output model formulated with make and use tables	21
3-4. An input-output model modified to include 3X vehicle activities	22
4-1. A schematic representation of the current automobile recycling infrastructure	37
4-2. Cost structure of the automobile recycling industry	42
4-3. Substitution of ferrous with aluminum	43
4-4. Effect of aluminum-for-ferrous substitution and metal and scrap metal prices on profitability of the recycling industry	44
4-5. Effect of added time required for Al separation on profitability of dismantlers	45
4-6. Effect of additional investment requirements on profitability of Al separation for dismantlers	46
4-7. Effect of dismantling scenarios on profitability of Al separation for dismantlers	47
4-8. Profitability of Al separation by non-ferrous separators	47
4-9. Effect on additional investment on profitability of Al separation by non-ferrous separators	48
4-10. Substitution of ferrous with glass-reinforced composites	49
4-11. Shredder profitability vs landfill tipping fees	49

ABSTRACT

To achieve its goal of producing vehicles that use two thirds less fuel than current vehicles, the Partnership for a New Generation of Vehicles (PNGV) is designing vehicles that will use lightweight materials in place of heavier materials used in current vehicles. Using new materials in automobiles will require the development of a supporting infrastructure to produce both the substitute materials and the components of the substitute materials, as well as the automotive parts constructed from the new materials.

This report documents a set of analyses that attempt to identify potential barriers—economic, infrastructure, and public acceptance barriers—to the materials substitution in New Generation Vehicles. The analyses rely on hypothetical vehicle market penetration scenarios and material composition. The approach is comprehensive, examining issues ranging from materials availability to their eventual disposition and its effect on the automobile recycling industry, and from supporting industries' capacity to the public acceptability of these vehicles. The analyses focus on two likely substitute materials, aluminum and glass-reinforced polymer composites.

The second chapter of the report documents the development and testing of a model to identify infrastructure and cost barriers. Though the application of the model is only illustrative, with better empirical data and engineering cost estimates it shows promise. Its application at this point shows that under the right conditions—where learning occurs, foresight is accurate, and there is no risk premium—the transition to new materials can occur without great difficulty.

The application of an input-output model—the subject of the report's third chapter—finds that from a macro economic perspective impacts will be small. It finds that the decline in the steel industry will be less than 3%, and that only a few industries will experience growth greater than 2% above base production. It predicts a 7% growth in the plastics industry under the composites scenario and 33% and 17% growth in the aluminum and secondary non-ferrous metals industries, respectively, under the aluminum scenario.

The fourth chapter documents the analysis of the potential effects on the automobile recycling industry that finds that the substitution of aluminum could have a positive effect on the industry's profitability, but that dismantling must increase and cost-effective separation technologies must be developed to achieve this profitability. The cost of the disposal of shredder residue is the primary threat to the recycling industry's profitability under the composites scenario.

A qualitative exploration of public acceptability issues is the subject of the fifth chapter. Taking the perspective of potential customers, the chapter explores issues related to the physical, social and institutional elements, as well as safety issues, policy, market niches and consumer expectations. Safety concerns—whether based in perception or reality—are the most significant barrier in terms of market acceptance.

Together, the analyses found no single issue that is likely to prevent market penetration of New Generation Vehicles. However, some notable economic changes may occur, critical industries need to expand, and new technologies need to be developed and adopted to accommodate the transition to these new vehicles.

1. INTRODUCTION

The Partnership for a New Generation of Vehicles (PNGV) program is developing designs for new automobiles that will reduce fuel consumption by two thirds while maintaining price, comfort, safety, and performance comparable to vehicles currently on the market. To achieve this goal, the vehicle designs will substitute lightweight materials, e.g., aluminum and composites, for the heavier materials such as steel and iron that currently dominate the composition of automobile components. The target mass of a PNGV vehicle is 1,960 pounds, as compared to the average current vehicle that weighs 3,240 pounds. This weight reduction may be combined with other engineering changes and the use of ferrous alloys to achieve the targeted fuel consumption. Adopting these designs and materials would require the development of a supporting infrastructure to produce both the substitute materials and the components of the substitute materials, as well as the automotive parts constructed from the new materials.

The purpose of this report is to identify infrastructure and acceptability issues associated with the transitioning to these fuel efficient vehicles. Specifically, this report attempts to identify potential barriers—direct and indirect economic barriers as well as infrastructure and public acceptance barriers—to the materials substitution anticipated for these New Generation Vehicles (NGVs). In this report we refer to these vehicles as 3X vehicles, in light of their goal of improving vehicle's fuel efficiency by a factor of three.

The analyses in this report build upon and refine some components of the life cycle analysis conducted by ORNL in 1996 and 1997 (Das et al. 1997). The earlier analysis identified what might be required to supply and use the substitute materials at six stages of material usage.¹ The life-cycle stages are mining or extraction of resources; smelting or other processing; producing components from the material; assembling the components into vehicles; using, maintaining, and repairing vehicles; and disposing of the vehicle, including recycling of materials for automotive or other use. The analysis considered the adequacy of and potential changes in the mineral and material supply, capital and equipment, labor and employment, energy, material complements, and environmental emissions and impacts. The life-cycle analysis identified areas that might require the attention of the PNGV program if they are to occur as needed. It found that significant changes in the production structure, including the development of new technologies and significant capital expenditures, could be required. However, using a rather coarse analytical method applied to maximum substitution scenarios, the analysis concluded that over the period extending to 2030, the transition to PNGV vehicles might be accomplished smoothly.

The analyses reported here employ increased methodological rigor, with each analysis of economic barriers relying upon a specific model to assess the potential for transitional barriers to the adoption of 3X vehicles. This work is primarily an effort to explore these issues and to test a set of methods for analyzing them. As in the life-cycle analysis, the

¹Because data about the automobile manufacturing industry are restricted, details about this stage of manufacture are not included in the analyses.

analyses employ scenarios for material substitution because no PNGV design from which to do a formal cost estimation or market analysis was available. These scenarios are described in Section 1.1. An overview of the goals of each of the four analyses follows the description of the scenarios (Section 1.2). The specific methodologies, discussions, and conclusions of the analyses are provided in Chapters 2, 3, 4, 5, and 6.

1.1 Scenarios

The analyses in this report start with a set of scenarios developed in collaboration with Argonne National Laboratory that assume production of 3X vehicles (cars and light trucks) will begin in 2007 and gradually increase their share of the market over the following 25 years. Scenarios meet the program's assumptions about vehicle cost and performance. These scenarios contain estimates of quantities of materials used in new generation vehicles.

The PNGV has set a goal of reducing vehicle mass by 40% as part of its strategy to significantly improve fuel economy. Current vehicle weight averages 3,240 lbs.; the PNGV goal is a reduction in mass to about 1,960 lbs. As Table 1-1 shows, this goal implies targets for various vehicle subsystems. Most mass reductions are likely to come from the vehicle body and chassis. Weight savings of this magnitude could be achieved by some combination of material substitution, redesign of all major subsystems (body, power train, and chassis), and secondary weight savings (i.e., additional weight savings in subsystems that depend on the total vehicle weight).

Table 1-1. Vehicle Mass Reduction Targets for 3X Vehicles			
System	Current Vehicle (lbs.)	3X Vehicle Target (lbs.)	% Mass Reduction
Body	1,134	566	50
Chassis	1,101	550	50
Power train	868	781	10
Fuel/Other	137	63	55
Curb weight	3,240	1,960	40

The analyses presented here focus on the effects and acceptability of material substitution. The PNGV considered several lightweight materials to meet the mass reduction target. They include ultra light steel for auto bodies (ULSAB), glass-reinforced polymer composites (GRC), carbon-reinforced polymer composites (CRC), aluminum, and magnesium. Except for magnesium, all of these lightweight materials have potential applications in vehicle structures as well as chassis and power train components. At the time this study was initiated, the PNGV program had not yet narrowed its focus. We focused our analyses on two major classes of materials that have wider substitution possibilities: aluminum and glass-reinforced composites.

The scenarios for material substitution use a “parametric” or “what-if” approach. Each scenario starts with a current vehicle (“base vehicle”), comparable in performance to the 3X vehicle, and estimates the maximum extent to which a particular material—either aluminum or glass-reinforced composites—could replace the base vehicle’s ferrous content. The scenarios assume that non-ferrous material content (other than the particular replacement material) remains at current levels. The scenarios developed here thus estimate an upper bound for GRC and aluminum substitution and allow us to examine the maximum potential impact from these substitute materials. In reality, the 3X vehicle would contain a combination of these various lightweight materials, each material appropriate for specific vehicle subsystems. In addition, improved design and secondary weight reductions—factors not considered in the scenarios—would further reduce material requirements.

Table 1-2 shows the material composition of the base vehicle and the two 3X vehicles defined according to the maximum materials substitution scenarios. The term “plastics” in this table includes traditional and advanced polymer composites as well as conventional plastics. For the GRC scenario, 50% of the baseline vehicle’s steel content is replaced by glass-reinforced polymer composites. Composites weighing 653 lbs. replace 947 lbs. of steel, reducing the base vehicle weight by 294 lbs. The aluminum scenario assumes that 75% of current steel and cast iron content is replaced by aluminum, as aluminum can be used in applications beyond body structures, particularly for engines. The scenario would replace 818 lbs. of steel body structures in the base vehicle with 450 lbs. of wrought

Table 1-2. Material Composition Scenarios for PNGV Infrastructure: Maximum Substitution of Individual Materials (lbs.)			
Material	Base Vehicle	GRC	Aluminum
Carbon Steel	1,526	763 (-763)	382(-1144)
HS Steel	369	185 (-184)	92(-277)
Cast Iron	350	350	88(-262)
Cast aluminum	178	178	654(+476)
Wrought aluminum	52	52	502(+450)
Plastics	342	995(+653)	342
Magnesium	5	5	5
Other materials	418	418	418
Total (lbs)	3,240	2,946(-294)	2,483(-757)
Percentage reduction	-	9%	23%

Note: Bold numbers within parenthesis indicate changes in composition from the base vehicle

aluminum.² This scenario also assumes substitution of 476 lbs. of cast aluminum in other components, primarily in chassis and engine applications. Assuming that substituting aluminum for steel and cast iron results in weight savings of 45%, the scenario would reduce the weight of the base vehicle by 757 lbs.

As discussed earlier, we examine the infrastructure issues arising from 3X vehicles' maximum potential use of aluminum and glass-reinforced composites. These estimated amounts of aluminum or glass-reinforced composites required are based on the product of additional quantity of lightweight material required per vehicle (Table 1-2) multiplied by the number of 3X vehicles (cars and light trucks). The number of 3X vehicles are derived from projections of annual sales volume of new light duty vehicles and penetration rates of 3X vehicles. Projected 3X vehicle sales by year are provided in Figure 1-1.³ Two cases are presented, one where market penetration reaches 60% by 2030—the high case—and another where market penetration of 3X vehicles is 30%—the low case.

Source: Das et al. 1997

Figure 1-1. Projected 3X vehicle sales scenarios

Estimates of the total amount of aluminum and glass-reinforced composites required by 3X vehicles in different years are shown in Table 1-3. We have adjusted requirements for lightweight materials to account for likely fuel economy improvements in new vehicles (referred to as base vehicle here) in the absence of 3X vehicles. We assume an increase of 0.6% per year in fuel economy of the baseline vehicle during the PNGV penetration period

²Similar aluminum substitution (i.e., 437 lbs) for body structure and closures is currently being considered attainable for the Ford Taurus/Sable-based aluminum-intensive vehicle using the unibody structure (PNGV 1995).

³See Das et al. 1997 for additional detail about the projected vehicle sale scenarios used here.

(EIA 1996). Historical data suggest that a 0.2% annual reduction in the total vehicle weight correlates with a 0.6% per year increase in fuel economy (Curlee et al. 1994).⁴ Future reductions in total weight of the base vehicle are assumed to result from materials substitutions that maintain the current proportional use per vehicle of that material—aluminum, glass-reinforced composites, and magnesium. Increases in the contents of lightweight materials depend on the replacement factors for the substitution of lightweight materials for ferrous materials, which are provided in Das et al. 1997. It is estimated that the base vehicle in 2030 will contain about 634 lbs. less ferrous materials, but 149 lbs. and 259 lbs. more of aluminum and plastics, respectively.

Table 1-3. Lightweight Material Requirements: Maximum Potential Substitution for 3X Vehicles, 2007-2030 (figures in 1000 metric tons)*						
MATERIAL	2007	2010	2015	2020	2025	2030
Cast aluminum	0–3	0–34	57–303	162–981	434–1784	1021–2043
Wrought aluminum	0–3	0–34	49–317	173–1053	479–1967	1160–2321
Glass-reinforced polymer composites	0–4	0–42	69–368	189–1148	487–1999	1092–2184

* Lower- and upper-end values correspond to the low and high penetration rates of 3X vehicles.
Note: Changes in material requirements are relative to the base vehicle demand.

Table 1-3 reports the estimates of material requirements in the form of a range. The lower- and upper-end values correspond to the low and high penetration rates of 3X vehicles (Figure 1.1). During the early years of PNGV, the lightweight material requirements are low because of the low penetration rates assumed for 3X vehicles in the automobile market. Lightweight material requirements are highest for glass-reinforced composites during most of the period—reaching a level of more than 2 million metric tons per year by the year 2030. Although the baseline vehicle and 3X vehicles in the aluminum scenario both have more cast aluminum than wrought aluminum, the increase above baseline for cast aluminum is 267%, while for wrought aluminum it is 865% (see Table 1-2). This comparatively large increase in wrought aluminum explains why the estimated PNGV requirements for wrought aluminum are higher than for cast aluminum (see Table 1-3).

1.2 Introduction to the Analyses

Each chapter of this report addresses a particular question related to the transition to 3X vehicles, developing and/or testing a model to address the issue. This section provides a general introduction to the analyses addressing these questions.

⁴Data for the period 1976-1993 indicate that there has been almost 52% improvement in the fleet fuel economy (16.1 mpg to 24.5 mpg) with a 17% reduction in the average weight of U.S.-built 3761 lbs to 3124 lbs) (Curlee et al. 1994).

In Chapter 2, we address technology acceptance and cost barriers related to transitioning to 3X vehicle materials. The study demonstrates an approach for modeling transitional barriers to new technology introduction. It investigates the effect of scale economies, foresight, and learning by doing. The model used looks for the least-cost solution to producing 3X vehicle materials over a multi-year time horizon.

The direct and indirect economic output and employment impacts that are likely to result from the transitioning to 3X vehicles are addressed in Chapter 3. The study uses an input-output model of the U.S. economy, focusing on the first four stages of the material's life cycle. The model addresses the direct financial transactions among the entities involved in the new material's production, as well as the indirect and induced impacts that follow from the initial payments, employing a round-by-round method to capture the ripple effects.

The fourth chapter is concerned with the last stage of the material's life cycle—the disposition of the product, particularly the recycling of the material for automotive or other use. We have developed a model of the current automobile recycling industry to assess and quantify potential impacts of the shift to aluminum or glass-reinforced composites. The model compares the baseline profitability of the three components of the automobile recycling industry—dismantlers, shredders, and non-ferrous separators—to the profitability they would experience given introduction of 3X vehicles that are either aluminum or glass-reinforced composite intensive.

Chapter 5 addresses the issue of consumer acceptance on 3X vehicles. The issues explored in this section relate to the deployment of new vehicle technologies, of which 3X vehicles are one type. From the perspective of potential consumers, the chapter focuses on potential barriers to market success. Using existing literature and interviews with automobile dealers, maintenance professionals, and other experts, we examine both infrastructure and market acceptability issues. Infrastructure issues include physical, social, and institutional elements, while market acceptance involves safety, policy consistency, market niches, and the accommodation of consumers' expectations.

The last chapter discusses the implications of the findings of the separate chapters as they relate to each other, as well as exploring the next possible steps in the analyses.

2. MODELING 3X VEHICLE MATERIALS SUPPLY TRANSITIONAL ISSUES

2.1 Introduction

This study demonstrates an approach for modeling and evaluating transitional issues in the introduction of New Generation Vehicle materials technologies. The focus is on possible transitional barriers to the production of 3X vehicle bodies from new or specialized materials, although the approach could be extended to other aspects of the PNGV and competing vehicle technologies. The model looks for the competitive market outcome, or least-cost solution, for 3X vehicle materials production over a multi-year time horizon.

