Automotive Painting:
Achieving a Technological, Economic, and Environmental Balance

by
Chuin Ping Chen

B.S., Civil Engineering
National Chiao Tung University, 1991

S.M. Civil and Environmental Engineering
Massachusetts Institute of Technology, 1993

Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Technology and Policy

at the
Massachusetts Institute of Technology
May 1995

©1995 Massachusetts Institute of Technology. All rights reserved

Signature of Author.................................................................

Department of Civil Engineering
May 12, 1995

Certified by ........................................................................
Professor Joel P. Clark
Thesis Supervisor

Certified by .................................................................
Dr. Frank R. Field
Thesis Supervisor

Certified by .................................................................
Professor Richard de Neufville
Chairman, Technology and Policy Program

Accepted by .................................................................
Professor Joseph M. Sussman
Chairman, Departmental Committee on Graduate Studies

JUN 27 1995
AUTOMOTIVE PAINTING: ACHIEVING A TECHNOLOGICAL, ECONOMIC, AND ENVIRONMENTAL BALANCE

by

CHUIN PING CHEN

Submitted to the Department of Civil and Environmental Engineering on May 12, 1995 in partial fulfillment of the requirements for the Degree of Master of Science in Technology and Policy

ABSTRACT

This thesis takes on a study of the automotive painting process. In this study, we look at ways to achieve a balance of the technological, economic, and environmental aspects of the process.

Automotive painting is a capital-intensive process in which the paint shop makes up 50% of the cost of an assembly plant. It is also a major source of the air, water, and solid waste emissions which are discharged from this facility in the form of VOCs and paint sludge. With rising concerns about the environment, legislation has been passed at the federal and state level mandating reduction of air, water, and solid wastes. As a result, the increasingly stringent regulatory environment has led industry to seek ways to achieve pollutant reduction in a cost-effective manner. This has resulted in the development and improvements in alternatives of solventborne paints such as waterborne and powder coatings. The need for weight reduction has also brought about an heightened interest in substrate alternatives and this study also looks at substrates such as aluminum and plastic that are being used increasingly as a substitute for conventional steel in the body-in-white.

Figures for costs, VOC emissions, and paint sludge are generated using the MSL automotive painting cost model and analyzed to find out what improvements are possible and would have impacts on achieving the multiple purposes of reducing pollution and keeping costs down. Sensitivity analyses of the costs, VOC emissions, and paint sludge to changes in transfer efficiency and film thickness are conducted in an attempt to see whether improving these variables would have any effects to reducing costs, VOCs or paint sludge.

This next step in this study is evaluating the alternatives in automotive painting that are available at the present time. Choices and tradeoffs among three attributes, namely, cost, VOC emission, and paint sludge, are evaluated for each alternative and comparisons made. The study concludes by summarizing the pros and cons of alternatives in paint technology and by presenting possible methods of valuation to enable the decisionmaker to make suitable choices and what future work might be done in this respect.

Thesis Co-Supervisor: Professor Joel P. Clark
Title: Professor of Materials Engineering

Thesis Co-Supervisor: Dr. Frank R. Field
Title: Senior Research Associate
# Table of Contents

Abstract.........................................................................................................................2

Table of Contents...........................................................................................................3

Acknowledgments...........................................................................................................4

Chapter 1   Introduction: The Economic and Environmental Impacts of
             Automotive Painting..............................................................................................5

Chapter 2   The Automotive Painting Process.................................................................8

Chapter 3   Present State of Technology and Recent Developments.........................21

Chapter 4   Steel and Alternative Substrates.................................................................27

Chapter 5   Cost Analysis of Automotive Painting.......................................................39

Chapter 6   VOC Emissions in Automotive Painting.....................................................61

Chapter 7   Waste Treatment in Automotive Painting.................................................73

Chapter 8   The Regulatory Environment......................................................................78

Chapter 9   Evaluating Alternatives: Choices and Tradeoffs........................................90

References.....................................................................................................................104
Acknowledgments

I would like to thank Professor Joel Clark for having enough faith to give me the opportunity to work in the Materials Systems Laboratory. His helpful advice and constant encouragement in the past two years have inspired my efforts to learn about engineering from the alternative views of economics and the environment.

Dr. Frank Field has truly been a pillar of support at MSL, as well as an immense source of general knowledge and sound advice. I am very grateful to Frank for being a patient teacher and friend, for taking time to explain an idea or to impart fresh knowledge. He has truly taught me a great deal, not only about my specific research topic, but also the basic framework and methodology which makes up the foundation of any course of study. I would also like to express my gratitude towards Dr. Jacqueline Isaacs for showing me the ropes and being my advisor in my first project at MSL, for always lending a sympathetic ear to my problems, academic or otherwise, as well as for giving me helpful suggestions and moral support. Many thanks to Dr. Richard Roth for his friendly advice on many trivial and nontrivial questions, as well as his infinite patience with us rowdy students when he shared the student office.

Thanks to Professor de Neufville for his informative thesis seminar, which gave me new insights in presenting my research. I would also to thank Ms. Gail Hickey and Ms. Rene Smith for their friendly assistance and concern during these two years at the Technology and Policy Program.

I would also like to acknowledge my past and present colleagues at MSL, Helen Han, Andrew Chen, Russ Cohn, Dimitris Politis, Konstantinos Sgoutas, J. Neely, Jason Amaral, Sam Newell, and Maija Lokka for their friendly camaraderie and useful advice. Thanks a lot, J., for bailing me out in my decision analysis crisis. Thanks also to Kostas and Dimitris for helping me see the funny side of certain situations and exchanging thoughts and opinions on classes and thesis-writing. All of you have made life at MSL amusing and interesting, and I will certainly miss that when I leave the group.

Thanks to my friends for their emotional and moral support in times of need, Ying-Jen Hsu, Lin-Shiow Liu, Cynthia Chuang, Sha-Li Tsai, Jen Hsu, Li-Hung Huang, and Feng-shan Hsiao. You have taught me the true meaning of friendship and I am very thankful for that. Thank you, Jenny, Hsinyi, Charles, John, Melody, Francis, Hsin-Tsong, Ollie, and Alex for your bright smiles and laughter, which have made me feel happy and at home. Playing with you kids has been the best part of being here at MIT.

To conclude, I would like to thank my parents Mr. and Mrs. Chyi Chen and my in-laws, Mr. and Mrs. Yin-Fu Chang for their love and concern. Thanks also to my siblings, Chuin-Sheng, Chuin-Fan, and Chuin-Fu, for your quirky cards and sarcastic encouragement. Last but not least, I would like to thank my husband Eric for his constructive criticisms and practical advice, and most of all, for being my best buddy and companion in life.
Chapter 1  Introduction: The Economic and Environmental Impacts of Automotive Painting

Automotive painting is the part of the automobile manufacturing process purported to be responsible for a significant proportion of the air, water, and solid waste emission streams to the environment. In view of these concerns, the automobile industry has made efforts to improve the automotive painting process in response to increasingly stringent environmental regulations imposed by the Environmental Protection Agency on the federal and state levels in an effort to reduce emissions of volatile organic compounds into our environment.

The demands of and performance required for automotive painting are considerable. The painted surface must fulfill requirements such as anti-corrosion and chip resistance for body protection and have a durable Class-A finish. A Class-A finish identifies the excellent coating resulting from high quality operations in the paint shop and must possess the following attributes: superior appearance in terms of uniform color, gloss, and distinctness of image; functionality in withstanding environmental factors and maintaining adhesive properties; and durability in protecting the automobile body from ultraviolet rays, other natural elements, and physical impact. The painting process must also be suitable for mass production and economically feasible.

The paint on a car, though frequently viewed as insignificant, is an important part of the automobile manufacturing process. The OEM's perception
of the automobile consumer's demand for superior appearance of a vehicle has resulted in the development of more complex and sophisticated coatings in an effort to produce a high quality finish. This has been perceived as the most significant goal in the past, which resulted in the development of paints with superior performance but posed serious problems in emitting volatile organic compounds (VOC) and waste disposal. However, increasingly stringent environmental legislation has led to a need to balance economic and environmental tradeoffs and to find a cost-effective way to maintain product quality without damaging our environment. Industry has responded to this need by looking at viable alternatives such as developing new paint technologies with superior finishing quality and low emissions, which are being accomplished by modifying paint components, facilitating reuse and recycling of materials, minimizing use of nonrenewable resources, decreasing energy consumption, or making waste disposal more efficient by minimizing space or treatment required for safe disposal.

The use of alternative substrates rather than steel is gradually increasing in light of the need for weight reduction. This may complicate the painting process, which is primarily established for the painting of steel automobile body-in whites. However, inherent properties of these substrates such as density, surface properties, and ease of manufacture might lead to the development of new technologies that would satisfy the multiple purposes of simplifying the painting process, reducing the curb weight, and abating
emissions and solid wastes. However, as is often the case with new technologies, there are advantages and disadvantages to each choice, and there is no "perfect" alternative that clearly dominates over all others from every aspect ranging from economy to technology and the environment.

This research examines the problems that face government, industry, and consumers as they deal with new and better technologies and analyzes the problems from the different perspectives of economy, technology, and the environment.

