NIST GCR 03–856

Closing the Competitive Gap:

A Retrospective Analysis of the ATP 2mm Project

Prepared for
Economic Assessment Office
Advanced Technology Program
National Institute of Standards and Technology
Gaithersburg, MD 20899-4710

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NIST/ATP/NBER Grant 30–5025–19–0–78

July 2004

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TECHNOLOGY ADMINISTRATION
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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

This report presents the findings of an economic evaluation of the Advanced Technology Program's (ATP's) "two-millimeter project" (2mm project), which ran from 1992–1995 in an effort to improve the product quality, competitiveness, and market share of U.S. motor vehicle producers relative to their Japanese and European counterparts. The ATP is a cost-shared program to carry out high technical risk industry-led research with a strong potential to produce economic benefits for the nation as well as benefits to the participants. It is a highly competitive program. The consortium of auto manufacturers, equipment suppliers, and universities that joined to propose this project submitted a proposal that scored sufficiently high against ATP's selection criteria to receive an award. To be selected, an ATP project must be one that would not be likely to go forward without government-industry cost sharing, or would take longer to complete and as a result would reach the market later than it would with ATP funding.

At the outset of the 2mm project, U.S. motor vehicle producers faced challenges that in effect were evolving into barriers to competition. A typical auto body has approximately 100 critical dimensions that control the quality of closure panel fits, which can cause various quality problems such as wind noise, water leaks, rattles, squeaks, and general appearance of low quality of the gaps between the body and the doors, hood, and deck lid. In Japan, best practices in the early 1990s resulted in total variation of critical body dimensions of no more than 2 millimeters. European automakers had a variation of approximately 3 millimeters, and U.S. automakers had a variation of 4 millimeters or more.

The 2 mm project was launched to improve the quality of domestically produced automobiles and light-trucks and increase manufacturers' understanding of scientific approaches to reduce variation and thereby improve quality and lower cost while shortening the new product launch time. The successful realization of these objectives would have a direct impact on the ability of the U.S. industry to remain competitive and in accordance with prevailing world quality standards. As this report details, the project:

- reduced variation of critical body dimensions towards meeting the 2 millimeter objective (with +/-1 mm variance);
- was the key driving force in changing the manufacturing quality control technology used to improve quality, reduce cost and shorten time to market by domestically owned vehicle manufacturers;
- helped domestic producers slow the loss of market share to offshore and transplant manufacturers;
- created no fewer than 1,400 new jobs;
- generated, by conservative estimate, an increase of almost $190 million in gross domestic product (measured over a ten-year period following the start of the ATP project); and
- achieved these gains without any significant wage or price inflation and without any distorting subsidies or changes in trade policy.

Findings presented in this report are based on information gathered through case study interviews conducted in 2000–2001, model development and estimation using a database constructed for this research, and a macroeconomic model capable of handling multiple production processes for the motor vehicle manufacturing industry.

The research is based on information and economic analyses concentrated in three areas: (1) interviewing project participants to identify significant changes in the manufacturing process and any cost impacts attributable to the application of the technology developed through the project, (2) developing a hedonic-price model to estimate the market value and production-cost implications of using the 2mm technology, and (3) estimating the macroeconomic impacts that result from using the technology (developed in the first and second areas of research) including the impacts of the research and development (R&D) expenditures, investment in necessary equipment, and the market impacts attributable to the availability of higher-quality vehicle manufacturing.

The report also details areas of improvement that have the potential to advance further and those that can be undertaken as next steps in an ongoing effort to improve quality, which in turn enhances competitiveness and ability to retain or increase market share.

Acknowledgments

We deeply appreciate the assistance of the various current and former plant personnel of the 2mm project participants and staff from the Auto Body Consortium who provided much of the detailed information upon which this report is based. We also received valuable guidance and comments from Mary Ellen Kelley, Stephanie Shipp, Jeanne Powell, Jack Boudreaux, Michael Daum, Susannah Schiller, Andrew Wang and Lee Bowes, who are or were staff at the Advanced Technology Program (ATP), and Adam Jaffe from the National Bureau of Economic Research (NBER). Rosalie Ruegg, Managing Director of TIA Consulting, Inc. and former Director of the Economic Assessment Office, provided comments on an early draft of this report. Elissa Sobolewski, acting ATP Deputy Director, and Brian Belanger, a former ATP Deputy Director (and currently a consultant to the ATP), provided additional comments on the final report. At MIT, Turi McKinley and Natalia Sizov provided excellent technical assistance.

We would also like to thank Dwight Carlson, founder of Perceptron and now CEO at Onset Technology Management Corporation, Victor Malinasky from Comau Pico, Jim Steimel at Classic Design, Thomas Weber, formerly at American Sunroof Corporation and now at Webertech, and Wayne Wilson from General Motors. We would also like to thank the project participants whom we interviewed (see Appendix 2-A).

This study, originally entitled "Estimating Contributions to Industry Productivity," was funded by NIST/ATP/NBER grant number 30–5025–19–0–78.

Executive Summary

We have conducted an economic evaluation of the Advanced Technology Program's (ATP's) "two-millimeter project" (2mm project). Our evaluation is based on information we gathered through case study interviews and model development and estimation using a database we constructed for this research. To make the calculations, we employed a macroeconomic model that is capable of handling multiple production processes for the motor vehicle manufacturing industry.

This report presents the findings of an economic evaluation of the Advanced Technology Program's (ATP's) "two-millimeter project" (2mm project), which ran from 1992–1995 in an effort to improve the product quality, competitiveness, and market share of U.S. motor vehicle producers. The ATP is a cost-shared program to carry out high technical risk industry-led research with a strong potential to produce economic benefits for the nation as well as benefits to the participants. It is a highly competitive program. The consortium of auto manufacturers, equipment suppliers, and universities that joined to propose this project submitted a proposal that scored sufficiently high against ATP's selection criteria to receive an award. To be selected, an ATP project must be one that would not be likely to go forward without government-industry cost sharing, or would take longer to complete and as a result would reach the market later than it would with ATP funding.

The 2mm project was intended to improve the quality of domestically produced vehicle bodies (automobiles and light-trucks) during assembly and increase manufacturers' understanding of scientific approaches to reduce variation to improve quality and lower cost while shortening the new product launch time. Improvements were deemed essential for the U.S. industry to remain competitive with the prevailing world standards set by Japanese manufacturers operating in the United States and abroad. The term "2mm" refers to the upper limit of variation in the gap between the vehicle body and its movable panels, such as doors, trunk lids, hatchbacks, and hoods. We conducted interviews with two of the major domestic vehicle manufacturers (General Motors and DaimlerChrysler), as well as five other industry service and equipment suppliers, two educational institutions (the University of Michigan and Wayne State University), and the Auto Body Consortium (ABC), the organization that oversaw project research. The project ran during the 1992–1995 period, and we conducted our interviews during the 2000–2001 period.

At the outset of the 2mm project, U.S. motor vehicle producers faced challenges that in effect were evolving into barriers to competition. A typical auto body has approximately 100 critical dimensions that control the quality of closure panel fits and can cause various quality problems such as wind noise, water leaks, rattles, squeaks, and general appearance of low quality due to the gaps between the body and the doors, hood, and deck lid. In Japan, best practices in the early 1990s resulted in total variation of critical body dimensions of no more than 2 millimeters. European automakers had variation of approximately 3 millimeters, and U.S. automakers had variation of 4 millimeters or more.

Key Findings

Research activities by the participant firms in the project centered around development and improvement in the use of optical coordinate measurement machines (OCMMs) during the assembly process to identify any and all vehicle bodies whose dimensions were out of specification, that is, where the variation in body dimensions exceeded 2mm. This goal was largely achieved in the several plants where the technology and methodology were implemented by university researchers and plant personnel. As the research was completed, the participants in the project obtained a fundamental understanding of the sources of vehicle body-size variation, and they developed new analytical statistical algorithms (for use on the 2mm computer workstations) to aid assembly-plant workers and managers in gaining control over the manufacturing process. It is very unlikely that these results could have been achieved in a three-year period in the absence of the Advanced Technology Program (ATP) 2mm project, as there was no single firm (or group of firms) willing to undertake such a risky avenue of research on their own.

Our research is based on information and economic analyses concentrated in three areas:

1. interviewing project participants to identify significant changes in the manufacturing process and any cost impacts attributable to the application of the technology developed through the project,
2. developing a hedonic-price model to estimate the market value and production-cost implications of using the 2mm technology, and

3. estimating the macroeconomic impacts that result from using the technology (developed in the first and second areas of research) including the impacts of the research and development (R&D) expenditures, investment in necessary equipment, and the market impacts attributable to the availability of higher-quality vehicle manufacturing.

The project was the key driving force in changing the manufacturing quality control technology used by domestically owned vehicle manufacturers. The initial investment was $4.4 million from the ATP and an additional $6.1 million in matching funds from the participant firms. These funds ultimately grew over the ten years from the start of the project to subsequent direct investment by U.S.-owned vehicle manufacturers of $115 million. This investment was for measurement equipment and systems and a net consumption increase of nearly $530 million for domestically produced vehicles. In all, no fewer than 1,400 new jobs and an increase of almost $190 million in gross domestic product growth are attributable (conservatively estimated) to the application of the 2mm technology, measured over a ten-year period following the start of the ATP project. These gains were achieved without any significant wage or price inflation and without any distorting subsidies or changes in trade policy.

The 2mm project helped domestic producers slow the loss of market share to offshore and transplant manufacturers for several years after the project, but our model results indicate that the gains in market shares are transitory, in that share growth continues as long as quality improves, but does not grow perpetually. After the quality improvement is recognized in the market, shares eventually stabilize at their new level. For shares to grow further, a pattern of continuous improvement is required, but this feature is not uniformly evident in the plants of domestic manufacturers. The world-class standard that was 2mm at the start of the ATP project continues to improve, but the standard remains one set by foreign competitors.

We summarize some of the major achievements of the 2mm project that support our generally positive findings in regards to economic impacts:

- Reduced variation of critical body dimensions towards meeting the 2 millimeter objective (with +/-1 mm variance).
- Plant personnel learned how real-time data could be used to diagnose and correct the multitude of problems that underlie dimensional variation and both GM and DaimlerChrysler established new procedures for identifying the underlying sources of variation in vehicle body manufacturing.

- Manufacturers noted reductions in rework/repair expenditures of approximately $3 per vehicle and anticipated reductions in warranty claims (although none had explicitly analyzed such impacts).

- Manufacturers were able to reduce measurement-equipment expenditures by substituting the OCMM for other measurement devices used in plants.

- Manufacturers experienced reductions in scrap costs (which initially had resulted from manufacturing errors) ranging from $1 to $3 per vehicle.

- Assembly-line integrators (firms that supply the tools used to form a vehicle assembly-line) gained improved understanding of how assembly tools can cause dimensional variation and have undertaken the adoption of new tool-mounted measurement technologies to gain improved control over tool-induced variation.

- Improved vehicle quality appears to have increased the market share of "2mm vehicles," but after considering investment and monitoring costs, we found that variation reduction appears to reduce profitability in the short-run.

- The 2mm equipment, which consists of optical measurement equipment and computer workstations for storing and analyzing the incoming measurement data, is now a standard capital investment for new assembly lines, having proven that higher standards of dimensional control are possible through their use without forcing a change in other assembly-line operations.

Some of the partial successes of the project worth noting are:

- All GM plants are now implementing analytical software developed during the research phase of 2mm, somewhat more slowly than envisioned, but setting the stage for possible improvements in vehicle design and manufacture as new models are developed.

- Owner evaluations of some domestically produced vehicles may have improved as a result of the project, but manufacturers are still unable to quantify this improvement.

- Labor relations in plants using 2mm technology improved as objective measurements help prevent misattribution of defects to labor when incoming materials or tooling problems are the source.

Some of the anticipated results that did not materialize were:

- New programs for assembly-line maintenance that are driven by performance measures incorporating dimensional variation as a key driver have not developed.
- New procedures to use the OCMM to obtain highly accurate nominal vehicle body dimensions proved too difficult to implement, resulting in continued reliance on costly sampling-based measurements obtained from contact measurement machines.
- Commercialization of the analytical software that was developed as one of the project's research activities did not occur, although GM did develop a similar package for its own internal use.

Based upon our analysis, we contend that the 2mm project did help increase demand for domestically produced vehicles and, at the same time, boosted short-run costs; however, on balance, the net effect is positive. Had the 2mm project not been implemented, the U.S. motor vehicle industry would probably have seen even larger declines in sales than those recorded during the 1990s.

Table of Contents

Tables

Figures

CHAPTER 1

Introduction

This report presents the findings of an economic evaluation of the Advanced Technology Program's (ATP's) "two-millimeter project" (2mm project), which ran from 1992–1995 in an effort to improve the product quality, competitiveness, and market share of U.S. motor vehicle producers. The ATP is a cost-shared program to carry out high technical risk industry-led research with a strong potential to produce economic benefits for the nation as well as benefits to the participants. It is a highly competitive program. The consortium of auto manufacturers, equipment suppliers, and universities that joined to propose this project submitted a proposal that scored sufficiently high against ATP's selection criteria to receive an award. To be selected an ATP project must be one that would not be likely to go forward without government-industry cost sharing, or would take longer to complete and as a result would reach the market later than it would with ATP funding.

During the 1980s, the U.S. motor vehicle producers were losing their market share to Asian and European producers. In order to reverse this trend, many agencies in the U.S. government, including ATP, made an effort in the 1990s to increase the competitiveness of the domestic motor vehicle industry.[1] The main goal of the 2mm project was to increase the competitiveness of the U.S. motor vehicle firms by reducing the dimensional variation for the U.S. motor vehicle body-in-white (BIW) openings. In the 1980s, U.S. car buyers were said to consider the fit, finish, and reliability of vehicles as the main factors affecting their purchase.

By the late 1980s, the dimensional variation was 2.0 mm (or less) for Japanese motor vehicle makers, about 2.5 mm for European makers, and more than 3.0 mm (even up to 10 mm) for U.S. makers. In an early report,[2] it was estimated that by the close of the project, the 2mm project had (1) lowered the production cost for the participating plants, (2) increased the demand for U.S.-made vehicles, and (3) distributed the technology to other non-auto

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[1] Throughout the remainder of this report, we use the term "U.S.-made" to designate a vehicle made domestically within the continental United States, and the term "American" to indicate vehicles that were made in the United States or Canada.

[2] See http://statusreports-atp.nist.gov/reports/91-01-0177.htm, ATP Status Report, "A Systems Solution to a Quality Problem in Auto Body Manufacturing."

companies. Our research team, which reviewed this ATP project, is composed of mechanical engineers, economists, and planners from the Massachusetts Institute of Technology (MIT), the Harvard Business School, and Case Western Reserve University. This multidisciplinary research team under a contract between MIT and the National Bureau of Economic Research conducted three distinct types of analyses of the effects of the 2mm project, which we report in the following three chapters.

First, we conduct a set of case studies of selected automobile and light-truck assembly companies and their suppliers to determine the economic impacts of the 2mm project on a firm-by-firm basis (Chapter 2). We begin that chapter by describing the technology in detail and identifying the (hoped-for) quantifiable outcomes from incorporating the technology into vehicle programs. Then, we summarize the results of the project, distinguishing among four general categories of impacts: (1) short-run production costs, (2) long-run production costs, (3) indirect costs, and (4) market-share impacts. We end the chapter by reporting the details of the case studies we did, based on interviews with key officials in seven of the ten firms still in business in 1999–2000. We summarize their answers to questions regarding the impact of the project and the resulting technologies on firm productivity, market position, product quality, and linkages between participants, suppliers, and customers. We try to determine which changes in the technology the plants implemented in order to manufacture improved vehicle bodies and to obtain resulting changes in quality of vehicle bodies.

Second, we evaluate the market-share and production-cost effects of the 2mm project (Chapter 3). Specifically, we use a hedonic-price model to conduct a partial assessment of whether the first two of the results anticipated in the 1997 study by CONSAD Research Corporation were achieved. Based upon our analysis, we contend that the 2mm project did help increase demand for domestically produced vehicles, while, at the same time, boosting short-run costs; on balance, the net effect is positive. Had the 2mm project not been implemented, the U.S. motor vehicle industry would probably have seen even larger declines in sales than those recorded. The effects on demand, although significant, are limited however to the several years following initial adoption of the technology. As application of the technology approached saturation, the economic impacts on demand and vehicle price diminished.

Third, we examine the economic impacts that the implementation of the 2mm project had on the U.S. economy (Chapter 4). We draw on results from our case study research and the hedonic model to estimate the macroeconomic impacts of the project on aggregate employment, income, and output. We do this using a novel application of the Regional

Economic Model, Inc. (REMI) model to define virtual regions of vehicle manufacturing defined by common manufacturing technology rather than spatial contiguity. Using this approach, we find that the 2mm project generated a net change in GDP of approximately $190 million, output that would not have been generated in the absence of ATP funding.

From the economic-impact estimates, we draw four conclusions:

1. Using a well-crafted consortium, such as the Auto Body Consortium, to coordinate and promote research, the motor vehicle manufacturers were able to overcome the legal and economic barriers to help demonstrate the viability of technology that otherwise would have remained underutilized. Doing so has improved the competitiveness of the U.S. motor vehicle manufacturing sector in a global market.
2. U.S. government aid to promote a particular technology does not necessarily reduce competition, and in the case of motor vehicles, helped promote the development of alternative technologies. Experience gained from work on developing the 2mm technology spurred development of newer techniques for quality control and measurement among participant firms (for example, tool-mounted sensors), fostering both expanded technological capabilities and business competition.
3. The identification and promotion of the 2mm technology appears to be a justified use of public resources, one that has helped improve “technical” capabilities and prospects for further improvement of domestic motor vehicle firms. It is also one that appears to have paid off in an economic sense.
4. One of the unexpected benefits of the technology appears to be improved labor-management relations. The vehicle producers and their suppliers were able to adopt the 2mm technology widely without disrupting existing labor practices, offering some workers an opportunity to broaden their skills with respect to process control and measurement. Personnel could rapidly trace assembly quality problems to their source, avoiding inaccurate identification of sources of quality problems.

During the past 15 years, many agencies in the U.S. government, including ATP, have helped to promote the introduction of a number of new technologies in U.S. motor vehicle and other industries. This analysis of the 2mm project is just one of a number of studies that could be made to examine the economic impact of these new technologies and to help determine how they have spread throughout and between each industry.

CHAPTER 2

Case Studies of Technology Development, Diffusion, and Impact

In the early 1990s, a Lexus television commercial made engineering precision an overnight star by demonstrating that a steel ball could roll smoothly down perfectly flush gaps along the panels of the company's flagship sedan. The advertisement, with its dramatic focus on quality, was widely noted in the United States, but it would not have merited as much attention had it aired before a European or Japanese audience.

As noted in the introduction to an ATP Status Report on this project,[3] just a few millimeters make a big difference on an automated assembly line as doors, hood, windshield, wheel housings, and other parts are installed on a body-in-white (BIW), the partially completed body of an automobile. ("BIW" refers to the vehicle body as it proceeds through the assembly line prior to being painted.) If BIW openings are slightly off kilter or parts vary much from specifications, the overall fit and finish of the completed car suffers. When dimensions vary more radically, a BIW may have to be re-worked by hand. In addition, if the variations grow too large, the entire BIW may be pulled from the assembly line and junked. In contrast, a tightly fitted car means fewer defects, faster assembly times for parts and components added later in the process, less time and money for factory repairs, better appearance and performance for the owner, and lower long-term maintenance costs.

The Auto Body Consortium, which comprises automobile manufacturers, suppliers, and university partners, initiated the Advanced Technology Program's (ATP) two-millimeter project (2mm project). Aware that a disparity in quality standards—a disparity that, as the Lexus commercial pointedly illustrated, was visible to the naked consumer eye—was putting them at a costly disadvantage, the members of the consortium sought a joint partnership with the U.S. government to help improve their sales performance in an increasingly competitive market.

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[3] See http://statusreports-atp.nist.gov/reports/91-01-0177.htm, ATP Status Report, "A Systems Solution to a Quality Problem in Auto Body Manufacturing."

Our multidisciplinary research team conducted a set of case studies through interviews with staff members at consortium companies to determine the economic impacts of the 2mm project. Our team is composed of mechanical engineers, economists, and planners at MIT, and consultants from Case Western Reserve University and Harvard Business School.

Background

The broad objectives of the 2mm project, as outlined in the original proposal from the Ann Arbor, Michigan, Auto Body Consortium (ABC, 1991) to the ATP, were two-fold: First, it would advance manufacturing techniques and process control to achieve "world" body-in-white (BIW) quality to compete in the global marketplace. Second, it would improve the scientific understanding of sheet-metal assembly processes and establish a technical infrastructure for future sheet-metal process-control and assembly systems. At the time the proposal was written, Japanese manufacturers were capable of building vehicles with dimensional variation of 2mm or lower, European manufacturers of 2.5mm, and domestic manufacturers of 3mm and greater (CONSAD, 1997, p. 3).

Participants in the initial project included the two automobile and light-truck assemblers (Chrysler[4] and General Motors), eight suppliers to the assemblers of vehicle parts, who furnished the parts or the measurement equipment (American Sunroof Corporation, Classic Design, Detroit Center Tool, ISI Automation Product Group, Modern Engineering, Perceptron, Inc., PICO, and Pioneer Engineering), and engineering researchers trained at the S. M. Wu Manufacturing Research Center in the College of Engineering at the University of Michigan. Wayne State University also participated as a subcontractor.

In this chapter, we discuss what the 2mm technology is, how the firms participating with the ATP adopted it, and what the economic impacts were on those firms. We describe all the impacts identified during interviews we conducted with seven of the ten participating firms still in operation during the 2000–2001 period. We present summaries of the case study interviews in the main text of the chapter, the list of interviewees in Appendix 2-A, and the details of selected case studies in Appendix 2-B.

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[4] In 1998, Daimler-Benz acquired Chrysler and adopted the name DaimlerChrysler. Throughout this report, we use the name "Chrysler" to refer to work at the firm during the 2mm program and until 1998, and the name "DaimlerChrysler" to refer to current practices at the firm.

In the course of nearly two dozen in-person and telephone interviews, we obtained data that demonstrate that the 2mm project was largely successful in meeting its broadly defined goal of helping domestic producers improve the quality of their products in a relatively short time. With respect to specific project goals, we found varying degrees of success, but no outright failures.

We caution, however, that domestic manufacturers may again fall behind in their efforts to remain competitive in this field. Despite rapid progress achieved by the time we conducted our interviews in the year 2000 (five years after the project's end), case study participants noted that while "state-of-the-art" BIW dimensional standards are improving, domestic producers seem to be satisfied with a 2–4mm BIW dimensional variation. Such a stance cedes long-term leadership concerning, at least, dimensional variation to foreign producers; however, this is not a shortcoming of the 2mm project, but is indicative of domestic producers' different perception of the value of product quality. It remains to be seen whether 2mm technology will be sufficient to close the competitive gap should producers deem it necessary. It is also possible that the evolution of assembly-line equipment enabled by the 2mm research could lead to the adoption of different measurement equipment and techniques; in that situation, the current 2mm technology could become obsolete in the next several years.

The gains achieved during the 2mm project came about through an unusual cooperative/competitive institutional arrangement embodied in the ABC. By working through the ABC, 2mm project participants shared research results they would have treated as proprietary had they conducted the research independently. From the standpoint of the participant firms' earnings, the participants would find sharing to be less attractive than proprietary control, but given the high level of uncertainty perceived as inherent in the 2mm project goals, they found the incentives for doing the research to be too small for them to justify undertaking this work on their own for two reasons. First, to improve BIW quality in the absence of the 2mm project, firms would have had to choose to pursue other lines of research with more quantifiable market potential. Second, had they chosen to invest unilaterally or individually, the firms would have found that the time required to attain quality achieved by the project would have greatly exceeded three years. In either case, the potential delay threatened to place domestic producers at an even greater qualitative disadvantage in competition with foreign producers. The delay would have risked accelerated loss of market share to imports.

2mm Technology Defined

To measure the dimensional variation in the BIW on the assembly line, all U.S.-owned automobile and light-truck manufacturing firms have adopted what is referred to as "2mm technology." This technology consists of measurement equipment, including an optical coordinate measurement machine (OCMM), analytical software, databases, and documentation. The primary purpose of the 2mm technology is to help manufacturers reduce dimensional variation of critical points on the BIW by alerting operators when tolerances are exceeded and prompting corrective action(s). Reduced variation in body aperture-size is desirable for many reasons, including (but not limited to) easier downstream assembly, reduced door and trunk-lid closing effort, lower potentials for water leakage and noise, and improved aesthetics. By measuring all bodies during production, vehicle manufacturers have adopted an approach that represents a significant departure from the limited sampling approach to quality control used previously. To achieve low dimensional variation, skilled technicians familiar with both statistical process control and assembly-line tool maintenance and repair are needed to interpret data, identify problem sources, and make corrections. Vehicle manufacturers can thus achieve a higher-quality vehicle body fit-and-finish than existed prior to the introduction of 2mm technologies by exercising a greater degree of control over assembly-line-tooling performance and incoming-part quality.

We begin by describing the 2mm technology in detail and by identifying the desired quantifiable outcomes from incorporation of the technology into vehicle programs. We note, at the outset, that participating firms do not universally view 2mm technology as critical to achieving high-quality vehicle body assembly in that the Japanese have achieved a 2mm standard without using the equipment used in the United States. In fact, most of the U.S.-based body engineers we interviewed maintain that, even after implementing the 2mm technology, U.S.-owned plants lag behind their Japanese counterparts in controlling dimensional variation in vehicle assembly.

Conversely, personnel in U.S.-based firms claim that 2mm technology is well suited to the production "style" common to firms operating in North America, as the technology enables firms to improve the control of existing processes rather than to redesign the assembly process. Firms implement the technology at the time of relatively infrequent changeovers in the line rather than incorporating it into an existing line. Our interviewees noted that body-assembly processes, capital equipment used, labor-skill requirements, and the general approach to quality control differ to varying degrees in other regions of the world. As a rule, U.S. assembly plants are characterized by a larger number of assembly-line tools, each of which performs more specialized assembly tasks than their Japanese counterpart. U.S. hourly workers, unlike those in Japan, usually are not responsible for routine maintenance and repair of the tooling at the stations at which they perform. In most U.S. plants, general tool maintenance and repair is performed by personnel specialized in such activities during scheduled line downtime.

According to marketing personnel at the Perceptron Corporation, a heavy reliance on OCMMs—the heart of the 2mm project—is a characteristic unique to plants operated by U.S.-based firms in North America. Perceptron, formed in 1981, was the sole supplier of the 2mm equipment during the 2mm project and remains the dominant producer of this type of equipment in the United States.

2mm Equipment

The OCMM equipment incorporated into 2mm technology consists of a number of cameras connected to a computer workstation. These cameras record the relative spatial coordinates of critical points on a vehicle during the production process. The workstation computer then calculates the deviation of these measurements from a pre-set "correct" value. The measurements are all relative ones, not nominal vehicle dimensions (such as measures of actual length, height, or width) or broad-area surface variations. For these latter types of measures, workers still use the older Coordinate Measuring Machine (CMM) technology on a small sample of vehicle bodies, a process that can take an hour or more for each vehicle body measured, depending on how many sample points are recorded. (CMMs operate by measuring the location of points on an object based on physical contact, recording the location of each point encountered.)

For the most part, the equipment and workstation systems developed in the late 1970s and early 1980s were still state-of-the-art at the beginning of the 2mm project. Subsequent improvements in the cameras (such as the use of digital imaging in place of analog) as well as vast improvements in computing technology used in the workstations have added the capability to measure more points at each workstation. These features have been incorporated into OCMM systems independent of the 2mm project. The 2mm equipment existed prior to the 2mm project; therefore, the project did not underwrite the development of the equipment. The major contribution of the project was for the plant personnel to learn how real-time data could be used to diagnose and correct the multitude of problems that underlie dimensional variation.

A typical 2mm system installation consists of four or five measurement stations, each measuring multiple points on completed sections of the BIW, including those on the underbody, side-frames, motor compartment, hatch/trunk, and roof. At each station, the equipment performs its measurements during the stationary period in the assembly cycle when other equipment or personnel are performing other tasks, such as welding, adding parts, or attaching subassemblies to the vehicles. As completed assemblies pass through the measurement station (in a tunnel-shaped structure), a number of cameras suspended around the tunnel measure specific points on the vehicle body. These data are transmitted to a computer at each station that stores a set of measurements for each body. Technicians can network these workstation computers to produce a complete set of measurements for a completed body, but plant personnel can also use them locally (at a specific measurement station), where they can access a graphic display to monitor dimensional variation of user-specified points on completed vehicle bodies. These displays show the estimated variances at prescribed points on the vehicles.

Plant personnel can use the workstation both for alarm functions (when something has been assembled that is out of specification) and for some data analyses. With this combination, both managers and assembly-line workers have access to tools with which to exert more precise control on the finished product than was possible in the past. The user, for example, can employ the alarm function to set a quality threshold for the fit of body panels and openings. If a value above this threshold occurs, the workstation can trigger a warning, send a pager message, or stop the entire line, preventing substandard vehicle bodies from moving further down the line. Workers can immediately repair the defective body or, in severe cases, scrap it before the plant wastes additional resources on a vehicle that may prove to be beyond repair. Thus, the alarm function can help prevent vehicle bodies with repetitive errors from moving down the line undetected. Both the alarm and local data-analysis functions existed in systems installed before the 2mm research project was started, although plant personnel lacked a systematic approach either to setting alarm thresholds or to understanding the underlying causes of dimensional variation.

The initiators of the 2mm technology hypothesized that the ability of line personnel to identify sources of dimensional variation rapidly would significantly speed time-to-launch (the time required to go from a new assembly-line start-up to the production of saleable vehicles). Even rather small incremental improvements in the launch process, such as those involving the installation and calibration of new assembly-line tooling and conveyance systems, could produce sizeable financial benefits, thereby justifying assemblers' program investments. As we will show, assemblers have achieved reduced time-to-launch. Consortium members, however, disagree over the extent to which 2mm equipment played a role in that reduction, because a number of improvements in addition to the use of 2mm technology have been made, such as the way in which Original Equipment Manufacturers (OEMs) designed or procured assembly-line tooling.

Databases

By monitoring production-variance data, operators "look" for non-random dimensional-variation patterns (i.e., abrupt changes potentially caused by tool malfunctions, such as broken clamps or blocks, or a slow "drifting" of the variation) that indicate the need for adjustments to compensate for tool wear. As line-operators gain experience in using the OCMMs, they can detect distinctive "signatures" in the graphic performance charts indicative of particular tool or line-equipment failures. Personnel familiar with these signatures gain insight and speed in identifying possible fault locations, deciding whether the fault requires maintenance or repairs, and determining the urgency of the action. Over time, plant personnel develop knowledge specific to an assembly line (and its component parts) with respect to maintenance activities and scheduling. They also form a body of knowledge that can aid them in monitoring longer-run performance (for example, shift-to-shift, or week-to-week) that sometimes reveals underlying systematic causes of dimensional variation.

