Titre: Title:	Technological accumulation and underlying techno-economic factors in automotive materials substitutions
Auteur: Author:	Nicolas Bélanger
Date:	1995
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Bélanger, N. (1995). Technological accumulation and underlying techno-economic factors in automotive materials substitutions [Mémoire de maîtrise, École Polytechnique de Montréal]. PolyPublie. https://publications.polymtl.ca/32586/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/32586/
Directeurs de recherche: Advisors:	Michel Normandin
Programme: Program:	Non spécifié

UNIVERSITÉ DE MONTRÉAL

TECHNOLOGICAL ACCUMULATION AND UNDERLYING TECHNO-ECONOMIC FACTORS IN AUTOMOTIVE MATERIALS SUBSTITUTIONS

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MÉMOIRE PRÉSENTÉ EN VUE DE L'OBTENTION
DU DIPLÔME DE MAÎTRISE ÈS SCIENCES APPLIQUÉES (M.Sc.A.)
(GÉNIE INDUSTRIEL)
AVRIL 1995

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Ce mémoire intitulé:

TECHNOLOGICAL ACCUMULATION AND UNDERLYING TECHNO-ECONOMIC FACTORS IN AUTOMOTIVE MATERIALS SUBSTITUTIONS

présenté par: BÉLANGER Nicolas
en vue de l'obtention du diplôme de: Maîtrise ès Sciences Appliquées
a été dument accepté par le jury d'examen constitué de:

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REMERCIEMENTS

Je voudrais tout d'abord remercier DURALCAN USA et son président Monsieur François Ameye, pour l'intérêt démontré à l'endroit de ma recherche et pour le soutien financier offert. Du même groupe, je tiens également à remercier Monsieur Floyd Buch, vice-président chez DURALCAN, ainsi que Monsieur Brian B. Chenoweth de chez ALCAN (Kingston) et Madame Denise Turnbull de chez ALCAN (Montréal).

Je remercie mon directeur de recherche, Monsieur Michel Normandin, pour m'avoir soutenu et guidé tout au long de ce projet. Je tiens à remercier tout spécialement Madame Marie Lavoie, sans qui ce projet n'aurait peut-être jamais vu le jour. Du tout début de mes études à l'École Polytechnique jusqu'au dernier instant, madame Lavoie a toujours cru en moi et elle m'a toujours offert sa plus entière coopération. Merci également à Monsieur Daniel Leblanc pour ses suggestions et sa coopération.

Parmi les gens qui ont contribué à la réalisation de ce projet, soit par leurs conseils ou suggestions, ou par leur coopération, j'aimerais remercier tout particulièrement Messieurs W. Scott MacDonald (General Motors, Cadillac Motor Car Division), Gordon R. Miesel (Ashland Chemical, Composite Polymers Division), Côme Belisle (DNN Galvanizing Corporation) et Christian Van Houtte (Association des Producteurs d'Aluminium du Québec).

De l'École Polytechnique, j'aimerais souligner l'aide et le soutien offert par le personnel du département de génie industriel, et plus particulièrement Madame Louise Bisson, qui a toujours été d'une grande gentillesse à mon égard. Merci également à Monsieur Louis A. Lefebvre pour m'avoir facilité la tâche en certaines occasions.

Finalement, merci à Eric, Julie, Sophie, Eric, Martin, Nicolas, Martin, Francis, mes parents, et à tous les autres qui m'ont appuyé tout au long de ce projet.

RÉSUMÉ

Les trois dernières décennies ont été témoin de changements majeurs dans l'industrie automobile en Amérique du Nord. Que se soit au niveau de la compétition ou de la réglementation, les constructeurs automobiles font face à une réalité tout autre que celle d'il y a vingt ou trente ans. La sélection et l'utilisation des matériaux dans l'automobile a été fortement influencée par ces changements au sein de l'industrie ainsi qu'à l'extérieur de celle-ci.

Ce mémoire porte sur les processus de substitution des matériaux dans le contexte spécifique de l'industrie automobile en Amérique du Nord. Plus particulièrement, on y cherche à comprendre l'influence des différents facteurs technologiques, économiques et sociaux sur ces processus de substitution de matériaux. Afin de pouvoir procéder à cette analyse, six cas de substitution de matériaux dans des applications automobiles bien spécifiques sont étudiés dans leur évolution. Ces six cas sont: les blocs-moteurs en aluminium, les roues en aluminium, les radiateurs en aluminium, les panneaux extérieurs en acier galvanisé, les ailes avant en polymères et les réservoirs d'essence en polymères.

L'analyse des six cas à l'étude a été réalisée à la lumière des quatre groupes de facteurs techno-économiques suivants: exigences fonctionnelles, exigences technologiques, facteurs économiques et facteurs sociaux. Les exigences fonctionnelles ont trait aux caractéristiques

requises d'un matériau (mécaniques et métallurgiques) en vue de remplir les fonctions particulières d'une application bien définie. Les exigences technologiques sont reliées aux procédés de transformation, de fabrication et d'assemblage du matériau en vue de son utilisation dans l'application en question. Les facteurs économiques regroupent l'ensemble des coûts associés à la fabrication d'une composante à partir d'un matériau particulier (coûts en matériaux, coûts de fabrication, investissements en capitaux, etc.), la compétition sur les marchés, les relations avec les employés et avec les sous-fabricants, ainsi qu'avec les consommateurs. Finalement, les facteurs sociaux découlent principalement des réglementations et des standards émis par les gouvernements.

L'analyse des six cas de substitution nous permet de voir que ceux-ci diffèrent passablement au niveau de la pénétration de leur marché respectif. Sur la période étudiée (1960-1995), les niveaux de pénétration varient de moins de 4% (ailes polymères) à plus de 95% (panneaux en acier galvanisé). Toujours à la lumière de l'analyse des six études de cas, il est possible de tirer certaines conclusions sur les facteurs qui ont pu influencer la rapidité et la profondeur de la pénétration d'un matériau pour une application automobile.

ABSTRACT

The North American automotive industry has changed dramatically over the last thirty years. In addition to a marketplace that has become more and more competitive, government regulations and standards have been increasingly influential on the automotive industry and the vehicles as such. One of the major area of change within vehicles has been the materials substitution processes that have taken place over the last thirty years.

The objective of this study is to analyse, over time, the influence of techno-economic factors on materials substitution processes that take place within the North American automotive industry. This is done by studying six cases of materials substitution in specific automotive applications (aluminum engine blocks, aluminum wheels, aluminum radiators, galvanized steel body panels, polymer front fenders and polymer fuel tanks).

The analysis of the six case-studies is realized according to four groups of techno-economic factors - functional requirements, technological requirements, economic factors and social factors. Functional requirements relate to the characteristics of a material (mechanical and metallurgical), such that it can fulfill all the particular functions of a specific application. Technological requirements, for their part, are related to the transformation, manufacturing and assembly processes necessary in order to use a material in a particular application. Economics factors encompass all costs related to a particular component from a given material (materials costs, manufacturing costs, capital investments, etc.), market competition between automakers, labor and suppliers relations, as well as customers. Finally, social factors are mostly related to government regulations and technical standards.

The analysis of the six case-studies allows us to see that there is a wide variety of market penetrations among the cases, over the period studied (1960-1995). Market penetrations range from less than 4% (polymer fenders) to more than 95% (galvanized steel body panels). It is also possible to draw interesting conclusions regarding the influence of certain factors on the pace and the extent of the penetration of a material in an automotive application.

CONDENSÉ

L'industrie automobile occupe une position prédominante au sein de plusieurs économies au niveau mondial, notamment en Amérique du Nord. Étant donné la taille de l'industrie ainsi que la diversité des composantes et des technologies qui entrent dans la fabrication des véhicules, un nombre impressionnant d'industries sont directement reliées à l'automobile. Parmi celles-ci, les différentes industries des matériaux, et plus particulièrement l'acier, l'aluminium et les polymères, voient une bonne partie de leurs produits utilisés par les constructeurs automobiles et leurs sous-fabricants.

Au cours des trente dernières années, un certain nombre d'événements et de tendances sont venus modifier les facteurs décisionnels dans la sélection des matériaux. On assiste donc à un nombre croissant de cas où il y a substitution des matériaux dans des applications automobiles bien spécifiques. Parmi ces événements et ces tendances, notons plus particulièrement les deux crises pétrolières des années soixante-dix, la hausse importante du niveau de compétition entre les fabricants automobiles sur les marchés nord-américains et la croissance des considérations environnementales au sein de la population et au niveau des gouvernements.

Suite à la première crise pétrolière au début des années soixante-dix, le gouvernement américain a émis des standards concernant la consommation de carburant de l'ensemble

des véhicules vendu à chaque année, et ce, à partir de 1978. L'objectif ultime de ces standards était de réduire la consommation nationale de pétrole en augmentant l'économie d'essence des voitures. Ceci fut accompli en augmentant graduellement les standards de 18 mpg (13 L/100 km) en 1978 à 27,5 mpg (8,5 L/100 km) en 1985 pour les automobiles et de 17,5 mpg (13,4 L/100 km) en 1982 à 20,2 mpg (11,6 L/100 km) en 1985 pour les camoins légers. Tout en réduisant la consommation globale des véhicules, on réduisait par le fait même les émissions polluantes. Une des conséquences directes de ces réglementations fut de réduire da façon significative le poids des voitures.

La pénétration graduelle des fabricants automobiles japonais sur les marchés nord-américains a également été un facteur de changement important au sein de cette industrie. L'arrivée des japonais a grandement modifié la scène automobile nord-américaine étant donné que ceux-ci offraient des véhicules passablement différents (taille, poids, prix, consommation d'essence) de ceux qui étaient alors offerts par les constructeurs automobiles américains. La pénétration des voitures européennes, quoi que passablement moins prononcée que celle des japonaises, a quand même eu une certaine importance, notamment aux niveaux des voitures de luxe et des différentes technologies automobiles.

Face à ce contexte qui s'est modifié de façon significative au cours des dernières décennies, nous sommes en mesure de nous demander de quelle manière tout cela a bien pu influencer le choix et la substitution des matériaux dans l'industrie automobile nord-américaine. L'objectif principal de cette recherche est donc d'analyser l'influence des facteurs techno-économiques sur les processus de substitution des matériaux dans l'industrie automobile. Pour ce faire, on y étudie, dans le temps (1960-1995), six cas de substitution de matériaux dans des applications automobiles bien spécifiques.

Les six cas à l'étude sont: les blocs-moteurs en aluminium qui remplacent ceux en fonte grise, les roues en aluminium qui remplacent celles en acier, les radiateurs en aluminium qui replacent ceux en cuivre/laiton, les panneaux extérieurs en acier galvanisé qui remplacent ceux en acier au carbone non-revêtu, les ailes avant en polymères qui remplacent celles en acier et les réservoirs d'essence en polymères qui remplacent ceux en acier.

Afin de procéder à l'étude des différents cas de substitution, il est important de bien définir les éléments selon lesquelles ces cas seront analysés. Les facteurs techno-économiques dont il était mention précédemment se regroupent en quatre catégories bien définies: les exigences fonctionnelles, les exigences technologiques, les facteurs économiques et les facteurs sociaux.

Les exigences fonctionnelles ont trait à la capacité d'un matériau à remplir les fonctions relatives à une certaine composante. Les caractéristiques intrinsèques du matériau (mécaniques et métallurgiques) nous permettent de déterminer si ce dernier est en mesure d'assumer certaines fonctions. Par exemple, pour ce qui est du bloc-moteur, le matériau doit posséder de bonnes caractéristiques au niveau de la rigidité, de la résistance à l'usure et de la conductivité de la chaleur, tandis que pour les réservoirs d'essence, on prime plutôt la résistance à la corrosion et au feu, ainsi que l'imperméabilité aux hydrocarbures.

Les exigences technologiques sont reliées aux procédés de transformation, de fabrication et d'assemblage nécessaires à l'utilisation d'un matériau dans une application particulière. Une part importante des exigences technologiques ont trait à la capacité du matériau substitut à être transformé et produit selon les procédés existants et les technologies qui sont bien maîtrisées. Afin de bien déterminer ces capacités, on se réfère aux caractéristiques du matériau par rapport aux technologies existantes, par exemple, la soudabilité et la formabilité de l'acier galvanisé, les caractéristiques de fonderie de l'aluminium (blocs-moteurs et roues), etc..

Parmi les facteurs économiques, on retrouve tout d'abord les coûts, qui peuvent prendre plusieurs formes. Le coût unitaire d'une composante comprend le coût des matériaux, le coût de fabrication et le coût d'assemblage. À cela s'ajoutent les investissements requis afin de pouvoir fabriquer la composante à partir du matériau substitut. Les relations de travail, les relations entre fabricants et sous-fabricants, la compétition entre fabricants, les changements sur les marchés au niveau des produits et les consommateurs sont autant d'autres facteurs économiques qui peuvent jouer un rôle dans les processus de substitution.

Finalement, les facteurs sociaux se retrouvent généralement sous la forme de réglementations et de standards techniques gourvernementaux. Que ce soit en matière de consommation d'essence, de sécurité en cas de collision, d'émissions polluantes ou de résistance à la corrosion, il existe un nombre grandissant de domaines où les gouvernements s'impliquent par le biais de réglementations. Notons particulièrement l'impact majeur qu'ont eu les standards du CAFE (Corporate Average Fuel Economy) sur la période 1975 à 1985.

Après avoir documenter et analyser les six cas de substitution selon le cadre analytique présenté ci-dessus, nous pouvons faires des observations intéressantes et tirer certaines conclusions sur l'influence de ces facteurs techno-économiques sur les processus de substitution des matériaux. Tout d'abord, les courbes de pénétration de marchés nous démontrent une grande variété à ce niveau. En effet, au cours de la période étudiée, 1960 à 1995, les niveaux de pénétration du marché visé varient de moins de 4% dans le cas des ailes avant en polymères à plus de 95% dans le cas des panneaux extérieurs en polymères. Les blocs-moteurs se retrouvent actuellement autour de 20%, les réservoirs d'essence en polymères autour de 30-35%, les roues en aluminium près de 40% et les radiateurs en aluminium à plus de 85%. On observe également une variété au niveau de la longueur et de la rapidité du processus de substitution.

Certaines conclusions, présentées sous formes d'énoncés, on put être tirées suite à l'analyse des six cas de substitution à l'étude. Ainsi, à la lumière des résultats obtenus, il nous est permis de croire que:

1) Le matériau substitut doit performer, au minimum, aussi bien que le matériau qu'il remplace, en termes d'exigences fonctionnelles.

2) Le processus de substitution peut-être entravé si le matériau substitut requiert des technologies de transformation, de fabrication ou d'assemblage différentes que celles qui sont utilisées pour le matériau existant.

3) Le processus de substitution peut-être entravé si la composante en question fait partie d'un système complexe, ou que sa fonction et/ou sa location est (sont) intimement reliée(s) à d'autres composantes.

4) La nécéssité d'importants investissements en capitaux entrave le processus de substitution et favorise le matériau existant.

5) Un coût unitaire plus bas va favoriser le processus de substitution.

6) Une valeur percue élevée de la part des consommateurs favorisera le processus de substitution.

7) La compétition entre les fabricants automobiles favorisera le processus de substitution.

8) Des standards plus élevés pour la consommation d'essence favoriseront grandement la substitution des matériaux.

9) Des matériaux facilement récupérables et recyclables seront favorisés dans les processus de substitutions.

Étant donné les ressources disponibles pour la réalisation de ce projet, il n'est pas possible de tirer des conclusions sur l'influence de certains éléments mentionnés dans la cadre analytique à cause du manque d'informations et de données. Il serait intéressant, dans le cadre de recherches futures, d'approfondir certains de ces éléments, notamment les réseaux d'entreprises fabricants/sous- fabricants, les changements dans le "mix" des produits et la compétition entre les technologies émergentes.

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INTRODUCTION

Throughout the twentieth century, the growing presence of the automotive industry has had profound effects on the economic development of many nations, particularly in North America (NA), Western Europe and Japan. In 1993, worldwide vehicle production stood at 48,4 million units, of which more than 75% were manufactured in the regions above mentioned (Automotive News, 1994). It also has significantly influenced many related industries such as machine-tools, materials and electronics. In the case of materials industries, the North American automotive market represents as much as 25% of total shipments for NA steel producers, 20% for aluminum and 20% for plastics producers.

Due to the high degree of interrelatedness with raw materials industries, particularly with steelmakers, the evolution of the North American automotive industry has been determinant in the development of new materials and related technologies. Since the very beginning of automobile mass-production, the manufacturing processes have been centered around the extensive use of steel products. Today, ninety years later, the fundamental manufacturing process, although dramatically improved by the advances in related techniques such as casting, welding, forming, machining, and so on, is still largely dedicated to the use of iron and steel. Competing materials, especially aluminum alloys and polymers, have been slowly introduced in selected applications through the decades.

The materials substitution process has accelerated and has significantly gained in importance in the last twenty-five years. In the course of that period, the North American automotive scene has been profoundly altered by many events and trends. Two elements among others, energy and the environment, have become major considerations. To begin with, the energy crises of the seventies have had direct repercussions on the price of gasoline and the costs of operating an automobile. These crises have led the American government to set standards on the average fuel economy of the fleet of vehicles sold by any automaker. In addition, federal safety standards and state regulations, such as California's Zero Emissions Vehicles (ZEVs) standards, may add to vehicle weight in the case of the former, or may potentially require lighter vehicles in the case of the latter. Recyclability of automotive materials is also an area of growing concern within the general public and federal standards regarding this issue are expected in the coming years.

The level of competitiveness has seriously increased in the last two decades with the growing penetration of fuel-efficient, high-quality and affordable Japanese and European imports. The Japanese automakers, in particular, have invested billions of dollars on assembly plants (transplants) in North America and a host of long-time suppliers have followed them across the Pacific. The market itself has evolved in many directions that were hardly predictable twenty years ago. The introduction of minivans and the growing popularity of Sport-Utility Vehicles (SUVs) have transformed the product lines of many manufacturers. These particular events and trends, along with a number of other technological and economic factors, have had direct and indirect influence on the automakers selection of materials and the ongoing process of materials substitution in the automotive industry.

> **The objective of this research is to analyse the influence of technological and economic factors on automotive materials substitution. With technological accumulation in background as a conceptual framework, the intent is to provide insight into the processes of materials substitution by bringing forward patterns and regularities among case-studies.**

This will be done primarily by studying, through time, six cases of material substitution in specific automotive applications (aluminum engine blocks, aluminum radiators, aluminum wheels, galvanized steel body panels, plastic fenders and plastic fuel tanks). These six cases will be documented and presented, at first, bearing in mind the technological and economic factors that may have hindered or promoted the pace and the extent of the substitution. The six cases will then be gathered together and analysed according to their similarities and differences, in order to draw out specific patterns in the substitution of automotive materials. Finally, these findings will be discussed within the conceptual framework of technological accumulation.

The general conceptual framework is based upon the principles of technological accumulation as proposed by Bell and Pavitt (1993). Technological accumulation, according to these authors, is the accumulation of a country's, an industry's or a company's technological capabilities and production capacity. This process takes place in an environment where existing and developing technological capabilities and production capacity, in addition to external factors as those mentioned earlier (economic, social, regulatory, etc.), play a determinant role on the nature, the pace, the extent and the direction of technological change.

There are many determinants that condition the process of technological change, among which - sources of adoption (Arthur, 1988) and learning (Malerba, 1992), inducement mechanisms (Dosi, 1988; Rosenberg, 1976), technological paradigms and trajectories (Dosi, 1982), user-producer networks (Lundvall, 1992) and the regulatory environment (Abernathy, 1978). These elements, upon which the findings will be transposed, provide us with a comprehensive conceptual framework that recognizes the predominent role of technological change and innovation on economic development.

This study is intended as a multidisciplinary effort that combines technological and engineering considerations with economic theory. The need to integrate these various disciplines has been evoked few years ago by William J. Abernathy (1976), who stressed the importance of an integrative framework to clarify the relationships of technological progress to changes in other factors (economic and technological). Nathan Rosenberg (1978), for its part, has suggested that our knowledge of the translation of technical events into events of economic significance is somewhat limited.

The study is divided into five chapters. Chapter one begins with an overview of the North American automotive industry in the last decades, with a particular emphasis on materials and related events (oil crises, CAFE, etc.). In the second section of chapter one, the conceptual framework based on technological accumulation is laid out and detailled, bearing in mind the specific automotive context of this study. The methodology appears in the first section of chapter two, along with information and data sources and limitations and constraints of this study. The analytical framework, based upon an analysis grid that encompasses technological and economic factors on the one side, and the six case-studies on the other side, is detailled in the final section of the second chapter.

Chapter three contains a technical presentation of the six case-studies and their development through time. The six cases are taken seperatly and presented according to the analytical framework brought forward in chapter two. Following presentation of technical data in chapter three, regularities and patterns found among the six case-studies are set out in the first section of chapter four. The findings are then analysed in the light of the conceptual framework of technological accumulation laid out in section 1.3. After some concluding remarks, chapter five ends with potential research avenues stemming from the analysis and the results presented, considering the limitations and constraints of this study.

CHAPTER I

1.1 An overview of the North American automotive industry

1.1.1 The Big Three automakers

The North American automotive scene has changed tremendously in the past three decades. The Big Four (General Motors, Ford, Chrysler and American Motors) are now three since Chrysler has bought American Motors and Jeep from Renault in 1987. There could have been easily only two US manufacturers left, since Chrysler brushed with bankruptcy on two occasions. The first time, in 1979, the American Government guaranteed Chrysler's loans in order to give the automaker time to restructure. The second time around, in 1990, Chrysler was considered by many analysts as moribund. But again, lead by charismatic leader Lee I. Iacocca, Chrysler performed a dramatic turn-around that amazed almost everyone. Today, less than five years after, Chrysler is widely considered as one of the most successful and profitable automaker in the world.

