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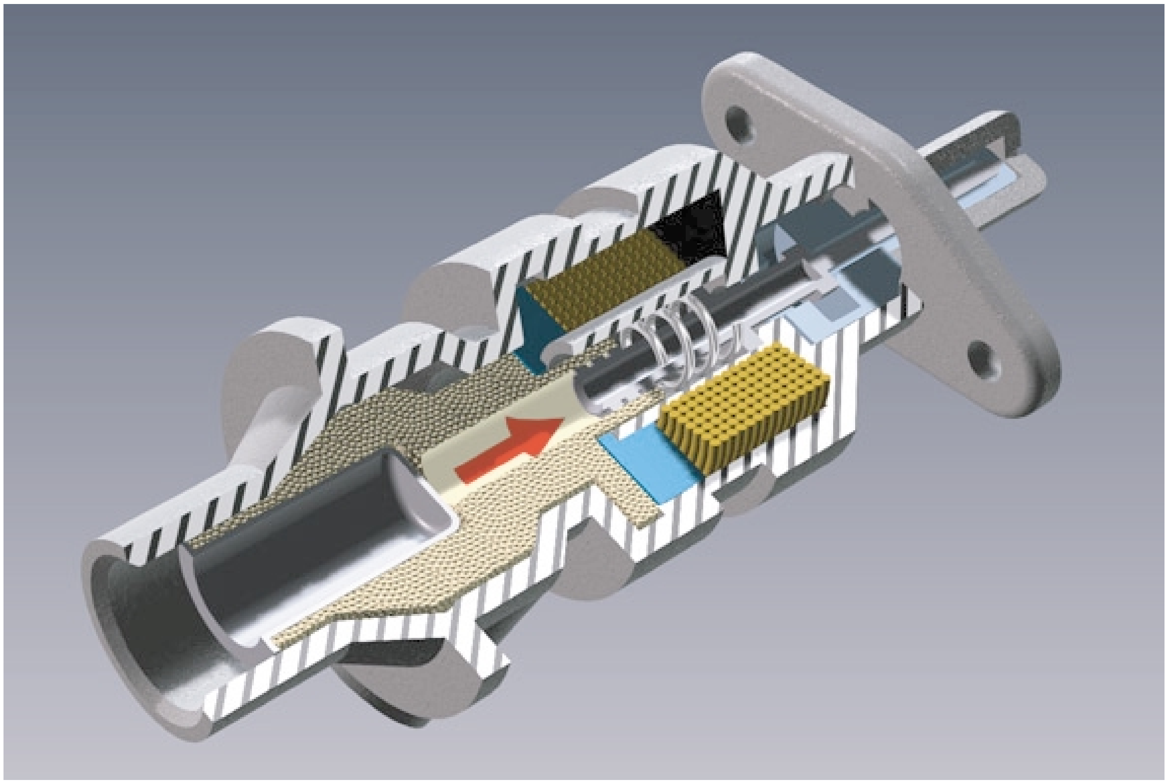
# Economic Impacts of Flow-Control Machining Technology: Early Applications in the Automobile Industry



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**U.S. Department of Commerce**
**Technology Administration**
National Institute of Standards and Technology

**Office of Applied Economics**
**Building and Fire Research Laboratory**
Gaithersburg, Maryland 20899

# Economic Impacts of Flow-Control Machining Technologies: Early Applications in the Automobile Industry

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# Abstract

This study investigates the impact of two new process technologies developed in the ATP Flow-Control Machining Project: abrasive flow-control machining (AFCM) and non-traditional combustion chamber sizing (NCCS). These new processes offer large potential benefits to manufacturers who need to increase the functional precision and performance of cast-metal machine parts.

The new processes advance the state-of-the-art in the finishing of cast-metal parts that carry fluids in interior passageways. Currently, these parts often have manufacturing imperfections which decrease their precision and therefore functional performance. Finishing processes exist which correct these imperfections, but they are time consuming and costly, relegating their use to high-value, low-volume production applications. The goal of the Flow-Control Machining (FCM) Project, a joint venture between Ford, GM, Extrude Hone, University of Nebraska at Lincoln, University of Pittsburgh, and the ATP, is to develop two new automated and cost-effective finishing processes which—by smoothing, sizing, and balancing passageways—markedly improve the performance of cast-metal parts. This collaborative project is on track toward completing its goals; when successful, the new processes will have potentially wide application in automobile, aircraft, diesel-injector, and other manufacturing industries.

The first application of the FCM processes is to airflow components in passenger-car and light-truck engines and is, therefore, the subject of this study. The new processes will allow automakers to manufacture engines that have higher precision and performance. The processes can be used to increase engine horsepower or fuel efficiency by an estimated six percent.

This study finds that under current market conditions automakers will likely use the FCM processes to increase the fuel efficiency of their automobiles. For the past twenty-five years, automakers have adopted fuel-efficiency technologies in an effort to meet federal CAFE fuel-economy regulations; the FCM processes achieve the same objective but with lower design and manufacturing costs. Profit-maximizing assumptions in the face of CAFE fleet regulations lead us to conclude that the first applications of the FCM processes will be in the light-truck classes of automobiles, such as large utility vehicles.

Using the historical adoption rate of technologies that enhance automobile fuel efficiency, we model the near-term five-year implementation path of the FCM processes in the ATP project. Ford and GM are familiar with the capabilities of the technology and have tested precursors to the processes on some production lines. Analysis indicates that adoption by Ford and GM in 130,000 light trucks, representing one manufacturing line for each company, would allow further production and sale of 116,000 of these automobiles within current CAFE regulations. This additional production would increase annual domestic product (GDP) by an estimated $142 million, annual personal income by $196 million, and annual tax revenues by $34 million, and create 1,800 new manufacturing jobs. In addition, we model a 15-year, longer-term implementation path, following the historical adoption rate of fuel injection technology. This implementation to 80 percent of the light-truck market is estimated to allow further production and sale of 1.6 million large-utility-class light trucks while staying within current CAFE regulations. The additional automobile production is projected to increase GDP by $1.9 billion, annual personal income by $3.3 billion, and annual tax revenues by $527 million, and create 29,000 new manufacturing jobs.

**Keywords**: advanced technology program, automobile industry, CAFE, economic impacts, evaluation, fuel efficiency, government technology programs, macroeconomic analysis, technology impacts.

# Preface

The Advanced Technology Program (ATP) at its outset developed a multi-component evaluation strategy geared to deal with the varied needs of a complex program. The strategy is designed to develop tools for providing feedback to management on the program's performance and to develop the capacity for meeting the many external requirements of and requests for ATP program results. The strategy components are (1) descriptive (statistical) profiling of applicants, projects, participants, technologies, and target applications; (2) progress indicators derived principally from the ATP's Business Reporting System; (3) real-time monitoring of project developments by ATP's staff; (4) status reports on the accomplishments of completed projects; (5) microeconomic and macroeconomic case studies of project impacts; (6) methodological research to improve the tools of longer term evaluation; (7) special-issues studies; and (8) econometric and statistical analyses of portfolios of projects.

The ATP is completing its first decade, and the number of microeconomic and macroeconomic case studies of ATP project impacts is growing. The study reported herein is the tenth detailed economic case study of an ATP project, and the second ATP study to employ a macroeconomic model to estimate national economic impacts of a technology resulting from an ATP-funded project. The first such study evaluated the impact of a new dimensional control technology used to reduce variation in auto body assembly and improve the quality of automobiles (the 2mm Project evaluated by CONSAD, Inc., 1995). This second study to use a macroeconomic model deals with a process technology that is also expected to find its first application in the automotive industry. In both of these cases, conditions were conducive to the use of a model to extend the impact estimates from the firm level to the national level. This type of model is not appropriate for all case studies.

Many of the technologies funded by the ATP have the potential for applications in multiple industries. Indeed, the flow-control technology described in this study has many potential applications, including uses in the automotive, aerospace, and manufacturing tooling industries, and possibly even in the medical industry. However, considerable time is usually needed for new technologies to become widely adopted within a given industry sector; even more time is required for diffusion to other sectors. Because of the long time generally required for diffusion, the case-study evaluations of ATP projects have thus far focused on only a single, near-term application of each of the resulting technologies. The case study herein similarly focuses on the earliest expected single application of the process technology: to enable increased production of light trucks within existing regulations for fleet fuel economies. But ATP's evaluation program is interested in advancing the understanding of technology diffusion, and it plans to support follow-on work to evaluate the potential of the flow-control technology to cross industry lines, and to track its diffusion within and across industry sectors.

For up-to-date information on the ATP and its evaluation program, the reader is referred to ATP's homepage: http://www.atp.nist.gov. Up-coming competitions are announced, meeting schedules are posted, funded projects are listed, evaluation is discussed at the Economic Assessment Office listing, and publications are available for downloading. To be added to ATP's mailing list, call 1-800-ATP-FUND. To request copies of this and other ATP evaluation studies, call 301-975-3189. Your comments and suggestions are welcomed.

Rosalie Ruegg
Director, Economic Assessment Office
Advanced Technology Program

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Thanks are given to Drs. Bill Boettinger and George Mattingly at NIST for their ideas about the potential application of the flow-control machining processes to other, non-automotive products and processes.

Thanks are also given to Jack Boudreaux, Harold Marshall, Jeanne Powell, and Rosalie Ruegg for their comments and suggestions.  Finally, special thanks are given to Stephen Weber for the numerous discussions upon which this analysis was based and the excellent editorial advice and support which brought the report to its final form.

Cover image courtesy of Visionary Design Systems, Inc. (http://www.vds.com)

# Executive Summary

This study investigates the impact of two new technologies developed in the ATP Flow-Control Machining Project: abrasive flow-control machining (AFCM) and non-traditional combustion chamber sizing (NCCS). These two processes, by enabling automobile manufacturers to increase engine horsepower and fuel efficiency and decrease emissions, offer significant potential benefits. For example, in the event that there is a significant decline in available petroleum products such as in the 1970s, the processes could be used in all autos to decrease fuel consumption. In the event that government increases car safety requirements and thereby vehicle weight, automakers can add these features and use the two new processes to keep the fuel economy of their fleets within the CAFE limits. If the government increases CAFE fuel economy requirements, automakers can meet these standards more easily.

The two processes advance the state-of-the-art in manufacturing finishing. Currently, a manufactured part that carries fluids through its interior passageways often has fabrication imperfections which reduce the part's "functional precision," that is, its ability to precisely allocate and distribute the fluid. Even though the geometrical design of the part may be precise, the fabrication process causes flow to deviate from the precise level for which the part is designed. Furthermore, a part which carries fluids through groups of passageways can have unbalanced and therefore inefficient flow. Non-traditional finishing processes exist which can correct these imperfections; in fact, they have been used to significantly increase the horsepower and overall performance of automobile-racing engines and aircraft engines. In their current form, however, the processes are done manually, are time consuming, and are relatively expensive. For these reasons they are only used in low-volume, high-value manufacturing.

The goal of the Flow-Control Machining Project, a four-year $7.9 million research joint venture between three businesses, two universities, and the Advanced Technology Program (ATP) at NIST, is to develop two new automated finishing processes and make them cost effective for large-production, low-value manufacturing. The Flow-Control Machining (FCM) processes advance the state-of-the-art in manufacturing by allowing manufacturers to more effectively fabricate parts to their intended functional performance. To achieve automation and the resulting cost savings, these FCM processes need new neural-network models, new methods of manufacturing control, and new forms of abrasion. The project is on track toward completion of its goals; when completed, the processes and associated manufacturing control equipment have the potential of significantly increasing functional precision and performance and decreasing the cost of engines and other machines made in many industries, including turbine engine, diesel injector, and rocket fuel orifice manufacturing.

The first application of FCM processes is aimed at increasing the functional precision of airflow in automobile engines and is, therefore, the focus of this study. Current engine performance is limited by fabrication-based restrictions and imbalances in airflow. The two processes under development, AFCM and NCCS, could significantly increase engine horsepower and fuel efficiency by increasing the functional precision of airflow and combustion. For example, the two processes could reduce a typical automobile engine's fuel consumption by six percent. The current forms of the two FCM processes are used successfully in racing engines to increase horsepower, proving they are technically well suited for low-volume, high-value specialty engines. The FCM Project, in developing neural-network algorithms, process control methods, and new abrading techniques, makes the processes economically well suited for high-volume, relatively low-value passenger-vehicle engines.

The FCM Project, begun in 1996, brought together members of industry who can successfully develop these advanced processes: Extrude Hone Corporation, a company currently using manual flow-machining fabrication and chamber sizing for low-volume, high-value automobile engines; the University of Pittsburgh and the University of Nebraska at Lincoln, who have expertise in developing neural-network models for process control equipment; and Ford Motor Company and General Motors, potential adopters of engines produced with the new processes. Three companies acting as advisors—Roush Industries (an engine designer), CMI Castings (aluminum castors), and ALCOA—complete the vertical integration of the project, thereby increasing the likelihood of its success. While Extrude Hone, the University of Pittsburgh, and the University of Nebraska at Lincoln receive ATP funding, Ford and GM are providing their own R&D funds for participating in the project.

This study estimates the economic impact of applying the two new FCM processes to automobile engines. It first makes an assessment of whether automakers will adopt the two processes to a significant degree, by analyzing the current structure of automobile demand and supply and their effects on competition and innovation. The study then charts the near-term and longer-term implementation paths of the FCM processes and estimates the impacts on individual firms, the automobile industry, and the U.S. economy.

The two FCM processes have great potential impact on the automobile industry. They can be used in all passenger-vehicle engines to increase and balance airflow, thereby increasing horsepower and fuel efficiency and reducing emissions. More horsepower allows automakers to increase the value embodied in a car—for example, its carrying capacity, options, and safety equipment—without compromising fuel economy. More horsepower also allows automakers to put smaller engines in cars, reducing costs. More fuel economy saves consumers fuel costs, especially important in times of tight energy supplies. Decreased emissions reduce the threats posed to the environment. These technical improvements offer enormous potential benefits to car buyers and the rest of the economy. From their participation in the project, GM and Ford are familiar with the capabilities of the technology and have had the opportunity to test it out over the course of the ATP project.

This study concludes that, under *current* market conditions and government policies, automakers will likely focus first on using the two processes to increase the fuel efficiency of their larger automobiles. Consumers, currently more concerned about options and capacity than fuel economy, are increasingly demanding large vehicles such as small trucks and sport-utility vehicles. U.S. automakers, under intense global competition in the small passenger-car market, are focusing on selling larger vehicles with their higher value added and profits. Federal Corporate Average Fuel Efficiency (CAFE) regulations set minimum fuel economies for each automaker's entire fleet of cars and entire fleet of light trucks, and are limiting the production of these large, low-fuel-economy vehicles. For the past twenty-five years, automakers have adopted fuel-efficiency technologies in an effort to meet federal CAFE fuel-economy regulations; the FCM processes achieve the same objective but with lower design and manufacturing costs. Automakers can increase the fuel efficiency and therefore sales of their largest, most profitable automobiles.

The new processes are likely to be implemented at a rate similar to that of other fuel-efficiency-enhancing engine technologies. In the first years of implementation, an automaker typically tests a new process technology on a small production line. Later—and higher—levels of implementation tend to be less certain, since they may be affected by changing market and production conditions. This study therefore provides two estimates of the potential economic impacts of the FCM processes: a conservative estimate of the most likely near-term implementation, and a less conservative, longer-term estimate.

The near-term estimate assumes that domestic automakers will use the FCM processes on a small production line over a five-year study period. This estimate assumes specifically that:

- consumers will continue to have demand for large light trucks in excess of what CAFE allows;
- total consumer demand for light trucks will remain fixed—therefore, new large light-truck sales will come at the expense of the existing sales of smaller, higher-fuel-economy light trucks;
- automakers will use the FCM processes to increase the fuel efficiency of large light trucks by six percent;
- the FCM processes make the added performance available at a cost of $5 per unit of horsepower gained; and
- the federal government holds the CAFE passenger-car and light-truck fuel economy requirements at their current levels (11.7 kilometers per liter [27.5 mpg] for passenger cars, 8.8 kilometers per liter [20.7 mpg] for light trucks).

The near-term estimate assumes that Ford and GM implement the processes to 130,000 large utility vehicles (65,000 each) in their *existing* production. The resulting FCM-based increases in CAFE fleet fuel economy allow the automakers to produce and sell an additional 116,000 light trucks with the technology (a total of 246,000 vehicles then are made using the FCM processes). Given that the price of each new large utility vehicle is $5,370 more than the average price of all other light trucks, our analysis estimates that in the fifth year:

- annual sales revenues for Ford and GM increase by $623 million,
- annual gross domestic product (GDP) increases by $142 million,
- annual personal income increases by $196 million (which is more that the GDP increase due to production shifting to higher-wage sectors that, in aggregate, use less capital),
- annual tax revenues increase by $34 million, and
- 1,800 new high-wage manufacturing jobs are created.

This estimate of impacts is sensitive to changes in the underlying technical and economic parameters. For example, if the FCM processes yield a lower fuel-efficiency improvement than six percent, automakers will be able to increase the sale of large light trucks by a lower amount. If future fuel prices increase sharply, car buyers may decrease their demand for larger, lower-fuel-economy vehicles. Automakers will then increasingly need fuel-efficiency improving technologies to keep these and other sales. If, as is currently being proposed by the EPA, the light-truck emissions standards are tightened to level of those for passenger cars, automakers will increasingly need and use the FCM processes to reduce emissions.

The less conservative estimate of longer-term implementation is based on a diffusion path comparable to that followed by fuel injection technologies in all cars. It assumes that domestic automakers will implement the FCM processes over a 15-year period to 80 percent of all light trucks. Under similar market, production, and CAFE assumptions as in the near-term estimate, the longer-term implementation would allow further production and sale of 1.6 million of the large-utility class of light trucks while staying within current CAFE regulations. The additional production is estimated to increase GDP by $1.9 billion, annual personal income by $3.3 billion, and annual tax revenues by $527 million, and create 29,000 new manufacturing jobs.

Future work will investigate the use of the two FCM processes in other, non-automotive industries. The work will survey industries for application of the processes, likelihood of adoption, and potential economic impacts. Future work will also track diffusion of the technology within the automobile industry and in other industry sectors.

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# 1. Introduction

The primary mission of the National Institute of Standards and Technology (NIST) is to promote U.S. economic growth by working with industry to develop and apply technology, measurements, and standards. The Advanced Technology Program (ATP) at NIST supports this mission by providing cost-share awards to industry to develop high-risk, “enabling” technologies which can ultimately increase economic growth, the quality of jobs, and the quality of life that comes from such growth.

ATP projects are designed to be partnerships between government and industry. Individual awards are made to single firms or joint ventures of firms to produce technologies that enable the development of new products, processes, and services across diverse application areas. Universities, state and federal laboratories, and other non-profit institutions also participate in the projects as members of jointventures and as subcontractors. Awards are made based on rigorous peer-reviewed competitions designed to select those proposals best qualified in terms of their cutting-edge technological ideas and potential fornational economic benefits. Emphasis is placed on the difference that ATP funding will make. Awards have specific cost-share rules: for example, joint-venture participants pay more than half of the total project costs, and each award has a set of specific goals and completion dates. Single-company awardees pay all indirect project costs and may also cover some of the direct costs.

The Flow-Control Machining Project is an ATP joint venture, its partners being Extrude Hone Corporation, Ford Motor Company, General Motors, the University of Pittsburgh, and the University of Nebraska at Lincoln. The four-year project began in 1996 and its total funding is $7.9 million; $4.0 million is provided by Extrude Hone, Ford, and GM, and the remainder is provided by ATP. The project goal is to develop two finishing processes—herein called “FCM processes”—which increase the functional precision of cast-metal parts which carry fluids in interior passageways. Its first targeted application is to airflow in automobile engines, where the increase in functional precision can be used to increase engine horsepower, increase fuel efficiency, reduce emissions, and reduce the cost of engines. If successfully developed and implemented in the automobile industry, the FCM processes could have significant economic impacts. If diffused into a wide array of industries, such as aerospace, manufacturing tooling, and medical, the impact could be quite large.

This report provides an economic impact assessment of the Flow-Control Machining Project in its first targeted application, in the automobile industry. It assesses the likelihood that the automobile industry will implement the FCM processes, establishes a likely implementation path, and develops estimates of the economic impact of near-term and longer-term implementation.

Chapter 2 describes the two FCM processes, the joint venture participants and their roles, and the current status of the project, including the technical challenges solved and those remaining. Chapter 3 outlines the economic impact framework, and Chapter 4 assesses the likelihood that the automobile industry will implement the FCM processes and describes the most-likely implementation path. Chapter 5 estimates the economic impacts of applying the FCM processes in the automotive industry over a near-term, five-year period, and Chapter 6 follows with estimates from the longer-term implementation. Finally, Chapter 7 summarizes, concludes, and outlines further areas of research.

# 2. The Flow-Control Machining Project

Many industrial machines rely on internal parts that carry and meter fluids precisely. For example, aircraft fuel-flow meters precisely measure, during flight, the amount of fuel used by the aircraft's engines; fuel injectors dispense precise amounts of fuel into engine combustion chambers. This component precision is largely dependent upon (1) how well the part is designed to meter flow, (2) how well existing machining techniques can create the part as it is designed, and (3) how well after-fabrication testing can measure whether the part is functioning as designed. This three-part dependency for precision is illustrated in the "Machining to Geometry" panel in Figure 1.