Plant personnel also can use cumulative variance data as a basis for more elaborate studies of dimensional variation on the vehicle body. They can conduct correlation studies to measure how dimensional variation at certain points on the body influences the variation at other points. Thus, operators can focus attention on the key sets of points and factors that affect dimensional variation, including design features of the vehicle itself, design and operation of tools used to assemble it, maintenance practices, and schedules for tools. In addition, they can see problems coming. They do not have to wait for an alarm to sound, but instead can intervene when they see the error approaching the alarm threshold.

Software

One goal of the 2mm project was to develop software that would enable plant personnel and researchers to model vehicle-body geometry based on actual OCMM data and perform analytical calculations that assist in identifying problem areas. In order to perform in-depth studies of dimensional variation on vehicle bodies, the 2mm project participant firms independently developed analytical software for the exploitation of the data generated by the OCMMs. They developed two different software packages during and after the project. The first was known as the "Process Navigator," developed by Classic Design, Inc., while the second was known as the "Body-In-White Data Analyzer," developed by General Motors, Inc. (GM). As part of their 2mm research, University of Michigan engineers developed computational algorithms designed to work with both 2mm software packages.

Classic Design successfully completed development of its package during the project years but failed in its attempt to sell the Process Navigator software package to the OEMs, who chose to use either their own in-house version (the "BIW Analyzer") or none at all. For example, near the end of the formal 2mm project in 1995, after deciding that the Process Navigator was too expensive, GM undertook development of the BIW Data Analyzer software. Personnel at GM assembly plants started to use the software in 1995, and as of 2000, they were in the process of outfitting all of their assembly plants with the software.[5] Appendix 2-B contains more detail on GMs use of its proprietary software package.

As of 2001, GM uses the BIW Data Analyzer both to support troubleshooting analyses by plant engineers and to aid advanced engineering research; as such, it is for use by trained dimensional-control engineers—a job title that is itself an apparent outgrowth of 2mm research. (During our interviews, we were told that the predominant use of the software is for troubleshooting of line-specific problems.) GM uses the BIW Data Analyzer as a proprietary product, and GM personnel indicated that they do not want to commercialize it.

Classic Design continued development of its Process Navigator Software for several years after completion of the ATP sponsored program. The product was prepared for commercialization by adding features and revising it to work in a networked Windows NT environment. By 1999, an unfavorable business climate forced Classic Design to eliminate support for any new product development and terminated efforts to market the Process Navigator.

DaimlerChrysler (DC) has yet to implement formal OCMM database analyses, but it is starting to use SAS (Statistical Analysis Software), an all-purpose, commercially available statistical-analysis software package, to conduct some research on its databases, such as at the new Jeep plant in Toledo. Inasmuch as DC started to use SAS only for analytical purposes, we are unable to evaluate its capabilities compared with those of the BIW Data Analyzer. GM's more formal approach to body quality analysis with the BIW Data Analyzer versus DC's ad hoc approach may reflect a more fundamental difference than simply the choice of software would imply. We provide further details of each participant's approach to quantitative analysis in Appendix 2-B.

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[5] Perceptron staff have incorporated some of the algorithms used in the BIW Analyzer functions into newer generations of the Perceptron workstations, although we were unable to obtain the specific details as to which ones or the type.

Documentation

Both DC and GM have developed systems for documenting the knowledge gained in the course of 2mm workstation monitoring, problem-solving, and database analyses. At DC, the information is commonly referred to as the "book of knowledge," while at GM, it is provided through a series of "enablers." Both provide a foundation for codifying a set of "best practices," although GM applies this company-wide, while DC focuses on plant-level documentation and learning.

In general, the DC approach appears to be the less formal of the two, with plant personnel using it most often as an aid to troubleshooting problems that arise in the course of vehicle assembly. As dimensional variation problems occur, DC body-shop personnel perform data analyses using the Perceptron workstations, trying to identify known patterns of dimensional variation that point to specific tools or work locations on the assembly line. Once the source is identified and the problem corrected, personnel enter the case into the plant computer database that references the problem, location on the vehicle body, and solutions for others to consult when beginning a troubleshooting process.

The GM enablers provide dimensional engineers and body-shop management with a formal methodology for the reduction of dimensional variation and the employment of prescribed analytic tools. They give personnel precise directions as to the points on the BIW to be measured, so that the database variables (and number and location of cameras) are standardized across assembly plants. Thus, the GM enablers provide corporate-level staff with information for conducting comparative analyses of performance measures across assembly lines and plants and for analyzing performance across similar places on different vehicle features.

Both the DC and GM approaches represent a move toward achieving one of the long-range goals of the 2mm project: using knowledge and understanding of the root causes of dimensional variation to influence the design of both new vehicles and the tooling used to construct them.

2mm Project Results

The 2mm project produced mixed results in achieving the goals outlined in the proposal. The 2mm technology was most successful in meeting goals for the reduction of scrap and repair costs and in furthering a scientific understanding of the causes underlying BIW dimensional variations and their relationship to vehicle-assembly quality. It was also instrumental in reducing line downtime and in eliminating some direct costs for measurement that rely on the use of checking fixtures. (Checking fixtures and layout plates are precisely constructed templates into which a worker places completed subassemblies to permit rapid and accurate evaluation of conformance to specified dimensions.)

With respect to its role in reducing important vehicle body-related costs linked to launch time, warranty, and line maintenance, on the one hand, most assembly-plant personnel interviewed believe that the cost impact of the project is clear and that costs have been lowered. On the other hand, the assembly-line consolidators believe that the cost impact is ambiguous. Certainly, the latter argue that assemblers were able to reduce some short- and long-run production costs through application of the project-generated technologies, but they argue that attribution is not straightforward, partly because the assemblers involved in the study changed other elements in the production system at the same time 2mm technologies began making inroads, thus making 2mm-based gains difficult to analyze in isolation.

One of the most important concurrent changes was the manner in which original equipment manufacturers (OEMs) designed or procured assembly-line tooling. Up until the mid-1980s, the OEMs performed their own assembly-line design work in-house while contracting for line components with numerous tool and equipment manufacturers. Once the tools, equipment, and conveyance systems were built, the OEMs were then responsible for building the line and getting all of the subsystems to operate as one. Since the 1980s, U.S. automobile and light-truck manufacturers have moved toward turnkey procurement, a practice in which the OEM specifies the vehicle characteristics and the desired line-performance characteristics, but leaves tool design and line-layout to companies that specialize in line integration. The line integrators build the entire line in their own plant, and once it runs satisfactorily with prototype parts, they install the line in the OEM's plant.

A second major change that was ongoing during the time of the 2mm project was the move by U.S. assembly plants to just-in-time (JIT) manufacturing. In practice, the JIT method offers firms the potential to realize significant savings in inventory-holding costs by establishing close working relationships with suppliers for the delivery of component parts to the assembly plant in smaller lot-sizes than before, in line with market demand. (Prior to JIT, vehicle firms typically stocked weeks' worth of parts to meet fluctuations in demand.) Additionally, assembly plants could shorten production runs on some components. The smaller number of parts available in inventory meant that they had to monitor run-to-run variation in part quality more closely than before. This may have led to some improvement in part quality. Several of the body-shop managers we interviewed were not convinced, however, that the internal divisions responsible for stamping body parts had improved their quality. They generally believe that measured improvement in body quality is the result of improved processes and monitoring in the assembly plant, as well as more careful material handling.

A third major change the assembly plants undertook in vehicle-production practices concerns the general area of labor-management relations. After dramatic "downsizing" in the 1980s, domestic vehicle manufacturers experienced contentious labor relations, marked by low levels of trust on both sides and little flexibility in terms of redesigning production processes. The introduction of the 2mm technology into the assembly process was not disruptive, however, because it had little effect on employment and did not visibly run afoul of existing labor agreements. In some plants, personnel greeted the new technology with enthusiasm, viewing it as an opportunity to work with advanced technology and computer systems and gain access to potentially higher long-term wage-earnings growth and greater job security. Labor thus viewed the evolution to 2mm technology as being consistent with union efforts to promote job "upskilling." Maintenance and repair of the 2mm hardware sometimes crossed job classifications. At different times, work might require a combination of trades, including electrical, tool repair, and data analysis. Because no such classification existed, everybody "turned a blind eye" to such work, rather than establish a new job title.

Table 2–1 summarizes the results of the 2mm project and distinguishes among four general categories of impacts:

1. short-run production costs,
2. long-run production costs,
3. indirect costs, and
4. market-share impacts.

We find evidence that short-run production-cost-reduction goals were largely achieved during the project and, to a lesser extent, so were the long-run production-cost-reduction goals. The indirect-cost impacts, notably the reduction in warranty costs, were probably achieved, although the evidence from the OEMs is unavailable. Finally, with respect to market-shares, the impacts (presented in Chapter 3) indicate that vehicle-body quality had a small, but statistically significant, impact on market shares and production costs for 2mm vehicles.

Table 2–1. 2mm Project Goals and Summary of Results from Case Studies

Goal	Result	Notes/Observations
	Short-Run Production Cost Impacts	
Reduce line downtime (increase capacity utilization and throughput).	Partially achieved.	• Faster problem troubleshooting, correction, and verification. • Higher sustainable line speeds, partially 2mm, partially improved tooling.
Reduce scrap/repair costs from: • Real-time quality feedback • Immediate BIW defect detection, removal, and/or repair • Rapid tool/equipment failure — identification, repair, or adjustment.	Achieved.	Estimated to be in the range of $1–3 per vehicle. (Eastern Michigan University (EMU) 1993 and plant interviews).
Reduce BIW rework/repair costs.	Achieved.	Estimated to be approximately $3.40 per vehicle (EMU, 1993).
Reduce body-shop labor inputs due to more efficient assembly-line maintenance and repair.	No observable change.	OCMM-use identified need to increase scope of maintenance activities. New labor inputs (e.g., dimensional engineers) now needed.
Reduce Substitute Metrology Costs: 1. Reduce CMM costs 2. Eliminate checking fixture costs.	Partially achieved. Achieved.	1. CMM still needed for other process control activities/research. 2. Elimination of checking fixtures estimated to be $2 million in one GM plant.
Reduce Launch Costs/Time.	Partially achieved.	OEMs have reduced launch time and costs, but line integrators note that time and costs have been shifted to their sites and these are not a product of 2mm. Reduction of approximately $2.50 per vehicle due to shorter launch.
	Long-Run Production Cost Impacts	
Reduce dimensional variation through body design and construction changes.	Partially achieved.	OEMs demonstrated slip-plane panel joinery reduces dimensional variation; little exploitation of body-shop experience in design activities.
Improve understanding of dimensional variation and its causes.	Achieved by University of Michigan.	Publicized findings in academic journals linked to 2mm activities.
Develop and test new procedures for mastering OCMMs (reducing launch times and costs),	No observable impact.	“Mastering” the OCMM cameras remains a problem. Nominal body dimensions still measured with CMM.

Table 2–1. 2mm Project Goals and Summary of Results from Case Studies, Cont.

Goal	Result	Notes/Observations
Indirect Production Cost Impacts		
Reduce warranty costs due to BIW quality defects.	Uncertain (some reductions likely.)	No OEM data available for estimating impacts.
Develop and establish market for analytic software for OCMM database analysis.	• Developed for in-house use at GM. • No commercial success for other efforts.	
Market Impacts		
Achieve 2mm (six-sigma) variation (“world-class” levels).	Achieved 2.5–3mm during project.	World-class standard continues to improve below 2mm.
Increase domestic-vehicle manufacturers’ market share.	Achieved (see Chapter 3).	
Improve owner evaluations of vehicle quality (J.D. Powers data.)	Uncertain.	Some plants report improvements that they attribute to 2mm; others see no change or are unwilling to attribute to 2mm.
Develop market and encourage use of OCMMs in automobile plants.	Achieved.	They are standard equipment in most U.S. auto plants.

Source: The authors.

Of the many detailed goals set forth in the project’s original proposal, we conclude that only three met with no, or limited, success:

1. achieve a reduction in body-shop labor inputs through improved maintenance and repair procedures,
2. reduce launch times attributable to faster “mastering” of the equipment to give accurate nominal measurements, and
3. develop and market analytic software to aid in dimensional-variation analysis and reduction.

Of these, only (1) represents an as-yet unrealized opportunity to achieve sizeable financial gains, perhaps because the potential gains from developing more efficient maintenance programs has an uncertain value from the perspective of the participant companies.

We are surprised that none of the participating companies has engaged in much research of their own concerning the effect of the 2mm technology on production costs or warranty claims. Firms either chose to ignore, or failed to realize, the potential benefits of using the wealth of available data for the analysis of the financial performance of the assembly lines after completion of the 2mm project. More important, they are not retaining much of the data for later use in product design and/or assembly equipment improvements in the future.[6] The increased quantity of capital and labor inputs now used for measurement and quality control as a consequence of the 2mm project is justified by participant firms using a "gut-feel" analysis.

All assembly-plant personnel whom we interviewed are unwavering in their assurances that the combination of equipment, software, and methods developed under the project are responsible for significant cost reductions and quality improvements. They have not subjected their conclusions to rigorous analysis but claim that cost reductions are so obvious that the analysis is unnecessary. They indicated that the ability of their firms to use the 2mm technology to identify production errors and contain problems to a small number of vehicles was sufficient justification for installing Perceptron's OCMM. They are now installed at virtually all North American auto and small-truck assembly lines in which Womack's "mass-production" model is in place (Womack, 1990), a fact we analyze in Chapter 3.

Even though the 2mm project results were generated through a cooperative effort, they were used by each of the two vehicle-assembly firms in a highly competitive fashion. Each sought to be first to market the 2mm vehicles, and the project offered an opportunity for engineers to display their expertise in understanding and correcting problems ranging from simple machine-tool adjustments to redesigning whole sections of the vehicle body. Several participants identified this capability as a key motivating factor to achieve rapid performance improvements. The availability of a quantifiable performance metric allowed participants to benchmark their products against the best in the world. It also equipped firms with an effective means of measuring progress and focusing attention on quantifiable objectives.

The project itself consisted of 11 R&D efforts, some of which proved that firms could employ 2mm technology to upgrade the performance of existing stamping and assembly-

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6. Model changeovers may limit the relevance of model-specific 2mm data, but personnel may be able to enhance their analyses of tool performance (for example, repeatability, up-time, and maintenance requirements/scheduling) and design characteristics by using the actual dimensional performance data generated by the optical coordinate measurement equipment. Framers of the initial proposal considered that long-term improvement in vehicle and tool design, as well as improved maintenance scheduling and procedures, would be key program benefits.

line tooling in their efforts to reduce BIW dimensional variation. Managers at the vehicle-assembly plants achieved this by keeping key line personnel up-to-date on current dimensional variation. Personnel could thus perform the necessary corrections or adjustments to intervene in near real time early in the process rather than at a much later point downstream after communicating with the customer. Personnel who use the alternative methods (coordinate measurement machines (CMM) and/or checking fixtures) obtain limited sampling data, but generally more points, than if they used OCMMs. OCMM proponents argue that by the time a technician measures the samples, other conditions may have further deteriorated and may even remain uncorrected for days and weeks at a time.

The 2mm project did not foster a reorganization of the workflow or methods, per se, in the vehicle body shop, although it did identify a number of weak areas in the current production process. It has effectively extended the limits of domestic manufacturers' capabilities within the bounds of the existing production scheme; but if world standards for dimensional variation continue to decrease in size, we believe that some reorganization of the production process in domestic firms may be needed to achieve this standard. Notably, both GM and Daimler-Chrysler stressed the purely subjective nature of a "2mm" target variation in vehicle assembly. Managers at both firms were skeptical of the customer's ability to detect quality improvements where BIW variation achieved levels less than 2–3mm.

In addition to certain cost reductions and market-share improvements that 2mm offered to the OEMs, we were frequently told that the 2mm technology also acted to improve labor relations in participant plants. The 2mm technology provides the primary benefit of an objective, quantitative metric upon which line operators can base accept/reject criteria for car bodies, including stopping the line. In the past, plant management often doubted the quality concerns voiced by skilled trades people. Now, armed with data provided by 2mm-based technologies, line operators can more easily than before communicate their concerns in a language that managers understand.

Conclusion

The 2mm project demonstrated that significant technological improvement in vehicle quality could be achieved over a short time-period on a small scale, but that in an industry as large and complex as this one, managers may not adopt the technology because of the existence of both institutional and technical barriers. The project demonstrated to its participants, and to their nonparticipating customers, that the technology works and can generate quality and productivity improvements quickly and potentially at low cost. The transformation of the industry, however, is tied to the "buy-in" of top management at the OEMs and the speed at which new equipment and trained personnel are moved into plants, with adoption being timed to new assembly-line installations and not necessarily the speed needed to meet competitive pressures. The 2mm project has permitted domestic manufacturers to go a long way to match foreign producers' quality, but looming in the background is the current existence of better-implemented methods that apparently do not use OCMMs very much, if at all.

In the areas of customer perception of post-2mm body quality, launch-time reductions, and warranty-cost impacts, we obtained no data and contradictory opinions from our interviews concerning these outcomes. In general, personnel at the OEMs contend that the equipment is critical for monitoring "the build" of vehicle bodies, but they concede that knowing the dimensional variation and actively undertaking to improve it are two different pursuits. OEM personnel do not have dimensional-variation standards to which they must adhere. If improving body quality of vehicles already selling well in the market at the existing quality level means slowing production, the OEM managers are reluctant to forego short-run revenue for "potential" long-run improvement in market perception.

We stress "potential" because neither GM nor DaimlerChrysler personnel have undertaken any research to match body-quality data to customer-opinion data, customer-satisfaction data, or warranty data. They are, as a former American Sunroof Corporation (ASC) engineer indicated, uninformed concerning the value of incremental improvements to body quality and are therefore unable to make educated estimates regarding a return on investment for this development path. Because they are fully aware of sales and profitability performance, we are not surprised that the OEM managers and engineers favor the outcome about which they have the most certainty, namely maintaining production volumes.

The Perceptron equipment clearly does not provide the only way to achieve a "2mm body," as demonstrated by the fact that Japanese and European manufacturers have done so using other methods. When line operators and managers use it in conjunction with continuous-performance analyses, they can develop body-quality standards. When they use it exclusively as a defect detector in its alarm-mode function, their ability to contribute to body-quality improvement is directly related to the tolerances they set for each alarm. From our observations, they set these tolerances to identify major flaws, not to promote continuous improvement. (In some cases, they use the OCMMs to ensure the presence of a critical part, such as a shock-tower reinforcement, not to measure quality of assembly.)

Managers at the vehicle-assembly firms have not realized all that they hoped for from the Perceptron equipment. They wanted to substitute Perceptron equipment for all of their dimensional control needs but found this to be too difficult. Nearly all case study respondents noted that "mastering" the Perceptron system to yield accurate nominal dimensional data is nearly impossible and that they have given up on using it for that purpose. They are able to obtain relative measurements over a set of points on the vehicle body, and this remains a significant achievement when enough critical points are measured.

The Perceptron equipment is still new enough that the OEMs have only now started to implement any kind of formal training program for hourly personnel responsible for its use and maintenance. The need and costs of providing such training were not fully anticipated by the initiators of the 2mm project in their move toward OCMM use. Perceptron, on the one hand, has found that a market exists to provide training in the use of its equipment, particularly with DaimlerChrysler. GM, on the other hand, has formalized the training as a part of each plant's annual training budget at around $200,000 per year per plant. They appear to be doing this with internal staff, however.

Perhaps more important than the attainment of the 2mm variation target itself was success of the project in demonstrating that industry-wide technological change could be stimulated by collaborative research focused on an industry-wide problem without threatening an otherwise competitive environment. In fact, the project created a competitive environment for engineers to reach the target variance, an important motivation for some participants, and a feature worth noting when designing future ATP projects. We also note the importance of recognizing impediments to the adoption of innovation at the institutional level. Future ATP designs should make every effort to account for such dynamics and build in the metrics and mechanisms necessary to ensure that organizational learning occurs. Failing to do so will result in efforts that routinely witness short-term, rather than lasting, industry change.

CHAPTER 3

Industry-Level Impacts: Analysis of the 2mm Project Impacts on U.S. Motor Vehicle Market Shares and Production Costs[+]

Introduction

This chapter utilizes model-based estimates and other research to assess the economic impact of the 2mm project on the domestic motor vehicle market and, by extension, U.S. economy.[7] In this chapter, we present results obtained from a hedonic-price model, which we used to help determine whether the 2mm project helped to reduce the cost and increase the overall demand for U.S.-made vehicles and to estimate the direct impacts of the 2mm project on the U.S. automobile and light-truck markets.

Framework of the Analysis

Economic analysts treat demand for complex heterogeneous products, such as housing, motor vehicles, or computers, by attempting to place value on the attributes that characterize such goods. Because no information is available on the price of each attribute, analysts use the hedonic approach. The approach involves analysis of a good's properties as hypothesized to affect selling price. In the case of automobiles and trucks, this means determining the degree to which vehicle size, performance, and option characteristics affect price.

[+] Ciro Biderman, Karen R. Polenske, and Nicolas O. Rockler wrote this chapter.

[7] Biderman, Polenske, and Rockler presented an earlier version of this chapter at the Summer Institute of the National Bureau of Economic Research in July 2001. We appreciate the assistance of the researchers who specifically contributed to this aspect of our work concerning the 2mm program: Stanley Abraham (Harvard Business School), Richard Roth and Daniel Whitney (MIT-Department of Mechanical Engineering), Eric Cahill and Alvaro E. Pereira (MIT-Department of Urban Studies and Planning), and Susan Helper (Case Western Reserve University). We also appreciate the automobile database furnished by Ariel Pakes and the truck database furnished by Amil Petrin, which we extended to produce our own database of vehicle attributes for automobiles and light-trucks.

For our study, we use characteristics such as wheelbase length, engine horsepower, or the presence of an automatic transmission in a multiple regression to measure their effect on price. The basic premise is that consumers purchase goods with different quantities of the various attributes so as to maximize their utility. Because there may be, in general, a difference in prices dependent on the quantity of the attribute, the analyst can infer the marginal price of each. We use a hedonic-price function developed by Berry, Levinsohn, and Pakes (1995) and, from this, derive two critical performance measures for 2mm vehicles: the effect of 2mm on market share and the effect of 2mm on producers' mark-ups (i.e., profitability). We show the full model development and discuss theoretical issues and concerns in Appendices 3-A and 3-B.

The main theoretical difficulty is that the attributes by which vehicles are characterized are, in reality, discrete ones; a limited set of choices exists, as in the case of engine horsepower or wheelbase length. This limited set yields a budget constraint that is non-linear and a demand function that is unconventional in that consumer preferences (with regard to an attribute) are represented by non-constant prices.

Databases

We have assembled three databases (vehicle-model, plant, and 2mm technology) from various sources to estimate attribute prices and production costs. The vehicle-model database has vehicle attributes, sales, and prices for virtually all U.S. car and light-truck models marketed each year from 1981 to 1998. The plant database contains annual information on the characteristics of plants that produced all domestic cars and light-trucks, including the number of assembly lines in each plant, the annual production capacity, the line-rate, plant square-footage, employment, and the different models produced. The 2mm technology database contains annual sales of 2mm optical coordinate measurement machines (OCMMs) to assembly plants, by plant, including the number of workstation systems and sensors purchased.

Vehicle-Model Database

For the vehicle-model database, we extended to 1998 the 1981–1990 data furnished to us by Berry, Levinsohn, and Pakes (BLP) (1995) for cars, hereafter referred to as BLP, and by Petrin (2000) for light-trucks. Because vehicle models come and go over time, we consider the model to be the same from one year to another if its name is unchanged and its size characteristics or engine displacement remains within 10% of its prior years' figures.[8] We estimate the hedonic prices of the following car/light-truck attributes:

- number of cylinders
- number of doors
- horsepower
- engine displacement
- length
- width
- height
- weight
- wheelbase
- the drive-type, i.e., front-wheel drive (fwd), rear-wheel drive (rwd), or four-wheel drive (4x4)
- U.S. Environmental Protection Agency (EPA) miles per gallon

We use the 2mm variable to control for whether or not a model in a plant is using Perceptron equipment.[9] We also use variables for special vehicle body-types, such as minivans, sport-utilities, full-size vans, pickup trucks, and station wagons, to determine the impact of body type on vehicle prices. We use another set of qualitative variables to control for the origin of non-domestic manufacturers, i.e., Japan, Korea, or Europe.[10]

Our vehicle-model database is virtually identical to that of BLP in terms of market coverage, including items such as aggregate sales value, number of vehicles sold, average horsepower-to-weight ratio, or average vehicle size. However, we do show a significantly higher number of models (about 20% more) than BLP, due to our inclusion of vehicles that share an identical name but have a different body style, for example, a sedan and station wagon.

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[8] This is compatible with the BLP criteria. It is important to track the vehicle model to allow for same-model correlations in different years.

[9] The 2mm variable has a value of zero if an observed data point does not have the attribute and a value of one if it does.

[10] We constructed these variables based on location of producers' headquarters or actual location of production. For instance, the variable "EURO" has a value of one if the vehicle was produced in Europe and zero otherwise; and the variable "IMPORTS" has a value of one if the vehicle production was located outside the United States or Canada and zero otherwise.

Table 3–1. Automobile Sales, 1988–1998 MRP Versus the Universe (Number of vehicles in 1000s)

	Total			U.S. Firms			Asian Firms			Imports		
Year	*Universe*	*MRP*	*Percent*	*Universe*	*MRP*	*Percent*	*Universe*	*MRP*	*Percent*	*Universe*	*MRP*	*Percent*
1988	10,594	9,908	94	7,303	7,062	97	2,713	2,389	88	3,068	2,286	75
1989	9,772	9,390	96	6,635	6,523	98	2,656	2,412	91	2,757	2,444	89
1990	9,296	8,690	93	6,113	5,913	97	2,724	2,405	88	2,453	2,028	83
1991	8,176	8,022	98	5,248	5,209	99	2,589	2,486	96	2,103	1,933	92
1992	8,211	8,122	99	5,301	5,246	99	2,579	2,572	100	1,994	1,546	78
1993	8,520	8,256	97	5,621	5,400	96	2,592	2,574	99	1,845	1,418	77
1994	8,991	8,749	97	5,809	5,742	99	2,794	2,636	94	1,809	1,432	79
1995	8,710	8,680	100	5,620	5,572	99	2,686	2,668	99	1,612	1,235	77
1996	8,529	8,453	99	5,328	5,289	99	2,699	2,677	99	1,389	1,137	82
1997	8,289	8,252	100	5,006	4,974	99	2,729	2,708	99	1,381	1,221	88
1998	8,187	8,139	99	4,701	4,698	100	2,789	2,728	98	1,441	1,227	85

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Note: Numbers do not add to the totals shown because categories are not mutually exclusive, for example, both U.S. and Asian firms account for some of the imports.

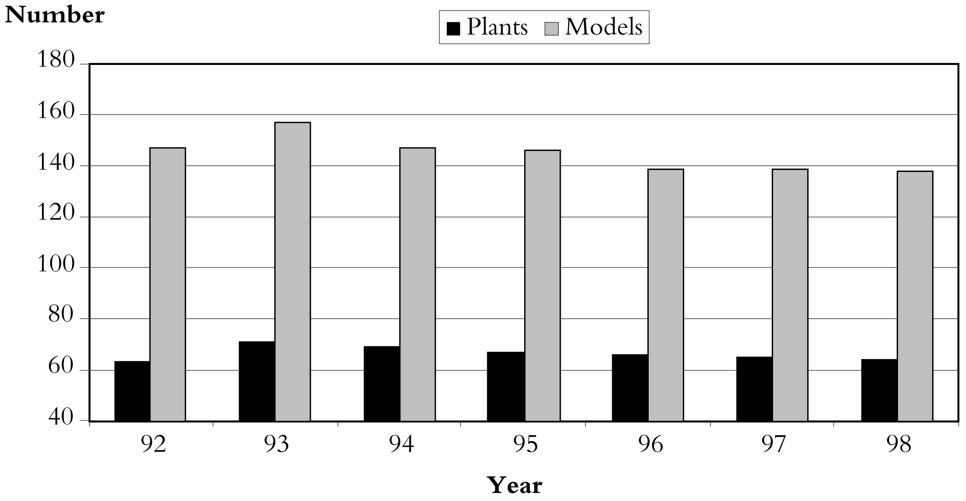
Source: Wards, Automotive News (multiple years); the MRP tabulations using the MRP automobile and light-truck database.

In aggregate, Table 3–1 shows that the multiregional planning staff database we constructed (called MRP) corresponds well to that given for the industry total in Wards Automotive Yearbook (Wards) and Automotive News Market Data Book (Automotive News). In some instances, however, large differences between imports and our database are evident.

The 2mm and Plant Databases

The MRP plant database covers North American assembly plants from 1992–1998. The number of operating plants peaked at 73 in 1993, up from a low of 63 in 1992, the year the 2mm project began (Figure 3–1). The total number of different vehicle models produced at all of these plants ranged from 138 in 1998 to 157 in 1993. The average number of models produced per plant has fluctuated from year to year, but has remained in a narrow range of 2.1 to 2.4 models per plant (Figure 3–2). There is a slight downward trend evident in the data with individual plants producing fewer models, but the interval shown is too short to draw any meaningful conclusion. We note that 2mm technology is supposed to increase flexibility on the assembly line to accommodate the larger variation in models sought by consumers.