To characterize the transitional cost and infrastructure-adjustment phenomena, we need a model which is both dynamic and capable of dealing with the “self-reinforcing” nature of many technologies. A dynamic model is one which not only describes outcomes over many years, but also accounts for the connections between early decisions and later outcomes, constraints on adjustment over time, and provides a means of explicitly controlling the assumed degree of foresight that decision-makers have when making long-lived investment decisions. A “self-reinforcing” system is one in which the attractiveness of a technology increases with its scale or breadth of application, with the availability of compatible equipment or infrastructure, and with accumulated learning experience and consumer familiarity (e.g., Arthur et al. 1987, Arthur 1989, 1990). Self-reinforcing systems appear to be increasingly common among competing technologies. Their existence can lead to path-dependent outcomes and to transitional cost barriers in the sense that whichever technology is entrenched early can deter or even “lock-out” its competitors.

In this study we do not consider a particularly large magnitude of capital investment or a particularly large quantity of materials production to be a transitional barrier *per se*. Rather, we ask whether there are economic considerations which may deter private agents from taking the early actions and making the initial investments that are necessary for certain materials to achieve their full potential in 3X vehicle applications. A framework for the identification of such “transitional cost barriers” may also indicate whether and which government policies may be suited to promote the transition to preferred technologies.

2.2 Materials Production Transitional Issues

For any evolving industry, we can subdivide the transitional barriers which may slow the penetration of new technologies, into physical barriers and cost barriers. Physical barriers are natural limits on the expansion and adjustment rates of new industries:

- Slow turnover of necessary productive capital equipment (e.g., slow turnover of both the vehicle fleet and the vehicle manufacturers’ productive plants);
- Limits on the rates at which the production of the new goods/materials can expand, due to constraints on raw materials supply, scarce trained labor, or the limited

availability of investment capital (due to capital market imperfections or the riskiness of the new technology).

True physical barriers rarely occur. Rather, what is described as a physical barrier is ordinarily a reflection of the much higher costs of rapid adjustment, and can often be better represented that way.⁵ In our modeling study we include a normal scrappage rate for vehicle production equipment, but do not posit any specific limits to the supply of raw materials or the rates of new investment. Rather, we focus on transitional *cost* barriers.

Transitional cost barriers are high initial costs which may be overcome if certain actions are taken. Examples include:

- Initial high costs due to the need for technical progress through R&D;
- Initial high perceived costs due to lack of familiarity (to consumers of the material or product);
- Initial high “effective consumer costs” due to the limited availability of some important complementary good, which may be:
 - another compatible product (e.g., software for a type of computer hardware, or betamax cassettes for a betamax VCR),
 - a support infrastructure (e.g., a refueling network for an alternatively fueled vehicle),
 - a network of compatible equipment owned by other consumers (e.g., an established base of compatible modems or FAX machines with which to communicate or inter-operate).
- Initial high production costs due to low production scale and large fixed production costs;
- Initial high production costs due to the need for experiential learning (“learning by doing”) (e.g., the need to shake out bugs in designs, streamline production processes, and see how the product performs in the field).

We cannot be certain that the actions necessary to overcome these kinds of transitional cost barriers will be taken by producers, for three reasons. First, producers may have too short a planning horizon, be too uncertain, or have insufficient foresight to be confident that future rewards will justify initial investments. Second, the benefits of pioneering or early technology adoption may not be privately appropriable by the pioneers. Thus it may be rational for many firms to avoid the high costs of pioneering, hoping to free-ride on the experiences and infrastructure developed by others. Finally, the benefits of pioneering may depend on other firms or consumers making compatible decisions, for example in purchasing compatible technology or developing compatible support infrastructure. There may be no practical way to anticipate or coordinate with the actions of others.

⁵For discussions of the adjustment-cost approach, see Gould (1968), Hayashi (1982), and Able (1990).

The production of the 3X vehicles will involve specialized processes particular to the new materials which may be used, and particular to the shapes, and forming and joining techniques which will be used to create the lightweight bodies. According to industry analysts, these specialized production processes have costs which decline substantially with the scale of production and with the learning which is gained through cumulative production experience. Thus, initially, the production of 3X vehicle body materials will face at least the last two of the cost hurdles listed above. These cost hurdles may be viewed as a potential transitional barriers. The transitional cost barrier for each material may be overcome only if the production of 3X vehicles from that material achieves adequate scale and matures over time through a sustained production effort. It is not certain that automotive industry has sufficient incentives to make the up-front investments and financial commitments necessary for the transition to occur.

2.3 Modeling the Transitional Path for 3X Vehicle Materials Production and Use

For this analysis we rely on an adaptation and extension of a model developed to assess transitional issues in the introduction of alternative fuel vehicles (Leiby and Rubin 1997a,b) . The dynamic features of the model are that it:

- Includes durable capital stock, and distinguishes fixed from variable costs
- Includes scale economies
- Reflects technological learning
- Accommodates limited or perfect foresight.

In distinguishing fixed from variable costs, the model associates the fixed costs with durable capital stock for materials production. The slow turnover of durable capital stock is characterized by a fixed scrappage rate in each year (i.e., reflecting equipment depreciation). The representation of fixed costs means that the model can include scale economies, that is costs which decline with the scale of production. The model reflects technological learning in vehicle production by specifying how costs decline with time (exogenous learning) or cumulative production (endogenous learning). Two solution methods may be used to explore the effects of limited foresight versus perfect foresight.

2.4 Factors Determining New Material Penetration

In our modeling framework, as depicted schematically in Figure 2-1, output—the amount of new material production—depends upon the level of 3X vehicle demand and the material choice of vehicle manufacturers. By material choice we mean the share of 3X vehicle production captured by each body material technology. The choice among materials will depend upon the production cost at the current scale and level of learning, and the value of non-price

Figure 2-1. Material supply and choice model, block diagram

material attributes.⁶ The current body production cost for each material type will depend on the history of investment decisions (determining scale and available capacity), and on the history of production decisions (determining the degree cost reduction from experiential learning). The path of investment and production will also be influenced by the degree of producer foresight (about future demand and learning). Investment could also be influenced by the additional risk assumed by the producer given the uncertain performance and cost of the technology, and the uncertain level of vehicle demand. However, we do not include an effective cost component for producer risk.

2.4.1 Demand for 3X Vehicles

For the purposes of this methodological demonstration, we take the time path of 3X vehicle demand (or, equivalently, production) to be exogenously specified. Our focus is then the choice among body materials technologies, and the possible effect of transitional cost barriers on the time path of material supply. The assumed time path for 3X vehicle production is taken from the 3X vehicle sales scenarios depicted in Figure 1-1. Detailed information is available in Das et al. (1997). This analysis uses the High Sales case, which assumes 60% market share by 2030.

2.4.2 Fixed and Variable Materials Production Costs, Scale Economies

The production cost data for each material are derived from Dieffenbach (1997). Dieffenbach estimates the fixed and variable costs for producing the automotive “body-in-

⁶In this demonstration study, the non-price benefits of each material are assumed to be identical, *on average*, but the appeal of each material to each manufacturer may differ due to unspecified attributes. The effect of unspecified attributes is treated as a random influence on individual choice, so that the market share of each material varies smoothly with its relative price according to the commonly used multinomial logit form (e.g., McFadden 1974).

white” (essentially the unpainted structure and exterior panels) from three materials: steel, aluminum, and polymer composites. These components of production cost are shown as a function of production scale in Figures 2-2, 2-3, and 2-4.

Figure 2-2. Declining capital cost per vehicle as plant scale grows (based on Dieffenbach 1997)

Figure 2-3. Fixed variable cost per vehicle across plant scale (based on Dieffenbach 1997)

2.4.3 Learning-by-Doing

"Learning-by-doing" is the effect of improving productivity (or reducing cost) by repetition of the production process. This phenomenon is observed in various industrial situations where it is described as a learning curve, progress function, or experience curve. It is important to distinguish learning-by-doing from learning by technological progress (the latter is closely related to R&D spending). Normally, pure learning-by-doing is the effect of productivity improvement simply by repetition of production process—it is the

Figure 2-4. Declining total cost per vehicle for body production, as plant scale increases (based on Dieffenbach 1997)

“autonomous” accumulation of understanding and expertise. Thus strictly speaking, the observed learning curve contains more information than learning-by-doing. On one hand, learning-by-doing, economies of scale and technological progress are different aspects of productivity improvement and should be discriminated one from another. On the other hand, since the production process is dynamic in nature and involves many factors, learning is an on-going and very complicated process. In the real world, it is hard or even impossible to clearly distinguish learning-by-doing from economies of scale and technological progress.

Arrow's (1962) classic form of the learning effect is represented by

$$A(G) = bG^{-n}$$

where G is cumulative gross investment (embodied in the existing capital equipment); $A(G)$ is the labor cost; b and n are constants. This simple model only considers labor cost reduction in the production process and assumes that at any time, new capital goods incorporate all the knowledge then available, but once built, their productive efficiency cannot be altered by subsequent learning. The important question is which index of experience is the best. While cumulative output gives much stronger results than calendar time, cumulative output and cumulative investment have close results, although the latter is slightly better.

Lieberman (1984) is a typical empirical study of the learning curve. Lieberman collected data on 37 chemical products (including methanol) and used a regression model to test the existence of learning effect. The basic model is similar to Arrow's classic model, excepting Lieberman used cumulative output and cumulative investment and even their weighted combinations as the indexes of experience. The results exhibit a strong and consistent learning effect. Learning is found to be a function of cumulative production and cumulative

investment rather than the calendar time. Standard economies of scale appear significant but small in magnitude relative to the learning effect. Variations in the slope of the learning curve are linked to difference in R&D spending and capital intensity.

Table 2-1 summarizes many empirical studies on the magnitude of learning-by-doing. For further discussion of major literature regarding learning effect in production, see Leiby et al. 1997. The knowledge of the nature of the learning process is still quite limited and sometimes even mixed. Nonetheless, empirical evidence indicates that the learning effect is important for decision-making at the firm and industry levels. For the purposes of this study of 3X vehicle materials production, the most applicable empirical estimates are those of Baloff (1971), who estimated learning rates for automotive assembly to be between 10% and 20% cost reduction for each doubling of cumulative output. Estimates for other industries are of the same general magnitude, so we use these rates for our preliminary analyses.

Table 2-1. Empirical Evidence on Rates of Learning-by-Doing		
Study	Data or Method	Results
Sheshinski (1967)	22 regressions, cross-nation, cross-industry data $\ln(A)=a+b \ln(G)$, A=productivity G=Cumulative experience a,b=coefficients	b ranges from 0.7 - 0.85
Baloff (1971)	regression on 3 labor-intensive factories (start-up model)	For each doubling of cumulative output, unit costs reduced by: 10%-12.5% musical instruments 20%-25% in apparel production 10%-20% in auto assembly
Hart (1983)	1929-1968 U.S. primary magnesium production	1% cumulative output increase, 0.16% price decrease
Lieberman (1984)	37 products in U.S. chemical processing industries (includes methanol)	Unit cost decreases on average 5.5% a year, economies of scale account for 15% of decrease, while cumulative output increases accounts for 85%
Adler and Clark (1991)	2 manufacturing dept. of an electric company	second-order learning accounts for about 70% of the total learning effect

In the model here, the experiential learning curve is implemented with a term L , the learning factor, that indicates the proportional reduction in cost from its initial level as a function of cumulative production. Based on the available empirical literature, we specify the learning

rate r as the percentage cost reduction per doubling of production. For cumulative production G , the number of doublings D since initial point G_0 are

$$D = \frac{\ln(G/G_0)}{\ln(2)}$$

The Learning factor L , or the proportional cost reduction from initial cost C_0 is then

$$L \equiv \frac{C}{C_0} = e^{-rD}$$

Note that this is approximately the same as $L = (1-r)^D$. We can simplify as follows, remembering that $a^{bc} = (a^b)^c$, and $e^{\ln(b)} = b$:

$$\begin{aligned} L &= e^{\left(\frac{-r \ln(G/G_0)}{\ln(2)}\right)} = e^{\ln(G/G_0) \left(\frac{-r}{\ln(2)}\right)} \\ &= \left(e^{\ln(G/G_0)}\right)^{-r/\ln(2)} \\ &= (G/G_0)^{(-r/\ln(2))} \end{aligned}$$

Thus, this learning approach corresponds to an elasticity of cost with respect to cumulative production G of $-r/\ln(2)$. For the results presented here, we use a learning rate of $r = 15\%$ cost reduction per doubling of production experience.

2.5 Results Available From Analysis

The method demonstrated here allows analysts to examine a variety of market outcomes or results. For different PNGV production paths and market conditions, we can observe

- Materials penetration time-paths
- Capital investment requirements
- Materials costs per vehicle over time

The model can be used to compare the effects of different permanent or temporary policies, which may be specified in the form of quantity mandates or taxes and subsidies. For example, one can compare the effects of 3X vehicle production requirements with those of a temporary materials subsidy.

These results presented here are meant to be illustrative only. The factors described above were successfully implemented in a model which characterizes the dynamic process of new technology (materials) introduction given durable capital stock and possible transitional cost barriers due to learning-by-doing, scale-economies, and imperfect foresight. Principally, we have found that given technology learning, perfect foresight and no risk premium, the new materials can quickly gain share with PNGV production experience (see the solid lines plotted in Figure 2-5). We caution, however, that the introduction of new materials may be impeded if learning is not achieved or appropriable, or is not anticipated due to limited foresight (see the dashed lines plotted in Figure 2-5).

Figure 2-5. 3X vehicle penetration depends on whether producers benefit from experiential learning and have accurate foresight

2.6 Outstanding Issues To Address and Next Steps

As stressed, while some effort was made to benchmark the model to empirical data and engineering cost estimates, the application is illustrative so far. The modeling approach is promising in that it allows consideration of a broad class of potentially important transitional barriers to new technology introduction. Our plan is to locate and use the best available data regarding current and mature-scale production costs, and apply the developed method to more rigorous market analysis and policy evaluation.

- Test assumption of “non-dedicated” fabrication equipment (implies malleable capital, hence scale less of an issue)
- Common presumption that aluminum space-frame and composite monocoque are risky and immature. We need data on current versus prospective mature costs, and on the anticipated learning rates.
- Infrastructure investments may be limited by uncertainty regarding market demand and production costs. The model needs to reflect risk avoidance by investors. We could use established methods to approximate the cost “premium” that firms may impose on investment in new 3X vehicle materials production, due to concerns about market and cost risk.

- For improved market share projection in the transitional analysis, we need estimates of the special benefits (other than their relative cost) of each material (e.g., fuel savings given lower weight, or improved durability).
- The planned approach will be parametric in cases of incomplete information. That is, imprecisely known input parameters will be varied over a reasonable range to assess their impact. This will allow us to highlight key contributors to any transitional barriers, and to examine the range of values over which they may be a concern.

3. ESTIMATING THE INDIRECT ECONOMIC IMPACTS OF 3X VEHICLE DEVELOPMENT

3.1 Introduction: The Input-Output Representation of the U. S. Production Sector

This study developed a core methodology and case study analysis that highlights the direct and indirect economic output and employment impacts that are likely to result as the U.S. economy makes the transition to the production of 3X vehicles. The approach used in this study is to quantify the level of the direct and indirect changes through the use of an input-output model of the U.S. economy.

In a previous report (Das et al. 1997), ORNL has identified the key changes in material demand under a shift to alternative materials. That study organized the transition information within the context of materials life cycle. The analysis highlighted the material used in automobiles in terms of six stages in the life cycle of materials. A series of critical issues that are likely to impact investment decisions by auto makers and their parts and materials suppliers were identified and discussed in the study.

Life cycle analysis defines six common stages of material usage. The first stage reflects activities at the raw material state, such as the mining or extraction of resources. The next group of activities is the material transformation process such as smelting that make the raw materials useful for production processes. The third stage is the production of parts and components from the processed material. Next activities that organize the assembly of component parts into complete items, such as motor vehicles. The fifth stage is the use of the object or material in final demand as well as activities related to repair and maintenance. The final life cycle stage is the disposition of the product, including any recycling of materials for automotive or other use. The earlier ORNL descriptive analysis of the six life cycle stages for new generation vehicles (Das et al. 1997) indicated that despite significant changes in the underlying production structure, the transition to PNGV might well be accomplished smoothly over the extended period from 1995 to 2030.