The purpose of this study is to provide recommendations for helping government implement new policies, guiding industry in making business and technical decisions, and assisting the consumer in making wise choices from the perspectives of economy and the environment.
Chapter 2  The Automotive Painting Process

The automotive painting process is a complex and expensive one. However, in spite of the high cost of painting, the automotive industry has no plans to replace the process or eliminate it entirely. Paint is currently the fastest and most economical way to create a durable coating that satisfies the aesthetic requirements as well as to protect the automobile body from environmental exposure. Painting is also a very flexible process where colors, textures, and gloss levels can easily be altered by modifying paint formulation and application techniques.

Automotive painting is a complicated process and can vary a great deal given the many different automobiles available today. These variations range from size to shape and color. In the interests of providing a comprehensive description of the process, the automotive painting of a steel body-in-white represented in this study is what we understand to be the general manufacturing practices in today's paint shops.

The automotive painting process is composed of five basic stages: pretreatment, electrocoat, sealer, primer-surfacer, and basecoat/clearcoat. With the exception of sealing, each painting stage can be roughly broken down into three steps for the purpose of calculating costs: application, curing and drying, and inspection & rework.
The primer-surfacer, basecoat, and clearcoat are applied by spraying at a range of transfer efficiencies. Hazardous and non-hazardous wastes in the form of VOCs and paint sludge are generated during the application, drying, and curing of the body-in-white, which raises serious issues in waste treatment and disposal. The sources of these wastes are paint overspray that result from lower transfer efficiencies, fast evaporating solvents that evaporate in the spray or very soon after application, and medium and slow evaporating solvents that evaporate during drying and curing. While industry has previously relied on end-of-the-pipe abatement technologies to deal with this problem, an increasingly stringent regulatory environment has forced them to look for ways to deal with the problem at the source. To deal with these problems, automobile manufacturers and their paint suppliers have been working together to develop waterborne or powder versions of these paints. To date, waterborne and powder primer-surfacer, waterborne basecoat, and powder clearcoat have been developed, and are beginning to be used in painting automobiles.

Following this brief overview of the automotive painting process, we will proceed to explain each process step in detail.

**Pretreatment**

Pretreatment consists of a series of cleaning and rinsing stages that prepare a body-in-white for painting. Pretreatment is necessary to accomplish multiple purposes, namely, to remove the impurities ingrained in the substrate
and any temporary protective coatings, to improve paint adhesion, and to provide a resistance barrier to the spread of corrosion under the paint film. The normal pretreatment process consists of rust removal, alkali degrease, phosphating, and demineralized water rinse. The metal phosphating acts as a corrosion inhibitor by covering the surface with phosphate crystals, a "ceramic" insulator against water when sealed with paint, which is a poor insulator by itself due to its permeability in a aqueous environment².

**Electrocoat**

The next step is electrocoating, which is accomplished by the electrodeposition of a waterborne primer. Electrodeposition is the depositing of the coating on the electrode, which is the body-in-white in this case, by electrolysis. The electrocoat, also called an E-coat, acts as a primer, whose function is to provide corrosion protection. Therefore, the electrocoat primer is formulated by incorporating anti-corrosive pigments carried in a resin system with the necessary mechanical and anti-corrosive properties.

Cathodic electroprimers are commonly used in automotive painting. Unlike anodic electroprimers, the part being coated does not dissolve during cathodic electrocoating, and therefore eliminates the problems of discoloration and decreased corrosion resistance caused by the dissolved ions of the anode.

An E-coat solution is similar in composition to conventional waterborne paint, but the resin molecules are chemically modified to enhance their water
solubility. As a result, the E-coat primer has to be electrically deposited and not just dipped in the bath so as to avoid diminishing the appearance and durability of the paint film.

After a part emerges from an E-coat bath, its deposited paint film is covered by a wet solution consisting of bath solids and water. Therefore, a thorough rinsing must follow the electrocoating in order to remove these solids, whose presence in the coating would downgrade the quality of the E-coat. Poor rinsing can result in E-coat roughness that must be remedied by slow, tedious sanding, which can increase labor costs.

After rinsing, the part goes through the final E-coat step of oven curing. The E-coat requires a moderately high-temperature bake (~300°F to 350°F) to cross-link the resins in the binder³.

Sealer

The sealer is applied between the primer (E-coat) and the topcoat to prevent topcoat solvent migration into the primer. Solvent migration, which in this case occurs when solvents in the topcoat permeate into the primer, can result in pigment leachout from the primer that would cause discoloration of the topcoat, swelling of the underlying paint layer, and solvent absorption through the fine scratch lines caused by sanding³.
Primer-Surfacer

The primary functions of the primer-surfacer are to serve as a filler and to provide a smooth surface for topcoat application. Its other properties include stone chip resistance, flexibility, and moisture resistance. Surfacers are formulated to allow for sanding to take place in order to provide a smooth even surface for the topcoat application to maximize the appearance and performance of the Class-A finish. Primer-surfacers often contain pigments that are color-keyed to the topcoat. Color-keyed implies an adaptation in color of one coat to another.

Anti-Chip Coatings

Anti-chip coatings are used to upgrade stone-chip resistance on vulnerable areas of a body-in-white. Stone-chip refers to small flakes of a finish losing adhesion from the substrate, usually caused by the impact of stones or hard objects. These areas include the door sills, front and rear ends below the bumpers, the underbody, and rocker panels.

Topcoat

The topcoat system most commonly used by auto manufacturers is the basecoat/clearcoat technology. It consists of a nonpigmented clearcoat over a color basecoat. This technology was first widely used in Europe and soon adopted by Japanese and North American manufacturers after it was shown that
the painted surface exhibited exceptionally high gloss which significantly improved the appearance of the automobile.

Basecoats provide the color of the automobile, and must meet general constraints for durability, opacity, gloss, cost, and color stability. Color stability is harder to achieve for some colors in comparison to others, which entails higher costs and involves greater VOC emissions. Red basecoat is a case in point. The pigmented basecoat will receive a clearcoat, which provides the shine.

Clearcoats are basically paints without pigments. They are applied over the basecoat to impart gloss, clarity, and durability. Clearcoats are especially effective with metallic finishes for which they were first used, since these surfaces generally have fragments of metallic flakes extending out of the paint, thus lowering the gloss. Today, auto manufacturers use clearcoats on both nonmetallic and metallic colors because of the high gloss they provide.

The basecoat/clearcoat technology is used to enhance the brilliance of a finish. The latest development in low VOC basecoat/clearcoat technology uses a waterborne color basecoat that undergoes quick dehydration in heated flash zones to evaporate 95% of the water. The basecoating process is followed by application of a high-solids clearcoat. A better appearance is achieved with color basecoats that have a large shrink factor, that is, paints with a high percentage of volatile materials. And since the use of organic solvents is limited due to regulatory restrictions on VOCs, water is the only solvent that meets necessary
requirements. Therefore, waterborne color basecoat technology has been improved greatly to meet this demand.

Our study is based on the General Motors plant in Lake Orion, Michigan. Our base case data comes from the production data of the Oldsmobile Aurora, which is painted using a high-solid solventborne primer-surfacer, a waterborne basecoat, and a high-solid solventborne clearcoat. The table below gives a description of the process an automobile goes through as it is painted in the Lake Orion facility.

**Paint Shop Description of General Motors Assembly Plant, Lake Orion**

<table>
<thead>
<tr>
<th>Pre-wipe</th>
<th>Hand operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Wipe</td>
<td></td>
</tr>
<tr>
<td>Deluge</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1. Dip Clean</th>
<th>Fluoride Additive for Aluminum Hoods</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Spray Clean</td>
<td></td>
</tr>
<tr>
<td>3. Spray Clean</td>
<td></td>
</tr>
<tr>
<td>4. Rinse Conditioner</td>
<td></td>
</tr>
<tr>
<td>5. Phosphate</td>
<td></td>
</tr>
<tr>
<td>6. City Water Dip</td>
<td></td>
</tr>
<tr>
<td>7. Chromate Seal Rinse</td>
<td></td>
</tr>
<tr>
<td>8A. Recirculated Deionized Spray</td>
<td></td>
</tr>
<tr>
<td>8B. Virgin Deionized Spray</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ELPO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dip Rinse</td>
<td></td>
</tr>
<tr>
<td>Spray Rinse</td>
<td></td>
</tr>
</tbody>
</table>

14
<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ELPO Oven</strong></td>
<td>1st of Co-Bake, 30 min @ 325°F</td>
</tr>
<tr>
<td><strong>Sealer Deck</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Spot Defect Sanding</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Solvent Body Wipe</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Miscellaneous Prime Booth</strong></td>
<td></td>
</tr>
<tr>
<td>No Body Prime Sprayed</td>
<td>Conventional Air Atomized - Stationary</td>
</tr>
<tr>
<td>Red Spotter Applied to Sail Joints</td>
<td></td>
</tr>
<tr>
<td><strong>Sealer Oven</strong></td>
<td>2nd of Co-Bake, 30 min @ 325°F</td>
</tr>
<tr>
<td><strong>Main Prime Booth</strong></td>
<td></td>
</tr>
<tr>
<td>Anti-Chip</td>
<td>Bell Applied Thin Film Material</td>
</tr>
<tr>
<td>Color Keyed Primer Surfacer to Exteriors</td>
<td>3 of 5 Body Styles</td>
</tr>
<tr>
<td></td>
<td>Bell Applied, Three Colors, Gray, White, Red</td>
</tr>
<tr>
<td></td>
<td>E-Stat Hand Guns</td>
</tr>
<tr>
<td></td>
<td>Under Hood, Under Deck, Deck Gutters, Door Openings</td>
</tr>
<tr>
<td><strong>Color Specific Prime</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Primer Bake</strong></td>
<td>17 Min @ 265°F</td>
</tr>
<tr>
<td><strong>Full Wet Sand of Exterior</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Body Washer</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Rinse Aid</strong></td>
<td>Rinse Aid Chemical Needed to Reduce Water Spotting of Light Metallics</td>
</tr>
<tr>
<td><strong>Wet Sand Dry Off Oven</strong></td>
<td>15 Min @ 225°F</td>
</tr>
</tbody>
</table>