Figure 3–1. North American Assembly Plants and Vehicle Models, 1992–1998 (Number of Plants/Models)

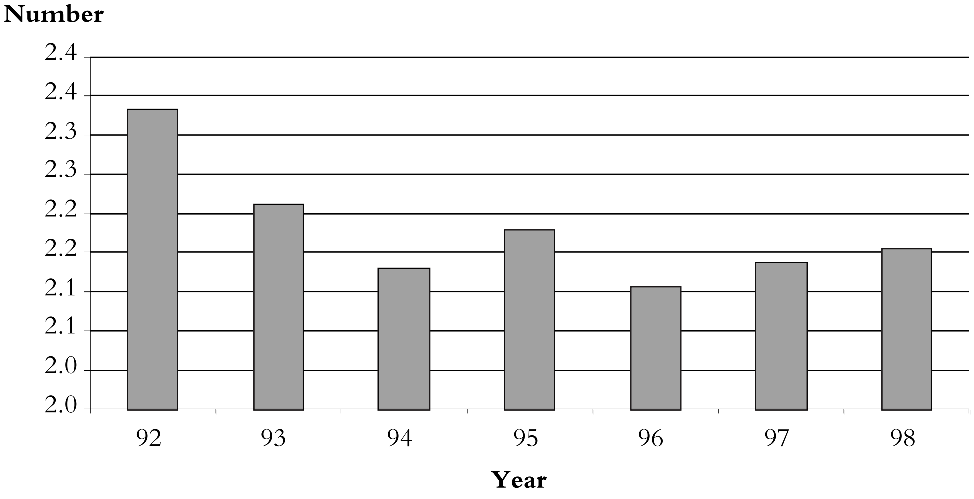


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–2. Average Number of Models Produced per Assembly Plant, 1992–1998 North American Car and Light-Truck Plants



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Of the 73 North American plants included in our database, we can consider only a portion of these to be 2mm, that is, a plant equipped with the necessary OCMM equipment, software, and personnel. We have examined the sales data provided to us by Perceptron, Inc., regarding number of systems and sensors sold to and installed in each plant in the year the sale was recorded.[11] From these data, we observed that among the assembly plants originally involved in the 2mm research project, the minimum number of systems was three, and the minimum number of sensors was 75. We applied these minimum threshold values to determine which plants were eligible to be termed "2 mm," resulting in 31 of 73 plants' being classified as 2mm by 1997. Of the remaining 42 plants, 26 were operated by GM, Ford, and DaimlerChrysler without any OCMM equipment or an insufficient number of systems/sensors and 16 were operated by non-North American-based firms, also without 2mm equipment.

We use Perceptron's annual plant-specific sales data for OCMM systems and sensors to characterize the vehicles produced as to their 2mm status. Perceptron's data cover all domestic and international sales of such equipment to assembly plants annually from 1988–1999. We note that a number of the "Big 3" (Ford Motor Co., General Motors Co., and DaimlerChrysler, Inc.) domestic plants had OCMM equipment identical to that used by project participants prior to the formal start of the project in 1992. The question arises as to how to treat vehicles produced in these plants using OCMM equipment during and after the formal research project but without benefit of the formal research process. There is the possibility, for example, that personnel in a properly equipped Ford plant could have learned a number of the techniques developed in the 2mm project and therefore have produced "2mm" vehicles.[12] We consider the possibility that the presence of the OCMM equipment might result in some measure of increased market-share or greater sales revenue even without the diagnostic and statistical procedures developed for fault identification, monitoring, and correction.[13] To incorporate this possibility into the analysis, we constructed

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[11] These plants, all of which were located in Michigan, included two GM plants: Orion Assembly (Lake Orion), Hamtramck Assembly (Detroit) and three DC plants: Warren Assembly (Detroit), Jefferson North (Detroit), and Warren Truck Assembly (Detroit). A number of stamping plants were also equipped with Perceptron systems used in the manufacture of subassemblies, such as rear doors of minivans and sport-utility vehicles (SUVs).

[12] These could have been gained through direct instruction from Perceptron personnel who make plant visits for service and technical updates, or through other vendors, such as the assembly-line integrators, who were able to apply 2mm research results as they were developed.

[13] If nothing else, the presence of the OCCM equipment in the plant indicates that corporate- or plant-level management has undertaken some steps to reduce dimensional variation in the body shop. We have no way of knowing how intensely the equipment was used to this end, however.

the following three measures to describe how thoroughly the vehicles were manufactured with OCMM equipment, depending on the year of construction, the specific manufacturer, and the plant(s) in which each model was produced.[14]

Unrestricted: We consider vehicles to be "2mm" if they are produced in a plant that has a sufficient quantity of 2mm equipment (as recorded sales by Perceptron), regardless of who owns the plant. We treat plants as 2mm in the year the sale occurs, but we impose a lag that ranges from 1 to 3 years to examine the possibility that it takes time for the quality improvement to be realized in the marketplace. Arguably, a one-year lag from the sales-booking date ought to be the minimum considered reasonable to account for the delay between ordering equipment from Perceptron and the time required to manufacture, install, start-up, break in, and train personnel needed for full operation of the system.

Restricted: We consider vehicles to be "2mm" during 1992–1994 if they are produced in a GM or Chrysler plant with sufficient 2mm equipment. For 1995 and later, Ford-produced vehicles can also be 2mm if manufactured in properly equipped Ford plants. With this definition, we distinguish vehicles from plants that had formal research and training (GM and Chrysler) from those that just had OCMM equipment. We allow Ford to produce 2mm vehicles on the presumption that knowledge gained in the research phase of the project becomes public through vendors, educational institution contacts, and industrial forums, meetings, etc.

Highly Restricted: We consider a plant to be "2mm" only if it was GM or Chrysler and had sufficient OCMM equipment. This definition permits us to test whether the formal research process and results, in combination with the OCMM equipment, appear to generate higher values or market shares than are realized for vehicles produced with the hardware alone.

We define "sufficient" equipment somewhat arbitrarily. In examining Perceptron sales data for 2mm participating plants, those plants that were engaged in the formal research of the project, we see that these plants were equipped with a minimum of three "systems" (self-contained computer workstations) and 75 sensors. The Perceptron sales data that

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[14] Some models of cars and light-trucks are produced in several plants. For instance, the Oldsmobile 88 was produced in Wentzville, Missouri, and Flint, Michigan. We do not have sufficient data to distinguish actual sales of each model by plant; thus, we are forced to assume an ad hoc split of sales to be 50/50 in the case of two plants, and other even proportions in the case of more. Some plants have multiple assembly lines. We have assumed that, once the plant is considered 2mm, all models produced in the plant are "2mm." It is possible that some models, however, were produced on a line not (yet) equipped with the OCMM equipment. Nevertheless, plant personnel could apply the analysis techniques on a very limited basis using substitute technology.

start in 1988 indicate that the firm sold a number of stand-alone Perceptron systems with fewer sensors to a variety of manufacturers, both domestic and foreign. According to Perceptron, these stand-alone systems were used in research activities for troubleshooting discrete assembly-line problems and not usually for production monitoring. A technical sales representative at Perceptron concurred that a 2mm plant would have needed to have at least 3 systems and 75 sensors to provide enough data to cover key body measurements. We used the three definitions to help assess the direct economic effect of 2mm technology.

In our modeling of the 2mm variable, we define a 2mm plant according to whether they have or do not have the minimum of 3 systems and 75 sensors. In actuality, we know that the number of sensors varies from 15 to 50 per workstation, and there are usually four workstations on a given assembly line. We could have constructed a variable that takes into account the number of OCMM systems by vehicle truncated at 0 (for vehicles that are not under the project). However, because any index is arbitrary and the 2mm variable has a very straightforward interpretation, we adopted the simplified variable as our proxy. Even though the presence of the OCMM equipment is a necessary condition for a vehicle to be considered "2mm," it is not a sufficient condition. We therefore recognize that the presence of one or more systems is an imperfect indicator that a plant is committed to the project.

At the start of the 2mm project in 1992, a very low percentage of all vehicles sold in the United States were produced in plants with the OCMM equipment. Vehicle-assembly plants adopted the OCMM equipment rapidly during the project years through 1995, with 54% of all vehicles sold coming from OCMM-equipped plants (Table 3–2). After 1995, this percentage grew, but at a much slower pace, reaching 66% by 1998. In later years, growth slowed dramatically and even turned downward somewhat for cars. We also

Table 3–2. Vehicle Sales: 1992–1998 by Production Plant OCMM Status (Number of vehicles in 1000s)

	Cars			Light-Trucks			Total Vehicles		
Year	OCMM Equipped	Total	Percent	OCMM Equipped	Total	Percent	OCMM Equipped	Total	Percent
1992	884	8,215	11	491	4,629	11	1,375	12,844	11
1993	1,327	8,518	16	1,963	5,346	37	3,290	13,864	24
1994	2,572	8,990	29	3,339	6,034	55	5,911	15,024	39
1995	3,799	8,636	44	4,164	6,054	69	7,963	14,690	54
1996	4,307	8,527	51	4,388	6,519	67	8,695	15,046	58
1997	4,351	8,272	53	5,498	6,797	81	8,695	15,046	58
1998	4,121	8,142	51	6,000	7,297	82	10,121	15,439	66

Source: Wards, Harbour Report, Perceptron, Inc., and www.doc.gov\bea "Motor Vehicle Sales."

calculated the vehicle sales separately for cars (Table 3–3) and light-trucks (Table 3–4) for the three different 2mm definitions. For cars, the percentages in 1992 ranged from 0% of the total units produced under the highly restrictive definition to 18% under the unrestricted 2mm definition (Table 3–3). For light-trucks, the figures are dramatically higher. In 1992, the percentages ranged from 10% under the highly restricted and 59% under the unrestricted definition (Table 3–4).

Table 3–3. Car Sales: 1992–1998 for Different 2mm Definitions (Number of vehicles in 1000s)

	Unrestricted				Restricted				Highly Restricted				Total	
Year	**Model**	**%**	**Units**	**%**	**Model**	**%**	**Units**	**%**	**Model**	**%**	**Units**	**%**	**Model**	**Units**
1992	16	9	1,502	18	2	1	288	4		0		0	173	8,215
1993	23	14	2,245	26	15	9	1,428	17	8	5	537	6	166	8,518
1994	30	19	2,899	32	13	8	1,100	12	6	4	369	4	160	8,990
1995	43	29	3,995	46	28	19	2,718	31	21	14	1,861	22	149	8,636
1996	48	34	4,307	51	37	26	3,369	40	37	26	3,369	40	141	8,527
1997	47	33	4,351	53	37	26	3,568	43	37	26	3,568	43	141	8,272
1998	45	33	4,122	51	39	28	3,705	46	39	28	3,705	46	138	8,142

Note: The first column in each set represents the number of vehicle models that were produced with 2mm technology; the second column represents the percentage of total vehicle models that were produced with 2mm technology; the third column is the number of vehicles produced with 2mm technology; and the fourth column is the percentage of total vehicles produced that were 2mm. The totals include non-2mm vehicles.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Wards, Harbour Report, Perceptron, Inc., and the MRP Automobile Database.

Table 3–4. Light-Truck Sales: 1992–1998 for Different 2MM Definitions (Number of vehicles in 1000s)

	Unrestricted				Restricted				Highly Restricted				Total	
Year	**Model**	**%**	**Units**	**%**	**Model**	**%**	**Units**	**%**	**Model**	**%**	**Units**	**%**	**Model**	**Units**
1992	21	36	2,731	59	5	8	911	20	4	7	441	10	59	4,629
1993	22	35	3,689	69	10	16	2,626	49	9	15	2,082	39	62	5,346
1994	28	46	4,577	76	16	26	3,584	59	13	21	2,806	47	61	6,034
1995	32	51	4,841	80	16	25	3,396	56	13	21	2,513	42	63	6,054
1996	36	59	5,375	82	22	36	3,999	61	22	36	3,999	61	61	6,519
1997	38	59	5,498	81	26	41	4,158	61	26	41	4,158	61	64	6,797
1998	39	57	6,043	83	29	43	4,697	64	29	43	4,697	64	68	7,297

Note: The first column in each set represents the number of vehicle models that were produced with 2mm technology; the second column represents the percentage of total vehicle models that were produced with 2mm technology; the third column is the number of vehicles produced with 2mm technology; and the fourth column is the percentage of total vehicles produced that were 2mm. The totals include non-2mm vehicles.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Wards, Harbour Report, Perceptron, Inc., and the MRP Automobile Database.

The higher rate at which plants adopted the technology for light-trucks versus cars highlights the tendency toward a greater reliance on technical-analysis characteristics of the light-truck engineering compared with automobiles, something we observed in the case study research. Although the origins of the difference between the two vehicle types are unclear, the data show it to be sizeable. Our anecdotal evidence does not indicate that it is market driven, that is, that light-truck customers are more sensitive to the fit-and-finish characteristics that are the product of better dimensional-variation control. Rather, it seems to be that engineers who have these concerns have been drawn to truck engineering, possibly because of the greater emphasis put on truck engineering performance in the domestic industry.

Vehicle Characteristics and Market Historical Overview

During the last two decades, the U.S. market for automobiles and light-trucks has undergone a significant change in composition. We show the annual sales volumes for 1984–1998 in Figures 3–3 and 3–4 for cars and light-trucks in quantity and value terms, respectively. In the first half of the 1980s, car sales increased constantly (in unit and in dollar terms) reaching a peak in 1986 (Figure 3–3). After 1986, the number of cars sold decreased constantly and stabilized around 8 million vehicles after 1991; most of the decrease can be attributed to the increase in light-truck sales. The automobile unit-sales decreased faster than value. Actually, starting in 1996, the two series diverge; consumers are buying fewer cars, but more expensive ones than they had purchased earlier.

Just as the composition of sales has changed dramatically since the 1980s, the domestic share of the market has seen considerable shrinkage. Sales by U.S. manufacturers (Chrysler, Ford, and General Motors) fell from 74% in 1981 to 57% in 1998 (Figure 3–5).[15] The manufacturers seem unable to reverse that trend. In the late 1990s, the European market share started to increase. After 15 years of remaining at slightly over 4% of the total sales, the European market share more than doubled from 1995 to 1998 (from 4.2% to 8.8%). Imports decreased from a high of 27% in 1981 to 15% in 1998 (Figure 3–6). Although there is considerable fluctuation during these years, we observe a clear downward trend. The decrease in the market share of the U.S. manufacturers and the decrease in the imports can be mainly explained by the increase in the transplanted import production. “Transplants” are cars manufactured by foreign producers in U.S. plants. In the 1980s, the transplants in the United States started with a very low market share, less than 1% of the market. By 1998, the transplants represented more than 25% of the market.

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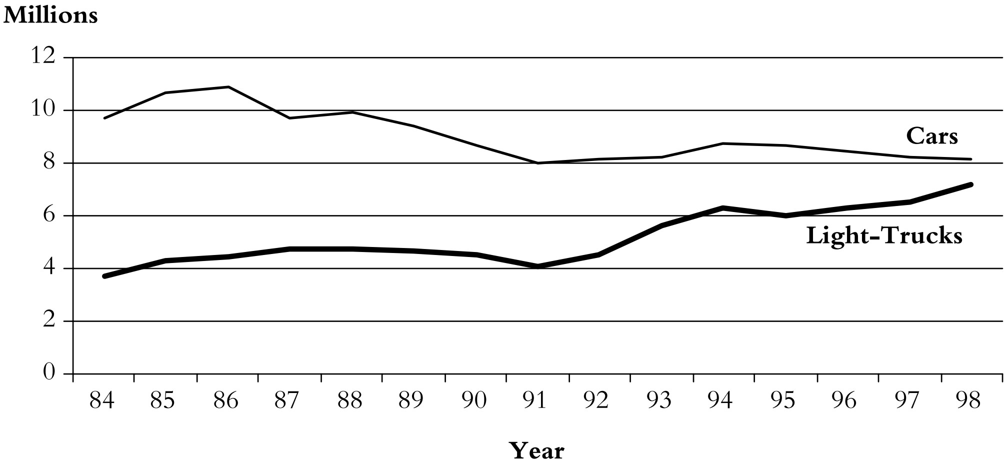
[15] Chrysler became Daimler Chrysler in 1998.

Figure 3–3. Car and Light-Truck Sales U.S. Market, 1984–1998 (Millions of Vehicles)

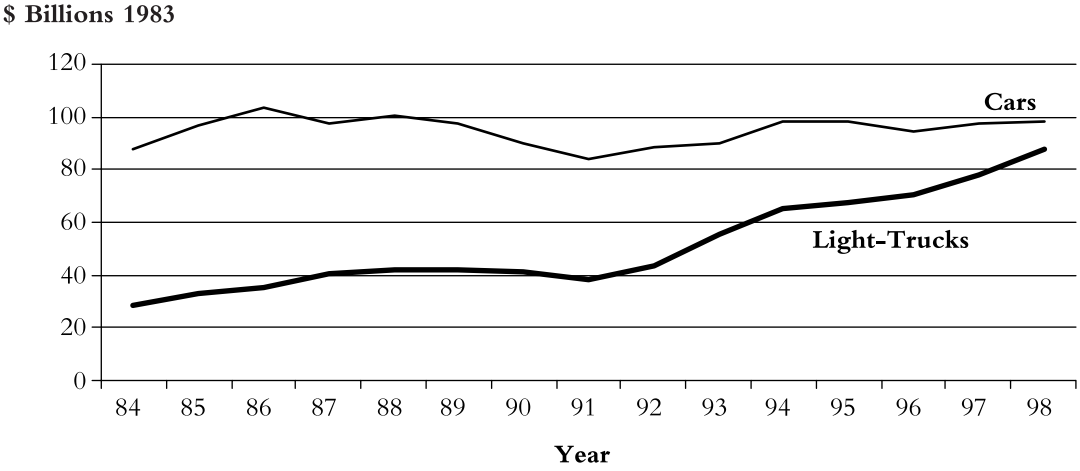


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–4. Car and Light-Truck Sales U.S. Market, 1984–1998

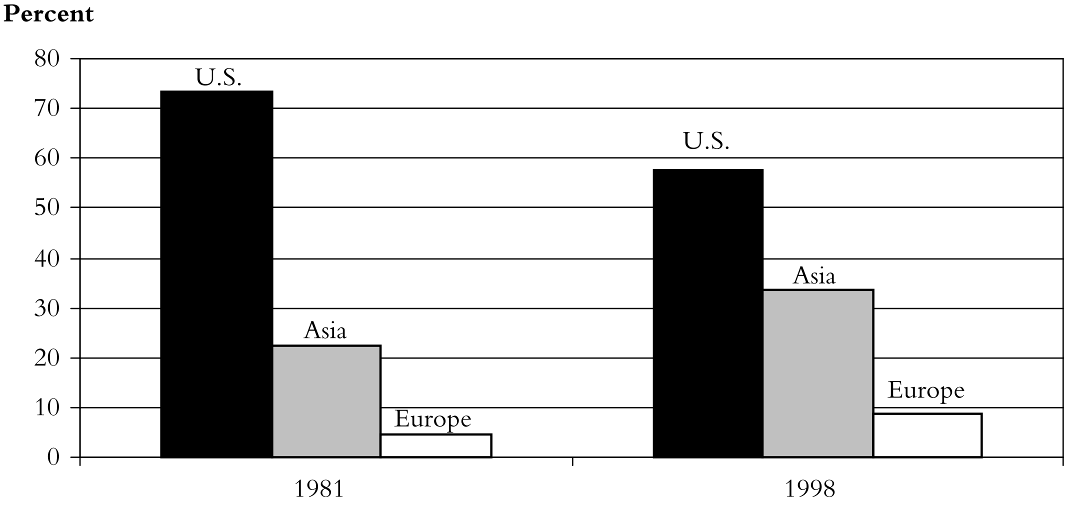


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–5. Share of U.S., Asian, and European Manufacturers in the U.S. Automobile Market 1981, 1998

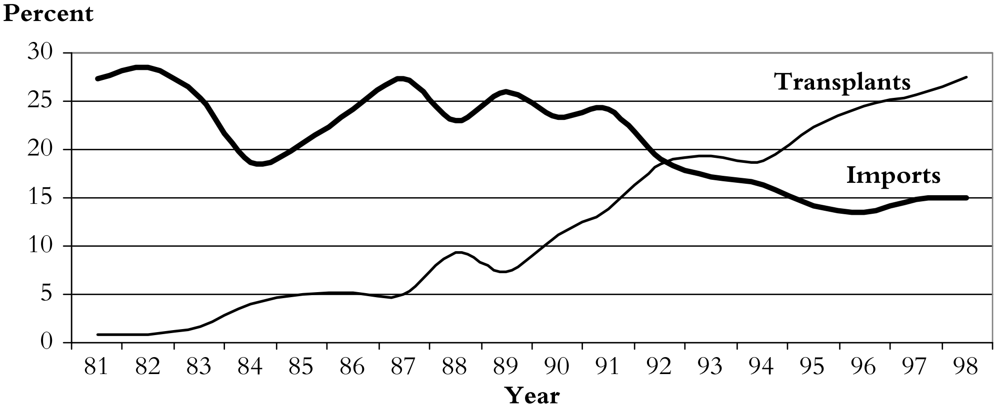


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP tabulations using the MRP automobile database.

Figure 3–6. Import and Transplant Automobile Shares in the U.S. Market, 1981–1998



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP staff tabulations using the MRP automobile database.

From 1984 to 1998, the trend toward increasing light-truck sales is clearly evident (see Figures 3–3 and 3–4). Until the late 1970s, sellers of light-trucks were focused on commercial buyers as opposed to households, although the idea of an all-purpose family compact van had been circulating in the car industry since at least the 1950s (Yates, 1996). In the early 1970s, in its "mini/max" program, Ford proposed a vehicle that it believed would satisfy an unserved portion of the market. The result was a front-wheel drive van better suited for family use than the station wagon, although Ford was afraid that this style of vehicle would cannibalize its station-wagon sales. Nevertheless, the minivan market became firmly established in the early 1980s with Chrysler's Plymouth Voyager and Dodge Caravan.

In 1984, more than 50% (2.4 million) of the light-truck sales were pickups (Figure 3–7). The market for the just-created new vehicle, now called a "minivan," was obviously very small at first. Even the sport-utility vehicle (SUV) market, the second largest category of light-trucks, was small compared with that for pickup trucks, with only slightly more than 0.6 million sport-utility vehicles (SUVs) sold in 1984 compared with 2.3 million pickup trucks. By 1998, this situation had completely changed; the SUV market was about the same size as that for pickup trucks (2.7 versus 2.9 million vehicles, respectively), and more than 1 million minivan vehicles were sold, despite an economic slowdown in the early 1990s. The sales of cargo vans and full-size vans did not increase, but remained at less than 0.5 million units throughout the period, which underscored the fact that the huge growth noted in the light-truck market was due to the extent to which light-trucks became substitutes for cars. We do not view a pickup truck as just a commercial vehicle, because the role of pickup trucks has changed and consumers now use small pickup trucks as personal vehicles.

Another important difference between these two markets is the behavior of the market share of U.S. companies. In 1984, they had 84% of the light-truck domestic market and 78% of the car market (Figure 3–8). By 1998, the domestic companies retained their share of the light-truck market but lost a vast part of the market for cars, which fell to a 58% share.[16] Transplants represent a small share of the light-truck market. In 1984, transplants produced 3.2% of the light-trucks sold in the United States, compared with 2.4% in 1998.

With the three databases, we have a complete set of auto and light-truck data that depicts models, characteristics, and the plants at which they were produced. During the 1970–1998 period, the U.S. vehicle market was subjected to two significant and wide-ranging

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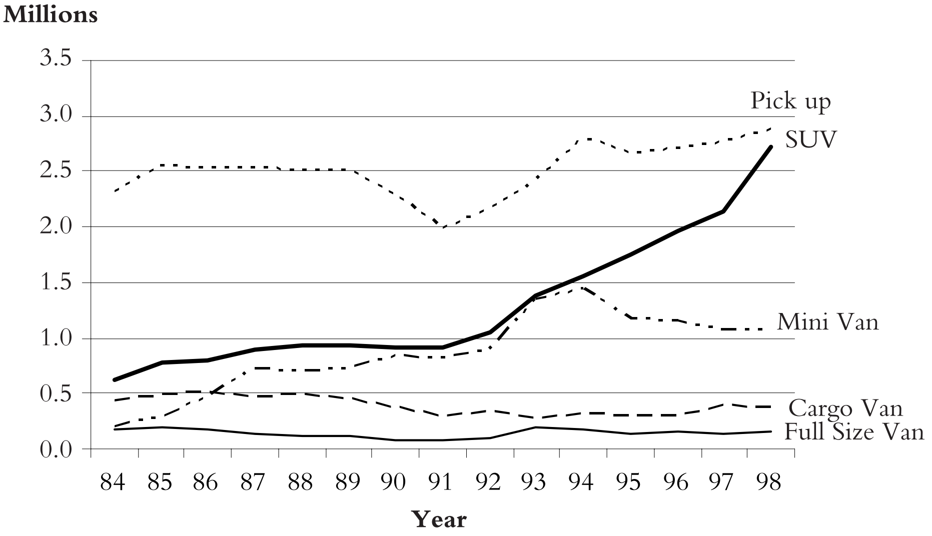
[16] We do not show European firms in the figure, but they are almost negligible in the light-truck market, so that Asian firms comprise most of the remaining 15% of that market.

Figure 3–7. Light-Truck Sales by Vehicle Type, 1984–1998 (Number of Vehicles)

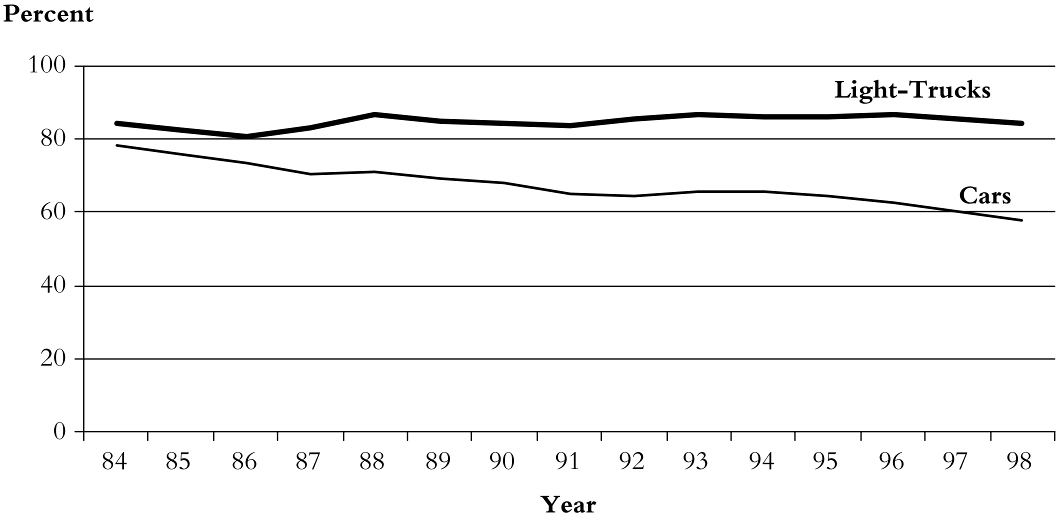


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP staff tabulations using the MRP light-truck database.

Figure 3–8. U.S. Market Share in Light-Trucks and Cars, 1984–1998



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

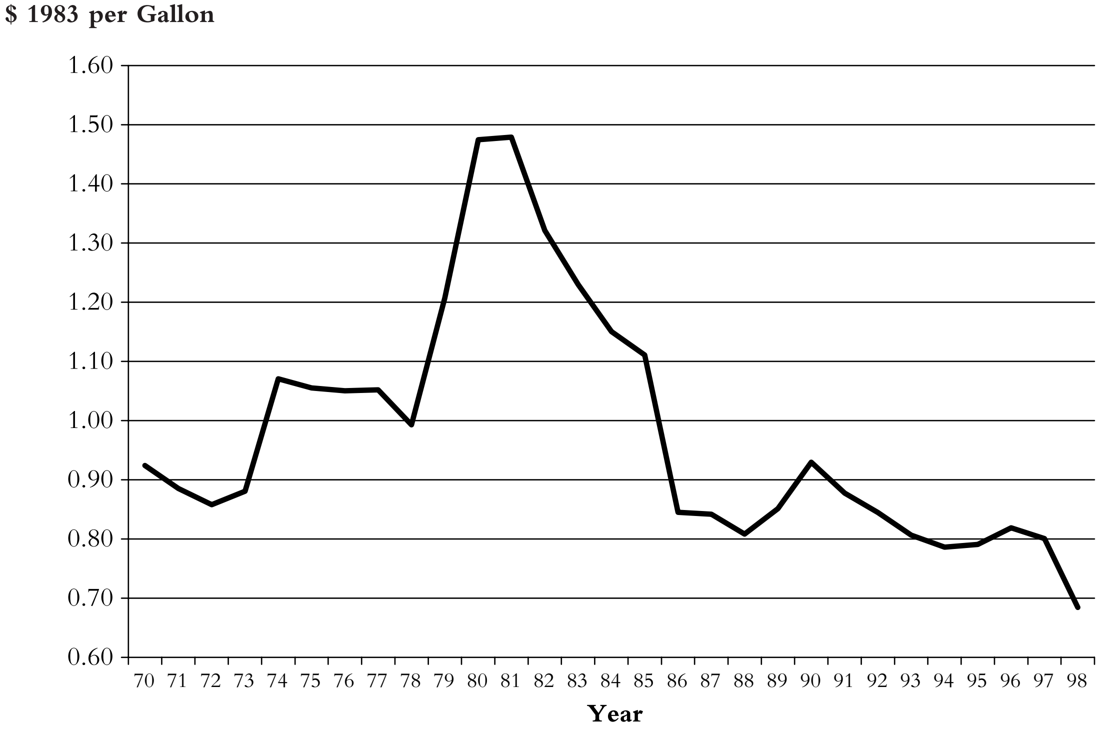
Sources: Wards, Automotive News (multiple years).

MRP staff tabulation using the MRP automobile and light-truck database.

shocks, both linked to volatile gasoline prices. The first was a two-stage increase in gasoline prices that occurred in 1974 and 1980 (Figure 3–9). These increases paved the way for smaller and more fuel-efficient imports to gain a foothold in the U.S. market. At first, imports competed on the basis of fuel economy, but later, their high manufacturing quality and comparatively low ownership costs were added selling points. By 1998, imports accounted for nearly 15% of total car sales, and transplants accounted for another 25% of the total.

The second shock was the dramatic fall in real oil prices starting in 1982. By 1986, prices had fallen below those seen during the "1970s gas crisis," and they continued to drift downward during the 1990s. The prolonged period of declining (and low) real gasoline

Figure 3–9. Retail Gasoline Prices, 1970–1998



Sources: American Petroleum Institute, Consumer Information, Historical Price Comparison, Updated 3/20/00 from www.api.org/consumer/gaspricecharts.htm.