Since automobile production is a major sector in the domestic economy even the gradual transition envisioned in the deployment of PNGV could significantly alter the U.S. economic base. The impact of such technological changes on the core economy may be very broad and diffuse. The potential PNGV adoption of substitute materials affects not only the production technology process as exemplified by the structure of inter-industry interactions, but also may affect household consumption patterns, the materials used by government, and the import/export markets. The direct and indirect economic impacts of such changes can be explored by the use of the input-output extensions of the National Income and Products Accounts framework. The purpose of the current study is to develop a modeling framework to identify and quantify changes in economic structure resulting from alternative material requirements and life-cycle factors.

To address these issues, ORNL modified the *Benchmark Input-Output Accounts of the United States, 1987* (Department of Commerce 1994) to highlight the key material components of automobile production. The component expenditures (i.e., bill of materials for each of the key input materials under alternative production alternatives) were then estimated using information from the earlier ORNL study. The impacts on the U. S. economy were then quantified through examination of the differential material demands arising from a base-case production scenario and two PNGV transition alternatives.

The current study focuses on the changes in the flow of materials arising from different materials requirements in the production of 3X vehicles. It examines only the first four life cycle stages. We limit the study in this manner because, while the input-output model is an ideal vehicle to examine the inter-industry impacts of changes in the input materials, the last two stages relate more clearly to consumptive activities than production. An expanded input-output model is often invoked to capture the full economic cycle of production and consumption. These approaches have been formalized into the Social Accounts Matrix (SAM) framework of the National Income and Product Accounts (NIPA) (World Bank 1993). While we have focused on production in this study, it is useful to place the production changes within the context of the full economy to highlight several of the key limiting assumptions of the current analysis.

The NIPA structure of the economy is often stylized by the concept of the circular flow of money as depicted in Figure 3-1. Money flows from consuming agents in the purchase of commodity and services to producers. Producers then use these funds to purchase input materials from other producers and basic factors of production, land, labor, and capital from the consuming agents or institutions (households, governments, and investors). The circular flow of money graphically depicts how funds continually travel around the circuit, unless they escape from the circular path. Goods and services for which the funds are exchanged travel in the direction opposite the flow of money. For any initial source of funds, leakage will occur over time to institutions outside the U.S. economy for the purchase of imported goods. Changes in the composition of consumption can change the structure of production and consequently the distribution of money to primary factors, i.e., income distribution. Similarly, changes in income distribution or expenditure patterns of domestic institutions can change the demand for commodities and consequently the materials used to meet this final demand. This model highlights the use of the pattern of financial transactions and expenditures to represent the state of the economic structure.

Figure 3-1. The circular flow of money.

The National Income and Product Accounts (Figure 3-2) represents the circular flow formulation of the economy by a transactions matrix that indicates the annual expenditure and receipts of entities in the economy. The major entities are grouped into Activities (e.g., industrial or service), Institutions, (households, government, investors), Factor Payments (i.e., labor payments, returns to capital and taxes) and Other (e.g., imports and exports). One easily can compute the first-order economic impacts of any hypothetical change in the pattern of expenditures and receipts or the type of entities. The transaction matrix, known more formally as the Social Accounts Matrix (SAM), indicates the direct financial transactions among the entities. The total impact, consisting of direct, indirect and induced impacts, are developed by examining the stream of expenditures that follow from the initial payments. The ripple effect of any initial change can be found by several mathematical methods, one of which is simply sequentially calculating the rounds of expenditures (the round-by-round methodology).

Figure 3-2. The social accounts matrix

<i>Receipts</i>	<i>Expenditures</i>				<i>Total Receipts</i>
	<i>Activities</i>	<i>Institutions</i>	<i>Factors</i>	<i>Other Account</i>	
<i>Activities</i>					
<i>Institutions</i>					
<i>Factors</i>					
<i>Other Accounts</i>					
<i>Total Expenditures</i>					

Note: Gray shading represents areas where transactions exist; no shading indicates no transaction is defined in the model.

An analysis of the round-by-round expenditures represented in the SAM provides a framework with considerable analytic flexibility to investigate the impacts of structural changes. The SAM includes labor and capital payments as primary factors. Consequently, employment impacts are provided as part of a SAM analysis. Similarly, other institutions, namely households and governments, are included. The induced impacts on these sectors can also be modeled as part of the SAM exercise. This approach incorporates and extends beyond the simpler input-output approach that focuses only on the financial flows within the production sector, i.e., the inter-industry interactions. In the typical input-output analysis, one computes the total production of all commodities required to make available a given specified level of each commodity to final demand.

A change in the choice of transportation vehicles such as envisioned by the deployment of 3X vehicles could well impact both the production and consumption structure of the economy. However, to sharpen focus on the major materials choices this study concentrates on the changes in the production structure. The composition of demand is assumed to be consistent with the basic consumption trends used in the Annual Energy Outlook (EIA 1997), which assumes current transportation technologies predominate.

Input-output analysis requires considerably more detail than the aggregated projections presented in the AEO scenarios, (EIA, 1996). Consequently, trend projections of the level of demand by

the individual final demand components, (i.e., households, state local government expenditures, federal government, investment, imports and exports) were developed for each of the approximately 500 commodities, e.g., auto parts, combustion engines and their component parts. The commodity output projections were constrained to aggregate long-term national projections of Gross National Product prepared by the National Planning Associations Data System (NPA 1997). These commodity demand projections were then proportionally adjusted such that their sum would match the GNP projections of the AEO. This approach assumes that (1) the demand for motor vehicles is constant regardless of which technology is selected and (2) that vehicle choice does not indirectly impact income distribution, commodity prices or the composition of demand. The level and composition of final demand is assumed constant. The method allows one to investigate how the level and composition of total production might change to meet the given level of final demand and the composition of motor vehicles determined by the alternative 3X vehicle deployment scenarios.

The current study, thus confines its analysis to production aspects of the economy, the transactions contained in the “activities” box of the SAM framework depicted in Figure 3-2. The analysis assumes, as a first approximation, that neither the level of automobile demand nor the distribution of income is changed under the different 3X vehicle penetration scenarios. The operating hypothesis is that the major impacts of the 3X vehicles will show up as changes in the demand for materials, induced by the different production requirements embodied in each motor vehicle technology.

The input-output approach is useful for examination of the impacts of detailed structural components of the economy (Lave 1995, Cobas-Flores 1996, Hendrickson 1997). However, it gains this detail at the expense of simplification in other economic interactions. Primarily, the input-output approach assumes constant production technologies (unless specifically modified as done in the scenario alternative) and fixed consumption patterns, i.e., that there are no market-induced price impacts. To capture the possible NGV deployment generated impacts on other economic sectors, the U.S. Benchmark Input-Output which represents current production technologies, necessarily needs to be extended to include the production structure required for alternative motor vehicle technologies. This was done to the extent possible at the materials level using additional information from the input-output “work-file” as described in the next section.

3.2 The Input-Output Representation of the Production Technology of 3X Vehicles

The Benchmark Input-Output table of the United States (DOC 1994) provides a detailed framework for assessment of inter-industry indirect impacts. Primary data on expenditures for approximately 500 sectors is organized into a set of industry by commodity use and industry by commodity produced tables. These tables are known, respectively, as the “Use” and “Make” tables. This formulation provides a consistent set of information from which a set of make and use coefficients can be derived to implement an input-output model. The use table (Figure 3-3) depicts the amount of expenditures that an industry has for each commodity that it uses in production. The make table depicts the dollar amount of production for each commodity

Figure 3-3. Input-output model formulated with make and use tables

<i>Receipts</i>	<i>Expenditures</i>			
	<i>Commodities</i>	<i>Industries</i>	<i>Factors</i>	<i>Total Receipts</i>
<i>Commodities</i>		USE TABLE	FINAL DEMAND	Total Commodity Consumption
<i>Industries</i>	MAKE TABLE			Total Industry Output
<i>Factors</i>		FACTOR PAYMENTS		GNP
<i>Total Expenditures</i>	Total Commodity Production	Total Industry Output	Total Consumption	

produced by a specific industry. In the terminology of Figure 3-3, it is the amount of money (receipts) that an industry receives for producing that commodity.

In the round-by-round approach, the money spent on a particular commodity is shared out to the producing industries based on each industries historic (or forecasted) share of production for that commodity. In the context of the current study, the aluminum and glass-reinforced composites scenarios can be implemented by sharing various amounts of motor vehicle expenditures to special industries representing the various technologies considered.

3.2.1 The Representation of Industrial Structure by the Make and Use Coefficients

The round-by-round expenditure stream is implemented using a set of “use” and “make” coefficients for each industry. The use coefficients represent the share of a particular industry’s total budget that it spends on each of the commodities it uses. The use coefficients represent the bill-of-materials required for a unit of production in that industry and indicate the direct materials and primary factors (labor and capital) utilized. The make coefficients represent the share of total commodity output made by each of the producing industries that contribute materials to the commodity.

To estimate the total industrial output for any given year, the round-by-round process requires an initial set of final demands for each commodity. The final demands for each commodity are applied to the make coefficients to determine the direct commodity requirements to meet the demand by end users. To produce these final demands, each industry must purchase inputs according to its bill-of-materials. The make and use multiplier process is sequentially applied to subsequent demands for intermediate materials until no more inputs are required. The end of the expenditure process provides an estimate of direct and indirect production. The total output required to meet the final demand is thus determined and is distributed to the amount used in meeting final demand and the amount used as intermediate materials in production. Leaks from

the intermediate purchase cycle can occur. These leaks are the purchase of factor inputs—labor, capital, and taxes—as well as imports.

The round-by-round process was implemented with a Visual FoxPro computer program that uses the make coefficients, use coefficients, and final demand projections as database inputs. In practice, it takes about 24 rounds constituting a set of industry purchases of input materials and the associated material sales allocated to producing industries to clear the final demand purchases and to estimate the total production of commodities and the output of each of the industries.

The round-by-round solution of the input-output matrix provides considerable analytic flexibility for the structural impact analysis pursued here. One can modify or define additional commodities simply by stating where production will take place, i.e., with existing or new industries. New production technologies can be defined as new industries by simply listing the bill-of-materials required, i.e., the use coefficients for the technology. Figure 3-4 shows an input-output model modified to include make and use tables for new generation vehicles.

Figure 3-4. An input-output model modified to include 3X vehicle activities

<i>Receipts</i>	<i>Expenditures</i>				
	<i>Commodities</i>	<i>Industries</i>	<i>3X Vehicle Production</i>	<i>Factors</i>	<i>Total Receipts</i>
<i>Commodities</i>		USE TABLE	3X VEHICLE USE	Final Demand	Total Commodity Consumption
<i>Industries</i>	MAKE TABLE				Total Industry Production
<i>3X Vehicle Production</i>	3X VEHICLE MAKE	3X Vehicle Intermediate USE		NGV Demand	Total 3X Vehicle Consumption
<i>Factors</i>		FACTOR PAYMENTS	NGV Factor Payments		GNP
<i>Total Expenditures</i>	Total Commodity Production	Total Industry Output	Total 3X Vehicle Output		

3.2.2 The 3X Vehicle Technologies Added to the Input-Output Matrix

The first step in the implementation of the modified input-output matrix was to construct the augmented input-output sub-elements for the conventional automotive production technology. We then developed the make and use table for two PNGV alternative technologies based on the material options described in Section 3.1 and Das et al. (1997). For both technologies the expenditure components for the input-output were developed and incorporated into the model. The direct and indirect economic impacts of the assumed transition path for these vehicles were

then computed based on a given demand GNP projections. The nature of the impacts is discussed in Section 3.3.

ORNL modified the Benchmark U.S. Input Output model to highlight and reflect the key material components of automobile production. The component expenditures (i.e., bill of materials) for each of the key materials input under several production alternatives was estimated. The 3X vehicle bills-of-materials were based on information in the previous ORNL report (Das et al. 1997). The data on composite- and aluminum-intensive vehicles production was reformulated to be consistent with the input-output model accounting concepts. The final demand for each of the input-output commodities was then developed for a “base case” and two 3X vehicle alternatives.

Inclusion of the current technology entity along with the new vehicle technology permits estimation of the economic impacts under alternate rates of market penetration of the new technology by using different purchase rates from the using activities. Invoking a “base case” set of economic projections for exogenous factors, one can generate a baseline time trend (i.e., zero penetration of the new technology). This base line time trend can then be a reference line for the alternate time trend reflecting the penetration of the new technology and can thus provide an estimate of the differential impacts over the analysis horizon.

3.2.3 Method of Analysis

The approach chosen for the analysis is comparative static. The total economic output of the business as usual economy in the years 2000, 2010, and 2020 are calculated using the input-output structure of the benchmark input-output tables. This baseline is used as a reference point from which to compare the economic changes brought about by 3X vehicle penetration into conventional motor vehicle sales. Two 3X vehicle technologies, aluminum- and composite-intensive, are analyzed. For each alternative, a scenario set for the years 2010, 2020, and 2030 is computed assuming market penetrations of 1%, 29% and 60 %, respectively.

To conduct the analysis, the benchmark input-output had to be modified to incorporate the new production technologies. The input-output model was maintained in the industry/commodity formulation. Since we were primarily interested in the material consumption changes, it was only necessary to add new industries to reflect the production technologies involved in the production of new generation vehicles. We assumed that the vehicles performed the same services and cost the same as conventional motor vehicles, and thus we did not expand the number of commodities. The baseline motor vehicles sales are shared to the alternative production processes by scenario dependent make coefficients.

The benchmark input-output definition of industries and commodities attempts to maintain key inter-industry interactions and organize for commodity and industry definitions such that production processes are similar for a given industry definition. Consequently, one can examine changes at various points in the product life cycle, from raw material extraction, parts fabrication, final production, consumption, and salvage.

With the shift to the alternative materials in 3X vehicles, one expects a decline in steel use and hence in the mining and smelting of steel. Aluminum 3X vehicle production will expand primary aluminum production as well as processing, i.e., rolling and drawing. The expansion in composite-intensive 3X vehicles will induce increased production of resins and plastics. In both cases, conventional automobile parts suppliers and automotive panels producers will substitute the new materials for metals, resulting in a shift in the production use coefficients of the sectors. These expected changes in economic structure are indicated in Table 3-1. It is the magnitude of these changes that this analysis attempts to quantify. These initial changes can induce even further changes in the level of commodity production for all other industries as the rise and decline in production of the direct suppliers filters throughout the rest of the economy. It is this total process which the input-output approach makes understandable.

Table 3-1. Expected Major Changes at Various Production Life-cycle Stages				
Life-cycle Stage	Activity	Base Case: 2030 Production (million \$ 1992)	Expected Change from Base Case	
			Composite intensive	Aluminum intensive
Raw materials	Iron ore	3,755	-	-
	Non-ferrous ores	9,873		+
	Plastics & resins	86,733	+	
Processing	Blast furnaces	98,322	-	-
	Primary aluminum	17,484		+
	Misc. plastic products	193,253	+	
Component production	Iron/steel foundry/forges	34,644	-	-
	Aluminum castings	12,257		+
Assembly	Auto parts	321,685	Shift in material use	Shift in material use
	Auto panels			
	Motor vehicles		Shift in material use	Shift in material use
Use	Not examined since assumed similarity of commodity in use.			
Disposal				

Note: - indicates decreased use; + indicates increased use; an empty cell indicates not significant change in use.

3.2.3.1 3X vehicle production formulated as additional industrial process

The study considered three basic technologies for the production of automobiles. First, the bill-of-materials required for the production of conventional automobiles was identified. Then two additional industries, reflecting the production of composite- and aluminum-intensive 3X vehicles were defined and prepared for the input-output table. The “use” table for these two 3X vehicles was generated by modifying the bill-of-materials for the production of the base case automobiles to reflect the change in materials composition.

The 1997 ORNL study of material use (Das et al. 1997) provided information to adjust the input-output use coefficients of the conventional motor vehicle production. The earlier study examined alternative material composition based on a weight basis. These relative comparisons were converted to a value base as required in the input-output analysis.

It is estimated that about half (by dollar value) of the carbon and high strength steel currently used in conventional vehicles will be replaced with composites in the production of composite-intensive 3X vehicle. The composite materials are associated to the input-output commodity and industry identified by plastics and synthetic materials. Composite-intensive vehicle production will use almost three times (by value) as much plastics as conventional vehicles. We also have calculated that the labor intensive production process for composite materials requires one-third more labor input than the conventional production process. Composite materials also use somewhat less capital than conventional production.