15
<table>
<thead>
<tr>
<th>Dual Main Color Booths &amp; Ovens</th>
<th>Conventional Air Atomized Hand Guns For Door Openings and Under Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterborne Basecoat</td>
<td>E-Stat Behr Bells for 1st Coat</td>
</tr>
<tr>
<td>Waterborne Basecoat</td>
<td>Non E-Stat Kremlin Guns on Robots For 2nd Coat</td>
</tr>
<tr>
<td>Black-out on Rocker Lower</td>
<td>Automatic Conventional Stationary Guns</td>
</tr>
<tr>
<td>Heated Flash</td>
<td>1 Min IR, 2 Min Convection (200°F)</td>
</tr>
<tr>
<td>2K Non ISO Clearcoat</td>
<td>E-Stat Hand Guns for Interior</td>
</tr>
<tr>
<td></td>
<td>2 Passes Behr Bells for Exteriors</td>
</tr>
<tr>
<td></td>
<td>PPG NCT II Clear (PPG ISO for 1996 MY)</td>
</tr>
<tr>
<td>Topcoat Bake</td>
<td>30 Min @ 250°F</td>
</tr>
<tr>
<td>Finesse Sanding</td>
<td></td>
</tr>
<tr>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>In-Line Repair - If required</td>
<td>1st Coat with Kremlin Guns on Robot Arms</td>
</tr>
<tr>
<td>Hand Defect Sanding</td>
<td>2nd Coat Conventional Hand Spray</td>
</tr>
<tr>
<td>Solvent Wipe</td>
<td>1 Min IR, 2 Min Convection</td>
</tr>
<tr>
<td>Waterborne Basecoat</td>
<td>1st Coat with E-Stat Behr Bells</td>
</tr>
<tr>
<td></td>
<td>2nd Coat Conventional Hand Spray</td>
</tr>
<tr>
<td>Heated Flash</td>
<td>PPG NCT II Clear (PPG ISO for 1996 MY)</td>
</tr>
<tr>
<td>2K Non ISO Clear</td>
<td>30 Min @ 250°F</td>
</tr>
<tr>
<td>Repair Oven Bake</td>
<td>Upper Radiator Support, Flow Brush out of a Pressure Pot</td>
</tr>
<tr>
<td>Waterborne Air Dry Blackout</td>
<td></td>
</tr>
</tbody>
</table>
Polish & De-Swirl

Off Line Spot Repair in Basic Paint
7 Stalls, Solventborne Basecoat, NCTII Clearcoat, Lamp Bake 30 Min @ 250°F

Glass Bonding Primer
Flow Brush, Air Dry

Waterborne Deadener
Hand Spray, Air Dry

The body-in-white is washed prior to the pretreatment process with a solution of detergent and water, and then flooded with water in the deluge zone. This is followed by pretreatment in a eight-stage phosphate system, which is a series of dip tanks and spray rinses designed to remove any dirt, oil, and debris from the vehicle body and to prepare the surface for paint adhesion by the formation of a zinc phosphate conversion coating. The vehicle first goes through the first two stages, which are a dip tank and a spray system containing alkaline cleaner and water. Then it enters stage three, a water rinse, followed by a dip tank containing rinse conditioner and sodium nitrate and a phosphate dip tank. Both dip tanks have exit sprays located at the end of the tank. Then the vehicle body is dipped in a tank containing cold water. The last two stages are sprays, the first of which contains a buffer, and the second of which consists of a rinse spray of deionized water.

The next step is electrocoating. At this stage, a direct current voltage is applied between the coating bath and the vehicle, which acts as a cathode. The vehicle is then dipped in the tank, which attracts the coating particles within the
tank. After rinsing to remove the solid bath particles, the vehicle body enters the oven for drying and curing.

After passing the electrocoating area, sealers are applied to various areas of the body-in-white to make the vehicle water tight and to provide sound deadening. Then the automobile proceeds to the dry/moist sanding area where it is sanded to remove blemishes from the surface of the body. These sanding booths are used along various stages of the paint line. The vehicles are wiped down with solvent to remove any dirt or grease prior to application of any materials to the body.

Red spotter is applied to the metal joints using conventional air atomized guns in the miscellaneous prime booth. Then the car enters the sealer oven, also called an ELPO co-bake cure oven. After red spotter application, the vehicle enters the antichip primer spray booth. Antichip primer, a solventborne coating, is applied to the rocker panels. This is followed by application of the primer surfacer coating, which is a high solids enamel. The primer surfacer colors are keyed to the specific color of the automobile.

Certain areas of the vehicle such as door jams, door openings, back side of door hinges, under hood, under decker, deck gutters, and trunk openings are coated with color specific primer, which is also a high solids enamel and serves as a basecoat replacement coating. Then the vehicle enters the primer bake oven for curing.
After exiting the cure oven, the vehicle proceeds to the sanding booth for a full wet sanding of the exterior. Then it is washed and rinsed with a rinse aid chemical to reduce water spotting of light metallics, and goes in a wet sand dry off oven.

After wet sanding, the vehicle enters the topcoat system where the basecoats and clearcoat are applied. Basecoat is first applied with conventional air atomized hand guns for door openings and under deck, after which the vehicle enters the bell zone, where the waterborne basecoat is applied with electrostatic bells, followed by another coating with robot operated air atomized applicators. The rocker panels are then coated with waterborne basecoat blackout. After basecoat application, the vehicle enters a infrared flash oven for one minute and a convection oven for two minutes. Then the vehicle is applied with two coats of a two-component solvent clearcoat, after which it enters a topcoat bake oven to cure the topcoat.

After topcoat cure, the vehicle undergoes finesse sanding and inspection for flaws. If vehicle repair is required, the body enters in-line repair. The first step of in-line repair in heavy defect sanding station, where the area of the vehicle that needs repair is sanded down. An air dry primer is sprayed on the area if the sanding exposes bare metal, and the vehicle is masked, exposing only the area requiring repair. The exposed area is wiped with solvent and coated with waterborne basecoat. Then the vehicle enters a heated flash area, followed by clearcoating of the exposed area. After clearcoating, the masking is removed.
and there is a solvent wipe of any overspray. The vehicle then enters the repair oven for curing, after which it returns to the inspection area. If any flaws remain, the vehicle is sent to the off-line spot spray stalls for repair. These stalls are equipped with manual air atomized spray guns and an electric heater to apply and cure the coatings, which are a solventborne basecoat and a two-component solventborne clearcoat.

Other steps of paint application are applications of air dry coating including a waterborne blackout to the radiator support, a glass bonding primer, and a waterborne deadener to the wheel wells of the vehicle to reduce road noise and stone damage.

This specific painting process is tailored to the production of a higher-end automobile, which accounts for additional steps such as wet sanding and application of additional coats to improve the surface finish. But regardless of what vehicle is painted, the basic framework of automotive painting does not vary a great deal. However, the fundamental painting process is undergoing drastic changes to meet increasingly stringent requirements in the environmental aspects. The next chapter will address the present state of technology and its recent developments.
Chapter 3  Present State of Technology and Recent Developments

In an effort to reduce emissions and improve or maintain product quality, new paint technologies have been developed and are being used increasingly in automotive painting. Low solid solvent paints have been completely replaced by high solid solvent paints, which have a solid content of greater than 50%. While increasing the solid content of the paints has resulted in significant reductions in volatile organic compounds (VOCs) and paint sludge, it would be difficult to increase the solid content further without diminishing the quality of the finished surface.

Solvent, thinners, and diluents play an important role in paint application. They are added to paints to reduce the viscosity of the paint for ease of application and to meet quality requirements. This enables a paint system to be applied in existing facilities; to control the flow of wet paint on the substrate; and to achieve a smooth finish that dries in a predetermined amount of time.

More recent paint technologies that are expected to decrease solvent usage are waterborne paints and powder coatings. However, these paint technologies have not advanced far enough to be used in all finishing applications, though
efforts have been made to improve these technologies in hopes of expanding their potential for lowering costs, VOC emissions, and paint sludge.

Paint technologies used nowadays in the automotive industry can be divided into three basic categories: solventborne, waterborne, and powder coatings.

**Solventborne Coatings**

These refer to solventborne coatings that are high in solid content, which is typically in the range of 50 to 70 percent by volume. These coatings are made with low-molecular-weight resins in order to achieve a viscosity low enough for normal application, since fluid viscosity rises rapidly with an increase in paint solids. Since fluidity of resins increases with a reduction in molecule size, chemically reactive short resin molecules at a low polymerization level are used. These resins are alkyds, polyesters, epoxies, urethanes, and acrytics, in many cases, chemically altered so that they can be made into a high solids formation. However, these short molecule resins give a lesser extent of cross-linking and are volatile, which result in paints that are soft and less resistant to water and abrasions. To prevent this, the short molecule resins must be chemically modified to be more reactive and less volatile so as achieve performance levels equivalent to comparable low-solid solventborne coatings.