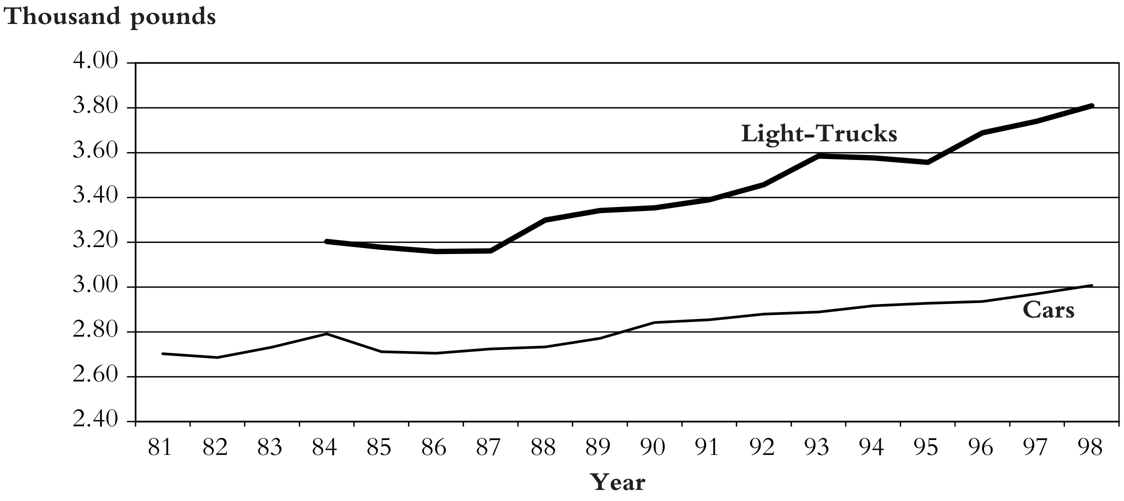
prices encouraged a shift toward larger, higher-powered, heavier, and less fuel-efficient vehicles during the latter part of the decade, evidenced by the emergence of the minivan and the sport utility vehicle (SUV) as high-growth segments of the overall vehicle market.

In the following sections of this chapter, we review changes in the characteristics of the vehicles in the U.S. market, as well as the size and growth rate of the market itself.

Size Characteristics

Using the MRP database assembled from BLP (1995), Wards, and Automotive News, analysts can view vehicles' physical characteristics in several ways. Among these are measures of curb weight (unloaded vehicle weight), overall vehicle length, overall width, wheelbase length, height, and footprint-size (length multiplied by width). In Figures 3–10 through 3–13, we show these size characteristics for cars and light-trucks, as well as time-series observations of size to see how these have changed over time. Not surprising is that light-trucks are, on average, heavier, wider, and have longer wheelbases than passenger cars. However, in overall body length, light-trucks are shown (with some variation) to

Figure 3–10. Average Vehicle Weight, 1981–1998

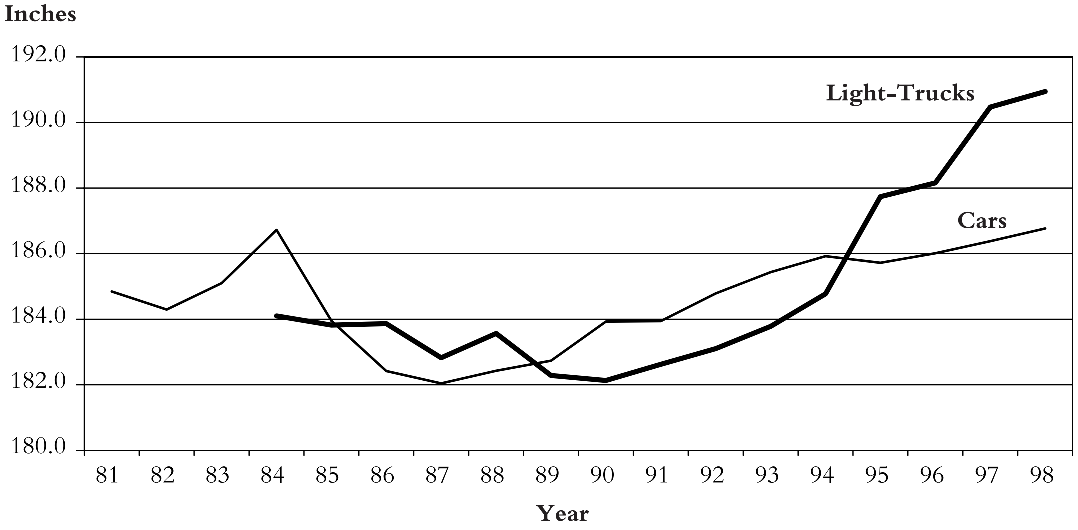


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP staff tabulations using the MRP auto/light-truck database.

Figure 3–11. Average Vehicle Length, 1981–1998

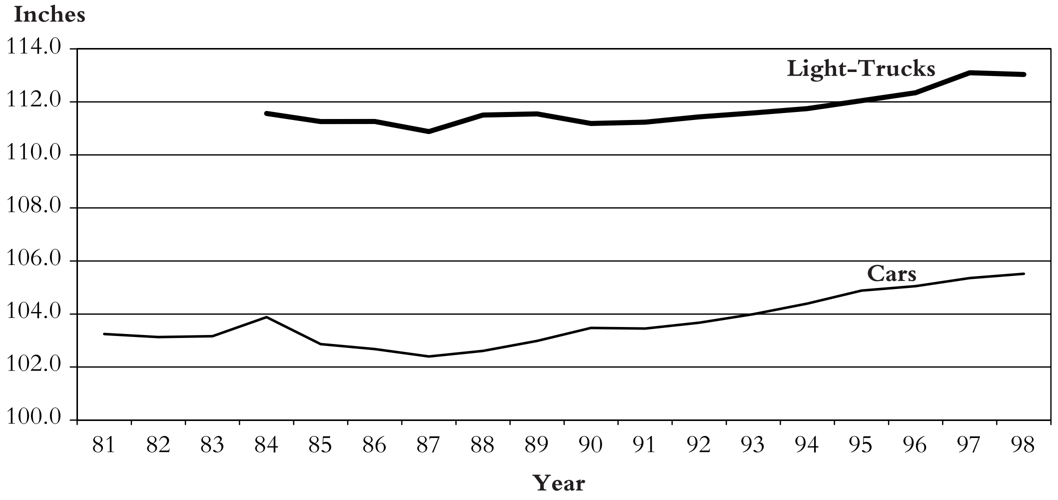


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–12. Average Vehicle Wheelbase Length, 1981–1998

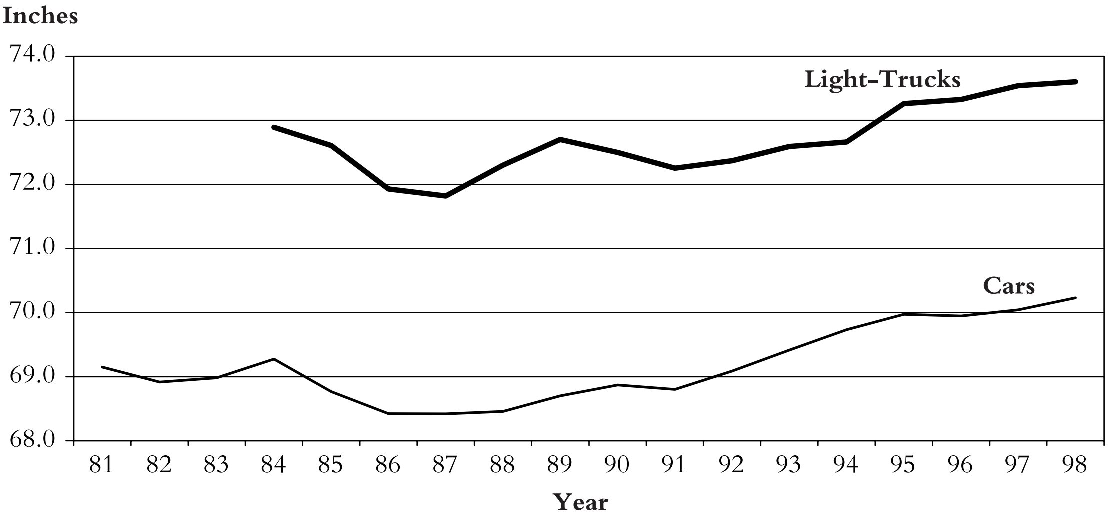


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–13. Averages Vehicle Width, 1981–1998



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

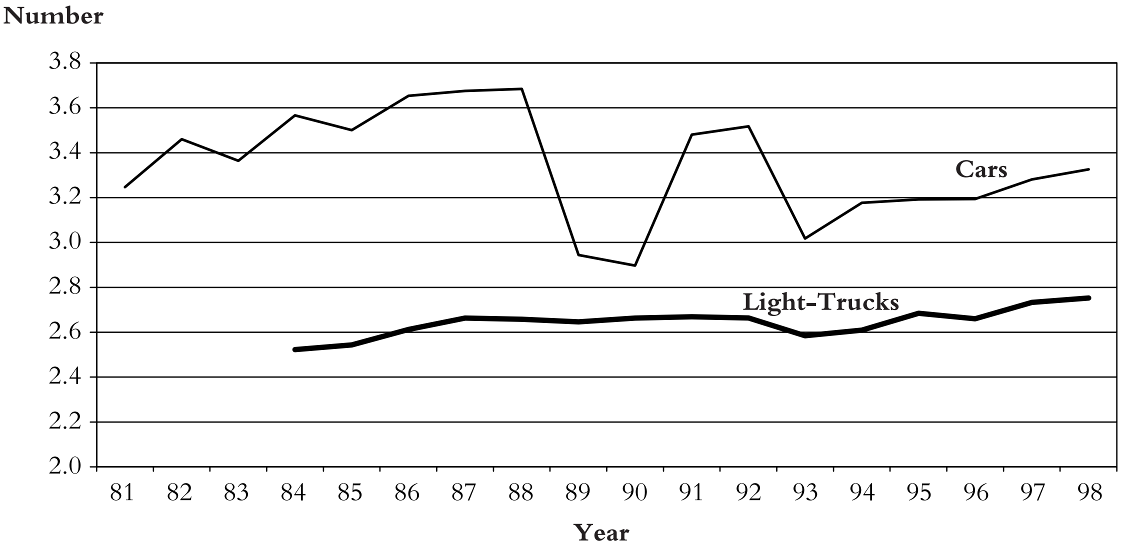
MRP tabulations using the MRP automobile and light-truck database.

be about the same size as the average passenger car through the mid-1990s, when light-trucks grew to be several inches longer than the average car.

We conjecture that increasing body size and vehicle weight exacerbates the difficulty of controlling body dimensional variation and therefore heightens the importance of 2mm technology. Larger vehicle bodies have larger and/or more components, thereby increasing the number of fixture points, material handling steps and/or welding operations in the assembly process. Together, these increase the complexity of the assembly operations linked to vehicle size and, therefore, the need for greater dimensional control.

In addition to larger sizes, greater complexity has resulted from a growing preference for more doors per vehicle, particularly in light-trucks (Figure 3–14). Although cars display little in the way of trend during the 18 years shown in the figure, the average number is volatile over time, ranging from 2.8 doors per vehicle to 3.7. Such a range over a relatively short time period indicates that manufacturers may benefit from being flexible in order to accommodate changing configuration preferences. In contrast, the average number of doors for light-trucks grew steadily from 2.5 per vehicle in 1981 to nearly 2.75 by 1998,

Figure 3–14. Average Doors per Vehicle, 1981–1998 (Doors/Vehicle)



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

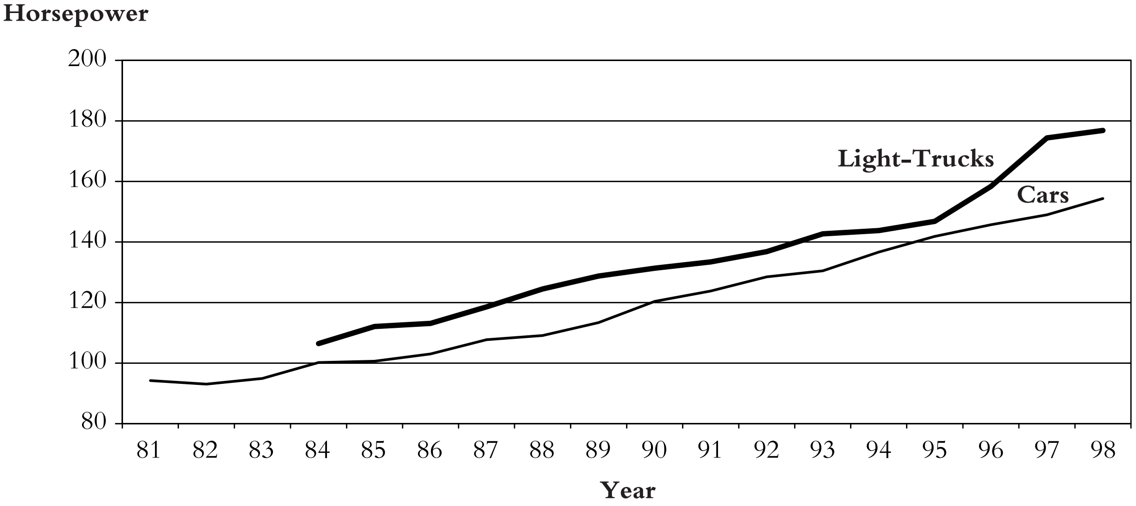
MRP tabulations using the MRP automobile and light-truck database.

an increase we attribute to the growing share of the light-truck category that comprises minivans and SUVs. The additional doors per vehicle may also increase the complexity of the assembly operation and the need for dimensional control.

Performance Characteristics

In addition to becoming larger over the last two decades, the average vehicle has seen dramatic increases in engine horsepower (h.p.) and power-to-weight ratio. This is true for both cars and light-trucks (Figures 3–15 and 3–16). In the case of cars, average h.p. has risen from approximately 95 in 1981 to almost 160 by 1998, an increase of more than 60%. The horsepower-to-weight ratio increased from .035 h.p./pound in 1981 to more than .05 h.p./pound in 1998, an increase of nearly 50%. These changes are seen for all vehicles regardless of origin, not just those from domestic producers. For light-trucks, gains in average engine horsepower and power-to-weight ratios parallel those of cars.

Figure 3–15. Average Engine Horsepower, 1981–1998

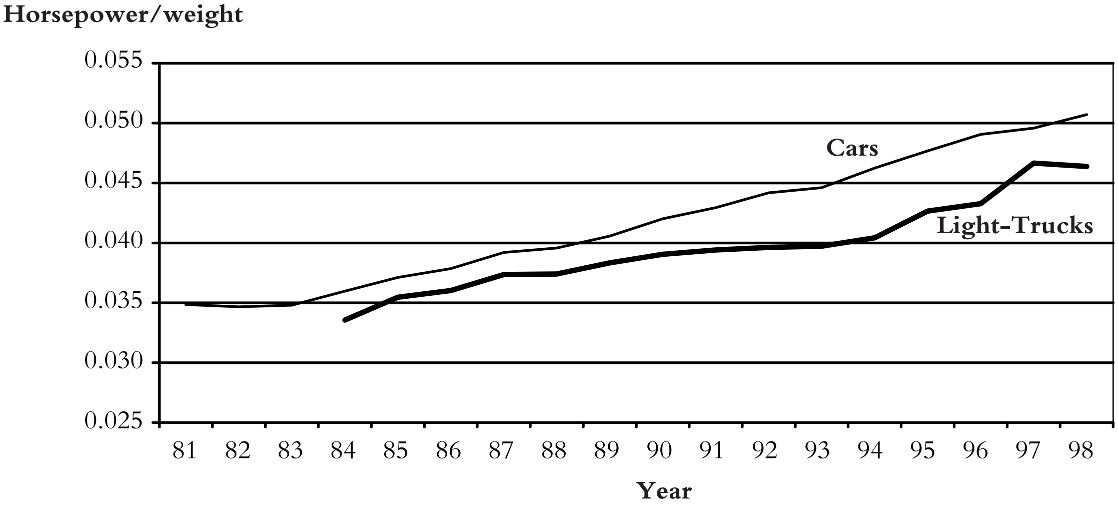


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–16. Average Horsepower-to-Weight Ratio, 1981–1998



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Although power and power-to-weight ratios rose dramatically, engine displacement (the combined volume of an engine's cylinders) did not change for cars and increased only about 10% for light-trucks (Figure 3–17). The achievement of greater power without an attendant increase in displacement indicates that engine technology improved during the period and that engine size itself does not appear to account for the growth in physical size or weight of cars or trucks. Even so, improvements in engine technology were offset by the escalation of vehicle size, such that overall fuel efficiency declined. Average miles per gallon decreased over the period covered by the database (Figure 3–18).

Price and Market Characteristics

With increasing size and changing performance characteristics, it is not surprising to find that the real price of vehicles rose significantly during the 1981–1998 period.[17] The average price of cars climbed from approximately $8,500 per car in 1981 to over $12,000 per car in 1998 (Figure 3–19). For light-trucks, the real price rose from an average of just below $8,000 per light-truck in 1984 to over $12,000 in 1998, an increase of nearly 60%. The 2mm project was implemented in the midst of substantial performance and price growth, and against this backdrop, consumers who were seeking higher power and performance may have viewed the improved body quality as a minor technical improvement.

Model Results

This section presents results based on a hedonic-price model.[18] We use the model to examine the relationship between relative market shares and various car and light-truck attributes.

Market Share

The results of this model finds that introducing the 2mm technology significantly increased the relative market share of cars and trucks by 0.3% for cars and 0.4% for trucks. As a result, consumers demanded fewer imported cars or light-trucks than similar vehicles produced in the United States or Canada. The benefits of introducing the 2mm technology diminished over time.

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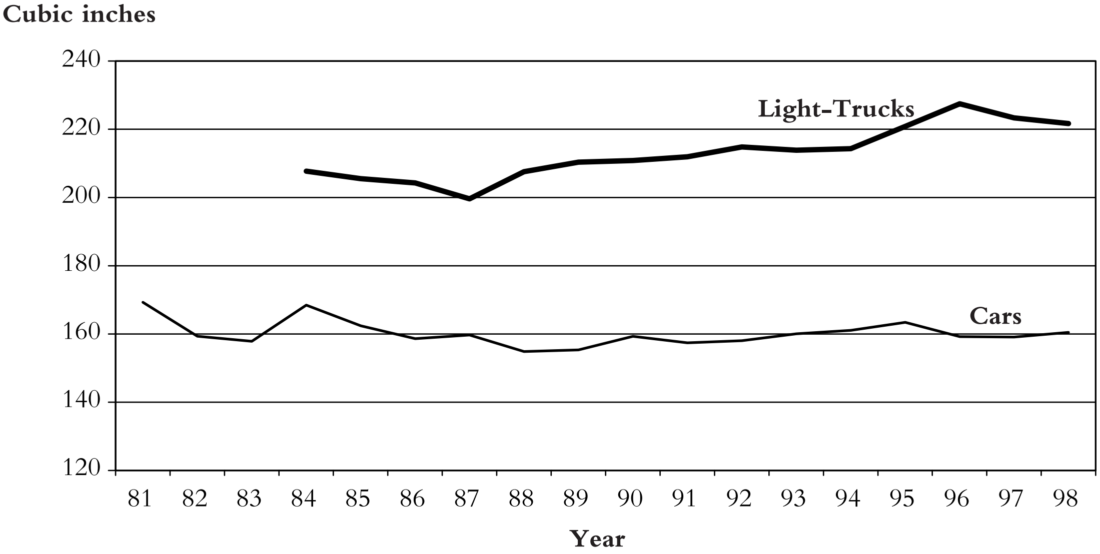
[17] Prices in this section are presented in constant 1983 dollars.

[18] The variable definitions, regression results, and discussion of the results are presented in Appendix 3-A to Chapter 3. Hedonic models explain the relationship between the price of the vehicle and the characteristics of the vehicle.

Figure 3–17. Average Engine Displacement, 1981–1998

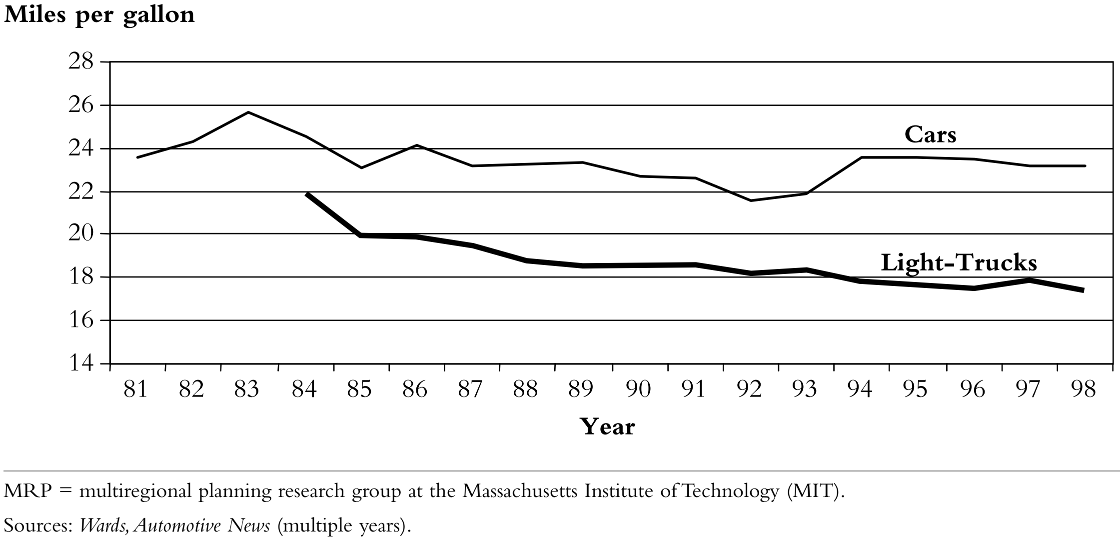


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–18. Average Miles per Gallon, 1981–1998

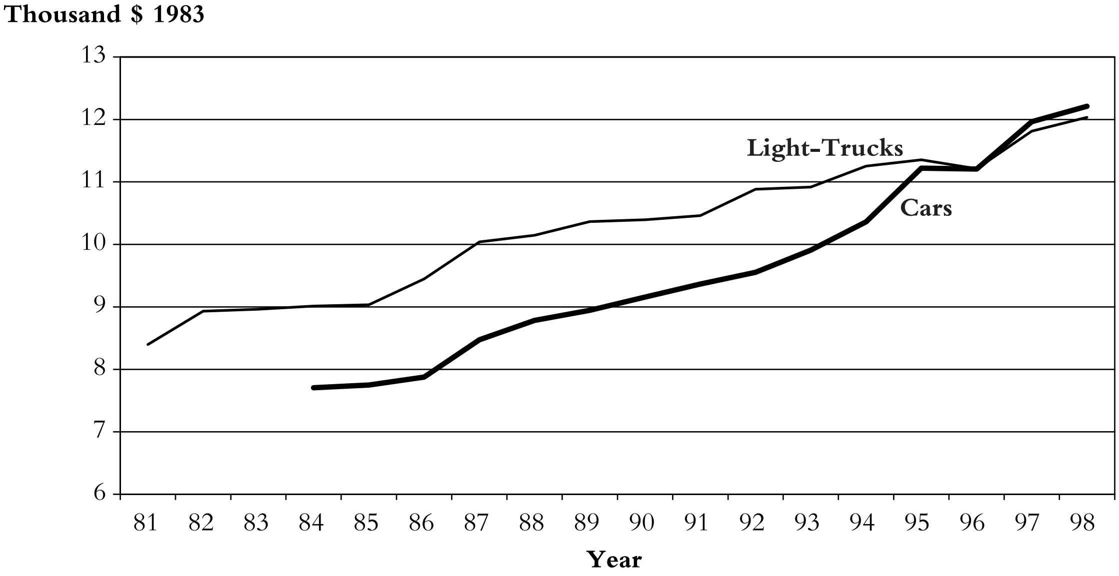


MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: *Wards, Automotive News* (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

Figure 3–19. Average Price per Vehicle, 1981–1998



MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Sources: Wards, Automotive News (multiple years).

MRP tabulations using the MRP automobile and light-truck database.

The results are stable for different specifications of the model. The only notable difference happens when we delete the variable for domestic cars. For cars, the economic impact of 2mm is reduced, and for light-trucks, it is increased. The reason is that consumers demand U.S.-made cars less than other cars with the same observable (by us) attributes, while the opposite happens with light-trucks. Two ways we used to check the consistency of the model and the effect of the 2mm variable were by changing the lag after the implementation of the 2mm technology and by reducing the sample of analysis, as set up through the restricted, partially restricted, and highly restricted categories, defined earlier. We assumed that as the program is spread among the plants, its impacts tended to vanish. Thus we hypothesized that, by 1998, when almost all domestic plants were already under 2mm technology, a plant probably would not have received additional profit from joining the project: the marginal cost for the last plants might be zero. We tested this hypothesis for market shares and for the mark-ups (see later sections analyzing producer mark-ups). The benefit to a plant of having the technology diminished over time. Competing producers would react, and, after some years, the advantage would disappear. We confirmed this hypothesis for market shares and mark-ups of both cars and light-trucks.

In Table 3–5, we show the effect of time in two ways, first by using a lag to determine whether the 2mm effect remains significant as the length of time a model has been 2mm grows longer, and second, by estimating whether the novelty of the 2mm effect wears off over time as we shrink the sample to include only vehicles of more recent vintages.

In the case of the first effect, we show that the longer a model has been 2mm, the smaller the market-share effect (measured as coefficient size). This can be seen where the impact declines from 0.33 percent higher market share for models just becoming 2mm (i.e., no lag) to 0.23 for a 2-year lag. The value for the 3-year lag is not significantly different from zero at a significance level of 87 percent and thus can be said to disappear altogether. For trucks, the range is 0.39 percent for no lag to 0.37 percent for a 1-year lag, after which the effect vanishes.

The question of whether the 2mm effect persists as the novelty of the technology is presumed to diminish can be answered by examining the market share estimates for the different date-interval estimates shown in Table 3–5. When we look at the share estimate for cars using a sample of vehicles that include the "early" years of 2mm (1993–1998), the market-share impact for cars is sizeable and significant. As we reduce the sample to include only more recent models, for example, those including 1994–1998 model years

Table 3–5. Effect of 2MM on Market Share of Changing the Lag or Sample Definition (Percent)

	Cars		Light-Trucks	
Lag/Sample	**Impact**	**Significance**	**Impact**	**Significance**
No lag	0.33	100	0.39	100
1-year lag	0.28	100	0.37	100
2-year lag	0.23	99	0.17	84
3-year lag	0.16	87	0.14	71
Sample				
93 to 98	0.33	100	0.44	100
94 to 98	0.31	100	0.45	100
95 to 98	0.25	100	0.41	100
96 to 98	0.18	94	0.37	99
97 to 98	0.14	80	0.41	99
1998 Only	0.04	20	0.46	99

Note: The lag refers to the number of years since the plant became 2mm, and the year(s) in the sample refer to the year(s) in which the vehicle was produced.

For Significance, 99–100 = 1%; 95–99 = 5%, and 90–95 = 10%.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Estimated by the Authors from the MRP Automobile and Light-Truck Data Base.

and the 1995–1998 model years, the market share impact estimates becomes smaller but remain statistically different from zero, i.e., they are significant. As we further reduce the sample to include only the most recent model years, the market share impact for cars vanishes, as the coefficients are no longer significant. We are not surprised to see the 2mm effect disappear in more recent vintages of cars, since by 1997, more than 50 percent of all cars sold were 2mm (Table 3–2).

For trucks, we observe that the novelty of the technology does not appear to wear off as we examine the different date-interval samples shown in Table 3–5. The market-share effect ranges from 0.37 to 0.46, with impacts estimated over the intervals that include "old" (1993–1998) and "new" trucks (1998 only). All intervals show large and significant 2mm market-share estimates. We are somewhat surprised to see the effect persist in trucks for the most recent years. This may be an indication that the popularity of domestic trucks, nearly 80 percent of which were 2mm by 1997, might be "captured" (or misrepresented) by the 2mm variable.

As we invoke a more restricted definition of "2mm-ness," we can see that for cars, the 2mm effect of higher quality diminishes. As shown in Table 3–6, when looking at cars that have just "become" 2mm (i.e., no lag) the market-share effect with the restricted definition of 2mm, 0.19 is slightly more than half the size of the unrestricted at 0.33. The highly restricted is smaller still at 0.12, about one-third the size of the unrestricted estimate. If we assume that the actual quality of the BIW is higher the more restricted the definition, then it does not appear to be the case that the higher quality is rewarded out of proportion to the approximate share of 2mm vehicles produced in the highly restricted subset of plants. On the contrary, the highly restricted estimate is significant only in the

Table 3–6. Effect on Market Share for Cars of Changing the 2mm Definition for Different Lags (Percent)

	Unrestricted		Restricted		Highly Restricted	
Lag	**Impact**	**Significance**	**Impact**	**Significance**	**Impact**	**Significance**
No lag	0.33	100	0.19	100	0.12	96
1-year lag	0.28	100	0.16	99	0.07	72
2-year lag	0.23	99	0.21	100	0.08	68
3-year lag	0.16	87	0.30	100	0.10	69

Note: The lag refers to the number of years since the plant became 2mm.

For Significance, 99–100 = 1%; 95–99 = 5%, and 90–95 = 10%.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Wards, Harbour Report, Perceptron, Inc., and the MRP Automobile Database.

Table 3–7. Effect on Market Share for Light-Trucks of Changing the 2mm Definition for Different Lags (Percent)

	Unrestricted		Restricted		Highly Restricted	
Lag	**Impact**	**Significance**	**Impact**	**Significance**	**Impact**	**Significance**
No lag	0.39	100	0.29	100	0.30	100
1-year lag	0.37	100	0.26	100	0.25	100
2-year lag	0.17	84	0.17	97	0.15	93
3-year lag	0.14	71	0.22	99	0.21	98

Note: The lag refers to the number of years since the plant became 2mm.

For Significance, 99–100 = 1%; 95–99 = 5%, and 90–95 = 10%.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Wards, Harbour Report, Perceptron, Inc., and the *MRP Truck Database*.

year in which 2mm was implemented, and it does not persist beyond the introductory years' vehicles.

A similar pattern of lower impacts for more restricted definitions of 2mm vehicles appears for light-trucks (Table 3–7). It is most evident in going from the unrestricted to the restricted estimate, shown as 0.39 to 0.29 for no lag and 0.37 to 0.26 for a 1-year lag. There is almost no change in moving to the highly restricted definition. The fact that the 2mm effect of higher quality for light-trucks is very sensitive to specifications makes us suspect that our estimates regarding the light-truck market may suffer from a small sample size, 838 observations over 15 years.

Producers' Mark-ups

To analyze the impact of the 2mm project on the producer's mark-ups, we used the results of the market-share estimates[19] to estimate the mark-up as the dependent variable for cars and light-trucks. Using the unrestricted definition of 2mm and for lags up to 2 years, we found that the impact of introducing the 2mm project on the mark-ups was negative for both cars and light-trucks. The 2mm project probably increased the cost of production. The effect, however, was very low: around -0.07% for cars and -0.04% for trucks. A decline in producers' mark-ups is equivalent to an increase in producers' costs; thus, the minus sign on mark-ups indicates rising costs.

Table 3–8 shows that the negative effects of producers' markups diminished after a 1-year lag for cars and then the effect disappeared. When we changed the 2mm definition for

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[19] See Equations (7a) in Appendix 3-B to Chapter 3.