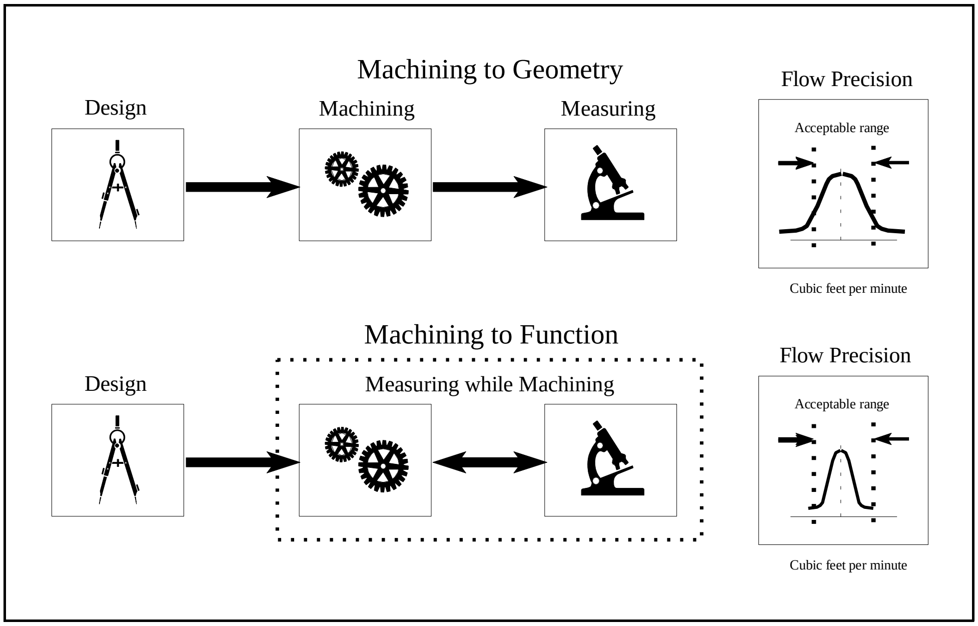

**Figure 1. Machining to Geometry vs. Machining to Function**

Errors in any one of these steps—or a sequential compounding of these errors—prevents the part from being functionally precise, that is, from carrying fluid within an acceptable range. Most fluid-carrying metal parts are machined to specific dimensions, which is often the designer's best predictor of eventual flow performance. However, there are limitations to machining to geometry. If the geometry is a poor predictor of performance, or there are significant errors in machining, the part's functional performance will not reliably fall within the desired range. In the case of fuel injectors, if measuring indicates that flow is outside the acceptable range, the injector is thrown away.

Manufacturers could see significant increases in functional precision if they could "machine to function," i.e., machine a part until it reaches a targeted functional flow or capacity. As the "Machining to Function" panel in Figure 1 illustrates, measuring the function of a part while it is being machined has the potential of reducing precision dependency to two steps. There exist several non-traditional finishing processes which offer the potential for true "machining to function," but they are limited, are in their early stages, and are time consuming and costly. While these non-traditional processes have been used effectively in the low-volume, high-value production of aircraft turbine blades, they are too slow and costly for high-volume, relatively low-value applications such as automobile-engine components.

## 2.1 Forming the ATP Joint Venture

The ATP Flow-Control Machining Project was formed by industry partners whose common goal is to advance the functional precision and performance of intake manifolds, intake ports, and combustion chambers. Ford and GM, looking for new ways to increase the horsepower and fuel efficiency of their engines while reducing emissions and cost, are participating as end users and component suppliers. Extrude Hone Corporation, a company that produces abrasive flow-machining equipment for use by the aircraft and diesel industries, would like to use the FCM processes under development to more closely "machine to function" parts in a wide array of industries, including automobile engines. The University of Pittsburgh and the University of Nebraska at Lincoln, having already performed research in advanced, non-traditional machining techniques, are looking for "real world" tests and applications of their research. While not direct members of the joint venture, Roush Industries (an engine designer), CMI Castings (castor of aluminum intake manifolds and cylinder heads), and ALCOA participated as supply-chain advisors, vertically integrating the project. Extrude Hone Corporation, the joint-venture leader, formed the project by eliciting the support of these key industry and university partners to apply to the ATP.

There are multiple reasons why the FCM Project would not likely have formed without the direct involvement of ATP. Ford and GM are unlikely to unilaterally adopt a new process that has not been proven to work; the FCM processes are particularly challenging since both constitute a radical departure in finishing processes—manufacturing directly to functional performance. Ford and GM are also unlikely to directly collaborate on a new process, since they are direct competitors on routine business matters and have concerns about federal antitrust-law enforcement. They tend not to fund the research of their suppliers. The suppliers would not perform the research themselves; they generally do not have the capital to do extensive in-house research—particularly not high-risk research. University researchers are typically interested in doing their own research, not the research of a supplier to automakers, and are not able to self-fund this type of research. In the words of Larry Rhoades, President of Extrude Hone, "this project would not have occurred without ATP."[1]

## 2.2 FCM Project Tasks and Roles of the Participants

The FCM Project is divided into two parts, each composed of tasks designed to extend the state-of-the-art in a manufacturing finishing process.

### 2.2.1 Part 1: Abrasive Flow-Control Machining (AFCM) of Intake Manifolds and Intake Ports

Most automobile engines have an intake manifold, such as that shown in Figure 2,[2] which carries outside air to the combustion chambers.

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[1] Based on discussion with Larry Rhoades of Extrude Hone on April 3, 1998.

[2] The manifold shown is for the 1996 Ford Contour SVT.

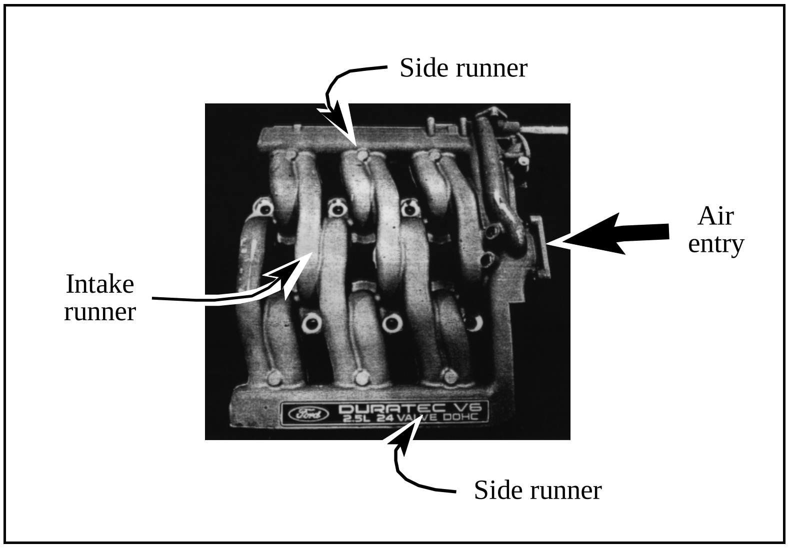

**Figure 2. Top View of Intake Manifold**

Air enters the manifold through an air entry and is then divided to side runners. The airflow in each side-runner is then divided again to intake runners which then carry the air to intake ports in the cylinder head. Valves in the ports control the entry of air into the combustion chamber. Once the air enters the chamber, a fuel injector sprays gasoline into the air. This air-fuel mixture is then compressed and ignited by a sparkplug. Combustion converts the mixture into power which pushes the piston, crankshaft, transmission, and ultimately the tires of the vehicle.

The efficiency of combustion—its ability to convert fuel into power—is sensitive to the level and distribution of airflow in the intake runners. Most intake manifolds and intake ports are cast from aluminum, and imperfections in the casting process cause airflow to deviate from the level dictated by the engine's design. If flow is lower than desired, the engine will operate reliably but inefficiently. If flow is much higher than desired, the engine will not operate reliably: the air-fuel mixture in the combustion chamber may spontaneously detonate or "ping" due to over-compression. Because repeated and prolonged detonation damages an engine, automakers typically design combustion to a lower-than-optimal level of efficiency. If the level and distribution of airflow were more functionally precise, significantly higher horsepower, higher fuel efficiency, and lower emissions could be obtained.

For the typical assembly-line car, the current state-of-the-art in manifold finishing is to use the cast-aluminum intake manifold "as is"; the size and internal smoothness of each manifold runner are determined by the quality of the design and aluminum casting processes. Automobile engineers conservatively tune the allocation of fuel so that detonation will not occur. For low-volume, high-value specialty engines, the state-of-the-art is to use the Extrude Hone process called *abrasive flow machining*, in which a viscoelastic media impregnated with grit smooths, sizes, and balances the intake manifolds and intake ports. Each manifold is flow-machined, measured for airflow, flow-machined, measured for airflow, and so on, until it has the desired level and distribution of airflow. The 1998 Ford Contour SVT engine, voted one of the top ten engines for 1998 by Ward's Autoworld, has Extrude Hone abrasive flow-machined intake manifold and secondary intake ports. Abrasive flow machining is also used by every major aircraft turbine engine manufacturer to increase the functional performance of rotor blades. The machining is time consuming and expensive and therefore is limited to low-volume, high-value production applications.

The first part of the FCM Project advances the state-of-the-art in finishing by using both in-process measurement and neural-network models to control abrasive flow machining until the part reaches its functional target (i.e., abrasive flow-*control* machining, or AFCM). Instead of determining the required flow-machining by iteratively measuring airflow before and after machining, the required machining is determined in “real time” using the characteristics of the viscoelastic flow-machining media. AFCM is expected to increase the fuel efficiency of engines by four percent. This provides significant economic benefits to automakers, who can increase horsepower and fuel efficiency, and to consumers, who, in the case of improvements in fuel efficiency, would benefit from decreased fuel costs.

The AFCM part of the project has four tasks, most of which are now completed. Extrude Hone and the University of Nebraska at Lincoln first outfitted existing abrasive flow-machining equipment with new flow-control components and new monitoring equipment developed in this project. The machine determines the required machining by using a neural-network model which has as inputs the data from acoustic-emissions monitoring equipment, the pre-machining airflow, and the in-process, viscoelastic flow characteristics. Extrude Hone and university researchers developed the initial neural-network model which correlates media flow with after-machining measurements of airflow. The model is based on rheology, continuum mechanics, computational fluid dynamics, and statistical design of experiments. Ford Motor Company measured the increase in functional performance by running numerous dynamometer and road tests on engines fitted with the abrasive-flow-control-machined manifolds.

In the second AFCM task, Extrude Hone built a laboratory prototype AFCM machine. In the third task Extrude Hone verified the process by running the prototype machine on 5,000 intake manifolds, and then tested the robustness of the neural-network algorithms by calibrating the machine on a completely different cast-metal piece. In the final task, to be completed, the AFCM machine will be installed in a joint-venture partner’s production line with a video link back to the Extrude Hone Technical Support group. The current challenge for the AFCM part of the project is to integrate the acoustic emissions equipment into a laboratory prototype of the AFCM online manufacturing cell.

As a result of the project, Extrude Hone and the joint venture partners will be able to apply the AFCM process to a wider class of intake manifolds and ports. Extrude Hone and other machining industries will ultimately be able to apply this flow-controlled machining to many non-automotive industries.

### 2.2.2 Part 2: Non-traditional Combustion Chamber Sizing (NCCS)

Most internal combustion engines, such as the one shown in Figure 3, have combustion chambers where fuel is mixed with air and ignited.

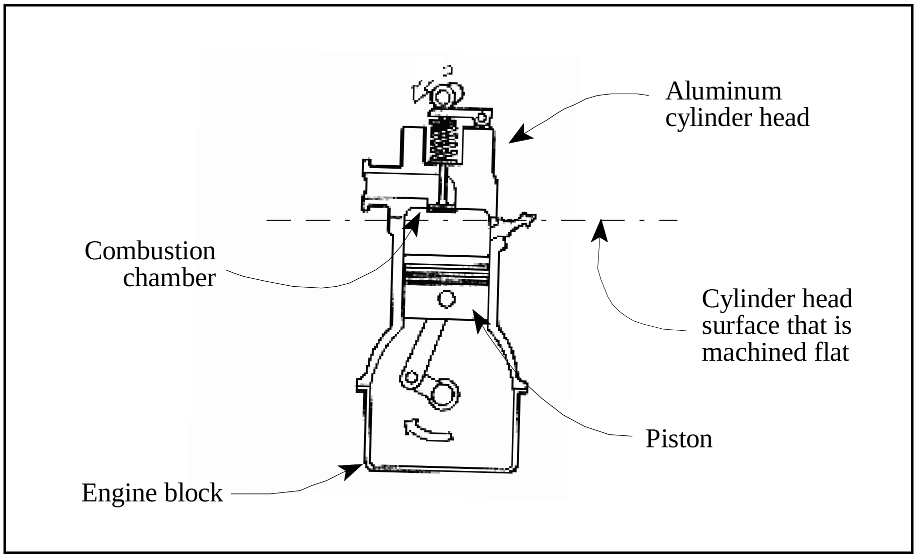

**Figure 3. Cross-section of Cylinder Head and Engine Block**

Because of imperfections created during the casting of the aluminum cylinder head, the set of combustion chambers in the head typically have different volumes, resulting in different levels of combustion. Analogous to flow in intake manifolds, increasing the functional precision of combustion chambers will result in more horsepower and fuel efficiency and lower emissions.

For the typical assembly-line car, the current state-of-the-art is to machine the cylinder head surface (see Figure 3) so that (1) none of the combustion chambers are small enough to induce detonation (pinging), and (2) the chambers have volumes as similar as possible. As a result, some chambers will be larger than what is optimal for efficient combustion. For the typical specialty car, the current state-of-the-art in chamber sizing involves manually grinding the interior of all but the largest chamber until they match the volume of the largest chamber. At least one foreign automaker has used *electrochemical abrasion* to size chambers, but difficulties with loss of tool abrasive and build-up of residue have prevented further use. In addition, this abrasion technique is relatively time consuming and expensive, relegating it to low-volume, high-value production engines such as those used in racing or luxury-car engines. Precision chamber sizing is challenging: given the irregular shape of most chambers, accurate measurements of volume are difficult to make.

The second part of the FCM Project, non-traditional combustion chamber sizing (NCCS), advances the state-of-the-art in chamber sizing by developing an automated and cost effective process which can accurately measure and size combustion chambers. Three sizing processes are to be evaluated for their effectiveness: *orbital abrasion*, *electrochemical machining*, and *electrochemical orbital abrading* (a hybrid of the first two processes). Electrochemical orbital abrading is relatively untested and needs development. Laboratory equipment that applies these processes to the engine assembly line needs to be developed and tested.

The potential benefits of precision chamber sizing are significant. If NCCS can decrease the mean variation in chamber volumes to 5 percent of the compression ratio[3] and increase the mean compression ratio by 0.225, engine fuel economy can increase by two percent. When coupled with the AFCM process on intake manifolds and intake ports, they can increase engine fuel efficiency by a total of six percent. NCCS provides significant economic benefits to automakers who—as in the AFCM case—can increase horsepower or fuel economy, and to consumers who would, in the case of increased fuel efficiency, benefit from reduced fuel costs.

The NCCS part of the project has four tasks. In the first task, Extrude Hone is to evaluate the effectiveness of the three aforementioned sizing processes. In the second task, Extrude Hone builds a laboratory prototype machine based on the best of the three. The machine will individually size each combustion chamber in the cylinder head; the goal is to reduce the volumetric variance between chambers and to increase the mean compression ratio by 0.225. In the third task, Extrude Hone and GM verify the process by machining 2,500 cylinder heads, and in the final task Extrude Hone installs the laboratory prototype machine in a joint-venture partner's facility for in-line testing of the process.

Currently, the joint-venture partners are evaluating a new, promising technique for measuring combustion chamber volumes, and are continuing to investigate the use of electrochemical orbital abrading. The challenge in this new abrading technique is determining how to combine the strengths of its two precursors: orbital abrasion, with its ability to aggressively remove material but without a feedback mechanism; and electrochemical machining, which, with its feedback mechanism, is able to more precisely (albeit slowly) remove material. Successful development of this chamber sizing process will allow automakers to increase the functional precision of all internal-combustion engines, resulting in improvements in horsepower, fuel economy, and emissions. In addition, the volumetric sizing and electro-orbital abrading processes developed by the project will allow other industries to increase the functional precision of cast-metal parts which must hold precise volumes.

## 2.3 Potential Economic Benefits of the FCM Processes

At this point in the project, it appears that the FCM Project will likely meet its technical goal of a six-percent increase in engine fuel efficiency. The AFCM process has been prototyped and a working machine has been tested on manifolds. This process seems capable of generating the four-percent increase in fuel efficiency expected. The NCCS process is in a more nascent stage but is on track toward completion of its goals; it will likely generate an additional two-percent increase in fuel efficiency beyond what the ACFM process generates. Therefore, throughout this analysis we assume that the FCM Project will meet its technical objectives of developing the two processes and the automated, in-line equipment required to implement them on intake manifolds, intake ports, and combustion chambers. The possibility of partial technical success, i.e., an increase in fuel efficiency of less than six percent, is considered in the sensitivity analysis in Section 5.4.

The AFCM and NCCS processes, by enabling automobile engine manufacturers to increase horsepower and fuel efficiency and decrease emissions, offer significant potential economic benefits. For example,

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[3] The compression ratio is the ratio of the volume of the air-gas mixture when the piston is at the bottom of its stroke to the volume of the air-gas mixture when the piston is at the top of its stroke.

in the event that there is a significant decline in available petroleum products (such as in the early 1970s), the processes could be used in all autos to decrease fuel consumption. In the event that government tightens car safety requirements and thereby vehicle weight, automakers can use the FCM processes, add these features, and keep fuel economy within the CAFE limits. If the government increases CAFE fuel economy requirements, automakers can meet these standards more easily. What the automobile industry will *likely* do with the FCM processes, however, is dependent on *actual* current and future market conditions, as explored in Chapter 4.

# 3. Economic Approach

Given that the AFCM and NCCS technologies meet all their technical objectives, a major goal of the FCM Project is to have Ford Motor Company and General Motors implement the FCM processes on a significant fraction of their automobiles. While potential application is wide, broad implementation is uncertain. This type of uncertainty has been examined by Edwin Mansfield, who identified three sequential probabilities of whether a new technology—such as the FCM processes—will be successful for a firm:[4]

1. The probability that technical goals will be achieved;
2. Given technical success, the probability that the resulting process or product will be commercialized; and
3. Given commercial success, the probability that the commercialized product will be economically successful.

This study follows a qualitatively similar approach in determining the economic impact of the FCM processes, dividing impact estimation into sequential tasks. The study first assesses the likelihood that the FCM processes will achieve technical success; this is covered in the previous chapter. Second, given this technical success, the study determines whether the new processes will likely be implemented (i.e., commercialized) by automakers and to what extent. Finally, given this implementation path, quantitative estimates of impacts are developed, and alternative paths and their impacts are discussed qualitatively, relative to the implementation path selected.

## 3.1 Economic Impact Framework[5]

Economic impacts are measured using the framework in Figure 4. The framework gives explicit structure to economic impacts: ATP cost shares with the Joint-Venture Firms to develop the FCM processes (Step 1). Once the processes are developed, the Joint-Venture Firms and Other Firms (such as the aluminum manifold and cylinder head casters) change the types, amount, and quality of the products they sell, and this in turn changes the price and quantity of goods sold in industry markets (Step 2). Finally, changes in market prices and quantities affect the larger, U.S. macroeconomy (Step 3).

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[4] Edwin Mansfield, *The Production and Application of New Industrial Technology* (New York, NY: Norton, 1977).

[5] For more discussion about the impact framework, see Mark A. Ehlen and Stephen F. Weber, *Estimating Economic Impacts of Government Technology Programs: Manufacturing Studies Using the REMI Model*, NISTIR 6107 (Gaithersburg, MD: National Institute of Standards and Technology, 1997).

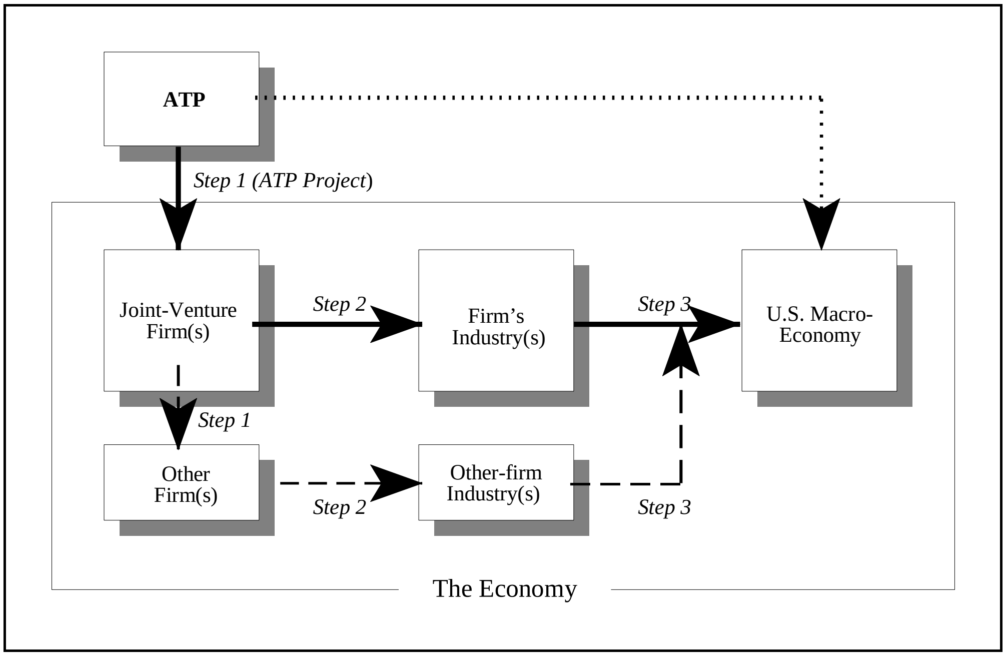

**Figure 4. Economic Impact Framework**

Each arrow in Figure 4 represents a computation requiring specific economic tools. Step 1 describes the microeconomic impact that the ATP has directly on individual firms. The ATP impacts firms directly by cost sharing the development and implementation of the FCM processes. The new technical capability enables firms to change the quality, quantity, and price of their goods, and this, in turn, affects their revenues and costs. Microeconomic analysis can be used to see if implementation of the FCM processes is consistent with firms' profit-maximizing goals. Step 2 estimates how entire industries change as a result of firm changes. The Step 2 framework used in this report is the *structure-conduct-performance paradigm*,[6] which states that the number and structure of firms in an industry determine those firms' price and non-price conduct—how they compete—which in turn determines industry performance, in particular whether the FCM processes will be implemented and to what extent. Finally, Step 3 estimates the impact of the industry changes on the U.S. macroeconomy. This report uses the REMI macroeconomic model of the U.S. macroeconomy to estimate the national impacts resulting from FCM-process-based changes to the automobile industry.