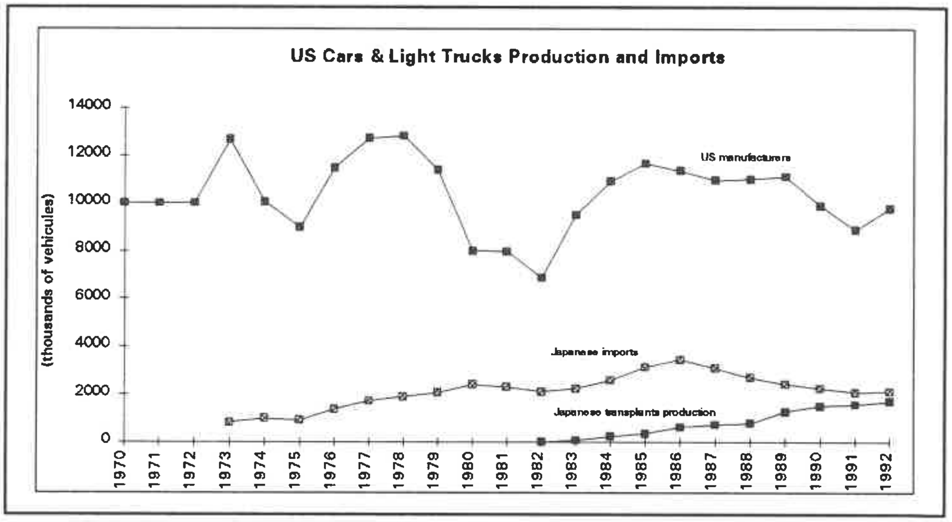
Although many sales records have been established in the 1980s, American automakers have been directly confronted by the increasing competition from Japanese automakers. Faced with cost-competitive adversaries, Big Three automakers were ill-prepared for a continuing struggle over market shares and profits. General Motors, in particular has had to close down facilities and lay off tens of thousands of workers in order to remain competitive. Even today, after many rounds of restructuring and downsizing, GM seems far behind both US and Japanese Competitors in terms of productivity and product leadership.

The 1980s and 1990s have been and still are a period of deep transformations and restructurings among the automakers and their suppliers. The new reality in the automotive industry has struck Big Three carmakers hard and has forced them to revise the way they conduct their business. Over the last twenty years or so, the North American automotive market has grown from a cozy oligopolistic situation into one of the most competitive environment in the world.

1.1.2 Foreign competition

One of the major element of change on the North American automotive scene has been the growing presence of foreign competition. At the end of the fifties, the Europeans came in with the ubiquitous Volkswagen Beetle, and then the Japanese followed suit in the sixties with small, affordable and fuel-efficient automobiles. The penetration of European automakers into the North American market has culminated with the production of Volkswagens in Western Virginia until the early 1980s. The Japaneses, however, have steadily gained market share and began to invest massively in North America in the early eighties. In all, several billions of dollars have been invested by Japanese auto manufacturers in American, Canadian and Mexican cars and light trucks assembly plants (transplants).

Today, Big Three automakers have a 74% share of the market (cars and Light trucks), versus 22,5% for Japaneses and 2,8% for Europeans[1] (Automotive News, 1995). At most, in 1991, Japanese carmakers have taken a 25,7% share of the US light vehicles market. In the last few years, with a rising yen and growing political concern in the US, the volume of imports from Japan has decreased as production from transplants has gradually increased. This trend clearly stands out in figure 1.1.



Source: Automotive News, selected years.

Figure 1.1: US cars and light trucks production and imports

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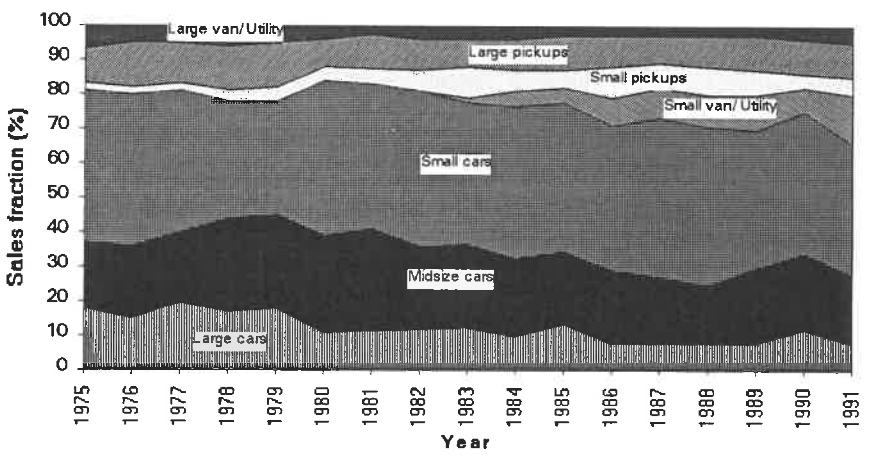
[1] US carmakers have 64,6% of the US passenger cars market and 85,8% of the US light trucks market. In comparison, Japanese carmakers have 29,5% and 14% of these markets respectively.

In addition to Japanese automakers establishing assembly operations in North America, a large number of Japanese automotive suppliers have invested in facilities in NA. Among those, steelmakers from Japan have been particularly active in following their long-time automotive customers across the Pacific. Japanese steelmakers have invested billions of dollars in joint-ventures with crippled US steelmakers in state-of-the-art galvanizing lines for automotive applications (Rosegger, 1991).

1.1.3 Changing markets and product lines

Another major element of change has been the introduction of minivans and sport-utility vehicles. Both products appeared on the market in the early 1980s and quickly established themselves as more than just fads. The original minivan, developed by Chrysler and introduced on NA markets in 1983, has been sold in more than 4,5 million examplars in less than 12 years. Overall, the annual minivan market has grown from zero to more than 1,26 million units in the United States over that period. The growing popularity of these vehicles, coupled with continuing strong sales in pickups and vans, have increased the share of light trucks on the overall light vehicles market. In 1994, light trucks sales (minivans, vans, pickups and sport-utilities) represented 40,4% of total light vehicles sales in the US. Figure 1.2 illustrates the change in market segments from 1975 to 1991.

US manufacturers have somewhat benefited from the increasing popularity of light trucks since they firmly command a large proportion of that market. If there is one area where US automakers have kept an edge over the Japaneses, it has to be in light trucks, especially minivans (Caravan, Voyager, Windstar, Aerostar, etc.), sport-utilities (Explorer, Grand Cherokee and Cherokee, Blazer and Jimmy, etc.) and full-size pickups (F-series, C/K, Sierra, Ram). It is in the small and midsize car segments that the Japaneses have had the most succes with vehicles like the Honda Accord and Civic, the Toyota Camry and Corolla, the Nissan Altima and Sentra. The Honda Accord has been the top selling car in the United States in 1989, 1990 and 1991.



Source: HEAVENRICH, R.M. et al. (1991). Light-duty automotive technology and fuel economy trends through 1991. Control Technology and Applications Branch, EPA/AA/CTAB/91-02.

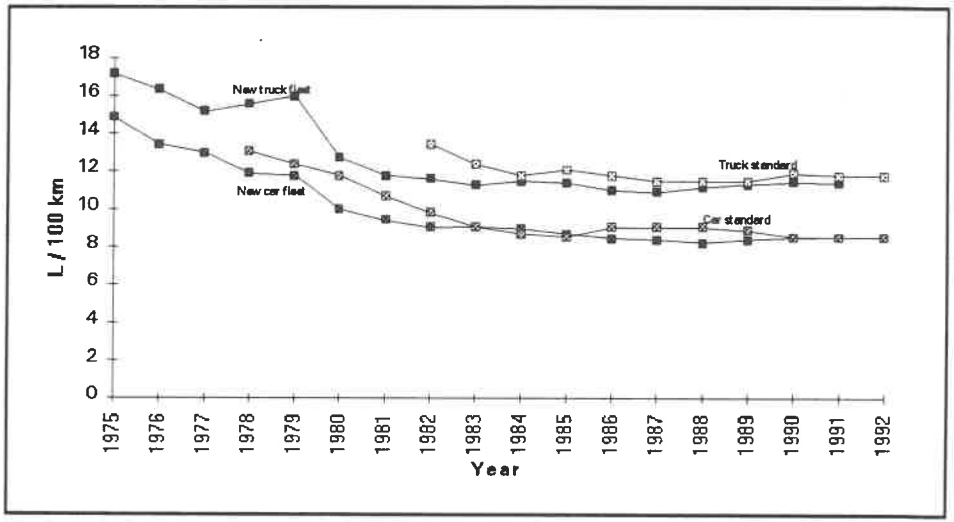
Figure 1.2: Car and truck sales by market segment, 1975-1991

1.2 Automotive materials

1.2.1 Regulations and standards

Since the 1970s, the North American industry has been confronted to a growing number of governmental regulations and standards. Among these, the Energy Policy and Conservation Act (EPCA), enacted by Congress in 1975 following the first oil crisis, which proved to be the most influential on the future of the automotive industry. As part of the EPCA, Corporate Average Fuel Economy (CAFE) standards were set in 1975 in order to dramatically improve the fuel economy of new vehicles.

CAFE standards required that the average fuel economy of any automaker's fleet of new passenger cars sold each year should be equal or less than 8,5 L/100 km (27,5 mpg) in 1985. The increase was made gradually, starting with a CAFE standard of 13 L/100 km (18 mpg) in 1978. The 1985 level of 8,5 L/100 km represented a 74% increase on the average fuel economy of the entire American new car fleet of 1975. The light-trucks CAFE began in 1982 with a requirement of 13,4 L/100 km (17,5 mpg). As of today (1995), CAFE standards for passenger cars are still at 1985 levels, light trucks are now set at 11,6 L/100 km (20,2 mpg). Additional increases in CAFE standards are awaited by automakers, although no formal plans are currently under review by Congress.



Source: Heavenrich et al. (1991).

Figure 1.3: Fuel economy trends, 1975 - 1992

In addition to CAFE standards, the state of California (through the California Air Resources Board - CARB) has adopted a mandate requiring that any car manufacturer selling over a predetermined annual volume within the state, would have to sell a least 2% of Zero Emissions Vehicles (ZEVs)[2], beginning in 1998. The fundamental objective of this mandate is to alleviate California's major problem with vehicle emissions (NO_x, carbon monoxide, etc.). Many Northeastern states are currently studying similar mandates.

Apart from fuel economy and vehicle emissions, safety standards have become increasingly demanding, particularly in the last few years. Safety standards such as

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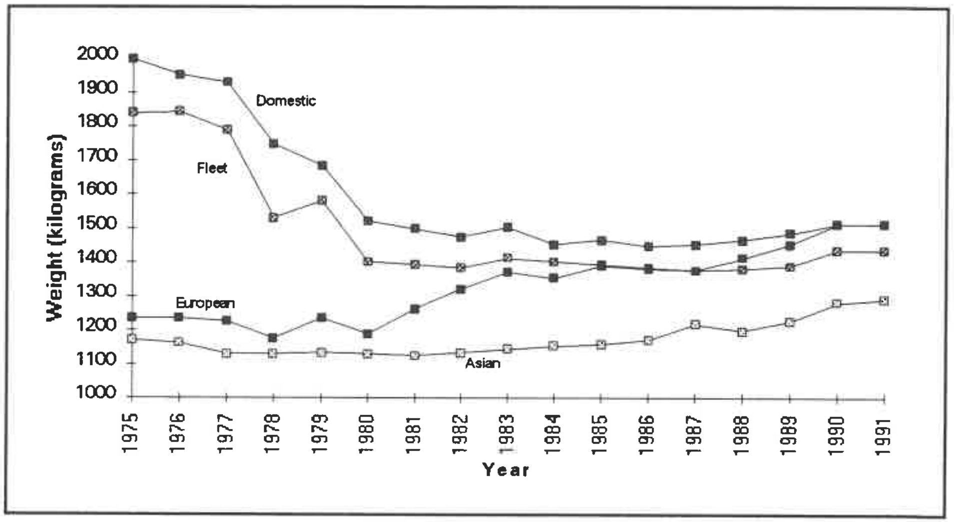
[2] 2% of total unit sales in the state of California.

occupant restraint systems and side-impact protection require additional components that may increase the weight of the vehicle. This trend is particularly noticeable since the early 1990s, when the introduction of airbags, door beams and other safety equipments began in popular models.



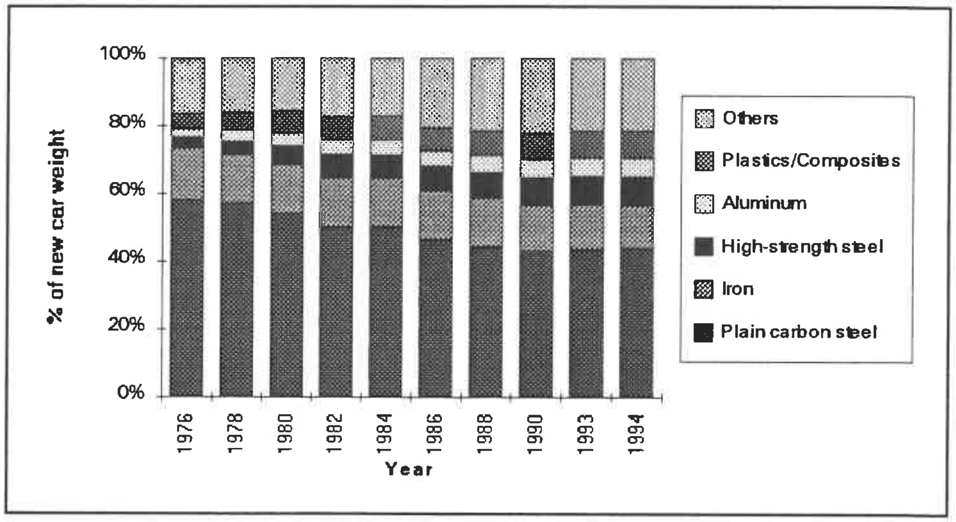
Source: Heavenrich et al. (1991).

Figure 1.4: Average weight for cars sold in the US, 1975-1991

1.2.2 Downweighting and materials usage trends

CAFE standards, and to a lesser extent, safety standards, have had important repercussions on the weight of North American vehicles in the last twenty years. As illustrated in figure 1.4, there is a clear trend, from 1975 to 1980, towards downweighting of North American automobiles. However, from 1981 to 1988 the weight of automobiles has not significantly changed. Furthermore, since 1989, the weight of automobiles has increased perceptibly. Europeans vehicles have gained significantly in weight throughout the whole period. We may suggest that the growing share of BMW and Mercedes-Benz in European imports (versus Volkswagen) has increased the average weight of those imports. As with Asian vehicles (almost exclusively Japanese), which are still well below the fleet's average, they have gained only a few tens of kilograms on average. This is rather a feat in itself, since Japaneses have managed to offer roomier and more luxurious vehicles over that period. We can think of the Honda Accord and the Toyota Camry as good examples. More recent data would probably demonstrate that the average weight of Japanese vehicles has gone up further because of the growing market penetration of large luxury cars such as Lexus, Infinity and Acura.

In order to achieve this general downweighing effort of the American light vehicle fleet, the automakers had two choices - downsize the vehicles or substitute existing materials with lighter ones. Both means have been utilised, but we will focus on materials substitution since it is the specific subject of this study. As can be seen in figure 1.5, the biggest loser in the material substitution process has been plain carbon steel, whereas the clear winners are plastics and composites, aluminum and high-strength steel.



Source: Ward's Automotive Yearbook, selected years.

Figure 1.5: Average materials contents in NA cars, selected years[3]

High-strength steel (HSS) has been increasingly used in structural components (body-in-white) as a substitute for plain carbon steel. The higher yield and tensile strengths of HSS allows to reduce sheet thickness without sacrificing rigidity or crashwothiness, therefore reducing weight. As for aluminum, whether cast, forged or wrought, it can be used in a variety of applications in order to save as much as half the weight of iron or steel components, with increased corrosion resistance. Among the applications that are most common for aluminum - engine blocks, wheels, radiators, cylinder heads, driveshafts, etc.

Polymers (plastics) and composites have gained wide acceptance in the automotive

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[3] In the category "others", we find materials such as copper, zinc, lead, glass, rubber, fabrics, carpets, fluids and lubricants, etc.

industry. They offer corrosion resistance, low weight, design flexibility, parts integration possibilities, and a number of other attractive characteritics. Among the components that are prime candidates for polymers substitution, there are - body panels, fuel tanks, dashboards, interior trim, intake manifolds, etc. In addition to providing direct weight savings, substitute materials, such as those just mentioned, can also allow for secondary weight savings. For example, in addition to the weight savings offered by the substitution of cast iron by aluminum for engine blocks, the automaker can benefit from secondary weight savings by downsizing suspension, load-bearing members, engine mounts, etc..

1.2.3 Research consortia

The major interests at stake in this ongoing process of materials substitution have forced the related materials industries to aggressively promote their materials. For the steel industry, which may be in a no-win situation on the long-term since it has everything to lose in the substitution process, this means it has to fight hard against aluminum and polymers in order to keep its current markets. To do so, American steelmakers, represented by the American Iron and Steel Institute (AISI), have teamed up with automakers to create the Auto/Steel Partnership. This research consortia has been established in order to promote the use of steel and to perform research on the different technologies associated with the use of steel in automobiles - welding, stamping, painting, etc.

The polymers and aluminum industries have also created such relationships with automakers, although not as formal. The SMC Alliance, for example, represents a group of resin suppliers and molders that want to promote the use of SMC polymers. Aluminum producers such as Alcoa and Alcan have worked closely with American and European carmakers to study the technical feasability and the economic viability of aluminum-intensive vehicles. Finally, the government is getting involved with automakers and materials producers on the 80 mpg SuperCar project. This project has for objective to develop an affordable, midsize vehicle with a fuel-economy of 80 mpg (2,94 L/100 km) that could be mass-produced early next decade. An important part of that research program is directed towards light weight materials and their adaptability to mass-production techniques.

1.3 Conceptual framework

1.3.1 Standard economics

Historically, and even actually, a majority of subjects have been, and are analysed through the theoretical framework of standard economics. Standard economics appear to provide a satisfactory and complete explanation to a wide range of considerations. In the specific area of industrial production, the so-called primary factors (labor and capital) that define the production isoquant are the basis for the production rationale, along with the relative prices of inputs. A positive shift in the production isoquant will be viewed as an improvement of the efficiency in the utilization of primary factors or inputs. Technology, which is considered as an exogenous variable that is usually taken for granted, may explain shifts in the production isoquant. However, technology is not an endogenous element of the traditional production function. Standard economics may, therefore, be somewhat inappropriate and incomplete to study the dynamics of technological change.

1.3.2 Technological accumulation

In order to perform this study and fully understand the elements at stake in the processes of automotive materials substitution, technology and its determinants must be considered as the fundamental analysis units. Furthermore, since substitution processes are, by definition, dynamic processes, the concept of technological accumulation must be brought to the forefront of the conceptual framework. It is simply useless to just consider technology as such, in a punctual and static way, because to do so would take us back to standard economics where technology is given at any time and exogenous to the system.

Substitution processes, which are technological changes in essence, require a conceptual framework that recognizes the dynamic nature of technology in an integrated network of industries and in an environment that constantly interacts with the processes. Technological accumulation, which is the accumulation of two stocks of resources (technological capabilities and production capacity), provides full recognition of the intrinsic characteristics of technology and the dynamic nature of substitution processes.

> "...By technological accumulation, we mean the accumulation..of two stocks of resources: (i) the skills, knowledge and institutions that make up a *(company's)* capacity to generate and manage change in the industrial technology it uses (i.e., its technological capabilities), and (ii) the capital goods, knowledge and labour skills required to produce industrial goods with 'given' technology (i.e., a *(company's)* industrial production capacity)"[4].

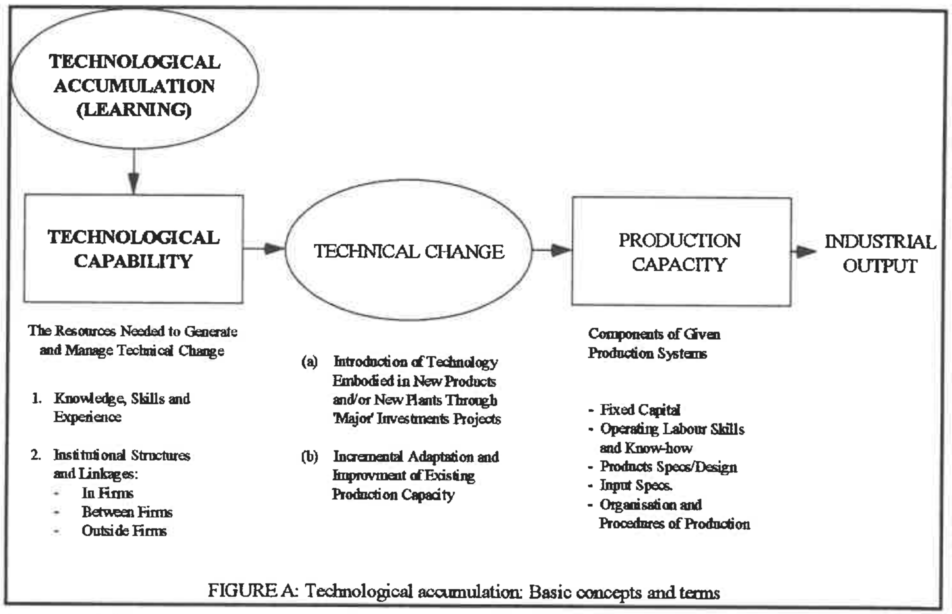

FIGURE A: Technological accumulation: Basic concepts and terms

Source: BELL, M. and PAVITT, K. (1993). Technological accumulation and industrial growth: contrasts between developed and developing countries. Industrial and Corporate Change, 2, no. 2.

Figure 1.6: Technological accumulation: Basic concepts and terms

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[4] BELL, M. and PAVITT, K. (1993). Technological accumulation and industrial growth: contrasts between developed and developing countries. Industrial and Corporate Change, 2, number 2, p. 159.