Table 3–8. Impact of 2mm on Producers' Mark-Up of Changing the Lag or Sample Definition (Percent)

	Cars		Light-Trucks	
Lag/Sample	**Impact**	**Significance**	**Impact**	**Significance**
No lag	-0.07	100	-0.04	95
1-year lag	-0.07	100	-0.04	95
2-year lag	-0.04	90	-0.04	94
3-year lag	0.00	5	-0.03	88
Sample				
93 to 98	-0.08	100	-0.04	94
94 to 98	-0.09	100	-0.04	94
95 to 98	-0.09	100	-0.04	94
96 to 98	-0.08	100	-0.04	93
97 to 98	-0.05	92	-0.03	79
1998 Only	-0.04	71	-0.03	68

Note: The lag refers to the number of years since the plant became 2mm, and the year(s) in the sample refer to the year(s) in which the vehicle was produced.

For significance, 99–100 = 1%; 95–99 = 5%, and 90–95 = 10%.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Estimated by the Authors from the MRP Automobile and Light-Truck Data Base.

cars (Table 3–9) as we did for the market-share effect (Table 3–6), we saw that the effect vanished after 2 years. For the unrestricted category, we saw that the impact on both mark-ups and on market shares decreased as the lag was increased. The results for the restricted category were not significant. An analyst needs to consider that when a plant implements the new technology, costs increase, but after the plant is already adapted, the cost effects disappear. Because some plants, like the GM plant in Spring Hill, Tennessee, implemented the program as recently as 1997, it might be the case that those plants were not completely adapted to the new technology and faced some extra costs.

For trucks, the effect was constant and not significant for any lag period, meaning that the use of the 2mm equipment did not impose any net increment to production costs. Table 3–10 shows that the greater the 2mm experience, measured by increasing level of restriction, the lower the cost impacts on producers—so much so that the cost impacts were beneficial ones to experienced producers (i.e., the coefficients were positive). Even so, the effect remains short-lived, between 0 years and 1 year. Apparently, in the "wrong hands," the technology can lead to persistent higher short-term costs, although the statistical significance vanishes after 1 year, for the most part. The short-lived reduction in producers' mark-ups is, in a real sense, the penalty for nonparticipation in the 2mm research in plants equipped with the OCMM equipment.

Table 3–9. Effect on Producers' Mark-Up for Cars of Changing the 2mm Definition for Different Lags (Percent)

	Unrestricted		Restricted		Highly Restricted	
Lag	**Impact**	**Significance**	**Impact**	**Significance**	**Impact**	**Significance**
No lag	-0.07	100	-0.01	45	-0.03	90
1-year lag	-0.07	100	-0.02	69	-0.04	97
2-year lag	-0.04	90	0.01	21	-0.02	60
3-year lag	0.00	5	0.03	80	0.00	2

Note: The lag refers to the number of years since the plant became 2mm.

For Significance, 99–100 = 1%; 95–99 = 5%, and 90–95 = 10%.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Wards, Harbour Report, Perceptron, Inc., and the MRP Automobile Database.

Table 3–10. Effect on Producers' Mark-Up for Light-Trucks of Changing the 2mm Definition for Different Lags (Percent)

	Unrestricted		Restricted		Highly Restricted	
Lag	**Impact**	**Significance**	**Impact**	**Significance**	**Impact**	**Significance**
No lag	-0.04	95	0.04	99	0.05	100
1-year lag	-0.04	95	0.02	89	0.04	98
2-year lag	-0.04	94	0.01	48	0.02	72
3-year lag	-0.03	88	0.02	75	0.01	35

Note: The lag refers to the number of years since the plant became 2mm.

For Significance, 99–100 = 1%; 95–99 = 5%, and 90–95 = 10%.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Wards, Harbour Report, Perceptron, Inc., and the MRP Light-Truck Database.

Direct-Impact Estimates of 2mm

As is evident from the previous section, incorporation of 2mm technology serves to increase market shares of 2mm vehicles with respect to program participation. Its effects on manufacturers' mark-ups for light-trucks is somewhat more cloudy, however, with mark-up increases when we use the narrowly defined sample of vehicles (Table 3–10), but with mark-up decreases for the broadly defined sample, that is, all vehicles produced in plants with OCMM equipment, without direct access to research-based applications and procedures for controlling dimensional variation.

For estimating the macroeconomic impacts of the 2mm project, we used the impacts on market shares and mark-ups as direct impacts, which we then used as inputs to simulate resulting changes in the U.S. economy. In this section, we transform the hedonic estimates to changes in the manufacturers' outputs due to market-share increases as well as changes in profit-type income due to mark-up changes.

Market-Share Impacts

From the estimated coefficients of the 2mm project's market-share impacts, we can estimate the direct net domestic impacts of the project on the value of U.S. vehicle production (Table 3–11). As discussed above, the 2mm project had the effect both of increasing the market share of vehicles produced using the technology and decreasing producers' mark-ups on 2mm vehicle production. In the case of market shares, we assumed that 2mm-related increases came at the expense of all non-2mm vehicles, both domestic and imported. The market-share gains of domestic producers that derived from 2mm vehicles were partially offset by reductions in sales of non-2mm vehicles. The displaced imports of vehicles is the net market-share gain that resulted from the project and is a key macroeconomic impact of the project.

To construct the direct-impact estimates, we chose to use the unrestricted set of parameter estimates, that is, those based on including all vehicles produced in plants with adequate

Table 3–11. Market-Share Impacts ($1992, Millions)

	Cars				Light-Trucks				Total			
Year	**Total Market**	**2mm Gain**	**U.S. Non-2mm Loss***	**Displaced Imports**	**Total Market**	**2mm Gain**	**U.S. Non-2mm Loss***	**Displaced Imports**	**Total Market**	**2mm Gain**	**U.S. Non-2mm Loss***	**Displaced Imports**
1993	83,824.5	53.9	-27.6	-26.3	119,607.5	67.5	-52.3	-15.2	203,432.1	121.4	-79.9	-41.5
1994	91,559.7	65.1	-32.9	-32.1	140,307.0	123.3	-85.4	-37.9	231,866.7	188.4	-118.3	-70.0
1995	91,652.3	65.9	-32.4	-33.5	145,258.7	55.4	-42.4	-12.9	236,911.0	121.3	-74.8	-46.5
1996	88,135.3	28.3	-16.1	-12.3	151,255.2	96.2	-66.2	-30.0	239,390.5	124.5	-82.2	-42.3
1997	90,651.3	5.3	-3.1	-2.2	167,711.0	104.3	-71.9	-32.4	258,362.3	109.6	-75.0	-34.6
Total	445,823.1	218.5	-112.1	-106.4	913,784.1	446.7	-318.2	-128.4	1,450,706.0	665.1	-430.3	-234.9

Note: The year refers to the year in which the vehicle was produced.

*Includes U.S.-owned and non-U.S.-owned production in the United States.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Estimated by the Authors from the MRP Automobile and Light-Truck Data Base.

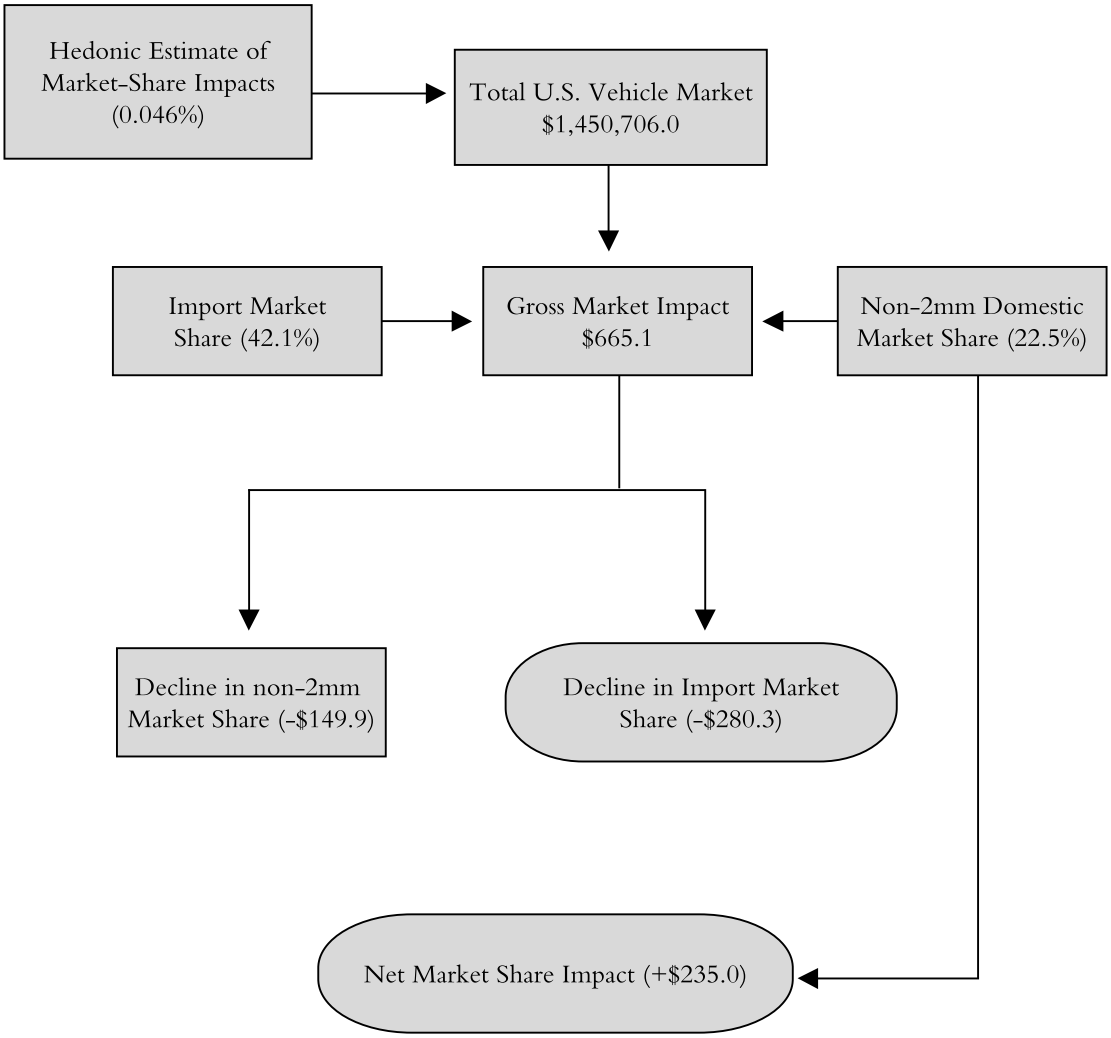
numbers of OCMM systems and sensors. We note that 2mm technology had a positive impact on market share for as long as two years in cars (Table 3–6) and light-trucks (Table 3–7). For cars, significant values range from 0.23% to 0.33%, depending on how long a plant had produced with 2mm technology. For light-trucks, the impacts ranged from 0.37% to 0.39%. For our impact estimates, we used the 1-year and 2-year lag coefficients for both cars and light-trucks. We believe this is a logical time period to achieve stable dimensional-variation control once a plant is operating with the 2mm technology. Thus, we applied values of 0.33% and 0.28% as the annual project impact for the 1993–1998 period to estimate the gains in market shares for cars and 0.39 and 0.37 for light-trucks, respectively, attributable to 2mm. We note that these figures may overstate the project impact if the market-share impact declines over time, as 2mm becomes the norm.

We applied these figures to the MRP vehicle-sales data to estimate the value of the project's direct impact, following the steps outlined in Figure 3–20. The resulting estimates indicate the size of the car and light-truck markets measured in real value, the value of the market share associated with the 2mm characteristic, the value of offsetting declines for domestic non-2mm cars and light-trucks, and the net change in national imports (Table 3–11). As shown, the total annual value for cars and light-trucks of the 2mm market share change ranged from a low of approximately $110 million in 1997 to a high of $188 million in 1994. During the 1993–1997 interval, the total gains associated with light-truck sales ($447 million) represented the bulk of the total impact ($665 million). To obtain the value for use in the economic-impact estimates (Chapter 4), we subtracted from this total the losses in production of non-2mm vehicles and made some additional adjustments to account for import substitution. The losses range from -$75 million in 1995 to -$118 million in 1994. We entered the adjusted net figures as a portion of the direct impact used in estimating the total impact of the project on the U.S. economy (Chapter 4).

Producers' Mark-up Impacts

The other major direct macroeconomic impact arises from increased producers' mark-ups. Increased mark-ups derive from both productivity improvements in plant operations and increased prices where producers are able to charge more for vehicles with high-quality body assembly. If increased mark-ups as a direct effect are passed through to stockholders (as dividends or capital gains) or to employees (as bonuses or salary increases), higher levels of personal-income growth, as well as induced growth in consumption and savings, will result. Even small changes in producers' mark-ups can have a significant macroeconomic income effect in view of the sheer size of the U.S. automotive industry. From the model

Figure 3–20. Market-Share Direct-Impact Estimates: 1993–1998 ($1992 millions)



estimates, we see that the 2mm project had small negative effects on mark-ups associated with cars and light-trucks. In estimating the initial mark-up effects, we used the unrestricted coefficient values of –0.07% and –0.04% for a two-year period for cars and light-trucks, respectively (Tables 3–9 and 3–10). The change in annual values of the mark-ups range from a total of -$12 million in 1997 to -$29 million in 1994, with cars and trucks each accounting for about half of the total losses over the time period (Table 3–12).

Table 3–12. Producers' Mark-Up Impacts for Light-Trucks ($1992, Millions)

	Cars		Light-Trucks		Total	
Year	**Total Market**	**2mm Gain**	**Total Market**	**2mm Gain**	**Total Market**	**2mm Gain**
1993	83,825	-13.4	119,608	-7.1	203,432	-20.5
1994	91,560	-16.1	140,307	-12.9	231,867	-29.0
1995	91,652	-16.0	145,259	-5.7	236,911	-21.8
1996	88,135	-6.7	151,255	-10.4	239,391	-17.0
1997	90,651	-1.2	167,711	-10.7	258,362	-11.9
Total	445,823	-53.4	724,139	-46.8	1,169,963	-100.2

Note: The year refers to the year in which the vehicle was produced.

MRP = multiregional planning research group at the Massachusetts Institute of Technology (MIT).

Source: Estimated by the Authors from the MRP Automobile and Light-Truck Data Base.

Conclusions

Based upon our hedonic-price analysis, we find that the 2mm project appears to have increased the market share by $235 million for domestically produced vehicles but decreased the producers' mark-ups by $100 million with a net effect of $135 million. Without the project, the U.S. automobile industry would probably have lost a greater share of the market than it did. We note that the effect on market share, however, may be short-lived. By the time the technology had become incorporated in the production at the majority of U.S. assembly plants, the impacts began to vanish. It is also important to recall that the market share for automobiles produced by U.S. firms has been decreasing since the early 1970s for many reasons, including those related to body-quality. The 2mm effort to reverse this trend was too small to alter that trend, although it probably helped stem some of the losses in market share.

The 2mm project was important as a catalyst for some changes, but certainly not all. Although the results were good for light-trucks, we do not know the effect of a new environmental regulation on those vehicles. The effort by the Advanced Technology Program (ATP) was important and was probably in the right direction.

We find from our case study interviews[20] that the installation and operation of the OCMM equipment was generally done simultaneously with the installation of new assembly-line tooling and conveyance systems. Improved tooling capability (some of

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[20] See appendices to Chapter 2, Appendix 2-A and 2-B).

which can be traced to 2mm research) and changes in the way assembly lines are designed, engineered, and installed underwent significant changes from those prevalent among domestic producers. Combined with what appears to be a cultural change in the production of vehicles by U.S. firms, the 2mm effect may be dwarfed by such changes.

Chapter 4

Macroeconomic Impact Analysis[+]

Introduction

The case study analyses in Chapter 2 and the hedonic-price model analyses in Chapter 3 provided two separate sets of data describing direct impacts of the 2mm project. They provide different estimates and therefore alternative sets of inputs to REMI (Regional Economic Model, Inc.), an economy-wide model for estimating the broader impact of the 2mm project on the U.S. economy.

In this chapter, we build on the estimated direct economic impacts of the 2mm project derived from our case study research and hedonic model and use them as inputs to the REMI economic model to estimate the overall economic impacts of the project. The results from the REMI calculations help us formulate conclusions regarding the value to the U.S. economy of the 2mm project relative to the public cost of subsidizing the research. It permits us to translate the millions expended in the form of project-related research and development (R&D) activities, investments in equipment, and market-related impacts of higher quality vehicles into estimates of changes in the number of jobs, amount of income earned, and size of the gross domestic product (GDP) of the United States.

Economic impacts are generally composed of direct, indirect, and induced impacts. These terms have specific meanings and refer to whether an analyst views the changes in 2mm project-related output or cost changes as exogenous to an economy or generated within

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[+] Nicolas O. Rockler and Karen R. Polenske wrote this chapter.

the economy. By convention, direct effects are an exogenous change in economic activity, such as the introduction of new investment into the economy, or the start-up of industrial enterprises funded from outside the region. An analyst derives indirect effects from changes in outputs that are, in turn, the intermediate industry responses to the direct effects.

For example, if regional vehicle manufacturers see a sharp drop in demand because of higher fuel prices, an analyst would estimate the indirect effect by estimating the total change in intermediate goods and services purchases. These would extend from steel, glass, plastics, rubber, etc. to the multitude of goods and services used to make them.

Induced effects are those generated through changes in output linked to personal consumption. The REMI model derives them from the changes in personal incomes that are generated from the direct and indirect effects, starting with changes in aggregate wages, rents, royalties, profits, etc.

The REMI model also includes one other impact measure, termed the "full effect." This includes direct, indirect, and induced effects as well as those linked to changes in demographic characteristics produced by internal migration. These are shifts in population in response to job opportunities, which alter the location of consumption. We estimate and use the "full" effects in our analysis here.

Direct Impacts

Drawing on the results of the case studies and hedonic-price analyses, we identify two groups of direct impacts. The first group results from project spending on R&D and project implementation in assembly-plants that made the transition to 2mm production technology, largely capital equipment expenditures and ongoing operations and maintenance expenditures on the 2mm systems. These include labor and materials expenses incurred by the assembly-plant operator for keeping the Perceptron equipment running and for training in-house workers to run it. In most respects, these are fixed costs of implementing 2mm technology, invariant with the volume of vehicles produced.[21] The second set of direct impacts consists of the market responses to 2mm vehicles and includes changes in estimated market shares of the 2mm and non-2mm vehicles, as well as changes in production costs for domestically produced vehicles. Direct impacts are itemized by category in Table 4–1.

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[21] Some volume-based variation in O&M expenditures is likely to exist for the Perceptron equipment, although once the sensors are set up and aimed, workers need to make only small adjustments and clean the lenses.

Table 4–1. Estimated Direct Impacts of the 2mm Project

Source of Impact	Type of Impact	Estimated Value of Direct Impacts (1992$ millions)							
Project Research and Implementation Impacts									
		1992	1993	1994	1995	1996	1997	1998	Total 1992–1998
ATP/Participant Research Funds		**0.8**	**3.5**	**3.5**	**2.5**	**0.0**	**0.0**	**0.0**	**10.5**
1. Automobile Manufacturer Research	Industry Output	0.2	0.7	0.7	0.5	0.0	0.0	0.0	2.1
2. Tool and Machinery Manufacturer Research	Industry Output	0.2	1.0	1.0	0.7	0.0	0.0	0.0	2.9
3. ABC Project Management	Industry Output	0.1	0.4	0.4	0.3	0.0	0.0	0.0	1.3
4. University Research	Industry Output	0.3	1.2	1.2	0.9	0.0	0.0	0.0	3.6
5. Perceptron, Inc. Research	Industry Output	0.0	0.2	0.2	0.1	0.0	0.0	0.0	0.6
Implementation Expenditures		**0.0**	**30.3**	**20.6**	**24.6**	**42.3**	**17.9**	**10.3**	**146.0**
6. OCMM Purchases	Industrial Investment	0.0	27.3	16.4	19.4	36.1	11.7	4.1	115.0
7. 2mm Monitoring and OCMM Equipment Operations and Maintenance	Vehicle Production Cost	0.0	3.0	4.2	5.2	6.2	6.2	6.2	31.0
Operational Impacts									
Market Share[22]		**0.0**	**46.5**	**70.1**	**46.5**	**42.3**	**34.6**	**0.0**	**235.0**
8a. 2mm Producers	Vehicle Output	0.0	121.4	188.4	121.3	124.5	109.6	0.0	665.2
8b. Non-2mm Domestic Producers	Vehicle Output	0.0	-37.7	-56.7	-26.1	-16.2	-13.2	0.0	-149.9
8c. Non-Domestic Producers	Vehicle Output	0.0	-42.2	-61.6	-48.7	-66.0	-61.8	0.0	-280.3
9. Production Cost (Producers' Mark-ups) Alternative Estimates									
a. Hedonic Model	Vehicle Production Cost	0.0	20.5	29.0	21.8	17.0	11.9	0.0	100.2
b. Case Study	Vehicle Production Cost	0.0	-17.9	-24.5	-18.1	-13.2	-8.2	0.0	-81.9
10. Import Substitution	Vehicle Output	0.0	41.5	70.0	46.5	42.3	34.6	0.0	234.9

Source: The Authors.

Direct Project R&D and Technology-Implementation Impacts

The project R&D expenditures, Perceptron equipment purchases, equipment investment, and operation and maintenance expenditures are used to estimate direct impacts of the 2mm project. These estimates enter the REMI model as (1) costs, (2) investment, and (3) output.

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[22] See Chapter 3, Table 3–11.

2mm Project Research Expenditures

We have determined that the final audited 2mm project expenditures from the Auto Body Consortium (ABC) and the ATP project budget are those that most accurately describe the dollar value expended by the ten participating firms. These figures, totaling $10.5 million, probably understate the amount of work actually done under the project if several of the case study participants are correct. Unfortunately, no better data were forthcoming concerning actual expenditures or in-kind resources allocated to the work.

We view the project R&D expenditures as exogenous increases in the output in each of the participant firm's respective industries. Thus, we treat the economic impact of research conducted by the University of Michigan and Wayne State University, which totaled $3.6 million, as an increase in educational services output, while we treat that of the assembly-line integrators as machinery-manufacturing output. Similarly, we regard research conducted by the automobile manufacturers as an increase in automobile output and research by Perceptron as increased output of instrument manufacturing. In addition, we classify the administrative expenditures by the ABC as management services. In this way, funds channeled through the project participants are expended consistent with producing their usual output, with indirect and induced effects that are derived from remaining sources consistent with each sector's purchasing, expenditure, wage rate, profitability, etc. patterns. The estimated R&D expenditures are shown in Table 4–1 as Items 1–5.

We do not view the R&D expenditures as representing a cost increase in automobile manufacturing, as the research expenditures represented a shift in resources already in service without creating additional increases in manufacturing costs (although operating the 2mm technology does affect operating costs, as described later). To the extent that we understate the total (and temporary) increases in production costs due to R&D, our impact estimates also will understate the negative implications for job and income changes due to the project. The missing expenditures are unlikely to be very large relative to other outcomes; therefore, they are unlikely to shift the overall impact of the project.

For impact-estimation purposes, we assume that the R&D expenditures occurred evenly over the 36-month period beginning in October 1992, and we have pro-rated the project total expenditures to reflect this. For all other impacts described below, we assume impacts begin in 1993.

2mm Equipment Investment/Expenditures

The costs of incorporating 2mm technology into assembly plants represents a direct economic impact attributable to the project in the form of investment in producers' durable equipment. We include the annual estimated amount of Perceptron systems purchases as an increase in the output of the instrument-manufacturing sector (Table 4–1, Items 6–7).

We did not have a direct estimate of the value of the 2mm equipment purchased, although we were able to obtain the number of systems purchased for each assembly plant from Perceptron. To estimate the value, we used data derived from Perceptron's 10–K Securities and Exchange Commission statements for 1995–1998, which give the total value of sales to the domestic "Big-3" producers.[23] We deflated these using national income and product accounts deflators for durable manufactured goods to obtain the real value of system purchases. We then estimated the cost per system using the four-year total of real sales and the four-year total of system sales data furnished by Perceptron (Table 4–2).

We derive our estimated expenditures on Perceptron systems by 2mm project participants by dividing the value of sales to the Big 3 between 1995–1998 by the number of Perceptron systems sold to the Big 3 in that period, and then multiply this per-system price by the numbers of systems sold per year to 2mm project participants to produce the series shown as Total Perceptron Sales in Table 4–2. We regard only systems purchased after 1992 as being linked to the 2mm project. Motor vehicle plants purchased more than 900 systems and 23,500 sensors from Perceptron between 1986 and 1998, but they purchased nearly half of this output prior to the start of the 2mm project.[24] For the most part, they bought these systems and sensors without any assurance that the 2mm project would receive ATP funding.

2mm Operation and Maintenance Expenditures

A final set of implementation impacts concerns the operations and maintenance (O&M) expenditures required to keep the Perceptron systems operating. In several plants, case study participants estimated these to be approximately $200,000 per plant. (According to one of the participants, this is the approximate figure used for the General Motors facilities equipped with the Perceptron systems.) These additional production costs cover training expenses for system operators and costs for routine adjustment of the systems' sensors (cameras), including aim-adjustment and lens cleaning. To estimate these costs, we used the number of newly operating "2mm" plants (based on the unrestricted definition discussed in Chapter 3) beginning in 1993. We did not estimate the costs for plants with pre-1993

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[23] "Big 3" denotes Ford Motor Co., General Motors Co., and DaimlerChrysler, Inc.

[24] In our most inclusive estimates of what defines a 2mm vehicle, we do not consider vehicles produced in plants equipped with systems purchased prior to 1992 as being 2mm unless the plant had three or more systems and 75 or more sensors. Many of the plants equipped with Perceptron's equipment prior to 1992 had insufficient numbers of systems, sensors, or both, to do 2mm measurements, and therefore, vehicles from these plants were not considered to be "2mm."

Table 4–2. Perceptron Sales, 1995–1998 Current and Real ($1992, Thousands)

	1995	1996	1997	1998
Total Perceptron Sales ($ thousands)	43,154	58,975	65,102	49,635
Big-3 Sales ($ thousands)	14,672	27,129	24,739	10,920
Big-3 share of sales (%)	34	46	38	22
Big-3 Sales ($ 1992 thousands)	14,438	26,125	23,180	9,839

"Big 3" denotes Ford Motor Co., General Motors Co., and DaimlerChrysler, Inc.

Source: U.S. Securities and Exchange Commission, Form 10–K, 1996–1999, Edgar, http://www.wec.gov/edgar.shtml

systems (eleven such plants are in the Perceptron sales database), because we cannot attribute incremental O&M to the 2mm project with certainty. To the extent that these plants did adopt a maintenance plan developed from the 2mm research and received additional funds to support these activities, the production-cost estimates we have included underestimate the true values by as much as $30 million over the 1993–1998 period. For the purposes of estimating impacts over 10 years, we have treated the O&M expenditures after 1998 as being fixed at $6.2 million, as if no additional 2mm equipment had been purchased.

Operational Impacts

The operational impacts of the 2mm project consist of changes in the level of domestic output or production cost that are tied to the sales of 2mm vehicles. In this category of impacts, we include changes in the market-share of 2mm vehicles relative to other types, changes in the volume of foreign imports, and production-cost changes that vary with the number of vehicles produced. These estimates enter the REMI model as 1) market share impacts and 2) production cost impacts.

Market-Share Impacts

The market-share impacts refer to changes in the proportion of vehicles that fall into one of four possible categories:

1. 2mm vehicles produced in North America,
2. non-2mm vehicles produced by domestically owned companies,
3. U.S.-produced vehicles in plants owned by non-domestic producers (the captive imports, such as Toyota in Kentucky, Honda in Ohio, Nissan in Tennessee, etc), and

4. imported vehicles not produced in North America.

We treat the market-share impacts of the 2mm project as impacts that change the distribution of sales among the four categories shown above. We assume that the introduction of 2mm vehicles does not represent a shift in total domestic demand. Rather, compensating shifts in demand occur, such that sales of 2mm vehicles come at the expense of all other vehicles' shares, both domestically produced and imports. The hedonic model (Chapter 3) provides us with an estimate of changes in market shares attributable to the 2mm project that considers both domestic and imported vehicles. To prepare the estimated impacts on the other segments of the market, we assume that 2mm vehicles draw from each category of other vehicles in constant proportion to their shares. Thus, if 2mm vehicles are estimated to represent 5% of the total market and non-2mm domestically produced vehicles comprise 10% of the market, then after deducting the 2mm share (5%) from the total, the non-2mm domestically produced vehicles will still comprise 10% of the new, smaller total.

As we noted in Chapter 3, the market-share effect is significant only for a two-year period after a plant "becomes" 2mm-equipped. For vehicle models that were already produced in Perceptron-equipped plants prior to 1993, we do not make a 2mm-effect estimate. Two years after a plant has been established as a 2mm producer, we assume that no share of its production displaces any portion of the market.

Obviously, 2mm vehicles may not compete against all vehicles equally, and their sales may have a greater or lesser impact on the share of a specific segment of the market rather than the constant rate we assume. We did not attempt to model interaction terms in the hedonic modeling (Chapter 3) to try to uncover such relationships. If there is a bias introduced here, we are unsure as to its direction. The most serious problem in this regard would be encountered with imported vehicles, many of which are Japanese vehicles exhibiting high-quality body construction that is equal to, if not better than, the 2mm vehicles. If, in reality, 2mm vehicles do not take a market share of the domestic market in proportion to import sales, then we will have mis-estimated the import-substitution effect on vehicle output. At present, we derive the import-substitution-induced increase in domestic-vehicle output from its constant share of the domestic market after reducing the total for the 2mm effect.

We show the estimated market-share effects of the 2mm project in Table 4–1 as items 8a–8c, using the results of the hedonic model presented in Chapter 3 (Table 3–11). The total market share impact of the 2mm project over the ten years shows increased sales of $665 million worth of 2mm vehicles, offset by reduced sales of non-2mm domestic vehicles of $150 million, and $280 million of U.S.-made non-domestic producer vehicles, leaving $235 million in reduced imports as the net domestic gain to the project.[25]

Production Cost Impacts

The effect of the 2mm project on vehicle production cost is uncertain. If the hedonic model described in Chapter 3 accurately captures the effect of 2mm quality on price and margins when we hold all vehicle characteristics constant except for 2mm status, then it should cost more to produce 2mm vehicles than lower-quality ones. The 2mm technology is designed to catch both random and systematic defects in the assembly process, thereby reducing repair and/or scrap costs. As we described in Chapter 2, adherence to a strict quality standard means slowing production to make corrections, thereby reducing output from the amount that would have been possible without close supervision of quality. Increased costs of production due to slower line-speeds, additional maintenance and repair, and the need to dedicate labor resources to quality control are offset by cost reductions achieved by producing fewer defective vehicles, less scrap, and less waste.