The dollar value differences between material usage for composite-intensive vehicles and conventional vehicles were used to develop coefficients that could be applied to the materials use dollar values of conventional vehicles in the input-output work file. The same was done for aluminum-intensive vehicles. The values for both 3X vehicle types are presented in Table 3-2. The bills-of-materials for each of the 3X vehicles was constructed by adjusting the base year purchases of primary materials, i.e., materials from blast furnaces, steel mills, and producers of primary aluminum and plastic materials and resins. For example to develop the bill-of-materials for steel use by an aluminum-intensive vehicle, the conventional production bill-of-materials for

Table 3-2. Use Matrix Adjustment Coefficients		
Material	Composite Intensive	Aluminum Intensive
Carbon and HS steel	0.50	0.25
Cast iron	1.00	0.25
Aluminum	1.00	4.11
Plastics	2.90	1.00
Labor	1.30	1.05
Capital	0.79	0.99

iron and steel was reduced to reflect decreased usage of these materials. To match the detail in the input-output file for primary metals producers, the use of iron and steel was pooled to determine the change in the amount purchased from blast furnaces and steel mills. Similarly cast and wrought aluminum were jointly treated as purchases from primary aluminum producers. To account for changes in the use of composite materials, we adjusted purchases from the plastic materials and resin industry. The relative amounts of labor and capital purchases were proportionately adjusted using a 3X vehicle material weighted-average of labor and capital factors for different materials (National Academy Press 1993).

The input-output use table includes almost five hundred commodities that may be used in production of any given commodity – reflecting the complete production life cycle, including, raw materials, processing, manufacturing, packaging, transportation, marketing, etc. Thus we assume the same underlying structure of production for the two new vehicles types is similar to conventional vehicles, only the value of selected materials purchases are changed. Placing the expected changes within the full commodity use set, assists the analysis by placing the changes within the context of the complete production process.

3.2.3.2 Capturing the primary automotive production technology

Examination of the input-output representation for motor vehicle production indicates that the key suppliers of primary automobile production are the motor vehicles parts, automotive stampings, and internal combustion engine industries. The production of the both types of 3X vehicles will likely use a different set of suppliers for parts and body panels (produced as automotive stampings) than are used for conventional vehicles. Also, the aluminum-intensive 3X vehicle will use aluminum rather than cast iron engines. The structure of the 3X vehicle industries may also depend on the outside suppliers, but these suppliers will be producing parts and panels more consistent with the materials composition of the new generation vehicles than conventional technologies.

To account for these changes, three new industrial complexes were developed, one each for conventional vehicles, aluminum-intensive vehicles, and composites-intensive vehicles. The conventional vehicles' materials use for automobile production, parts, and stampings were combined and entered in the input-output table. The adjustments for primary purchases of the composite 3X vehicle were then made to the conventional vehicle's "bill-of-materials" to generate a composite vehicle industry. Finally, the conventional use data were modified to include production of aluminum internal combustion engines and the materials mix of aluminum-intensive vehicles. Conventional and composite-intensive vehicles are assumed to purchase conventional internal combustion engines. Creating an automotive complex allows us to determine the amount of change that aggregation of sectors may impart to the final results. In addition, as a departure from the standard input-output model, the use table includes purchases of imports; thus the total impacts are moderated if a change in structure increases imports. This method provides the new industrial complexes for inclusion in the input-output model as shown in Table 3-3.

Table 3-3. New Industrial Complexes Are Added to the Input-Output Model to Capture 3X Production

Industry	Standard Input-Output Automotive Complex	Input-Output Consumption (Adjusted to account for materials imports)			
		Base Input-Output Automotive Complex	Automotive Complexes		
			Conventional Vehicles	Composite 3X Vehicles	Aluminum 3X Vehicles
Motor Vehicle	59.0301	59.0301	59.0304	59.0306	59.0307
Parts	59.0302	59.0302			
Automotive stampings	41.0201	41.0201			
Internal combustion engine	43.0200	43.0200	43.0200	43.0200	

Estimates for the three augmented industry complexes and the value presented for the standard input-output treatment of imports (Department of Commerce 1992) are presented in Table 3-4. The table presents the total direct and indirect economic impact generated per dollar of production. The input-output table indicates that each dollar of demand for automobiles generates about \$2.69 of commodity demand. This includes the original dollar plus another dollar and sixty-nine cents. However, we assume that all the industries involved in this production split their domestic and imported purchases proportional to their split in 1987, and thus the domestic multiplier is only 2.615, adjusting for import purchases that “leak out” of the round-by-round generation of activity. Also the table shows that the base conventional auto-complex we defined provides estimates that are consistent with the independent treatment of the industries—the complex approach generates a multiplier of 2.864 as compared to the 2.615 generated using the round-by-round procedure for the separate industries. The higher impact multipliers for the complex result from the implicit intra-complex transactions obtained by the aggregation of industries reduce the level of import purchases as compared to the separate industry transactions. Estimates of the individual industry’s increase in production that would result from an increase in automobile production and associated automobile-sector purchases are also presented in the table to place the analysis results in perspective.

3.2.3.3 The baseline scenario

To exercise the input-output model, an exogenous set of final demands for each of the approximately 500 commodities is required for each of the projection years. The underlying economic scenario was based on commodity demand projections to 2030 reflecting the GNP and motor vehicle demand projections of the Department of Energy’s *Annual Energy Outlook* (EIA 1997). The AEO scenario was extrapolated to generate data for the entire 2000 to 2030 period. The final demand for motor vehicles projections were developed by extrapolating the base year final demand for motor vehicles using the AEO time series of growth rate in number of vehicles. The projections are presented in Table 3-5. The other detailed commodity projections were developed using both the NPA Data System long-term projections (NPA 1994, 1997) constrained to the AEO total GNP projection.

Table 3-4. Direct and Indirect Impacts from an Increase of \$1 in Automobile Production					
Industry	Standard Input-Output Automobile Production	Input-Output Consumption: 3X Vehicles (adjusted to account for materials imports)			
		Base Input-Output Automotive Complex	Automotive Complexes		
			Conventional Vehicles	Composite 3X Vehicles	Aluminum 3X Vehicles
Motor vehicles	1.012	1.008	1.286	1.353	1.373
Motor vehicles parts	0.332	0.221			
Automotive stampings	0.076	0.051			
Internal combustion engines	0.021	0.014	0.013	0.017	
Wholesale trade	0.148	0.091	0.102	0.127	0.130
Advertising	0.045	0.027	0.031	0.039	0.038
Misc. plastic products	0.044	0.027	0.030	0.039	0.038
Motor freight	0.041	0.025	0.028	0.036	0.038
Electrical equipment	0.035	0.022	0.023	0.029	0.029
Industrial chemicals	0.030	0.013	0.018	0.037	0.023
Electric services	0.039	0.016	0.020	0.025	0.032
Primary aluminum	na	0.004	0.006	0.007	0.065
Plastic materials and resins	na	0.010	0.011	0.055	0.014
Blast furnaces and steel mills	0.06	0.037	0.055	0.047	0.033
Total: All industries	2.693	2.615	2.864	3.407	3.437

na= not available

Table 3-5. Economic Projections of Motor Vehicle Demand (Billions of \$1992)			
Final Demand Component	2010	2020	2030
GNP	8,644.8	10,124.9	11,496.2
Total automobile demand	260.8	283.4	308.3
3X vehicle demand	2.6	82.2	185.0

The base year values for each commodity were projected using the NPA trends for commodity groups by major final demand sectors (e.g., households, federal, state and local government, investment and exports). These trends were then constrained to fit the AEO GNP. The GNP, total motor vehicle demand and 3X vehicle consumption projections are presented in Table 3-5 for the target analysis years. The 3X vehicle deployment scenario, developed in the earlier

ORNL study, has increasing market share for new generation vehicles after 2010. For the purpose of analysis, this study focuses on the years 2010, 2020 and 2030.

3.3 Results

The key result of the study is that the direct and indirect economic impacts for intermediate materials are very modest in scale, as expected. No significant bottlenecks were uncovered in the analysis. Compared to present automobile material composition the 3X vehicle technologies tended to be slightly more labor intensive. There is a slight increase in labor requirements and an increase in intermediate materials that provide an expansionary boost to the economy—increasing wages and gross national product slightly. The aluminum-intensive vehicle industry has slightly more stimulus effect than composite vehicles.

These results are discussed in more detail in the remainder of the section. First, we present an overview of the macro-economic impacts to place the detailed results in perspective. Next we address industry-specific effects. Because both 3X vehicle scenarios displace ferrous materials currently used in conventional vehicles, both scenarios generate similar impacts on adversely affected industries. Thus, the impacts are presented together. Then we examine separately the positively affected industries for the composite- and the aluminum-intensive scenarios.

3.3.1 Overview of Macro-economic Impacts

The penetration of 3X vehicles does not appear to unduly stress the economy. The summary results of the three cases for each of the forecast years are presented in Table 3-6. We assume the GNP (equal to final demand) is constant across all motor vehicle scenarios in a given year and rates of market penetration of both 3X vehicle options are the same. The table presents net intermediate material figures using the scenario generated incomes. Each 3X vehicle scenario will slightly increase the level of intermediate materials required to meet the structure of demand and the composition of motor vehicles produced in that scenario. Even in 2030 the change in intermediate materials is relatively small, approximately 58.8 and 65.5 million 1992 dollars, for composites and aluminum, respectively. This is an increase of approximately 0.6 – 0.7 percent of the baseline level.

Table 3-6. Summary of Macro-economic Impacts in 2030					
Year	3X Vehicle Penetration	GNP (billion \$1992)	Intermediate Materials Production (billion \$1992)		
			Baseline	Difference from Baseline	
				Composite	Aluminum
2010	1%	8,644	6,894	0.8	0.9
2020	29%	10,124	8,179	27.0	29.0
2030	60%	11,496	9,307	58.8	65.5

Although the macro impacts are relatively small, it is instructive to explore some of the implications of the commodity shifts. Given the same initial stimulus level of GNP, the 3X vehicle scenarios use relatively more labor and less capital ("other value added") but generate increases in both, as well as more total output (Table 3-7). In the case of aluminum vehicles, the increase in industry output generates a slight increase in wages but relatively greater payments to capital than the composite vehicle. Production of the much higher labor-intensive composite vehicle however generates additional labor income, which further stimulates income growth.

Table 3-7. Comparison of 3X Vehicle Scenario Differences in 2030 (Billions \$1992)			
Indicator	Base	3X Vehicle Scenario	
		Composite (difference from base)	Aluminum (difference from base)
GNP	9,660	41	40
Labor	5,268	33	26
Other value added	4,390	9	15
Total industry output	18,967	101	106

3.3.2 Industry Impacts

Although the aggregate impacts are small, industry-specific changes may give rise to adverse adjustment situations. A small-dollar value impact may be insignificant for the economy as a whole, but if concentrated in a specific industry it may be a significant factor for that industry. Consequently, in examining industry impacts, one needs to consider both the scale and the relative value of a change. We examined each scenario's result to identify any industry that would experience change greater than 2% of its base production. There are relatively few such impacts (see Table 3-8). Declines occur predominantly among conventional motor vehicle and ferrous metals industries. While even the 2030 composites scenario shows no industry declining over 2%, each of the three major iron and steel related industries decline almost 1%. Generally, the impacts for the 3X vehicle scenarios tend to be diffuse.

Table 3-8. I-O Industries with 2% or Greater Change in Output due to 3X Vehicle Penetration (of a total of 484 industries)			
Scenario	2010 (1% 3X vehicle penetration)	2020 (29% 3X vehicle penetration)	2030 (60% 3X vehicle penetration)
Composite	0	0 decline 7 increase	0 decline 10 increase
Aluminum	0	2 decline 15 increase	4 decline 22 increase

3.3.2.1 Industries with negative impacts

The major non-automotive industries that had negative impacts under one or the other 3X vehicle scenario are indicated in Table 3-9. As expected the largest losing industries are those related to steel. As noted above, similar negative impacts arise from either 3X vehicle scenarios. Exceptions arise from the aluminum scenario's substitution of aluminum for the internal combustion engine. This substitution generates a greater and more diffuse impact on steel products than the composite scenario, and the effect is not offset by the slight, overall expansion generated by both scenarios.

Table 3-9. Industries Adversely Affected by a 3X Vehicle Scenario (Million \$1992)			
Industry	Baseline	Composite (difference from base)	Aluminum (difference from base)
Blast furnaces & steel mills	98,322	-915	-2620
Internal combustion engines	29,382	469	-1834
Cold rolled steel sheet	13,192	-128	-369
Steel pipe and tubes	9,673	-92	-264
Iron ore mining	3,755	-22	-67
Construction machinery	39,244	13	-25
Steel wire drawing and nails	8,432	21	-26
Electrometallurgical products*	2220	-7	-17
Clay refractories	1,439	-5	-14
Non-clay refractories	1,621	-2	-6

**except steel*

3.3.2.2 The composite 3X vehicle spurs growth in several materials related industries

Under the composite-intensive 3X vehicle scenario, several related materials industries experience growth over \$1 billion (Table 3-10). The largest absolute growth occurs in plastic materials and resin industries, which exhibit a \$6.052 billion dollar growth, amounting to almost 7% of the base level production. Of particular interest is the increase in the support industries of wholesale trade and the motor freight transport. This growth reflects the increase in intermediate materials. In all cases, these same industries exhibit a positive impact in the aluminum-intensive vehicle scenario.

3.3.2.3 The aluminum 3X vehicle provides growth impetus to a different set of industries

In the case of the aluminum-intensive 3X vehicle focus, growth is centered primarily on aluminum-related industries (see Table 3-11). The largest absolute gain occurs in the primary aluminum industry, which also exhibits the largest percentage gain—33%. This impact

Table 3-10. Industries That Experience $\geq$ \$1,000 Gains Under the Composite Scenario (Millions of \$1992)			
Industry	Baseline	Composite (difference from base)	Aluminum (difference from base)
Plastic material	86,733	6,052	457
Wholesale trade	645,551	4,576	5,130
Industrial inorganic	228,494	3,517	793
Miscellaneous plastic products	193,253	1,579	1,298
Motor freight transport	221,546	1,347	1,699

Table 3-11. Industries That Experience $\geq$ \$1,000 Gains Under the Aluminum Scenario (Millions of \$1992)			
Industry	Baseline	Composite (difference from base)	Aluminum (difference from base)
Primary aluminum	17,484	121	5,896
Wholesale trade	605,551	4,516	5,103
Secondary nonferrous metals	14,044	79	2,446
Electric utility	362,193	811	2,019
Motor freight	221,546	1,347	1,699
Miscellaneous plastics	193,253	1,579	1,298
Iron and steel foundries	25,989	315	1,194

represents the sole example of a potential bottleneck, in that the industry would need to expand by this amount by 2030. However, given the gradual market penetration of 3X vehicle, there would be adequate response time for appropriate investment in aluminum processing infrastructure. The other industry with a significant impact is the secondary non-ferrous metals with a growth rate of 17%. Again, wholesale trade and motor freight industries have growth due to the expansionary impact of the 3X vehicle scenarios. Since aluminum production is electricity intensive, additional demand will occur in the electric utility sector. The expansion in aluminum appears to also place indirect impact on iron and steel foundries. Note that the 3X vehicle scenario reductions in ferrous metals occur initially in demand for blast furnaces and steel mills. It is most likely that some of the actual decline in ferrous metals use would affect production further down the ferrous production pipeline and offset some of the growth indicated here.

Nonetheless, it is interesting that the expansionary impact on the aluminum sector and other non-ferrous metals also may indirectly impact iron and steel foundries.

3.3.3 Summary

The levels of output for selected industries under the three scenarios for the year 2030 are summarized in Table 3-12. The industries are organized by the material life-cycle stage described in Sect. 3.3.1. In general, impacts for the non-automotive industries tends to be small, occurring mostly in the expected industries and in the expected directions. The largest impacts are the direct impacts on the three automotive industry complexes. The magnitude of the impacts lessens as the changes in commodity demands diffuse further back in the life cycle of the materials. The only apparent potential bottleneck problem is in primary aluminum production, but a phased expansion of the industry could alleviate the production constraint.