Technological change has many determinants, which I have regrouped in four categories - the nature of technology per se, user/producer networks, governments and economic conditions. In addition to being influential elements upon the direction and the pace of technological change, these determinants also interact among themselves. Together they represent the environment in which the technological accumulation process takes place.

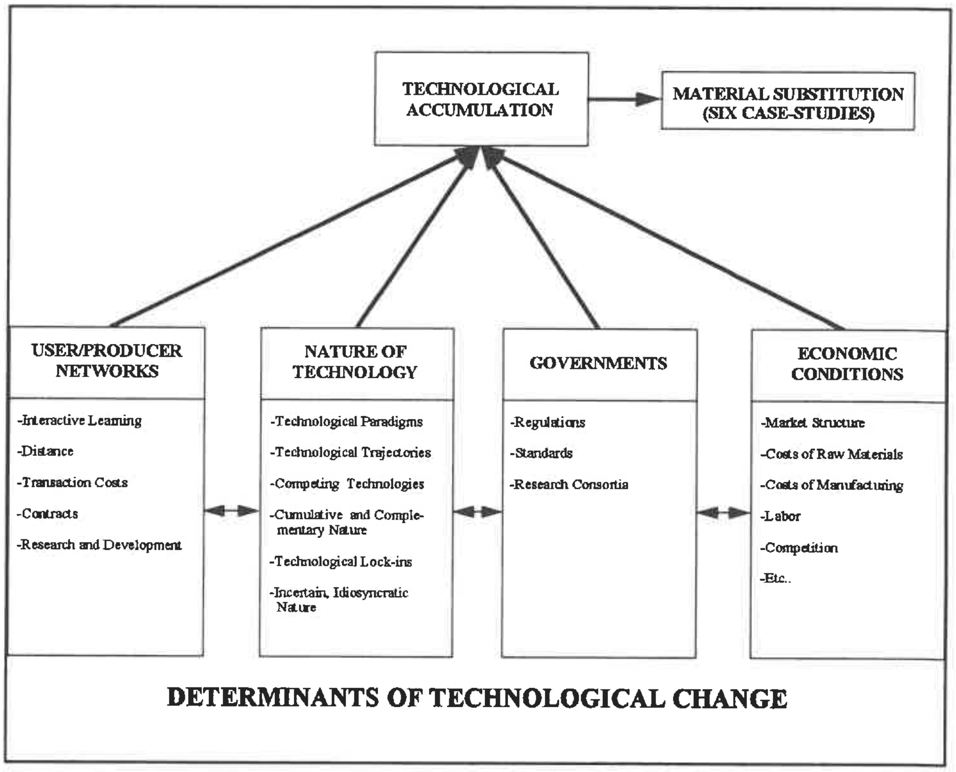

figure 1.7: The technological accumulation environment

1.3.3 The determinants of technological change

1.3.3.1 The nature of technology[5]

The first and foremost feature of technology is that it is cumulative (Dosi, 1988; Pavitt, 1993; Amendola, 1990), and therefore path-dependant since the latest development is always based, somehow, on the precedent level of knowledge and skills. We can thus suggest that the technological stock of an entity, whether it is embodied in patents, physical capital or know-how, is a good indicator of future technological decisions and activities. However, although cumulative and path-dependant, technology is also uncertain since it is difficult to predict the rate at which progress will take place and the scale or scope of subsequent innovations (incremental versus radical). The few characteristics mentioned above allow us to think that technology is definitely idiosyncratic in nature.

The intrinsic characteristics of technology lead us directly to the concepts of technological trajectories and technological paradigms. A paradigm, which may encompass multiple trajectories, can be seen as a 'model' and a 'pattern' of solutions for selected techno-economic problems or challenges, drawing upon specific principles derived from natural sciences and specific material technologies. An important implication of the paradigm definition is that "..innovative activities are strongly *selective*, *finalized* in quite precise

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[5] Dosi (1982) defines technology as a set of pieces of knowledge (practical and theoritical), know-how, methods, procedures, experience of successes and failures and also, of course, physical capital.

directions, *cumulative* in the acquisition of problem-solving capabilities."[6].

Technological trajectories are defined by the boundaries of the paradigm in which they evolve. They can be represented by the movement of multi-dimensional (technological, economic, regulatory, etc.) trade-offs among the technological variables underlying the paradigm. Progress, along the trajectories, can be considered as the improvement of these trade-offs[7]. Technological trajectories, within the limits of the paradigm, provide a set of solutions to the fundamental problems or challenges from which the paradigm initially originated. In these sets of solutions, problem-solving activities and incremental innovations are predominant.

The fact that there is generally more than one technological trajectory inside a single paradigm make the case that change may occur in various directions, at different paces. We can therefore suggest that competing technologies (Arthur, 1988) might progress along different trajectories within the same paradigm. Competition among technologies is not limited to "new" versus "old" technologies, but also applies among emerging "new" technologies.

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[6] DOSI, G. (1988). Sources, procedures, and microeconomic effects of innovation. Journal of Economic Litterature, XXVI, September, p. 1128.

[7] "Technological progress along any one trajectory is linked with (a) the development of specific infrastructures; (b) system scale economies; (c) complementary technologies; and (d) particular technical standards that positively feed upon specific patterns of innovation", in DOSI, G. (1988). Sources, procedures, and microeconomic effects of innovation. Journal of Economic Litterature, XXVI, September, p. 1146.

In a competing technologies environment, lock-ins can occur, promoting (or hindering) the development and/or the diffusion of a particular technology. Lock-in situations often originate from the increased "attractiveness" of a particular technology, due to factors such as learning by using, learning by doing, network externalities, economies of scale, informational increasing returns[8] and technological interrelatedness[9] (Arthur, 1988; Dosi, 1988; Malerba, 1992). Lock-ins may be reinforced by the cumulative nature of technology, which implies a certain degree of irreversibility of technological trajectories. Irreversibility, which is somehow embodied in a number of elements such as physical capital, supplier contracts, labor contracts, etc., may discourage companies from selecting alternative technologies.

Although different technological trajectories may compete among themselves within a paradigm, technologies (whether "old" or "new") may be complementary to each other. This is an important consideration since a competing technology that replaces another one may be considered as complementary insofar as it may avoid the obsolescence of the paradigm altogether[10].

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[8] Informational increasing returns are related to the fact that as a technology is increasingly known and understood, its diffusion and adoption may be further promoted. This is particularly true for risk-averse companies that prefer to "wait and see".

[9] The interrelatedness between different technologies that compose a technological system or a complex product help us understand why companies may end up being "locked" into technologies.

[10] Recent advances in ceramics and metal-matrix composites may improve somewhat the efficiency of the internal combustion engine and therefore prevent, or at least retard, its substitution by electric engines.

1.3.3.2 User/producer networks

An industry as wide and varied as the automotive industry must draw upon an impressive number of related technologies that together build an automobile as we know it. To develop, design, experiment and produce or implement these many product or process technologies, automakers rely on an extensive network of suppliers. Technology is considered, in this specific context, as an important unit of interaction between users (automakers) and producers (suppliers).

Technological accumulation becomes much more meaningful when considered in a user/producer network. The interactive learning and creation processes (Lundvall, 1992) that take place among users and producers, and also among producers (different levels of suppliers, tier 1,2,3)[11], is fundamental to the accumulation of technological capabilities and production capacity. Interactive learning processes are governed by constant feedbacks within the network and by market signals such as costs and contracts. The distance[12] between users and producers is highly influential on the intensity and frequency of feedbacks. Distant networks may rely more on market signals than close networks in order to conduct their businesses, since they cannot rely on the information, the knowledge and

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[11] Tier 1 suppliers are suppliers that deal directly with the automakers. They usually manufacture and assemble systems or supply raw materials. Tier 2 suppliers are not directly related to automakers, they usually supply tier 1 suppliers with components and sub-systems. Tier 3 suppliers provide basic elements and parts to tier 2 suppliers.

[12] Distance relates to the level of interaction, interrelation and communication between users and producers in economic and technological activities.

the experience that are brought through constant feedbacks.

Technological lock-ins are also an important consideration in user/producer networks. The length of contracts and the amount of knowledge, skills and physical capital dedicated to a particular technology may create a lock-in situation within an existing network. In making a commitment to a particular network, a company takes a decision that will be highly influential upon the technological accumulation that will take place in the future for a certain component and/or material.

1.3.3.3 Economic conditions and governments

Economic conditions, governmental regulations and standards are essentially inducement mechanisms (Dosi, 1988) that can redefine the problems, the challenges and the trade-offs underlying technological paradigms and trajectories by modifying the environment in which technological changes occur and decisions are taken. This is consistent with the fundamental purposes of technology in the automotive context: to be competitive (economic conditions) and to meet regulation requirements and standards (governments) (Arnold, 1993).

The development of both subjects (economic conditions and governments) here is restricted since they will be further discussed in sections 2.3.4 and 2.3.5.

CHAPTER II

2.1 Methodology

2.1.1 Empirical research and the conceptual framework

The attempt undertaken in this study is to present empirical evidence in order to analyse the processes of materials substitution in the North Amrican automotive industry. The conceptual framework laid out in section 1.3 will assist in structuring the analysis of empirical evidence and positioning the findings into a broader economic perspective. Thus, this study is not intended as a validation or a refutation of the conceptual framework (and the underlying theory) presented earlier.

The automotive industry offers a limitless source of innovations and technological change. The number of technologies and scientific domains related to the automobile is simply astonishing. The size of the automotive industry is such that even small modifications in the manufacturing processes, the materials used or the regulations can have a significant influence on related industries or even the economy as a whole through diffusion. The automotive industry therefore provides us with the best opportunity to study the process of technological accumulation in an integrated network of industries and in an environment highly influenced by both internal and external factors.

The empirical evidence brought forward to analyse the process of technological change in automotive materials is taken from past and present cases of substitution in specific applications. Most of the development and penetration in each of these cases have occured in the last three decades, starting in the 1960s and up to this day, so the time frame of this study is set according to that period. Geographically, the study is limited to the North American automotive industry (United States, Mexico and Canada), but it does encompass foreign automakers assembly plants in North America as well as Big Three operations (and American Motors before 1987).

Using various technical and economic information sources (section 2.1.3), each case-study is documented and presented from the moment the material is considered by an automaker to be used on one or more vehicle model for a specific application. Process technologies and subsequent improvements are presented in the light of the nature, the requirements and the function(s) of the component(s).

2.1.2 Data and information sources

The technical data and information on each case-study of automotive materials substitution are drawn primarily from technical reports of the Society of Automotive Engineers (SAE). Several hundreds of technical reports on automotive technologies are published by the SAE each year. These reports, written and presented by engineers and research personnel of auto-related companies, cover a wide range of subjects, from occupants safety to engine management technology. SAE technical papers go back as far as the 1920s, it is thus possible to perform a longitudinal analysis of a specific case and the development of related technologies.

Additional information is found in specialized and trade publications. These publications deal with specific area of interest related to materials and automotive engineering. A partial list of publications that have been consulted is presented in table 2.1.

Table 2.1: partial list of publications consulted

Materials related	Automotive related
-Journal of Metals -Materials Engineering -Welding Journal -Advanced Materials & Processes -Iron Age/New Steel -Modern Casting -Metal Finishing -Plating & Surface Finishing -Materials & Design -Materials & Society -Modern Plastics -Plastics Technology -Metal Bulletin Monthly -Iron & Steelmaker	-Automotive Engineering -Automotive Industries -Automotive News -Ward's Auto World -Ward's Engine and Vehicle Technology Update

Complementary data have been retrieved from annual reports and promotional material published by a variety of trade associations such as the Aluminum Association, the American Iron and Steel Institute (AISI), the International Iron and Steel Institute (IISI), the American Plastic Council, The American Foundrymen's Society (AFS), etc.. Finally, government studies (Department Of Energy (DOE), Batelle National Laboratory, US National Research Council - Committee on Fuel Economy of Automobiles and Light Trucks, etc.) provide information on actual automotive materials technologies and current and upcoming regulations.

2.1.3 Limitations and constraints related to this study

There is an abundant literature pertaining to this study that is readily available. However, critical information regarding costs, investments and corporate strategies is often kept within automakers, suppliers or raw materials producers. Although it is possible to estimate such data by various means, it is a rather elaborate and costly process that goes beyond the scope of this study and the resources available. A major portion of the research effort is therefore the gathering of fragmentary data and information by thorough bibliographic searches, in order to recreate, as accurately as possible, the actual continuum of events and developments.

This study is not intended as a multicriteria statistical analysis, but rather as a qualitative study of the dynamics of materials substitution drawing upon the empirical evidence provided by the six case-studies. The data and informations that are presented must be considered as guideposts defining the boundaries of a technological trajectory and as indicators of the change process taking place within them. Accordingly, the final objective of this study is not to make forecasts about future market penetration and usage of particular materials in passenger cars and light trucks based on precedent trends, but rather to analyse and understand the role and the influence of the various factors upon automotive materials substitution.

The study focuses on North American production of automobiles and light trucks. The automotive industries in Asia and Europe are not directly studied as such, they are occasionally mentioned for comparison purposes or when an important technology originates from abroad, or also when dealing with government regulations.

2.2 The analytical framework

2.2.1 The case-studies

The six case-studies that are at the center of this research have been selected in order to be the most representative of the ongoing process of materials substitution in the automotive industry. Unlike many studies related to automotive materials (Eggert, 1986; Gjostein, 1986; Arnold, 1993; Weizer and Kuenzel, 1990; US DOE, 1993; and others) which tend to cover the entire vehicle and use average materials content per vehicle as fundamental data, this study focuses on the material substitution for specific components and use market penetration statistics as the main indicator.

The components and related materials that have been chosen to perform that study meet certain selection criteria. The material being considered as a substitute must replace a material that is firmly established in an existing application. Materials that are introduced in a new application along with a new component are not retained. The substitution process (actual penetration in current production models), in opposition to the development stages and experimental trials, must have begun in the 1960s or later. The substitute material must have gained a visible share of the market through the years, on vehicles built in commercial quantities (> 1 000 units annually). Finally, the components selected must assume a certain role in the functioning, the integrity or the overall aspect of any vehicle.

The components and related materials have also been selected in order to represent the variety of components and materials that are found in any vehicle. For components as well as for materials, the variety will bring complementary elements of analysis that could have been disregarded in the case where a single component or material would have been studied. As it will be seen, the six cases of substitution offer a wide range of market penetration in their respective application. This may provide us with a perspective on the maturity and life-cycle of materials technologies in the automotive industry. The multi-components, multi-materials approach will definitely add to the significance and the completion of the results and the analysis.

2.2.2 Aluminum engine blocks

Aluminum engine blocks have been known and produced for quite some time and have been used in aeronautical and outboard marine applications since the beginning of these industries. In automobile vehicles, aluminum replaces cast iron in engine blocks. The first use of aluminum blocks in mass-produced North American automobiles was in 1959. Today, market penetration of aluminum engine blocks is around 20% in NA. The introduction of aluminum blocks has required the development and the refinement of many technologies such as alloy composition, casting, machining, etc.

2.2.3 Aluminum wheels

Aluminum wheels are substitute to steel wheels. They have been used for the first time in a mid-fifties Cadillac. Most of the market penetration of aluminum wheel has occured since 1980. There are three kinds of aluminum wheels: cast, forged and fabricated sheet aluminum wheels. Aluminum wheels offer a simple and effective way to reduce unsprung weight. They also provide very stylish appearance and design flexibility. Actual market penetration is near 40%.

2.2.4 Aluminum radiators

Aluminum radiators are substitutes for copper/brass radiators. There first application was in the 1960s. It was not before 1980 that they received wide acceptance from automakers because the manufacturing process was not satisfactory enough. Since then, however, the pace of the substitution has been remarkable. Actual market penetration is more than 80%. There are many processes to manufacture aluminum radiators. The main advantages of aluminum radiators are that they are lighter, more durable and more corrosion resistant than copper/brass radiators.

2.2.5 Galvanized steel body panels

Galvanized steel provides one advantage over uncoated steel in body panels applications: corrosion resistance. The growing use of road deicing salts in the 1960s has prompted the development and introduction of galvanized steel. Most of the substitution between coated and uncoated steel has occured in the 1980s, when cosmetic corrosion and perforation became a major issue. Today, galvanized steels are utilized in more than 95% of body panels applications. There are two major processes for galvanizing steel: hot-dipping and electrogalvanizing.

2.2.6 Polymer fenders

Polymer fenders are substitutes for steel in front fenders applications. In addition to being lighter, they provide absolute corrosion resistance. They were first used on the 1954 Chevrolet Corvette which featured an all-plastic body shell. It took thirty years before the next application, on the 1983 Pontiac Fiero. Although they are used on a limited number of high-volume vehicles, polymer fenders represent a real and direct threat to steel. Market penetration of polymer fenders is actually limited to less than 4%. SMCs, RIMs and Injection Molded Thermoplastics (IMTPs) are the main products and processes used for fenders.

2.2.7 Polymer fuel tanks

Polymer fuel tanks are gradually replacing steel tanks because they are more corrosion-resistant and they offer greater design flexibility. They were first used in Europe, on the 1972 Volkswagen Passat. In North America, they have been introduced since the late 1970s. Actual market penetration is around 30%. Unlike other components or substituting materials, plastic fuel tanks are primarily produced by one major process, blow-molding. However, there are several technologies used to ensure fuel permeation reduction.

2.3 Technological and economic factors

2.3.1 The basic analysis grid

As has been seen, these case-studies represent a good variety of market penetration situations and introductory lead-times. We want to understand the differences and similarities among these cases and draw out regularities in the substitution patterns. In order to achieve that, we must therefore base our analysis on an established set of parameters, common to all. In doing so, we will provide a conducting thread to the presentation and the analysis of the six case-studies.

The techno-economic factors, or inducement mechanisms, that promote or hinder the substitution of a material for another are regrouped in four categories: functional and technological requirements, economic and social factors. An illustration of the entire analysis grid is shown in table 2.2.

Table 2.2: The basic analysis grid

	Functional Requirements	Technological Requirements	Economic Factors	Social Factors
Aluminum Eng. Blocks				
Aluminum Radiators				
Aluminum Wheels				
Galv. Steel Body Panels				
Polymer Fenders				
Polymer Fuel Tanks				

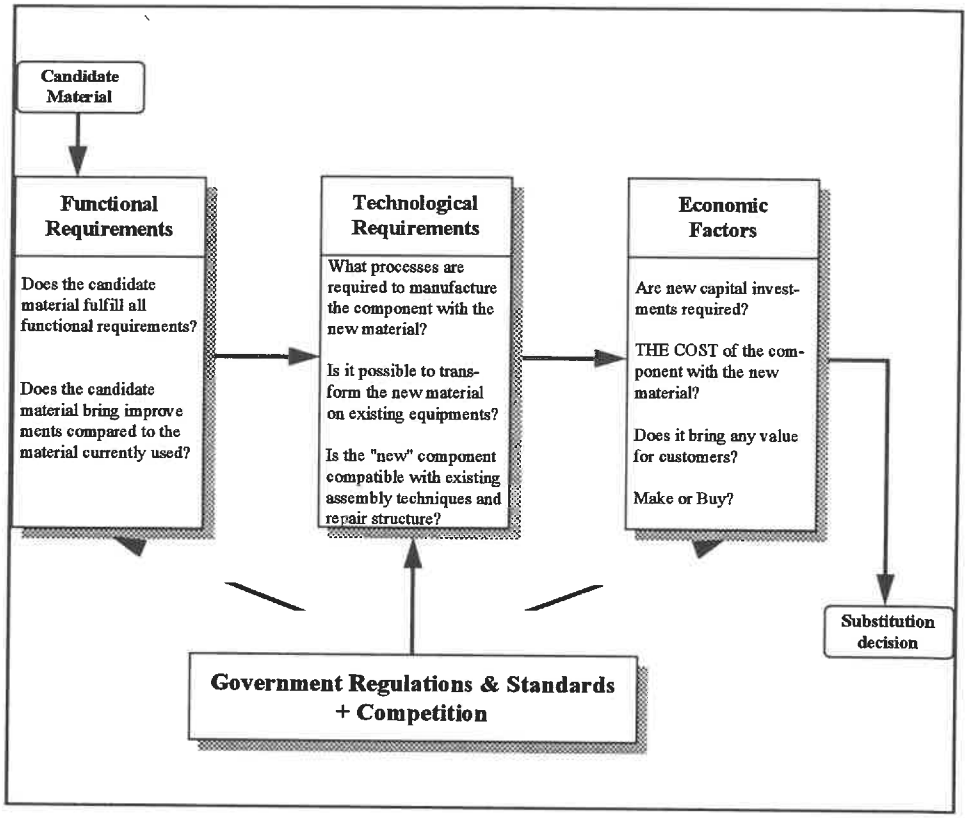
The appellation of the four categories of techno-economic factors is borrowed from *Des Matériaux* (Dorlot, Baïlon and Masounave, 1986). It is well suited to the analysis undertaken and allows for the needed flexibility in categorizing the numerous factors. Within each category, a number of elements represent the problems or the challenges that are brought to the attention of decision-makers when considering a substitute material for a specific application. A comprehensive list of the factors of analysis in each category is presented in table 2.3.

Table 2.3: The techno-economic factors*

Functional Requirements	Technological Requirements	Economic Factors	Social Factors
-Low Density -Corrosion Resistance -Fatigue Resistance -Rigidity -Yield Strength -Tensile Stength -Low Coefficient of Thermal Expansion -Dimensional Stability -Thermal Stability -Heat Conductivity -Wear Resistance -Surface Appearance -Dent Resistance -Fuel Permeation Protection -Capacity -Compatibility with Existing Components and Systems	-Castability -Forgability -Machinability -Stampability -Moldability -Coatability -Surface Treatability -Brazability -Weldability -Paintability -Formability -Style and Design Flexibility	<u>Costs:</u> -Component's Unit Costs -Materials Costs -Manufacturing Costs -Capital Investments -Production Volume <u>Labor Relations:</u> -UAW - Big 3 -Labor Contracts <u>Suppliers Relations:</u> -Make or Buy -% of outside sourcing <u>Automotive Markets:</u> -Competition -Growth -Market Shares -Product Mix <u>Customers:</u> -Vehicule Costs -Perceived Value	<u>Regulations and Standards:</u> -Recycling -Corporate Average Fuel Economy (CAFE) -Safety -Zero Emissions Vehicles (ZEVs) -Fuel Permeation -Corrosion Resistance

*: Some factors are specific and do not apply to all case-studies.