## 3.2 Process Implementation vs. Process Diffusion

In this study, we focus exclusively on *implementation* of the FCM processes within the automobile industry and not its *diffusion* to other, non-automotive industries, although that potential also exists.[7] The economic benefits of implementation are modeled to flow only along market channels, that is, by firms

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[6] For a description of the structure-conduct-performance paradigm, see J.S. Bain, *Barriers to New Competition* (Cambridge, MA: Harvard University Press, 1956).

[7] We expect to address cross-industry diffusion of the FCM technologies in a later study.

selling either the processes themselves or products and processes made from them. ATP affects automakers by cost-sharing research and development; automakers affect the auto industry by introducing new, competitive technologies; and the automobile industry affects the rest of the economy, for example, by increasing demand for other goods and services, selling more goods to other industries, and paying more wages to workers.

We use the term *diffusion* to describe how the FCM processes are transferred to other, non-automotive firms and their industries. The processes can diffuse to these non-automotive industries via *market* means (such as licensing to a supplier base) and *non-market* means (such as industry trade associations, journals, and university researchers). Figure 5 gives an example of this difference between process implementation and process diffusion. Of course, non-market mechanisms can also help foster adoption of the knowledge within the automobile industry.

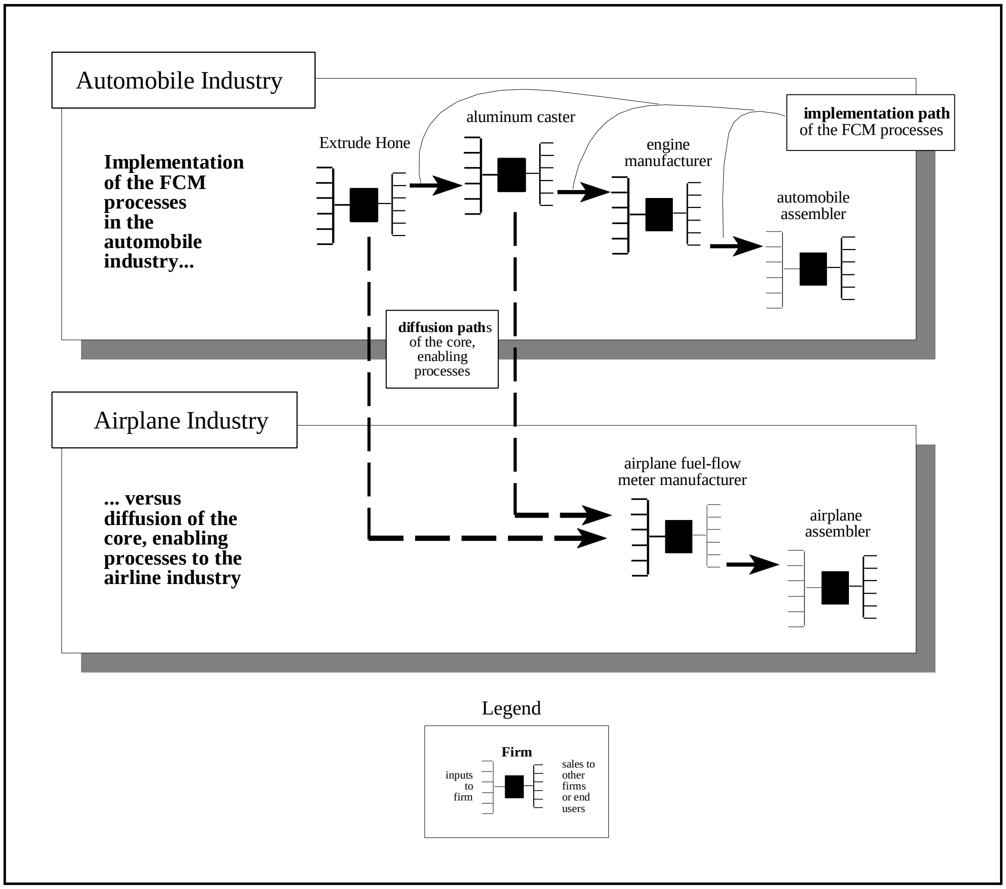

**Figure 5. An Example of Process Implementation and Process Diffusion**

Each black box in the figure represents a firm with inputs (on the left) and sales (on the right). In the Automobile Industry panel, Extrude Hone sells FCM-process machines to the aluminum caster, the aluminum caster sells FCM-manifolds and cylinder heads to the engine manufacturer, and the engine manufacturer then sells FCM-process engines to the car assemblers. The benefits of FCM-process implementation accrue via market channels—to the aluminum castor,  the engine manufacturer, the car assembler, and finally the consumer.  The FCM processes diffuse to the airplane industry if the aluminum casters apply their knowledge in automobile FCM-process machining to produce fuel-flow meters with the FCM processes, or flow-meter manufacturers start developing meters and production processes based on licensing of the core FCM processes from Extrude Hone.  These core processes can be described as

> the process of smoothing, sizing, and balancing interior cavities of metal parts based on manufacturing models which use, in real-time, the characteristics of the grinding media and the metal part to grind until the metal part has the desired characteristics (e.g., flow or volume capacity).

For example, AFCM of intake manifolds is based on a process which uses the characteristics of the viscoelastic media and the intake manifolds runners to control grinding until each runner has the desired (predicted) level of air flow.  The combustion chamber sizing is based on a process which uses the characteristics of the orbital abrading tool, the media, and the chamber volume to abrade until the chamber reaches the desired (predicted) volume.

Cross-industry diffusion of the technology is feasible in the case of the FCM processes; it is not just a hypothetical construct.  For example, an industry *product* to which the FCM processes could diffuse is the precision flow meter, a crucial component in products ranging from machines that manufacture semiconductors to jet-aircraft fuel systems.  The ability of these meters to accurately measure air and liquid flow is sensitive to the internal geometry of the meter.  The FCM processes could be applied to these flow meters to increase the precision to which they measure flow.  An example of an industry *process* to which the FCM processes could diffuse is one form of metal casting in which hot, liquid metal is shot from a circle of nozzles into a central high-pressure stream of air.  The air vaporizes the liquid metal into powder which deposits on a plate to form a predefined metal shape.  The functional precision to which the metal-powder manufacturing machine can fabricate a part is sensitive to the circle of nozzles that shoot hot metal.  Injector precision could be increased using the FCM processes, increasing the quality of the metal-powder-produced part.  As noted earlier, however, the quantitative impact estimates made here do not address cross-industry diffusion.

## 3.3  Scope of Estimated Economic Impacts

This study focuses on the economic impacts on three entities: the firms directly and indirectly involved in the FCM Project, the automobile industry, and the U.S. macroeconomy.  It quantifies how these three are expected to be changed by implementation of the technology: prior to the FCM processes, each automaker sold certain models and numbers of cars, the cars were sold at certain prices, and the U.S. macroeconomy generated a certain level of output, employment, and income.  After the FCM processes, these cars, prices, output, employment, and income change.  *The estimated changes throughout the economy represent the economic impact of the FCM processes*.

This study estimates only some of the market-based impacts that result from the direct sale of automotive-related goods from firms to other firms or to consumers. For example, it does not estimate changes in consumer surplus.  It also does not estimate impacts resulting from the manufacture and sale of non-automotive goods (such as surgical supplies made using the new processes), the licensing of the technology to other automotive and non-automotive firms, or the observed but not-paid-for use of the processes by engineers in other industries.  There may be additional organizational benefits—such as influences on companies to collaborate—which have a downstream effect on firms' economic performance. This study, however, does not estimate these non-market organizational, knowledge, and other benefits.

## 3.4 The REMI Macroeconomic Model[8]

This study uses the REMI (Regional Economic Modeling, Inc.) macroeconomic modeling software to estimate the impact of industry changes on the U.S. macroeconomy. Given changes in automobile-industry output and prices caused by implementation of the FCM processes, REMI can estimate the total effect on national output, employment, and personal income. Because of the central role the REMI model plays in the study, a brief description is given here.

REMI is a computer program that models the U.S. macroeconomy as a whole, for example, the aggregate production of goods and services, employment, personal income, consumer spending, wage and price determination, and international trade. As illustrated by Figure 6, the program is a set of structural equations that link economic variables—such as output, prices, and consumer spending—via theoretical and empirical relationships. These relationships, parameterized with publicly available historical data, model the fundamentally dynamic and circular nature of the real economy. For example, output generates employment, employment generates income, income generates spending on new output, this new output generates new employment, and so on. The program is typically used to simulate the effects of hypothetical changes in this dynamic and circular economy.

Variables are grouped to reflect their part in the causal linkages. The Output block contains variables representing the amount of goods produced; the variables are divided both by SIC industry—e.g., SIC 35, Industrial Machinery and Equipment—and by the "demand category" of the good—consumption, investment, government spending, or net exports. Within the Output block, an input-output matrix determines inter-industry demand and final demand, by industry.

The Population & Labor Supply block contains variables that track population levels and migration between regions of the country (which are not important in the single-region, national REMI model used in the study). The Labor & Capital Demand block contains variables that track the factors that impact firms' decisions about how much product to produce, how many workers to employ, and how much equipment and other capital to acquire. The Market Shares block contains variables that track, by industry, the supply-side and demand-side market shares, i.e., the fractions of U.S. production sold to domestic and foreign customers and the fractions of U.S. demand satisfied by domestic production and foreign goods. The bottom block, Wages, Prices, & Profits, contains price-related variables such as the wage rate, the cost of producing goods, the profitability of firms, and the sales prices of goods. All of the aforementioned variables are used to both simulate an economic change and to measure the impacts of it.

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[8] For a comprehensive description of the REMI model, see G.I. Treyz, D.S. Rickman, and G. Shao, "The REMI Economic-Demographic Forecasting and Simulation Model," *International Regional Science Review*, Vol. 14, No. 3, 1992, pp. 221-253. For an example of the use of REMI in a study of the NIST MEP, see Ehlen and Weber, *Estimating the Economic Impacts of Government Technology Programs: Manufacturing Studies Using the REMI Model* (Gaithersburg, MD: National Institute of Standards and Technology, 1997).

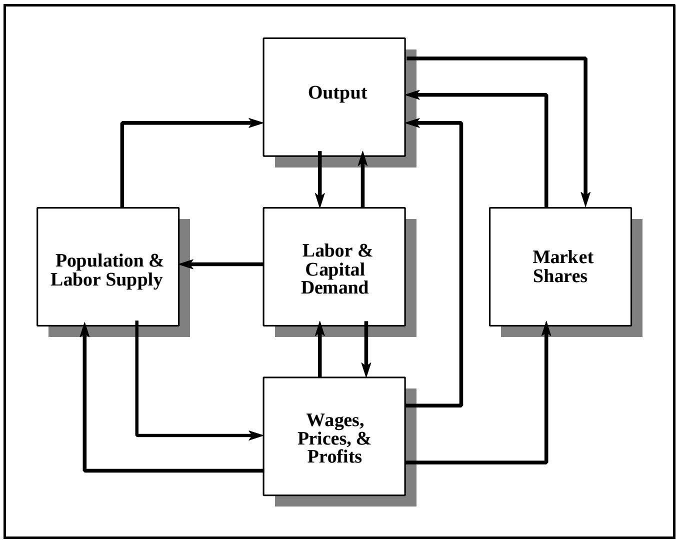

**Figure 6. Economic Variables and Causal Relationships in the REMI Model**

Each economic relationship in the model is one of three types:

| | |
|---|---|
| ● a *technical* relationship: | e.g., how much of the aluminum castings industry's output is used by the automobile industry as an input, |
| ● a *definitional* relationship: | e.g., what the national income accounts are, or |
| ● a *behavioral* relationship: | e.g., how consumer demand for cars responds to changes in personal income or automobile price. |

For example, the arrow pointing from Output down to Labor & Capital Demand represents a technical relationship stating that industry output determines industry employment. The arrow pointing from Labor & Capital Demand to Wages, Prices, & Profits represents technical relationships stating that the number of workers and equipment in production determine wages and the prices of goods.

The parameters in these relationships are estimated using publicly available 1969-1996 government data. Gross domestic product (GDP) measures are obtained from the Bureau of Economic Analysis and the *Survey of Current Business.*[9] The data on employment, wages, and personal income come from the Bureau of Economic Analysis and the Bureau of Labor Statistics. The cost of capital is computed from data in the *Quarterly Financial Report for Manufacturing*[10] and from the *Survey of Current Business.*

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[9] U.S. Bureau of the Census, *Survey of Current Business.*

[10] U.S. Bureau of the Census, *Quarterly Financial Report for Manufacturing, Mining, and Trade Corporations.*

State and U.S. corporate profits tax rates are obtained from the *Government Finances (Revenue)*[11] and the *Survey of Current Business*.

The REMI model is used to simulate the effect on the total economy of changes to components of it. An analysis is carried out in two steps. First, a *baseline forecast* of the U.S. economy is computed in which there is no change to the economy. Second, an *alternative forecast* is generated in which a set of *simulation variables* model a change in the economy. The economic impacts of the policy are measured as the differences between the baseline and alternative forecasts.

The set of input variables should be comprehensive and balanced. To be comprehensive, the set should model all changes relating to the new policy, such as changes in industry output, prices, consumption, and government taxation and spending. To be balanced, the set of variables should leave unchanged the economic resources used to carry out the policy. For example, suppose the policy calls for an increase in transportation spending. Unless taxes are increased, one of the input variables must be a decrease in spending in another area. Similarly, when modeling a new government program that requires new staff, the set of input variables should include a decrease in employees in other sectors.[12] As a general rule, the set of input variables should reallocate resources from one part of the economy to another.[13]

Figure 7 illustrates how REMI measures impact. Consider a government policy that increases spending on the nation's highway infrastructure. One possible impact of this spending is an increase in personal disposable income (the income available to workers). The lower, solid line in the figure shows the baseline forecast of personal disposable income over the 1996-2001 period (i.e., without the new infrastructure spending); the upper dashed line shows the alternative forecast of income (with the new infrastructure spending). REMI measures the impact of the new spending as the difference between the alternative and baseline forecasts for personal disposable income.

It is important to consider the years in which impacts occur. In the REMI baseline forecast, all markets are assumed to be in equilibrium—that is, supply equals demand in each—and national employment is assumed to stay at its long-run trend level. In the alternative forecast, however, individual markets, much like real markets, can have excess supply or excess demand, and employment can deviate from its long-run trend. Since these disequilibrium conditions as modeled can last three to four years, measures of impact in the first four years of a simulation do not necessarily represent permanent changes to economy but rather include temporary changes which diminish as the economy regains equilibrium. For this reason, the best measures of permanent impact occur at least four years after the simulated changes have stabilized.

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[11] U.S. Bureau of the Census, *Government Finances (Revenue)*.

[12] It is possible that if the economy were at less than full employment—where not all those who can work do work, then a government agency could hire employees with no loss of private sector jobs. We are, however, trying to model the general behavior of the economy based on employment at the full-employment level.

[13] REMI simulations in which the government does not offset new spending with higher taxes or lower spending in other areas have attracted unwarranted criticism of the REMI model itself. For example, see Edwin J. Mills, "Misuse of Regional Economic Models," *Cato Journal*, Vol. 13, No. 1, Spring/Summer 1993.

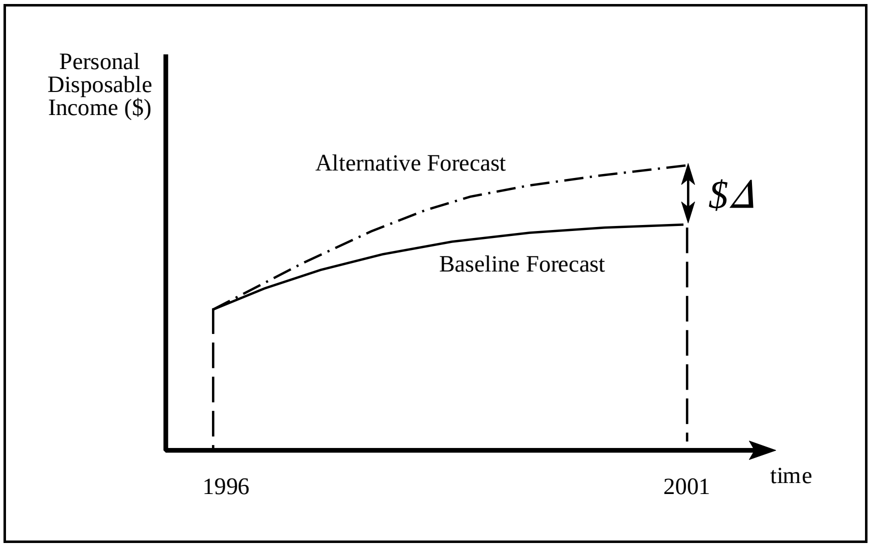

**Figure 7. Example of Estimating Economic Impacts Using the REMI Baseline and Alternative Forecasts**

Additionally, in the alternative forecast, REMI uses the results of recent research to characterize the Federal Reserve's efforts to control inflation. According to the resulting REMI model, the Federal Reserve Board takes action designed to keep national employment rate and inflation rate at long-run trend levels. The Fed's underlying policy is based on the belief that there is a long-run, economically optimal rate of employment which maximizes national employment without causing inflation. When employment is higher than its long-run trend level, signaling the potential for inflation, the Federal Reserve Board induces employment to decrease by increasing market interest rates. Higher rates increase the cost of business investment, causing investment and employment to decline. Conversely, if employment is lower than its trend level, the Federal Reserve Board decreases market interest rates to stimulate investment and therefore new output and employment. According to researchers[14] the Federal Reserve takes an average of three years to respond to deviations from the trend line and to return employment to the long-run trend employment rate. The long-run, steady-state measures of impact therefore occur at least four years after the modeled changes have been introduced.

The net impact of both market and Federal Reserve effects on employment levels can be illustrated with an example, shown in Figure 8. Consider an impact that increases output in a particular industry. In the first few years, national employment increases above the trend, as new jobs are created in both that industry and the industries that supply inputs to it.

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[14] O.J. Blanchard and D. Quah, "The Dynamic Effects of Aggregate Demand and Supply Disturbances," *American Economic Review*, Vol. 79, No. 4, 1989, pp. 655-673; and W. Nordhaus, "Policy Games: Coordination and Independence in Monetary and Fiscal Policies," *Brookings Papers on Economic Activity* 2, 1994, pp. 139-199.

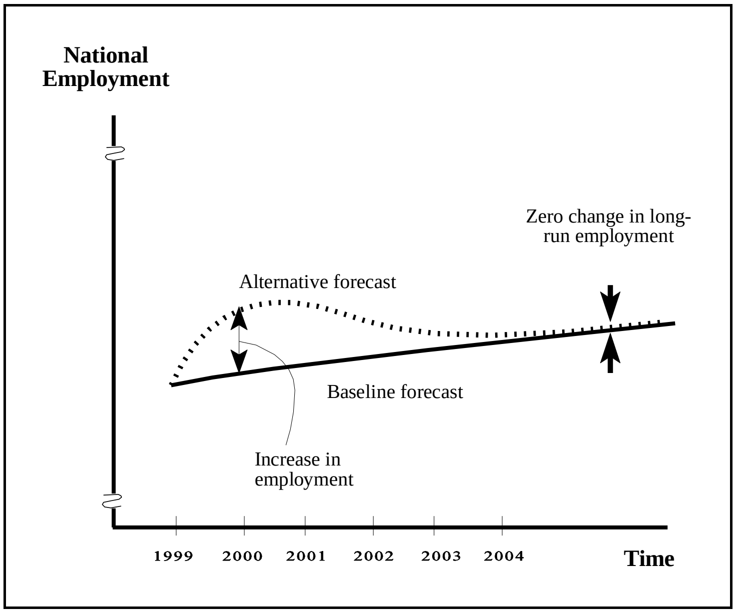

**Figure 8. Dynamic Employment Response of REMI Model**

REMI models the alternative forecast of employment, shown as a dotted line in the figure, as a dynamic disequilibrium response that persists for three years, at which point the Federal Reserve Board is assumed to raise market interest rates to ward off inflation (caused by the newly tighter labor markets). This rise in rates increases the cost of capital, decreases investment, and decreases employment until the national employment returns to its long-run, baseline-forecast level. By the fourth year the deviation of employment from its trend is brought to zero.