Our hedonic estimate of the change in marginal cost to produce 2mm vehicles (Chapter 3) indicates that plants using 2mm technology reduce their mark-ups by approximately 0.07% of aggregate sales for cars and 0.04% for trucks (Tables 3–9 and 3–10). This seemingly small change actually accounts for $100 million in additional production costs measured over the 1993–1998 period (Table 3–11 and Table 4–1, item 9). As we are unable to simulate exogenous changes in industry profits owing to the model's structure, we treat these changes in producers' mark-ups as equivalent to an increase in production costs. They occur only among the vehicles produced under the 2mm technology and only for the two years immediately after the technology is placed in the plant, as indicated in our lag-tests of the hedonic model.[26]

On the other hand, if our case study results presented in Chapter 2 are representative of the experience at all 2mm plants, then production costs do not rise as the hedonic model

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[25] In reality, substitution of domestically owned production for non-domestically owned production may not produce a zero-sum impact when we calculate the indirect effects. If non-domestic producers import a higher proportion of sub-assemblies, such as engines and interior components, than do domestic producers, then reducing the non-domestic producers' market share may yield further indirect gains to the U.S. economy. Although this is likely to be the case, neither REMI nor any of the existing input-output models distinguish among the different producers. Thus, our impact estimates from market-share gains for 2mm will understate domestic output effects of gaining market share at the expense of captive imports.

[26] The REMI model uses relative production costs and relative profits, both measured at a regional level (and relative to the nation as a whole), to forecast shifts in regional output and capital investment. Changes in these variables lead to changes in later periods of such measures as employment, income, and consumption.

indicates, but fall by approximately $82 million over the 1992–1998 period, as shown in Table 4–1 item 9b. We account for this reduction by the drop in per vehicle production costs of $6.90 through lower repair and scrap costs. Although we were unable to obtain detailed data from the plants, we used our interviews with plant personnel who had some familiarity with operating costs to develop a consensus approximation of the technology's impact.

Neither source of cost-impact information is definitive; however, we favor the hedonic estimate as being more objective and less likely to be biased by failure to account for the full range of cost effects attributable to the 2mm technology. There is a strong likelihood for personnel to attribute some of the operating cost increases arising from the use of 2mm, such as the need for tool repair and adjustment, not to the 2mm technology but to the offending piece of equipment. Perhaps this attribution is partially justified, but in the quest for improved vehicle body quality, we think an accounting for foregone repair and scrap costs ought to be balanced by accounting for the increase in factor inputs that underlie the result, adjustments being one example.

For the impact estimates we present later in the chapter, we have estimated the impacts for both sets of production-cost estimates. We present the hedonic result as a conservative estimate of the 2mm project impact and offer the case study-based estimate as an upper limit of the project's impact.

Import-Substitution Effects on Domestic Output

As we noted in the discussion of the market-share impacts, we estimate the import-substitution effects from the assumed reduction of imports that occurs in response to the appearance of 2mm vehicles on the market. We estimate the reduction in imports to occur as a dollar-for-dollar trade-off with domestic demand, based on our assumption that no change in aggregate demand occurs as a direct result of the project.[27] To allocate this change in the market composition, we distribute the value of import substitution across all three types of domestically produced vehicles. We do this separately for cars and light-trucks and show the combined figure in Table 4–1. In total, we estimate that import substitution accounts for $235 million of domestic vehicle output attributable to the 2mm project. This is a sizeable figure in view of the investment in equipment and O&M.

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[27] REMI accounts for indirect increases in output from intermediate users of vehicles, as well as personal consumption purchases made possible by 2mm-induced income growth.

Summary of Direct Impact Estimates

In summary, the 2mm project involves $10.5 million worth of R&D conducted by ten firms and expended over a 3-year period. The economic impact of the project is not limited to the jobs and incomes generated by this amount however. It extends to the ancillary investment, expenditures, and income that followed implementation of the 2mm technology at numerous plants or was spurred by R&D findings related to the project.

The major project-related "direct" impacts include the $10.5 million of R&D expenditures but are relatively small compared with the market share, production cost, import substitution, operation expense, and maintenance expense generated by the 2mm improvements as measured from 1992 through 2001. (Although the 2mm project existed officially from September 1992 through January 1996, we extend the coverage period to account for subsequent investment by the vehicle manufacturers, operating cost changes, and market impacts that are related to the project.) These direct impacts are summarized in Table 4–1 and used as inputs to the REMI model for estimating macroeconomic impacts of the 2mm project.

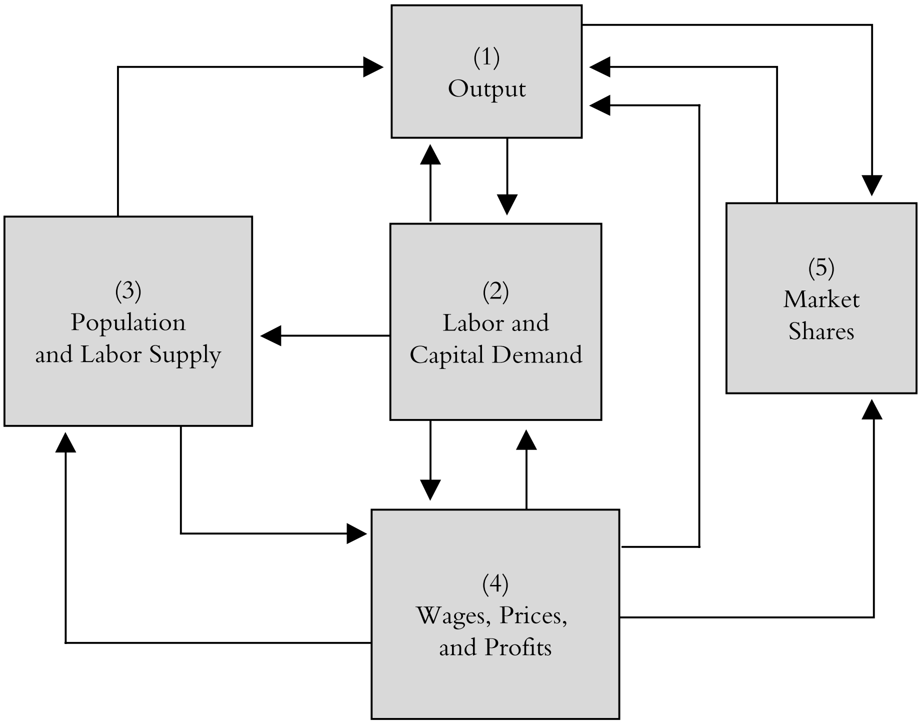
The REMI Model

The Regional Economic Models, Inc. ("REMI") model utilizes blocks of regional equations that the vendor estimated on the basis of conventional behavioral assumptions commonly found in macro-econometric models. Characterized by highly flexible geographic coverage that has the capability to range from single counties to the entire country, its components include an equally geographically flexible non-survey-adjusted input-output model that is useful for disaggregating and "localizing" the effects of certain changes in final demand.

The REMI model is distinguished from other regional models by its application of regional purchase coefficients, for example measurements of relative regional self-sufficiency compared with the nation as a whole, for estimating regional imports and exports. This concept is developed in Treyz, Friedlaender, and Stevens (1980). We show the basic model linkages (Figure 4–1), and Ehlen and Brown (2000) provide a useful compact summary of its operations and assumptions.

The model comprises five "blocks" of behavioral equations estimated using multiple-regression techniques that link output, labor/capital demand, population/labor supply, wages/prices/profits, and geographically defined market shares. Using the model, an analyst can draw on the output, employment, and income blocks to make estimates at

Figure 4–1. Basic Model Linkages in the REMI Model



Source: George I. Treyz. 1993. Regional Economic Modeling: A Systematic Approach to Economic Forecasting and Policy Analysis. Boston, MA: Kluwer Academic Publishers.

either a 53- or 172-sector level of detail. With the 53-sector model, we conduct our 2mm impact analysis at the 2-digit Standard Industrial Classification (SIC) level for non-manufacturing sectors, and at the 3-digit SIC level for the manufacturing categories.[28] For example, when we introduce an exogenous change in 2mm vehicle output, we can direct this to the motor vehicle assembly subcategory (SIC 371). Similarly, when we account for purchases of the Perceptron systems, we can estimate changes due to increased output in measuring and controlling devices (SIC 382).

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[28] The REMI model used here is not revised to reflect the shift to the North American Industry Classification System or "NAICS." The model used in this research is REMI Policy Insight, version 4.0, built on October 24, 2001.

The REMI model has been a great benefit to regional analysts who face the daunting prospect of assembling and constructing local models that usually employ ad hoc structures with regard to behavioral assumptions and sectored detail. It brings impact timing—something common in national econometric models but almost always lacking in regional analyses, which often use multiplier and input-output techniques—into regional economic analyses.

When estimating the 2mm economic impacts for our "regional" analysis, we employ regions not defined by common geographic areas and physical connectedness in space, but rather collections of relatively small areas (counties) connected by common technology. In fact, they are almost all physically separated from one another in space except for counties in the densest vehicle-manufacturing areas centered in the Midwest region. For our estimates, we are concerned with measuring the impacts of vehicle-assembly activities that are housed in plants that are sparsely distributed at the county-level (in 1998, there were 58 assembly plants in the entire United States). The United States comprises 3,125 counties, and therefore multi-plant counties are very rare; only 7 counties have two or more vehicle-assembly plants. We are thus able to construct regions of common technology in a highly efficient manner and to estimate the impacts as if we had estimated a macroeconomic model with highly disaggregated sector detail for the vehicle-assembly technology. Were these plants not as few in number and as spatially distinct as they are, it is unlikely that the sectored decomposition, which is key to this analysis, could be achieved at all. There are, to our knowledge, no conventional national macroeconomic models that can support this type of analysis.

The REMI model generates economic and demographic forecasts on an annual basis, constructed from more than 30 years of historical data. Its forecast horizon extends 35 years. However, its construction and software do not have the flexibility to permit users to select time periods or set a preferred forecast horizon for model estimates. Rather, the model is delivered to the user in its most current form, with the regional model coefficients estimated using a standard specification for each endogenous relationship. The general form of the different equations for each category of economic measure is given in Treyz (1993), but when using the model, users are not given access to either the estimated coefficients or the statistical properties of the estimated relationships.

Because we could not request a model developed using history through 1992 to forecast subsequent impacts of the 2mm project, we have opted to use the current model and impose the 2mm direct impacts as if they were occurring over the period 2000–2009. There are some obvious problems with using the model in such a way, most important of which is that the 2mm impacts have already exerted their influence and are, in a very real sense, "in" the historical data. The industry's cost structure has undergone some changes since 1992, but we were unable to estimate the distortion that this creates in our estimates. Fortunately, our direct impacts are small in scale compared with the size of the industry, and the production technologies in a mature industry like vehicle manufacturing are slow to change at the level of detail influenced by the 2mm project. Because we use the forecasts for 2000–2009 as a proxy for the 1992–2001 period, we present our impact estimates over "Years 1–10," with Year 1 being the start of the 2mm project.

Macroeconomic Impact Estimates Using REMI

We show a summary of the estimated economic impacts of the 2mm project using the hedonic model estimates and case study-based estimates in Tables 4–3 and 4–4, respectively. By either measure, the net effect of the project is generally a positive one. With the hedonic estimate, gross domestic product (GDP) grows by almost $190 million and full-time equivalent jobs by 1,400 over the ten years from the start of the project (Table 4–3). With the case study based estimates, the GDP growth is approximately $600 million and the full-time equivalent jobs is almost 10,000 (Table 4–4). In motor vehicle production, employment increases by nearly 1,600 persons, but small losses in other industries drive the net figure slightly downward (Table 4–3). With rising employment (and personal income), the unemployment rate and transfer payments decline under both alternatives.

Using the hedonic-based estimates in Table 4–3, total personal income rises by approximately $300 million, largely on wage and salary income increases that are offset by lower transfer payments and dividend income, the latter being consistent with lower profitability due to higher production costs. (In the case study estimates, dividend income rises slightly.) Income growth is achieved without any measurable inflationary effect because labor productivity increases are only slightly offset by wage rate increases. Even with the reduction in motor vehicle imports, changes in net imports are negligible, as consumer expenditures generate small increases of imported goods other than motor vehicles.

In view of the scale of the estimated direct impacts, we believe the total effects shown here are of a reasonable size, with no unusual contrary findings. In general, the 2mm project had a small stimulating effect, led by increases in domestic producers' market shares, in excess of offsetting declines in non-2mm vehicle sales, and the increased costs incurred to produce higher-quality vehicles.

We favor the hedonic estimate as being more objective and less likely to be biased by failure to account for the full range of cost effects attributable to the 2mm technology.

Table 4–3. Economic Impacts of 2mm: Years 1–10, Changes from Control Forecast Incorporating Hedonic-Based Production-Cost Changes (Total, including direct, indirect, induced, and demographic)

Variable	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Total
National Income and Output											
Gross Domestic Product (1992 $ million)	2.9	44.9	7.8	-58.6	-34.2	-4.9	39.1	71.3	63.5	53.7	185.6
Personal Income (1992$ millions)	2.4	54.7	48.8	-6.8	3.9	22.5	34.2	57.6	53.7	46.9	317.9
Wage and Salary Disbursements	2.0	56.6	55.2	-0.5	9.8	26.9	35.2	58.6	58.1	52.3	**354.0**
Property and Other Labor Income	0.5	5.0	-1.5	-10.1	-6.2	-2.0	5.5	10.4	8.9	7.4	**17.9**
Labor and Proprietors' Income	2.4	61.5	53.7	-10.3	3.4	24.9	41.0	69.3	66.4	59.6	**372.1**
Social Insurance Contributions	0.2	4.2	3.9	-0.2	0.5	2.0	2.8	4.6	4.5	4.1	**26.6**
Net Residence Adjustment	0.0	-0.2	-0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.1	**-0.1**
Dividends, Interest, and Rent	0.0	0.0	0.2	0.2	0.0	-0.2	-0.7	-1.2	-1.7	-2.2	**-5.6**
Transfer Payments	-0.2	-3.2	-1.2	3.4	1.5	-0.5	-3.3	-6.2	-6.2	-5.9	**-21.9**
Taxes	0.4	10.3	8.2	-2.0	0.4	3.8	6.5	11.0	10.4	9.3	**58.1**
Real Disposible Personal Income (1992$ millions)	1.5	44.0	40.0	-4.9	3.9	17.6	28.3	45.9	44.0	38.1	258.3
Employment and Labor Force											
Labor Force (1000s)	0.0	78.1	62.5	-109.4	-109.4	-125.0	-62.5	0.0	0.0	-15.6	-281.3
Employment (1000s)	46.9	671.9	-187.5	-1,281.0	-812.5	-328.1	562.5	1,109.0	890.6	734.4	1,406.2
Motor vehicles and equipment (1000s)	0.5	294.0	467.0	289.9	272.3	225.8	8.2	16.5	14.0	12.6	**1,600.8**
Wages and Prices											
PCE-Price Index (1992=100)	0.0	0.9	1.6	1.3	1.2	1.1	0.5	0.4	0.3	0.3	7.5
Wage Rate (1992$, 000)	0.0	0.2	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	1.8
Foreign Trade											
Net Trade (exports-imports, 1992$ billions)	-1.2	-18.8	-25.3	5.4	3.4	-2.1	7.8	-15.4	-18.3	-14.7	-79.1
Imports (1992$ billions)	1.2	19.9	26.3	-3.9	-0.6	5.4	-2.4	19.8	21.5	17.6	**104.6**
Exports (1992$ billions)	0.0	1.1	1.0	1.5	2.8	3.3	5.4	4.4	3.2	2.9	**25.5**

PCE = Personal consumption expenditures

Source: The authors using the REMI model.

Table 4–4. Economic Impacts of 2mm: Years 1–10, Changes from Control Forecast Incorporating Case Study-Based Production-Cost Changes (Total, including direct, indirect, induced, and demographic)

Variable	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Total
National Income and Output											
Gross Domestic Product (1992 $ million)	**2.9**	**247.1**	**243.2**	**78.1**	**40.0**	**13.7**	**-39.1**	**5.9**	**8.8**	**24.4**	**625.1**
Personal Income (1992$ millions)	**2.4**	**208.0**	**235.4**	**113.3**	**79.1**	**54.7**	**-13.7**	**13.7**	**10.7**	**19.5**	**723.2**
Wage and Salary Disbursements	2.0	207.5	238.8	118.7	85.0	57.6	-15.1	11.7	9.8	15.6	**731.5**
Property and Other Labor Income	0.5	32.8	31.3	8.5	2.7	0.0	-6.5	0.6	0.7	2.8	**73.5**
Labor and Proprietors' Income	2.4	240.2	269.5	127.4	87.4	58.1	-21.5	12.7	10.7	18.6	**805.6**
Social Insurance Contributions	0.2	15.5	17.8	8.9	6.3	4.3	-1.1	0.9	0.8	1.2	**54.7**
Net Residence Adjustment	0.0	-0.6	-0.7	-0.3	-0.1	0.1	0.6	0.3	0.3	0.1	**-0.3**
Dividends, Interest, and Rent	0.0	0.1	0.7	0.9	1.0	1.3	1.5	1.2	0.9	1.2	**8.8**
Transfer Payments	-0.2	-15.9	-16.2	-5.1	-2.6	-0.4	4.0	0.7	0.5	0.0	**-35.2**
Taxes	0.4	40.2	43.2	20.3	14.0	9.3	-3.2	2.2	1.7	3.4	**131.5**
Real Disposible Personal Income (1992$ millions)	**1.5**	**168.0**	**192.4**	**93.3**	**64.5**	**44.9**	**-10.7**	**11.7**	**9.8**	**15.6**	**590.9**
Employment and Labor Force											
Labor Force (1000s)	**3.6**	**6.8**	**10.8**	**38.7**	**23.9**	**38.3**	**38.7**	**11.8**	**2.8**	**-5.5**	**169.9**
Employment (1000s)	**46.9**	**4,453.0**	**4,094.0**	**1,078.0**	**343.8**	**-46.9**	**-750.0**	**46.9**	**31.3**	**265.6**	**9,562.5**
Motor vehicles and equipment (1000s)	0.5	365.6	551.0	339.7	300.0	236.8	-9.1	2.8	3.4	4.5	**1,795.2**
Wages and Prices											
PCE-Price Index (1992=100)	**0.0**	**0.5**	**0.9**	**0.7**	**0.8**	**0.7**	**0.5**	**0.3**	**0.2**	**0.1**	**4.7**
Wage Rate 1992 $, 000)	**0.0**	**0.5**	**0.7**	**0.5**	**0.4**	**0.4**	**0.1**	**0.1**	**0.0**	**0.0**	**2.7**
Foreign Trade											
Net Trade (exports-imports, 1992$ billions)	**-3.9**	**-557.3**	**-604.5**	**-240.5**	**-160.2**	**-87.6**	**78.4**	**-11.5**	**-15.1**	**-36.1**	**-1,638.5**
Imports (1992$ billions)	3.9	556.6	600.6	235.4	155.3	84.0	-78.1	11.7	15.6	37.1	**1,622.1**
Exports (1992$ billions)	0.0	-0.7	-3.9	-5.1	-4.9	-3.7	0.2	0.2	0.5	1.0	**-16.4**

PCE = Personal consumption expenditures

Source: The authors using the REMI model.

We present the hedonic result as a conservative estimate of the 2mm project impact and offer the case study-based estimate as an upper limit of the project's impact.

Even with the conservative hedonic-price analysis-based results, when we consider the positive impacts of shifting demand toward domestic vehicles net of investment costs for 2mm equipment, increased operations and maintenance (O&M) and production costs, approximately 1,400 jobs are gained over the ten years from 1992–2001. Concurrently, real (1992) GDP increases by approximately $190 million, for a multiplier of 1.7. This is an impressive result when we consider that the ATP award of approximately $4.4 million leveraged $6.1 million in matching and additional funds among participants, and led to more than $100 million in capital equipment expenditures that are largely attributable to the initial ATP funding and participation.

Chapter 5

Conclusions to the Report

Based on our findings concerning the direct and secondary impacts of the 2mm project as estimated in the REMI model, we offer three conclusions concerning the project's overall economic importance:

1. The 2mm research demonstrated to vehicle manufacturers that they could improve vehicle body quality through measurement and subsequent process adjustments to reduce dimensional variation. Having learned this through research funded by ATP's $4.4 million and a $6.1 million investment in cost-shared funds, vehicle manufacturers subsequently invested more than $100 million to equip the majority of their assembly lines with the equipment needed to improve their technology. The improvement in market share gained by 2mm vehicles, in addition to the equipment investment, generated a net increase in GDP of nearly $190 million and an increase of 1,400 full-time-equivalent jobs over the ten years from the start of the project. This is an impressive result relative to the size of the public's investment, and importantly, one that would not have occurred to the same degree without ATP's support.

2. The 2mm project demonstrated that a carefully designed forum for collaboration, such as the Auto Body Consortium (ABC), could increase knowledge and foster economic growth without jeopardizing the competitive environment.

3. The 2mm project increased the technological capabilities of domestic manufacturers, and thus it may help speed adoption of other technologies that promote continuous improvement in this and related industries. It has created new incentives for product

improvement (for example, among line integrators, to control better than before the part of the assembly process for which they are responsible). This result may lead to even more competitive, higher-quality products, ones that can compete better in a global industry than before the ATP 2mm project.

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Appendix 2-A to Chapter 2

Company Participants in the Case Studies

(Listed by company or institution in alphabetical order)

Companies Interviewed

American Sunroof Corporation*
Auto Body Consortium, Inc.
Chrysler (DaimlerChrysler since 1998)*
Classic Design, Inc.*
Detroit Center Tool, Inc.*
General Motors Corporation*
Perceptron, Inc.*
PICO (now Comau Pico)*
University of Michigan, S. M. Wu Manufacturing Research Center, College of Engineering
Wayne State University

Companies Not Interviewed

ISI Automation Product Group (firm no longer in business)
Modern Engineering (CDI Transportation Group, firm no longer in business)
Pioneer Engineering (APX International, firm no longer in business)

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*Case studies are in Appendix 2-B to Chapter 2.

Appendix 2-B to Chapter 2

Case Study Summaries for Companies Interviewed

Of the seven firms whose staff members we interviewed for this study, Chrysler Corporation and General Motors are vehicle-body assemblers, American Sunroof Corporation is a component manufacturer and converter of finished vehicles, Detroit Center Tool, PICO/Comau, and Classic Design are tool manufacturers, and Perceptron is an instrument manufacturer. We conducted interviews with many different plant engineers and managers at Chrysler and GM in order to obtain the broadest view and to allow for variation in the way the program was implemented in different plants.

Chrysler Corporation

Chrysler Corporation's (Chrysler's) implementation of the 2mm technology was and is only a partial one. No company-wide dimensional variation goals exist, although a common set of measures that permit plant-to-plant comparisons can be found in the company's "Body System Audit (BSA)." These measures, interestingly, continue to be drawn from the samples developed using coordinate measurement machines (CMM), not the 2mm equipment.

DaimlerChrysler (DC)[29] uses the 2mm technology for two primary purposes, for its alarm function and for troubleshooting problems. Plant managers use the alarm function to inform them of a severe dimensional problem with vehicle bodies in production, which permits them to make more rapid corrections than was the case with the BSA data. They use the troubleshooting function to correct some systematic problems uncovered in the BSA or through use of the 2mm equipment. Before 2001, DaimlerChrysler performed

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[29] In 1998, Daimler-Benz acquired Chrysler and adopted the name DaimlerChrysler. Throughout this report, we use the name "Chrysler" to refer to work at the firm during the 2mm program and until 1998, and the name "DaimlerChrysler" to refer to current practices at the firm.

no statistical analyses of the 2mm database other than those generated at the 2mm workstations. They are undertaking more extensive analysis using general application standard analysis software, not the dimensional analysis software originally to be developed as one of the 2mm research projects. Plant managers credit 2mm with an increased focus on body quality, but they provided no formal estimates of the 2mm technology's contribution to plant productivity improvement.

Chrysler Corporation (Chrysler) faced significant difficulties during the 1970–1980s, not the least of which was impending bankruptcy. During this period, the firm worked to overcome its products' reputation for poor quality. With the financial recovery of the company and development of "common body architecture," i.e., a design in which several vehicle models and types can share a limited number of platforms and drive-trains, Chrysler had a strong interest in having its plant personnel learn to control the body-assembly process, something the 2mm technology offered. Chrysler placed 2mm equipment both in stamping and assembly plants, a more extensive application than we found at GM, which introduced 2mm technology to assembly plants only.

For our research, we interviewed body-shop managers at the Warren, Michigan, truck-assembly plant and adjacent stamping plant, the Jefferson North Jeep-assembly plant in Detroit, Michigan, and at the new Toledo North truck-assembly plant in Toledo, Ohio, because the current (2000) Toledo manager implemented 2mm technology at Jefferson North in 1992.

On a day-to-day basis, Chrysler implements the 2mm technology by having body-shop engineers use the Optical Coordinate Measurement Machines (OCMM) to signal out-of-tolerance conditions. When an alarm sounds, the engineer searches for corrective actions that generally involve repairing and/or adjusting the tools or the unfinished Body-in-White (BIW) or discarding the unfinished item if the flaw is irreparable. The line operators and managers stated that only several alarms occur per week at Jefferson North, for example, which may be typical for a vehicle that has gone well beyond the launch phase and where the personnel are fully familiar with the tooling and inherent problems of any given model.

Chrysler's dimensional engineers have "codified" their experiences in confronting specific problems on vehicles into an intranet-based system that they refer to as their "book of knowledge." The engineers report their analyses of the plant-level dimensional performance in the "Body System Audit" (BSA), a CMM-based weekly report provided to plant management. In this report, they document conformance to targeted dimensional specifications for more than 100 points per vehicle on a sample of vehicles produced, showing capability statistics, for each sample point, as well as a two-quarter time-series of weekly conformance for a variety of measures.[30] These are standard statistical process-control measures, not specific to the 2mm program. It is at this stage that they use the OCMM to analyze dimensional variation at a location on the body to begin a "root-cause" analysis, following practices that evolved during the 2mm program. The other feature of the OCMM of demonstrable value is the alarm function, which helps monitor deviations from limits at critical points on the vehicle bodies.

DaimlerChrysler personnel cited two other major themes. One was that the firm felt that 6-sigma levels were more critical than achieving 2mm. The second was that a key aspect of the 2mm program, rather than the implementation of a given technology, was making the workers aware of the finished product. The management actions that were initiated at DC to help them improve body quality were directed to building the technical infrastructure of the company, and they may be actions that lead to long-run improvement of dimensional characteristics.

General Motors Corporation

General Motors implemented all elements of the 2mm technology at its U.S. assembly plants and is generating regular reports on dimensional variation by plant, accessible in real-time over the company's intranet. At the time of the interviews, GM no longer adhered to a strict 2mm target (3mm was the acknowledged target), it has made dimensional variation one of the key performance measures for vehicle-assembly quality. GM engineers acknowledged that the target was a loose one, claiming at that time that 3mm was good enough for the U.S. market. At 3mm, GM engineers noted that the assembly process was manageable with existing labor and management resources and that to maintain a higher level of quality would exceed such resources.

We note that GM body-shop managers were generally pleased at the low level of disruption of existing labor relations and conditions that resulted from implementation of 2mm technology in its plants. Minimizing shop-floor labor-management conflicts seems to be a critical factor for implementing any technological change in assembly plants covered by a union operating contract. To this end, it has instituted a formal program to track performance and has prescribed a standard set of measurement points to permit cross-plant and

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[30] The "capability" measures, Cp and Cpk, are ratios of performance relative to specifications. Cp is the ratio of the specified dimensional range to six times the standard deviation; Cpk is the ratio of the range of specified deviation from the process mean value to six times the standard deviation. These measurements lead to the 6-sigma concept, which we were told during our interviews was more critical than 2mm.

cross-model comparisons. (This is in sharp contrast with the plant-level measurement scheme in effect at DaimlerChrysler.)

GM personnel use data generated by the 2mm equipment as an input to their research and analysis of dimensional variation, using analysis software that incorporates knowledge gained from 2mm research projects. Their reliance on 2mm equipment has resulted in changes in metrology in GM plants. GM personnel have reduced the use of Coordinated Measurement Machines (CMM) for dimensional variation estimation, eliminated many checking fixtures. In addition to prompting measurement-technique changes, participation in the 2mm program also led them to reduce the amount of parallel processing in body assembly, whereby multiple tools would perform an identical action in an effort to eliminate a bottleneck at certain points on an assembly-line. Overall, interviewees credited 2mm with cost reductions, but they had no formal estimates of the magnitude of the reductions.

At the time General Motors elected to participate in the 2mm program, GM's North American operations were divided into two major groups, truck and car. This is true up to the time of our interviews in 2000. Prior to the 2mm program, each group operated its body-assembly plants somewhat independent of any centralized dimensional quality control and/or engineering oversight. With the program's inception in 1992, GM officially assigned this activity to the Engineering Group Manager at the Body Closures Center, a division within the GM Technical Center in Warren, Michigan.

GM interviewees trace their first attempt to measure vehicle bodies during the production process to 1981, when GM established its first non-contact-measurement system, utilizing vision sensors mounted on robots. In the mid 1980s, GM implemented its first OCMMs using both Perceptron and Diffracto (a competitor to Perceptron at the time) equipment. GM was behind Ford in introducing on-line gauging systems and in applying these data to estimate BIW dimensional variation. Ford operated contact systems as early as the late 1970s, employing statistical measurements.

Prior to the formal start of the 2mm program in 1992, GM had installed OCMMs in at least 12 different assembly plants in North America. No one at GM with whom we spoke mentioned any impacts of these early installations. At present, GM has incorporated Perceptron systems in all plants except joint-venture plants with Toyota and Suzuki and those plants located in Mexico. At an approximate cost of $2 million for each system and the need for operator training, this is a significant investment. GM now uses (or plans to use) Perceptron systems in all of its plants at five workstations per line: (1) side frame, (2) underbody, (3) doors, (4) full body, and (5) motor compartment. Each workstation has anywhere from 15 to 50 sensors, and the number can change according to the analytical needs of the dimensional engineers, i.e., the engineer can move the sensors from one workstation to another, as needed.

GM personnel identify two fundamental reasons for their interest in improving vehicle body quality: The first is based on competitive advantage and the second on profit. Concerning the first, GM is struggling to narrow the quality differences with its Japanese competitors. Since the early 1980s, the Japanese vehicle makers have been conducting research to improve the body-assembly processes to minimize variation in gaps (the variation in the space between moving panels on vehicles, such as doors, hoods, and trunks), and flush (the continuity of a surface ignoring intervening gaps). Concerning the second factor, GM expected its profits to grow through successful application of 2mm-derived technologies, which were designed to help (1) reduce vehicle launch times, (2) reduce scrap and other waste, (3) increase assembly-line speed, and (4) improve assembly-line maintenance practices.