An important advantage of high solids coatings is the reduced VOC emissions compared with the low solids coatings previously used. Reduced
solvent usage can result in benefits such as lower costs, inventory reductions, and reduced fire hazards. Other advantages of having increased solids in paints are reduced number of paint application strokes to achieve a given paint thickness which could conceivably increase conveyor speed, as well as achieve more efficient reclamation of overspray for reuse, which would reduce paint usage and solid waste generation.

However, high solids coatings have their disadvantages. The low molecular weight resins needed to formulate these coatings generally require high cure temperatures, and the paints have narrow time-temperature-cure windows, which call for close control of the process. High solids coatings also require thorough cleaning of the substrate due to their sensitivity to surface contamination, which could result in craters, blisters, and other defects on the painted surface. Its higher viscosity at room temperature may require paint heaters in the system to lower the viscosity for proper application and good appearance. However, a sharp decrease in viscosity can lead to formation of sags in the paint film during the cure cycle³.

Waterborne Coatings

Waterborne coatings have water as their main fluidizing media. Replacing most of the solvent with water to produce waterborne paints is another approach towards decreasing VOC content in coatings. But waterborne paints are more susceptible to application problems such as sagging and running
as well as blisters and solvent-popping in the curing stage\(^3\). Fewer varieties of resins are available for formulating waterborne coatings in comparison with solventborne coatings. The inherently high viscosity of waterborne paints, however, restricts its solid contents to relatively low levels\(^3\). The problem of electrostatic application of waterborne paint has been overcome by solving the formulation deficiencies such as poor adhesion, insufficient coverage, plus temperature and humidity sensitivity through modifications in paint chemistry and electrically isolating the overly conductive waterborne paint reservoir\(^4\). However, factors such as low solid content, low transfer efficiency, and higher manufacturing cost of the coating results in a higher cost of application for waterborne painting in comparison with solventborne coatings on the basis of equivalent surface area painted. However, improved transfer efficiencies are making the costs of painting with waterborne paints more competitive with solventborne coatings. Waterborne coatings are now being used for all basecoats in the GM Lake Orion plant\(^5\) and for metallic basecoats in the Toyota Georgetown plant\(^7\). Water-based primer surfacers are used for most GM cars in Europe\(^8\).

**Powder Coatings**

Powder coatings are practically 100% solids, and take a novel approach from conventional painting in that the coating as manufactured and applied is totally dry. Its constituents are practically identical to wet paints except for very
little or no solvent, eliminating the need for a flash period before entering the 
bake oven. The elimination of abatement equipment can result in significant cost 
savings. However, due to its high solid content, powder coating does not flow 
until baking, which makes distribution of powder during the process a 
challenging issue.

Powder coating is a relatively new technology with great potential for 
recyclability, high transfer efficiency, and high solid content, all of which can 
contribute to emissions reduction. However, its recyclability is still a matter of 
contention due to the difficulties encountered in dirt contamination on the paint 
line and separating powder coatings of different colors during recycling. This 
may limit powder usage to coatings such as primer surfacers and clearcoats that 
are consistent from vehicle to vehicle. But powder usage is still very limited 
due to its requirement for heat and the difficulty in achieving a uniform paint 
film on the surface being coated. The high film thicknesses of powder coating 
makes it a more expensive alternative in terms of material cost. Color matching 
is also a difficult task since powder coatings of different colors can not be 
blended like liquid paints to obtain a specific color. It requires a great deal of 
trial-and-error, which can consume a considerable amount of raw materials. 
Another limitation is that it must be manufactured in large amounts to achieve 
cost efficiency, but this can be overcome as the use of powder coatings increases. 
At the present time, powder primers are being used at three GM facilities for 
truck production. Powder clearcoats, which are being used in one GM plant in
Eastern Europe, may lead to further reductions in VOCs, but leads to problems on the application side. Powder applications have also been used as black-out coating materials and chip-resistant coatings on areas most prone to paint chipping such as rocker panels and leading edges of sheet metal.

Solventborne coatings are gradually being replaced by waterborne paints in certain applications in an attempt to reduce VOCs, and as the same trend may follow with powder coatings as the paint technology improves. Paint technologies are being developed and improved in a steady effort to achieve the ultimate goal: a coating that provides excellent surface appearance with low VOC emissions in a cost-effective manner.
Chapter 4     Steel and Alternative Substrates

Automobiles have traditionally been made of steel, but the use of aluminum and plastic is gradually increasing in the automobile industry as materials and technologies are being developed and improved. However, sheet steel still defines and constrains the automotive painting process today, with application technologies that are designed around the conductivity, oxide-free surface, and thermal stability of steel. Painting alternative substrates can be accomplished through two approaches: to modify the material to fit present painting technologies which are based on steel, or to develop new technologies suitable for painting the alternative substrate itself. Given the present state of technology, the first approach is vastly preferable because of lower capital costs, easier color management, and compatibility. However, the limitations of the first approach may make it feasible to look at properties of alternative substrates and see how these substrates can be put to good use.

Steel - the status quo

Steel has long been touted for its strength and stiffness, making it an ideal material for engineering applications. It has long been the primary substrate used in automobiles because of its low cost, general availability, and excellent metal properties. But with the growing trend towards a lighter, stronger, and more environmentally-friendly vehicle, steel is gradually being replaced by
alternative substrates. Due to its overwhelming advantages, this replacement is limited, and steel is still widely used in automobile manufacturing. The customary method of painting a steel body-in-white starts out with a zinc-phosphate treatment, followed by application of a cathodic electrocoat, primer-surfacer, and topcoat.²

**Aluminum - the lightweight alternative**

The use of aluminum in automotive structure and body skin applications has become more attractive in light of the need to meet the stringent demands for weight reduction. Aluminum has the advantages of high strength, relative low density, and good corrosion resistance (relative to steel). In addition to its high raw material cost, aluminum still has the following disadvantages: cosmetic corrosion in the form of poor paint adhesion due to insufficient pretreatment, spreading of filiform corrosion from the cracking of paint film, paint blisters due to galvanic corrosion of exterior parts, and perforation from galvanic corrosion at and around the areas where the aluminum joins with different types of metals.¹²

Tests on the corrosion resistance of aluminum sheets have been conducted with different alloys with various processes of pretreatment and electrocoating and subjected to different conditions of use.

A study conducted by Honda for the development of the Honda NSX carried out a series of tests on aluminum to determine a suitable pretreatment
and painting technology for the all-aluminum body. Test items were aluminum components made of 5000 series and 6000 series alloys. Different types of aluminum alloys were chosen for their inherent properties. The 6000 series development material and the 5052 alloy were chosen respectively for the outer and inner panels for their high formability and high corrosion resistance. The 5182 alloy was chosen for the skeleton for its high strength and high weldability. The 6000 series development material in extruded form was chosen for the side sills for its high extrudability and high weldability.

All the test components were pretreated in one of four methods: zinc phosphate, chromium phosphate, chromium chromate, and non-chromate treatments. Then they were coated with a high-build cathodic E-coat, surfacer, and topcoat. After testing the resistance of these components to water, humidity, hot salt water, filiform corrosion, salt spray, and cyclic corrosion, chromium chromate was found to be the optimal pretreatment system for the all-aluminum body. The only deficiency was that the anti-filiform corrosion property was insufficient for the 6000 series aluminum material. Studies of the relation between the material component and the anti-filiform corrosion ability led to the discovery that filiform corrosion can be controlled by decreasing the copper content in the aluminum alloy. Therefore, decreasing the copper content and adjusting the contents of magnesium and other metal elements would make it possible to develop an alloy material which is superior to formability and anti-filiform corrosion that can be used for outer panels. A sodium phosphate
system was chosen as the degreasing reagent to remove the impurities that decrease the adhesion of the coating film\textsuperscript{12}.

A comparative study on the corrosion resistance of painted aluminum sheet for automobiles conducted by the Japan Light Metal Association evaluated the appearance and adhesion of paint film, depth of pitting corrosion and the condition of the corrosion area cross section after road and outdoor exposure tests. Results showed that AA-5182 had the best corrosion resistance, followed by AA-6009. Pretreatment methods were also compared and chromate chromium and hydrofluoric acid added zinc phosphate were excellent. This presented auto manufacturers with the choice of continuing the use of the conventional zinc phosphate pretreatment system and adding hydrofluoric acid to treat aluminum components\textsuperscript{13}.

Another study conducted by Alcan demonstrated through its evaluations that electrocoating aluminum to obtain resistance to structural corrosion is unnecessary, and that spray priming aluminum body panels and/or structures in areas only where paint is required is a viable alternative. Cyclic corrosion and neutral salt spray tests were conducted on unpainted and electrocoated specimens made from AA5251, an alloy for structural applications. Filiform corrosion tests were conducted on unpainted and electrocoated specimens of AA-6009, a heat treatable alloy suitable for body skins. Unpainted and electrocoated specimens made of cold rolled steel and electrogalvanized steel were also tested for cyclic and filiform corrosion for the sake of comparison. The
test results showed that unpainted and electrocoated aluminum had better anti-corrosion properties that mild or galvanized steel. These studies show that aluminum usage is flexible in that it can be adapted to conventional steel painting facilities, yet has unique properties that may potentially simplify the painting process, thus resulting in substantial cost savings. If the painting technology can be tailored to the substrate, the considerable savings in painting cost might compensate for the high cost of aluminum material and make it a cost-effective alternative for the automobile body-in-white in many cases.