These various factors represent the majority of elements that are taken into account when a material substitution decision is taken. The problems, challenges or modifications in the economic and social environment that bring forward and influence the substitution decision are highly interrelated among themselves. The decision process is illustrated in figure 2.1.



Does the candidate material fulfill all functional requirements?

Does the candidate material bring improvements compared to the material currently used?

What processes are required to manufacture the component with the new material?

Is it possible to transform the new material on existing equipments?

Is the "new" component compatible with existing assembly techniques and repair structure?

Are new capital investments required?

THE COST of the component with the new material?

Does it bring any value for customers?

Make or Buy?

Figure 2.1: The automotive material substitution decision

2.3.2 Functional requirements

Functional requirements are the conditions of utilization that must be met in order for a material to be considered for a certain application (Dorlot et al., 1986). These are the basic criteria upon which engineers and designers can evaluate if the material is suitable, from a metallurgical and mechanical standpoint, for a specific application in a well defined environment. It is also by using these criteria that they will be able to judge the reliability and durability of any material in any application. Functional requirements are the first elements to consider when a material is brought to the attention of automotive engineers for a component. The potential improvement in one or many functional requirements is often the primary reason for which substitute materials are considered.

There is a wide variety of functional requirements and they are generally specific to a component. Durability, reliability and compatibility are common to all components, although they can assume different forms of requirements. For example, durability and reliability can mean corrosion and fatigue resistance in a certain application, but mean wear resistance and thermal and dimensional stability in another. In the case of compatibility, the location, design and dimensions, the assembly and finishing techniques (welding, adhesive bonding, coating, painting, etc.), are all elements that must be accounted for when considering the possibility to adapt the substitute material to the technical environment already in place.

Functional requirements can vary in importance as other factors are brought into account. Regulations such as CAFE or safety standards, consumers preferences and competition (discussed in sections 2.3.4 and 2.3.5) can modify the weight given to a specific functional requirement in a substitution decision. This is best illustrated by CAFE regulations that have significantly added to the importance of low density and potential weight savings.

2.3.3 Technological requirements

Similar to functional requirements, technological requirements are numerous and mostly application-specific. Since they are process-intensive, materials go through many operations in order to become fully operational, durable and reliable components. The materials must allow to go through these transformation processes while keeping or even improving the characteristics that made them promising substitution candidates at first. The various technologies (techniques) employed to transform materials into useful components may have a significant influence on the metallurgical and mechanical properties of the substrate, it must therefore be taken into account when considering a material.

The materials must lend themselves to well-known and well-proven technologies, or otherwise they have to be modified in order to meet certain specific requirements. This can be done by going through complementary transformations or by material composition modifications. However, in the case where the material offers very interesting characteristics, R&D activities may be undertaken to develop an appropriate process that can exploit the potential of the material to its fullest extent, at the lowest possible cost. The improvement process in materials-related technologies, whether incremental or punctuated by radical innovations, is of the utmost importance for the technical feasibility and the economic viability of a particular material substitution.

Technological requirements are closely related to the economics of producing a component out of a certain material since transformation costs are often equal or greater than raw materials costs. There are also serious considerations given to the adaptability of a new material to existing processes, tooling and equipments. If a substitute material requires major capital investments and/or specific equipments, it must be taken into account in the final substitution decision.

2.3.4 Economic factors

2.3.4.1 Costs

Unit costs have long been the single most important criteria in any single substitution decision. To suggest that costs are no longer a predominant concern to automakers would be rather illusive. However, since the numerous techno-economic factors that influence materials substitution may be somehow interrelated and that the growing importance of a particular factor may modify the importance of another, costs must now be put in a broader perspective. For example, in order to achieve additional weight reductions, an automaker may be willing to pay a premium for the substitute material for each kilogram saved. Costs are also usually closely related to production volumes, so intuitively, the unit cost of a component should go down as the market penetration of the substitute material rises.

Final unit costs can be divided in fixed and variable costs. Fixed costs represent investments in new facilities, tooling and equipments. Variable costs primarily encompass materials, labor and energy costs. The share of each type of costs in final unit costs varies from component to component, and also from material to material. Therefore, even if material A is less expensive than material B, unit cost of component using B can be significantly lower than component using A if, for example, machining and surface treatments are not required for component B. Also, as mentioned in section 2.3.3, capital investments must be taken into account when new facilities and new equipments are necessary. This can be advantageous to the material already used or a substitute material that can be transformed using existing equipments because capital investments have been made for a certain time and may be amortized.

2.3.4.2 Labor relations

Labor relations may not be a central element in the automotive materials substitution processes. However, they can influence two other factors that may be of higher importance: the "Make or Buy" decision and labor costs. In the former, life-long employment labor contracts or similar arrangements sometimes get in the way of the automakers' intentions to outsource the component and shut down old facilities and reduce the workforce (discussed in section 2.3.4.3). In the latter, materials and components that are labor-intensive and are not manufactured on automated production lines may suffer from higher labor costs due to binding labor contracts. In addition to these considerations, automakers must sometimes manage with the "steel culture" that is deeply rooted within the workforce, especially among engineers. In order to bypass that cultural bias, the automakers may choose to go outside the company for certain components.

2.3.4.3 Suppliers relations

The importance of suppliers has grown significantly in the last decades. The present trend among North American car manufacturers is to spin-off non-core parts operations and to focus on components and sub-systems assembly. The automakers are thus outsourcing a growing number of components, and by the same token, they are more and more involving suppliers early on in the development process of next-generation vehicles. Chrysler is currently outsourcing near 70% of the value of its vehicles, versus 50% at Ford and 30% at General Motors (Automotive News, 1995). Although the percentage of outsourcing is going up, the absolute number of tier 1 suppliers directly dealing with automakers is going down dramatically. For example, Ford has gone from more than 2400 NA suppliers in 1980, to 1400 in 1993, and has targeted 1000 NA suppliers in the year 2000 (Automotive News, 1993).

The "Make or Buy" decision regarding certain components may be affected by the fact that a new material will be used. If the automaker's facilities and equipments are not suited for manufacturing using the substitute material, they may choose to close the plant and outsource the component, therefore avoiding to make the additional capital investments. However, as mentioned in section 2.3.4.2, binding labor contracts may influence the automaker's decision towards the "Make" choice, since it may have to remunerate its employees whether they actually work or not.

2.3.4.4 Automotive markets

The North American automotive scene has changed tremendously since the 1960s. The competition has never been so fierce between the growing number of competitors in the North American market (section 1.1). The use of substitute materials can become a competitive advantage in certain market segments. For one, cast aluminum wheels certainly offer a very stylish appearance that makes a vehicle much more attractive. The same is true with galvanized steel panels that do not rust with time like earlier automobiles did. The growing number of makes and models may influence the substitution decision of the automakers in order to gain an edge, differentiate its products, or simply to keep up with the competition. Foreign manufacturers and suppliers investing in assembly plants or even just selling their products in NA may bring with them new technologies from abroad.

The growth of the automotive market itself is an important element since it can directly affect a number of inputs such as sales level, profits, market shares which are, in turn, determinants of the financial health of any automaker or supplier. The general condition of the market must then be considered as a leading indicator of the investment, R&D and marketing efforts. Depressed markets may not be the best environment for substitution processes or innovative undertakings. Then again, it may prove the best time to introduce new materials and new technologies that may boost sales and market shares.

Market shares can be considered from two perspectives. First, market shares are directly related to production volumes, and that may be an element by itself. Second, they can demonstrate the position of leadership of an automaker in certain market segments. Production volumes are definitely a major input when considering manufacturing economics. Low volume productions may offer the best opportunity for innovative features and material trials, but on the opposite, high volume production may justify the investments and provide the best opportunity for economies of scale. Leadership in a market segment is another element that must be dealt with - is the vehicle leading the segment because it is innovative, cheap, attractive, or else?

Finally, the product mix has evolved significantly since the last thirty years (section 1.1.3), light trucks in general have gained an important share of the total market. This trend is primarily due to the introduction of minivans ans Sport-Utility Vehicles (SUVs). There is a major difference in light trucks and passenger cars CAFE, the former is set at 11,6 L/100 km, the latter at 8,5 L/100 km. Weight reduction efforts may be marginally more rewarding in large and heavy vehicles than in small subcompact vehicles.

Within market segments are many levels of luxury and performance that are offered to the public by various manufacturers. On the one hand, expensive high-end vehicles may provide a golden opportunity to introduce substitute materials since potential price increases will be relatively smaller than in popular models. Also, innovative features and materials may be viewed by the public as prestigious or distinctive, thus adding to the cachet of a luxurious vehicle (e.g., all-aluminum Audi A8). On the other hand, economies of scale may play in favor of high-volume popular models.

2.3.4.5 Customers

Vehicle cost is the price the consumer will pay for the vehicle, and that encompasses optional equipments and the costs of innovative features. We are therefore allowed to ask ourselves to which extent are consumers willing to pay for lightness and fuel-efficiency, for performance, for a distinctive vehicle, etc. The answer may lie in the apparent value of these features to the car buyer. One must consider the added value, from the customer standpoint, of a substitute material, and is willingness to pay a potential premium. As an example, car buyers may not care if the fuel tank is made out of plastics or steel, and therefore may not be willing to pay a premium for that feature.

2.3.5 Social factors

The last thirty years have seen a growing number of vehicle regulations and standards, from fuel economy to airbags and side impact protection. The reasons that have brought these various regulations and standards are not central to this study, it is rather their influence on automotive materials substitution that might be of great interest. The actual trend is that the automotive industry will get more and more constrained by a growing number of federal and state regulations and standards.

CAFE regulations are certainly a major concern to automakers. When forced by law to reduce vehicle fuel consumption, there are not many ways to do so. The automakers can either reduce vehicle weight, reduce drag resistance or improve the efficiency of internal combustion engines. There are still room for improvement in the last two areas, but the weight reduction approach could prove to be the most rewarding. As seen in section 1.2.1, the average fuel economy of the fleet has improved significantly in the 1975-1985 period. However, since CAFE have remained at the same levels since 1985, this may have influenced the automakers to curtail their weight reduction efforts. State regulations such as California's ZEVs mandate must definitely be taken into account since they may require new powertrain and chassis technologies. They could prove to be the trigger point for a new electric vehicles paradigm that would challenge the actual internal combustion engines paradigm.

Safety standards, such as airbags, side impact door beams and other passengers safety features, may influence the material substitution decision in two ways. First, the functional requirements of certain components may be changed. Therefore, an analysis of the current material is needed to evaluate its capacity to meet these new requirements. In the event that the actual material does not fulfill the new requirements, a substitute material may be considered. Second, mandatory safety features may add to the final weight of the vehicle and automakers may be willing to offset that weight increase by downweighting other components. Other standards such as fuel permeation of fuel tanks and corrosion resistance of outer body panels may be less influential on the vehicle as a whole, but they are still very important for the specific components targeted.

Finally, recently adopted German regulations that require the automakers to be responsible for the vehicles throughout their life-cycles, from production to their reclamation and subsequent treatments, may prompt North American governments to legislate accordingly. The growing public awareness of the importance of recycling may also become a major incentive and even a marketing tool for automakers. The substitution decision must then take into account reclamation and recycling considerations such as scrap value, ease of dismantling, landfill costs, ferrous and non-ferrous metals segregation, growing share of plastics in automobiles, etc. (La Mantia, 1993; Brooke et al., 1992; Birch, 1993; Selke, 1989; Jody et al., 1994; Field III and Clark, 1991 and 1994; Bhakta, 1994; Testin, 1981; Gorban et al., 1994; Sanders et al., 1993).

CHAPTER III

3.1 Aluminum engine block

3.1.1 Introduction

The engine block is the heaviest component in any passenger car or light truck. Its weight can reach up to 90 kg (200 lb) or more, depending on the design, number of cylinders and, most of all, the material used. The qualities engineers are looking for in a good engine block are - rigidity, wear resistance, low weight, compact design, favorable noise and vibration behavior, consistency of properties with temperature and low casting and machining costs (Hofmann et al., 1983).

Since the very beginning of the automotive industry, engine blocks have always been made from cast gray iron. There hasn't been much change in the chemical composition of the material used through the decades. The sand casting techniques, although much more automated and efficient, are basically the same they used back in the Ford T era. The costs of machining grey iron engine blocks, roughly twice those of casting (Marcks von Würtemberg, 1994), have come down significantly in the last twenty years with the advent of carbide and polycristalline diamond tools. However, they are still higher than the ones for relatively softer materials like most aluminum alloys. Cast iron engine blocks can still be found in a large majority of cars and light trucks made in North America. Japanese and

European carmakers are far ahead of their American counterparts in switching to light-alloy engine blocks. Since 1990, Honda equips its entire line of cars with aluminum engine blocks.

The all-aluminum engine is not a recent idea, it was first developed and used in aircrafts where weight is of the utmost importance (Pomeroy, 1920). The next extensive use of aluminum for internal combustion engines came from the marine outboard motor industry. Since the late 1930s, the Outboard Marine Corporation (OMC) has been producing small die cast aluminum cylinder blocks (Conover and Nelson, 1959). The North American automotive industry has toyed with that concept since the early days of automobile mass-production. Several models in the 1920s and 1930s offered light-alloy engines (Marmon, Franklin, Dusenberg, etc.). Although the results seemed satisfactory, the idea did not take on in large proportions because many car manufacturers had reserves regarding cylinder bore wear resistance, casting techniques and the cost of such an engine.

3.1.2 Early research and production of aluminum engine blocks

Since sand casting was the only casting method available for large parts and it could not compensate for the higher metal cost of aluminum, automotive engine blocks remained in gray iron. The development of large die casting machines by the Doehler-Jarvis division of the National Lead Co. in the early 1950s lead to the production of the first die cast six-cylinders aluminum engine block in 1955 (Bauer, 1960). Unfortunately, none of these die cast blocks ever was completely machined, assembled, and tested under field conditions because of basic changes at Doehler-Jarvis' research partner, Kaiser-Frazer of Kaiser Aluminum & Chemical group. However, the adaptability of aluminum to modern fast-cycling and economically viable casting methods, such as permanent mold and die casting, had been demonstrated.

The first mass-production aluminum engine block in North America is found in the 1960 Chevrolet Corvair. The air-cooled engine, located at the rear of the Corvair, was produced by permanent mold process[1]. Several other aluminum engines were introduced in 1961 by Chrysler, AMC, Buick, Pontiac and Oldsmobile. Those made by Chrysler and AMC were of open-deck design, with cylinder bores standing free. Buick, Pontiac and Oldsmobile used the same basic block which featured a closed-deck. Chrysler and AMC produced their engine by die casting, whereas GM used semi-permanent mold casting. Altough this first generation of aluminum engines in North American automobiles captured as much as 10% of the market in 1961, it was very short-lived, since all aluminum engines were dropped in 1964, except for the Corvair. The latter was gradually phased-out from 1966 to 1969 (Abernathy, 1978).

Prior to these introductions, research programs at ALCOA, Reynolds Metals, General

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[1] A few years earlier, in 1957, Porsche and Volkswagen had introduced similar air-cooled aluminum engines in Europe.

Motors and Chrysler, among others, had lead to similar conclusions: engine cylinders made from conventional aluminum casting alloys did not have scuff and wear characteristics comparable to those of cast iron.

> "Scuffing is a phenomenon characterized by mass movement of surface elements to form linear scratches and local welds on surfaces in relative motion. It usually occurs on cylinder bore surfaces, piston skirts and/or piston rings when the lubrication conditions deteriorate so that the two metal surfaces come into contact."[2]

Two alternatives had been known for quite some time, the protection of cylinders bore surfaces by adding cast iron liners or by chrome plating, or by using a different aluminum alloy with high silicon content that would make a sleeveless engine block possible. Although both alternatives have their own merits, the jury is still out, almost four decades later, whether which one is the best.

The use of iron liners, although seen at that time as the most practical alternative[3], had and still have a few drawbacks: they add to engine cost (materials, labor and manufacturing rate), reduce the thermal conductivity advantage in the cylinder wall area (Jorstad, 1971), reduce the weight-saving advantage of aluminum. The iron liners have a different coefficient of expansion than the block and the piston which can cause gasket sealing problems. Also, their presence can lead to corrosion problems caused by galvanic attack

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[2] COLE, G.S. and BIN, F. (1992). Scuffing resistance of selected materials as protection for bores in aluminum engine blocks. SAE Paper #920285.

[3] Every alluminum engine introduced in the early 1960s (Corvair, Buick, Oldsmobile, Pontiac, Chrysler and AMC), featured iron liners for improved cylinder bore wear resistance.

associated with the composite nature (Al-Fe) of that engine (Montgomery, 1961).

The second alternative, sleeveless engine blocks made of hypereutectic[4] aluminum-silicon alloys, were tested and proven by some (Chrysler, GM) to provide superior cylinder bore wear protection when compared to cast iron or chrome plating. However, these hypereutectic alloys, generally with a Si content greater than 18%, had two major shortcomings: poor machinability due to the high wear resistance of the extremely hard primary silicon phase and poor foundry characteristics (castability, high melting and casting temperatures, solidification).

3.1.3 Sleeveless - hypereutectic alloy engine blocks

At that point in time, General Motors determined that, for an aluminum engine block to be cost competitive with a similar cast iron block, the cast iron cylinder liners or plated bores would have to be eliminated. Aluminum engines with iron liners or plated bores were more expensive than a comparable cast iron engine. In order to solve that problem, the block and bores would have to be cast as an integral aluminum unit, using an appropriate alloy.

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[4] An hypereutectic aluminum-silicon alloy is a Al-Si alloy with a silicon content greater than 12,7%, by weight.

In 1958, Reynolds Metals had began an extensive research program to develop an hypereutectic aluminum alloy "...containing sufficient primary silicon to impart the required wear resistance, yet not enough of this phase to cause serious casting and machining difficulties"[5]. GM Research Laboratories got involved early in the program and worked closely with Reynolds, especially on the casting process for such an alloy. The result was the development and testing of hypereutectic alloy 390 in the mid-1960s. The 390 alloy has the following chemical composition - 16,0 - 18,0% silicon, 4,0 - 5,0% copper, 0,6 - 1,1% iron, 0,45 - 0,65% magnesium, 0,02 - 0,03% phosphorus and traces of manganese, zinc and titanium. This silicon range offers the greatest fluidity for Al-Si alloys at normal casting temperatures and a degree of wear resistance equal or better than cast gray iron (Jorstad, 1971).

The 390 alloy offers acceptable casting properties, and machinability similar to cast iron rather than pure aluminum (Kneisler, Martens and Midgley, 1971). The Acurad casting process, basically for 390 alloy technology, was developed by GM to overcome the internal porosity problems associated with conventional die casting when casting large and complex components. The Acurad process is, in fact, a refinement of die casting with additional attention given to the control of primary silicon size.

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[5] JORSTAD, J.L. (1971). The hypereutectic aluminum-silicon alloy used to cast the Vega 2300 engine block. Modern Casting, October, 59-64.

In 1968, the Vega Program was launched at General Motors. Using Reynolds 390 alloy technology, GM goal was to produce the first die cast sleeveless aluminum engine block. The Vega engine, a 2300 cc (140 cu. in.) overhead cam in-line 4 cylinders, came out in the early 1970s, powering the new Chevrolet Vega. It was later used in the Chevrolet Monza, Chevrolet Town Coupe, Pontiac Astre and Pontiac Sunbird. By 1976, all Vega engines offered an unprecedented 5 years / 96 000 km warranty. In all, more than two and a half million Vega aluminum engines have been produced.

The Vega engine was cast at Chevrolet Massena, NY foundry. After casting, the cylinder block was aged for 8 hours at 232°C (450°F) to achieve dimensional stability. The block was then bored and honed with conventional production equipment. After honing, the cylinders bores were etched by an electrochemical machining process referred to as ECM. "As the bore surface is etched, the aluminum is removed, leaving the pure silicon in the original state, reffered to as "silicon standing proud""[6]. As the people from GM put it "The successful development of bore-to-piston and bore-to-piston ring compatibility represents the "major breakthrough" of the Vega engine"[7]. Given that a conventional aluminum piston was not compatible in a high silicon bore, the best alternative proved to be the iron-plating of these aluminum pistons.

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[6] KNEISLER, F.J., MARTENS, D.A. and MIDGLEY, R.W. (1971). The Vega 2300 engine. SAE Technical Paper #710147.

[7] Idem.

The Vega engine block, of open-deck design, had a weight of 16,3 kg (36 lb) after machining. In comparison, the Chevrolet cast iron 2509 cc (153 cu. in.) L-4 weighted 39,5 kg (87 lb). Despite the relative succes of the Vega car and engine, the best powertrain warranty in the world at that time, the engine was pulled out of the market in the late 1970s because of customers concerns about its reliability and durability. Other North American automakers did not venture with the aluminum engine block as far as GM did in the 1960s and the 1970s. But in the meantime, across the Atlantic, some European car manufacturers were getting deeply involved in 390 alloy technology.