# 4. Assessing Implementation of the FCM Processes

In this chapter we assess the likelihood that U.S. automakers will implement the FCM processes, and if so, to what extent. The FCM processes should, in theory, be important to the automobile industry; they make available engines that have higher horsepower, better fuel economy, and lower emissions. Under current market conditions, some of these potential benefits may be more important than others to the decisions of automakers. Near-term implementation of the processes will depend on current market forces, and future implementation will depend on how these forces change over time.

The sheer size of this industry makes predicting technology implementation arduous. The industry generates $352 billion in sales and $92 billion in gross domestic product (GDP). It directly employs over 800,000 workers in a supplier-manufacturing base comprising over 4,000 plants in 48 states; another 900,000 workers are indirectly employed in 30,000 dealer franchises. Sometimes called "an industry of industries," the sector has a complex production and management structure designed to respond quickly to changes in consumer taste, production needs and costs, and competition among firms.

Because of this size and complexity, implementation assessments based solely on the current specific state of the industry may be misleading. Current conditions may not represent general trends. Longer-term assessments based on the historical, current, and expected future behavior of the industry give a stronger foundation for predicting technology implementation. Indeed, the U.S. automobile industry has changed dramatically since its inception in the 1890s. Fueled by the public's continually increasing reliance on automobiles, it has evolved through at least five eras to its current state of heavy market competition and cost cutting. In the first era, from the 1890s to the 1910s, many independent companies formed to produce cars based on a wide variety of power-train technologies. As many as 33 independent companies were selling cars with gasoline, steam, and electric engines. Ford Motor Company ushered in a new era by rationalizing these alternative technologies. It produced cars with a standardized power train and produced them on a large, efficient scale. In doing so, Ford was able to significantly lower its production costs and the prices of its cars. By 1923, Ford had 46 percent of U.S. market share.[15]

General Motors, built from a consolidation of independent car companies,[16] led the third era, shifting focus from the Ford strategy of standardization and specialization to selling a diverse set of products. While Ford sold the Model T "in any color as long as it was black," GM sold "a car for every purse and purpose."[17] GM blanketed the market with a wide variety of cars and modified them each year with styling changes and convenience improvements. By increasing the costs of design, tooling, and production, GM increased what it believed was the *replacement demand* for cars. By 1933, GM had 41 percent of U.S. market share, and Ford's share had dropped to 21 percent.[18]

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[15] Walter Adams and James W. Brock, *The Structure of American Industry* (Englewood Cliffs, NJ: Prentice Hall, 1995), p. 69, Table 3-1.

[16] These companies were Olds, Cadillac, Buick, and Chevrolet.

[17] Adams and Brock, *The Structure of American Industry*, p. 66.

[18] Ibid, p. 69, Table 3-1.

Consolidation continued in the era from the 1930s to the 1970s, as the number of U.S. automakers declined from twelve to just three: General Motors, Ford Motor Company, and Chrysler Corporation. Together, they constituted 96 percent of U.S. market share. From the 1970s to the present, however, foreign car companies significantly increased their sales to U.S. buyers and eventually their production in the United States as well. Today, only two U.S. car companies remain, GM and Ford, reflecting the current trend of global consolidation of auto producers.[19]

Our main questions are: given this history, will current and future market trends motivate the two U.S. automakers, both of whom are participating in the ATP project, to implement the FCM processes? If so, what type of vehicles will utilize the processes and to what extent? We answer these questions within the context of the *structure-conduct-performance paradigm*,[20] a useful causal framework for assessing technology implementation. The paradigm states that the structure of buyers and sellers in a market determines the market's conduct and ultimately its performance. Germane to this study, the framework helps us examine the current and future *structure* of automobile buyers and sellers, how this structure affects the price and non-price *conduct* of sellers, and how this conduct (and government policies) affect the *performance* of the market—the price and quantity of goods sold and the utilization of new technologies, such as the FCM processes.

## 4.1 Market Structure

The market for automobiles is composed of distinct buyers and distinct sellers. According to the structure-conduct-performance paradigm, how cars are bought and sold—and, most importantly, whether the FCM processes will be implemented—depends on the structure of buyers and sellers.

**Automobile Buyers**

Automobiles are an important, often necessary part of life in the United States. Domestically, there are 550 passenger cars per 1,000 people, the highest ratio in the world,[21] and the annual miles traveled per car has been steadily increasing.[22] Most U.S. buyers fit within two broad categories: consumers who purchase individual cars for themselves, and businesses—such as rental-car agencies, business firms, and government agencies—who purchase fleets of cars.[23]

Short-run demand for new cars is strongly influenced by changes in the economy. Since a car purchase represents a major investment and can be delayed by keeping one's current car, new-car demand is

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[19] In 1998 Chrysler merged with Daimler-Benz to form DaimlerChrysler.

[20] For a description of the structure-conduct-performance paradigm, see J.S. Bain, *Barriers to New Competition* (Cambridge, MA: Harvard University Press, 1956).

[21] American Automobile Manufacturers Association (AAMA), *Motor Vehicle Facts & Figures 1997,* p. 46.

[22] Ibid, p. 64.

[23] Consumers and businesses each currently account for 50 percent of new-car purchases.

affected greatly by changes in: personal income,[24] car price, the prices of substitutes (e.g., used cars, leased cars), market interest rates, and non-automobile purchases (e.g., medical expense, entertainment).[25]

Underlying trends indicate that long-run demand for new cars may be leveling off or even declining. The size of the U.S. driving population has leveled off[26] and the average life of a passenger car has increased from 6.6 years in 1980 to 8.6 years in 1996.[27] The preferences of U.S. car buyers have changed over time. From the 1960s to the 1980s, these buyers preferred smaller cars, owing to a change in consumer taste and a marked increase in gas prices.[28] With gas prices currently about half of what they were in 1975,[29] consumers are now shifting back to large vehicles which weigh more,[30] protect occupants better,[31] and have more interior space, but which have relatively poor fuel economy.[32] These are increasingly in the "light-truck" class of automobiles, including small trucks, mini-vans, and sport utility vehicles.

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[24] A REMI panel data study of consumer purchases on "Vehicles and Parts" found automobile demand to be almost twice as income elastic as it is price elastic (1.42 vs. -0.82; see Regional Economic Modeling Incorporated, "Panel Study of Consumer Purchases," mimeo, May 1998). Earlier studies (during the 1920s through 1960s) found income elasticities in the 1.0 to 4.0 range (Lawrence J. White, *The Automobile Industry Since 1945* (New York: MacMillan Publishing Co., Inc., 1971), pp. 94-95).

[25] Over the 1980-1995 period, the share of household expenditures going to vehicle purchases increased from 7% to 8% of all expenditures, but the cost of housing increased from 29% to 32%, health care from 4.5% to 5.4%, and entertainment from 4.5% to 5.0%. The largest decrease in percent spending was for food, dropping from 19% to 14%. AAMA, *Motor Vehicle Facts & Figures 1997*, p. 61.

[26] The U.S. driving population increased 2.9 percent annually between 1967-1975, 1.9 percent annually between 1975-1985, and 1.1 percent annually between 1985-1995. Ibid, p. 56.

[27] Ibid, p. 39.

[28] Gasoline prices increased drastically as a results of the two OPEC-related oil crises in the 1970s.

[29] Center for Transportation Analysis, *Transportation Energy Data Book*, Oak Ridge National Laboratory Report ORNL-6898, August 1996, Table 1.3.

[30] See Murrell, Hellman, and Heavenrich, "Light-Duty Automotive Technology and Fuel Economy Trends Through 1993," p. 7, Figure 15.

[31] For example, a National Highway Traffic and Safety Administration report, "The Effect of Decreases in Vehicle Weight on Injury Crash Rates," (Washington, D.C.: NHTSA, 1997) found that a 45.4-kilogram (100-pound) decrease in the average light-truck weight results in an increase of 1,800 incapacitating injuries to the light-truck occupants.

[32] A study conducted in 1980 and in 1994 compared the ranking of vehicle attributes which new-car buyers considered most important. In 1980, fuel economy was the 2nd most important attribute and safety features were 9th; in 1994, fuel economy was ranked 15th and safety features 4th (AAMA, "Environmental Responsibility," web site http://www.aama.com/environmental/cafe3.html, September 14, 1998). Regarding safety, a 1997 J.D. Power and Associates survey found that 59 percent of new-car buyers surveyed said that they "definitely wanted" anti-lock brakes, 32 percent wanted "smart" passenger air bags, 23 percent wanted day running lights, and 18 percent said they wanted electronic traction control (J.D. Power and Associates, "1997 APEAL Feature Contenting Report," Agoura Hills, CA, 1997).

### Automobile Sellers

Seller concentration is very high in the U.S. automobile market. The two U.S. automakers are General Motors and Ford Motor Company, with combined 1996 retail sales of 4.5 million[33] passenger cars and 4.0 million[34] light trucks. While as early as 1985 these two had 88-percent market share,[35] in 1994 they accounted for only 52 percent of domestic passenger car sales and 58 percent of domestic light truck sales, as shown in Figure 9. The light-truck market is increasingly important to GM and Ford, as domestic buyers switch from passenger cars to light trucks. In 1998, U.S. light-truck sales exceeded passenger-car sales for the first time.

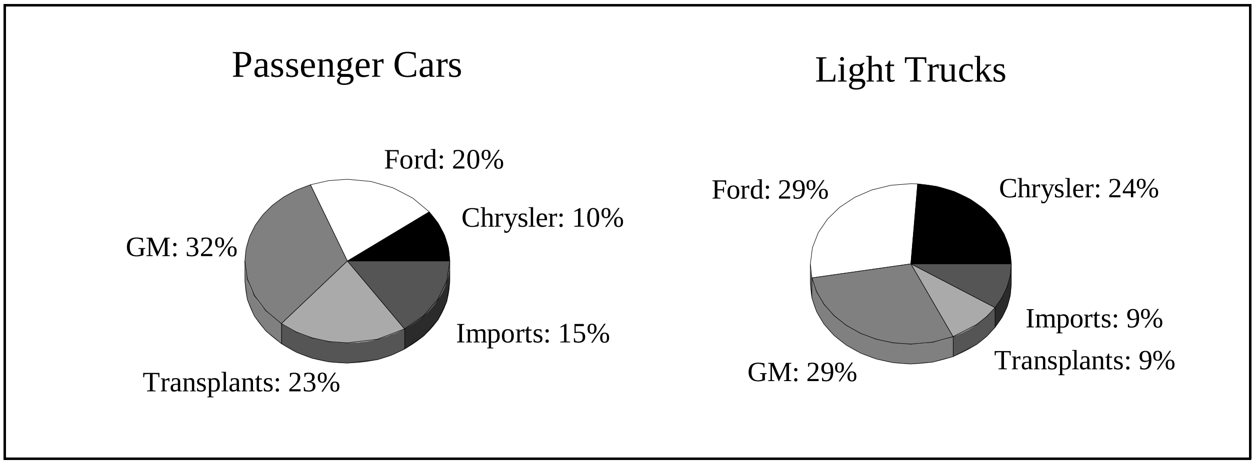

**Figure 9. U.S. Passenger-Car and Light-Truck Market Shares: 1994**

For the past 6 years, Ford and GM have been steadily losing passenger-car market share to foreign firms. As shown in Figure 10,[36] the foreign share, consisting of imports and transplants,[37] grew from 18 percent in 1975 to nearly 48 percent in 1994, concurrent with the rise in the number of foreign nameplates sold domestically. Japan and other foreign car producers that initially concentrated on selling small cars in the U.S. have branched out to large cars, luxury cars, and light trucks.

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[33] AAMA, *Motor Vehicle Facts & Figures 1997*, pp. 16-17.

[34] Ibid, p 20.

[35] Adams and Brock, *The Structure of American Industry*, p. 69.

[36] R.M. Heavenrich and K.H. Hellman, *Light-Duty Automotive Technology and Fuel Economy Trends Through 1996*, Technical Report EPA/AA/TDSG/96-01 (Ann Arbor, MI: U.S. Environmental Protection Agency, 1996), Appendix E.

[37] Transplants are foreign-owned automobile plants located in the United States.

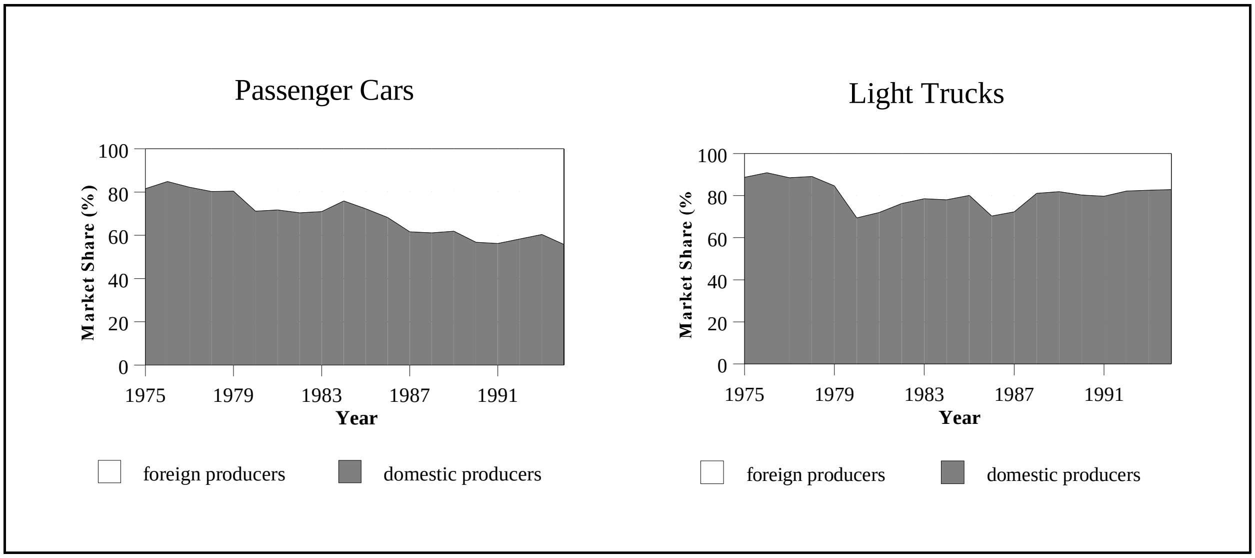

**Figure 10. U.S. Passenger-Car and Light-Truck Market Shares: 1975-1994**

This decline in domestic-firm share is less threatening if world sales are strong. Domestic automakers had combined 1996 world market share of 23 percent,[38] and this share is increasing, but largely due to economic growth in Mexico and Canada, which may not last. The potential for passenger-car export growth is very limited, since the world supply of new cars far exceeds world demand. As well, the potential for light-truck export growth is limited, since these vehicles have relatively poor fuel economy and the price of gasoline abroad is very high. With world-sales growth uncertain and the number of domestic buyers constant or declining, regained sales will need to come from domestic markets.

The spatial integration of automakers continues to change dramatically. GM and Ford have historically been integrated vertically, horizontally,[39] and internationally. Starting in the 1930s and up to recently, GM and Ford further increased vertical integration by buying supplier companies, thereby internalizing automobile-parts production. By the early 1990s GM and Ford produced the majority of their parts in-house. In the 1980s, Ford and GM increased vertical integration by purchasing minority stakes in rental car agencies, the single largest business buyer of fleets of cars. Recent efforts, however, are to drastically reduce vertical integration to reduce costs[40] and to be better able respond to changes in consumer preferences.[41] In an effort to reduce costs and remain responsive to changes in market demand, first-tier and second-tier suppliers are producing an increasingly larger fraction of the total value of a car.

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[38] AAMA, *Motor Vehicle Facts & Figures 1997*, p. 13.

[39] In 1993 the Big Three—GM, Ford, and Chrysler—operated 38 plants distributed across the United States, Canada, and Mexico. Adams and Brock, *The Structure of American Industry*, pp. 71-73.

[40] See Michael J. Smitka, "The Invisible Handshake: The Development of the Japanese Automotive Parts Industry," *Business and Economic History* 19 (1990): pp. 163-171.

[41] Adams and Brock, *The Structure of American Industry*, p. 76.

To sum up, U.S. car buyers are increasingly demanding larger vehicles. Ford and GM, once garnering most of domestic sales, are now steadily losing passenger-car market share to an increasing number of foreign car companies. Light-truck sales and market share, however, remain strong. To compete more effectively, Ford and GM are divesting of supplier and buyer businesses to cut costs and to better respond to changes in market conditions.

## 4.2 Market Conduct

These recent changes in market structure have caused marked changes in the competitive behavior, or market conduct, of GM and Ford. We divide this behavior into price conduct and non-price conduct. Analysis of conduct helps determine the likelihood that the automakers will implement the FCM processes.

**Price Conduct**
Prior to the 1970s, most U.S. buyers purchased from the Big Three: GM, Ford, and Chrysler. The pricing of these firms was interdependent and oligopolistic, each recognizing that avoiding serious price competition—especially "price wars"—was in their collective best interest. In the 1920s and early 1930s, Ford led with price announcements and the other manufacturers followed with prices close to Ford's or saw their sales decline. After World War II, General Motors led price announcements in a similar way, with Ford and Chrysler following with close prices. Since the 1970s, this three-firm oligopoly has transformed into a more competitive market where automakers set prices more independently. Currently there is no clear leader-follower price conduct, although a certain amount of coordination still exists.[42] In addition to directly competing on sticker price, Ford and GM are reducing the total purchase cost of a car, through marketing, incentive, and service programs. These programs include increasing the period of the car loan,[43] offering cash rebates, lowering loan interest rates, subsidizing leases,[44] selling program cars,[45] and offering warranty and buyer-protection programs.

Several studies appear to agree that, indeed, car price matters greatly to car buyers, especially as the car becomes larger and more specific in vehicle class and manufacturer. One study found the price elasticity for all new cars to be between -0.5 and -1.5,[46] while another found the elasticity for large cars to be about

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[42] For example, the automakers may coordinate prices by first announcing "preliminary" planned price changes and then, once having seen each others' prices, announce their "final" price changes. In another example, in 1981, when the federal government put restraints on the number of Japanese imports into the U.S., Japanese automakers started exporting their larger, higher-priced cars. GM, Ford, and Chrysler then followed the import-car price increases with price increases of their own.

[43] The average payment period of new-car loans has increased from 45 months in 1980 to 52 in 1996. AAMA, *Motor Vehicle Facts & Figures 1997*, p. 59.

[44] Leases as a percent of new-vehicle retail transactions has increased from 3.5 percent in 1985 to 27.2 percent in 1996. Ibid, p. 42.

[45] Program cars are cars that automakers sell to rental companies and buy back after a short period, allowing the automakers to sell them as used cars.

[46] White, *The Automobile Industry Since 1945* (New York: MacMillan, 1971), pp. 94-95.

-3.0 and that of a particular brand to be about -10.0.[47] This means that automakers can increase sales by lowering prices relative to other vehicles in its class; that is, they can compete on price. As the number of sellers in the car and light-truck markets increase, price competition becomes increasingly important.

**Non-Price Conduct**

Automakers spend considerable effort determining what consumers' key needs and desires are and then developing a product strategy for cars with these characteristics. These characteristics include styling, options, horsepower, and fuel economy, the latter two of which tend to be mutually exclusive.[48] Automakers also engage in non-price competition through advertising, the introduction of new car models, and research and innovation. For example, prior to intense foreign competition in the 1970s, the Big Three often avoided "radical" product innovation or technological improvements, instead making only styling changes each year. More recently, as the number of sellers has increased and domestic-firm share has decreased, automakers have been aggressively non-price competing. For example, the total number of models offered increased 100 percent over the 1974 to 1988 period, significantly more than the increase in the number of automakers selling in the United States.[49] GM and Ford have been rigorously competing on a non-price basis with Japanese companies which, after mastering shorter development cycles, lean production techniques, just-in-time delivery, and small batch production, have shifted from selling inexpensive utilitarian cars (similar to the Ford strategy in the 1920s) to the current strategy of extensive product diversity (similar to the GM strategy in the 1930s).

To summarize, the increased number of sellers in the market and decreased domestic-firm market share have drastically increased Ford's and GM's need to compete, both in price and non-price terms; Ford and GM will likely be early adopters of the FCM processes if the processes allow them to better compete in either or both of these terms.

## 4.3 Market Performance: Price, Profits, Costs, and Quality

This increased price and non-price competition among automakers ultimately affects market prices, profits, and production costs, and the non-price qualities of new cars in the market. Regarding market prices, while car prices have tripled in real terms over the 1967-1984 period alone,[50] current prices are expected to be flat and may decline 2 percent over the next few years. This price decline is not caused by reduced income or other long-run market conditions: in 1996, the first year that car prices declined, personal income increased 5 percent, general inflation increased 3 percent, and car sales increased by 2.2

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[47] Andrew N. Kleit, "The Impact of Automobile Fuel Economy Standards," Federal Trade Commission Working Paper No. 160, February 1988, Technical Appendix, p. 3.

[48] For example, acceleration and top speed tend to decrease as fuel economy increases; see Murrell, Hellman, and Heavenrich, "Light-Duty Automotive Technology and Fuel Economy Trends Through 1993," p. 25.

[49] S. Berry, J. Levinsohn, and A. Pakes, "Automobile Prices in Market Equilibrium," *Econometrica*, Vol. 63 No. 4, July 1955, pg. 870. The 100-percent "model" increase compares with (only) a sixty-percent increase in automakers selling in the U.S. over the same period; AAMA, *Facts & Figures 1997*, pp. 15, 80.