Plastics

The use of plastic materials is increasing rapidly in light of the need for weight reduction and processing flexibility. Plastics also have excellent corrosion and dent resistance. There is also the possibility of parts consolidation, though this may not be feasible because it would result in difficulties in paint application due to corners and pockets in the component as well as higher repair costs.

However, plastic does have its disadvantages when painted on-line using conventional technology. Its low conductivity makes it difficult to achieve high transfer efficiencies when painting the substrate using conventional technology. Plastics generally can not withstand high temperatures, which poses problems in conventional painting where the drying and curing of the electrocoat requires a
maximum resistance temperature of 400° F and the baking of the primer-surfacer and topcoat, when the oven may be set as high as 350° F\textsuperscript{16}. Its stiffness and strength properties can not compare with steel, and therefore, plastic panels have to be made thicker than corresponding steel components in order to equal the material properties of steel. It also has low resistance to paint chipping and is less crashworthy due to the substrate's lower ability to absorb energy\textsuperscript{15}. Other issues involve the characteristics of paints for plastics, which must be flexible to avoid peeling and cracking when the material deforms. But this flexibility also constrains the scratch resistance of the paint, and as a result, the paint loses luster after only 18 months, half the life of paints for metals. The non-conductivity of the plastic surface gives an added disadvantage of not retaining paint as well as metal, forcing carmakers to add steps and cost to the plastic painting process\textsuperscript{17}.

Some of these difficulties are being overcome as new plastic materials are being developed with improved thermal, impact, and chipping resistance properties and new surface treatment processes improve the conductivity and adhesion of a plastic substrate. However, a new study of painting non-conductive surfaces indicates that by generating ultrasonically atomized electrically charged water particles behind a non-conductive surface, i.e. plastic, the waterborne paint is charged by induction under the influence of the space charge behind the surface, thus enabling the non-conductive surface to be painting by a mechanical spray gun maintained at ground potential. The
inherent advantages of this approach are: elimination of the need for non-conductive substrates such as plastics to be treated before painting and lower voltage and power requirements. It also does not require isolation of the paint supply, but does require electric isolation of the enclosure to painted on the outside surface. This new technology has the potential of significantly increasing transfer efficiency as no paint should land on the booth or operator since all electric field forces are directed at the car body\textsuperscript{18}.

The painting of plastic substrate requires a longer flash period between the spray booth where paint application takes place and the baking oven where the product is dried and cured. It also requires additional heat up time in the oven in the drying and curing stage\textsuperscript{19}.

Attaching the plastic components at the later point on the paint line or painting them completely off-line is another approach to resolve the thermal resistance problem. However, there are problems with color matching between plastic components and the rest of the vehicle body\textsuperscript{17}.

Many forms of plastics are used in the manufacturing of automobiles. These include RIM (Reaction Injection Molding) Polymers, TPU (Thermoplastic Polyurethane), ABS (Acrylonitrile-Butadiene-Styrene), TPO (Thermoplastic Olefins), and SMC (Sheet Molding Compound). Each type of plastic possess certain inherent features that make it a good material for automotive panels, and can also be reinforced with fillers such as glass fibers to form a unique composite material with improved physical properties. A study by Dow Chemical
incorporates polyurea technology and internal mold release advances to produce various reaction injection molding systems (RIM) that offer minimal distortion and increasing degrees of thermal stability, for example, the SPECTRIM 80S polymer system, which can be used in off-line painting/assembly processes at a paint oven bake temperature below 275° F, the Polyurea HF system for on-line painting to 325° F, and the Polyurea HT system for on-line painting through E-coat at 400° F. The raw material cost of these polymer systems range from the base cost of SPECTRIM 80S to the more costly Polyurea HF and Polyurea HT, which amount to respective increases of 25% and 35% in material cost. Therefore, the choice of a RIM polymer can be determined by considerations of thermal stability requirements, RIM processing capability, and economics.

Plastic materials are corrosion resistant, thus making elimination of phosphate coating a possibility. This provides an opportunity for cost reduction and energy savings. Researchers at Nissan Shatai Co. Ltd. are working on a program which focuses on developing an on-line paintable bumper that would be painted on a primerless painting system. The objectives of this project were broad cost reductions in the paint facility, parts transfer, paint process steps, paint costs, and others, as well as good surface quality and good color match. The material chosen for the bumper was PPE/PA (polyphenylene/polyamide), which fulfill the necessary material requirements by having a heat resistant temperature above 170° C, low temperature impact, good adhesion without primer, good flow and melt flow rates, and thermal stability. The paint line
process sequence chosen was attachment of the bumper after E-Coat and entering the process before the undercoat. This was done to avoid distortion of the bumper in the electrocoat bake oven, where the temperature can go as high as 180° C.20.

TPO is the abbreviation of Thermoplastic Polyolefin, which is comprised of a blend or a copolymerization of polypropylene and rubber. Paintability of the substrate improves with an increase in rubber content. TPO has been gaining widespread acceptance in automotive applications due to their recyclability, low cost, good mechanical properties, ease of molding, and Class-A surface. Although TPO is being used extensively in the automotive industry, its poor surface qualities as molded make it a difficult material to paint, which gives rise to the need to develop ways to improve paint adhesion properties. TPO has low surface tension, and therefore, its surface must be oxidized or activated to achieve good paint adhesion. These pretreatment processes include chemical oxidation, flame treatment, corona discharge, plasma treatment, or Benzophenone/UV treatment, and the use of adhesion promoters. BASF Corp. has conducted a study that looks into the painting of TPO and the development of new adhesion promoter technologies that offer significant improvements in reducing solvent emissions (attributable to higher solid content) and improving the painted surface of the final product. These adhesion promoters are made from specialty polymers such as chlorinated polyolefin, and can be adapted in different ways. Adhesion promoters can be pigmented allowing for uniform
application, or made conductive so that electrostatic paint processes can be used. They can also hide mold defects and improve surface smoothness. These new technologies are receptive to a wide range of topcoats, and both high solids or waterborne basecoats can be used in conjunction with these adhesion promoters. In this study, waterborne basecoats were found to be provide the lowest VOC emissions with superior appearance, especially in metallic colors\textsuperscript{21}.

Sheet Molding Compound (SMC) is widely used in the automotive industry. SMC, being a thermoset material, is a very stable substrate. It does not rust or oxidize, and is also resistant to organic solvents and acid. These properties combined with its low water absorption and high flexural modulus, gives SMC the durability that makes it so attractive as a substrate for body panel applications. SMC has many advantages that make it a better material than other plastics in terms of paintability. Of all non-metallic materials, SMC is most compatible with steel painting techniques due to similar linear thermal coefficient of expansion and heat resistance, which make it possible for SMC panels to be processed through conventional painting facilities. SMC, like other plastics, is corrosion resistant and does not require phosphate coating, but its high distortion temperature makes it able to withstand the higher cure oven temperatures typically used with electrocoats, provided it is supported in an unstressed condition. The use of SMC is being promoted by organizations such as the SMC Automotive Alliance and the SPI Composites Institute. Research in improving the technology has advanced significantly in the past few years,
especially in the area of improving the surface smoothness and appearance of compression molded automotive exterior body component parts\textsuperscript{15}. General Motors' APV Van Hood is an example of an SMC component used in the industry\textsuperscript{22}.

In spite of the many advantages of SMC, the fact that it is a thermoset material poses serious problems about recycling. With the growing concern for our environment, manufacturers and consumers are interested in substrates that can be recycled at the end of the use stage. Thermoplastics, with its inherent abilities to be resoftened and reshaped by molding and extrusion with no further chemical reactions, offer that possibility along with traditional plastic advantages such as weight reduction, lower cost tooling, parts consolidation, design flexibility, and cost competitiveness. However, other performance criteria must also be met: thermal stability, Class-A surface, end-use impact performance and chemical resistance. GE Plastics completed a design study for thermoplastic exterior body panel systems. The fender application was chosen for this study, and the material of choice was the NORYL GTX\textsuperscript{®}917 resin, an unreinforced thermoplastic resin based on polyphenylene oxide (PPO\textsuperscript{®})/Polyamid resin technology. Material characteristics such as shrinkage and the coefficient of thermal expansion are important considerations at the painting stage, and is taken into account through product design, prime annealing for 30 minutes at \(\alpha\) above the highest temperature (approximately 182\(^{\circ}\)C or 360\(^{\circ}\)F) it will encounter in the painting process, and slip fastening.
Stress relaxation is prevented by inducing stress in the fender through molding, sub-assembly of bracketry, and assembly of the fender system to the vehicle. Current production body panels molded from NORYL GTX® resins include fenders on the Buick Park Avenue and LeSabre, Oldsmobile Eighty Eight and Ninety Eight, Pontiac Bonneville and Cadillac Fleetwood and Deville models, as well as production fenders and quarter panels on the Saturn SL, SL1 Sedan and SL2 Coupe. Another study by DuPont looks into thermoplastic compression molded horizontal automotive panel, which is based on the DuPont XTC, which is a long glass fiber polyethylene terephthalate (PET) based stampable sheet product produced by a wet forming process in mill roll form. It was developed as a horizontal panel system aimed initially at hood, roof, and trunk lid applications. But with its in-mold-coating (IMC) system, this substrate has a heat distortion temperature of 257°C at 1.8 MPa, making it a candidate any Class-A external panel application requiring processing with steel panels through the E-coat treatment bake cycle (nominally 190°C for 30 minutes).