The first European 390 alloy application was Porsche's 911 engine (6-cyl.), later came similar sleeveless engines from Audi and Mercedes-Benz. Despite intense 390 engine development by some, the biggest aluminum engine program at that time in Europe was the PRV one (Peugeot - Renault - Volvo), which did not use 390 technology, but rather an hypoeutectic 380 alloy (Si ≈ 8,0 - 9,5 %) with wet cast iron liners. The PRV is a 2664 cc (162 cu. in.) V6 engine of open-deck design with a machined weight (without Fe liners) of 14,2 kg (31,3 lb). Today, high-end European manufacturers such as Porsche, Mercedes-Benz and Audi are the only automotive companies to offer sleeveless 390 alloy aluminum engines. Lexus also uses 390 alloy but has decided to add iron liners.

3.1.4 Top-deck design

It appears important, since they are major technical considerations when designing and casting aluminum blocks, to further elaborate on closed versus open-deck design and dry versus wet sleeves arrangement. Top deck design is closely related to the casting technique and liners arrangement. The open-deck block is generally produced by high pressure die casting (HPDC) which offers high productivity rates (short cycle time). Open-deck can accommodate both wet or dry cylinder liners. The major advantage of the open-deck engine blocks is low cost associated with less intricate design and fast-cycling casting (HPDC). Nevertheless, in spite of the fact that there is still more than 70% of worldwide annual aluminum engine block production being of open-deck design (Kennedy and Bex, 1992), this approach has a few disadvantages compared to closed-deck blocks: cylinder head gasket reliability, increased noise and vibration and lower stiffness.

Closed-deck blocks cannot be made by HPDC because the use of sand cores for the water jacket[8] is not possible since they cannot withstand such high pressure. Also, the top deck prevents the use of metal water jacket cores because of obvious core withdrawal problems. In order to cast these closed-deck blocks, it is necessary to turn to slower casting processes like permanent mold casting (low pressure (LPDC), medium pressure (MPDC) and gravity (GDC)) and sand casting (no bake, low pressure (precision sand) and lost foam

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[8] The water jacket is the area, underneath the top deck, where engine coolant flows around cylinder walls and/or liners.

(Evaporative Process Casting)). The closed-deck aluminum engine block, in addition to addressing the open-deck's problems, offers better NVH (noise, vibration and harshness) characteristics and reduces permanent cylinder bore distortion. But admittedly, the slow-cycling processes and the use of sand cores necessary for casting closed-deck block are more expensive than die cast open-deck blocks.

As for bore liners, the choice of the arrangement, wet or dry, depends largely on top deck design. Wet liners are almost exclusively found in open-deck engine blocks, although it is possible to use wet liners in a closed-deck. As for dry liners, pressed in or cast in, they are compatible with and found in both open and closed-deck design. A dry liner is:

> "...a cast-in gray iron sleeve with aluminum cast around it over its full length. Since water does not come in direct contact with the sleeve, this design is called the dry sleeve arrangement. ...the sleeves are held only by the residual stresses which develop when the molten aluminum cools off and shrinks onto the sleeve resulting in a strong mechanical bond with good thermal conductivity."[9]

Wet liners are also cast in or pressed in, the only difference with dry liners is that they are not surrounded by any aluminum, they are in direct contact with engine coolant. There is a lot of concern about possible galvanic corrosion in that case, since we are in presence of different material. Furthermore, some carmakers have rejected the wet liner arrangement because it reduces cylinder block rigidity and it is prone to sealability problems (combustion gas, coolant and oil) (Ohgami, Ohsawa and Saito, 1991). Wet

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[9] BAUER, A.F. (1960). Engine blocks and their components in aluminum die casting. <u>SAE Transactions</u>, <u>68</u>, pp.388-389.

liners offer such advantages as engine block casting simplification, faster mold or die equipment operation and overall engine length reduction.

3.1.5 Casting technologies

Today, out of the 6 million or so aluminum engine blocks manufactured annually, more than 75% are produced by high pressure die casting, especially in Europe and Japan. HPDC can achieve high production rates (cycle time ≈ 2 min.), has close dimensional tolerances, thin section capabilities (0.8 mm for Al alloys) and good surface finish (Clegg, 1991). On the other side, HPDC requires high plant and tooling costs, has restrictions regarding the alloy that can be cast. The extremely rapid and turbulent filling of the die cavity allows gases to be entrapped in the metal, thus reducing metallurgical integrity and prohibiting heat treatment. The GM Acurad process was developed to address that specific problem and the resulting Vega engine block was in fact heat treatable, as mentioned earlier.

Low pressure die casting represents about 20% of aluminum block castings. The quiescent filling eliminates much of the HPDC problems regarding mechanical and metallurgical properties, resulting in castings that can be heat treated and have better integrity. Again in comparison to HPDC, LPDC is less intensive in capital expenditures. The use of sand cores is possible due to the relatively low filling pressure, thus permitting the casting of closed deck blocks. One of the major drawback of LPDC is the slow production rate, cycle time is generally around 15 minutes per casting. Some recent advances at Nissan and Toyota, particularly in die cooling and filling (counter or differential pressure casting), have reduced cycle time in the 10 minutes area (Ohgami et al, 1991; Clegg, 1991). Surface finish and thin section capabilities are not as good as HPDC. LPDC is generally used for the casting of large engine blocks for high-end models (Lexus, Infinity, Mercedes, Porsche).

With the opening of Ford's Windsor Aluminum Plant (WAP) in 1993, aluminum engine block casting as taken a new road with the adaptation of the Cosworth racing oriented precision sand process to mass production for passenger cars (Duratec V6). The process, which features highly-automated zircon sand core assembly, offers weight savings, minimum machining and good metallurgical consistency. Annual production at WAP is scheduled to reach 1 million engine castings at full capacity. The advantages brought by this precision sand process are - weight over other casting techniques, minimum machining and excellent mettalurgical properties.

Finally, another sand casting process, Evaporative Pattern Casting (EPC), has been recently selected to produce aluminum engine blocks. Saturn, beginning in 1991, utilizes the lost-foam casting technique for all its aluminum engines, a world's first.

> "The (polystyrene) pattern .... is placed in a box. Loose sand is then poured around the pattern. ...Molten metal is directly poured onto the solid

> polymer pattern to produce the casting. As the metal fills the mold, the foamed pattern undergoes thermal degradation through a series of complex transitions and the depolymerized products are vented into the sand, leaving an exact metal duplicate in place of the polymer pattern."[10]

Lost-foam casting offers near-net shape capabilities, therefore machining is minimal. This process requires less capital investments than the precision sand process since an elaborate sand core assembly line is not necessary. Saturn uses 319 alloy for both engines (SOHC and DOHC) it produces by lost-foam. The cycle-time for sand casting techniques is harder to evaluate since the process is generally produced by batch.

Table 3.1: Summary: aluminum engine blocks

Positive Factors	Negative Factors
-Weight Reduction (≈30-40%) -Secondary Weight Savings -High Heat Conductivity -Lower machining costs	-Higher Material Costs -Liner material / Wear Resistance -High Capital Investments (Casting) -Actual Knowledge, Facilities and Equipments for Gray Iron Castings -Customers' Perceived Value

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[10] SHIVKUMAR, S., WANG, L. and APELIAN, D. (1990). The lost-foam casting of aluminum alloy components. Journal of Metals, November, p.38.

3.2 Aluminum wheels

3.2.1 Introduction

Along with engine blocks, wheels offer an interesting potential for weight reduction through the use of light aluminum alloys. It is rather recent (20 years) that aluminum wheels have penetrated the OEMs wheel market. Traditionally, automobile and light-truck wheels have been made out of plain carbon steel. Since the early 1980s though, mild steel has been gradually replaced by High-Strength Low-Alloy steels (HSLA) such as SAE 950X, SAE 980X and GM 980X. These high strength grades provide weight reduction possibilities through downgauging of sheet metal. Despite early claims of weight savings up to 25% over plain carbon steel (Rashid and Lawrence, 1978), HSLA wheels have not demonstrated weight reductions higher than 10-15% (Bambenek et al., 1982). The steel wheel manufacturing process, whether using plain carbon or HSLA steels, has not changed much through the years and remains quite simple.

> "The construction of the typical steel wheel consists of two components, a rim and a disc, each formed separately and attached by welding. The wheel discs are typically formed in a progressive die on a transfer press...The wheel rim is formed into a hoop and flash butt welded...The disc is then pressed into the rim and arc welded or spot welded...The wheel is then cathodic electrocoat primed, oven cured, and is ready for shipment."[11]

The characteristics that make a good wheel are the following: good appearance, lightweightness, corrosion resistance, ease of manufacture, low cost, resistance to abuse,

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[11] BAMBENEK, C.L., MOCARSKI, S., MITCHELL, J.W., BIDOL, M.K. and LUMM, J.A. (1982). 1983 Ford Ranger truck HSLA steel wheel. SAE Technical Paper #820019.

rotary and radial fatigue resistance (Brown, 1983). In order to successfully meet all these requirements for good wheel construction, the material used must in turn possess some of these qualities: lightweightness, corrosion resistance, high formability, endurance, strength, fatigue resistance, good weldability (Fauth and Scott, 1980).

Aluminum wheels have been produced in very limited numbers since the beginning of the automotive industry. During the 1970s, however, the massive downweighing effort prompted by recent CAFE standards and the growing importance of wheel styling and appearance have been greatly beneficial to the introduction of aluminum wheels in the market. The penetration of aluminum wheels has been steadily rising ever since, from less than 7% in 1983 to more than 40% of the North American new cars market in 1993 (Child, 1994). Aluminum wheels are also gaining ground in the light trucks market, although the pace of the penetration is slower. Three major types of aluminum wheels have been developed through the years and have gained significant shares of the OEMs wheel market: forged, cast and fabricated sheet aluminum wheels.

3.2.2 Forged aluminum wheels

The first forged aluminum wheels on the market were developed and made by Alcoa for heavy trucks in 1948. These truck wheels were initially forged from 2024 alloy and then from 6061 alloy starting in 1966. In the passenger car market, the first use of forged aluminum (2014 alloy) was for the wheel disc on the Cadillac Eldorado in the mid 1950s. The aluminum disc was riveted to a standard steel rim. The 1973 Pinto featured all aluminum 6061-T6 alloy forged wheels, it was followed very closely by the 1973½ Maverick and by Jeep Division's Cherokee and Renegade models.

Forged wheels are of a one piece design, the disc and the rim are forged from a single blank. Presently, 6061 alloy heat-treated to the T6 temper[12] is the most widely used material for forged wheels. Due to the process, forged aluminum wheels exhibit high strength properties. They also offer a broad latitude in styling, although not as much as with cast aluminum wheels. Forged aluminum wheels offer a weight reduction potential of 20 to 30% over steel wheels.

3.2.3 Cast aluminum wheels

Cast aluminum wheels are of a one piece design. They are generally produced by permanent mold processes (low pressure die casting and gravity die casting) or high pressure die casting. A specific HPDC process has been developed, pore-free casting, in which the die cavity is flushed with oxygen prior to metal fill. The oxygen combines with the molten aluminum to form solid metallic oxides rather than the usual porosity forming

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[12] Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold the constituents in solution (Aluminum Association).

gases generally found in HPDC castings. Thus, the castings can be heat treated and exhibit excellent properties. Cast aluminum wheels offer the highest level of fine detail, deep sculptured features and high styling. 356-T6 is the most widely used alloy for aluminum wheel castings.

European luxury automobiles and sports cars have been the first to feature cast aluminum wheels in the 1970s. The fitment of cast alloy wheels had become a "status symbol" due to their stylish appearance (Woodward, 1979). Even today, cast aluminum wheels are generally found on high-end models or as optional features on popular ones. Cast wheels are usually more expensive than forged or sheet aluminum wheels. The weight reduction potential with cast wheels is 20-30% over steel wheels.

3.2.4 Sheet aluminum wheels

Sheet aluminum wheels have been developed in the late 1970s by Kelsey-Hayes and Reynolds Metals. Both companies decided in 1976 that these new aluminum wheels would be fabricated in a similar way to steel wheels and above all, on the same equipment. The first application of sheet aluminum wheels, produced by Kelsey-Hayes, was on Chrysler automobiles in 1979. Fabricated sheet aluminum wheels offer a weight reduction potential of 40-50% over comparable sheet steel.

In order to manufacture sheet aluminum wheels on existing sheet steel lines, engineers at Reynolds and Kelsey-Hayes had to develop a flash butt welding technique suited for aluminum sheet. When it was finally done, the production began with only slight modifications to existing equipments. The material used is wrought 5454 alloy. This type of aluminum wheel is the least expensive, but styling and design are limited by the process. Whereas forged and cast aluminum wheels offer styling and appearence as their main advantages, sheet aluminum wheels are much more dedicated to weight reduction.

3.2.5 Development of aluminum wheels

Since the development of fabricated sheet aluminum wheels, many opportunities have arised in order to reduce the costs of stylish cast or forged wheels while improving the appearence of fabricated wheels. It is now common to produce "composite" wheels with a sheet aluminum rim and a cast or forged disc. It is therefore possible to benefit from weight and costs reductions while having attractive designs and styles. Another combination is available, it is a sheet steel rim with a forged or cast aluminum disc.

There is a variety of finishing treatments in order to obtain highly attractive and corrosion resistant aluminum wheels. Among the many processes used, the most common are electroplating, anodizing and organic coatings. Prior to coatings, mechanical finish of the substrate by buffing, sanding of abrasive blasting is performed. Clear and translucent coatings, as well as opaque ones can be applied to the aluminum wheel, depending on finish selection.

Table 3.2: Summary: aluminum wheels

Positive Factors	Negative Factors
-Weight Reduction (20-50%) -Style and Appearence (Forged and Cast) -Design Flexibilty (Forged and Cast) -Customers' Perceived Value -Corrosion Resistance -Production on Existing Equipments (Sheet Aluminum Wheels) -Better Ride and Handling -Secondary Weight Reduction	-Higher Cost -High Capital Investments (Forged and Cast)

3.3 Aluminum radiators

3.3.1 Introduction

The radiator, or heat exchanger, is the most critical component of the thermal management system of a vehicle. "The primary function of the radiator is to remove heat from the engine coolant by transferring that heat through the tube wall to the extended fin surface and to the air passing through the core"[13]. Altough different materials and production techniques can be utilized in radiator constructions, the general design is usually similar from one to another. The typical radiator is made of four major components: the tubes,

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[13] PARK, K.H., BLUMEL, B.W., ZALESKI, R.J. and SCORE, M. (1986). New vacuum brazed aluminum radiators for Ford light trucks. SAE Paper #860078.

fins, headers, and tank. The tubes and fins constitute the core of the radiator. Hot engine coolant circulates through the tubes, where the heat is transfered to the fins. The fins, made of highly heat-conductive materials, dissipate the heat in the air flow passing through the core.

The principal characteristics of a good radiator are performance, weight, cost, durability (mechanical and metallurgical) and reliability. Performance and efficiency are usually measured according to the following criterions: package space (kJ/m^3 and kJ/m^2), material usage (kJ/kg) and performance/price ratio (kJ/$). Durability is closely related to structural integrity and corrosion resistance. Due to its frontal location, the radiator is exposed to a wide array of external hazards, mainly deicing road salt and acid exhaust fumes. The radiator is also subject to both static and dynamic loadings such as the weight of the core itself with coolant and attached hardware (fan, motor, shroud, brackets, etc.), vibration, internal pressure and thermal cycle. Galvanic corrosion and localized pitting are the two major types of corrosion that threathen any radiator's durability (Park, Barkley and Woody, 1986). As for the materials utilized, the advantages engineers and designers are looking for are heat-conductivity, low-density, formability, strenght and corrosion resistance.

The copper/brass radiator has been the most popular with carmakers for the most part of the century. The tubes and tank are made of brass and the fins of copper. Apart from gold and silver, which are extremely expensive, copper is the material which has the best heat conductivity (398 W/m·K), and it is also quite resistant to corrosion. The tube and fins, as well as the tank and header, are joined together with a lead solder. The copper/brass radiator, altough it proved satisfactory for more than 5 decades, faced rising competition from the aluminum radiator during the seventies and eighties. The auto manufacturers were looking for cost and weight reduction and also higher reliability and durability. From a material perspective, it is noteworthy that the relative price of aluminum and copper changed dramatically during the 1940s and 1950s in favor of the former. It should also be considered that aluminum radiators are generally lighter than their copper/brass counterparts, further reducing material costs per unit.

Altough some experiments were made in the past, serious research efforts for an all aluminum radiator began in the early 1950s among U.S. automotive manufacturers and aluminum producers. The examination of current manufacturing techniques trials revealed major corrosion problems caused in most part by the residual flux used in the brazing process. The first assembly technique was in fact the salt dip brazing process.

> "In this method, complete units are immersed in a molten salt bath where the salt acts both as the flux and the means for raising the assembly to the brazing temperature (~600°C). A major limitation of this process, as with other chloride flux processes, is the necessity to completely remove the flux residue because it is corrosive."[14]

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[14] FORTIN, P.E., KELLERMAN, W.M., SMITH, F.N., ROGERS, C.J. and WHEELER, M.J. (1986). Aluminum materials and processes for automotive heat exchanger applications. SAE Paper #860076.

Altough the results were acceptable from a mechanical point of view, the removal of the corrosive flux was a major concern. In addition to higher manufacturing cost insued by the thorough removal operations as such, the wash water was of course contaminated with chlorides, creating a disposal problem. Flux brazed radiators were first produced by the Harrison Division of General Motors for the Chevrolet Corvette in 1960. For a period of roughly 12 years, over a quarter of a million of these flux brazed units were produced.

3.3.2 Mechanically Assembled Aluminum Radiators (MAARs)

At that point, in the late 1960s, aluminum radiators manufacturers realized that it was not with flux brazed units that they would take over the copper/brass dominance on the worldwide heat exchangers market. A European firm, Sofica, came out with a totally new approach to aluminum radiator manufacturing: the Mechanically Assembled Aluminum Radiator, or MAAR. In that process, the total absence of brazing fluxes of any kind permits better corrosion resistance and also lowers manufacturing costs due to the fact that there is no post-assembly cleaning or rinsing and that no heating cycle is employed in the process.

> "The core assembly, consisting of tubes, fins, end plates and synthetic gaskets is joined mechanically using a two-stage hydraulic press. End tanks of molded plastic are also mechanically attached through crimp tabs of the header sheet to form a compression seal against the end sheet gasket."[15]

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[15] KAECHELE, D.A. and HERR, H.K. (1977). Today's view of the aluminum automotive radiator. Presentation at September 26 1977 SAE meeting.

The ease of assembly with conventionnal equipment and knowhow were important advantages of the MAAR over traditional copper/brass and alternative aluminum radiators known at that time. Sofica, in conjunction with Volkswagen, has been the major supplier of MAARs to nearly all European auto manufacturers since the 1970s. In 1977, more than 3 million units have been produced for the European market. The introduction of MAARs in the North American market began with the importation of European cars equipped with the unit. In 1980, Ford initiated North American production of MAARs which were destined to the 1.6L non air conditioned Escort/Lynx vehicles (Veling et al., 1986).

In addition to manufacturing simplicity and inherent low costs, the MAAR has a mechanical rigidity generally superior to other radiator constructions. However, the mechanical joints between tubes and fins reduce heat rejection capacity. In fact, MAAR units are generally suitable for small displacement engines without any additional loads such as air conditioning. Also, the weight and size reduction are not as great as they could be with other kinds of aluminum radiators (Park et al., 1986).

3.3.3 Fluxless brazing of aluminum radiators

Back in the late 1960s, other technologies were experimented in order to address the shortcomings of the flux brazing process. General consensus was that any form of fluxes should be eliminated in the manufacturing of brazed aluminum radiators if the durability and reliability objective of North American automakers for a mininum 10 year service life was to be achieved. Two major new technologies, directed towards the fluxless brazing of aluminum radiators, were developed and put to trial for eventual mass production - vacuum and inert gas brazing.

Ford has been a pioneer in the development of fluxless vacuum brazing. It started in the late 1960s with the mass production of aluminum air conditioner evaporator units. The process of fluxless vacuum brazing is well described by Warner and Weltman (1978):

> "In commercial vacuum systems with oil diffusion pumps the pressure is typically 0,1 to 10 MPa (10^{-6} to 10^{-4} Torr), and about half of the total gas is water vapor. As vacuum brazing sheet is heated in the vacuum atmosphere the aluminum oxidizes, removing some of the oxygen from the system. When the sheet heats above 560°C (1038°F), ternary Al-Si-Mg liquid forms; some of this liquid exudes through the oxide. Magnesium vaporizes, gettering the system further. At about 580°C (1075°F) the amount of liquid in the cladding becomes great enough to flow. Some metal penetrates through the oxide and capillary action draws more liquid into the joint. The oxide skin in the fillet area is forced out, forming the fillet."[16]

The process can be done either in a batch or semi-continuous operation. In order to ensure that the oxide film does not inhibit the molten filler metal from properly wetting the parts to be joined, and thus resulting in poor mechanical properties, it is very important that the atmosphere in which brazing is taking place contains little oxygen and moisture. The affinity of aluminum to oxygen is very high at brazing temperatures (Rauschenbusch, 1978). It is also important that part temperature is uniform because an area that heats faster

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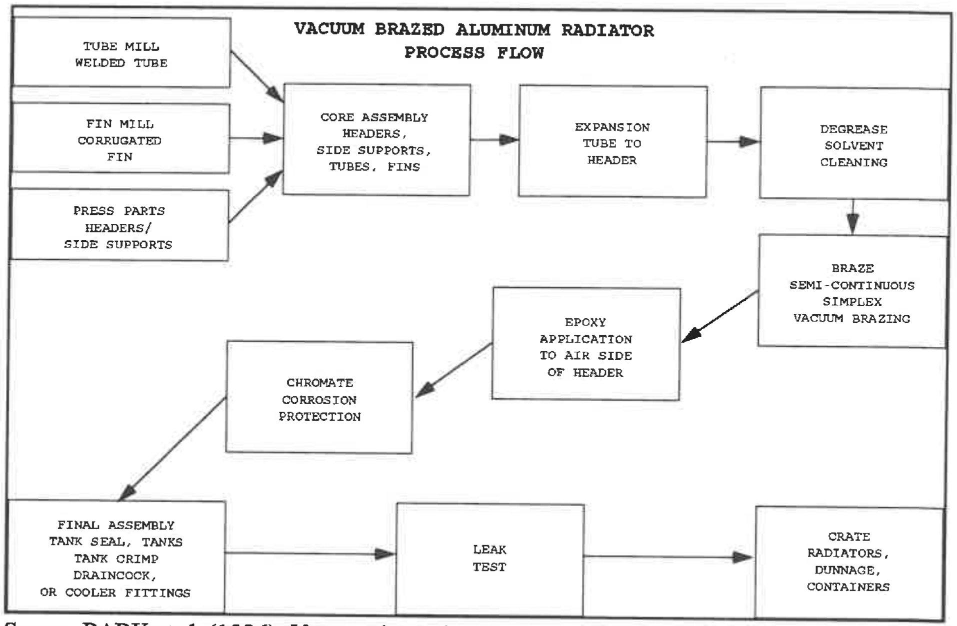
[16] WARNER, J.C. and WELTMAN, W.C. (1978). The fluxless brazing of aluminum radiators. SAE Paper #780299.

than another may act as a getter for the entire chamber and develop a heavy oxide that could jeopardize brazing quality. Figure 3.5 illustrates the vacuum brazing process.