Table 3-12. Industrial Impacts by Materials Life-cycle Stage				
Life-cycle Stage	Activity	2030 Production (million s\$ 1992)		
		Base Case	Composite intensive	Aluminum intensive
Raw materials	Iron ore	3,755	3,733	3,686
	Non-ferrous ores	9,873	9,927	10,017
	Plastics & resins	86,733	92,786	87,191
Processing	Blast furnaces	98,322	92,786	95,749
	Primary aluminum	17,484	17,640	23,453
	Misc. plastic products	193,253	195,170	194,623
Component production	Iron/steel foundry/forges	34,644	34,258	35,293
	Aluminum castings	12,257	12,689	13,103
Assembly	Conventional motor vehicles Conventional auto panels & parts	321,685	128,674	128,674
	Composite 3X vehicles Composite panel & parts		253,528	
	Aluminum 3X vehicles			254,768
Use	Not examined since assumed similarity of commodity in use.			
Disposal				

The use of the input-output framework is not only able to identify the scale of the general impact on the economy, but also can selectively focus on key industries related to the various life-cycle stages in production. If it identifies a problem or bottleneck, indicated by a significant growth in capacity, the model can also provide information that identifies the impact chain bringing the situation about. Anomalous or unexpected impacts can be investigated as well.

3.4 Cautions, Caveats, Further Research

3.4.1 Cautions

The input-output analysis presented here assumes that the underlying economic structure embodied in the benchmark input-output data will be a reasonable reflection of the key components of the U.S. economy during the entire projection horizon. No attempt has been made to modify the composition of activities to reflect extrapolation of observed or hypothesized industrial sector trends. In that respect the study is a comparative static analysis, superimposing the 3X vehicle technologies on the existing compositional structure with levels of industrial activity determined by the various economic projections.

It is possible that in the next thirty years, ongoing economic and social forces may induce substantive structural changes in the composition of economic activities, and indeed that even the deployment of 3X vehicles may coincide with other environmental oriented policies that may induce such changes. For example the analysis does not explicitly address the recent changes in the U.S. economic structure (e.g., outsourcing and downsizing) that will be captured by the soon to be released 1992 benchmark input-output tables. Also recent trends or alternative scenarios of future trends in the metals sector have not been fully explored. Use of the benchmark 1987 input-output table does not capture the impact of a potential decline in domestic primary aluminum and steel production.

Nonetheless, the analysis presented here, conditioned as it is on continuity of the current structure, does present a reasonable indication of the source and the order-of-magnitude of likely impacts.

3.4.2 Caveats

In addition to the general caution discussed above, the analysis mode chosen simplifies several other economic characteristics that need to be considered. Specifically, neither induced impacts in the capital infrastructure, localized regional or process specific impacts, nor changes in economic structure induced by life-cycle economics are addressed in the traditional input-output framework.

The input-output framework inherently focuses the analysis on changes in the composition of production resulting from the shift in motor vehicle market shares. Limitations of this analysis procedure may miss some avenues of potential impacts. The input-output model, as a demand-driven approach does not explore the capital constraints or capital investment approach. Rather, the analysis assumes that the required production infrastructure will be generated and represented

in the model as expenditure streams for the annualized return on capital. The analysis does not explore the level of specific real investment nor the indirect economic impacts associated with the deployment of that infrastructure.

Even with the number of sectors incorporated in the Benchmark input-output, important details may be obscured. In particular, while the analysis may indicate no critical industrial bottlenecks, localized bottlenecks may arise from a regional concentration of critical activity. Similarly, significant increases in the demands for specific occupations or industrial processes may inhibit smooth deployment. The benchmark input-output structure does not adequately reflect the full life-cycle impacts of changes in transportation services and may thus mask some aspects of impacts. The current study limited itself only to motor vehicle production impacts and did not address other life-cycle issues such as change in fuel demand or recycling options.

3.4.3 Further Research Issues Related to Infrastructure Development

Several issues raised above could be resolved by expanding the study methodology. The current input-output frame work, could be extended to address the full life cycle impacts by restructuring some sectors, including additional engineering data and using information on scrap recycling in the work-table. The input-output model could be extended to more fully capture the process specific aspects of automobile production and materials uses (see for example, Dieffenbach and Mascarin 1993). A more in depth analysis of capital requirements for the alternative production modes could incorporate the indirect impacts associated with the deployment in 3X vehicle production.

The regional output and employment impacts could be derived by linking the projected changes in national activity with the regional (state or county) location of economic activity. Small national changes may give rise to large local change due to concentration of key activities.

Analysis of the alternative 3X vehicle scenarios within the expanded context of a complete and detailed Social Account Model would also permit a more comprehensive analysis, including examination of auto usage impacts, recycling shifts, income effects and indirect impacts on exports and imports.

4. 3X VEHICLES AND AUTOMOBILE RECYCLING

Automobile recycling in the United States is estimated to be a \$3.7 billion industry currently, employing over 40,000 people at more than 7,000 businesses (ADRA 1996). With the recent trend toward the substitution of ferrous materials with lightweight materials (e.g., aluminum and composites), the economic viability of the industry is in question. In the absence of cost-effective recycling technologies for lightweight materials, vehicles with lower ferrous content reduce the recycling industry's revenue while increasing the landfilling cost for the disposal of non-metallic materials. The economic viability of the automobile recycling industry becomes an important infrastructure issue for the PNGV as the material composition of 3X vehicles is anticipated to differ significantly from what it is today. The PNGV program intends to develop 3X vehicles that will reduce fuel consumption by two thirds but otherwise have price, comfort, safety, and other measures of performance similar to the typical automobile now on the market. 3X vehicles will contain a considerable amount of aluminum and composites to achieve the PNGV overall weight reduction goal of 40%. A recent report by Oak Ridge National Laboratory (ORNL) (Das et al. 1997) provided a cursory examination of the potential impacts of 3X vehicles on the current automobile recycling infrastructure and the future viability of conventional automobile recycling industry. This report follows that work with the development of a spreadsheet model of the current automobile recycling industry to assess and quantify potential impacts of the major shift in the material composition of 3X vehicles on three distinct players in the automobile recycling industry.

4.1 Recycling Infrastructure

The recycling infrastructure can be divided into several components, depending how steps required to process scrapped cars are integrated. Here we consider the infrastructure as consisting mainly of three components, i.e., dismantlers, shredders, and non-ferrous separators. Figure 4-1 shows a schematic representation of the current automobile recycling infrastructure. Dismantlers remove parts for sale and crush what remains of the vehicle into "hulks" which are delivered to shredders for further processing. At shredders the hulks are shredded into fist-sized pieces, and most of the ferrous content and a small amount of aluminum is removed. The

Figure 4-1. A schematic representation of the current automobile recycling infrastructure non-metallic materials that remain are landfilled as automotive shredder residue (ASR) at this

non-metallic materials that remain are landfilled as automotive shredder residue (ASR) at this step. What remains after the shredder removes ferrous and non-metallic materials is called the “heavy blend.” From this red-metal-rich heavy blend, non-ferrous separators process aluminum, zinc, and red metals. Table 4-1 shows the current composition of an average automobile, along with the recovery/disposal rates of each material by the three recycling process components considered here. The percentage value under each recycling stage indicates the percentage of total initial material composition that is processed at that stage either by recycling and/or landfilling. Only plastics and the small fraction of metals that remains due to the inefficiency of recycling processes are assumed to be landfilled.

Table 4-1. Current Composition of an Average Automobile along with Material Recovery/Disposal Rates^a at Each Recycling Stage				
Type	Weight (lbs)	Material Recovery/Disposal Rate		
		Dismantling (% wt)	Shredder (% wt)	Non-ferrous Separation (% wt)
Carbon steel	1526	35	64	1
High strength steel	369	35	64	1
Cast iron	350	90	9	1
Cast aluminum	178	15	20	65
Wrought aluminum	52	15	20	65
Plastics	342	0	90	10
Magnesium	5	0	20	80
Copper	45	20	0	80
Zinc	15	0	0	100
Other materials	358	50	50	0
Total weight	3240	na	na	na

^aDisposal is by recycling and landfilling combined.
na=not applicable

There are about 10,000 dismantlers in the United States today, processing about 11 million cars annually. They remove valuable items such as engine blocks, transmissions, reusable or remanufacturable spare parts as well as parts that from the shredder’s standpoint are undesirable, i.e., batteries, tires, catalytic converters, radiators, fuel tanks, fluids, etc., before they flatten the vehicle into a hulk and sell it to a shredder. Dismantling of vehicles currently is limited to ferrous parts (see Table 4-1) and, to a small extent, aluminum and other non-ferrous parts. Today, about 15% of aluminum scrap—mostly wheels and radiators—is removed by dismantlers (Tessieri

1997). The copper removed by dismantlers is limited to radiators, from which more than 95% of the copper and copper alloy fraction they contain are currently recycled (Sundberg 1996). The composition of the automobile hulk is determined by the dismantler. The viability of the downstream recycling components (i.e., shredders and non-ferrous separators) depends in part on the extent of material removal occurring at dismantlers.

About half of U.S. dismantlers are family-run operations, employing less than a dozen people. Purchases of obsolete vehicles are usually made from insurance contractors and adjusters, auto dealers, auctions, and individual customers. A 1996 survey of the industry by the Automobile Dismantlers and Recyclers Association indicates that most vehicles are purchased from salvage pool auctions; other sources account for equal portions of the vehicles but each is significantly less than the amount acquired from salvage pool auctions (ADRA 1996). Dismantlers sell their inventory—priced about 50% less than the comparable new parts—to commercial operations including body shops, new and used car dealers, repair shops, and auto and truck fleets (Wall 1997). There exists considerable variation in the dismantling industry with some dismantlers concentrating on used parts and sending cars elsewhere to be crushed before they are sent to a shredder. Some dismantlers specialize in late model year cars, e.g., 35% of all dismantlers specialize in cars less than five years old (ADRA 1996). It is comparatively rare today due to poor economics that dismantlers remove parts (e.g., engines) for scrap, engines are generally sold as used parts.

Hulks from dismantlers are sold to shredders, where along with other white good materials they are shredded. (White goods make up 20% of shredders' feed.) The heart of any automobile shredder system is the hammer mill or shredder where an automobile is broken into fist-size pieces. Hammermills operate by rotating a series of hammers mounted to discs at a fixed distance past an anvil. The material to be crushed is fed into the rotating hammers and is squeezed between the hammers and the anvil. The material is then discharged through fixed grates or carried by the hammers and squeezed again. A shredder can reduce a car to fist-sized pieces in about 45 seconds. These machines, however, require extensive maintenance. A normal work day is only 10 to 12 hours followed by a 6- to 8-hour maintenance shift.

The material from the shredder is conveyed to a series of magnetic and air separators. These units separate the shredder scrap into three fractions: ferrous, non-ferrous metals, and non-metallic. Ferrous materials are removed mostly by means of magnetic separation, whereas non-metallic materials (i.e., plastic, foam, and rubber) are collected by cyclone separators. Ferrous scrap usually goes to steel mills as an important feed material. The non-ferrous portion of the shredder scrap goes through a series of eddy-current separators that divides the stream in two parts—one containing aluminum sold for secondary foundry alloy castings and another fraction rich with red metals (e.g., copper, zinc, and lead). Downstream processing technologies are comparatively new and are still evolving. Specifically, eddy current separators became popular as an integrated operation among scrap processors about 7–8 years ago.

Further processing of the red-metal rich fraction of shredder materials is very limited; there are about one dozen non-ferrous separators operating in North America today. Inadequate supply of input materials has been the major cause for the stagnant growth of non-ferrous separators in the industry. The red-metal- rich fraction of shredder materials is usually sold under different commodity codes (e.g., Zorba) at 50-60% of the original scrap metal price. It is further processed using heavy-media separator type systems (e.g., sink/float) to separate its constituent metals. The separation of the various non-ferrous metals depends upon the interaction between the metals and a particulate suspension (a heavy media separator). The float product in heavy media separation is mostly aluminum, whereas the sink product is a metal mixture containing copper, zinc, and residual iron. The sink product is further separated by means of handpicking into zinc and copper scrap metal fractions.

4.2 Recycling Infrastructure Model

A spreadsheet cost model of the automobile recycling infrastructure was developed to estimate the potential effects of 3X vehicles on the future economic viability of the recycling industry. Starting with dismantlers, then shredders and non-ferrous separators, each component's operations were represented in an aggregate form in the model. A typical facility is represented for each of the steps of the recycling as discussed earlier. In addition, outputs of each of the three processing components are dependent on the mass of the input, which is affected by the change in the materials composition of the automobile and/or the mass of the material separated for disposal at preceding process steps. Recycling efficiency is included at the shredding and non-ferrous separation steps, which estimate the amount of material that is to be landfilled. Costs for each processing step include the costs of feed material, capital (equipment), operation, facility, and disposal. Revenues at the dismantling stage are based on three times the metal price, whereas at the shredder and non-ferrous separation stages they are determined by scrap metal price. Revenue at the dismantling stage (i.e., three times the metal price) is estimated based on the recent resale value of parts obtained by a dismantler (Wall 1997). In fact, there exists quite a variation in the resale value of parts whose effect on the profitability of dismantlers is examined later in Sect. 4.3.2. Profitability of the operation is determined as the ratio of net revenue to cost.

In addition to reviewing relevant literature, we obtained cost information from industry members. Although an analysis based on individual parts is preferable to analysis based on percentage material composition (shown in Table 4-1), it was not considered here due to limited data availability. Particularly at the dismantling stage, parts are sold for their functional capabilities (reuse) rather than their material content, with some notable exceptions such as lead in batteries and platinum-group metals in catalytic converters. Dismantling of an automobile based on a part's material content is being considered to obtain homogeneous material streams. The following paragraphs discuss the major assumptions made for each of the recycling stages.

A representative dismantling facility involved in both used parts and scrapped car business is modeled here based on the information collected from various sources in the industry (Wall 1997, Gesing 1997). The facility under consideration is assumed to handle 10 cars/day or 2500

cars/year, requiring \$0.6M capital investment and 6 man-hours/car of labor. The price paid by dismantlers for a scrapped car varies widely in the range of \$100-\$2000, depending on the quality of parts that could be obtained from it. The price paid for scrapped cars correlates with the price obtained from parts sale. We assume the average price of scrapped cars to be \$750/car, that about 800 lbs of parts are removed from the car having an average total weight of 3240 lbs, and that used parts are sold at a price three times the virgin metal price (as discussed above). Operating costs include mainly direct labor costs, assumed to be 6 hours/car. The source of revenue at this step includes hulks, ferrous materials, and to a limited extent non-ferrous materials.

A typical 2500 HP shredder unit with a processing capacity of 70 tons/hr is modeled here. Based on industry sources, the capital investment is estimated to be \$3M. Due to frequent maintenance requirements for hammer mills, operating costs of shredding are high, assumed to be \$22/ton processed. The feed material at this step is hulks at a cost of \$75/ton. Revenues are derived at this step from ferrous (\$145/ton) and non-ferrous fraction (\$750/ton). Landfilling non-metallic materials (i.e., ASR) is assumed to cost \$40/ton. The removal efficiencies of ferrous and non-ferrous materials at this step are assumed to be 90% and 70%, respectively.

A typical non-ferrous separator facility of 25 tons/hr capacity and capital costs of about \$400K is employed in this model. The industry estimates that the typical heavy-media separator currently has operating costs of between \$80-\$100 per ton (assumed here the lower end, i.e., \$80/ton), and the input feed material cost of \$600/ton. Non-ferrous removal efficiency is assumed to be 95%. The following sections discuss the model results obtained under the base case and aluminum and polymer composites substitution scenarios.

4.3 Results

This section presents empirical results from the recycling infrastructure model. The analysis conducted is divided into three parts — (i) the selection of base-case parameter values and estimates of the profitability of dismantlers, shredders, and non-ferrous separators; (ii) an assessment of the effect on the recycling industry due to substitution of ferrous with aluminum; and (iii) an assessment of the effect on the recycling industry due to substitution of ferrous with glass-reinforced polymer composites.