With the many advances in material technologies, the thermal resistance problem of plastic panels during painting is gradually being overcome, making it less of a consideration in choosing a substrate for automotive body panels. As the use of alternative substrates increase, it will become more cost-effective to adapt our painting facilities accordingly to take advantage of their inherent properties, and this will result in significant cost reductions and energy savings.
Chapter 5  Cost Analysis of Automotive Painting

The painting process adds significant cost to the automobile, and the costs for setting up a paint shop account for approximately half of the total capital cost of an entire assembly plant. State-of-the-art automotive painting facilities cost hundreds of millions of dollars, and the costs incurred in maintaining these facilities are high. Expanded regulatory control on the local, state and federal level have also resulted in a requirement for increased expenditures for emission-control equipment and other abatement measures.

The figures were generated using the MSL cost model\textsuperscript{28} and data inputs supplied by Pittsburgh Paint and Glass (PPG) and General Motors (GM). The basic steps of the automotive painting process in the model are as follows:

1. Pretreatment
2. Electrocoat - Application, Drying and Curing, Inspection and Rework
3. Sealer - Application
4. Primer-Surfacer - Application, Drying and Curing, Inspection and Rework
5. Basecoat - Application, Drying and Curing
6. Clearcoat - Application, Drying and Curing, Inspection and Rework

Other parts of the cost model include Data Input, VOC Treatment, and Cost Summary.

In the course of this study, certain assumptions were made when modeling the cost of painting a car in the paint shop of an assembly plant.
Results may vary as these premises change, but they should give a realistic representation of actual conditions in automobile production. These assumptions are as follows:

Annual Production Volume: 250,000 vehicles

Vehicle Type: Oldsmobile Aurora

Color: Red

Operating Days per Year: 250 days/year

Shifts per Day: 2 shifts/day

Hours per Shift: 10 hrs/shift

Paint Line Speed: 28 ft/min

Spacing Between Hangars: 2 ft

Pieces Per Hangar: 1

Hangar Occupancy Rate: 80%

Dedicated Paint Line: 100%

In the absence of detailed capital cost data for the Lake Orion facility, internally developed capital costs based on other existing painting facilities are used in this analysis. To retain consistency, costs have been estimated based on an annual production volume of 250,000 vehicles, reflecting the operating conditions at the facility upon which the data is based. Note that reducing the production volume to 200,000 vehicles (Lake Orion production volume), increases painting costs by roughly $50/car. The vehicle type was chosen based on specific technical information provided by GM, which used the Oldsmobile
Aurora as an example. A red basecoat was chosen because of its difficulties in application in comparison with other colors.

The baseline case is based on is understood to be the standard end-product of the Lake Orion plant. The vehicle being painted is a steel body-in-white, painted with a solventborne primer-surfacer, a waterborne basecoat, and a solventborne clearcoat.

Given the lack of information from GM on the paint shop facility, there may be differences in our data (based on information supplied by PPG) and theirs regarding the paint line speed, spacing between hangars, and hangar occupancy rate. But since the paint line is dedicated and underutilized, these numbers can increase up to a point without a need for additional parallel paint lines. Unless there are additional paint lines, there will be no increase in capital costs.

Certain cost factors are determined by general conditions and may change with other externalities. These include:

- Capital Recovery Rate: 12.0%
- Capital Recovery Period: 10 years
- Building Lifetime: 20 years
- Building Space Cost Factor: $75.00 /sq.ft.
- Direct Labor Cost: $24.00 /hr
- Electricity Price: $0.08 /kWh
- Natural Gas Price: $4.00 /MBtu
Costs generated for each step of automotive painting using the assumptions, cost factors, and technical data from PPG and GM are listed below. The shaded portions of the table indicate that the choice of paint technologies is not applicable for that process step (e.g., electrocoat being a waterborne coating). The question marks denote non-availability of the paint technology for the process at the present time.

### Costs of Automotive Painting Steps ($/car)

<table>
<thead>
<tr>
<th>Substrate/Paint Technology</th>
<th>Pretreatment</th>
<th>Electrocoat</th>
<th>Sealer</th>
<th>Primer Surfacer</th>
<th>Basecoat</th>
<th>Clearcoat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel</strong></td>
<td>$8.90</td>
<td></td>
<td>$23.75</td>
<td>$96.07</td>
<td>$134.05</td>
<td></td>
</tr>
<tr>
<td>High Solids</td>
<td></td>
<td></td>
<td>$22.21</td>
<td>$101.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterborne</td>
<td></td>
<td>$54.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder Coat</td>
<td></td>
<td></td>
<td>$63.64</td>
<td></td>
<td></td>
<td>$181.90</td>
</tr>
<tr>
<td><strong>Aluminum</strong></td>
<td>$8.90</td>
<td></td>
<td>$23.75</td>
<td>$96.07</td>
<td>$134.05</td>
<td></td>
</tr>
<tr>
<td>High Solids</td>
<td></td>
<td></td>
<td>$22.21</td>
<td>$101.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterborne</td>
<td></td>
<td>$54.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder Coat</td>
<td></td>
<td></td>
<td>$63.64</td>
<td></td>
<td></td>
<td>$181.90</td>
</tr>
<tr>
<td><strong>Plastic</strong></td>
<td>$8.90</td>
<td></td>
<td>24.12</td>
<td>$96.39</td>
<td>$134.54</td>
<td></td>
</tr>
<tr>
<td>High Solids</td>
<td></td>
<td></td>
<td>22.61</td>
<td>$101.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterborne</td>
<td></td>
<td>$54.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder Coat</td>
<td></td>
<td></td>
<td>63.64</td>
<td></td>
<td></td>
<td>$181.90</td>
</tr>
</tbody>
</table>

The cost of painting different substrates does not vary very much because of present painting strategies, where the material is modified to accommodate existing paint facilities. This approach is preferred to a drastic redesign of the paint line to accommodate a distinctive substrate so as to avoid a major outlay in capital costs, simplify color management, and avoid incompatibilities. The costs
of painting steel and aluminum are virtually identical, whereas the cost of painting plastic with solventborne or waterborne paints is slightly more expensive due to the longer flash period before the component enters the oven for drying and curing.

Cost variations for different paint technologies can be attributed to several influencing characteristics such as transfer efficiency, paint film thickness, and solid content of the paint. Waterborne paint technology has advanced so much, especially in the improvement of transfer efficiency, that it is almost competitive with solventborne paints in terms of cost and surface performance. Powder coatings incur substantially greater costs due to application of a thicker paint film, which drives up the raw material costs.

Figure 5.1 shows the cost breakdown of the painting process based on the GM process (solventborne primer-surfacer, waterborne basecoat, and solventborne clearcoat) by categorizing them in different types of fixed and variable costs. Material costs, which takes up approximately 50% of total cost, are further broken down into the costs of individual paints as represented by their end functions, i.e., primer-surfacer, basecoat, clearcoat, etc. This figure shows that the raw material costs of basecoat and clearcoat play an important role in determining cost. Therefore, substantial cost reductions could be achieved by decreasing paint thickness or increasing transfer efficiency.
Fig. 5.1 Breakdown of Costs by Category

Fig. 5.2 Breakdown of Costs by Process Step
Figure 5.2 represents the cost breakdown categorized in costs incurred during each step of the automotive painting process. This breakdown of costs indicates that costs incurring during application of the basecoat and the clearcoat make up more than 60% of the total cost. Therefore, improving these process steps of paint application would have a greater effect on lowering the total cost of painting the automobile.

Improving transfer efficiencies or reducing film thickness are important approaches towards making the painting process more efficient. This can be accomplished by modifying the application process or the components of the paint itself. The following table shows the transfer efficiencies and paint film thicknesses expected of different paint technologies at the present time, as well as the costs involved in paint application.

<table>
<thead>
<tr>
<th>Production Factors</th>
<th>Transfer Efficiency</th>
<th>Film Thickness (mils)</th>
<th>Application Cost ($/car)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-Solids Solvent Paints</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primer-Surfacer</td>
<td>75%</td>
<td>1</td>
<td>$11.97</td>
</tr>
<tr>
<td>Basecoat</td>
<td>55%</td>
<td>1.2</td>
<td>$88.59</td>
</tr>
<tr>
<td>Clearcoat</td>
<td>80%</td>
<td>2.5</td>
<td>$106.67</td>
</tr>
<tr>
<td><strong>Waterborne Paints</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primer-Surfacer</td>
<td>60%</td>
<td>0.8</td>
<td>$10.63</td>
</tr>
<tr>
<td>Basecoat</td>
<td>50%</td>
<td>1</td>
<td>$91.78</td>
</tr>
<tr>
<td><strong>Powder Coatings</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primer-Surfacer</td>
<td>90%</td>
<td>3.5</td>
<td>$52.35</td>
</tr>
<tr>
<td>Clearcoat</td>
<td>60%</td>
<td>6</td>
<td>$150.70</td>
</tr>
</tbody>
</table>

The table above indicates that regardless of paint technology, the costs of applying basecoat and clearcoat are consistently higher than primer-surfacer.
Therefore, sensitivities of cost to changes in transfer efficiency and film thickness for the basecoat and clearcoat have been conducted as part of this analysis.