[50] Car prices increased 18 percent more per year than general inflation.

percent. All else being equal, car prices should have risen; instead, they *declined* by 1 percent.[51] This price decline (i.e., market-performance change) is caused by price competition (i.e., conduct) that follows from stable or declining demand for cars, an increase in the number of foreign firms selling domestically, decreasing domestic-firm market share, and decreasing prospects for long-term world market share (i.e., market structure).

Industry profits are largely a function of car size[52] and of demand, the latter being sensitive to business cycles and other economic conditions. Passenger-car profits have declined sharply as a result of severe competition from foreign producers. Overall profits, however, have recently been large, owing to increased sales of large, profitable light trucks and to massive cost cutting.

Historically, production costs have been high due to the lack of competition, resulting in lax raw-materials procurement, excess overhead, vertical collusion between the automakers and labor unions, and multi-layered bureaucracy. Only in the last 10 years has price competition caused U.S. producers to markedly increase efficiency in raw materials procurement, to increase recycling of tooling, and to make parts management more efficient.[53] Costs have also been drastically reduced in marketing, distribution, and retailing (the latter of which represents 20 to 30 percent of the cost of a new car[54]).

Regarding quality, competition has forced U.S. automakers to increase the quality of their cars while keeping costs down. U.S. automakers have closed the labor productivity gap[55] and quality gap[56] with the Japanese, but generally still require more production units per model to be economically efficient. Product development times have improved as well: the average time to market of U.S. automakers has fallen to 52 months, below the Japanese average of 55 months in the early 1990s. Entire automobile sub-assemblies, such as the power train and dashboard, are increasingly made by others than the automakers, improving component quality and reducing costs.

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[51] AAMA, *Facts & Figures 1997*, pg 60.

[52] One study (S. Berry, J. Levinson, and A. Pakes, “Automobile prices in market equilibrium,” *Econometrica*, Vol 63, No. 4, July 1995, pg. 882, Table VIII) estimated profits (as measured by markup over marginal cost) to be between 16 percent of price for small cars and 29 percent for large luxury cars. Another study (P. Goldberg, “Product differentiation and oligopoly in international markets: the case of the automobile industry,” *Econometrica*, Vol. 63. No. 4, July 1995, pp. 891-951) found similar profits for similar car categories.

[53] GM has set up a system of worldwide competitive bidding, which saves an estimated $4 billion per year. See Fine, St. Clair, Lafrance, and Hillebrand, *The U.S. Automobile Manufacturing Industry*, p. 60.

[54] Ibid, p. 65.

[55] For example, Fine, St. Clair, Lafrance, and Hillebrand (1996) found that the Big Three improved their productivity from 24.1 direct labor hours per vehicle in 1989 to 20.7 hours per vehicle in 1994, a figure similar to that for Japanese-owned plants; Fine, St. Clair, Lafrance, and Hillebrand, *The U.S. Automobile Manufacturing Industry*, p. 10.

[56] In the 1998 Initial Quality competition conducted by J.D. Power and Associates, three of the seven car categories were won by U.S. cars, three by Japanese cars, and one by a German car. In the light truck category, two of the six categories were won by U.S. cars and five by Japanese cars (there was one tie). See J.D. Power & Associates, “1998 Initial Quality Study 2,” June 3, 1998.

## 4.4 Market Performance: Adoption of New Technologies[57]

Most important to our analysis is determining whether current and future market conditions will cause the domestic industry to adopt new technologies such as the FCM processes. Except for the period during the 1940s, when independent car producers were a particularly fertile source of product innovations,[58] relatively few technological changes have been made to automobile technology. Laurence White stated (in 1971), "the major features of today's automobiles—V-8 engines, automatic transmissions, power steering, and power brakes—are all WWII innovations. The suspension, ignition, carburetion, and exhaust systems are fundamentally the same. Only the pressure of Federal regulation on air pollution has effected any change in these last three systems."[59] John De Lorean noted (in 1981), "today's transverse-engine, front-wheel-drive layouts differ little from the British Leyland mini of 25 years ago."[60]

General Motors and Ford previously relied heavily on their parts suppliers for technological advances, allowing these suppliers to absorb the initial costs and risks. Currently, the influx of foreign automakers and the resulting competition are creating a market where new technologies are increasingly used if they generate new sales, decrease costs, or both. Toward this end, domestic automakers invest heavily in R&D. GM and Ford both have large research departments: General Motors is the top corporate investor in R&D, spending $8.9 billion in 1996, and is the largest private employer of PhDs. Ford Motor Company is second in R&D spending and has 650 full-time scientists and engineers.[61]

**Effects of Federal Fuel Economy and Emissions Policies on Technology Adoption**

One of the largest factors affecting the sale of automobiles in the U.S. is federal regulation of fuel-economy and emissions. In 1975 the federal government, responding to increased oil consumption[62] and uncertainty regarding the availability of oil reserves, passed the Energy Policy and Conservation Act. The act required automakers selling cars in the United States to increase by 1985 the Corporate Average Fuel Efficiency (CAFE) of their passenger-car fleets and light-truck fleets to 11.7 kilometers per liter (27.5 miles per gallon [mpg]) and 8.8 kilometers per liter (20.7 mpg). It drastically affected the production decisions of automakers, since at the time they were not producing fleets with fuel economies—or emissions levels[63]—even close to the required levels. According to two studies, pollution emissions

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[57] The rate at which a market adopts new technologies is sometimes called its *dynamic efficiency*.

[58] See Adams and Brock, *The Structure of American Industry*, p. 154.

[59] Adams and Brock, *The Structure of American Industry*, p. 154..

[60] Ibid.

[61] AAMA, *Motor Vehicle Facts & Figures 1997*, p. 53. See also Fine, St. Clair, Lafrance, and Hillebrand, *The U.S. Automobile Manufacturing Industry*, p. 41.

[62] Light-duty vehicle petroleum consumption was and is significant; for example, it is currently 43 percent of all U.S. petroleum consumption. National Research Council, *Automotive Fuel Economy: How Far Should We Go?* (Washington, D.C.: National Academy Press, 1992), p. 13.

[63] The Clean Air Acts of 1970 required *90-percent* reduction in the level of hydrocarbons (HC) and carbon monoxide (CO) by 1975 and a similar reduction in nitrogen oxide ($NO_x$) by 1976.

controls added $1,270 in compliance-related costs to each car[64] and reduced automobile industry output over the 1974-1985 period by 15 percent.[65] By 1985, automakers had achieved the required emissions and CAFE fuel efficiencies. Past and recent changes that automakers have implemented to increase fuel efficiency include:

- reductions in vehicle weight, including the use of light-weight aluminum and plastic components;
- decreases in the exterior dimensions of the car (concurrent with *increases* in interior volume);
- the use of fewer cylinders, fuel injection, microprocessor-based engine-control systems;
- catalytic systems;
- increases in drive-train efficiency, such as front-wheel drive;
- better aerodynamics; and
- reductions in tire-rolling resistance and other frictional losses.

Indeed, as seen in Figures 11 and 12,[66] over the 1986-1997 period the Big Three were able to develop and sell fleets of cars and light trucks whose fuel efficiencies are very close to the required levels.

Since the Energy Policy and Conservation Act was passed, many of the original factors which motivated the CAFE requirements have diminished: known oil reserves have increased since the 1970s, the price of gasoline has dropped to levels prior to the oil shocks, and total fuel consumption per vehicle has been reduced substantially. There is new international concern, however, about the link between automobile pollution and global warming, spurring new (albeit unsuccessful) efforts to increase the CAFE requirements to as high as 17.0 kilometers per liter (40 mpg). Furthermore, the shift of consumer taste to large light trucks has increased interest in making the light-truck class of vehicles abide by the more stringent passenger-car CAFE and emissions regulations.

While CAFE legislation discourages the sale, or supply, of fuel-inefficient vehicles, there is also legislation which discourages the demand for large, low-mpg automobiles. This legislation imposes "gas guzzler" taxes on buyers of low-mpg vehicles, and these taxes have increased substantially since their inception. The tax on new cars that get less than 5.3 kilometers per liter (12.5 mpg; combined city and highway driving) has increased from $550 in 1980 to $7,700 in 1991, while the tax on cars with 9.4 to 9.6 kilometers per liter (22.0 to 22.5 mpg) has increased from zero to $1,000. While these taxes increase the real price of cars, consumers are still increasingly purchasing low-mpg light trucks, due to the shift in tastes and the low price of gasoline. In fact, consumer demand is so strong that automakers, seeking

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[64] T. Bresnahan and D. Yao, "The nonpecuniary costs of automobile emissions standards," *Rand Journal of Economics*, Vol. 16 No. 4, Winter 1985, p. 451. These include nonpecuniary costs such as decreased driveability.

[65] D. Jorgenson and P. Wilcoxen, "Environmental regulation and U.S. economic growth," *Rand Journal of Economics*, Vol. 21 No. 2, Summer 1990, p. 316.

[66] AAMA, *Automobile Facts & Figures 1997*, pp. 80-81. In the light truck figure,"Domestic Fleet" data prior to 1992 is for two-wheel drive vehicles. Due to lack of data availability in and after 1992 the "Domestic Fleet" data is for domestic and import two-wheel drive and four-wheel drive combined.

to meet their CAFE targets, sometimes shift consumer purchases away from large cars to small cars by increasing the price on their large cars and decreasing prices on small cars.

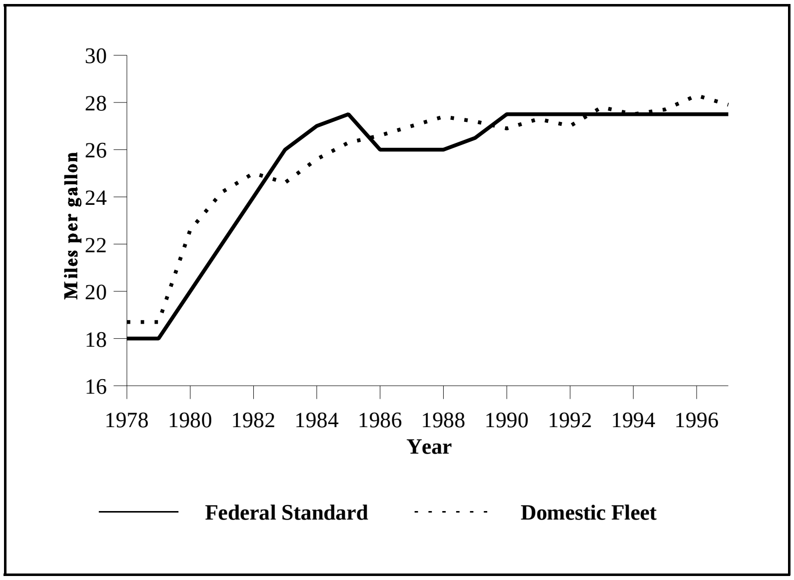

Figure 11. Actual and Required CAFE Levels for Passengers Cars: Model Years 1978-1997

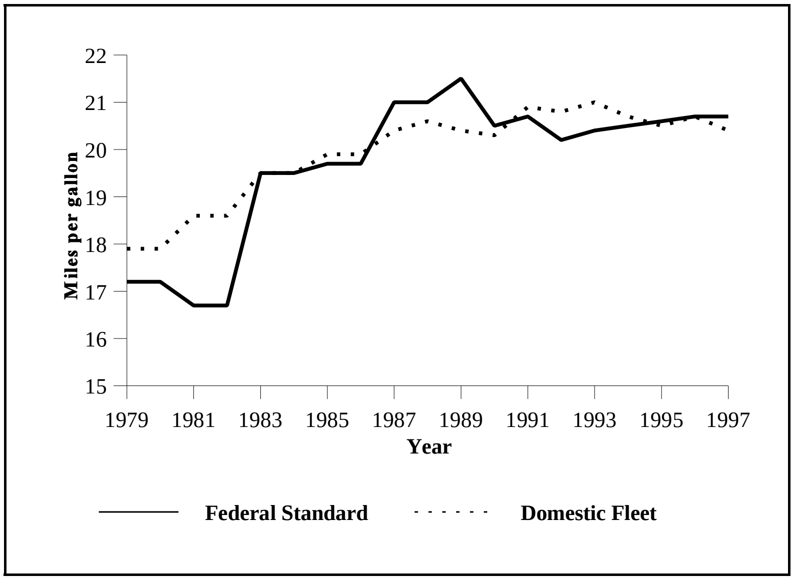

Figure 12. Actual and Required CAFE Levels for Light Trucks: Model Years 1978-1997

Industry will likely implement the FCM processes if there is a current and future need for increased horsepower and fuel efficiency, and if the processes are cost effective. As it turns out, for the past 20 years Ford and GM have drastically modified automobile engines so that they meet consumers' increasing demand for large vehicles that, as a fleet, satisfy CAFE requirements. As seen in Figures 13, 14, and 15, automakers have been *consistently and simultaneously decreasing engine size and increasing horsepower*, that is, increasing an engine's *specific power* (horsepower per liter displacement). Increasing specific power has allowed them to put smaller, more fuel-efficient engines in increasingly larger vehicles. Port fuel injection, four-valve engines, and the FCM processes are examples of technologies that increase specific power.

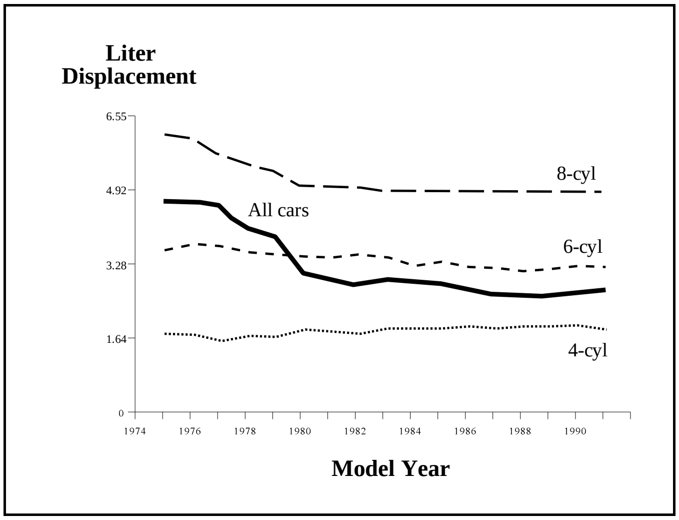

**Figure 13. Engine Displacement, by Number of Cylinders: 1975-1991**

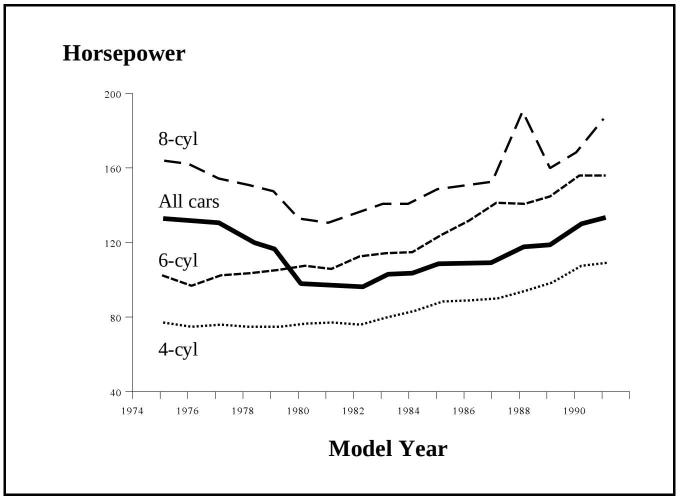

**Figure 14. Engine Horsepower, by Number of Cylinders: 1975-1991**

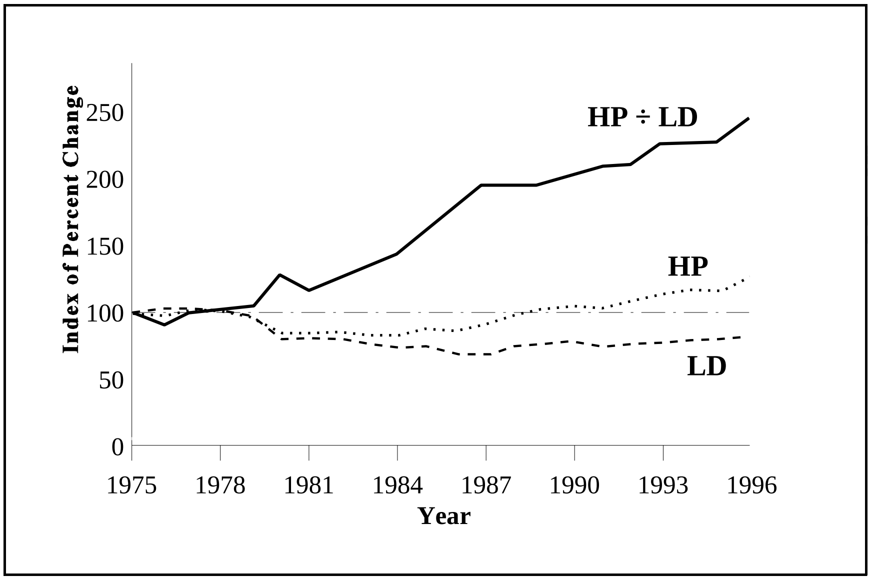

**Figure 15. Horsepower (HP), Liter Displacement (LD), and Specific Power (HP ÷ LD) of Light Trucks: 1975-1996**

As Figure 14 illustrates, domestic automakers have used this increased specific power to increase the horsepower of engines. But the specific power increase can also be used to keep fuel efficiency constant as the weight of vehicles increases. Indeed, light-truck weight has increased by sixteen percent and passenger-car weight by five percent over the 1987-1996 period, while fuel efficiencies have remained essentially the same.[67]

**Effects of Federal Safety Regulations on Technology Adoption**
Another factor affecting industry technology implementation is safety regulations imposed on new cars. These regulations target air bags, side impact panels, and front and rear crumple zones, most of which add weight. They also add costs, an average of $130 to the price of a car over the 1990-1995 period.[68] As consumers increasingly demand larger automobiles, and as federal regulations increase the safety requirements placed on cars and light trucks, Ford and GM constantly look for new ways to increase the fuel efficiency of their vehicles.

## 4.5 Likelihood of FCM Processes Being Adopted

Given these current and expected future characteristics of the automobile industry, the FCM processes are likely to be adopted. They can be used to increase horsepower, fuel efficiency, or both, and will be inexpensive when compared to competing horsepower and fuel-efficiency enhancing technologies. FCM-

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[67] Heavenrich and Hellman, *Light-Duty Automotive Technology and Fuel Economy Trends Through 1996*, p. 7, Figures 3 and 4.

[68] AAMA, *Motor Vehicle Facts & Figures 1997*, p. 82. Figure is expressed in 1996 constant dollars.

based horsepower gains allow automakers to add weight-increasing features to a vehicle without compromising fuel economy. For example, styling options and safety features are key product characteristics to many car buyers. These features, however, add weight, thereby reducing performance characteristics such as acceleration and top speed.

Participation of two large U.S. automobile manufacturers in the vertically structured joint venture includes them in the technology development process. This inclusion both signals their interest in the technology and positions them for its early adoption.

The fleet of light trucks currently sold by Ford and GM just barely satisfies federally required CAFE fuel economy. The FCM processes allow automakers to increase the fuel efficiency of their highly demanded and highly profitable large vehicles, increasing the fleet's average fuel economy, and therefore enable them to sell more of the profitable light trucks. Fuel efficiency gains can also reduce the "gas guzzler" tax imposed on a car, thereby reducing the real price to consumers. The FCM processes can also be used to produce vehicles with a combination of horsepower and fuel efficiency increases.

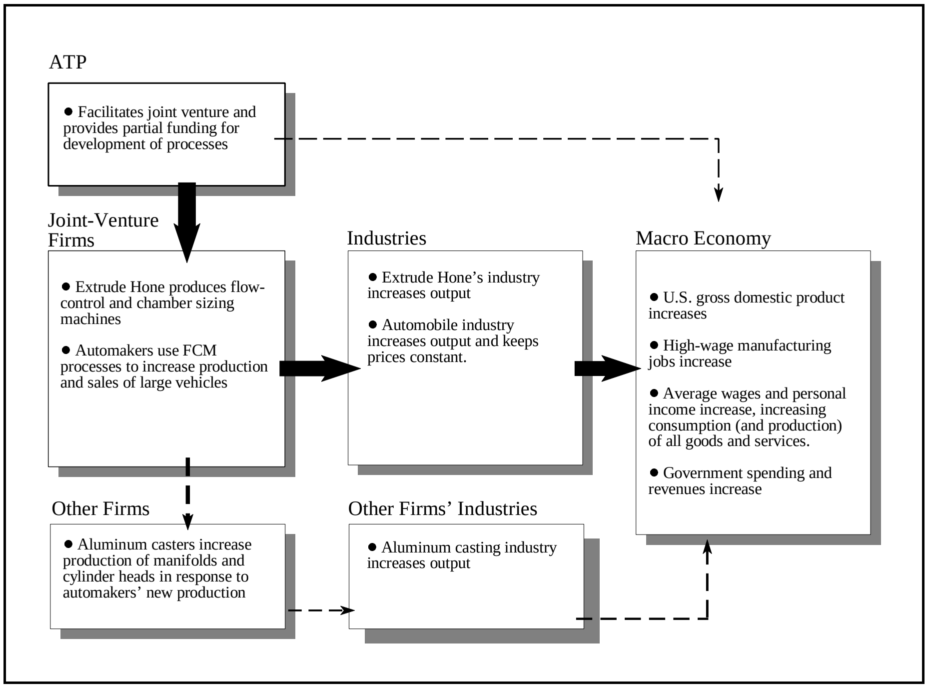
The FCM processes are a relatively low-cost alternative to other engine performance technologies. Increasing performance by switching to fuel injection or 4-valve combustion chambers involves a "radical" change in the design of the engine (adding or changing parts). Implementing the FCM processes would require no changes in parts and only minor changes to design, fabrication, and tuning. The FCM processes do not fundamentally change engine assembly, a distinct advantage over other efficiency-enhancing technologies that have historically been adopted, such as fuel injection and four-valve engine designs. Automakers can use the FCM processes to substitute smaller, less costly engines in their cars: for example, if an automaker currently uses a 2.79-liter (170-cubic-inch) engine to produce 143 horsepower, FCM processes that increase specific power by six percent would enable the automaker to use a 2.64-liter (161-cubic-inch) engine and still get the same 143 horsepower. Engines can also be made at a lower cost if the FCM processes displace more-costly technologies such as four-valve combustion chambers or dual-fuel systems. From their participation in the ATP-funded FCM project, GM and Ford are becoming familiar with the capabilities of the technology and testing it on some production lines.