Source: PARK et al. (1986). Vaccum brazed aluminum radiator for Ford Tempo/Topaz. <u>SAE Technical Paper #860644</u>.

figure 3.5:VBAR process flow

The Vacuum Brazed Aluminum Radiator (VBAR) proved rapidly to be more efficient and cheaper than conventionnal copper/brass, but a little less durable and reliable than the MAAR. VBARs are nevertheless much more efficient than MAARs from a packaging space and weight perspective. Some comparison data (table 3.3) from the Climate Control Division of Ford (Park et al., 1986) give us an idea of the relative performance and characteristics of different radiator constructions.

Table 3.3: Comparison data for various radiator constructions

	Comparison to Base: Better/(Worse)			
	Base Conventionnal Copper/Brass	Optimized Copper/Brass	Mechanically Assembled Aluminum	Vacuum Brazed Aluminum
Weight	100%	120%	106%	190%
Package Space	100%	121%	(62%)	124%
Mechanical Endurance	100%	100%	420%	170%
Reliability	100%	100%	140%	120%
Cost	100%	110%	130%	128%

Source: PARK et al. (1986). New vacuum brazed aluminum radiators for Ford light trucks. SAE Technical Paper #860078.

The inert atmosphere fluxless brazing, or inert gas, works in the same way as the vacuum brazing process, except that instead of pumping the air out of the brazing chamber, an inert gas is pumped in. The inert gas, usually dry nitrogen (N_2), keeps air, and therefore oxygen and moisture, away from the aluminum brazing surfaces. The gas also helps in transfering heat so that parts are quickly and evenly heated up. In comparison to vacuum brazing, the inert gas process produces similar results from a mechanical and metallurgical standpoint, but necessitates less capital investments since costly vacuum systems are not required. Both processes are particularly touchy; heat and atmosphere must be monitored and controled very closely, otherwise the whole batch can be easily ruined.

3.3.4 Non-corrosive flux brazing of aluminum radiators

In addressing the corrosion and environmental problems of flux brazing, fluxless brazing processes have, admittedly, somewhat made the production of aluminum radiators more complex, and therefore more costly. In recognizing the virtue of the flux brazing simplicity, ALCAN began a research program, in the early 1970s, to develop a non-corrosive flux brazing process. The results came out in the late 1970s with the introduction of the NOCOLOK process (Cooke et al., 1978). Instead of using a corrosive chloride flux, this process uses a non-corrosive, non-hygroscopic potassium fluo-aluminate flux (eutectic mixture of K_3AlF_6 and $KAlF_4$). The flux is completely inactive below the brazing temperature range, so it is not necessary to remove it after the operation. Furthermore, it has been reported that the flux residue does, in fact, inhibit corrosion of brazed aluminum components (Cooke et al., 1978).

The NOCOLOK process does not require as much capital investments as the inert gas and vacuum brazing processes since the brazing furnace environment tolerances are much wider. The process lends itself both to batch and continuous production and is also capable of handling various types of heat exchangers (evaporators, condensers, oil coolers and radiators). Without further treatment, radiators coming out of the brazing furnace can be readily chromate conversion coated or electrocoated for improved corrosion resistance.

As of today, General Motors and Ford have completely switched to aluminum radiators, Chrysler already uses a majority of aluminum units. Some Japanese transplants still use copper/brass radiators supplied by Nippondenso.

Table 3.4: Summary: aluminum radiators

Positive factors	Negative Factors
-Weight Reduction (≈20-50%) -Better Corrosion Resistance -Better Durability and Reliability -Better Performance -Smaller Size -Equal or Lower Cost -Compatibility and Adaptability to Existing Parts and Components, Design	-High Capital Investments -Customers' Perceived Value

3.4 Galvanized steel for outer body panels

3.4.1 Introduction

The most apparent components of any automobile are certainly the exterior panels that make the "skin" of the vehicle. Exterior panels comprise the hood, fenders, door panels, quarter panels and trunk lid. These panels have limited or none structural functions and are simply welded or attached to the frame. However, the outer panels definitely have aesthetic and aerodynamic functions. The first are related to the general appearence of the vehicle, more specifically the coating and painting, and also the forming of the panels such that they can give the vehicle its particular shape and personality. Vehicle aerodynamics are greatly influenced by the exterior panels shape and design as they are directly related to air flow and drag coefficient.

What the automakers are looking for in materials for outer body panels is good paintability and surface appearance, weldability, formability and corrosion resistance. Since the early days of automobile manufacturing, plain carbon steels (hot and cold-rolled) have been used for most of the panels. The carmakers have gained great knowledge of plain carbon steels through the decades and the entire manufacturing process is centered around the use of these materials.

During the last decades, as motorists in northern regions have asked for safer roads, the use of road deicing salts such as calcium chloride has gone dramatically up. The increased use of road salt, and to a lesser extent higher atmospheric pollution levels, have had disastrous repercussions on automobile durability, particularly exterior panels corrosion resistance. There are two major types of corrosion hazards: cosmetic corrosion and perforation. Cosmetic corrosion takes place on the external surfaces of the vehicle and is often caused by defects in the paint coating, due to stone chipping and scratches. Red rust and paint blisters appear, reducing the cosmetic value of the car. Perforation, or inside body corrosion, originates at joints and seams and progresses towards the external side of the panel. In the late 1970s, early 1980s, several governments, among which the Canadian and the U.S. governments, have issued standards regarding corrosion resistance of cars.

3.4.2 The nature of galvanized steels

In order to address consumers complaints, and later governmental standards on corrosion protection, automakers began to experience and use various remedies for protecting automobile bodies against corrosion in the 1960s. There are many ways to tackle the problem, among them: modifications in construction, improvements in pre-treatment and painting systems and the use of coated steels and/or plastic coatings, greases and waxes (Porter and Walden, 1967; Takahashi et al., 1980). These various methods of corrosion protection are generally regrouped in two categories. First, barrier protection methods work in preventing corrosion by forming a physical barrier between the steel substrate and the environment. There is a wide range of barrier protections and most of them, such as phosphating, electrodeposition priming (E-Coat) and finish painting, are complementary. These methods have a direct effect on cosmetic corrosion resistance and also on general surface appearence. Second, galvanic (or sacrificial) protection is provided by adding a metallic coating (zinc) to the steel substrate. This kind of protection is provided by virtue of the fact that zinc is more electronegative than iron in the electrochemical series (Llewellyn, 1992). There are many variations in the exact composition of the coating (pure Zn, Zn/Fe, Zn/Ni, organo-metallic (Zincrometal), etc.) and also many different processes to produce such coated steels.

The use of barrier corrosion techniques such as phosphating and electrodeposition priming began earlier than the use of coated steels. It was believed, back in the 1960s, that such protections would be sufficient in providing adequate corrosion resistance. Galvanic and barrier protections, although they can be complementary, were not viewed as such, but rather as substitutes for one and other. However, as a consequence of weight reduction and downsizing trends that began in the early 1970s, the downgauging of sheet steel for panels required additional protection by using both galvanic and barrier protection[17]. From that point in the late 1960s, early 1970s, even if barrier protection technologies have continuously improved since, most of the developments in corrosion protection have came from the various steel coating technologies.

There are two major types of zinc coated steels: hot-dip galvanized and electrogalvanized. As mentionned earlier, the main difference between these products is the coating process, which ultimately has a certain effect on coating composition and substrate condition. Both processes have been known for quite some time and were already operating on a continuous basis (as opposed to batch) in the 1960s. First application of coated steel was in the 1960 Ford Falcon, and other companies rapidly followed suit. In 1967, all mass-produced American automobile contained galvanized steel, most exclusively for unexposed and semi-exposed parts such as rocker panels, door sills, fender shields, transverse and longitudinal load-bearing beams, fuel tanks, etc.

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[17] The corrosion resistance of steel is diminished as the thickness of the sheet is reduced (Davies and Easterlow, 1985).

Hot-dip galvanizing of sheet steel is generally performed on a Continuous Galvanizing Line (CGL). Coils of hot and cold-rolled steel enter the line and are first cleaned by various combinations of brushes, chemicals and electrolytic cleaning. The strip is then annealed as it passes through the annealing furnace for 1 to 5 minutes at 790-900°C. The annealing operation can be performed before entering the CGL by batch (box) or continous process as the last of basic steelmaking operations. Coming out of the annealing furnace, the strip enters the coating pot that holds the molten zinc bath (with minute quantities of aluminum) and stays immersed for a few seconds. The strip exits the galvanizing bath and passes through coating thickness control, and then forward to the quench tank, skin passing and tension leveling. The strip is then recoiled and ready to be sent to the stamping plant. Hot-dip galvanized steels (HDG) generally have coating weights from 25 to 150 g/m^2 per side, depending on their use (exposed or unexposed).

Through the same process, it is also possible to obtain a Zn/Fe alloy coating by passing the strip, as it comes out of the coating pot, into an annealing furnace that causes the zinc to alloy more fully with the base steel and causes the iron in the substrate to migrate to the coating's surface (Berry, 1990). This product is called galvannealed (GA) and offers slightly different metallurgical and mechanical properties than free zinc HDG steel. HDG steel is available in one side, one side and a half and two side coatings, whereas GA steel is only available in two side coating. Both grades can be produced with equal or differential coating weights on each side of the sheet.

Electrogalvanized steel (EG) is also produced in continuous operations. The strip is first cleaned and then annealed, much in the same way HDG is. The major difference between the two processes lies in the coating operation, instead of being immersed in a molten zinc bath, the strip passes in an electrolytic bath made up primarily of zinc sulphate, where zinc is provided to the electrolyte by means of zinc anodes (Llewellyn, 1992). A strong current is passed through the sheet and the zinc is deposited on one or both surfaces. Electrogalvanizing is carried out slightly above room temperature and therefore the coating operation has very limited effect on the forming behaviour and mechanical properties of the substrate. Electrodeposited coatings are generally thinner than HDG and GA coatings. Galvannealed products are also available from the electrogalvanizing process (EGA).

Apart from basic zinc coatings, several other coatings such as organo-metallic coatings can be produced by electroplating. These composite coatings generally feature one or two bi-metallic layers (Zn/Fe, Fe/Zn, Zn/Ni, Zn/Co, Zn/Cr) and a thin resin or resin-silica film on top (Uchida, 1991). Although these products are available in North America, they have been developed and mostly utilized in Japan, where energy costs are high. Electroplating requires large energetic inputs and they tend to grow as the thickness of the coating increases. Organo-metallic coatings require less energy since they have thicknesses in the 2-5 μm range, versus 10-15 μm for more conventional coatings.

3.4.3 The introduction and development of galvanized steels

The introduction of galvanized steel in the automobile industry can be divided into four major periods that approximately tally with the decades (1960s, 70s, 80s, 90s). As mentionned earlier, the first applications of coated steels have occured during the 1960s. At that time, automakers felt that barrier protection (phosphate, E-Coat, paint finish) would be sufficient for exterior panels corrosion resistance. In addition to that feeling, they also considered galvanized steels to be inadequate in terms of paintability and surface appearance, weldability and formability. As the progressive downgauging of sheet steel began in the 1970s, manufacturers became aware of rising corrosion hazards. Consequently, galvanized steels were gradually phased in for exterior panels. However, it is important to note that most ot these steels, whether HDG or EG, were one side and one side and a half coated[18], with the coated side on the interior. Car manufacturers were still not satisfied with the paintability and suface appearence of galvanized steels and they felt more confident painting and finishing bare steel on the exterior.

In the 1980s, The recent passing of severe corrosion standards by many countries and the rising competition among manufacturers for corrosion resistance forced the majority of them to switch gradually to two side free zinc electro steel for exterior panels. They generally chose EG steel because coating is more uniform from side to side of the strip and

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[18] One side and a half coated steel is a sheet coated on one side with free zinc and on the opposite side with a thin layer of zinc-iron alloy.

from coil to coil than HDG. Also, automakers were dissatisfied with the spangled surface of HDG. The spangling of HDG steel occurs when the strip exits the molten zinc bath.

> "The outer layer of a hot dip galvanized coating solidifies as a cast crystalline structure starting at isolated nucleation sites and developing into a more or less regular "frost flower" or a "spangled" pattern. These macroscopically visible surface grain structures or spangles consist of a number of facets of related orientation radiating from a single nucleating point."[19]

Galvannealed steel has also benefited from the continuing introduction of coated steels for exposed applications. Automakers, led by Honda and Chrysler have started lo look closer to GA steel since the late 1980s. GA does not have any spangling problems, due to the Zn/Fe alloy coating, and has good paintability/surface appearence characteristics.

In 1990, the primary selection of galvanized coatings for exposed applications by selected North American auto manufacturers was as follows: General Motors and Ford, free zinc EG; Chrysler, GA and EGA; Honda, GA; Nissan and Mazda, EG (Zn/Ni); Toyota and Diamond-Star, EGA with Fe-rich Zn/Fe flashing. It is noteworthy that in 1990, apart from all other major competitors, Ford still used a significant proportion of one side coated steel (bare side on the exterior). In 1988, Chrysler had converted most of its exterior panels from HD to EGA. Honda went previously from Zincrometal (organo-metallic) to one side EG in 1987.

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[19] PATIL, R.S., HENGER, G.M. and GLATTHORN, R.J. (1984). Minispangling of hot dip galvanized steel. SAE Technical Paper #840211.

As of 1995, the picture is practically the same, except that hot dip is making a come back as many manufacturers are closely monitoring the latest developments in HDG coatings. Since the beginning of coated steel introduction, HDG always had poorer coating uniformity and surface appearence. The coating uniformity issue has been the major factor that restrained car manufacturers from making a wider use of HDG for exposed panels. Paintability, weldability and formability can be greatly affected by the lack of coating uniformity.

Today, with the continuous improvements in process controls such as annealing temperature control, galvanizing bath composition and dross reduction, air/nitrogen knifes and closed loop coating weight control measures with information feedback, HDG and GA are challenging electro steel in uniformity of coating weight. Closer control of galvanizing bath composition has also permitted to produce spangle-free HDG. This could have significant repercussions on future coating selection since hot dip is approximately 25% cheaper than electro (with GA between HDG and EG).

In addition to better process control, galvanized steels in general have greatly benefited from mechanical and metallurgical improvements of steel substrates. Apart from High-Strength Steels (HSS and HSLA), which are mostly used in structural applications, two major new grades of steel have been progressively introduced in automotive applications: Bake Hardenable (BH) and Interstitial Free (IF) steels. Bake-hardenable steels have been developed to offer a solution to the basic sheet metal usage conflict: high component's yield strength (high stiffness) for dent resistance versus low sheet metal yield strength for good formability (Bleck et al., 1993). BH steels are medium strength products that are strengthened by the heat of the automaker's paint bake ovens, typically raising yield strength by 10-15% (Berry, 1990). It is therefore possible to further reduce sheet thickness and weight without sacrificing dent resistance or component integrity. BH steels are available since the mid-eighties in electrogalvanized grades and have been increasingly used by GM and Ford. BH steels are not yet available in HDG and GA grades, but steelmakers have been working on that for several years and have already put a number of products on trial.

Interstitial Free (IF) steels are generally used for HDG and GA coated sheet. These ultra low carbon steels (< 50ppm C) possess excellent mechanical properties in terms of formability. The advent of vacuum degassing in basic steelmaking operations has made the mass production of ultra low carbon IF steels possible. IF steels have greatly improved the formability of HDG and GA products which are now available in Drawing (DQ), Deep Drawing (DDQ) and Extra Deep Drawing Quality (EDDQ).

Alhtough continuous improvements have been made to all grades of coated steels, there still remains some differences between them and in comparison to uncoated steel. First, regarding weldability, automakers have adapted their resistance spot-welding equipments to the various coated steels. Galvanized steels require higher current levels and have a shorter electrode life than uncoated steel. Among them, galvannealed has the best weldability due its Zn/Fe alloy coating, followed by EG and then HDG (Natale and Irving, 1992; Howe and Kelley, 1988).

Second, formability of coated versus uncoated steels has improved through the years, still, galvanized grades are not yet at par with their predecessors. Three factors are generally put forward to explain that situation: the thermal cycles experienced by the substrate in the coating process, zinc's presence changes the friction experienced by the sheet in the die, the zinc layer modifies formability of the steel sheet by interacting with it somehow (Stevenson, 1985). The advent of IF and BH steels have benefited the formability of coated steels. Automakers have learn to cope with the potential difficulties and hazards associated with stamping and forming operations. Automakers differ in opinion regarding formability among coated steels, each one asserting that the steel they use has the best formability. This is a predictable situation since each of them has developed a specific knowledge and has modified tooling for a particular coating.

Finally, the increased use of galvanized steel, particularly since the 1980s, is becoming a major concern for the recycling industry. As the automobiles of the last decade are taken out of traffic and sent to dismantlers and shredders, steelmakers remelting automotive steels are receiving increasing amounts of zinc coated products. Steelmakers and Minimills equipped with Electric Arc Furnaces (EAFs) rely heavily on steel scrap, consequently they face a rising supply of galvanized steels. When charged in the furnaces, the zinc contained in the scrap is vaporized and winds up in the dust collected by baghouses or precipitators (McManus, 1992). The zinc-rich dust has been declared hazardous waste by the EPA, thus it cannot be landfilled and has to be treated in order to remove the zinc. Steelmakers who operate Basic Oxygen Furnaces (BOFs) use a lower percentage of scrap per heat, but since the total volume is much more higher, the quantities of zinc are important. In BOFs the zinc has considerably less time to vaporize out of the melt because heats in that process are faster than in EAFs, it has therefore a greater tendency to stay in the liquid steel (Hoeffer, 1994). BOFs operators are looking for ways to remove zinc from steel scrap before it is charged in the furnaces. However, due to the enormous quantities at stake, such processes could prove to be particularly expensive.

Table 3.5: Summary: galvanized steels

Positive Factors	Negative Factors
-Better Protection Against Cosmetic Corrosion and Perforation -Costumers' Perceived Value -Downgauging of Sheet Metal -Limited Modifications to the Manufacturing Processes	-Higher Costs -Potential Difficulties with Weldability, Formability and Paintability -Recyclability

3.5 Polymer front fenders

3.5.1 Introduction

As discussed in the previous section, body panels have aesthetic and aerodynamic functions, with limited or none structural functions. This is particularly true in the case of front fenders. Due to their prominent frontal location, these panels have an important influence on vehicle design, style and aerodynamics, without having any structural functions. Fenders are simply welded, adhesive bonded or mechanically attached to the body-in-white assembly. In comparison to hoods or door panels, fenders have less demanding requirements regarding structural integrity and dimensional stability. It is thus relatively easier for engineers and designers to specify polymers as fender material than for most other outer body panel.

The characteristics that are stressed for in good fenders or fender materials are generally the following: corrosion resistance, light weight, formability, design flexibilty, surface finish and appearance, rigidity, impact resistance. Certain kinds of plastics do offer many of these characteristics and are therefore considered for substituting steel. However, when it comes to plastics, automakers have a long list of specific requirements that must be met by resin suppliers and molders (Hemphill, 1988). The polymer fenders must have a high rigidity (flexural modulus) in order to provide the necessary stiffness to support itself in all conditions. They must possess good dimensional and thermal stability and a low

Coefficient of Linear Thermal Expansion (CLTE) to minimize part distortion and ensure part fit when exposed to temperature cycling and extreme conditions. Impact resistance is required over a broad range of temperature, especially in cold conditions when embrittling of plastics is possible. A class "A" surface such that the plastic fenders match with adjacent steel panels after painting and finishing. The parts must have a short molding cycle, as close as possible or faster than the assembly line production rate. In order to minimize modifications to existing assembly processes and equipments (for steel), the polymer panel must allow to be installed on-line and then be able to withstand the 200°C (400°F) bake oven temperature commonly reached in E-Coat paint baking ovens.

The first application of plastic for fenders dates back to 1954 when the all-new Chevrolet Corvette was introduced. The Corvette featured an all-plastic body shell weighing only 155 kg, i.e., a little more than half the weight of a comparable structure (Premo, 1954). The body parts were composed of glass fibers and polyester resins combined in a laminating process. Since the initial production volume was low (< 10 000 units), the manufacturing process was rather considered as craftsmanship. In spite of the fact that it is still produced at low volumes (1994 production: 25 322 units), the one-millionth all-plastic Corvette was built in 1992. It was thirty years later before another car featured plastic body panels in North America, the Pontiac Fiero, which had a rather short life (1983-1989). Today, there are two major types of polymeric materials and processes that are currently considered for fender applications - thermosets and thermoplastics. Thermosets can be produced as Sheet

Molding Compounds (SMCs), whereas thermoplastics may be Reaction Injection Moldings (RIMs) or Injection Molded Thermoplastics (IMTPs).