Sensitivity analyses of costs to transfer efficiency and film thickness for the clearcoat and the red basecoat were completed. Fig. 5.3, which graphs the sensitivity of total painting cost to clearcoat transfer efficiency, gives consistent indication that for equivalent transfer efficiencies, powder coating is more costly than solventborne paint. Given the fact that lower transfer efficiencies are being achieved with powder coatings with current technology, the transfer efficiency of powder coatings must be significantly improved before powder can even become a cost-effective option in large-scale production. Figures 5.4 to 5.7 which graph the sensitivity of the costs of clearcoating as well as its individual categories of paint application, drying & curing, and inspection & rework to clearcoat transfer efficiency respectively, are also included for reference. During paint application and inspection & rework, where costs incurred are largely dependent on material cost and make up a large portion of total cost, powder is still more costly than solvent for the same transfer efficiency. However, during the drying & curing stage, where material costs do not play a role, the opposite is true. Powder may be a cost-effective option in the paint shop if the material cost were lower. This may be accomplished if powder were widely used enough to make large scale production of powder coatings a viable option.

Figures 5.8 to 5.12 show sensitivity analysis of the costs of the entire painting process, clearcoating, clearcoat application, clearcoat drying & curing,
and clearcoat inspection & rework to the clearcoat film thickness. The general
trend observed in these sensitivity analyses is that for an equivalent film
thickness, solventborne clearcoat is more expensive than the powder alternative.
However, with present technology, a powder clearcoat applied on a automobile
has a film thickness of 6 mils in comparison with a film thickness of 2.5 mils for a
solventborne clearcoat. This makes the powder alternative more costly, and a
less practical choice from an economic point of view. Therefore, reducing film
thickness by improving powder application techniques has great potential for
improving present technology and making powder more cost effective.

Figures 5.13 to 5.16 are sensitivity analyses of costs to the basecoat transfer
efficiency. At equivalent transfer efficiencies, painting with aqueous coatings is
consistently more expensive than solventborne coatings in terms of total painting
cost, basecoating cost, as well as the costs of application and drying & curing of
the basecoat. Even if the aqueous basecoat application technology were to
improve so that its transfer efficiency would match that of the solventborne
basecoat, the aqueous alternative would still not be competitive in terms of cost.

Figures 5.17 to 5.20 are sensitivity analyses of costs to the basecoat film
thickness. At equivalent film thicknesses, waterborne coatings are more costly
more solventborne coatings. This trend is similar to that previously observed in
the sensitivity analyses of costs to basecoat transfer efficiency, except that a
lower film thickness has already been achieved for the aqueous basecoat in
comparison with the solventborne alternative without realizing a lower cost.
Fig. 5.3 Sensitivity analysis of total painting cost to clearcoat transfer efficiency

Fig. 5.4 Sensitivity analysis of clearcoating cost to clearcoat transfer efficiency
Fig. 5.5 Sensitivity of clearcoat paint application to clearcoat transfer efficiency

Fig. 5.6 Sensitivity analysis of clearcoat drying & curing cost to clearcoat transfer efficiency
Fig. 5.7 Sensitivity analysis of clearcoat inspection & rework cost to clearcoat transfer efficiency

Fig. 5.8 Sensitivity analysis of total painting cost to clearcoat film thickness
Fig. 5.9 Sensitivity analysis of clearcoating cost to clearcoat film thickness

Fig. 5.10 Sensitivity analysis of clearcoat paint application cost to clearcoat film thickness
Fig. 5.11 Sensitivity analysis of clearcoat drying & curing cost to clearcoat film thickness

Fig. 5.12 Sensitivity analysis of clearcoat inspection & rework cost to clearcoat film thickness
Fig. 5.13 Sensitivity analysis of total painting cost to basecoat transfer efficiency

Fig. 5.14 Sensitivity analysis of basecoating cost to basecoat transfer efficiency
Fig. 5.15 Sensitivity analysis of basecoat application cost to basecoat transfer efficiency

Fig. 5.16 Sensitivity analysis of basecoat drying & curing cost to basecoat transfer efficiency
Fig. 5.17 Sensitivity analysis of total painting cost to basecoat film thickness

Fig. 5.18 Sensitivity analysis of basecoating cost to basecoat film thickness
Fig. 5.19 Sensitivity analysis of basecoat application cost to basecoat film thickness

Fig. 5.20 Sensitivity analysis of basecoat drying & curing cost to basecoat film thickness
The sensitivity analyses of costs to transfer efficiency and film thickness give general indications of how paint technology can be improved. To sum up, solventborne and waterborne paints and their application techniques have been matured to a point where potential improvement is minimal, whereas powder coatings have greater potential for improvement, especially in reducing the film thickness, reducing raw material costs, and increasing the transfer efficiency.

Costs generated by the MSL model have been submitted to GM personnel for validation. Due to competitive concerns, only vague feedback was received from GM. They indicated that the figures generated by our cost model were lower than actual production costs in the paint shop. Therefore, attempts were made to analyze what factors affect cost and how we differed in determining these factors. Information on the GM Orion plant was based on an environmental analysis conducted by Dames & Moore for the Auto Team of the President's Council for Sustainable Development\textsuperscript{26}. The factors we looked at dealt mainly with the utilization of labor and paints.

A table has been compiled listing the factors that influence the overall cost of automotive painting and the data on hand at present. These assumptions reflect the cost input we obtained via PPG. The solid contents of the coatings are based on data supplied by GM. We would like to reconcile our differences regarding the figures used in our calculations of cost and emissions so the data inputs can be modified to reflect actual conditions in automotive painting.
Given the differences in the cost factors listed below, we would like to find out where the discrepancies lie and modify our data inputs accordingly.

**Factors that influence the Overall Cost of Automotive Painting**

<table>
<thead>
<tr>
<th>Cost Factor</th>
<th>Pretreatment</th>
<th>Electrocoat</th>
<th>Sealer</th>
<th>Primer Surfacer*</th>
<th>Basecoat*</th>
<th>Clearcoat*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of direct laborers (men/station)</td>
<td>2</td>
<td>3</td>
<td>30</td>
<td>4</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Cost of Labor ($/hr)</td>
<td>$24</td>
<td>$24</td>
<td>$24</td>
<td>$24</td>
<td>$24</td>
<td>$24</td>
</tr>
<tr>
<td>Number of Parallel Stations</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Labor Percentage (Process/Total)</td>
<td>3.775%</td>
<td>5.66%</td>
<td>56.60%</td>
<td>7.55%</td>
<td>3.775%</td>
<td>22.64%</td>
</tr>
<tr>
<td>Paint Cost ($/gal) (as applied)</td>
<td></td>
<td>$10.26</td>
<td>$8.50</td>
<td>S:$26.50</td>
<td>S:$73.92</td>
<td>S:$131.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W:$11.25</td>
<td>W:$35.21</td>
<td>P:$114.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P:$114.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paint Cost ($/gal) (100% solids)</td>
<td>$50.00</td>
<td></td>
<td></td>
<td>S:$50.00</td>
<td>S:$200.00</td>
<td>S:$250.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W:$45.00</td>
<td>W:$220.00</td>
<td>P:$120.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P:$120.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solvent Solution Cost ($/gal)**</td>
<td>$0.01</td>
<td></td>
<td></td>
<td>S:$3.00</td>
<td>S:$3.00</td>
<td>S:$3.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W:$0.01</td>
<td>W:$0.01</td>
<td>P:$3.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P:$3.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Content (%)</td>
<td>20.5%</td>
<td></td>
<td></td>
<td>S:50%</td>
<td>S:36%</td>
<td>S:52%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W:25%</td>
<td>W:16%</td>
<td>P:95%</td>
</tr>
</tbody>
</table>

*S: solventborne, W: waterborne, P: powder coating

**Solvent Solution in waterborne paints includes water content, which accounts for the lower cost per gallon.

After looking at the cost factors, it has been determined that man-hours, hourly wage and paint cost were the major factors that brought about the
difference in modeled and actual painting costs. The indirect costs of labor, which can come to as much as 100% of direct labor costs, were not taken into consideration in generating costs with the MSL cost model. The cost model also shows under-utilization of the paint line, which results in a labor commodity cost of 1.05 man-hours/job, which differs from the 6.82 man-hours/job presented in the Dames & Moore report.

Paint cost is a influential factor in determining the total cost of manufacturing a automobile. Since this is a matter of confidentiality among automakers and suppliers, there have been difficulties in obtaining valid data. The data available at present result from discussions with PPG and have been verified to be within a reasonable cost range of the raw materials. However, these costs do not agree with estimates given by GM as the clearcoat price of $131.44/gal verified by PPG is disproportionately high in comparison to the GM estimate of $40/gal.

The next step toward refining our cost figures is to reverify our data in regards to labor hours and wages, raw material costs, and capital equipment costs to reflect actual conditions of production. However, it is difficult to obtain these figures due to concerns related to confidentiality and competition.