4.3.1 Base Case

The profitability of dismantlers, shredders, and non-ferrous separators under the base-case conditions assumed here are estimated to be 30%, 64%, and 14%, respectively. Profitability of the operation is determined as the ratio of net revenue to cost. Figure 4-2 shows the total cost breakdown of various processing steps of the recycling industry. The “material” category denotes the input material (e.g., hulks for shredders); whereas, the cost of facility, capital maintenance, and landfilling are included under the “other” category. For all processing steps, the material cost contributes more than 60% of total cost; for non-ferrous separators it accounts for almost 90%. Capital is a small share of the total cost, especially for non-ferrous separators,

Figure 4-2. Cost structure of the automobile recycling industry

where it accounts for less than 1%. Most of the cost at the non-ferrous separator stage is due to only two components, i.e., material and operating costs. Shredders have the largest share of operating costs, estimated to be 19% of total cost due to extensive maintenance required for the wear of contact parts. Since the cost of capital as a share of total cost is small at each step, changes to the infrastructure due to potential changes in material composition of automobiles, if any, will not be large as compared to other potential impacts.

4.3.2 Aluminum

The substitution effect of ferrous materials with aluminum on the profitability of the automobile recycling industry is shown in Figure 4-3, where we assume no changes from the base case other than vehicle composition. Each pound of aluminum is assumed to replace 1.45 lb of steel (45% weight savings). It is assumed here that potentially serious technical problems (e.g., incompatibility of cast and wrought aluminum, contamination from paints and adhesives) likely to be faced with the increased use of aluminum do not alter the current economics (i.e., per unit costs and revenues) of the industry. At the dismantling stage, the substituted material parts continue to be recycled for parts reuse; whereas the recycling share of the remaining materials at the next two recycling stages is assumed to be the same as under the base case.

The viability of dismantlers will be positively impacted with the increase in aluminum. The dismantling rate will be significantly higher than the 15% range today as more parts containing aluminum will be dismantled. With the higher value obtained of aluminum parts, the profitability of dismantlers will increase from the base case value of 30% to 50% with the 55% aluminum substitution.

Figure 4-3. Substitution of ferrous with aluminum

Shredders also will experience improved profitability due to lower hulk weight and increased revenues from aluminum (shown in Figure 4-3). With a 15% aluminum substitution, the profitability of shredders will increase by 40%. The effect on non-ferrous separators is positive, but much less so than for shredders as non-ferrous metals other than aluminum form a very small fraction of total material input. Given the current state of non-ferrous separation technologies, it is assumed here that the aluminum scrap is sold as a mixed scrap by non-ferrous separators without obtaining any premium value for wrought aluminum.

The volatility of metal and scrap metal markets, particularly non-ferrous metals, poses a concern to the economic viability of the recycling industry. Figure 4-4 is similar to Figure 4-3, but shows the effect on profitability of dismantlers, shredders, and non-ferrous separators resulting from fluctuations in scrap and metal prices. The fluctuations in prices are indicated in terms of number of times (e.g., 3x) the actual metal or scrap price assumed here. Note that “3x” has been considered as the base case for dismantlers, and “1x” for shredders and dismantlers in Figure 4-4. As one would expect, profitability declines as metal and scrap prices decline. For example, the profitability of non-ferrous separators improves sharply as scrap metal prices increases from 1x to 1.5x.

Recycling higher-aluminum-content vehicles is expected to be limited by the availability (or unavailability) of technologies to separate wrought and cast aluminum cost-effectively. Today, the recycling rate of automotive aluminum is estimated to be between 85 and 90%, and the product of recycling—secondary foundry alloy castings—constitutes fully 60–70% of the aluminum used on current vehicles. The sheet and extrusion scraps which form the minority portion of the total weight measured, are recycled into casting alloys, because secondary castings in general have a greater tolerance for alloying elements and impurities than do sheet or extrusion products. With the increased growth in the use of sheet and extrusions, there will be a need to

Note: Scenarios indicate the different metal scrap and metal price scenarios in terms of base case values.

Figure 4-4. Effect of aluminum-for-ferrous substitution and metal and scrap metal prices on profitability of the recycling industry

separate sheet, extrusions, and castings during the recycling process. The need will arise when the volume of extrusions and sheet is sufficient to simulate the recycling infrastructure to segregate these scraps for the additional value over cast alloys. In the absence of sorting there would be an excess of mixed aluminum scrap, unless large new markets were to be developed outside the automotive sector. It is projected that the growth in the primary casting alloys (i.e., sourced from virgin primary metal) between 1990-2010 will be 451%, significantly higher than the 79% projected for secondary castings (Tessieri 1997). Recycling of more than 80% of aluminum can be achieved only with some kind of separation. Besides the difficulty in the separation of wrought vs. cast alloys, potential problems during recycling include the paints/coatings and adhesives used to join different aluminum components.

Additional sorting of the mixed scrap will be driven by the prices of different aluminum scraps since the value of the aluminum scrap is enhanced as it becomes more segregated through sorting techniques. Aluminum separation could either be done at the dismantling stage or at the non-ferrous separator stage. Aluminum recycling by dismantling allows closed-loop recycling by maintaining a higher degree of alloy segregation. Automakers' keen interest today for design for disassembly lies in facilitating the careful segregation of vehicle's material content in order to achieve quality (and market price) comparable to that of virgin materials. However, if a higher rate of aluminum removal by dismantling occurs (i.e., from 15% range today to as much as 50 to 70% by 2020 by removing larger, easier-to-remove aluminum parts [Tessieri 1997]), it may threaten the viability of downstream processors by reducing their revenues. On the other hand,

aluminum separation is favored at the separator stage because, while it may be possible to remove and segregate some of the closure panels and the major aluminum castings at the dismantling stage, the main body structure will still need to be shredded to facilitate both the separation of the various aluminum and other materials and also the subsequent thermal decoating of paint films and adhesives. Fluidized bed decoating and alloy sorting using analysis by laser induced optical emission spectroscopy technologies are currently being considered to recover the full value of the aluminum from scrapped aluminum intensive vehicles (Litalien et al. 1997). The continued use of the existing infrastructure (i.e., shredding followed by separation) further favors the non-ferrous separator. Whether aluminum separation is done at the dismantling stage or non-ferrous separation stage, infrastructure needs to be developed. As mentioned earlier, less than a dozen non-ferrous separators exist today.

The spreadsheet model developed here for the recycling industry was used to examine the cost-effectiveness of aluminum separation by dismantlers versus non-ferrous separators for vehicles containing 50% more aluminum than today. Figure 4-5 examines the effect on the dismantlers' profitability due to added removal time (based on the base case removal time of 6 hours per car) for three different aluminum removal rates. The current industry profitability of 30% under base case conditions (labeled as "base case") is also shown in this figure. For a 35% aluminum removal rate, the current industry profitability can only be maintained if the added removal time necessary is less than 8 hours. The current industry profitability is affected if the rate of aluminum removal is limited to about 30% or less. The lost revenues due to lower ferrous content are partly offset by the higher value of aluminum, but more aluminum than is currently dismantled (15%) must be removed to maintain dismantlers' profitability. Exactly how much dismantling will occur depends on the percentage of ferrous substitution made.

Figure 4-5. Effect of added time required for Al separation on profitability of dismantlers (50% higher Al content vehicles)

Figure 4-6 examines the impact on dismantlers' profitability if additional investments were necessary instead of labor hours under similar aluminum removal rate scenarios as shown in Figure 4-5. The effects are very similar to those resulting from additional removal time. For a 35% aluminum removal rate, the current industry profitability can only be maintained if the added investment necessary is less than about 4.2 times the base case investment (assumed to be \$600K). A removal rate lower than about 30% will affect the current profitability of dismantlers.

Figure 4-6. Effect of additional investment requirements on profitability of Al separation for dismantlers (50% higher Al content vehicles)

We expect a combination of higher level of investments and labor hours to be used to increase the amount of aluminum dismantled. Figure 4-7 shows the effect on dismantlers' profitability under three different scenarios for the same three aluminum removal rates. The three scenarios considered are (i) Base—no change in the current investment and labor hours; (ii) High Investment—both investment and labor hours are assumed to be two times the base case; and (iii) High Labor—investments and labor hours are assumed to be 1.5 and 4 times the base case, respectively. If current industry profitability (i.e., 30%) is to be maintained, only the 50% aluminum removal case would be feasible. Under all aluminum removal rates, the “high investment” scenario is more cost-effective than the “high labor” scenario.

The effects of recovering aluminum at the non-ferrous separation stage instead of at the dismantling stage on the profitability of non-ferrous separators are shown in Figures 4-8 and 4-9. Again the analysis considers vehicles containing 50% more aluminum than today's vehicles. Again, two kinds of aluminum separation operations are considered. The first is a labor-intensive operation (see Figure 4-8) where labor is translated into operating cost/ton; the second is a capital-intensive operation (see Figure 4-9). In both of these cases, three scenarios reflect the additional value obtained due to separation of scrap. The additional value results from the price difference between cast and wrought aluminum scrap. The

Base: Labor: 6 hrs/car; Investment: \$600K
 High Investment: Labor: 2X Base; Investment 2X Base
 High Labor: Labor: 4X Base; Investment: 1.5X base

Figure 4-7. Effect of dismantling scenarios on profitability of Al separation for dismantlers (50% higher Al content vehicles)

Note: Scenarios Indicate the price difference between wrought and cast aluminum scrap

Figure 4-8. Profitability of Al separation by non-ferrous separators (50% higher Al content vehicles)

Note: Scenarios incorporate the price difference between wrought and cast aluminum scrap.

Figure 4-9. Effect of additional investment on profitability of Al separation by non-ferrous separators (50% higher Al content vehicles)

scenarios are 1.25x, 1.5x, and 2x. For example, the “1.25x” scenario indicates the price of wrought aluminum scrap is 1.25 times the cast aluminum scrap price. For the added operating cost range (i.e., \$10-\$80/ton) considered in Figure 4-8, the profitability is estimated to remain greater than base case profitability (14%) because of higher aluminum content and the value of wrought aluminum. The profitability is estimated to be 23% for an added operating cost of \$80/ton (or \$160/ton). On the other hand, additional investment’s effect on profitability is insignificant as shown on Figure 4-9. Note that capital contributed about 1% of total cost for non-ferrous separators (see Figure 4-2).

4.3.3 Composites

The substitution of composites (only glass-reinforced composites are considered here) for ferrous materials will considerably affect the profitability of the current recycling industry. Each pound of composites is assumed to replace 1.6 pounds of steel (a 60% weight savings). As assumed before under the aluminum substitution scenarios, the substituted material parts continue to be recycled for parts reuse at the dismantling stage; whereas the recycling share of the remaining materials at the next two recycling stages is assumed to be the same as under the base case. As shown in Figure 4-10, the profitability of dismantlers will increase because the value of composite parts is assumed to be higher than corresponding steel parts. For example, the profitability increases from 30% to 35% with a 25% composites-for-ferrous substitution. The profitability of dismantlers will improve as long as the current practice where dismantlers sell parts mainly for their functionality rather than for their material content is maintained. The automotive material choice (particularly composites) is of little direct consequence. On the other hand, shredders’ revenues will decrease as they will have less product to sell. Their operating and input costs will also decrease because of the lighter material (costs are in \$/ton). The exception to operating cost decreases are landfilling costs which will increase because of the additional

Figure 4-10. Substitution of ferrous with glass reinforced composites

amount of ASR that will require landfilling. With a 25% composites-for-ferrous substitution, the profitability of shredders decreases from 64% to 60%. The rate of decrease in profitability of non-ferrous separators is comparatively less than other process components; however their profitability already is smaller and drops below 10% with a 25% substitution.

Currently, no cost-effective composites recycling technology exists. It is expected that with the increase in composites content in automobiles, landfilling costs—already almost 50% of the operating costs of some shredders (Jody and Daniels 1991)—will affect shredders' profitability. Trends in landfill tipping fees for ASR disposal show increasing costs as available landfill space decreases. Figure 4-11 shows the effect of landfill tipping fees on shredders' profitability (including the effect of reduced landfill tipping fees). For a 50% composite-intensive vehicle and

Figure 4-11. Shredder profitability vs landfill tipping fee

a landfill tipping fee of about \$175/ton or more, the disposal of ASR by landfilling is not cost-effective. Under the base case, ASR disposal by landfilling ceases to be cost effective at about \$275/ton. Although a large value, this fee is not inconceivable in some regions of the U.S. and some countries (to which U.S. autos are exported) that have land shortages. These fees are also possible if ASR becomes classified as a hazardous waste. Note that the current average landfill tipping fee in the United States is in the range of \$30–\$40/ton.

The recycling of composite-intensive vehicles will require the development of a complete new infrastructure, along with new cost-effective recycling technologies. A recent study examined the question of whether the current free-market automotive recycling infrastructure can be expected to improve the amount of recycling, particularly composites (Spicer et al. 1997). The study found that despite potential changes in recycling prices for non-metals or potential changes in disassembly costs, there would likely be no change in the current practice of dismantlers and no increase in the amount of disassembly for recycling. The study concluded that recycling of non-metals via traditional disassembly will not be economically feasible despite attempts at design for recycling or changes in the marketplace. Development of new technologies (e.g., automated destructive disassembly and, shredding and sorting of multiple non-metallic parts) is needed to solve the automotive shredder residue problem.

A number of recycling options for ASR have been investigated including energy recovery (combustion), recovery of organic components for fuel and feedstock applications (pyrolysis), chemical recycling such as glycolysis and hydrolysis, separation of individual plastics, recycling ASR into composite materials utilizing thermoplastic processing or isocyanate-based binders, and utilization of ASR in concrete and asphalt for road applications. So far, these approaches are not sufficiently cost-effective to compete with disposal. Dismantling of automobiles, in addition to recycling and landfilling of ASR, has been an important consideration for composites. However, with the current, labor-intensive dismantling techniques and the necessity to shred any complex composite parts to recycle, a combination of dismantling and shredding will be used in the future recycling of the composite intensive vehicles.

4.4 Conclusions

The higher value of aluminum is likely to cause a positive impact on the recycling industry, given that cost-effective separation technologies are developed to sort aluminum by type. Easier disassembly and larger homogeneous parts offer new opportunities for profit from intrinsic material value in addition to traditional parts recovery by the dismantler. The value of aluminum will be determined to a large extent by how large quantities of aluminum from automobiles impact on aluminum primary and secondary markets. However, the recycling of aluminum will be limited to the availability of cost-effective separation technologies for different forms of aluminum, i.e., wrought vs. cast. Development of cost-effective aluminum scrap sorting technologies will be crucial to: (i) separate sheet or extrusion vs. castings; (ii) enhance the value of each alloy separated, (iii) allow for continued use of the current infrastructure, i.e., shredding followed by separation; and (iv) achieve a >80% recycling goal, since the market for mixed scrap

is limited only to the automotive market. Aluminum separation could be done either at the dismantling or the separation stage. Based on the limited analysis presented here, sorting by non-ferrous separators is cost-effective due to additional revenues generated from more, higher-value aluminum. Since non-ferrous separation is limited to less than a dozen companies today, significant capacity building will be necessary, but very limited capital needed, if aluminum separation is done at this stage.

The substitution of composites threatens the economic viability of the current recycling industry. Traditional dismantling raises concerns for dismantlers' viability since dismantling will be limited to only simple-to-remove composite parts. The recycling infrastructure beyond dismantlers will be affected the most. Shredders, in particular, are threatened because their revenues will decrease while their costs associated with ASR disposal will increase. The viability of the landfilling option is considerably reduced as tipping fees increase. For example, for a 50% composite-intensive vehicle and a landfill tipping fee of more than \$175/ton, the disposal of ASR by landfilling is not cost-effective, compared to a value of \$275/ton under base case conditions. No cost-effective technologies exist to recycle composites today. Besides the trend of increasing landfill tipping fees, public concern about and opposition to disposing composites by landfilling is growing. Relying solely on dismantling to recycle composites will not be the solution because of its expense. Also, in some cases shredding will be necessary to recycle complex parts composed of multiple materials. It is anticipated that a combination of dismantling of reusable parts with shredding of the remaining scrap in future recycling of composite intensive vehicles will be used to achieve the 80% recycling goal. Along with new automated dismantling, shredding and sorting technologies, a new associated infrastructure will be necessary.

5. PNGV INFRASTRUCTURE AND MARKET ACCEPTABILITY ISSUES

5.1 Introduction

Technological sophistication, the ability to manufacture adequate numbers of vehicles, and the lure of remarkable fuel efficiency are necessary for the ultimate market success of automobiles manufactured through the PNGV. However, these items, alone, are insufficient to assure market success. The simple fact is that market success depends on consumers' willingness to purchase the vehicles over time; the existence of 3X vehicles—the *opportunity* to purchase them—does not automatically translate into actual vehicle sales. Therefore, this chapter explores issues influencing the successful deployment of alternative vehicle technologies from the perspective of potential consumers.⁷ Our focus is on possible barriers to market success, not on factors that induce market success.