3.5.2 The development and introduction of polymers for fenders

RIMs are rather recent, they were initially developed by Bayer AG in the late 1960s but first appeared in automotive body panels on the 1983 Pontiac Fiero. The second application of RIMs has been on the all-plastic GM's APV for front fenders in 1990. The outlines of RIM processing are well described by Slocum (1990).

> "..the essential character of the process involves high speed mixing of two or more reactive chemicals as an integral part of the injection of those chemicals into the mold. RIM equipment allows the injection of essentially all the mixed chemicals into the mold, obviating the need for flush waste, either materials or solvents. The injection mixture flows into the mold under relatively little pressure and at low temperatures, resulting in savings in energy and equipment."[20]

When first introduced on the Fiero, the RIM thermoplastic used was polyurethane-urea-based. In the last months of production, panels were switched to polyurea RIMs. Since then, RIM materials, whether for fenders or fascias, are increasingly polyurea-based RIMs. Reinforced RIMs (RRIMs) can be obtained by adding relatively short fibers or flakes that can be injected with the chemicals through the mixhead. Structural RIMs (SRIMs) are another variant to the initial process that can be made by preplacing a long

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[20] SCOLUM, G. (1990). Reaction Injection Molding. in Composite Materials Technology - Processes and Properties, MALLICK, P.K. and NEWMAN, S., Eds., Hanser Publishers, p.105.

fiber reinforced mat in the mold and then injecting the reactive chemicals through the mat. The most common RIM polymers considered for fender applications are Dow Chemicals' Spectrim and Bayer's (Miles) Bayflex.

Injection molded thermoplastics use a process similar to RIM since they also rely on the injection of chemicals into a closed mold. There is a major difference between both processes though, in the mixing and reaction of the chemicals that takes place.

> "In injection molding all this (mixing and reaction) takes place before the injection, instead of during the injection and molding as with RIM. This means that to be injected into the mold, the already formed polymer must be heated to the point where it flows and then cooled back to the point where it has sufficient integrity for demolding. Thus, unlike RIM, the injection molding process involves temperature cycling rather than actual chemical polymer formation."[21]

Injection molded thermoplastics can also be reinforced by adding fibers into the mold prior to injection. There are two major types of reinforced thermoplastics that are used in the automotive industry for fenders, polyphenyline oxide (PPO)/nylon such as GE's Noryl GTX and polyethylene terephthalate (PET)/glass such as Dupont's Bexloy and XTC.

Sheet Molding Compounds (SMCs) have been used in automotive body panels since the introduction of the Corvette in 1953. The manufacturing of SMCs can be divided in three major operations - compounding, maturation and compression molding. In the

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[21] SCOLUM, G. (1990). Reaction Injection Molding. Composite Materials Technology - Processes and Properties, MALLICK, P.K. and NEWMAN, S., Eds., Hanser Publishers, p.105.

compounding stage, the resin, filler, catalyst and thickener are mixed together at first, then the SMC sheet is produced by embedding fibers between layers of resin paste. During maturation, the viscosity of the paste is allowed to increase so the sheet can be handled prior to the molding stage. In the final operation, the SMC sheet is molded into the desired shape.

> "In the compression molding stage, SMC sheets are cut, stacked, and placed in a heated mold. With the application of heat and pressure, the sheet molding compound first flows and fills the cavity and then cures into a solid part. In the curing reaction that takes place in the mold, the resin molecules are cross-linked to form a three-dimensional network structure."[22]

SMCs have been used on GM's APV since 1990 for side panels. They will first appear (apart form the Corvette) on a fender application on the 1995 Lincoln Continental. The Budd Company will manufacture the fenders from its newly developed Hi-Flex SMC. SMCs are also becoming more and more popular for hood applications because of their low CLTE and good dimensional stability in high temperature environments.

In fact, one of the main differences between SMCs, RIMs and injection molded thermoplastics is the behavior of the polymer at high temperatures. SMCs have a marked advantage over both is competitors in terms of thermal and dimensional stability, that explains the fact why plastic hoods have been made exclusively of SMC. SMCs have a coefficient of linear thermal expansion almost equivalent to steel and it has been able to

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[22] MALLICK, P.K. (1990). Sheet Molding Compounds. Composite Materials Technology - Processes and Properties, MALLICK, P.K. and NEWMAN, S., Eds., Hanser Publishers, p.28.

withstand bake oven temperatures for quite some time. On the opposite, RIMs and IMTPs have only recently been able to go through that process along with SMCs and steel. This is a major concern for automakers since they do not want to cause any disruptions in the actual assembly process. By using polymer fenders that can be installed on the body-in-white at the very beginning of the assembly, the need for parallel coating and painting operations for polymer parts is avoided.

An important issue regarding the use of polymers in automobiles is the cycle-time required to mold a panel from the various processes. Compared to steel panels, which have a stamping cycle-time below 10 seconds (Clark et al., 1989), polymer panels are very slow. SMCs and IMTPs have cycle-times in the 60 seconds area, whereas RIMs are twice as long at two minutes (Market Search Inc., 1994; Gabriele, 1994). All polymers have reduce their cycle-time over the years with such improvements as Internal Mold Release (IMR) which facilitates panel removal from the mold and therefore increases cycle-time. The main factor that explain the differences in cycle-time is the cure-time that is longer for RIMs.

Compared to a basic steel fender weighing 3,5 kg, a similar SMC fender would weigh about 2,5 kg, a RIM-polyurea fender would weigh 2,2 kg and an IMTP-PET fender would weigh 2 kg. Thus, depending on the polymer used, weight savings from 28% to 43% are achievable over steel fenders. As for cost, SMCs are the cheapest polymer alternative, followed by RIMs (polyurea) and then IMTPs (PET) at the upper end. One of the factor that plays an important role in the costs of polymers, in addition to material costs, is the capital investments required to mold the panels. Whereas the press tonnage required for RIMs and SMCs are about 125 tons and 300 tons respectively, IMTPs may require press tonnage as high as 2000 or 3000 tons (Market Search Inc., 1994; Fisa, 1990). However, capital investments for polymer fenders are still much smaller than for steel. For example, the IMTP fenders on the Cadillac DeVille required 600 000$ in tooling, whereas tooling costs for a comparable steel fender would have been as high as 2,3 million $ (O'Malley, 1990).

There is a continuing debate over the economics of polymer fenders production. In general, the economics of polymer panels are the opposite of steel; relatively low tooling costs and relatively high material costs. Nevertheless, the numerous parties involved with polymers do not seem to agree on the production level at which the use of polymers stops making economic sense versus steel. A recent study by Mascarin and Dieffenbach (1992) puts the threshold at 75 000 units for SMC and 95 000 units for RIM for fenders. In 1987, Busch, Field and Clark had estimated that threshold at approximately 55 000 units for SMC and 70 000 units for RIM. Throughout the North American auto industry, the basic assumption is that polymers are competitive up to 100 000 units. Japanese automakers, which have highly productive and cost-efficient steel stamping operations, tend to put that threshold as low as 10 000 to 25 000 units. Finally, some resin suppliers and molders have put forward production volumes in the 150 - 200 000 units range.

Lately, resin producers and molders have come to realize that polymers may at best win a limited share of the fender market, and that deep penetration would remain theoritical in the current manufacturing, technological, regulatory and economic environments. Polymers have even become victims of their own success in certain cases, Chrysler is seriously studying the possibility of switching back to steel for fenders on LH cars since production of the Dodge Intrepid, Chrysler Concord and Eagle Vision reached 290 964 units in 1994. Furthermore, the all-plastic bodied GM APV minivan (Chevy Lumina, Olds Silhouette and Pontiac Trans Sport), produced at 136 125 units in 1994, is slated to go back to steel panels in 1997. Saturn, with a production of 282 842 units in 1994, appears to be the only high-volume model producer dedicated to polymer panels (vertical polymer panels and horizontal steel panels)[23].

One final consideration about polymers in automotive applications is the recyclability of these materials. Polymers in automobiles used to be considered as fluff or Automobile Shredder Residues (ASRs)[24] that were simply landfilled. Since the share of polymers in vehicles has been steadily growing and that the costs of landfilling have increased

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[23] Vertical panels are the fenders, quarter panels and doors. Horizontal panels are the hood, roof and deck lid.

[24] Fluff and ASRs are elements such as carpets, fabrics, glass and polymers that are seperated from recoverable metallics (ferrous and non-ferrous) and discarded since they can not be readily recycled or have limited value as such (Field III and Clark, 1994; Bhakta, 1994).

dramatically in the 1980s, due to the reduction in landfill capacity (Preston and Frank, 1989), alternative ways must be developed in order to reclame and recycle polymers. Thermosets have very limted recycling potential since they cannot be melted and reformed. Two alternatives are currently used - grinding for use as filler, and chemical or thermal (pyrolysis) decomposition into small molecules which can potentially be used as chemical raw materials or fuel (Selke, 1989). Thermoplastics offer a better potential than thermosets because they can be remelted and reformed. However, different types of thermoplastics cannot be be mixed indiscriminantly and therefore require identification (Selke, 1989; Brooke et al., 1992; Berry, 1992). Reinforcements, such as fibers, that are often used in polymers can greatly reduce the ease of recyclability of the material since they may have to be separated from the polymer matrix. At present, we can suggest that polymers recycling is not firmly established yet within the automobile reclamation and recycling infrastructure already in place.

Table 3.6: Summary: polymer fenders

Positive Factors	Negative Factors
-Weight Reduction (≈30-50%) -Corrosion Resistance -Design and Styling Flexibilty -Non-Structural Panels -Low Capital Investments -Lower Unit Cost (< 10K - 100K)* -Better Impact Resistance at Low Speeds -Customers' Perceived Value	-Higher Unit Cost (> 10K - 100K)* -High Cycle Time -Temperature Resistance (Paint Oven) -Surface Finish -Low Temperature Impact Resistance -Recyclability

*: Depending on the manufacturer or the study.

3.6 Plastic fuel tanks

3.6.1 Introduction

The fuel tank is a rather simple component which main function as a container is to securely contain fuel. It is generally located underneath the vehicle, in an area that is not directly endangered by a crash. The capacity and size of fuel tanks vary from one model to another and are mostly influenced by design and material used. Fuel tanks have not changed much through the decades and have mostly kept the same rectangular shape. Until lately, fuel tanks were almost exclusively made out of two stamped sheet steel halves welded together. Since the 1960s, plain carbon steel has been gradually replaced by galvanized steel for improved corrosion resistance.

Although its primary function (containing fuel) is rather simple, fuel tanks must meet a number of stringent requirements. Among these requirements: impact resistance, mechanical strength, permeation, resistance to fuel, resistance to fire, behaviour under high temperatures, static charge and safe installment (Liehr, 1988). The first two requirements are related to the structural integrity under various circumstances. Impact resistance is critical in accident situations, particularly at low temperatures when embrittling of materials is possible. Mechanical strength is necessary to ensure that there are no deformations due to internal pressure changes. Permeation is regulated in many countries and is related to the amount of hydrocarbons that permeate through the walls of fuel tanks. The fuel tank must be resistant to the effects of fuel on the material, particularly softening, swelling and cracking. The tank must also be resistant to direct flame for a certain period and keep its dimensional stability at high temperatures. In order to prevent explosions, sparks from friction or fuel flow must be avoided at all time. Finally, as mentionned earlier, the tank must be installed in a safe location. The importance of that last requirement has been recently highlighted by the controversy surrounding GM's C/K full-size pickups.

In addition to complying with the functional requirements of fuel tanks, designers and engineers are looking for materials that offer the following characteristics: corrosion resistance, light weight, design flexibility, low material and manufacturing costs. The development of automotive Plastic Fuel Tanks (PFTs) in the early 1970s brought an interesting alternative to common steel tanks. The first use of a PFT was in Europe, in the 1972 Volkswagen Passat.

3.6.2 Development of plastic fuel tanks

Although PFTs exhibit good characteristics and performance, there have always been and there still are major concerns regarding fuel permeability and related regulations. These regulations vary from one country to another and also in their contents. European and Japanese hydrocarbon permeation limits are set at 20 g/24 hours for the fuel tank only. US regulations are much tougher since they require hydrocarbon permeation to be less than 2 g/2 hours for the entire vehicle, including the fuel tank, fuel lines, carburetor or fuel-injection system, paint and tires (Brockschmidt, 1987). Fuel injection systems have sharply reduced overall hydrocarbon emissions. The American testing procedure is called the SHED Test (Sealed Housing for Evaporative Determination).

PFTs are all made from blow-molded High Density PolyEthylene (HDPE). "While HDPE offers a low cost, high impact strength material, it has a disadvantage of allowing hydrocarbons to permeate through the wall"[25]. In order to address HDPE's shortcomings, much of the attention in developing PFTs has been directed towards barrier technologies that reduce fuel permeation. The first technologies that have been used for reducing fuel permeability of HDPE are sulfonation and fluorination. These chemical treaments are effective in reducing permeation and allow to easily surpass current US regulations (2 g/2 hours) (Kreischer, 1992). Historically, sulfurtrioxide gas (SO_3) has been predominantly used (96% of all PFTs made in US in 1987 (Brockschmidt, 1987)), the remaining being treated by fluorination (F_2/N_2). However, since the last few years, fluorination has gained more than half of the market because the treatment can be carried out during blow molding. Both processes, although successful in reducing fuel permeation, may be hazardous to worker safety and the environment and thus require high capital investments.

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[25] BELL, R.L. and VINODKUMAR, M. (1988). Production of plastic fuel tanks using laminar barrier technology. SAE Technical Paper #890442.

US federal authorities are currently reviewing a new legislative proposition for tougher hydrocarbon emissions. The new proposal calls for a maximum permeation limit of 2 g/24 hours, approximatively 10 times more stringent than current regulations. These new limits that are slated to be in place in 1995 or 1996 will require fuel tanks that are virtually emission-free, what is only possible with steel tanks at present. In order to comply to these new, tougher regulations, blow molders and chemicals companies have developed new barrier technologies that could bring an answer to the permeation question.

The two technologies that have been developed since the late 80s are the multiple-layer continuous extrusion (coex) and the laminar barrier technology. These technologies can be complementary since the former is a refinement of the blow molding process and the latter is a barrier material that blends with HDPE. The first coextrusion accumulator-head machines, based on technology licensed from IHI of Japan, have been developed by Krupp-Kautex of Germany and have been available to blow molders since the mid 80s. Coex machines are similar to accumulator-head blow molding equipement, the main difference is that coex can produce multilayer HDPE/nylon structures (5 or 6 layers), whereas the accumulator-head machines are restricted to single layer HDPE tanks. In the coex process, nylon is dry-blended in-line with HDPE at the blow molding machine in order to form a barrier of overlapping platelets within the HDPE matrix. Dupont Co. has been a leader in these recent developments with its Selar laminar barrier technology, in which a modified nylon 66/6 is added to HDPE in low concentrations (4 to 6%). Laminar barrier technology can also be used with standard single layer accumulator-head blow molding equipment.

The actual situation, as new hydrocarbon permeation regulations will soon be in place, is critical to the continuing penetration of PFTs in the North American market. The latest technologies will be decisive in reassuring PFTs' position as subsitutes for metal tanks. As of 1992, market penetration of PFTs in North America was near 25%, versus more than 70% in Europe and just 5% in Japan.

Table 3.7: Summary: plastic fuel tanks

Positive Factors	**Negative Factors**
-Non-Corrosiveness -Weight Reduction -Design Flexibility -Increased Capacity	-Fuel Permeability -Customers' Perceived Value -Recycling

3.7 Summary of technical presentations

In order to draw out the most important aspects of each case, table 3.9 presents the technological and economic factors that have played the most decisive role in the substitution processes. The number of factors has been limited to three per case per category to ensure that only the most decisive are presented. The selection of these factors has been made by the author, in the light of thorough bibliographic research performed on each case.

Table 3.8: Principal factors in each case

	Functional Requirements	Technological Requirements	Economic Factors	Social Factors
Aluminum Engine Blocks	Low Weight Wear Resistance Heat-Conductivity	Castability Machinability	Costs Capital Invest.	CAFE
Aluminum Wheels	Low Weight Fatigue Resist. Corrosion Resist.	Castability Forgability Formability	Costs Capital Invest. Perceived Value	CAFE
Aluminum Radiators	Low Weight Corrosion Resist. Mech. Endurance	Brazability Formability	Costs Capital Invest. Make or Buy	CAFE
Galv. Steel Panels	Corrosion Resist. Surface Appear.	Paintability Weldability Formability	Costs Perceived Value Competition	Corrosion Resist.
Polymer Fenders	Low Weight Corrosion Resist. Design Flexibility	Moldability Paintability	Costs Perceived Value Product. Volume	CAFE Corrosion Resist. Recycling
Polymer Fuel Tanks	Corrosion Resist. Fuel Impermeat. Design Flexibility	Moldability Surface Treat.	Costs Capital Invest. Make or Buy	Fuel Perme. CAFE Recycling

CHAPTER IV

4.1 Results from the case-studies

4.1.1 Market penetration patterns

The six case-studies offer a wide variety of market penetrations, in terms of penetration as such, and also from a time span perspective. Aluminum radiators, as well as aluminum engine blocks and polymer fenders, have been on the market since the early 1960s, whereas in other cases the substitution began in the early to mid 1970s. Figure 4.1 illustrates the market penetration pattern of each material, in its specific application, in passenger cars and light trucks manufactured in North America from 1960 to 1995.

Galvanized steel panels and aluminum radiators stand out has the most complete substitutions among the cases studied. In less than 20 years or so, they have captured 98% and 85% of their market respectively. It must be noted, however, that these materials had already been used in a limited number of applications for a certain period before they firmly established themselves on the market. At the other end, polymers are still having only a marginal share of the fender market although they have been used for more than forty years (1953 Corvette).

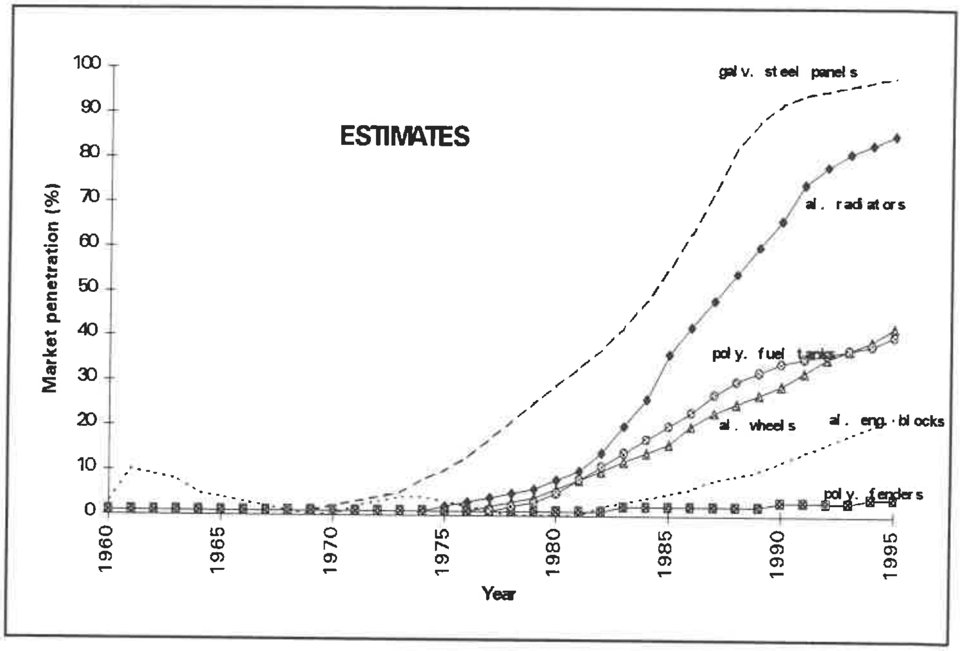

Figure 4.1: Market penetrations 1960-1995[1]

Polymer fuel tanks and aluminum wheels have similar patterns since they have been both introduced in the mid 1970s and they now command around 35-40% of their respective market. Aluminum blocks have had two false starts in their substitution pattern, once in the early 1960s, and again in the early 1970s. Since the 1980s, however, the trend is uninterrupted. Overall, there is a clear trend beginning in the late 1970s, concordant, as a matter of fact, with the adoption of Corporate Average Fuel Economy standards (CAFE).

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[1] All market penetration trends have been estimated by the author using various sources of data as indicators (Modern Plastics, 1995; Market Search Inc., 1994; Booth, 1990; Ward's Automotive Report, 1990; Automotive News, 1994; Kanicki, 1994; Kehoe, 1994; Abernathy, 1978).

4.1.2 Techno-economic factors

In addition to general similarities and differences in the market penetration patterns, there are also some regularities that appear in the influence of techno-economic factors upon the materials substitution processes. Certain factors seem to stand out as being important elements in the substitution decision and the following market penetration in a number of cases. Stemming from the analysis of each case-study according to the original analytical framework, the following conclusions are brought forward:

> *1) It appears that the substitute material must at least perform as well, in terms of functional requirements, as the existing material in a specific application.*

As trivial as it may seem, this has not been the case in all substitution cases. The fact that aluminum engine blocks have been unsuccesfully introduced two times in the sixties and seventies is a good illustration of this. Early aluminum engines had major reliability problems and were simply not at par with their cast iron counterparts. Today, the picture has changed dramatically however, since aluminum engine blocks are now featured on almost every luxury and performance vehicles (Mercedes-Benz, BMW, Audi, Lexus, Infinity, Porsche, Lincoln, Cadillac, Ferrari, etc.). This is an unquestionable mark of confidence towards the reliability of aluminum engine technologies and their superior performance over cast iron engines (leaving costs out of account).

Another case in point is the aluminum radiator, which, according to Ford's Climate Control Division (table 3.3), is superior in every aspect to the copper/brass units they replace. When initial assembly and brazing problems were finally settled in the 1970s, the pace of the substitution process increased dramatically (figure 4.1). In the case of polymer fenders, automakers are still concerned with the ability of the materials to meet certain functional requirements as well as steel does.