Given current and expected market trends, U.S. automakers are likely to use the FCM processes to increase the fuel efficiency of their larger, more profitable light trucks. Buyers continue to demand larger vehicles with more federally imposed, weight-adding safety requirements. Domestic sellers, facing increasing competition from foreign firms and declining market share, are competing heavily in passenger-car price, options, and styling. Whereas domestic passenger-car demand is far less than domestic supply, demand for large light trucks is far more than supply. To make more of them and still satisfy CAFE, domestic automakers must find new ways to increase fuel efficiency. The FCM processes allow them to increase the sale of these vehicles and stay within the federal CAFE fuel economy requirements.

Estimates of the cost to implement the FCM processes and historical data on actual fuel-efficiency and emissions costs suggest that the FCM processes are a cost effective alternative to competing technologies. For the past four years the average horsepower per car has increased from 118 to 126 (Figure 14) and the increase in retail prices attributable to emissions improvements (fuel efficiency, exhaust emissions) has been \$203.[69] If these price increases reflect costs that automakers have incurred to increase horsepower while keeping fleet fuel efficiency unchanged, the automakers have spent $\frac{\$203}{(126 - 118)\text{ horsepower}} = \$25.38$ per horsepower gained for fuel efficiency improvements and emissions controls. The cost of the FCM processes, on the other hand, is expected to be in the range of \$3 to \$5 per horsepower gained per car.[70] Given that the average horsepower of large-utility vehicles is estimated to be 200 and the anticipated horsepower improvement from the AFCM and NCCS processes is six percent, a conservative estimate of the cost to Ford and GM of implementing the FCM processes in light-truck engines is (200 horsepower) × (0.06) × (\$5 per horsepower per engine) = \$60 per engine, far less than the average cost of existing fuel efficiency and emissions technologies.

## 4.6 The Most-Likely Implementation Path for the FCM Processes

Implementation of the FCM processes will follow a specific path in the automobile industry. Figure 16, an application of the impact framework in Figure 4, gives a qualitative summary of the assumed path, in terms of actions taken and the impacts of implementing the FCM processes to increase the fuel efficiency of large automobiles.



- Facilitates joint venture and provides partial funding for development of processes

- Extrude Hone produces flow-control and chamber sizing machines
- Automakers use FCM processes to increase production and sales of large vehicles

- Extrude Hone's industry increases output
- Automobile industry increases output and keeps prices constant.

- U.S. gross domestic product increases
- High-wage manufacturing jobs increase
- Average wages and personal income increase, increasing consumption (and production) of all goods and services.
- Government spending and revenues increase

- Aluminum casters increase production of manifolds and cylinder heads in response to automakers' new production

- Aluminum casting industry increases output

**Figure 16. Qualitative Summary of Firm, Industry, and Macroeconomic Impacts**

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[69] AAMA, *Motor Vehicle Facts and Figures 1997*, p. 56.

[70] Based on discussion with Larry Rhoades of Extrude Hone on April 3, 1998.

ATP impacts firms by cost sharing the development of the FCM processes. These firms then produce the technologies, implement them on the automobile-engine production floor, and increase production and sales. Extrude Hone Corporation produces the new machines and sells them to the aluminum casters, who make the FCM machines part of their manifold and cylinder head finishing processes. The new production by automakers, Extrude Hone, and the aluminum casters create new output for their industries (SIC 3711, SIC 3541, and SIC 3365, respectively). These industries then impact the general U.S. macroeconomy by creating jobs, income, and consumption. ATP and the Flow-Control Machining Project also affect the U.S. economy directly by changing government spending (on the program) and tax revenues (the difference between program costs and increased taxes generated by the economic impacts). (The dotted line across the top of Figure 16 indicates government spending for the ATP Flow-Control Machining Project.) The next two sections give more complete definitions of the assumed near-term and longer-term implementation scenarios, and make quantitative estimates of their impacts.

# 5. Economic Impacts of Near-Term Implementation in the Automobile Industry

Given that the FCM processes are successfully developed and broadly implemented, they will impact (1) Ford, GM, Extrude Hone, and the aluminum casters that make intake manifolds and cylinder heads; (2) the industries in which these firms operate; and (3) the U.S. macroeconomy. This chapter sequentially describes the potential economic impacts on these three of the most-likely, near-term implementation of the processes. Chapter 6 describes the impacts of a longer-term implementation of the processes.

The rate of FCM-process implementation depends on both automaker production needs and the maximum possible adoption rate of the process technologies. The rate and level of implementation achievable can be estimated from historical adoption rates of other fuel-efficiency enhancing technologies, examples of which are shown in Figure 17.[71]

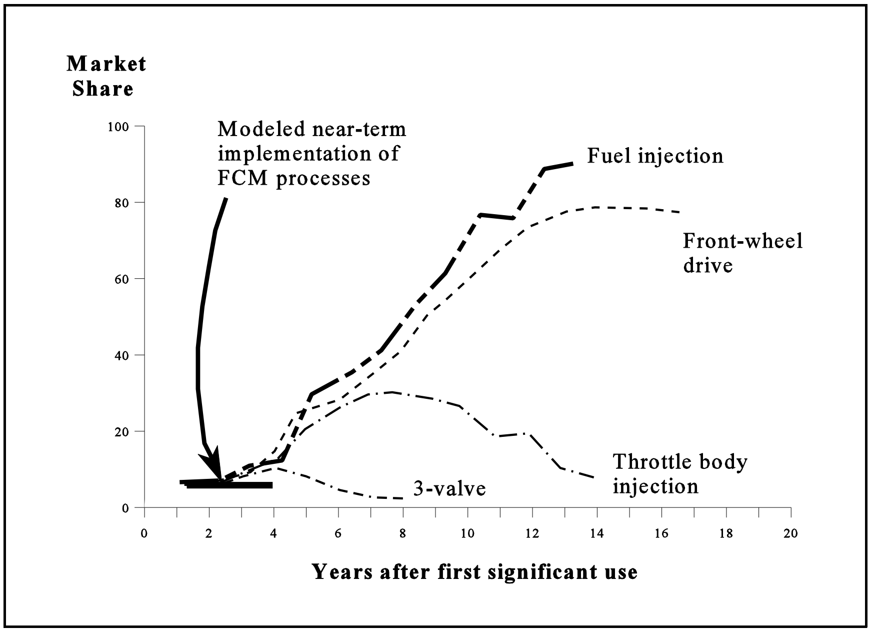

**Figure 17. Historical Adoption Rates of Technologies that Enhance Fuel Efficiency**

These fuel-efficiency technologies have been implemented to varying degrees. Fuel injection and front-wheel drive, both following somewhat S-shaped curves,[72] have achieved majority shares of the market.

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[71] Murrell, Hellman, and Heavenrich, “Light-Duty Automotive Technology and Fuel Economy Trends Through 1993,” p. 14, Figure 12.

[72] Studies of the diffusion process show that adoption can be characterized well by an ogive curve such as the cumulative logistic. See W. Baldwin and J. Scott, *Market Structure and Technological Change* (Chur: Harwood, 1987), pp. 128-144; and C. Thirtle and V. Ruttan, *The Role of Demand and Supply in the Generation and Diffusion of Technical Change* (Chur: Harwood, 1987), pp. 77-124.

Three-valve engines and throttle body injection, on the other hand, reached 10% of the market before diminishing in use. Each of the displayed technologies, however, has a similar initial five-year period of implementation. We assume the FCM processes will at least achieve the five-year implementation rate common to all of the displayed technologies. We model the near-term, five-year implementation as Ford and GM each applying the FCM processes to a single line of their vehicles. The following sections describe this implementation and its impacts. Based on the experience of these other fuel efficiency technologies, the FCM processes may go on to achieve majority market share thereafter, or may diminish in use.

## 5.1 Firm Impacts

**Use of FCM Processes by Automakers**

If Ford and GM each use the FCM processes on a portion of their existing line of light trucks, and the processes increase fuel economy by six percent, Ford and GM can produce and sell more of these vehicles and still satisfy CAFE fleet fuel-economy requirements. The CAFE formula uses a harmonic mean, in which low-fuel-economy vehicles are more heavily "penalized" than they would be in, say, an arithmetic mean. Given an existing portion of production to which the FCM processes are applied, we can determine the maximum additional production which will allow an automaker to still satisfy its CAFE requirement.

**CAFE Fuel Economy Formula**

Ford and GM each produce a fleet of light trucks whose CAFE fuel economy must be greater than or equal to the required level. The CAFE formula for determining compliance of an automaker's fleet is

$$m_{CAFE} \leq \frac{\sum_{i=1}^{I} N_i}{\sum_{i=1}^{I} \frac{N_i}{m_i}}, \qquad \textbf{(1)}$$

where $m_{CAFE}$ is the required minimum fuel economy, $I$ is the number of CAFE vehicle classes, $N_i$ is the number of class-$i$ vehicles sold, and $m_i$ is the kilometers-per-liter (miles-per-gallon) fuel economy of class $i$. The light-truck $m_{CAFE}$ is 8.8 kilometers per liter (20.7 miles per gallon) and the passenger-car $m_{CAFE}$ is 11.7 kilometers per liter (27.5 mpg). To illustrate how the formula is used, Table 1 shows the sales and average fuel economy of each light-truck class in 1996 (in both kilometers per liter [kpl] and miles per gallon [mpg]), along with the computed CAFE fuel economy for the entire group.[73]

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[73] U.S. Department of Transportation, *National Transportation Statistics 1998*, Table 1-33.

## Table 1. Sales and Average Fuel Economy of Light Trucks, by Class: 1996

| Class | $N_i$ (1000s) | Share (%) | $m_i$ (kpl) | $m_i$ (mpg) |
|---|---|---|---|---|
| Small pickup | 391 | 6.3% | 11.2 | 26.3 |
| Large pickup | 2,202 | 35.4% | 8.1 | 19.0 |
| Small van | 1,230 | 19.8% | 9.7 | 22.7 |
| Large van | 370 | 6.0% | 7.3 | 17.2 |
| Small utility | 1,379 | 22.2% | 9.1 | 21.3 |
| Large Utility | 641 | 10.3% | 7.7 | 18.1 |
| **All classes** | **6,213** | **100.0%** | **8.6** | **20.26** |

The fuel economy for "All classes" listed at the bottom of the table is computed as

$$\frac{(391+2202+1230+370+1379+641)}{\left(\frac{391}{11.2}+\frac{2202}{8.1}+\frac{1230}{9.7}+\frac{370}{7.3}+\frac{1379}{9.1}+\frac{641}{7.7}\right)} = 8.6 \text{ kilometers per liter (kpl)}\,, \qquad \textbf{(2)}$$

which indicates that the CAFE fuel economy of all light trucks sold in the United States in 1996 was actually *below* the required level of 8.8 kpl (20.7 mpg).[74]

**Estimating the Additional Sales Allowable from a Six Percent Increase in Fuel Efficiency**
Automakers will likely first apply the FCM processes on light trucks since per-unit profits are greater than that for passenger cars.[75] Assuming that the most profitable light trucks have fuel efficiencies below the required level of 8.8 kpl (20.7 mpg),[76] the automaker can use the FCM processes to increase fuel efficiency, thereby increasing allowable sales. We model Ford and GM each increasing the production of their profitable large utility vehicles (the "Large Utility Vehicle" [LUV] class in Table 1). The allowable change is estimated by using the CAFE formula and the 1996 distribution of light-truck

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[74] Each automaker, however, may still be individually satisfying the 20.7 mpg requirement. Indeed, both domestic automakers are currently producing fleets of light trucks whose fuel economy meets the federally required minimum level.

[75] See footnote 54 for evidence that large vehicles have higher profits than small vehicles.

[76] This is required so that automakers have a profit-maximizing incentive to use the FCM processes. If the most profitable light truck already gets more than 8.8 kpl (20.7 mpg), then increasing its sales, with or without the FCM processes, will improve the CAFE fleet fuel economy; in this case, the FCM processes are not needed.

production in Table 1 as the current truck distribution of a "representative automaker" who wants to use the FCM processes to change its distribution of sales.[77]

Some additional variables are needed to calculate additional allowable sales. Since our representative automaker's fleet is assumed to currently be exactly at the CAFE required level of fuel economy,[78] the automaker will have to implement FCM processes on part of the *existing* fleet in order to increase production. We denote the LUV class of light trucks as the $k$th class, and let $\gamma$ be the fraction of the $k$th class that gets the FCM processes and $\beta$ be the increase in fuel efficiency achieved with the FCM processes. Assuming (conservatively) that total consumer demand for light-trucks is fixed, new LUV sales must then come at the expense of reduced sales in the other light-truck classes (Table 1).[79] If these reductions occur as a fixed proportion $\alpha$ of each non-LUV light-truck class, then the term $\sum_{i \neq k} \alpha N_i$ represents the purchases that will shift from non-LUV to LUV vehicles. Finally, we denote $\bar{N} = \sum_{i=1}^{I} N_i$ as the total number of light trucks produced and $n_i = N_i / \bar{N}$ as the production share of each class.

After substituting these variables into equation 1, the automaker's problem can be formulated as follows. Given the fraction $\gamma$ of existing production the automaker is willing to apply the FCM processes to, it must choose the shifted-production share $\sum_{i \neq k} \alpha N_i$ such that the average kilometers per liter (miles per gallon) of its fleet is not less than the CAFE level, that is, it must choose $\alpha$ such that

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[77] Ford and GM in actuality have markedly different compositions of light truck production, but we are discussing the FCM-technology-based production increase as a generic decision to be made by firms in general.

[78] Note again that, while the actual requirement of each automaker's light-truck fleet is 8.8 kpl (20.7 mpg), to simplify construction we are modeling the representative automaker's decision process as being subject to a constraint of 8.6 kpl (20.26 mpg).

[79] This is a conservative assumption since light-truck demand is increasing and often comes at the expense of new passenger-car sales. The sum of vehicle car demand and truck demand, however, is relatively fixed; see AAMA, *Motor Vehicle Facts & Figures 1997*, p. 23.

$$m_{CAFE} \le \frac{N_k + \sum_{i \ne k} \alpha N_i + \sum_{i \ne k} (1 - \alpha) N_i}{(1 - \gamma)\frac{N_k}{m_k} + \frac{\gamma N_k + \sum_{i \ne k} \alpha N_i}{(1 + \beta) m_k} + \sum_{i \ne k} \frac{(1 - \alpha) N_i}{m_i}}$$

$$= \left[ \frac{\bar{N}}{(1 - \gamma)\frac{N_k}{m_k} + \frac{\gamma N_k + \sum_{i \ne k} \alpha N_i}{(1 + \beta) m_k} + (1 - \alpha) \sum_{i \ne k} \frac{N_i}{m_i}} \right] \tag{3}$$

$$= \left[ (1 - \gamma)\frac{n_k}{m_k} + \frac{\gamma n_k + \alpha \sum_{i \ne k} n_i}{(1 + \beta) m_k} + (1 - \alpha) \sum_{i \ne k} \frac{n_i}{m_i} \right]^{-1} .$$

Solving this equation for α,

$$\alpha = \left[ \frac{\frac{1}{m_{CAFE}} - \frac{n_k}{m_k}\left(1 - \frac{\gamma\beta}{(1 + \beta)}\right) - \sum_{i \ne k} \frac{n_i}{m_i}}{\frac{(1 - n_k)}{(1 + \beta)\, m_k} - \sum_{i \ne k} \frac{n_i}{m_i}} \right] . \tag{4}$$

Assuming that the automaker uses the FCM processes on 130,000 LUVs in its existing production (representing Ford and GM lines of 65,000 units each), the fraction $\gamma = \left(\frac{130{,}000}{641{,}000}\right) = 0.20$. The largest increase in production of LUVs which still satisfies CAFE, expressed as the shift in consumer purchases $\sum_{i \ne k} \alpha N_i$, is therefore

$$\sum_{i \neq k} \alpha N_i = \sum_{i \neq k} \alpha \bar{N} n_i$$

$$= \alpha \bar{N} \sum_{i \neq k} n_i$$

$$= \alpha \bar{N} (1 - n_k)$$

$$= \left[ \frac{\dfrac{1}{m_{CAFE}} - \dfrac{n_k}{m_k} \left( 1 - \dfrac{\gamma\beta}{(1 + \beta)} \right) - \sum_{i \neq k} \dfrac{n_i}{m_i}}{\dfrac{(1 - n_k)}{(1 + \beta)\, m_k} - \sum_{i \neq k} \dfrac{n_i}{m_i}} \right] \bar{N}\ (1 - n_k) \qquad \textbf{(5)}$$

$$= \left[ \frac{\dfrac{1}{8.6} - \dfrac{.103}{7.7} \left( 1 - \dfrac{(.20)(.06)}{1.06} \right) - 0.04365}{\dfrac{(1 - .103)}{(1.06)(7.7)} - 0.04365} \right] (6{,}213{,}000)\ (1 - .103)$$

$$= 116{,}000 \text{ additional LUVs.}$$

Said another way, by using the FCM processes to increase the fuel economy of 130,000 LUVs by six percent, the automaker can produce and sell 116,000 more LUVs (with the FCM processes) and still satisfy CAFE requirements.

As compared with other light trucks and passenger cars, LUVs have greater carrying capacity, protect their occupants better in collisions, drive better in inclement weather, and have larger towing capacity. These LUVs are in high demand, as seen by their very high profit margins. Since their sticker price is estimated to be $5,370 more than the weighted average price of all other light-truck classes,[80] combined annual revenues of the two automakers increase by (116,000) × ($5,370) = $623 million.

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[80] The figure of $5,370 is computed as the difference between the price of the GMC Suburban and the sales-weighted average price of all other light trucks. Source of sales and price data: Automotive News, *Market Data Book 1997* (Detroit, MI: Crane Communications, 1997), pp. 42-56.

**Aluminum Casters**

The benefits to aluminum casters of the FCM processes are both an increase in the production of manifolds and cylinder heads (by 116,000 units) and an increase in unit prices. As discussed in Section 4.5, automakers are willing to pay $60 per LUV engine for FCM processing. Assuming that Extrude Hone supplies aluminum casters with AFCM and NCCS process machines at a cost of $6 per engine, the unit production costs for aluminum casters will be between $6 - $60 per engine.[81]

**Extrude Hone Corporation**

Extrude Hone Corporation benefits from the production and sale of AFCM and NCCS process machines to aluminum casters at an estimated price of $6.60 per engine processed. Implementation of the FCM processes would increase Extrude Hone's revenues in the third year by an estimated (246,000 engines × $6.60 per engine) = $1.6 million. Using the industry cost structure for Extrude Hone's primary SIC industry (SIC 3541), production costs will be approximately (0.79) × ($6 per engine) = $4.74 per engine.

Table 2 summarizes these impacts of implementation on automakers, aluminum casters, and Extrude Hone Corporation.

## Table 2. Impact on Firms of Near-Term, Five-Year Implementation Path

| Change caused by FCM processes | Effect on Firm(s) | Annual Amount |
|---|---|---|
| **Automakers** | | |
| Purchase FCM-process manifolds and cylinder heads | Increases cost per engine | $60 per engine |
| Increase large utility vehicles fuel efficiency by 6 percent | Increases allowable sales of large utility vehicles | 116,000 large-utility vehicles |
| **Aluminum Casters** | | |
| Implement AFM and NCCS processes | Increases production costs | $6.60 per engine |
| Produce more manifolds and cylinder heads | Increases sales of manifolds and heads | manifolds and heads for 246,000 engines |
| Increase price of manifolds and heads | Increase unit prices | $60 per engine |
| **Extrude Hone Corporation** | | |
| Produce AFM and NCCS machines and consumables | Increases sales | Machines for 246,000 engines/year at cost of $6.60 per engine |

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[81] This is supported by the fact that the capital fraction of output for the aluminum casting industry is 11 percent, suggesting that an allowable capital cost for producing $60 of additional casting output would be $60 × .11 = $6.60. Source of capital data: REMI, *REMI Policy Insight* (software), (Amherst, MA: Regional Economic Modeling, Inc., 1998).

## 5.2 Industry Impacts

The changes in sales and prices for automakers, aluminum casters, and Extrude Hone Corporation impact quantities and prices in their industries. These industry changes can be expressed in terms of changes in supply and demand, as shown in Figures 18 and 19.