By 1993, GM had started using the 2mm technology at its Michigan plants at Hamtramck (Detroit), Grand Blanc, and Lansing. It also started to use the technology at its plants in Baltimore, Maryland, and Fairfax, Kansas. GM initially applied the 2mm technology to measure the dimensional variation in vehicle bodies and doors, but not in other sub-assemblies, such as side frames or underbodies. At present, GM has "institutionalized" a number of 2mm practices in assembly plants under the concept "Enabler-31." Rather than use 2mm as a target value, it focuses on "high-quality body assembly" without a uniform standard to be applied to all vehicles.

Given its experience at Hamtramck on luxury cars and at Linden, New Jersey on light-trucks, GM seems to have achieved some of its goals. Since 1993, both plants have increased line-rates; these rose at Hamtramck from 62 vehicles per hour in 1993 to 66 in 1999 and from 45 to 59 at Linden over the same interval, and both plants have maintained body-quality while reducing scrap costs. Plant managers claim that one of the factors supporting increased line-speed is the constant monitoring that the OCMMs perform, focusing personnel on potential quality-related bottlenecks on the line.

Although Hamtramck personnel were unable to distinguish scrap reduction from other cost savings, the engineers estimated that the plant had saved approximately $2.80 (in 1992 dollars) per vehicle through the use of vision systems. At Linden, the plant achieved reductions in body-shop-related scrap costs from $5 per vehicle to $1 per vehicle, although their body-shop manager noted that improved robot reliability and better assembly-line tools and vision systems generated the bulk of the savings. The systematic improvements facilitated by OCMM data have helped to reduce scrap and waste costs attributable to defects in body construction and any subsequent manufacturing costs incurred on substandard bodies that must be ultimately scrapped.

We were not given access to any of the customer-satisfaction data from the JD Power & Associates surveys, but at the Linden plant, the body-shop manager noted a significant improvement in the survey data with respect to problems associated with door-opening and door-closing efforts. At Hamtramck, where engineers have achieved approximately 3mm variation, plant managers have not looked to see whether or not reduced dimensional variation correlates with (1) JD Power data, (2) GM's own customer audit, or (3) warranty claims charged to the factory, although they use all three data sets regularly to track plant performance.

In addition to not linking OCMM data with the evaluation of post-production quality-perception and/or warranty-claim data, the GM personnel have attempted only a limited application of this information to improve tool-maintenance scheduling. They have not explored the possibility of using the analysis of tool performance to develop predictive maintenance practices; rather, they rely on the alarm features to identify broken welding tips and/or clamps.

We are concerned that, thus far, none of the assemblers has leveraged the 2mm database to test measured body quality against other downstream measures of performance. The lack of a pre-designated set of metrics from which to define and gauge the success of investments in vision-system technologies makes ascribing a return on such investment an exercise in semantics. We, however, can make some qualitative observations—discussed in later sections—based on the insights that such a review lends us.

Despite this evident failure of most, if not all, plants to generate a documented improvement in perceived product quality through use of 2mm technology, GM has now installed Perceptron equipment at all of its assembly plants. GM also established a standard set-up of the sensors to measure a prescribed set of points on all vehicles. Also, plant personnel produce a common set of body-quality performance reports from OCMM data. GM staff make the reports available to various levels of management by transferring them over the GM telecommunications network, where they are used to monitor plant performance and quality. By investing in 2mm equipment, the corporation no longer requires a separate financial justification for the purchase and use of the vision-system equipment, because GM classifies such purchases as "key-process equipment," which financial managers include as part of the "bill of process."

One of GM's key program goals at the outset was to see OCMMs become dominant measurement tools, replacing checking fixtures and CMMs, both of which are time-consuming operations primarily used on a small proportion of the output. By eliminating the use of checking fixtures, the Linden plant managers have cut capital investment at the plant by $1.5 million, a significant offset to the $2 million invested in Perceptron systems. GM, however, does not plan to replace all CMMs with OCMMs. Several GM engineers noted that one of the disappointing features of the OCMMs is that they are "impossible to master." They are not useful, in other words, for producing nominal measurements of key vehicle dimensions; rather, they can only estimate dimensional variation at selected measurement points from one body to another. Because they need both sets of measurements to maintain control of vehicle dimensioning, the GM plant personnel will continue to use CMMs for gauging actual vehicle dimensions.

Ironically, by using OCMMs, plant personnel increase reliance on the use of CMMs in certain plants. In those plants whose assembly processes use automated-guide vehicles (AGV) and/or pallets to move Body-in White (BIW) through the different assembly stages, use of the CMMs has increased in scope. One lesson that plant managers learned in the course of using the 2mm technology was that significant dimensional variation in the BIW results from variation and wear in the AGVs and pallets that position the body during the tooling. At Hamtramck, personnel now perform scheduled CMM inspection of pallets, while at Linden, they similarly inspect AGVs; therefore, their measurement burden, overall, has increased as a result of the 2mm program.

Another lesson they learned from the 2mm program is that multiple-tooling (or parallel-processing) of complex tasks during the assembly process makes it difficult for personnel to control dimensional variation. According to engineers at the GM Truck Validation Center, it is too difficult to keep several machines performing the same task all within acceptable dimensional limits. For this reason, GM is phasing out such processes by redesigning tools (and generally adding tools and cost) to keep line-speed up while eliminating the parallel tools. We could not obtain any estimates of the cost effect of these process changes.

Introduction of the 2mm technology provided GM plant managers with a strong justification to change one important aspect of vehicle body design and assembly: replacing traditional butt-joint assembly with a "slip-plane" (overlapping joint) panel construction. By using slip-planes, the engineers found that inaccurately sized stamped components need no longer result in dimensional variation, provided that they position key locating points on the pieces correctly. When overlapping joints are formed, the engineers determined that dimensional variation "disappears" in the joint itself. They developed this construction method independent of 2mm research, but when they conducted analyses on the sources of the variation as part of the program research, engineers found that they could validate the superiority of slip-plane joinery from a dimensional-variation standpoint.

As a result of 2mm research, GM personnel also instituted another change in the process: the redesign of various panels to reduce sources of dimensional variation. As an example, Linden engineers modified the design of the door-opening panel, so that the part is now fabricated from a single stamping, rather than from a panel constructed from 32 smaller stampings welded together. The single stamping, however, is far more complex and entails greater expense for the tool-and-die fabricating division. In addition, the GM Metal Fabricating Division (MFD), GM's in-house stamping group, produces it at slower rates than the individual stampings. They found that they could offset some of the extra expense by simpler assembly on the auto body combined with greatly improved quality. The reduced use of equipment and numbers of tools often results in cost savings regardless of the assembly-cost savings. Hamtramck personnel have had a similar experience with fuel-door "pockets," for which they selected a more complex stamping in an effort to improve the assembly process and finished quality.

By 2000, GM was producing vehicles with a dimensional variation of approximately 3mm (at six standard deviations or "six sigma"), and the GM personnel we interviewed saw the assembly process as being "under control." And by 2000, five years after the end of the formal 2mm program, that GM engineers were prepared to move forward with analyses using the "BIW Data Analyzer," proprietary software developed in-house to perform statistical analyses using OCMM data. GM engineers confronted a number of barriers to developing software linked to the OCMM database, from accessing the database to processing the huge volume of data generated during the production process, which were derived from several hundred points per vehicle.

Throughout the 1990s, rapidly changing computer technology and costs related to implementing that technology made software development difficult. At the beginning of the 2mm program, Classic Design, Inc. (Classic Design), a tool-design firm interested in expanding into software-based services, had sole responsibility for software development. By 1995, GM became interested in developing a proprietary software package for its own use, while DaimlerChrysler had less interest in software altogether. GM has since placed the software in service at all of its OCMM equipped plants. Classic Design engineers originally developed their prototype software for the Windows 3.1 operating system. By the time funding of the 2mm program had ended, this software was in need of being updated to Windows NT (or Windows 95).

Since the conclusion of the 2mm program in 1995, GM has not extended 2mm technology to upstream- or downstream-processing stages. For example, the GM MFD does not employ 2mm equipment for dimensional-variation control or inspection, but it has implemented some corrective changes in activities that were identified through the 2mm program. One of these changes was the improvement in the protection of stampings during shipping.

The implementation of the 2mm program provided GM personnel with a performance measure for vehicle body assembly. The race between GM and Chrysler to achieve the 2mm target was a critical motivating factor in keeping both firms focused on gaining a new understanding of the assembly process and implementing product and process changes that helped reduce dimensional variation. Although personnel in both firms were wary of sharing knowledge gained from the research activity, the competitive atmosphere appears to have been essential to the success of the program. The program also appears to have been a useful forum in which to exchange technical knowledge in a much more timely fashion than the traditional academic approach involving meetings and journal publications.

Chrysler and GM Compared

From our interviews, we note that implementation of 2mm technology at Chrysler differs from that at GM in at least three distinct ways:

First, at Chrysler, there was less centralization and control of assembly practices from any corporate authority as compared with GM.

Second, Chrysler and GM differ in the extent to which the two firms applied key lessons drawn from 2mm participation. Chrysler, for example, through its 2mm research, gained an appreciation of the impact of body design on the potential for dimensional variation during the assembly process. To anticipate future dimensional-variation problems, Chrysler also determined that design engineers require shop-floor experience to understand this relationship. In contrast, GM appears to limit its application of 2mm lessons to assembly processes and procedures, except for the increased use of slip joints, which now are used at all its vehicle plants.

Third, DaimlerChrysler (DC) has yet to develop applications for the quantitative database that the 2mm program helped create, and it is not applying quantitative analysis to BIW dimensional variation. GM, on the other hand, has initiated dimensional-variation-reduction research and analysis at each assembly plant, coordinated by research centers staffed by dimensional-variation-control engineers.

With respect to centralization, DC has not attempted to standardize reporting and measurement procedures using data generated with the 2mm equipment and software, nor has it attempted to exploit the analytical potential of the BIW assembly database. In general, DC plant personnel limit their use of the 2mm equipment/software to problem identification and alarm functions. The lack of centralized control over how 2mm-derived data are generated (for example, the specific points on the BIW to be measured) or lack of standardized reporting are not problems, per se, provided that body-shop and plant managers maintain process control and strive for performance that remains within the range of the target dimensional variation.

As noted earlier, DC has not developed applications of its quantitative database for analyses of BIW dimensional variation, whereas GM has started to do so. Thus, although plant personnel at DC appear to be applying the 2mm lessons more broadly on the assembly line than are their colleagues at GM, we could not determine whether management at DC made much use of the 2mm information they were provided. Both companies do have specialists available in the plant to handle dimensional-variation problems when they arise during the assembly process.

American Sunroof Corporation

American Sunroof Corporation (ASC) is a supplier of sunroofs to OEMs and the aftermarket, and it was also a post-assembly converter of hardtop vehicles to convertibles for Toyota and GM. By participating in the 2mm research, ASC hoped to improve the quality of its work by incorporating accurate measurement of the vehicle bodies it received from the manufacturer into the manufacturing process. At the same time, the company anticipated that 2mm technology would improve the quality of the vehicles it received, making its job that much more accurate.

Prior to the inception of the program, ASC experienced significantly larger warranty claims on its conversion business work for GM compared with Toyota and attributed much of the difference to dimensional variation of the incoming vehicles. Therefore, use of the 2mm technology had been expected to be a valuable resource for ASC, but the company shifted its market focus away from conversions at the time 2mm was ongoing. This eliminated the pressure to implement the technology in its conversion plant. As a consequence, productivity benefits that might otherwise have been achieved by ASC as a result of the program ceased to be relevant to its business.

ASC received approximately $615,000 in total funding from NIST, and the former ASC engineer claims that the firm actually spent more than $1 million on the work. With this funding, two to seven technicians and/or engineers performed research work over the three-year period. Although ASC managers claimed to have learned valuable technical lessons as a result of participation, he believes that a combination of ambivalence on the part of ASC upper management and inconsistent OEM support for lower dimensional-variation-reduction targets failed to motivate the necessary follow-through on new opportunities.

The net result is that the firm can claim little long-term economic gain for its 2mm research efforts. The former engineer further stated that ASC did not expand market share or broaden its product/service line based on 2mm-derived capabilities. The former ASC engineer provided us with some estimates of the value of a 2mm standard for BIW on convertible top conversion work. ASC was charged an average of $2–3 per vehicle for warranty claims on GM vehicles at a time (in the late 1980s) when GM vehicles were at a 10mm variation. At the same time, ASC experienced claims of $0.10 per vehicle on the work done on Toyota vehicles, already at the 2mm target. Although we cannot assume that ASC performed work for both customers to an identical standard, we can see that BIW dimensional variation has a large potential impact on warranty claims.

Detroit Center Tool

Detroit Center Tool (DCT) is a full-service assembly-line integrator that provides tooling, conveyance systems, and welding systems. DCT gained valuable knowledge from the 2mm research project; it learned that assembly-line tooling is both a significant source of dimensional variation and that by improving tool performance, line integrators can meet stricter OEM specifications for assembly line performance.

The company managers credit the one-time gain in knowledge with causing a permanent change in its approach to constructing assembly lines. For example, it has incorporated measurement equipment into the tooling itself rather than rely on post-assembly measurements given by the 2mm and other measurement equipment. DCT personnel credit 2mm with drawing attention to problems, but they claim that these subsequent tool improvements have gone a long way toward eliminating the need for 2mm equipment.

They note that launch-time reductions credited to the use of 2mm equipment may be largely the result of a change in the location of certain setup and adjustment activities from the final assembly plant to the line-integrator's plant, with only a small net effect on overall productivity. They also report that in lines they have constructed that incorporate the 2mm equipment, the OCMM systems are among the last to be setup and calibrated; therefore, there is little potential for time-savings.

The nature of the market for line-integrator services began to change dramatically starting in the mid-1980s. Prior to that time, the OEMs performed their assembly-line design using in-house engineering personnel. Companies contracted with numerous tool manufacturers located all over the country but concentrated around Detroit. Starting as one of the tooling manufacturers, DCT's role evolved into line integration as the OEMs shifted from in-house design and integration to turnkey system procurement. For the OEMs, the process of getting many separate tools to operate together to produce saleable bodies was time consuming and a significant cost to their model changeover.

DCT representatives noted that vehicle launch times as long as six months were not unusual in the industry in the early 1980s. During the last decade, this period has dropped to as little as eight weeks, largely as a result of doing the tool integration in the suppliers' plant prior to reinstallation at the customer site. The tooling supplier puts the entire line together and tests, adjusts, and modifies it as needed. Thus, from the time the line is ready in the integrator's plant, it can be moved into the final production site and ready for use in a matter of weeks, rather than months. The turnkey assembly-line supply approach is now the current operating model in the industry. DCT (and Comau Pico) personnel cite this transition as the single most important factor in lowering vehicle launch times at the OEM facility. However, unless tooling design occurs in tandem with product design at the OEM, launch-time reductions are largely bookkeeping matters, with more launch time occurring at the line supplier, rather than at the assembly plant. Overall, we were told that some reduction in launch time has been achieved, but that it is largely attributable to the improved logistics of installation of OCMMs and changes in the setup made possible by going from many tool suppliers to one.

Both DCT and Comau Pico personnel give credit to the 2mm program for helping them to identify those aspects of the assembly process that are most responsible for dimensional variation. Now, cognizant of the sources of dimensional variation, they have developed the tooling needed to meet customer requirements. They have been able to do this partly, they say, through their use of OCMM data analyses that monitor problem areas in the finished product. At the same time, these two line integrators want credit for improved tooling that reduces dimensional variation. They note that new hardware add-ons to tools that monitor tool performance directly are widely used in the industry, so that personnel use alarms and conduct data analyses directly on the tool, rather than on the product.

Increasingly, DCT engineers favor the tool-specific monitoring approaches, because they can know when tools are performing to specification. They claim that even with multiple Perceptron workstations on the assembly line, the OCMM-based process of pinpointing problem areas can be too time-consuming during the frenzied launch process. In fact, they note that the Perceptron equipment is generally one of the last parts of the line to be "turned on;" hence, it has had no effect on the reduced launch times observed since implementation of the 2mm program. They credit the 2mm program with the one-time gain in knowledge that has permitted tighter tolerances and resulted in improved incoming material quality, but they do not give credence to the notion that 2mm practices and equipment form the foundation of continuous improvement.

Comau Pico

Comau Pico, the largest line integrator in the United States, is a full-service, assembly-line integrator that designs and installs lines, including welding fixtures, automated systems, and the special machinery that joins fenders, frames, and exterior panels of cars. The company also manufactures stamping dies for making vehicle body parts and produces other equipment for aerospace, recreational vehicles, consumer products, and defense industries. Comau Pico's customers include all of the largest domestically owned vehicle manufacturers, and it is the largest line integrator in the United States. It is also a major supplier of assembly-line tooling and equipment to customers in Europe.

The one significant improvement that Comau Pico personnel attribute to the 2mm technology is the use of the equipment to perform tooling-repeatability studies, whereby tool capabilities are demonstrated far more rapidly than could be achieved with checking fixtures or CMM measurements.

As in the case of DCT, Comau Pico personnel design and install complete assembly lines, including Perceptron equipment when requested by the customer.

They noted that the primary usefulness of such equipment is to identify immediate maintenance needs when the machine operators' primary function is to react to problems, not to improve performance. In our interview, we conjectured that Perceptron systems used during the launch of a new model might accelerate line "buy-off" time, i.e., the time at which a manager deems the line to be ready and the integrator gets paid by the OEM.

Comau Pico believes that this is actually a subset of three contractual items that determine buy-off, namely: (1) equipment-performance specifications, (2) plant-performance specifications, which includes Perceptron dimensional data, and (3) cycle-time objectives.

The one application that Comau Pico personnel attribute to the use of 2mm equipment and research is the performance of repeatability studies conducted on assembly-line tooling. In these studies, the engineers test tools (primarily welding robots and tools) for accuracy and repeatability to help them identify line-maintenance needs. Comau Pico managers indicated that this is an important development in improving maintenance schedules to ensure that items with the highest priority (from a dimensional-variation standpoint) get appropriate attention by the line operators. They anticipate that the use of these tools by the OEMs may instigate a shift away from a rule-of-thumb approach (or using pre-2mm maintenance schedules) to more of a "root-cause" process for determining the major sources of dimensional variation.

Comau Pico managers, however, did not provide estimates of the financial impact of such a move. Thus, as at DCT, Comau Pico managers and engineers ascribe a very limited role to the 2mm program in terms of reduction in dimensional variation.

Classic Design, Inc.

Classic Design, Inc. (Classic Design) is a specialty tool designer and manufacturer whose primary customers are the OEMs. Its participation in the 2mm program was as a developer of the "Process Navigator" software that would give assembly-line workers the capability to perform real-time analysis of the database with a view toward making adjustments to improve dimensional accuracy.

Software would be a new line of business for Classic Design, one perceived as highly dynamic. At the same time, improved understanding of dimensional variation facilitated by the software would ultimately improve the accuracy and capabilities of tools the company designed for the OEMs.

The firm's personnel design manufacturing systems and develop both prototype tooling and prototype mechanical systems for automated manufacturing. The Process Navigator is a statistical-analysis package specifically tailored to vehicle body analysis. It uses a database constructed from normal Perceptron system monitoring operations to perform simple charting, principal-components analysis, and more complex correlation studies to identify origin points of dimensional variation on the vehicle body. It generates printed reports and/or two-dimensional graphical displays. Firm personnel originally wrote it for Windows 3.1, but several years ago, they revised it to run under an NT operating system.

Classic Design marketing personnel were unsuccessful in selling the product, which is otherwise commercially ready except for a little updating and testing. They were close to selling it to GM, when organizational changes at GM involving EDS (a GM subsidiary) resulted in internal development of similar software, known as the Body-In-White Data Analyzer. They were even less successful at Chrysler, where no funding line existed for such a purchase. This combination of circumstances all but eliminated the possibility of a sale once the product was ready for the market.

The GM Body-In-White Data Analyzer software is in use today and is, at long last, soon to be part of the standard set-up of 2mm systems and software in all GM assembly plants. Classic Design managers attribute the failure to complete sale of their product to GM to be a result of bureaucratic confusion. In their recounting of the uncompleted sale, GM managers identified price as a factor, but they added that the Classic Design software lacked the needed technical sophistication (for example, ability to perform three-dimensional principal components analysis) for the product to be useful. As of 2003, Classic Design is attempting to license or sell their software to interested parties better equipped to market the product.

There is a basic difference between the two software packages in their intended use. Although both use analytical routines and techniques developed under the 2mm program at the University of Michigan, Classic Design personnel intended their software for use on the shop floor by the hourly workforce to analyze real-time data to identify which processes were in- or out-of-control. Presently, the GM software is located in the CMM room and is used by process engineers and managers to conduct special studies.

The Process Navigator software might have been somewhat outside Classic Design's demonstrated area of expertise, but attributing the failure of the product to that, or to the price, appears to be only part of the story. The firm may have made the product available prematurely. With widespread use of the Perceptron equipment only now becoming industry standard, GM managers may have resisted the purchase of the Process Navigator software because of uncertainty regarding its effective use by their plant personnel. Unlike five years ago, GM managers now view the equipment as more of an indispensable capital asset. Consequently, they appear much more interested than they had been in applications that exploit the database of vehicle information related to dimensional variation. Classic Design managers credit the 2mm program with accelerating the development of the Process Navigator/BIW Data Analyzer as an offshoot of focusing on body quality.

Perceptron, Inc.

Perceptron, Inc. (Perceptron) supplies in-line gauging stations, workstations, sensors (cameras), computer monitors, database support software, and system-management software, all of which we refer to as the 2mm equipment. It also provides training in the operation of measurement and monitoring systems, and, as such, serves as the primary means of transferring this technology across firms in the automotive industry. The company was established in 1981 with automotive and light-truck OEMs as the primary focus. In 1998, the company, which is headquartered in Plymouth, MI, had approximately 330 employees worldwide, and it derived 80% of its total 1998 revenue from the automotive and light-truck industry. Approximately 85% of its vehicle firm sales are to domestic OEMs. Its non-vehicle market consists almost entirely of the forest-products industry, which uses laser measurement to optimize sawmill yield in lumber production.

Of all the firms participating in the 2mm program, Perceptron had the greatest interest in demonstrating the effectiveness of optical measurement in improving dimensional accuracy of vehicle bodies, because it was the sole supplier of the measurement systems. Almost all of the analysts who undertook research studies to determine the sources of BIW dimensional variation, to develop OCMM database analysis tools, to develop statistical analysis algorithms, and to undertake problem-solving case-studies relied on Perceptron equipment for measurements, with others using CMM databases to support their research. The successful application of the results of these studies and demonstrable improvement in body quality was the missing evidence that Perceptron needed to gain an audience it assumed was awaiting proof that use of its systems could lead to reduced BIW dimensional variation, higher line rates for a given level of quality, improved customer perceptions of body quality, and, hopefully, reduction of vehicle-launch times and lower warranty costs.

Our research team concludes that the 2mm program served to accelerate the improvement of auto-body assembly by those domestic producers that participated in the program, thereby speeding higher-quality domestic vehicles to market. Central to this achievement was the Perceptron measurement system. By almost all accounts, the Perceptron system delivered as promised in providing the data necessary to improve vehicle body quality while enabling higher line rates that generated a positive productivity effect.

At the beginning of the 2mm program, one of the long-term goals of the research was to demonstrate that non-contact measurement systems had applications for use beyond the automotive and truck firms. This has yet to be realized in a manner beneficial to Perceptron, although some of the smaller-scale, tool-specific optical measurement applications developed by competitors may be gaining ground. By all measures, Perceptron benefited from having demonstrated that its products could be a reliable means of monitoring the assembly process. Perceptron's business grew dramatically during the 2mm program. Prior to 1992, the number of Perceptron systems sold ranged from 1 in 1987 to 9 in 1991. During the program, sales rose to 68 systems in 1995, and they peaked at 133 systems in 1996. From that time onward, sales have fallen just as dramatically as they previously rose, reaching just 7 systems in 1999. If the market consists primarily of vehicle body-assembly lines, the 83 lines listed as being in operation at Ford, GM, and DC in 1999 (Harbour, 2000) represent a total market potential of 415 systems at 5 systems per line (side frame, underbody, doors, full body, and motor compartment). With sales of 459 systems through 1999,[31] it is evident that the market is likely to reach saturation, and that Perceptron's future sales will likely depend on new line investments, system replacements/upgrades, services, and new product development.

Perceptron's revenue performance peaked in 1997, immediately following the end of the 2mm program, at around $65 million per year, and in subsequent years, it saw declining revenue. This is attributable at least in part to market saturation; with the OEMs adopting the Perceptron systems as a standard feature of their assembly lines, the market for its product is largely dependent on new assembly-line sales. Of course, the company's revenue performance during the early 2000s versus the late 1990s also has been influenced by the downturn in the economy and the slowdown of corporate investment in new technologies.

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[31] The reasons for sales greater than our simple potential estimate is that a number of stand-alone systems were sold to firms other than the Big-3 for research and/or troubleshooting applications or for use on assembly lines already equipped with a basic OCMM set-up for diagnosing and managing a problematic assembly task.

Appendix 3-A to Chapter 3

Hedonic-Price Model Results

Appendix Table 3–1 provides the regression-variable descriptions. Appendix Tables 3–2 and 3–3 show the results of an ordinary least squares (OLS) estimation from a regression of "relative market shares" on car and light-truck attributes using the unrestricted 2mm definition, respectively. (See Equation (7a) in Appendix 3B.) Appendix Tables 3–4 and 3–5, discussed later, show the same type of results, but this time in relation to mark-ups for car and light-truck attributes (see Equation (15a) in the Appendix 3B), respectively, again using the unrestricted 2mm definition.

Market Share

In Tables 3–2 and 3–3, the 2mm variable is significant for cars and trucks in all specifications. Using the hedonic-price model, we estimated that the market share increased approximately 0.3% for cars and 0.4% for light-trucks (refer to the 2mm row in the tables). Our estimates are very stable in the different specifications, described further below. The only notable difference happens when we delete the domestic variable (DOM). For cars, the economic impact of 2mm is reduced, and for light-trucks, it is increased. The reason is that consumers demand U.S.-made cars less than other cars with the same observable (by us) attributes, while the opposite happens with light-trucks.

For each of the eight regressions, we used slightly different specifications. For Regressions (1) and (2), we attempted to determine the best proxy for engine power. For cars, we found that the best proxy was the natural logarithm of the horsepower, and for light-trucks, it was horsepower-over-weight. An important issue concerned the proxy for vehicle size.

We found that the use of length, width, and height at the same time is confusing. We might have obtained negative signs for width and positive signs for height and length, for instance. The same applied for using size and height together. We decided that the best proxy seemed to be volume, which we defined as length times height times width. For Regressions (4) through (7) for cars and (4) through (6) for light-trucks, we deleted some variables that were not significant to test the sensitivity to changes in the specification. We saw no changes in sign and no significant change in level for most variables considered, two common concerns with multiple regressions.

In Regression (8) for light-trucks and also for cars, we examined the effect on the 2mm variable parameter when we did not control for domestic production (deleting the variable DOM). One interesting result for cars was that the station wagon had a negative impact on consumer demand. That is, for cars with the same size, power, etc., consumers would demand fewer station wagons than non-station wagons. The elasticity of miles per gallon was significantly higher than 1.0 both for cars and light-trucks, suggesting that manufacturers might find it worthwhile to invest in improving fuel efficiency from the point of view of demand. The coefficients on the variable for European cars and for U.S.-made cars were both negative; therefore, there may have been excess demand for Japanese cars, or there may have been some attributes of the Japanese car that we could not observe in our data. The opposite is true for light-trucks, however. In that market, U.S.-made vehicles were the ones displaying excess demand (that is, the coefficient was positive), and the demand for the few European light-trucks was not statistically different from the others. Consumers demanded fewer imported cars or light-trucks than similar cars that were produced in the United States or Canada.

The time-trend variable for cars and light-trucks (shown as "TREND" in Appendix Tables 3–2 and 3–3) was negative. For cars, this was consistent with Figure 3–3 in Chapter 3, presented earlier, but not for light-trucks. The problem is that the number of different light-truck models also was increasing; therefore, the market share by vehicle model was not changing, although the total demand was growing. Furthermore, the trend was highly correlated (more than 50% in all specifications) with the 2mm variable. Another interesting aspect of the demand for light-trucks was the behavior of the different kinds of light-trucks. We can see that consumers under-demanded all vans compared with their demand for SUVs or pickups. Actually, the smallest effect was on minivans; consequently, we could make a sort of hierarchy (in terms of consumer demand) for the light-truck taxonomy: SUVs on the top, then pickups, minivans, and cargo vans, and, on the bottom, full-size vans. From Figure 3–7 (in Chapter 3), we see that SUVs and pickups were indeed the leaders in the increased sales of light-trucks.

To analyze the impact of the 2mm project on the producer's mark-ups, we used the results of the market-share estimates from Equations (7a) in Appendix 3-B to estimate the mark-up as the dependent variable for cars and light-trucks (Appendix Tables 3–4 and 3–5). Using the unrestricted definition of 2mm and for lags up to 2 years, we found that the impact of introducing the 2mm project on the mark-ups was negative for both cars and light-trucks at a 10% significance level. Using the unrestricted sample, the 2mm project probably increased the cost of production. The effect, however, was very low: around -0.07% for cars and -0.04% for trucks. A decline in producers' mark-ups is equivalent to an increase in producers' costs; thus, the minus sign on mark-ups indicates rising costs.

Appendix Table 3–1. Variables Description

	Description
CTE	Constant term
P	Real price (1983 U.S.$)
L_DR	Natural log of number of doors
DRV	Dummy = 1 if the vehicle is front wheel drive
FWD	Dummy = 1 if the vehicle is four wheel drive
SW	Dummy = 1 if the vehicle is a station wagon
MINIVAN	Dummy = 1 if the vehicle is a mini van
FSVAN	Dummy = 1 if the vehicle is a full size van
CARGO	Dummy = 1 if the vehicle is a cargo van
PICKUP	Dummy = 1 if the vehicle is a pick up
L_WB	Natural log of length of wheelbase
L_LNG	Natural log of length
L_WDT	Natural log of width
L_HT	Natural log of height
SIZE	Natural log of size (length times width)
VOLUME	Natural log of volume (size times height)
L_WT	Natural log of weight
LN_CY	Natural log of number of cylinders
L_DISP	Natural log of displacement
L_HP	Natural log of horse power
HP/WT	Horse power over weight
AT	Dummy = 1 if the vehicle has automatic transmission
L_MPG	Natural log of miles per gallon (EPA)
EURO	Dummy = 1 if the vehicle was produced by an European company
DOM	Dummy = 1 if the vehicle was produced by an American company
IMPORTS	Dummy = 1 if the vehicle was imported
2mm	2mm Dummy
TREND	Trend

Source: Developed by the Authors.