> *2) It appears that the substitution process will be hindered if the substitute material relies on transformation and manufacturing technologies different than those used for the existing material.*

In other words, in the event that competing materials (substitute versus existing materials) rely on similar complementary technologies, the introduction of substitute materials may be facilitated. In the particular case of aluminum blocks, the casting of aluminum and iron requires different skills and know-how. The experience in iron casting may be of limited use to the casting of aluminum components because the metallurgical properties and behaviour of these two materials are quite different. Still, in other manufacturing operations such as machining, existing processes and technologies may be easily adapted to aluminum.

Fabricated sheet aluminum wheels are a solid example of a substitute material that adapts itself to the existing equipments, skills, methods and procedures. Among the case studied herein, sheet aluminum wheels and galvanized steel panels are the substitute materials that required the least modifications and adaptation in their respective application. On the other hand, the blow-molding of high-density polyethylene (HDPE) for polymer fuel tanks and the stamping and welding of sheet metal for steel tanks have absolutely nothing in common.

> *3) It appears that if the component is part of a complex system, or its function or location are related to a number of other components, such that even a small change can greatly affect other components, the substitution process may be hindered.*

The best case in point here is the engine block. The nature of the material and subsequent modifications in block design can greatly affect a significant number of components and sub-systems. Just to name a few, we can think of valvetrains, pistons, connecting rods, crankshafts and cylinder heads that may require redesign or modifications if cast iron is substituted by aluminum. On the opposite, aluminum wheels can be fitted on any vehicle without any major changes. Usually, if automakers do make some modifications or redesign of related components (brakes, axles, steering, etc.), it will be to benefit from secondary weight reductions or to optimize the entire system.

Polymer fuel tanks also do not require many modifications to the existing fuel system to be fitted on vehicles. Furthermore, the use of polymer fuel tanks can even simplify the design of other components or systems such as the powertrain or the suspension, since its own shape can be blow-molded to accomodate a wide range of designs and dimensions.

Finally, the aluminum radiator can be fitted in place with just minor modifications to the engine coolant chemical composition. Its smaller size can also facilitate the design of surrounding components (e.g., a lower hood line).

> *4) It appears that the need for large capital investments will hinder the substitution processes and favor the existing materials.*

This conclusion is somewhat related to conclusion #2 since a substitute material that can be transformed and manufactured with existing technologies and know-how will generally not require large capital investments. This is true for fabricated sheet aluminum wheels that are manufactured on the same equipments than steel wheels, with only minimal modifications. The same applies to galvanized steel panels that can be formed, welded and painted with basically the same tooling and equipments than for uncoated steel. As for polymer fenders, although they require only small investments in tooling and equipments, they have not gained a significant share of the market, but that may be explained by other factors.

In the case of aluminum engine blocks, the need for large capital investments in foundry operations can be a major factor against their introduction. In addition to the new investments required, automakers must sometimes forgo large investments already made and amortized in iron foundries. The case of Saturn is unique since it has been built from scratch, so one way or the other (iron or aluminum), it needed foundry operations.

Polymer fuel tanks and aluminum radiators also necessitate large investments because their production is in no way related to the materials (and the components) they replace.

5) It appears that lower unit costs will promote the substitution processes.

As obvious as it may seem, the influence of costs upon the substitution processes must still be put in a perspective. Costs may well be the most decisive factor in materials selection. However, since a number of other factors have grown in importance over the last decades (weight, recycling, corrosion, etc.), trade-offs must now be made in order to optimize the total value of a component or a vehicle, considering the entire set of influential elements.

An automaker may be willing to pay a premium for a substitute material for each kilogram saved, it can also be willing to pay a premium for improved recyclability, corrosion resistance, security, reliability, etc.. Thus, unit costs are not absolute factors anymore, they must now reflect the numerous trade-offs between technological, regulatory and economic considerations. Aluminum engine blocks and aluminum wheels are the best cases in point, since they offer tremendous opportunities for weight reduction. The automakers must pay a certain premium on each kilogram saved over similar cast iron or steel components. According to the premium it has to pay, an automaker may decide to introduce the substitute material in luxury models rather than in popular models. The advances in process technologies over time may reduce the amount of the premium and therefore promote the penetration of substitute materials into more popular models. We can think of Saturn that has chosen to use aluminum blocks for its entire line of entry-level passenger cars because of advances in casting (Evaporative Pattern Casting, EPC).

6) It appears that a high perceived value to the customers will promote the substitution processes.

Automakers may be encouraged in going along with a substitute material if the customers are positively influenced by the new feature, or even more if they are willing to pay a premium for the substitue material in a specific application. The perceived value to the customer of a substitute material may be interpreted in many ways - utility, distinctiveness, performance, security, reliability, etc.. It is according to these elements that customers will decide how much more they are willing to pay for a particular feature.

Aluminum wheels have certainly benefited from customers interest. Their style and design improve the overall appearance of the vehicle by creating a distinctive image of performance and luxury compared to steel wheels with plastic covers. Aluminum were first featured as standard equipment on high-end and performance models, then as options on more popular models. Today, a growing number of popular models feature stylish aluminum wheels as standard equipment. Galvanized steel panels and plastic fenders are also a case where customers have been allowed to appraise the added value of such features as corrosion resistance (cosmetic corrosion and perforation) and dent resistance. In both these cases, however, customers may have been willing to pay a premium at first, but have quickly come to expect such features as standard or at no additional costs (Saturn).

On the other side, aluminum radiators, aluminum engine blocks and polymer fuel tanks may not appeal much to the common customer since they are not apparent. It is therefore harder to convince the customers that they must pay extra dollars for a substitute material that has no perceived value to them. Usually, customers are more or less aware of such technicalities and do not consider these elements in their buying and spending decisions.

> *7) It appears that the competition from other auto manufacturers will promote the substitution of materials.*

There are many ways by which the competition among the automakers can stimulate the substitution of materials. First, a particular automaker may want to distinguish its product from competitors by featuring new materials in certain applications. This has certainly been the case with aluminum wheels, galvanized steel panels and plastic fenders at first. Afterwards, customers may come to expect similar features on other brands of vehicles, therefore promoting or accelerating the substitution processes among competitors. Finally, a certain automaker may be forced to substitute materials, if a majority of automakers have done so, simply to keep up with the competition and avoid losing sales and/or market share.

This conclusion is closely related to conclusion #6 since the competitiveness of a particular brand or automaker is closely related to the perception of customers. Again, in the case of aluminum engines, radiators and polymer fuel tanks, it is more difficult to make competitive advantages out of these features than with apparent ones such as aluminum wheels and polymer panels. Nevertheless, these "obscure" material substitutions may add up and help improve the overall value of the vehicle in the long run by increasing quality, performance, security, fuel economy, etc..

8) *It appears that higher government standards for fuel economy (CAFE) will promote materials substitution.*

There is a clear trend, following the adoption of CAFE standards in 1975, towards the reduction of vehicles weight (more than 500 kg from 1975 to 1982, figure 1.4). Since 1985 however, CAFE standards have remained at the same levels. Accordingly, the weight of vehicles has not been further reduced, and has even gone up a little since the late 1980s. It is true that this upward trend can be partially explained by the fact that tougher security standards require additional equipments and components that may add weight. Also, the growing popularity of optional equipments such as air conditioning, ABS brakes, larger engines, etc., have added weight to the majority of vehicles.

The first round of weight reduction (1975-1982) has been achieved mostly by downsizing and substituting plain carbon steel by high-strength steel in structural components. Since a few years however, the size of vehicles and engine displacements are going up, along with the weight of vehicles. Overall, in the last few years, the net effect of substitutions for lighter materials and components was merely to offset the added weight brought by additional safety features, optional equipments, large engines and light trucks in the domestic fleet.

9) Readily recyclable substitute materials will be promoted in their introductions.

This has not been the case with polymers and it may be one of the reasons why they have been limited to less than 4% of the fender market over forty years. Although technologies are being developed (pyrolysis, methanolysis, etc.), the technical feasability and economic viability of polymers recycling remains unclear. The infrastructures needed to reclaim and reprocess polymers are not yet as developed as the infrastructures already in place for ferrous and non-ferrous metals. As long as the recycling technologies for polymers will not be firmly established and proven, and that a structured and efficient market for recycled polymers will not be in place, the use of polymers (and especially reinforced polymers) will be limited to a marginal share of the market.

On the other hand, supposedly recyclable materials such as aluminum and steel are now facing growing concerns about metallurgical considerations in recycling. The increasing variety of aluminum alloys found in vehicles is becoming a major concern as to the miscibility of various alloys with different compositions (Sanders and Wood, 1993;

Gorban et al., 1994; Marcks von Würtemberg, 1994). As for steel, the growing use of galvanized steel since the 1980s is becoming a major concern to recyclers and steelmakers because of the zinc content of coated steel. The problem is actually increasing since cars of the 1980s are gradually being removed from the market. Recycling is thus a complicated matter, but we can still bring forward conclusion #9 with confidence.

Among the factors mentioned in the analytical framework, suppliers relations (user/producer networks) and changing product mix do not seem to stand out clearly in the analysis. Due to the lack of evidence and information, it is not possible to draw any valid conclusions about the influence of these suppliers relations on the substitution of materials. The importance of the elements taken into account and the outcomes of the "Make or Buy" decisions are mostly unknown or unavailable. We can suggest that suppliers play a certain role on the substitution decisions and processes, depending on the automaker with whom they are dealing. But we are not allowed, with the actual evidence, to make any statements on the matter. As with changing product mix, the lack of specific data and evidence regarding light trucks keeps us from drawing any clear conclusions on the influence of light trucks versus passenger cars on the substitution processes.

4.2 The conceptual framework

Although some of the conclusions drawn in the previous section may seem obvious to the reader, they nevertheless carry great significance as to the materials substitution processes in the automotive industry. We must not only consider the technical or the economic elements found in each conclusions, but also the interrelatedness of these findings within the broader perspective of technological accumulation. By doing so, we will reinforce the validity and the pertinence of the above conclusions.

To begin with, the concept of technological accumulation takes its full meaning in the light of the analysis of the six case-studies and their development over time. It seems clear that all substitutions, partial or complete, have been made over a certain period of time in which the accumulation of technological capabilities and production capacity have been progressive. The substitution of materials in the automotive industry is not a punctual event, but rather a lenghty process that builds upon the development of process technologies, skills, know-how, methods and procedures. We can think of the elaborate R&D programs such as the ones for hypereutectic aluminum engines (Reynolds and GM) and for aluminum radiators (Alcan, Alcoa, Ford), the trial-and-error and experimentations in the case of aluminum radiators and galvanized steels, the knowledge drawn from good (sheet aluminum wheels) and bad experiences (aluminum engines in the sixties and seventies).

In order to understand the processes of technological accumulation taking place within each case of materials substitution, we must go back to the very nature of technology since it is the basic unit being "accumulated" through technological capabilities and production capacity. To begin with, the cumulative nature of technology clearly stands out in all cases. As stated in conclusions #2 and #3, substitute materials are largely influenced in their introductions by existing processes and know-how, and also by related components and systems. This is a clear demonstration that even between competing technologies or complementary technologies, the cumulative nature of technology is predominant since the substitute materials must build upon the environment in place (fabricated sheet aluminum wheels). In the event where the substitute materials are in no way related to the existing materials, in terms of technological background (e.g., polymer and steel fuel tanks), they must still be related somehow to other components and systems.

Also in the event where substitutes materials do not share common process technologies and know-how with existing materials, the irreversibility of technological change will play against these substitute materials. Thus, any disruption in the cumulative nature of the existing technology will be confronted with its irreversibility feature. In other words, a new technology that does not build upon the existing technology will have to confront the inertia and the "commitments" related to the existing technology. These "commitments" represent the investments (conclusion #4), the development of processes, procedures and methods, skills, suppliers contracts, and all other elements that together reinforce the irreversibility of a technological trajectory.

The substitution from uncoated carbon steel to galvanized steel panels is a good illustration of the cumulative feature of technology. The development of carbon steel has been determinant to galvanized steel since the latter uses the former as its substrate. We can therefore think of galvanized steel has simply being an "extension" of carbon steel technology, with any subsequent improvements in carbon steel being readily passed over to galvanized steel. Galvanized steel has thus taken full advantage of the cumulative nature of technology and has, by the same token, kept the "confrontation" with the irreversibility aspect at an absolute minimum.

In the particular case of galvanized steel, we can think of the substitution as taking place within the same technological trajectory. In most other cases, however, we are in presence of truly competing technological trajectories that may share supporting technologies (e.g., machining, surface treating, etc.). Competition between technologies takes place at two different level - among the various substitute materials technologies and between the emerging substitute materials technologies ("new") and the existing materials technologies ("old").

The substitution processes between competing "new" and "old" technologies will be promoted if they share supporting technologies. If this is the case, the substitute material will be allowed to draw upon the technological accumulation achieved by the existing material. In the event where the substitute material cannot benefit from any progress or advantages stemming from the use of the existing material, the irreversibility aspect may lead to a technological lock-in. The lock-in may, in turn, be reinforced by what is called the "sailing-ship effect"[2], which is, in essence, the continuing improvement of the existing technology so that the substitution is retarded.

The competition among several substituting materials technologies is present in every case studied. We can think of hot-dip versus electrogalvanized steel, cast versus forged versus sheet aluminum wheels, sleeveless aluminum blocks versus iron liners, etc., has being competing "new" technologies. The effect of the intensity of the competition among "new" technologies is unclear as whether it promotes or hinders the overall substitution process for a specific application. Competing "new" technologies can be seen as complementary in some cases, thus helping in meeting the specific requirements of various automakers. Or, on the contrary, the lack of a leading technology may keep automakers from reaching a consensus, and subsequently benefiting from certain advantages of standardization.

There are no paradigm shifts in the cases studied herein, just competing technological trajectories within the complementary paradigms of the steel-bodied automobile and the internal-combustion engine. Both these paradigms have been around since the beginning of the automotive industry. They may well be confronted by emerging paradigms in the

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[2] The sailing-ship effect refers to the substitution of sailing-ships by iron hull cargo steamships that was retarded by the subsequent improvement of the sailing-ships. A lot of the improvements made to the sailing-ships were taken from iron hull steamships (Rosenberg, 1976).

future (10-20 years), if expected laws requiring zero-emissions vehicles are fully implemented. These emerging paradigms are likely to be electric vehicles and light-alloys and/or composites spaceframes. Both sets of technologies are currently under development at major automakers and suppliers, in order to meet the 1998 California ZEVs mandate.

Since technology is cumulative in nature, we can therefore suggest that the emerging paradigms will draw upon certain elements of the current paradigms. Accordingly, some material technologies will leap forward into the next paradigms, leaving behind material technologies unable to adapt. A "bridging" of the emerging and existing paradigms will be done, following the definition of the underlying problems and challenges of the emerging paradigms. Intuitively, we can think of material technologies such as metal-matrix composites, powder metallurgy, polymer composites and light-alloys as being prime candidates for the "bridging". Steel and cast iron, in particular, may well be the biggest losers in such a transition.

Emerging paradigms could greatly benefit from the progress and the advances currently being made in material technologies in order to expand the life expectancy of existing automobiles paradigms. In such a broader perspective, technologies that were initially considered as competing, could well prove to be complementary. For example, the substitution of cast iron engine blocks by aluminum blocks may retard the substitution of the internal-combustion engine by electric motors.

CHAPTER V

5.1 Concluding remarks

The automotive industry is facing growing pressures, both from within and outside. Impending regulations and standards regarding a number of elements will be decisive upon the future of the automobile as we know it. These, coupled with ever increasing levels of competitiveness among global automakers, are requiring tremendous amounts of new technologies, among which materials technologies. The development of materials technologies, whether for regulatory or competitive purposes, leads directly to automotive materials substitution processes.

This study has attempted to shed light upon the influence of technological and economic factors on these processes of materials substitution. The conclusions that have been drawn are generally in agreement with popular wisdom throughout the industry. Among the specific findings that have been brought forward, two stand out clearly has being decisive in most material substitution cases - governmental regulations and standards, and costs.

As has been seen with CAFE, governmental standards have had a predominant influence on the substitution of materials. The fact that automakers have only improved fuel economy when forced to do so is an element of answer by itself. Today, if automakers take interest in alternative materials, it may largely be due to the fact that tougher CAFE standards are expected any time soon. In the meantime, at least, the competition among manufacturers seems to promote the substitution of materials. But even these stimuli do not appear to be of great concern for some automakers.

Costs have been put in a much broader perspective than before. They are not considered as absolute determinants anymore, but rather as relative indicators of the many trade-offs encountered in a substitution decision. Therefore, no single factor can be the sole element taken into account since a number of trade-offs are directly implicated in every decision. The material chosen for a specific application will be the one that provides the best trade-off among the many factors that are taken into account.

Again, we can clearly bring out the notion of technological trajectories. Progress along these trajectories, as suggested in section 1.3, can be considered as the improvement of the trade-offs above mentioned. At first, an automaker may not be willing to pay the premium for a substitute material. However, with time, the trade-offs (functional requirements vs. price, technological requirements vs. recyclability, price vs. low weight, etc.) can progress one way or the other. First, external factors such as governmental regulations and standards, or the competition, may increase the level of the optimal premium (treshold) by setting new requirements.

Second, technological advances, economies of scale, experience and know-how can lower the "cost" of the trade-off, therefore making it more attractive. If the premium is higher than the "cost" of the trade-off, the substitution will be promoted. Conversely, if the "cost" is higher than the premium, the substitution will be severely hindered.The technological trajectory (the material) that will prevail in the long-term will be the one that optimizes the entire set of trade-offs the most.

Costs and government regulations and standards can be seen as inducement mechanisms that can bring forward the need for substitute materials or keep a promising material from being used in a particular application. In reality, these elements act as triggers or tresholds to substitution processes. Once the process has been triggered, a majority of the remaining techno-economic factors represent the capacity of the substitute material to integrate itself inside the existing environment. Whether it is transformation, manufacturing or assembly processes, related systems and components, skills, know-how, experience, etc., the substitute material must cope with a large number of existing elements that can promote or hinder its penetration.

As has been seen in certain cases (aluminum blocks, polymer fenders, aluminum wheels), the importance of these integrating considerations is enormous. Since there is a strong inertia against disruptive or revolutionary technologies within a complex industry such as the automotive industry, substitute materials must "get into the system" with minimal modifications to the existing environment. This is not to suggest that substitute materials must not bring much better performances, reliability or durability, but rather that they should do so with limited changes to related components, technologies or skills and know-how.

This is consistent with the component-by-component approach privileged in this study. Although the entire vehicle approach which stresses the average material content could appear to be more system-oriented or "holistic", it fails to consider the importance of each component and the way they interact among themselves. It seems clear that a sensible and comprehensive understanding of automotive materials substitutions must rely on a component-by-component basis. However, it is of the utmost importance to anyone interested in the matter to keep in mind that any component must be integrated into larger systems (again related components, assembly processes, skills, etc.).

There is a natural resistance to change within any industry or organisation. The automotive industry, by its size and complexity, represents a major challenge to anyone willing to promote technological change and innovation. In the case of automotive materials, the task may be even harder since currently predominant materials, iron and steel, have been around for almost a century. The pace and the extent of different substitution processes may vary, but the resistance encountered when introducing a material will be significant in any case. In the end, two elements will be decisive upon any substitution process, the intensity of inducement mechanisms initiating and promoting the process, and then, the ease of the substitute material to integrate itself within the existing environment.

5.2 Avenues for future research

Overall, although some valid conclusions have been drawn following the analysis of the six cases of material substitution, the study would have benefited from additional empirical evidence and statistical data. The limited ressources made available to this research have somewhat restricted the amount of information and data at hand. Among the elements upon which no clear conclusions could be made, considering the limitations and constraints of this study, the following would represent particularly interesting avenues for future research - user/producer networks, the changing product mix and competing "new" technologies.

5.2.1 User/producer networks

The influence of the user/producer networks upon the automotive materials substitution remains unclear according to the empirical evidence presented herein. There are numerous aspects of user/producer networks that would require further research. First, the interactive learning processes between users and producers such that both can benefit from the progress and the advances from the others, depending on the intensity of the relationships. The lenght of contracts between users and producers, which can influence the behaviour of the participants towards a firm commitment to a technology. The lenght of contracts may also be an element that play a role on the occurance of lock-in situations. The Make or Buy decision is also one of the fundamental questions pertaining to user/producer networks since it deals with many considerations (labor, physical capital, know-how, etc.) that are central to both users and producers.

By studying, over time, specific cases of network interactions, it should be possible to bring answers to these various elements. In order to provide the most accurate empirical evidence, this study should draw upon interviews with people from users and producers.

5.2.2 The changing product mix

The important changes in the product mix in the North American market in the last fifteen years may have had significant repercussions upon the materials substitution processes. The materials content of light trucks may differ from that of passenger cars, thus affecting substitution processes. The lack of specific data regarding materials content of particular types of vehicles and other elements pertaining to materials substitution versus vehicle types keeps us from drawing any conclusions herein. In order to make a full analysis of the matter, specific statistical data would have to be gathered, especially regarding the differences in materials content.

5.2.3 Competing "new" technologies

As has been seen in all cases studied, the substitute material is always brought out on the market in a number of competing technologies. We can think of the radiator that can be flux-brazed, fluxless-brazed, mechanically assembled or non-corrosive flux brazed, aluminum wheels that can be cast, forged or stamped and welded, etc.. These competing technologies generally differ from each other by their manufacturing and transformation processes, or by the composition of the material (e.g., different aluminum alloys for engine blocks).

It should prove quite useful and pertinent to further investigate on the influence of competing "new" technologies upon the substitution processes. By studying, over time, cases where a number of technologies have emerged from a substitute material, it may be possible to determinate if competing "new" technologies promote the overall substitution process or whether they hinder it. Again, in that case, the effort would benefit from ample empirical evidence and statistical data.

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