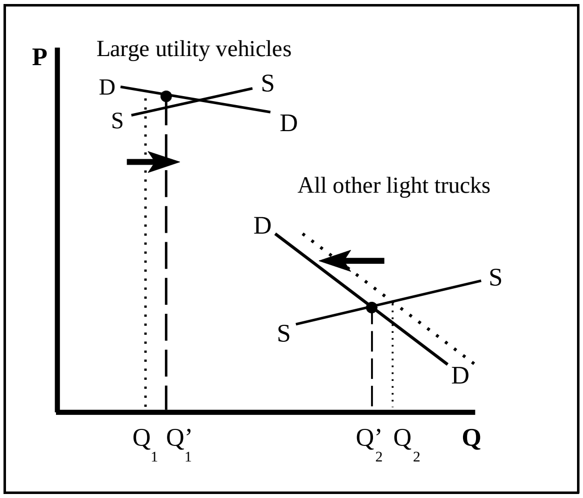
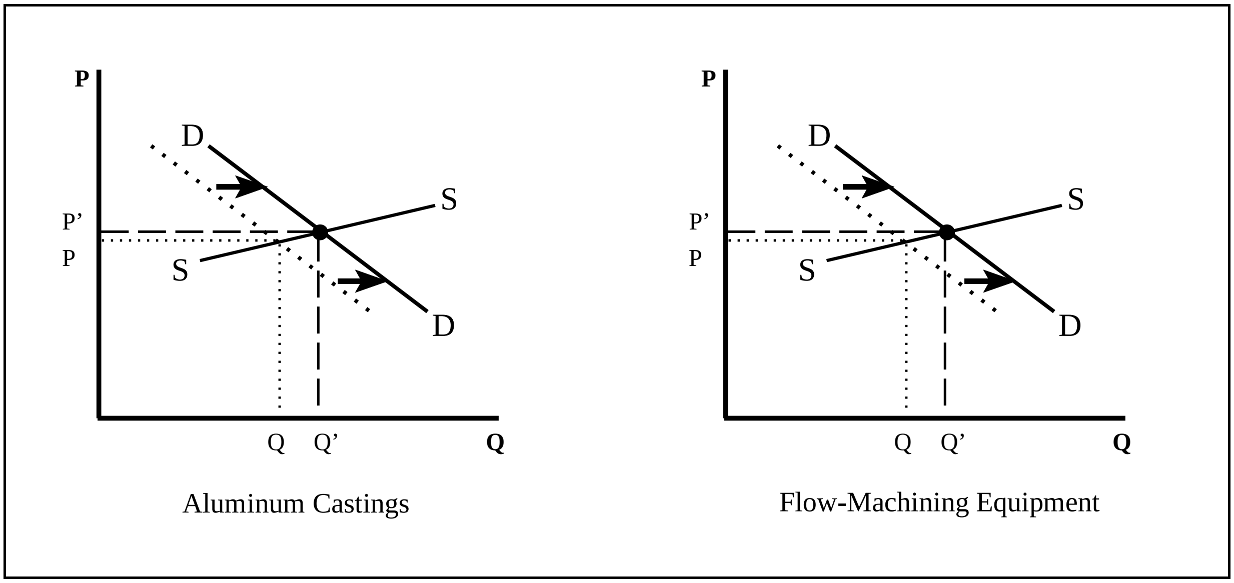


**Figure 18. Change in Supply and Demand for Light Trucks**



Aluminum Castings

Flow-Machining Equipment

**Figure 19. Change in Supply and Demand for Aluminum Castings and Flow-Machining Equipment**

In Figure 18, there is current excess demand for large utility vehicles, created by the CAFE fuel economy requirements; the market for "all other light trucks," on the other hand, is in equilibrium. As the arrows indicate, the FCM processes allow automakers to increase the sale of the large utility vehicles, shifting the market quantity $Q_1$ to $Q_1$'. Under the assumption that total light-truck demand remains unchanged, demand for "all other light trucks" shifts to the left and the net change in total light truck demand is zero. The average market price for light trucks, however, increases as sales shift from the less expensive "all other light trucks" market to the higher priced large utility vehicles market. In the aluminum castings and flow-machining equipment markets (Figure 19), implementation creates an increase in the demand for goods, shifting the demand curves to the right. In both cases, the equilibrium output Q increases to Q', with some increase in the market price.

These changes in market conditions change market prices and quantities, summarized in Table 3. These market quantities are use in the REMI analysis of macroeconomic impacts.

**Table 3. Impact on Industries of Near-Term, Five-Year Implementation Path**

| **Industry (Four-Digit SIC)** | **Change in Industry Performance** | **Change in Annual Sales Amount ($)** |
|---|---|---|
| Automotive<br>(3711: Motor Vehicles) | Increase in sales<br>No increase in prices | $623 million |
| Aluminum Casting<br>(3365: Non-Ferrous Foundries) | Increase in sales<br>Marginal increase in prices | $13.0 million |
| Extrude Hone<br>(3541: Metalworking Machinery) | Increase in sales<br>Marginal increase in prices | $1.6 million |

## 5.3 Macroeconomic Impacts on the U.S. Economy

These changes in industry supply and demand impact the rest of the U.S. macroeconomy. Additional automobile production increases parts and subassembly production, increases manufacturing employment and wages, and increases personal income. More income increases consumer spending on goods and services. To estimate these macroeconomic impacts, a REMI simulation was run in which the industry changes were modeled over the five-year 2000-2004 implementation period. Since, as described in Section 3.4, in the first 3-4 years individual markets can be in disequilibrium and national employment can deviate from its long-run, natural rate, we use REMI's estimates in the fifth year, 2004, as our measures of macroeconomic impact.

Table 4 lists selected results from the simulation. The first column of numbers lists the levels in the baseline forecast (without the FCM processes), while the second column lists levels in the alternative forecast (with the FCM processes). The "Impact (Difference)" column lists the difference between the forecast and baseline levels, i.e., the macroeconomic impact of the FCM processes.

## Table 4. Annual Impact on U.S. Macroeconomy of Near-Term, Five-Year Implementation Path: Year 2004

| Item | "Without FCM Processes" Forecast | "With FCM Processes" Forecast | Impact (Difference) |
|---|---|---|---|
| **Gross Domestic Product ($ millions)** | $9,353,745 | $9,353,887 | **$142** |
| Manufacturing | $1,926,180 | $1,926,407 | **$227** |
| Durables | $1,102,410 | $1,102,623 | **$213** |
| Non-durables | $823,770 | $823,784 | **$14** |
| Non-manufacturing | $7,427,565 | $7,427,480 | **($85)** |
| **Employment (#)** | 138,775,300 | 138,775,300 | **0** |
| Manufacturing | 17,823,188 | 17,824,985 | **1,797** |
| Durables | 9,873,558 | 9,875,191 | **1,633** |
| Non-durables | 7,949,630 | 7,949,794 | **164** |
| Non-manufacturing | 120,952,112 | 120,950,315 | **(1,797)** |
| **Personal Income ($ millions)** | $8,661,460 | $8,661,656 | **$196** |
| **Income Tax Revenues ($ million)** | $1,260,978 | $1,261,011 | **$34** |

Note: Dollar concepts are in 1998 constant dollars.

By the year 2004, annual GDP increases by $142 million (constant 1998 dollars), largely in durables manufacturing ($227 million). Non-manufacturing output declines by $85 million, as consumers switch spending from these goods and services to automobiles. The new automobile production initially raises the level of national employment, but as indicated by the "Employment (#)" line, in a full-employment economy it is assumed that the Federal Reserve actions to control employment and inflation bring the employment back down to its long-run trend level.[82] Still, there are employment effects: workers move from non-automotive to automotive industries, durables manufacturing employment increases by 1,797 workers (occurring predominately in SIC 371, Motor Vehicles), and aggregate non-manufacturing employment drops by the same amount. As a result of this move to high-wage sectors, personal income—the sum of wage and salary disbursements, proprietors' income, and other labor income—increases by $196 million annually and taxes paid on new income are $34 million per year.

What appears to be a peculiar result—that increases in personal income (or returns to labor: $196 million) exceed the increases in GDP (total returns to factors: $142 million)—can be readily explained with the aid of Figure 20.

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[82] The long-run trend level of employment, however, can increase as population levels increase, and job gains in one area of the economy can offset job losses in another area.

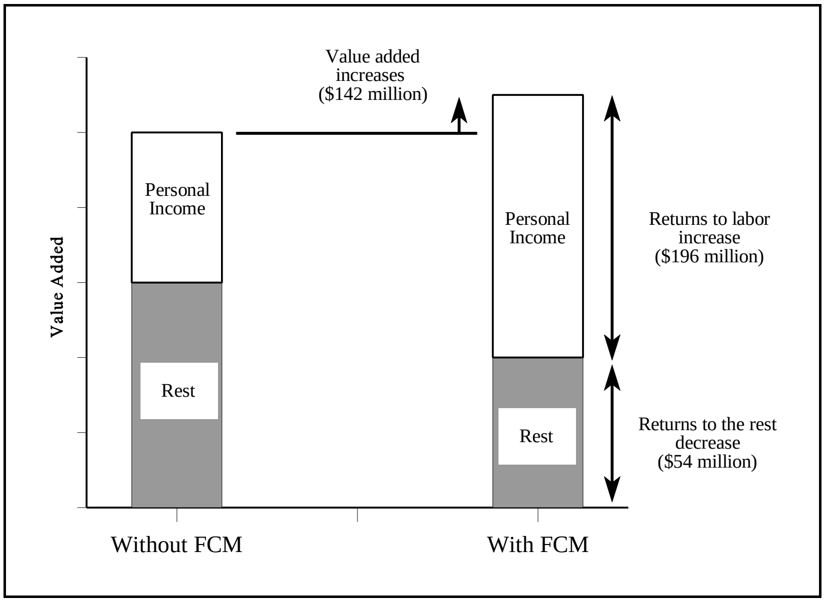

**Figure 20. The Impact of FCM Processes on Value Added and Returns to Labor and Capital**

As consumers shift purchases from non-automotive products to automobiles, industry production shifts from lower-wage, non-automotive sectors to higher-wage automotive sectors. While all value-added created is returned to the economy in the form of payments to labor and capital, the particular combination of industries affected cause aggregate returns to labor to increase and returns to capital to decrease.

The economy's dynamic response, a result of both disequilibrium in markets and employment actions by the Federal Reserve, can be characterized by the changes in demand for goods, industry output, and employment and income. The increase in demand for automobiles and its indirect effect on the rest of demand is illustrated in Table 5. The table shows how consumers switch their purchases toward automobiles and how the new output alters over time the structure of demand.

In the year 2000, the first year that the FCM processes are assumed to be implemented, GDP increases by $913 million, largely due to both the increased consumption of Autos and Parts ($626 million) and increased investment ($308 million). By 2004, however, this distribution of demand changes. The Federal Reserve, in response to employment being above the long-run trend level, is assumed to increase interest rates, which causes domestic investment to decline. As consumers continue to spend more on Autos and Parts ($594 million), they spend less on other categories such as Food and Beverages ($31 million) and Housing ($27 million). Total Fixed Investment—the sum of residential, non-residential, and producers durable investment—declines by $158 million.

## Table 5. Change in Output, by Demand Categories: 2000-2004

| **Item** | **2000** | **2001** | **2002** | **2003** | **2004** |
|---|---|---|---|---|---|
| **TOTAL GDP (C+I+G+X-M)** | **$913** | **$821** | **$454** | **$144** | **$142** |
| | | | | | |
| **TOTAL CONSUMPTION (C)** | **$910** | **$844** | **$614** | **$416** | **$409** |
| AUTOS AND PARTS | $626 | $621 | $607 | $594 | $594 |
| FURN & HSEHLD EQUATION. | $30 | $23 | $1 | ($17) | ($18) |
| OTHER DURABLES | $11 | $9 | $0 | ($6) | ($7) |
| FOOD & BEVERAGES | $68 | $54 | $8 | ($30) | ($31) |
| CLOTHING & SHOES | $26 | $20 | $1 | ($14) | ($14) |
| GASOLINE & OIL | $10 | $8 | $0 | ($7) | ($7) |
| FUEL OIL & COAL | $1 | $1 | $0 | ($1) | ($1) |
| OTHER NONDURABLES | $6 | $5 | $0 | ($3) | ($3) |
| HOUSING | $12 | $10 | ($9) | ($26) | ($27) |
| HSEHLD OPERATION | $27 | $22 | $0 | ($19) | ($20) |
| TRANSPORTATION | $17 | $13 | $1 | ($9) | ($10) |
| HEALTH SERVICES | $4 | $3 | $1 | $0 | $0 |
| OTHER SERVICES | $73 | $57 | $3 | ($45) | ($46) |
| | | | | | |
| **TOTAL FIXED INVEST (I)** | **$308** | **$259** | **$28** | **($164)** | **($158)** |
| **TOTAL GOVERNMENT (G)** | **$3** | **$3** | **$0** | **$0** | **$0** |
| **TOTAL EXPORTS (X)** | **$0** | **$0** | **($18)** | **($37)** | **($41)** |
| **TOTAL IMPORTS (M)** | **$307** | **$284** | **$170** | **$70** | **$66** |

All values in 1998 constant dollars

To sum up, the increase in domestic automobile consumption initially increases demand in all categories except exports, but as the Federal Reserve responds, the higher cost of capital puts downward pressure on investment, income, and purchases in non-automotive sectors, ultimately changing the composition of demand.

Industrial output also responds dynamically to the new spending patterns. Table 6 lists the 2000-2004 change in output, by two-digit SIC manufacturing industry.

## Table 6. Change in Industry Output, by SIC : 2000-2004

| Industry | SIC | 2000 | 2001 | 2002 | 2003 | 2004 |
|---|---|---|---|---|---|---|
| **Durable Goods ($ millions)** | | | | | | |
| LUMBER | 24 | $15.1 | $12.3 | $3.3 | ($3.9) | ($3.5) |
| FURNITURE | 25 | $12.0 | $10.7 | $5.2 | $0.7 | $0.8 |
| STONE,CLAY,ETC. | 32 | $14.3 | $12.5 | $6.4 | $1.5 | $1.5 |
| **PRIMARY METALS** | **33** | **$61.1** | **$57.4** | **$44.8** | **$34.3** | **$33.8** |
| **FABRICATED METALS** | **34** | **$68.8** | **$63.9** | **$48.3** | **$35.3** | **$34.4** |
| MACH / COMPUTERS | 35 | $55.4 | $47.2 | $14.3 | ($12.6) | ($13.6) |
| ELECT. EQUIPMENT | 36 | $46.0 | $41.5 | $18.3 | ($1.8) | ($2.1) |
| **MOTOR VEH.** | **371** | **$716.8** | **$710.9** | **$684.7** | **$661.5** | **$660.8** |
| REST TRANS EQUI | R37 | $10.6 | $9.1 | $0.8 | ($6.1) | ($6.2) |
| INSTRUMENTS | 38 | $22.5 | $19.9 | $5.7 | ($6.3) | ($6.2) |
| MISC. MANUF. | 39 | $4.1 | $3.4 | $0.5 | ($1.9) | ($1.9) |
| **Non-durable Goods ($ millions)** | | | | | | |
| FOOD | 20 | $39.9 | $32.0 | $5.6 | ($16.8) | ($17.4) |
| TOBACCO MANUF | 21 | $0.4 | $0.3 | $0.0 | ($0.3) | ($0.3) |
| TEXTILES | 22 | $11.8 | $10.4 | $5.2 | $0.8 | $0.7 |
| APPAREL | 23 | $13.0 | $11.7 | $6.9 | $2.8 | $2.8 |
| PAPER | 26 | $16.6 | $14.6 | $7.2 | $0.8 | $0.7 |
| PRINTING | 27 | $19.3 | $16.6 | $7.4 | ($0.5) | ($0.6) |
| CHEMICALS | 28 | $37.2 | $34.2 | $20.7 | $9.0 | $8.5 |
| PETRO PROD | 29 | $18.3 | $15.6 | $4.4 | ($5.4) | ($5.6) |
| RUBBER | 30 | $48.1 | $46.5 | $37.8 | $30.1 | $30.3 |
| LEATHER | 31 | $0.6 | $0.4 | $0.0 | ($0.4) | ($0.4) |

All values are expressed in 1998 constant dollars

In the year 2000, output in all sectors rises in response to new motor vehicles production and consumption. By the year 2004, after the assumed Federal Reserve-based interest rate increase, motor vehicle output has maintained relatively the same increase ($660.8 million, shown in bold). The production levels of Primary Metals and Fabricated Metals also increase in support of the automobile production (shown in bold), but most other sectors experience declines.

Sectoral employment and personal income respond dynamically to the output changes, and since automobile-related sectors have high-wage jobs, the transfer of workers to these sectors increases aggregate personal income. As illustrated in Figure 21, automobile production increases employment mostly in high-wage durable-goods sectors, thereby increasing aggregate personal income.

When aggregate employment returns to its long-run trend, employment has shifted from non-manufacturing sectors to durables and non-durables sectors. Since durables sectors have the highest average annual wages, aggregate personal income increases.

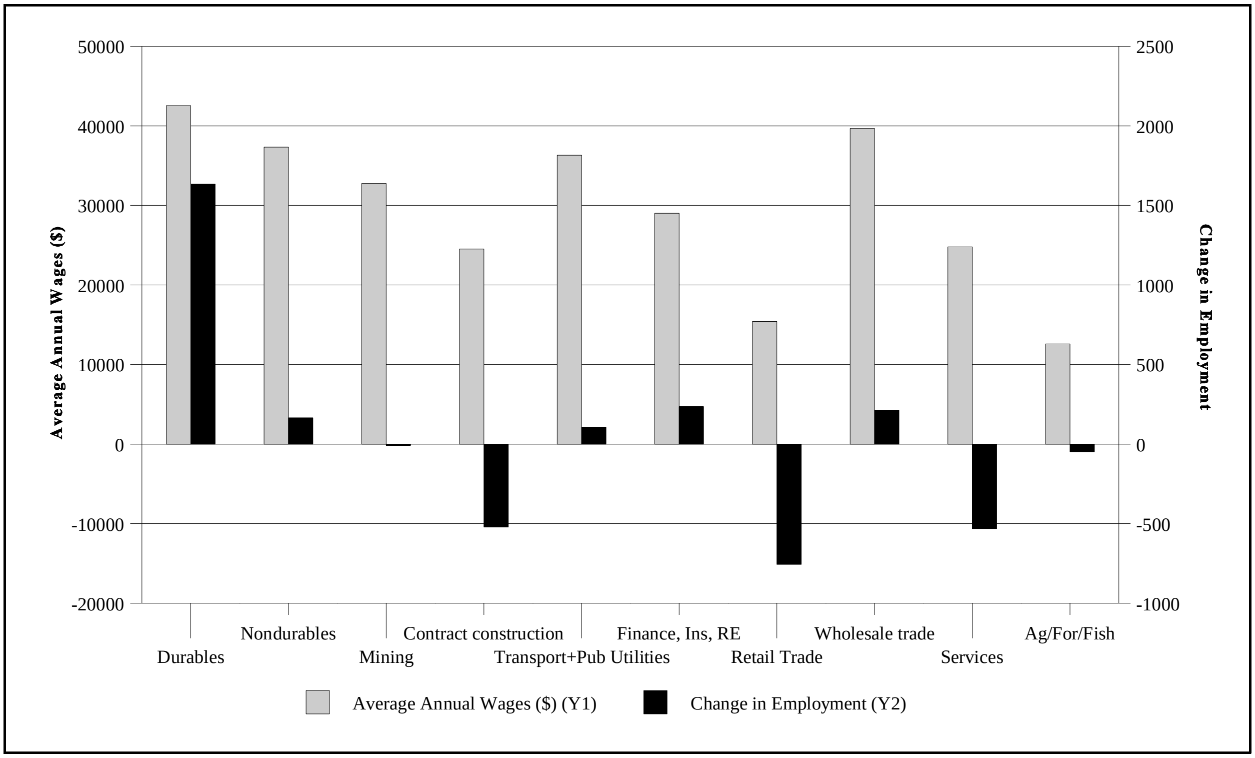

**Figure 21. Average Annual Wages and Change in Employment, by Sector: Year 2004**

## 5.4 Sensitivity Analysis

These impact results depend on the estimates and assumptions made about several key parameters. Variations in these parameter values will affect the firm, industry, and macroeconomic impacts. The implications of such variations are considered here.

**Technical Success of FCM Processes**
If the realized fuel efficiency increase turns out to be less than six percent, then the potential additional sales and associated economic impacts would be less. For example, if the achieved increase in fuel economy were only five percent, then additional LUV production would be 85,000 vehicles. Holding everything else constant, the macroeconomic impacts reported would also decrease. The economic impacts are therefore quite sensitive to the realized gain in fuel efficiency.

**Gasoline Prices**
Buyers' purchase decisions are sensitive to the price of gasoline at the pump. The real price of gasoline is low today relative to thirty years ago, making it a minor factor in the purchase decision. If the price of gasoline were to increase, say due to a shortage of oil reserves, buyers would likely revert back to buying smaller cars with higher fuel efficiency, which are less profitable for automakers. Automakers would then have an increased incentive to use the FCM processes on more light trucks. To the extent that they can offset the increased fuel prices with increased fuel efficiency, automakers could retain at least a portion of the (profitable) light truck sales.