We have organized potential market barriers into two overarching categories, infrastructure and market acceptability issues. Infrastructure includes physical as well as social and institutional elements. Market acceptance encompasses safety issues, policy consistency, market niches, and the ability of 3X vehicles to accommodate consumers' expectations. Although this chapter identifies a considerable number of potential market barriers, it is clear that safety is the highest priority concern. We discuss safety largely under the heading of “market acceptance,” since markets for safety are likely to influence both vehicle prices and consumer demand. However, safety concerns permeate physical and social infrastructure issues.

5.2 Physical Infrastructure

The physical infrastructure necessary to manufacture 3X vehicles has been discussed elsewhere in this report. In this chapter, we discuss elements of the physical infrastructure necessary for people to be able to drive their vehicles where they want to go. We raise issues regarding two categories of physical infrastructure that may impede the widespread acceptance of 3X vehicles, fueling and constraints on driving.

5.2.1 Fueling

The exploration of issues in this section relates primarily to alternative fuels that are not widely available and with which the public has little experience (at least in an automotive context). Issues of safety, availability, and distribution are fuel-specific. In this section we provide only a general exploration of issues associated with alternative fuels.

Clearly, consumers must be able to purchase alternative fuels within the range of locations in which they drive. Although a network of fueling stations will be essential, and it seems logical that alternative fuels would be dispensed from existing stations converted to dispense alternative fuels, some obstacles may hinder or thwart the process of siting these stations. Such undesirable

⁷ Information in this chapter is drawn from literature on the PNGV (hard-copy reports and the PNGV web site), discussions with persons knowledgeable about cars and PNGV, and informal interviews with a small number of automobile dealers and maintenance personnel.

characteristics of refueling as noises and odors may influence nearby residents and businesses to object to siting fuel stations in particular locations. Hazards, or disamenities associated with alternative fuels generally, may lead to inconvenient fueling locations, away from densely populated or developed areas. Fuel characteristics, including requirements for refueling methods different from pumping gasoline, may lead to new liability issues for fuel station owners and operators. Together, this set of issues could contribute to difficulties in obtaining permits to site fuel stations.

The characteristics of some alternative fuels may impose different or greater health risks to those individuals refueling vehicles and to vehicle occupants than is the case for gasoline. Specialized equipment may be necessary for fuel storage and refueling, perhaps leading to additional equipment costs compared with a gasoline station-and an additional cost burden on consumers. Taken together, the risks associated with fuels and with operating refueling technologies may lead to requirements for trained or licensed station attendants. Even if such training or licensing is not required, self-service may no longer be an option for consumers and the costs associated with fuel-station attendants would be passed on to consumers. Public perceptions of the relative safety of refueling with different alternative fuels may influence individuals' willingness to refuel, themselves (if that option is allowed), or to purchase the vehicles at all.

Some of the fuels that may be used for 3X vehicles might require particular equipment or conditions at residential and business parking facilities. Ventilation for hydrogen-powered vehicles is regarded by the technologists developing the systems as "more a problem of perception than reality." A metal hydride system, which is being used in experimental buses, would not require venting of hydrogen gas, which would be required if a cryogenic system were used; besides which, gasoline vapors may be considered more dangerous than hydrogen. Nonetheless, perceptions are a powerful market reality, and for some the Hindenberg disaster (the highly publicized German dirigible filled with hydrogen exploded while landing after its maiden trans-Atlantic flight, essentially halting the use of dirigibles for transportation) is their only knowledge of hydrogen applied to transportation purposes. One cannot afford to ignore perceptions when laying the foundations for a new technological system. Safety concerns—both "real" and "perceived"—may lead to changes in how new residential and business parking facilities are built, and may require retrofits for existing facilities.

Fuel distribution and transportation are essential for creating and maintaining a network of fueling stations. Will alternative fuel distribution and transportation create new or greater hazards to people, property, and the environment? For instance, when accidents occur, fuel volatiles and ignitability may differ from those associated with gasoline (e.g., with hydrogen fuels). If so, emergency response personnel might require specialized training (see Section 5.3.3). Additionally, accident-related damage patterns to the highway infrastructure may be different from those associated with vehicles transporting gasoline.

5.2.2 Constraints on Driving

Vehicles that use alternative fuels might constrain individuals' driving in at least two ways. First, fuel characteristics could lead to constraints on where vehicles are allowed to be driven. Passenger vehicles using certain fuels (e.g., hydrogen fuels) might be barred from bridges and tunnels that have hazardous materials restrictions. Continued development of fuel cells probably would alleviate this potential concern. Second, the distribution of fueling stations may restrict where NGVs can be driven. Initially, the geographical distribution of fueling stations may be insufficient to permit long-distance travel in NGVs. Drivers' uncertainty about the specific locations of fueling stations could inhibit long-distance travel, even if the fueling stations exist. Further, if fueling stations are located sporadically along major thoroughfares like interstate highways, a limited, off-thoroughfare distribution may inhibit how far people are willing or able to travel beyond those main routes. Greater market penetration of the vehicles would result in a greater frequency and distribution of refueling stations across the country, but it is not clear the extent to which the lack of such a distribution network would depress initial demand for the vehicles, thus reducing the likely availability of alternative fuels across the country—a classic catch-22.

5.3 Social and Institutional Infrastructure

Not all infrastructure is concrete and steel. Institutions grow up around new technological systems to provide various types of support needed to keep machinery operating at the times and places people want to have it available. Because these components of infrastructure are less visible than the technologies themselves (although most of them are certainly well known), the costs of developing new components and modifying existing ones may not be included in the initial, technology cost estimates. Nonetheless, these flesh-and-blood and paper-and-ink infrastructure components were costly to develop for conventional vehicles. Any required modifications would involve additional costs to accommodate the engineering components of the new technological systems that comprise 3X vehicles. We consider four of these modifications: the system for compensating for damages (insurance), the system for keeping the new vehicles running as they were designed (service and maintenance), the system for keeping people in the relevant industries abreast of how to operate their respective parts of the new technologies (training, certification, and licensing), and the system that ensures technological compatibility in different locations (uniformity of standards).

5.3.1 Relationship of Vehicle Construction to Insurance Costs

Recent trends in construction of light-weight vehicles have improved the safety of passenger compartments by making many of the surrounding components collapsible. That is, axles, engine mount, etc., are designed so as not to deliver the force of impact of a crash straight into the passenger compartment. Instead, they are designed to collapse, break off, or slide under or around the passenger box. This type of design increases passenger survivability in crashes, but it can increase the damage and repair costs of relatively minor accidents. To the extent that 3X vehicles are lightened to improve fuel mileage by incorporating, and even extending, collapsible construction, insurance rates on these vehicles would rise to compensate for the higher costs of

more frequent, minor accidents. Such higher rates would dampen the demand for collapsible-construction vehicles. However, to the extent that collapsible construction reduced injuries and associated medical costs, bodily injury insurance costs would tend to fall, leaving the net change uncertain beforehand.

A further insurance implication of the type of construction contemplated for 3X vehicles follows from the use of larger, integrated components, aluminum, and advanced plastics. First, damage to one of these larger parts might be more difficult to isolate for repair purposes. Damage to one segment of such a larger component might weaken the entire component or at least a larger part of it than the immediately affected area. This would tend to raise repair costs. Second, insurance companies tend to prefer repairs to replacements, and it might take a period of learning between the repair industry and the insurance industry to find a new equilibrium between repair and replacement. This would not be expected to pose a long-term problem, but could affect insurance companies' attitudes toward repairs early in the marketing of these vehicles. Third, the new materials may perform differently under repairs. In particular, aluminum tends to weaken permanently after being crunched, even though it can be straightened and smoothed. Repairs to large, plastic components may require replacement of expensive parts that have suffered only relatively minor damage. Markets can be anticipated to adjust to these "challenges," but some of the cost- and weight-savings of the new construction may have to be traded off against a new, and possibly higher, regime of repair costs.

5.3.2 Maintenance and Service

The training for the maintenance and service of these new vehicles probably will occur primarily within the network of dealers. Some aspects of these vehicles will differ considerably from corresponding aspects of conventional vehicles, leaving service and maintenance suppliers outside the dealer network at some disadvantage. For example, some of the metals that are likely to be used in the new vehicles must be worked with differently, even with special equipment, from conventional automobile steel. Some components may actually be damaged if they are treated with conventional methods by repair personnel who are not properly trained and equipped.

This potential bottleneck on the supply of service and maintenance for 3X vehicles could have some implications for long-distance travel with these vehicles. To the extent that more sparsely populated, rural areas in the central part of the country can expect a much smaller number of these vehicles, dealers in such areas may find it unprofitable to make the investment in training and specialized equipment. Breakdowns in such areas with severely limited service availability could be very expensive and time-consuming. If such a situation emerged, it could dampen the demand for vehicles that would be used routinely in long-distance travel and might even constitute a tipping consideration in the markets for vehicles that are used only occasionally for such travel.

The potential restrictions on the supply of maintenance and repair services could affect the emergence of a second-hand parts market. Although dismantlers are expected to get used parts

from 3X vehicles, the possible tilt toward dealer-provided maintenance and repair services may restrict demand for these used parts. Therefore, the supply may exist for a used part market, but the demand may not meet the supply. Although many non-dealer maintenance and repair shops use second-hand parts, dealers—whom we believe would initially assume repair and maintenance functions for 3X vehicles—tend not to use second-hand parts. The used parts market for many components of conventional vehicles is very well developed. By keeping down operation costs, the use of such parts can extend the economic life of a vehicle.

Conversely, with considerably more restricted availability of used parts for 3X vehicles—particularly in the early years of 3X vehicle introduction—the expected life of the aggregate 3X vehicle fleet would be lowered, as vehicles at the margin of economic maintenance or repairability with new parts would be scrapped. This knowledge would be incorporated by the market for 3X vehicles, and the shorter expected operational life could depress demand. The magnitude of this effect by itself is unknown, but a large number of small effects of this sort could significantly affect the aggregate market for 3X vehicles.

Vehicle owners, being creatures of habit vis-à-vis their vehicles, are accustomed to the maintenance schedules of conventional vehicles *and* to their vehicles' tolerance of delayed maintenance. It is too early to know what the maintenance schedules for 3X vehicles will be. If less frequent maintenance schedules are suggested by manufacturers, then demand for these vehicles may increase. However, more frequent regular maintenance may have a dampening effect. A more frequent maintenance schedule for 3X vehicles would raise their operating costs, but probably of greater significance for demand is the reaction of the new vehicles to delayed maintenance. Would any 3X vehicle components be sufficiently sensitive to cause sharp decreases in vehicle performance, or possibly even danger to vehicle operation, if the recommended maintenance schedule were not strictly observed?

5.3.3 Training, Certification, and Licensing

Another potentially significant social and institutional infrastructure issue for 3X vehicles is training, certification, and licensing. The sophistication of new technologies, alternative fuels or fuel mixtures, and materials used in 3X vehicle construction may require specialized knowledge; the lack of such knowledge could be damaging to the vehicles and their passengers. A relatively mundane example is the process of repairing dents in auto bodies. Some dents in metal bodies can be hammered out; hammering some composite materials can inflict damage greater than the initial dent. Training may be necessary for the wide range of persons who deal with or drive 3X vehicles. A smaller set of workers may require certification or, perhaps, licensing.

Emergency response personnel need to assess accident situations quickly and know how to respond appropriately. Particularly because even the highest projections for 3X vehicle market saturation falls well below 100%, emergency response personnel may need to identify the kinds of vehicles involved in accidents, the kinds of fuels used, and the correct response. Refueling attendants may need to learn how to refuel different kinds of vehicles, and may need some fundamental safety and accident response training. Vehicle inspectors may have to learn the

particularities of NGVs, which may require different kinds of inspections than gasoline-fueled vehicles. Service and maintenance personnel who work on 3X vehicles may require specialized training or certification. Likewise, people who repair vehicles—whether body, engine, or other systems—may require such training or certification. And, the drivers themselves may need training to learn the particularities of what to do and, perhaps more importantly, what not to do with 3X vehicles.

5.3.4 Uniformity of Standards

What standards will emerge for the content of training, certification, and licensing programs? What safety standards will emerge for refueling or service and repair facilities? Because standards can be set by manufacturers, within jurisdictions, or nationally, it is not clear whether standards would be uniform across the country. Non-uniform standards may set the stage for safety and other market acceptance problems to emerge. Information about safety problems in one area of the country likely would spread to other parts of the country, particularly with increasing use of the Internet. 3X vehicles or their fuels may be stigmatized as “unsafe” or “unreliable,” even if standards either do not exist or are lax only in small portions of the country. Further, safety standards may vary across the globe. If those standards are sufficiently variable, it is possible that international trade potential may be reduced.

5.4 Market Acceptance

The Edsel was a good car, but it cost Ford a bundle. It is a well known fact in the technology innovation/technology acceptance literature that technical excellence, if not entirely incidental to market success, is definitely not sufficient to ensure success in the market place. Bombardment with advertising is only a partial substitute for fulfilling the expectations of consumers who have alternative products available to meet their demands for performance and convenience. We discuss three major factors that we believe will be important in 3X vehicles gaining acceptance and popularity in the market: safety, initial uncertainties regarding technical performance, and the cost/convenience trade-off. Another aspect of commercial success involves identifying markets for specific aspects of the multi-dimensional products that motor vehicles represent. “The market” for any particular type of vehicle almost always is a specific segment of the entire market for vehicles. Recognizing the demands represented by market niches can help in tailoring the technological packages in combinations that will require consumers to buy as little as possible of what they don’t want while offering them as much as possible of what they do want. Accordingly, the final part of this section discusses several market niches that may be important to 3X vehicles.

5.4.1 Safety

There is no question that safety is the highest-priority issue for consumer and market acceptance of PNGV automobiles. Concerns about safety permeate social and institutional infrastructure considerations from the mechanical operation and maintenance level to the policy level, and safety is the foremost potential “show stopper” for the market acceptance of 3X vehicles. Concerns about safety can inhibit consumer purchases of 3X vehicles from the start; a poor

safety record can underscore those concerns and have a long-term influence on market acceptance. And, the initial and early markets for 3X vehicles may be particularly vulnerable to high-profile events that can stigmatize the vehicles as “dangerous.” The current, and costly, efforts of the Mercedes-Benz Corporation to modify its new A-Class vehicle after it failed some “extreme driving maneuvers”—the so-called elk test—is an object lesson in the commercial importance of completing the safety homework before manufacturing rather than after. The nearly \$200 million additional engineering work required to develop a completely new chassis tuning for the vehicle will put off its financial break-even date for the company by several years (Mercedes Benz 1997a,b).

Automobile dealers anticipate that the dangers associated with 2000-pound vehicles colliding with 3500–4000-pound vehicles will be prospective buyers’ major concern. The safety-related risks associated with these large weight differentials do not constitute a short-term problem that marks the transition from no 3X vehicles to an established market for 3X vehicles for at least two reasons. First, because participants in the PNGV foresee that 3X vehicles will develop into only a portion of passenger vehicles on the road, fuel-efficient 3X vehicles persistently may be among the lightest on the road. Second, even if one assumes total saturation of the automobile market with light-weight vehicles, truck will remain. The ratio of truck weights to car weights roughly will double, with predictably grim consequences for car-truck accidents.

In addition to weight differentials, car design also can be significant in influencing the harm from crashes. For instance, the position (height) of one vehicle’s bumper relative to the other’s passenger compartment can influence the nature and gravity of harm to passengers. The popular press has begun to surface such concerns because of evidence from crashes involving the increasing numbers of large, sport-utility vehicles on the road. Sport-utility vehicle bumpers tend to be higher off the ground than the bumpers for typical automobiles. Consequently, in crashes, the sport-utility vehicles’ bumpers may hit the cars’ passengers at upper-body level-causing serious injuries and deaths (Bradsher 1997a, 1997b). Fuel-efficient 3X vehicle designs that involve cars riding lower to the ground than other vehicles on the road may create similar safety-related hazards for 3X vehicle drivers and passengers.

Because 3X vehicle technologies may be new and unfamiliar to many consumers, market acceptance of 3X vehicles may be particularly vulnerable to adverse publicity. Therefore, a high-profile accident attributable to 3X vehicle characteristics (e.g., a runaway flywheel, fuel malfunction or explosion, or failure of the advanced braking system) could become a catalyst for market failure, a market poison-pill.