Appendix Table 3–2. Summary Results from the Market-Share Regressions for Cars

	(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
Variable	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂
CTE	-19.58^a	4.98	-21.11^a	4.99	-20.48^a	4.97	-21.77^a	4.96	-21.96^a	4.94	-21.52^a	4.89	-22.19^a	4.80	-22.40^a	4.81
P	-0.04^a	0.00	-0.04^a	0.00	-0.04^a	0.00	-0.04^a	0.00	-0.04^a	0.00	-0.04^a	0.00	-0.04^a	0.00	-0.04^a	0.00
L_DR	0.31^a	0.07	0.31^a	0.07	0.34^a	0.07	0.39^a	0.07	0.39^a	0.07	0.39^a	0.07	0.40^a	0.07	0.41^a	0.07
Drv	0.04	0.05	0.04	0.05	0.04	0.05	0.07	0.05	0.07	0.05	0.07	0.05	—	—	—	—
Fwd	-0.61^a	0.25	-0.63^a	0.25	-0.59^b	0.25	-0.50^b	0.24	-0.49^b	0.24	-0.49^b	0.24	-0.54^b	0.24	-0.52^b	0.24
SW	-1.26^a	0.06	-1.26^a	0.06	-1.27^a	0.06	-1.24^a	0.06	-1.24^a	0.06	-1.23^a	0.06	-1.23^a	0.06	-1.25^a	0.06
L_WB	2.70^a	0.78	2.75^a	0.79	3.17^a	0.76	2.92^a	0.76	2.93^a	0.76	2.88^a	0.75	2.81^a	0.75	2.75^a	0.75
L_LNG	1.71^a	0.70	1.93^a	0.69	—	—	—	—	—	—	—	—	—	—	—	—
L_WDT	-1.78^b	0.84	-1.70^b	0.84	—	—	—	—	—	—	—	—	—	—	—	—
L_HT	2.52^a	0.63	2.48^a	0.63	2.64^a	0.63	—	—	—	—	—	—	—	—	—	—
Size	—	—	—	—	0.2098	0.45	—	—	—	—	—	—	—	—	—	—
Volume	—	—	—	—	—	—	1.01^a	0.37	1.02^a	0.37	0.99^a	0.37	1.07^a	0.36	1.06^a	0.36
L_WT	-0.29^a	0.10	-0.24^b	0.10	-0.29^a	0.10	-0.30^b	0.10	-0.30^a	0.10	-0.30^b	0.10	-0.31^a	0.10	-0.32^a	0.10
LN_CY	0.21	0.15	0.24	0.15	0.13	0.15	0.17	0.15	0.19	0.14	0.17	0.14	—	—	—	—
L_DISP	0.08	0.11	0.10	0.11	0.07	0.11	0.04	0.11	—	—	—	—	—	—	—	—
L_HP	0.34^b	0.14	—	—	0.33^b	0.14	0.24^b	0.14	0.25^b	0.14	0.26^c	0.14	0.28^b	0.13	0.35^b	0.13
HP/WT	—	—	0.44	0.30	—	—	—	—	—	—	—	—	—	—	—	—
AT	-0.05	0.06	-0.06	0.06	-0.03	0.06	-0.04	0.06	-0.04	0.06	—	—	—	—	—	—
L_MPG	1.61^a	0.20	1.49^a	0.19	1.5348^a	0.2	1.65^a	0.19	1.64^a	0.19	1.64^a	0.19	1.61^a	0.19	1.71^a	0.19
Euro	-0.59^a	0.07	-0.59^a	0.07	-0.60^a	0.07	-0.54^a	0.07	-0.54^a	0.07	-0.54^a	0.07	-0.56^a	0.06	-0.50^a	0.06
Dom	-0.23^a	0.07	-0.25^a	0.07	-0.26^a	0.07	-0.28^a	0.07	-0.28^a	0.07	-0.28^a	0.07	-0.27^a	0.07	—	—
Imports	-0.91^a	0.07	-0.91^a	0.07	-0.91^a	0.07	-0.87^a	0.07	-0.87^a	0.07	-0.87^a	0.07	-0.88^a	0.07	-0.70^a	0.05
Trend	-0.04^a	0.01	-0.03^a	0.01	-0.04^a	0.01	-0.04^a	0.01	-0.04^a	0.01	-0.04^a	0.01	-0.04^a	0.01	-0.04^a	0.01
2mm Impact	0.31^a	0.08	0.31^a	0.08	0.33^a	0.08	0.32^a	0.08	0.32^a	0.08	0.32^a	0.08	0.33^a	0.08	0.26^a	0.08
Adjusted R^2	0.51	—	0.51	—	0.51	—	0.50	—	0.50	—	0.50	—	0.50	—	0.50	—

Note: Abbreviations are identified in Appendix Table 3–1.

^{a}Significant at 1%; ^{b}Significant at 5%; ^{c}Significant at 10%.

Source: Authors' calculations.

Appendix Table 3–3. Summary Results from the Market-Share Regressions for Light-Trucks

	(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
Variable	**ß**	**∂**	**ß**	**∂**	**ß**	**∂**	**ß**	**∂**	**ß**	**∂**	**ß**	**∂**	**ß**	**∂**	**ß**	**∂**
CTE	-19.96^{a}	7.14	-20.76^{a}	7.17	-20.74^{a}	6.93	-30.76^{a}	6.87	-32.62^{a}	6.34	-30.15^{a}	5.92	-30.76^{a}	5.94	-27.33^{a}	5.76
P	-0.04^{b}	0.02	-0.04^{b}	0.02	-0.04^{b}	0.02	-0.06^{a}	0.02	-0.06^{a}	0.02	-0.07^{a}	0.02	-0.07^{a}	0.02	-0.08^{a}	0.02
L_DR	0.84^{a}	0.18	0.84^{a}	0.18	0.84^{a}	0.17	0.85^{a}	0.18	0.89^{a}	0.17	0.87^{a}	0.17	0.81^{a}	0.17	0.92^{a}	0.17
Drv	0.25	0.16	0.25	0.16	0.25	0.16	0.01	0.16	—	—	—	—	—	—	—	—
Fwd	-0.62^{a}	0.13	-0.62^{a}	0.13	-0.62^{a}	0.13	-0.42^{a}	0.13	-0.44^{a}	0.13	-0.46^{a}	0.13	-0.46^{a}	0.13	-0.39^{a}	0.12
Minivan	-0.41^{a}	0.16	-0.41^{a}	0.16	-0.41^{a}	0.16	-0.37^{b}	0.16	-0.36^{b}	0.16	-0.35^{b}	0.16	-0.35^{b}	0.16	-0.33^{b}	0.16
FSvan	-2.29^{a}	0.21	-2.28^{a}	0.21	-2.28^{a}	0.21	-1.89^{a}	0.21	-1.91^{a}	0.20	-1.90^{a}	0.20	-1.89^{a}	0.20	-1.87^{a}	0.20
Cargo	-1.65^{a}	0.19	-1.64^{a}	0.19	-1.64^{a}	0.19	-1.32^{a}	0.19	-1.30^{a}	0.19	-1.26^{a}	0.18	-1.25^{a}	0.18	-1.23^{a}	0.18
Pickup	0.49^{a}	0.17	0.49^{a}	0.17	0.49^{a}	0.17	0.09	0.16	0.15	0.14	0.18	0.14	0.13	0.14	0.20	0.14
L_WB	2.22^{a}	0.84	2.25^{a}	0.84	2.25^{a}	0.76	0.51	0.72	—	—	—	—	—	—	—	—
L_LNG	-1.35	1.05	-1.40	1.05	—	—	—	—	—	—	—	—	—	—	—	—
L_WDT	-1.42	1.06	-1.41	1.06	—	—	—	—	—	—	—	—	—	—	—	—
L_HT	6.08^{a}	0.94	6.05^{a}	0.94	6.05^{a}	0.89	—	—	—	—	—	—	—	—	—	—
Size	—	—	—	—	-1.41^{b}	0.72	—	—	—	—	—	—	—	—	—	—
Volume	—	—	—	—	—	—	1.66^{a}	0.52	1.79^{a}	0.48	1.55^{a}	0.43	1.62^{a}	0.43	1.33^{a}	0.42
L_WT	-1.33^{a}	0.52	-0.75	0.58	-0.75	0.58	-0.70	0.59	-0.64	0.59	—	—	—	—	—	—
LN_CY	-1.16^{a}	0.35	-1.17^{a}	0.35	-1.17^{a}	0.35	-1.16^{a}	0.36	-1.18^{a}	0.36	-1.19^{a}	0.36	-1.17^{a}	0.36	-1.17^{a}	0.36
L_DISP	2.52^{a}	0.39	2.47^{a}	0.40	2.47^{a}	0.40	2.21^{a}	0.40	2.18^{a}	0.40	2.01^{a}	0.37	2.07^{a}	0.37	2.24^{a}	0.35
L_HP	0.50^{c}	0.31	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HP_WT	—	—	1.45^{c}	0.80	1.45^{c}	0.80	1.81^{b}	0.82	1.86^{b}	0.81	2.27^{a}	0.72	2.46^{a}	0.72	1.59^{a}	0.63
AT	-0.27^{b}	0.11	-0.27^{b}	0.11	-0.27^{b}	0.11	-0.39^{a}	0.11	-0.38^{a}	0.11	-0.37^{a}	0.11	-0.36^{a}	0.11	-0.35^{a}	0.11
L_MPG	2.62^{a}	0.45	2.61^{a}	0.45	2.61^{a}	0.45	2.46^{a}	0.46	2.44^{a}	0.46	2.48^{a}	0.45	2.52^{a}	0.46	2.61^{a}	0.45
Euro	0.25	0.31	0.24	0.31	0.24	0.31	0.45	0.31	0.40	0.30	0.44	0.30	0.41	0.30	0.60^{b}	0.29
Dom	0.39^{a}	0.15	0.39^{a}	0.15	0.39^{a}	0.14	0.37^{a}	0.15	0.38^{a}	0.15	0.42^{a}	0.14	—	—	0.49^{a}	0.14
Imports	-0.50^{a}	0.14	-0.50^{a}	0.14	-0.50^{a}	0.14	-0.53^{a}	0.14	-0.54^{a}	0.14	-0.53^{a}	0.14	-0.81^{a}	0.11	-0.49^{a}	0.14
Trends	-0.03^{c}	0.01	-0.03^{b}	0.02	-0.03^{b}	0.01	-0.02	0.02	-0.02	0.02	-0.03^{b}	0.01	-0.04^{a}	0.01	—	—
2mm Impact	0.43^{a}	0.12	0.43^{a}	0.12	0.43^{a}	0.12	0.40^{a}	0.12	0.40^{a}	0.12	0.39^{a}	0.12	0.49^{a}	0.12	0.25^{a}	0.10
Adjusted R^2	0.46	—	0.46	—	0.46	—	0.44	—	0.44	—	0.44	—	0.43	—	0.43	—

Note: Abbreviations are identified in Appendix Table 3–1.

^{a}Significant at 1%; ^{b}Significant at 5%; ^{c}Significant at 10%.

Source: Authors' calculations.

Appendix Table 3–4. Summary Results from the Mark-Up Regressions for Cars

	(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
Variable	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂
CTE	12.43^a	1.29	6.66^a	1.39	12.03^a	1.29	12.89^a	1.30	12.89^a	1.30	12.75^a	1.29	12.50^a	1.28	12.33^a	1.29
L_DR	0.00	0.02	-0.02	0.02	0.00	0.02	-0.03^c	0.02	-0.03^c	0.02	-0.03^c	0.02	-0.04^b	0.02	-0.03^c	0.02
DRV	0.02	0.01	0.01	0.01	0.02	0.01	0.00	0.01	—	—	—	—	—	—	—	—
FOURWD	0.28^a	0.07	0.22^a	0.07	0.28^a	0.07	0.22^a	0.07	0.23^a	0.07	0.23^a	0.07	0.22^a	0.07	0.23^a	0.07
SW	0.07^a	0.02	0.08^a	0.02	0.07^a	0.02	0.05^a	0.02	0.05^a	0.02	0.05^a	0.02	0.05^a	0.02	0.04^a	0.02
L_WB	1.68^a	0.21	2.20^a	0.22	1.84^a	0.20	2.00^a	0.20	2.01^a	0.20	2.02^a	0.20	2.00^a	0.20	2.00^a	0.20
L_LNG	0.23	0.18	1.02^a	0.20	—	—	—	—	—	—	—	—	—	—	—	—
L_WDT	-1.03^a	0.22	-0.83^a	0.24	—	—	—	—	—	—	—	—	—	—	—	—
L_HT	-1.94^a	0.17	-1.96^a	0.18	-1.89^a	0.17	—	—	—	—	—	—	—	—	—	—
Size	—	—	—	—	-0.31^a	0.12	—	—	—	—	—	—	—	—	—	—
Volume	—	—	—	—	—	—	-0.83^a	0.10	-0.83^a	0.10	-0.82^a	0.10	-0.79^a	0.10	-0.79^a	0.10
L_WT	0.10^a	0.03	0.31^a	0.03	0.103^a	0.03	0.11^a	0.03	0.11^a	0.03	0.11^a	0.03	0.12^a	0.03	0.11^a	0.03
LN_CY	0.10^a	0.04	0.18^a	0.04	0.07^a	0.04	0.05	0.04	0.05	0.04	0.07^c	0.04	—	—	—	—
L_DISP	0.02	0.03	0.08^a	0.03	0.01	0.03	0.03	0.03	0.03	0.03	—	—	—	—	—	—
L_HP	1.22^a	0.03	—	—	1.22^a	0.03	1.28^a	0.03	1.28^a	0.03	1.29^a	0.03	1.31^a	0.03	1.33^a	0.03
HP_WT	—	—	2.15^a	0.08	—	—	—	—	—	—	—	—	—	—	—	—
AT	0.21^a	0.02	0.22^a	0.02	0.21^a	0.02	0.22^a	0.02	0.22^a	0.02	0.22^a	0.02	0.23^a	0.01	0.22^a	0.01
L_MPG	-0.01	0.05	-0.36^a	0.05	-0.04	0.05	-0.11^b	0.05	-0.11^b	0.05	-0.12^b	0.05	-0.14^a	0.05	-0.11^b	0.05
Euro	0.49^a	0.02	0.52^a	0.02	0.487^a	0.02	0.45^a	0.02	0.45^a	0.02	0.45^a	0.02	0.45^a	0.02	0.46^a	0.02
Dom	-0.09^a	0.02	-0.12^a	0.02	-0.10^a	0.02	-0.09^a	0.02	-0.09^a	0.02	-0.08^a	0.02	-0.08^a	0.02	—	—
Imports	0.11^a	0.02	0.14^a	0.02	0.12^a	0.02	0.09^a	0.02	0.09^a	0.02	0.09^a	0.02	0.09^a	0.02	0.15^a	0.01
Trend	-0.01^a	0.00	0.00^b	0.00	-0.02^a	0.00	-0.02^a	0.00	-0.02^a	0.00	-0.02^a	0.00	-0.02^a	0.00	-0.02^a	0.00
2mm impact	-0.08^a	0.02	-0.11^a	0.02	-0.08^a	0.02	-0.07^a	0.02	-0.07^a	0.02	-0.07^a	0.02	-0.07^a	0.02	-0.09^a	0.02
Adjusted R^2	—	0.86	—	0.84	—	0.86	—	0.85	—	0.86	—	0.86	—	0.85	—	0.85

Note: Abbreviations are identified in Appendix Table 3–1.

^{a}Significant at 1%; ^{b}Significant at 5%; ^{c}Significant at 10%.

Source: Authors' calculations.

Appendix Table 3–5. Summary Results from the Mark-Up Regressions for Light-Trucks

	(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
Variable	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂	**ß**	∂
CTE	2.13^b	1.10	1.80	1.11	2.99^a	1.07	5.56^a	1.07	3.01^a	1.07	2.62^a	1.07	2.69^b	1.11	2.57^b	1.07
L_DR	0.18^a	0.03	0.17^a	0.03	0.19^a	0.03	0.19^a	0.03	0.19^a	0.03	0.19^a	0.03	0.17^a	0.03	0.19^a	0.03
DRV	0.07^a	0.03	0.07^a	0.03	0.07^a	0.03	0.13^a	0.03	0.07^a	0.03	0.07^a	0.03	0.09^a	0.03	0.07^a	0.03
Fwd	0.18^a	0.02	0.18^a	0.02	0.18^a	0.02	0.14^a	0.02	0.18^a	0.02	0.18^a	0.02	0.14^a	0.02	0.18^a	0.02
Minivan	0.04^b	0.03	0.04^c	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.42^a	0.03	0.41^a	0.03	0.43^a	0.03
FSVan	-0.05	0.03	-0.05	0.03	-0.05	0.03	-0.15^a	0.03	-0.05^c	0.03	0.34^a	0.04	0.31^a	0.04	0.34^a	0.04
Cargp	-0.05^b	0.03	-0.05	0.03	-0.06^c	0.03	-0.13^a	0.03	-0.06^b	0.03	0.33^a	0.03	0.32^a	0.04	0.34^a	0.03
Pickup	-0.40^a	0.03	-0.40^a	0.03	-0.39^a	0.03	-0.30^a	0.03	-0.39^a	0.03	—	—	—	—	—	—
SU	—	—	—	—	—	—	—	—	—	—	0.39^a	0.03	0.39^a	0.03	0.39^a	0.03
L_WB	-0.39^a	0.13	-0.38^a	0.13	-0.23^c	0.12	0.17	0.12	-0.24^b	0.12	-0.24^b	0.12	-0.26^b	0.13	-0.23^c	0.12
L_LNG	0.01	0.17	0.01	0.17	—	—	—	—	—	—	—	—	—	—	—	—
L_WDT	-1.16^a	0.14	-1.17^a	0.14	-1.30^a	0.14	—	—	-1.30^a	0.14	-1.30^a	0.14	-1.26^a	0.14	-1.30^a	0.13
L_HT	—	—	—	—	0.37^a	0.11	—	—	0.37^a	0.11	0.37^a	0.11	0.37^a	0.12	0.38^a	0.11
Size	—	—	—	—	—	—	-0.35^a	0.08	—	—	—	—	—	—	—	—
Volume	0.57^a	0.08	0.84^a	0.09	0.59^a	0.08	0.64^a	0.08	0.59^a	0.08	0.59^a	0.08	0.66^a	0.08	0.58^a	0.08
L_WT	0.57^a	0.08	0.84^a	0.09	0.59^a	0.08	0.64^a	0.08	0.59^a	0.08	0.59^a	0.08	0.66^a	0.08	0.58^a	0.08
LN_CY	0.02	0.06	0.02	0.06	0.02	0.06	0.03	0.06	—	—	—	—	—	—	—	—
L_DISP	0.11^b	0.06	0.09	0.06	0.09	0.06	0.16^a	0.06	0.10^c	0.06	0.10^c	0.06	-0.08	0.05	0.11^b	0.06
L_HP	0.25^a	0.05	—	—	0.26^a	0.05	0.23^a	0.05	0.26^a	0.05	0.26^a	0.05	0.49^a	0.04	0.26^a	0.05
HP_WT	—	—	0.67^a	0.13	—	—	—	—	—	—	—	—	—	—	—	—
AT	0.03^b	0.02	0.03^c	0.02	0.03^c	0.02	0.06^a	0.02	0.03^c	0.02	0.03^c	0.02	0.03^c	0.02	0.03^c	0.02
L_MPG	-0.25^a	0.07	-0.25^a	0.07	-0.24^a	0.07	-0.21^a	0.07	-0.24^a	0.07	-0.24^a	0.07	-0.31^a	0.07	-0.24^a	0.07
Euro	0.50^a	0.04	0.49^a	0.04	0.50^a	0.04	0.48^a	0.04	0.50^a	0.04	0.50^a	0.04	0.47^a	0.04	0.50^a	0.04
Dom	0.04	0.02	0.04	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	-0.01	0.02	0.04^b	0.02
Imports	0.05^b	0.02	0.05^b	0.02	0.05^b	0.02	0.06^a	0.02	0.05^b	0.02	0.05^b	0.02	0.03	0.02	—	—
Trend	0.02^a	0.00	0.02^a	0.00	0.02^a	0.00	0.02^a	0.00	0.02^a	0.00	0.02^a	0.00	—	—	0.02^a	0.00
2mm Impact	-0.05^a	0.02	-0.05^a	0.02	-0.04^b	0.02	-0.03^a	0.02	-0.04^b	0.02	-0.04^b	0.02	0.04^b	0.02	-0.03^c	0.02
Adjusted R^2	0.88	—	0.88	—	0.88	—	0.87	—	0.88	—	0.88	—	0.87	—	0.88	—

Note: Abbreviations are identified in Appendix Table 3–1.

[a]Significant at 1%; [b]Significant at 5%; [c]Significant at 10%.

Source: Authors' calculations.

Appendix 3-B to Chapter 3

Hedonic-Price Model for Cars

Griliches (1961) is generally considered to have introduced hedonic analysis and techniques into mainstream economics in his seminal paper about commodity heterogeneity.[32] The "hedonic price function" for motor vehicles with various attributes, P(Z), is the result of consumer-utility maximization. Consumers maximize their utility of consuming all the attributes (Z) of the vehicle plus the consumption of all other goods (X), subject to the conventional budget restriction. The solution to this maximization problem is derived here.

Although the hedonic model represents a theoretically coherent foundation for explaining the relationship between the price of a vehicle and its attributes, estimation of the attribute prices still presents many theoretical and empirical difficulties. The main theoretical difficulty is that the attributes are discrete—a limited set of choices exists, as in the case of engine horsepower or wheelbase length. This yields a budget constraint that is non-linear and a demand function that is unconventional in that consumer preferences concerning an attribute are represented by non-constant prices.

To obtain a demand system, we depart from a discrete-choice model: consumers will buy a car j ($j = 1, \ldots, J$) if the utility of buying this car is higher than the utility of buying any other car (or not buying any car at all, i.e., if $j = 0$). The level of utility is supposed to depend on the consumers' characteristics (c) and the car's characteristics (x, p), where x is a vector of a car's attributes, and p is the price of the car, i.e., consumer i will buy car j if:

$$U(c_i, x_j, p_j) \geq U(c_i, x_r, p_r) \quad r = 0, 1, \ldots, J \tag{1a}$$

If we had micro-data, we could assume a distribution on the residuals and estimate the demand pattern; however, micro-data on car purchases are very hard to obtain and manage. For this analysis, we worked with a data set aggregated by car model (see data section).

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[32] Griliches (and many others) referred to Court (1939) as a pioneer in the application of these techniques. However, Sheppard (1999, p. 1597) claims that "the study of Waugh (1929) appears to be the first to provide a systematic analysis of the impact of 'quality' on the price of a commodity."

To derive the aggregate demand system, we have to integrate out the choice function in Equation (1a) over the distribution of c in the population. Let

$$A_j = \{c:U(c_i,x_j,p_j) \geq U(c_i,x_r,p_r), \text{ for } r = 0,1,\ldots,J\} \tag{2a}$$

In Equation (2a), Aj is the set of values for c that induce the choice of car j. Then, assuming that consumers are distributed as P(dc), the market share of good j will be:

$$s_j(p, x) = \int_{c\in A_j} P(dc) \tag{3a}$$

Assuming a linear-utility specification:

$$U(c_i, x_j, p_j) = x_j\beta - \alpha p_j + \varepsilon_{ij} \equiv \delta_j + \varepsilon_{ij} \tag{4a'}$$

$$U(c_0, x_0, p_0) = \varepsilon_{i0} \tag{4a''}$$

where $j = 0$ means that the consumer decided to buy no car at all. Assuming that ε_{ij} is distributed independently and identically across both consumers' characteristics and cars' attributes, we can easily compute the market shares by:

$$s_j = \int_{\varepsilon q\neq j} \prod P(\delta_j-\delta_q+\varepsilon)P(d\varepsilon) \tag{5a}$$

As is well known, if e has the Weibull distribution function exp[-exp(-ε)], Equation (5a) has a closed form, and the solution can be found analytically as:

$$s_j(p,\ x,\ \varepsilon)=e^{\delta_j} \Bigg/ \left(1+\sum_{j=1}^{J} e^{\delta_j}\right) \tag{6a}$$

Given Equation (6a), we can estimate δ_j from:

$$ln(s_j)-ln(s_0)=\delta_j-ln\left(1+\sum_{j=1}^{J} e^{\delta_j}\right)+ln\left(1+\sum_{j=1}^{J} e^{\delta_j}\right) = \delta_j \tag{7a}$$

In this simplified model, we can therefore estimate the parameter of interest (δ) from a simple ordinary least squares on market shares. We define the dependent variable, δ_j, as the logarithm of the market share of the model in a given year, s_j, minus the natural logarithm of the number of households (from the March annual supplement of the U.S. Bureau of the Census for 1986–1998, *Current Population Survey* (CPS)), less the number of vehicles sold, divided by the number of households, (s_0). We term this combination the "relative market share," because it reflects the market share of the model relative to the total number of households. To estimate the parameters of the demand, we therefore regress the relative market share on the price and other characteristics of the vehicle.

To close the model, we introduce the vehicle's producers. Producers have a cost function given by C(Z, N, γ) that depends on the quantity of attributes, Z, the number of vehicles produced, N, and a vector of parameters, γ. Producers are assumed to be profit maximizers. We provide details on the solution to this (multi-product) maximization problem here. Following Berry, Levinsohn, and Pakes (1995), we assume that the market is in equilibrium, represented as the locus of tangencies between marginal cost and marginal demand. To obtain an estimate of the attribute prices, we derive the aggregate supply function, where m_j is the marginal cost, w_j is a vector of cost characteristics, γ is the vector of vehicle attributes, and w_j is a vector of non-observable variables, all for vehicle j:

To estimate the supply, we assume that there are F firms, each producing a subset G_f of the J products. The marginal cost of production (m) is log linear in a vector of cost characteristics (cost shifters, w):

$$\ln(m_j) = w_j \gamma + \omega_j \tag{8a}$$

Assuming an oligopolistic market with markups, the profits of firm f will be:

$$\prod\nolimits_f = \sum_{j \varepsilon G_f} (p_j - m_j) M s_j \tag{9a}$$

where M is the total production of cars and sj is the market share of model j given by Equation (6a). The first-order condition on Equation (9a) implies that:

$$s_{j+} \sum_{r \varepsilon G_f} (p_r - m_r) \frac{\partial s_r}{\partial p_j} = 0 \tag{10a}$$

We can write all J equations implicit in Equation (10a) in vector notation as:

$$s - \Delta[p - m] = 0 \tag{11a}$$

where s, p, and m are the (1xJ) vectors of market shares, prices and marginal costs, respectively. Δ is a JxJ matrix defined as:

$$\Delta \equiv \begin{cases} {}^{-\partial s_r}\!/_{\partial p_j} & ; r, j \in G_f \ (f = 1, \ldots, F) \\ 0 & Otherwise \end{cases} \tag{12a}$$

Note from equation (12a) that a typical element from Δ $(a_{r,j})$ will be:

$$a_{r,j} \equiv \begin{cases} s_j(1-s_j) & j=r \\ -s_j s_r & j \neq r;\ r,\ j \in G_f\ (f=1,\ldots,\ F) \\ 0 & \textit{otherwise} \end{cases} \tag{13a}$$

The vector of marginal cost therefore depends only on the parameters of the market-shares system and the equilibrium price vector (assuming that the market is in equilibrium), and we can estimate it as:

$$m = p - \Delta^{-1}s \tag{14a}$$

We can then analytically find the marginal cost, and we can find the parameter of interest in the supply function by regressing the log of marginal costs on cost shifting:

$$\ln(m_j) = w_{j\gamma} + \omega_j \tag{15a}$$

This is the model that we use to determine the hedonic prices for U.S. automobiles and light-trucks.

Our analysis leaves at least three issues untested. First, we could test the effect of the new technology by pooling cars and light-trucks. This procedure could help solve the problem of the small size of the light-truck sample, and it is reasonable because today there is not a big difference (from the consumer point of view) between a light-truck and a car. Thus, a consumer who decides to buy a car will make the decision looking at both types of vehicles. At least SUVs and minivans compete directly with other cars.

Second, we cannot observe all vehicle attributes that influence purchasing decisions and production costs. We therefore do not know if our results are accurate or if they are connected to the "non-observable factors." This is a problem if the non-observable factors are correlated with the attributes that we do observe, and we have reasons to believe they are. For instance, an expensive vehicle is more likely to have a more powerful motor than an inexpensive one, giving rise to endogeneity conditions. In order to correct for this, we could use an instrumental-variable approach. The difficulty is finding appropriate instruments, i.e., instruments that are orthogonal to ε and ω in Equations (4a') and (8a). Appropriate instruments for our problem cannot rely on "exclusion" restrictions as is typical in the simultaneous-equation approach to the specification problem. Under certain conditions Chamberlain (1986) shows how to find optimal instruments as a function of a set of endogenous variables.

A third problem is related to the simplifications on the market-share side. Because there is just one market share associated with each δ-vector in Equation (7a), two vehicle models with the same market share will have the same cross-price derivative with respect to a third car and the same own-price demand derivatives. For instance, in 1996, 36,000 KIA Sephias and 38,000 Mercedes 190s were sold, accounting for an almost identical market share. Equation (7a) implies that an increase in the price of a BMW, for instance, would generate an equal increase in the market share of Mercedes and KIA. Besides, it implies that both KIA and Mercedes have the same mark-up. The conventional way to deal with the problem is adopting a nested logit approach. The problem is that the nests are usually arbitrary.

Another approach proposed by Berry, Levinsohn, and Pakes is allowing each individual to have a different preference for each different characteristic. Hence, consumers with a preference for sport cars, for instance, will attach high utilities to all sport cars (since their characteristics are similar), which will induce large substitution effects between sport cars. Unfortunately that "random vector" model does not have a closed solution, so that we have to run simulations to aggregate the market share and solve the function by some robust method. In practice, it means replacing β on equation (4a') by:

$$\beta_k=\overline{\beta}_k+\sigma_k v_{ik} \tag{16a}$$

where k indices are the car attributes and vik is a zero-mean random variable. Scaling vik such that $E(v^2_{ik})$ = 1 implies that the mean and variance of the marginal utility of attribute k are . Substituting Equation (16a) into Equations (4a') and (4a''), we have that:

$$U(c_j, x_j, p_j) = x_j\,\overline{\beta}-\alpha p_j + \sum_k \sigma_k x_{jk} v_{ik} + \varepsilon_{ij} \equiv \delta_j + \mu_{ij} \tag{17a}$$

We can still decompose the utility obtained from consuming good j into a mean and a deviation from the mean, but now the second term depends on the interaction between consumer preferences and product characteristics and cannot be obtained analytically.

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