### Consumer Preferences

Consumers are increasingly demanding larger vehicles. If this demand were to stop or revert back to smaller cars, automakers would have less incentive to implement new fuel-efficiency technologies, unless the technologies significantly reduce production costs. To the extent that the FCM processes are cost effective alternatives to currently used fuel-efficiency enhancing technologies (net of implementation costs), automakers would still likely adopt the new processes.

### Industry Structure

Our modeling assumption is that the structure of the light-truck market stays in its current form, where demand is high and domestic producers have the majority of sales. If, however, Ford and GM's share were to erode significantly, they would be forced to compete vigorously on price and on non-price factors such as performance (e.g., horsepower). FCM process implementation, then, would hinge on its ability to reduce production costs (and thus car prices) and to increase performance.

On the other hand, if Ford and GM were to gain more share of the light-truck market, FCM-process implementation would be less likely. With increased market share comes market power and the ability to influence car price, even if key product characteristics—such as performance, options, and quality—decline. Unilaterally developing new technologies to enhance performance or reduce costs is not required.

### Who Implements the Technology and Where

Not considered in the study is the implementation of the FCM processes by foreign firms selling automobiles in the United States, and the export by GM and Ford of FCM-process vehicles. First, foreign automakers seem less likely to use the FCM processes in the cars or trucks they sell in the U.S., since their fleets of both types of vehicles currently exceed the CAFE required fuel economies. If a foreign firm were to initiate implementation, Ford and GM would likely implement quickly: research suggests that technology is likely to be imitated faster in highly concentrated industries such as the automobile industry than in less-concentrated industries.[83]

Ford and GM could use the FCM processes in exported vehicles but, again, this not estimated to be sizeable. Domestic light trucks currently have poor fuel economies which make them prohibitive in most foreign car markets, marginal increases are not likely to significantly induce demand. Passenger-car exports are not likely to be affected by fuel efficiency increases since world supply far exceeds demand and competing foreign cars already have higher fuel efficiencies.

### Government Fuel Efficiency Requirements

The current CAFE fuel economy requirements are 11.7 kilometers per liter (27.5 miles per gallon) for passenger-car fleets and 8.8 kilometers per liter (20.7 miles per gallon) for light-truck fleets. Because automobile use and total emissions are increasing, the government is not likely to repeal these requirements. In fact, currently there are efforts to make the light-truck emissions requirements as stringent as those for passenger cars. This would put further pressure on light-truck producers to implement fuel-efficiency enhancing technologies such as the FCM processes.

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[83] See W. Baldwin and J. Scott, *Market Structure and Technological Change* (Chur: Harwood, 1987), pp. 128-144; and C. Thirtle and V. Ruttan, *The Role of Demand and Supply in the Generation and Diffusion of Technical Change* (Chur: Harwood, 1987), pp. 77-124.

## Competing Fuel-Efficiency Technologies

Other fuel-efficiency technologies are being developed, tested, and implemented in domestic vehicles. Variable timing ignition, for example, once used only in luxury cars, is now being implemented in some minivans.  A key assumption of the study is that there is not another technology that produces as much increase in fuel efficiency at as low a cost. If there were, it could supplant use of the FCM processes and thereby decrease its likelihood of implementation and impact.

# 6. Economic Impacts of Longer-Term Implementation in the Automobile Industry

## 6.1 Implementation to 80 Percent of the Light-Truck Market

The previous chapter takes the near-term, conservative view that the FCM processes would be adopted at an introductory level and maintained for five years. A longer-term, broader implementation of the FCM processes could also occur, likely at the historical adoption rate of fuel injection technologies, which were implemented to 80 percent of the market (Figure 22). If the FCM processes are implemented just to light trucks at this rate, automakers would be able to produce substantially more LUV-class light trucks while still satisfying CAFE requirements.

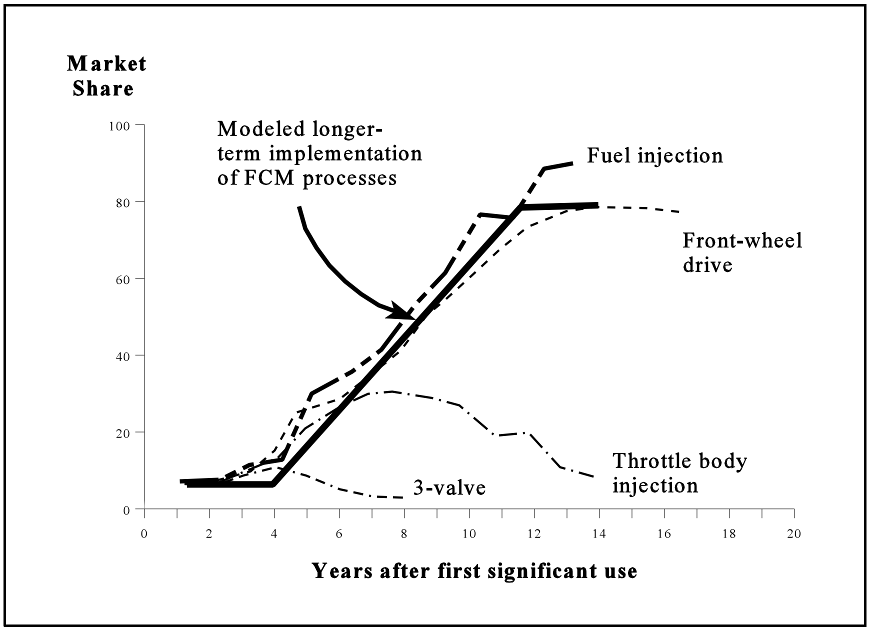

**Figure 22. Historical Adoption Rates of Technologies that Enhance Fuel Efficiency, and Longer-Term Implementation Rate**

Equation 3 is used again to estimate how much the production of LUVs can increase if the FCM processes are applied to 80 percent of light trucks. As in the near-term five-year implementation, we assume that total demand for light-trucks is fixed and that consumer purchases shift between the classes. If $\sigma$ represents the fraction of each class that uses the FCM processes, then total light-truck production can be expressed as the sum of the five values listed in Table 7.

## Table 7. New Distribution of LUV Production

| # | Description | Value |
|---|---|---|
| 1 | Non-LUVs that use the FCM processes and are not displaced by the FCM-process LUVs | $\sum_{i \neq k} \sigma (1-\alpha) N_i$ |
| 2 | Non-LUVs that do not use the FCM processes and are not displaced by new LUV production | $\sum_{i \neq k} (1-\sigma)(1-\alpha) N_i$ |
| 3 | Existing LUVs that use the FCM processes | $\sigma N_k$ |
| 4 | Existing LUVs that do not use the FCM processes | $(1-\sigma) N_k$ |
| 5 | New LUVs that use the FCM processes | $\sum_{i \neq k} \alpha N_i$ |
|  | **Total LUVs** | $\bar{N}$ |

Equation 3 is rewritten as

$$m_{CAFE} \le \frac{\bar{N}}{\sum_{i \neq k} \frac{\sigma (1-\alpha) N_i}{(1+\beta) m_i} + \sum_{i \neq k} \frac{(1-\sigma)(1-\alpha) N_i}{m_i} + \frac{\sigma N_k + \sum_{i \neq k} \alpha N_i}{(1+\beta) m_k} + \frac{(1-\sigma) N_k}{m_k}} . \qquad \textbf{(6)}$$

Following the methodology for the near-term implementation, we use the distribution of light trucks in Table 1 as the fleet of the "representative automaker." Setting $\sigma = 0.80$, and solving equation (6) for $\alpha$, the increase in LUV production made possible by the use of the FCM processes can be expressed as the number of displaced sales of non-LUVs:

$$\alpha \sum_{i \neq k} N_i = \alpha \bar{N} (1 - n_k)$$

$$= \left[ \frac{\frac{1}{m_{CAFE}} - \left(1 - \frac{\sigma\beta}{1+\beta}\right) \sum_{i \neq k} \frac{n_i}{m_i} + \left(1 - \frac{\sigma\beta}{1+\beta}\right) \frac{n_k}{m_k}}{\frac{(1-n_k)}{(1+\beta) m_k} - \left(1 - \frac{\sigma\beta}{1+\beta}\right) \sum_{i \neq k} \frac{n_i}{m_i}} \right] \bar{N} (1 - n_k) \qquad \textbf{(8)}$$

$$= 1.6 \text{ million LUVs.}$$

Therefore, automakers can increase production of LUV-class light trucks by 1.6 million units while satisifying CAFE requirements. If the value of each new LUV-class vehicle is $6,000 more than the average value of all vehicles in all other light-truck classes,[84] industry revenues increase by ($6,000) × (1.6 million large utility vehicles) = $9.6 billion.

## 6.2 Macroeconomic Impacts on the U.S. Economy

As in the near-term implementation case, estimates are made of the total impact of this additional automobile output on the U.S. economy. A 15-year simulation is run in REMI over the 2000-2014 period, in which automobile production is gradually increased to reflect the implementation rate shown in Figure 22. Table 8 lists the estimates of the steady-state annual change on the macroeconomy after 15 years of implementation.

### Table 8. Annual Macroeconomic Impacts of Longer-Term, 15-Year Implementation: Year 2014

| Item | Baseline Forecast | Policy Forecast | Impact (Difference) |
|---|---|---|---|
| **Gross Domestic Product ($ millions)** | **$10,776,624** | **$10,778,501** | **$1,877** |
| Manufacturing | $2,229,751 | $2,234,203 | $4,452 |
| Durables | $1,301,636 | $1,305,932 | $4,297 |
| Non-durables | $928,115 | $928,271 | $156 |
| Non-manufacturing | $8,546,873 | $8,544,298 | $(2,576) |
| **Employment (#)** | 146,511,500 | 146,511,500 | 0 |
| Manufacturing | 16,404,606 | 16,433,203 | 28,597 |
| Durables | 8,770,639 | 8,795,962 | 25,323 |
| Non-durables | 7,633,967 | 7,637,241 | 3,274 |
| Non-manufacturing | 130,106,894 | 130,078,297 | (28,597) |
| **Personal Income ($ millions)** | $14,238,366 | $14,241,645 | $3,279 |
| **Income Tax Revenues ($ million)** | $1,890,022 | $1,890,549 | $527 |

Note: Dollar concepts are in 1998 constant dollars.

The dynamics of the macroeconomic impacts are similar to those of the near-term implementation but occur on a larger scale and over a longer period of time. By the fifteenth year, GDP has increased by $1.9 billion per year, largely due to new durables manufacturing ($4.5 billion). Twenty-nine-thousand new manufacturing jobs have been created, largely causing the $3.3 billion increase in annual personal income. As with the near-term implementation, personal income increases more than GDP does, as production shifts to sectors that, in aggregate, return more to labor factors of production than to capital factors.

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[84] The figure of $6,000 is computed as the difference between the price of LUVs and the sales-weighted average price of all other light trucks. Source of sales and price data: Automotive News, *Market Data Book 1997* (Detroit, MI: Crane Communications, 1997), pp. 42-56.

# 7. Summary and Conclusions

## 7.1 Summary

The Advanced Technology Program at NIST cost shares research in promising but high-risk new technologies with the goal of producing large and broadly diffused economic benefits. The goal of the Flow-Control Machining Project, a joint venture between Extrude Hone Corporation, Ford Motor Company, General Motors, the University of Pittsburgh, and the University of Lincoln at Nebraska, is to develop two advanced, automated, and cost-effective finishing processes that will be applied in the automobile industry as well as in other industries. The technology will allow automakers to produce automobile engines that are more powerful, more fuel efficient, produce less pollution, and cost less to build. It will also allow other, non-automotive industries to produce machines and parts with significantly higher functional precision and performance.

To date, the joint venture partners have achieved significant technical success toward achieving the project goals. The abrasive flow-control machining (AFCM) algorithms have been developed and prototype machines have been tested with intake manifolds. In the non-traditional chamber sizing (NCCS) part of the project, the partners have researched a precision means of measuring chamber volumes, tested the three alternative chamber sizing techniques, and are on track for completion of project goals. Together, the two processes will make possible long-term gains in fuel efficiency and horsepower of approximately six percent.

The automobile industry is likely to adopt the two flow-control machining (FCM) processes since they allow automakers to continue their long-run trend of increasing the specific power (horsepower divided by liter [cubic-inch] displacement) of engines at a cost substantially lower than the current technologies. Higher specific power allows automakers to increase the sale of sport utility vehicles, minivans, and large utility vehicles—autos that consumers currently demand—while keeping overall Composite Average Fuel Efficiency (CAFE) at the federally required level. Adoption, however, hinges on two conditions: (1) that the joint venture successfully complete the development of machines both that embody the AFCM and NCCS process and that can withstand the rigors of the automobile manufacturing environment, and (2) that the two processes are cost effective when compared with alternative fuel-efficiency enhancing technologies. A high level of interest in applying the technologies is demonstrated by the automakers' participation in the joint venture.

The AFCM and NCCS processes will have significant economic impacts if they are successfully and broadly implemented. A most-likely near-term implementation scenario was developed and simulated, based on the initial implementation paths of other fuel-efficiency enhancing technologies. It assumes that over a five-year period

- consumers will continue to have demand for large light trucks in excess of what CAFE allows;
- total consumer demand for light trucks will remain fixed—therefore, new large light-truck sales will come at the expense of the existing sales of smaller, higher-fuel-economy light trucks;

- automakers will use the FCM processes to increase the fuel efficiency of large light trucks by six percent;
- the FCM processes make the added performance available at a cost of $5 per horsepower gained; and
- the federal government holds the CAFE passenger-car and light-truck fuel economy requirements at their current levels (11.7 kilometers per liter [27.5 mpg] for passenger cars, 8.8 kilometers per liter [20.7 mpg] for light trucks).

The study assumes that Ford and GM implement the processes on one production line each, for a total of 130,000 large utility vehicles in existing production lines. The resulting FCM-based increases in CAFE fuel economy allow the automakers to produce and sell an additional 116,000 light trucks with the technology (a total of 246,000 vehicles then are made using the FCM processes). Given that the price of each new large utility vehicle is $5,370 more than the average price of all other light trucks, our analysis finds that in five years

- annual sales revenues for Ford and GM increase by $623 million,
- annual gross domestic product (GDP) increases by $142 million,
- annual personal income increases by $196 million (which is more that the GDP increase due to production shifting to higher-wage sectors that, in aggregate, use less capital),
- annual tax revenues increase by $34 million, and
- 1,800 new high-wage manufacturing jobs are created.

Changes to the underlying assumptions affect the magnitudes of these impacts. For example, a gain in fuel efficiency of less than 6 percent will yield lower additional sales and macroeconomic impacts. If gasoline prices were to increase in real terms to their levels in the 1970s, the large, low-fuel-economy light trucks would be less desirable to consumers; this would give automakers added incentive to implement the FCM processes. Additional market competition or additional federal regulations on light-truck fuel economy and emissions would also increase incentives to use the processes. The numbers reported, then, can be used to represent the order of magnitude of impacts.

If implementation over a subsequent 10-year period follows the path of past fuel injection technologies to 80 percent of the market, the FCM processes will produce substantially higher impacts. Under similar market, production, and CAFE assumptions as in the near-term estimate, a longer-term implementation over 15 years to 80 percent of the light-truck market would allow further annual production and sale of 1.6 million of the large-utility class of light trucks while staying within current CAFE regulations. The additional production would increase GDP by $1.9 billion, annual personal income by $3.3 billion, and annual tax revenues by $527 million, and create 29,000 new manufacturing jobs.

## 7.2 Conclusions

This study has shown that there are at least five important issues to consider when evaluating the impacts of new technologies like the two flow-control machining (FCM) processes: (1) whether there are incentives for the intended industry to use the technologies and whether they are involved in the technology development process; (2) whether there is an effective means (cost and otherwise) for developing and implementing them; (3) how the technologies affect the economy; (4) whether there are alternative technologies that provide the same benefits but at a lower cost; and (5) how economic and other important conditions may change over time.

The automobile industry has strong incentives to use the two new processes, as indicated by participation by the automakers in developing them. The industry is hindered by CAFE regulations from selling the light-truck classes of vehicles that consumers currently demand. The earlier, precursor processes on which the FCM processes are based have been proven on race circuits and in other low-volume, high-value production, signaling that the resulting engine modifications have passed a proof-of-concept stage. Automakers and automobile engineers know the desirability of these processes if they are automated in a cost-effective manner.

The ATP facilitates technology adoption by funding technologies that match industry needs. The automobile industry is constantly seeking and developing new technologies that help it sell cars, reduce production costs, and meet federal fuel, emissions, and safety regulations. This report demonstrates how economic market analysis is used to verify whether industry is likely to adopt the technologies that ATP funds and to what extent.

Equally important is determining whether there are effective means for implementing the technologies. The FCM processes are relatively easy to adopt, given that the FCM Project can develop finishing processes that cost between \$3 and \$5 per horsepower gained, much cheaper than other approaches. Extrude Hone Corporation can produce and license to others the two finishing machines for use in aluminum casting plants. ATP facilitates development and implementation of the technology by not just awarding “seed” money but by stimulating the formation of a partnership comprised of various firms and academic researchers with the necessary expertise. Microeconomic and industry analyses verify whether the development and application is cost effective for industry.

It is also important that the broader economic consequences of a technology are understood. Our analysis has shown that FCM processes will permit automakers to produce more of the larger light trucks while still complying with CAFE requirements, as well as to produce more fuel-efficient vehicles in general. The light-truck category of vehicles is typically associated with higher pollution than smaller passenger cars. Because of the harmonic averaging used to compute CAFE, it is not possible with available information to determine whether the assumed implementation path would increase or decrease total fleet pollution. Clearly, using the technology across the fleet to increase fuel efficiency would decrease their total fleet pollution.

It is important to determine what alternative means might exist for achieving the goals of the ATP project. If the FCM-technology is not used, then some other fuel-efficiency enhancing technology will likely be developed. The automobile industry needs technologies that allow it to continue increasing the average fuel efficiency of its cars. Since current U.S. market demand favors light trucks, and there are technical limitations to making larger cars increasingly lighter, an attractive option is to increase fuel efficiency by increasing the *specific power* of an engine—the horsepower produced per liter (cubic inch) of engine displacement. Car producers have increased specific power by adopting fuel injection and four-valve cylinders; the two FCM processes have the same benefits but are less costly and easier to implement.

Aluminum casting plants continue to find ways to make the interior cavities of intake manifolds and cylinder heads more balanced, precise, and smooth. Researchers are developing new precision molds and inexpensive plastic intake manifolds. The Partnership for a New Generation of Vehicles (PNGV) at the Department of Commerce is promoting strategic alliances between automakers to develop an entire new vehicle and power system with fuel efficiency of 21 kilometers per liter (50 mpg) or more. Automakers continue to work on viable electric-powered cars. USCAR, a partnership between DaimlerChrysler, Ford, and GM, does pre-competitive research in new automobile technologies.

Finally, one must consider that the other conditions affecting demand for the technology could change, such as changes in fuel prices, consumer preferences, and government regulations. Indeed, the implementation path we use to estimate impacts is subject to change. Our estimates of impact do, however, serve to suggest the order of magnitude of implementation and resulting impacts. And, indeed, implementation may occur also in other industry sectors.

## 7.3 Suggestions for Future Research

This study identified several additional evaluation projects that would help better assess the incentives for using new technologies, the means for effectively implementing the technologies, and the potential broad economic impacts of the technology's use. First and foremost is a better understanding of the other potential markets for the FCM processes, and how the technology might diffuse to them. Economic analysis can then be conducted to identify the broader, long-run impacts of advances in flow-control machining on economic growth, quality jobs, and a better quality of life.

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# About the Advanced Technology Program

The Advanced Technology Program (ATP) is a partnership between government and private industry to conduct high-risk research to develop enabling technologies that promise significant commercial payoffs and widespread benefits for the economy. The ATP provides a mechanism for industry to extend its technological reach and push the envelope beyond what it otherwise would attempt.

Promising future technologies are the domain of the ATP:

- Enabling technologies that are essential to the development of future new and substantially improved projects, processes, and services across diverse application areas;
- Technologies for which there are challenging technical issues standing in the way of success;
- Technologies whose development often involves complex systems problems requiring a collaborative effort by multiple organizations;
- Technologies which will go undeveloped and/or proceed too slowly to be competitive in global markets without the ATP.

The ATP funds technical research, but it does not fund product development. That is the domain of the company partners. The ATP is industry driven, and that keeps it grounded in real-world needs. For-profit companies conceive, propose, co-fund, and execute all of the projects cost-shared by the ATP.

Smaller companies working on single-firm projects pay a minimum of all the indirect costs associated with the project. Large, Fortune-500 companies participating as a single firm pay at least 60 percent of total project costs. Joint ventures pay at least half of total project costs. Single-firm projects can last up to three years; joint ventures can last as long as five years. Companies of all sizes participate in ATP-funded projects. To date, more than half of the ATP awards have gone to individual small businesses or to joint ventures led by a small business.

Each project has specific goals, funding allocations, and completion dates established at the outset. Projects are monitored and can be terminated for cause before completion. All projects are selected in rigorous competitions which use peer-review to identify those that score highest against technical and economic criteria.

Contact the ATP for more information:

- On the World Wide Web: http://www.atp.nist.gov;
- By e-mail: atp@nist.gov;
- By phone: 1-800-ATP-Fund (1-800-287-3863);
- By writing: Advanced Technology Program, National Institute of Standards and Technology, 100 Bureau Drive, Stop 4701, Gaithersburg, MD 20899-4701.

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The Office of Applied Economics, part of the Building and Fire Research Laboratory at NIST, provides economic research and consulting to industry and government agencies in support of productivity enhancement, economic growth, and international competitiveness.