We previously mentioned the possibility of inconsistent safety standards within the country and internationally. However, there are at least two other issues associated with potential policy inconsistencies. One issue is the possibility that the PNGV program could be perceived as conflicting with federal goals for highway safety, if the damages inflicted on humans and property from car accidents involving 3X vehicles are greater than those involving other vehicles on the road. Another, perhaps more significant policy issue is the possibility that, by promoting this

program, the federal government could be perceived as asking citizens to trade off fuel efficiency and emission reductions for their families' safety.

5.4.2 Performance Uncertainties

Recent advances in investment theory have produced what is called a "bad news principle": rather than making investment decisions on the basis of expected values (i.e., projected averages), investors focus on the worst possible outcome of an investment. As information on actual equipment performance emerges, these worst-possible-outcome estimates would be revised to align more closely with recorded performance. On new, big-ticket items like vehicles, consumers tend to wait for information to emerge that may give them an idea how well they will like the items. For better or worse, the Internet has become an important and rapid method of communication about vehicle performance, considerably expanding local, word-of-mouth communication and intensifying the message content of relatively formal, printed media.

5.4.3 Comfort, Accommodating Consumer Expectations, Costs

Market acceptance involves a number of subtle interactions between product and consumer, particularly when the consumer must actively participate in the consumption of the product. For example, to "consume" a vehicle, the vehicle owner must perform a number of activities, ranging from driving to refueling, to getting in and out of the vehicle, to understanding the handling properties of the vehicle in various circumstances. There is considerable transferability of experience in each of these areas between vehicles, but differences do emerge when an operator makes a major change in such characteristics as weight, size (length and width), fuel type (e.g., gasoline versus diesel), etc. A simple but striking example of different operating characteristics is how operators respond to automatic shoulder seatbelts—the kind that snaps into the door, engages across the passenger (including the operator) when the vehicle is started, and disengages several seconds after a door is opened. People can get hurt trying to exit such a vehicle at the same pace they could exit one without such seatbelts. Long-standing patterns of nearly automatic movement must be adjusted. As another example, 3X vehicle refueling also may require drivers to alter familiar patterns of behavior. For instance, design constraints that are part of reaching the light weights required to get the high mileage might require that the placement of fuel receptacles be different for 3X vehicles than traditional cars. Further, refueling with some alternative fuels, such as fuel cells, might differ enough from the familiar activity of pumping gasoline to put off some potential buyers. And, operators of dual-fuel vehicles may have to remember which fuel goes where. Individually, each of these adjustments may be "no big deal," but combining several together could leave a potential purchaser looking for some price compensation to accept the required changes in operating behavior.

The market acceptability consequences of changes in comfort are closely related to those of changes in operational characteristics. Smoothness of ride may be an issue to keep in mind with 3X vehicle design because of the weight reductions anticipated to be required to obtain the targeted mileage improvements. Efforts to reduce weight could reduce the ratio of sprung weight (essentially, everything above the chassis) to unsprung weight, which would make for a rougher ride and hamper such handling actions as turning and rounding curves. A reputation for "riding

like a truck” could diminish the market for family vehicles with these characteristics. Modification of tire widths and materials to reduce weight and increase fuel efficiency could operate similarly to a reduction of sprung to unsprung weight. Compensation with alternative suspension systems, such as air suspension, could prove expensive.

Vehicle performance includes a number of subtle issues as well. Power and acceleration are highly desirable characteristics for many consumers. Reports of satisfactory acceleration in a light-weight vehicle may be based on single-passenger occupancy tests, but when loaded with the family or some other riders from work, along with some luggage in the trunk, the acceleration performance of the light-weight vehicle relative to its heavier cousin may deteriorate substantially. Urban expressway driving poses the frequent need for quick acceleration regardless of vehicle occupancy. The reputation 3X vehicles develop for acceleration under the typical *range* of driving conditions (not simply one condition) can be expected to affect their market acceptability.

Another of the more subtle performance issues is how the vehicles handle under different weather conditions and in different terrains and climates. The handling characteristics of small vehicles under these various conditions are generally well known. If making these vehicles even lighter changed some of these operational characteristics, questions about these dimensions of performance could push many potential purchasers into the “wait-and-see” category.

5.4.4 Market Niches

There are several natural market niches for 3X vehicles, but each should be studied for the match between some of these vehicles’ characteristics and the usual characteristics demanded in these market segments. The first apparent niche is actually quite a large market: drivers in urban areas. Trips in urban areas tend to be shorter than the typical trip in non-metropolitan areas, and drivers whose travel is dominated by shorter trips tend to use lighter vehicles (Hu and Young 1990). This characteristic certainly fits the 3X vehicles. However, urban driving incurs a higher incidence of relatively minor accidents—the fender-bender. With collapsible construction to reduce vehicle weight, this other characteristic of urban vehicle travel could yield higher repair costs for a given accident than would be expected in a conventional vehicle. Higher repair costs would translate into higher insurance rates and, in turn, into higher vehicle operation costs. Additionally, the possibility of having a vehicle under repair longer for any given repair would add to inconvenience.

Moving to personal characteristics of operators as the basis for a market niche, the traditional customer base for light-weight, non-sport vehicles has been the short-distance driver (urban residents) and the lower-income operator who wants a low first-cost but is not especially concerned with fuel mileage unless additional mileage comes at a very low addition to first-cost. Will the light-weight 3X vehicles be inexpensive enough to enter this portion of the light-weight vehicle market? To the extent that these vehicles are toward the lower part of the mid-price range, they could lose demand at the low-income end of the light-weight vehicle market. Whether they gain at the higher-income end of that market because of some of their other

characteristics is an important question. The traditional customer base for fuel-efficient, low-emission vehicles has not been low-income drivers, and many upper-income buyers tend to focus on other vehicle characteristics associated with specialty engineering and high cost and visibility. So-called “greens” span the income distribution, but people with the income to pay for their environmental preferences become more heavily distributed in the mid-range of the income distribution. If operators with preferences for environmentally friendly vehicle characteristics also tend to value safety relatively highly, then their willingness to trade the safety that comes with greater weight for fuel efficiency may become an important issue in market penetration.

Age may be an important market-niche characteristic of consumers. During the first decade of the next century, the large, baby-boom cohort of the U.S. population will begin to enter their sixties. For the following fifteen to twenty years, the U.S. population will age. Older drivers tend to purchase heavier vehicles, for both comfort and safety. They also can be expected to be less likely to opt for new ways of doing things when familiar ways are available at roughly comparable cost. If operating 3X vehicles entails modification of long-standing driving (or even habits acquired by passengers) habits, the older end of the vehicle market may tend to shy away from them.

Comparing anticipated 3X vehicle characteristics with closely matched market niches raises the question whether the market for those vehicles will expand markedly in the near future without another sharp oil price increase or the introduction of stringent regulation of greenhouse gas emissions and urban/regional air quality. Since the size of the market is so important to the ability to drive down production costs, it is important to assess in close detail the extent to which purchasers will accept higher initial costs (adjusted for the price-compensation for different operational and performance characteristics) for a 3X vehicle in exchange for future fuel savings and air-quality improvements.

5.5 Summary

This chapter has raised questions about a number of 3X vehicle features that may pose potential barriers to their acceptance. We have categorized them in terms of physical, social, and institutional infrastructure and market acceptance. Some of the barriers we have discussed can inhibit the successful introduction of 3X vehicles to the passenger vehicle market; others might dim the prospects for 3X vehicles during their first years on the market. Safety concerns constitute the most significant barrier, both to short- and longer-term prospects for market acceptance. An early, high-profile accident attributable to 3X vehicle fuels or design could stigmatize NGVs as being “dangerous”—a market poison pill. Even without such a high-profile event, people who associate the light weight and design of 3X vehicles with a higher incidence of serious injury or death than would occur with “regular” cars in accidents might decide not purchase the vehicles from the start. This group of people may base its decisions on probabilities or projections, and may require considerable evidence of safety over a period of several years before reconsidering its decisions. Other people may be more inclined to purchase 3X vehicles,

unless there is a high-profile accident, a pattern of safety problems emerges, or other negative characteristics are connected to 3X vehicles.

Other possible, near-term barriers to 3X vehicle acceptance that warrant consideration by PNGV managers include the availability of fuel and qualified service personnel in the places people want to drive. These barriers create a kind of “catch-22” situation in which the provision of fuel and qualified service are linked to the demand for those items; a small market for 3X vehicles may reinforce these infrastructure barriers. We also have raised the broader issue that, without such external forces as sharp oil price rises or stringent air quality regulations, the fuel efficiency and low-emissions that 3X vehicles offer may not be sufficient to create a market for revolutionary car design, engineering, and materials.

While some of the barriers discussed in this chapter could operate from the beginning, stopping the initial purchase of 3X vehicles, others could emerge over time, working singly or in combination to erode an initially satisfactory market share. These barriers include repair records, insurance issues, training and certification, safety standards, siting issues, 3X vehicle performance, comfort, and costs. We certainly do not claim that each of these potential barriers will in fact hinder 3X vehicle acceptance, but we do believe that they bear scrutiny. In some instances, the responsibility for “checking things out” would be with an automobile manufacturer’s marketing director, sometimes with the manufacturer’s engineering staff, and sometimes with officials of government agencies when the issues involve areas where markets are weak or non-existent.

PNGV can avoid becoming a case of advocates developing a technology to suit a need they define, and in their single-mindedness of purpose filtering out issues that don’t fit a narrow definition of the problem: developers and proponents repeating as a mantra “Energy efficiency, energy efficiency, energy efficiency . . .,” while consumers say, “Color, ride, head room, . . .” To reinforce the potential seriousness of the array of issues we have identified, we remind the reader of the fate of the civilian nuclear power industry in the United States. Early in the development of that industry’s technology and infrastructure, people warning of future acceptance problems were dismissed as Cassandras by the development engineers and physicists who believed they understood and had under control all the issues that might worry rational people—the “real” issues rather than “just perceptions.”

6. CONCLUSIONS

Relying on hypothetical 3X vehicle market penetration scenarios and material composition, we have attempted to identify supporting infrastructure and acceptability issues that could affect the transition to 3X vehicles. Our approach is comprehensive, examining issues ranging from materials availability to their eventual disposition and its effect on the automobile recycling industry, and from supporting industries' capacity to the public acceptability of 3X vehicles. These analyses focus on two likely 3X vehicle materials – aluminum and glass-reinforced polymer composites.

In short, our analyses have not identified any single insurmountable barrier to the changes in the market and economy that would be required to effect the transition to 3X vehicles. However, we have identified several areas where considerable change in markets, industries, technologies and perceptions might be required to provide for a smooth transition to 3X vehicles. Of particular importance to the PNGV program are areas where the Program's intervention might be required to effect this smooth transition. For example, we have identified areas where new technologies – e.g., composites recycling technologies – and thus investment in technology development would be required to maintain an industry's economic viability. Also of importance are acceptance issues – e.g., public perceptions of 3X vehicle safety – that could require information or marketing programs to address them.

To advance our capacity to identify and estimate infrastructure and cost barriers to the transition to materials that will comprise 3X vehicles, ORNL has developed, tested and implemented three different models that address potential economic barriers to the transition to 3X vehicles. The first of these models identifies infrastructure and cost barriers; the second – an input-output model – addresses changes to the macro-economy and primary and secondary industries involved in producing 3X vehicle materials; and the third addresses the effects that new materials will have on the existing automotive recycling industry. In addition, using a more qualitative methodology, we have begun to examine barriers related to market acceptability of 3X vehicles.

ORNL developed and tested the validity of a model to identify infrastructure and cost barriers to transition to the use of 3X vehicle materials. While the application is only illustrative so far – having been applied to the hypothetical scenarios of 3X vehicles and their market penetration – it holds promise for later use with better empirical data and engineering cost estimates. Principally, the analysis has found that with technology learning (“learning-by-doing”), accurate foresight, and no risk premium, the new materials can quickly gain share with PNGV production experience. Conversely, we find that if this learning-by-doing does not occur and foresight is inaccurate, 3X vehicles will fail to penetrate the market. Furthermore, we find that learning is a function of cumulative production and cumulative investment rather than of time and that compared to the learning effect, the effect of standard economies of scale is small in magnitude.

The Input-Output model demonstrates that no major difficulties are likely to arise during the transition to either composites- or aluminum-intensive 3X vehicles. The study examines both macro (GNP-wide) impacts as well as industry-specific impacts. From a macro economic perspective, we find impacts to be relatively small. However, the transition would slightly

macro (GNP-wide) impacts as well as industry-specific impacts. From a macro economic perspective, we find impacts to be relatively small. However, the transition would slightly increase labor requirements (especially the labor-intensive composite vehicle) and require a <1% increase in intermediate materials, resulting in an expansionary boost to the economy.

Although the aggregate economic impacts are small, industry specific changes may give rise to adverse adjustment situations. The I-O analysis found that the transition to 3X vehicles would cause only a few industries to experience a >2% change in base production. In general the level of impacts for the non-automotive industries tend to be small, but in both scenarios the Wholesale Trade and Motor Freight Transport Industries experience notable growth. As expected, negative impacts will occur to several steel-related industries, but declines, even for the aluminum scenario, are expected to be less than 3%. The aluminum scenario, because of its aluminum-based internal combustion engine, will introduce slightly greater and more diffuse negative impacts than the composites scenario will introduce. The two industries that would require the most growth are the plastics industry—7% growth in the composites scenario—and the aluminum and secondary non-ferrous metals industries—33% and 17% growth, respectively, in the aluminum scenario. This indicates that significant growth in the primary aluminum production industry is necessary, but phased expansion of the industry could alleviate any potential bottleneck.

A model that organizes the automobile recycling infrastructure into three components—dismantlers, shredders, and non-ferrous separators—is used to determine the impacts of 3X vehicles on the recycling industry. A typical facility is represented in the model for each of these three steps. Outputs from each of these steps depend on the mass and makeup of the input, which is affected by the changes in materials composition of automobiles. We model the industry's profitability first under the base case, then substituting aluminum for ferrous, and substituting glass-reinforced polymer composites for ferrous. We can then identify where changes in profitability of each of the three components of the industry are likely.

We find that recycling of aluminum-intensive vehicles will likely have a positive effect on the recycling industry, if some changes occur. These changes include increasing the dismantling rate beyond the current 15% to make up revenues lost from ferrous materials. Another important need is the development of cost-effective separation technologies to separate wrought from cast aluminum. Capacity building in the non-ferrous separator industry will be necessary if aluminum separation is done at this stage, where we have determined it cost effective to do.

The cost of ASR disposal and its effect on the industry's profitability is the primary threat resulting from composite intensive vehicles. Shredders in particular are threatened because their revenue will decrease while their costs associated with ASR disposal will increase. No cost effective technologies exist to recycle composites. Automated dismantling, shredding and sorting technologies (and the infrastructure to use the new technologies) will be needed to accomplish the increased dismantling and separating that glass-fiber composite automobiles will require.

Recognizing that consumer willingness to purchase 3X vehicles is essential to the penetration of these vehicles into the market, we have examined potential market barriers, organizing them into two categories: infrastructure issues and market acceptability issues. Infrastructure includes physical as well as social and institution elements. Market acceptance includes safety issues, policy consistency, market niches, and the ability of 3X vehicles to accommodate consumers' expectations. We find that safety concerns—based either on extrapolated experience with other lightweight cars or on anecdotal evidence, which has the potential for widespread, rapid delivery given the Internet and mass media—constitute the most significant barrier both in the short and long term for market acceptance. Other, less significant issues include the availability of fuel and qualified service personnel, which could affect adoption in the short term. Some barriers, e.g., 3X vehicle performance and repair records, are more apt to emerge over a longer time period. We expect that no individual infrastructure or market acceptance barrier alone is likely to effect market penetration, but combined they could have a significant effect. Given the United States' experience with the introduction of other new technologies, we offer the caution that whether the issues is based on perception or reality, there is no difference in outcome.

Considering a broad range of issues and technological and market factors, we do not find any single issue that is likely to prevent market penetration of 3X vehicles, particularly when considering the vehicles' anticipated, gradual penetration into the market. However, using hypothetical materials composition figures and market penetration scenarios, we do find that some notable economic changes may occur, critical industries need to expand, and new technologies need to be developed and adopted to accommodate the transition to 3X vehicles.

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