While cost is a very important factor in automobile production, environmental concerns are also being considered in automotive painting. In this chapter, we have concentrated on costs and have come to the conclusion that although solvent alternatives such as aqueous and powder coatings have
improved to a point where they are no longer impractical from an economic point of view, most of these alternatives are still not competitive with solventborne paints in terms of cost. However, in view of today's strict regulatory environment, elements such as emissions and solid waste must also be taken into account when determining which paint technology would be most feasible. And these environmental factors and their effects on automotive painting will be discussed in more detail in the following chapters.
Chapter 6  VOC Emissions in Automotive Painting

Volatile organic compounds (VOCs) make up a major portion of the air pollutants discharged in an automobile assembly source, and the paint shop is a major source of these emissions. VOCs have been identified as a significant environmental problem. They not only pose toxic hazards but threaten to aggravate the greenhouse effect by increasing ozone in the lower atmosphere where it is undesirable and destroying it in the upper atmosphere where it is needed. In view of these risks, VOC emissions from manufacturing facilities have been put under more stringent controls under environmental regulations such as the 1990 Clean Air Act Amendments\textsuperscript{27}. Most VOCs come from solvent-based coatings, and early attempts to control the release of VOCs regulated the maximum system discharge of reactive solvents with exemptions for water based systems with solvent structure 80% water and 20% organic solvent by volume and solvent systems at 80% volume solids. This was strongly biased toward water-based systems as it turned out these systems were equivalent to 60% volume solids when water was excluded. This advantage vanished when the regulatory agencies realized that the amount of solvent emitted per unit of production was a better measure of pollution potential since it took efficiency into account. The pollution controls were then given in terms of grams of organic solvents per liter of paint. This is the volatile organic content (VOC) standard currently in place today\textsuperscript{28}.
Strategies to conform to pollution standards were studied, and the coating industry attempted to meet environmental goals by reducing the VOCs in paints. High solids coatings showed significant improvement in the environmental aspect since they reduced solvent emissions by approximately 50% as compared with low solids coatings. However, the quality of the basecoat declined, as it displayed an orange-peel appearance and lack of sufficient gloss. Further VOC reduction is not possible via high solid coatings, but the water-borne paints show potential of VOC reduction as well as better quality. Another recent development is the use of powder coatings, which contain zero or close to zero VOCs and can potentially generate no paint sludge (powder not transferred onto the vehicle can be collected and reused). The powder coatings are not mixed with liquid solvents that turn into hazardous vapors during the paint spraying process. Instead, they are sprayed on dry and melt into a smooth finish when they go through the paint bake oven, potentially eliminating the need for expensive pollution-control equipment. However, the drawbacks to using powder-based coatings are the high capital costs due to thick coating required and problems with the surface quality such as difficulties in making the surface finish smooth and flawless as well as problems with chipping and peeling. Other technologies under study are solvent abatement through carbon absorption for solvent recovery or fuel use or the development of newer and more efficient methods to transfer paints on to the car.
Varying amounts of volatile organic compounds are emitted during each part of the painting process, and the sources are generally categorized according to process step below. These figures are computed using data from PPG (Electrocoat, Sealer, Solvents/Purging Agents) and GM (Primer-Surfacer, Basecoat, Clearcoat) detailing how much volatile organic compounds are emitted based on the amount of coating applied. Since present technology is based on adapting the substrate to the paint line, alternative substrates are treated so that they can be painted like steel. Therefore, the emissions are very similar except when applying waterborne basecoat on plastics, which emits a slightly greater amount of VOCs due to a longer flash period on the paint line.

**Emissions generated at each step of Automotive Painting: (lbs/car)**

<table>
<thead>
<tr>
<th>Substrate/Paint Technology</th>
<th>Electrocoat</th>
<th>Sealer</th>
<th>Primer Surfacer</th>
<th>Basecoat</th>
<th>Clearcoat</th>
<th>Solvents/Purging Agents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel</strong></td>
<td></td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Solids</td>
<td></td>
<td></td>
<td>1.13</td>
<td>3.9</td>
<td>2.51</td>
<td></td>
</tr>
<tr>
<td>Waterborne</td>
<td>0.91</td>
<td></td>
<td>0.61</td>
<td>2.27</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Powder Coat</td>
<td></td>
<td>0.2</td>
<td></td>
<td>?</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td><strong>Aluminum</strong></td>
<td></td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Solids</td>
<td></td>
<td></td>
<td>1.13</td>
<td>3.9</td>
<td>2.51</td>
<td></td>
</tr>
<tr>
<td>Waterborne</td>
<td>0.91</td>
<td></td>
<td>0.61</td>
<td>2.27</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Powder Coat</td>
<td></td>
<td>0.2</td>
<td></td>
<td>?</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td><strong>Plastic</strong></td>
<td></td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Solids</td>
<td></td>
<td></td>
<td>1.13</td>
<td>3.9</td>
<td>2.51</td>
<td></td>
</tr>
<tr>
<td>Waterborne</td>
<td>0.91</td>
<td></td>
<td>0.61</td>
<td>2.42</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Powder Coat</td>
<td></td>
<td>0.2</td>
<td></td>
<td>?</td>
<td>0.57</td>
<td></td>
</tr>
</tbody>
</table>
VOCs are largely emitted during the application and the drying & curing stages after application of each coating of paint on to the automobile. Sources of VOC emissions during the automotive painting process include cleaning and purging solvents, sealing, electrocoating, primer-surfacing, basecoating, and clearcoating. There are essentially two exhaust streams in the paint shop: the low-volume oven exhaust, which is very concentrated and occurs at high temperatures, and the high-volume spray booth/flash-off exhaust, which is the major source of paint line exhaust air due to the magnitude of the exhaust volume circulating in the spray booths.

There are many ways to reduce VOC emissions in the painting operation. The first and most obvious way is to switch to low or zero-VOC coatings. Unfortunately, these coatings very often do not meet the performance standards required. A second option is to make VOC reduction more effective at the source. This is accomplished by making changes in the paint line design such as booth redesign to reduce the exhaust volume, air recirculation which partially recycles back the exhaust air from a zone, or air cascading where exhaust air from one zone is reused as supply air for an adjacent zone. These approaches reduce the volume of exhaust air that needs to be treated, and increases the solvent concentration, thus making the VOC treatment more effective and efficient. Another alternative is installing add-on controls. These controls include incineration, filters, and solvent recovery. But at present, these options are limited in terms of expected improvement and require significant capital
investments. Therefore, an approach that would resolve the problem at the source would be to reduce waste in paint usage, which would achieve the multiple purposes of reducing cost, emissions and solid waste.

A first step towards eliminating waste in paint usage is to find out where the VOCs come from and which part of the painting process should be focused on in dealing with this problem. Fig. 6.1 breaks down VOC emissions by source, which are derived using the base case assumptions of a solventborne primer-surfacer, a waterborne basecoat, and a solventborne clearcoat. Fig. 6.2 is an equivalent breakdown with the same assumptions except, in this case, a solventborne basecoat is applied in the painting process. A comparison of the two figures indicate that choosing a waterborne basecoat over the solventborne alternative can result in a significant reduction of VOC emissions.

Figures 6.1 and 6.2 both show that basecoating and clearcoating are the largest sources of VOC emissions in the automotive painting process. In view of this fact, it is important to find out the extent to which VOC emissions can be reduced by taking steps such as increasing transfer efficiencies or decreasing film thicknesses. To accomplish this purpose, sensitivity analyses of VOC emissions to transfer efficiency and film thickness have been completed for the clearcoat and basecoat and are graphed in Figures 6.3 to 6.6.

Figures 6.3 and 6.4 show how the amount of VOCs emitted per car painted varies with changes in the transfer efficiency and film thickness of the clearcoat respectively. Both figures indicate that VOC emissions are more
sensitive to changes in the transfer efficiency and film thickness of the solventborne clearcoat than of the powder clearcoat. This can be attributed to the high solid content of powder coating, which has an inherently low solvent content, and as a result, contributes very little to the emitting of VOCs during the painting process.

Figure 6.5 and 6.6 show the sensitivity analyses of VOC emissions to basecoat transfer efficiency and film thickness respectively. The solventborne basecoat consistently emits more VOCs than the aqueous basecoat, but for the same transfer efficiency or film thickness, the difference between the two alternative coatings in terms of VOCs emitted decreases with increasing transfer efficiency or decreasing film thickness.

At higher transfer efficiencies or lower film thicknesses, the level of VOC emissions tapers off regardless of what type of coating is used. Therefore, improving application methods to increase transfer efficiency and decrease film thickness is an effective approach to reducing VOC emissions. This might be more effective than the present system of modifying paint components to reduce solvent content, which in turn would result in lower VOC emissions as demonstrated by the development and growing use of aqueous and powder coatings.
Fig. 6.1 Sources of VOCs in painting process: waterborne basecoat

Fig. 6.2 Sources of VOCs in painting process: solvent basecoat
Fig. 6.3 Sensitivity Analysis of VOC emissions to clearcoat transfer efficiency

Fig. 6.4 Sensitivity Analysis of VOC emissions to clearcoat film thickness
Fig. 6.5 Sensitivity Analysis of VOC emissions to basecoat transfer efficiency

Fig. 6.6 Sensitivity Analysis of VOC emissions to basecoat film thickness
Alternative strategies to reduce VOCs include developing paint application methods to allow the use of low-VOC coatings without sacrificing performance standards, making changes in paint components, and developing alternative coating methods. A spray application developed by Union Carbide (91005) uses supercritical fluids to replace 50% to 80% of the volatile solvents in existing solventborne coatings. Carbon dioxide and nitrous oxide are attractive supercritical fluids for the spray application of low-VOC coatings because they are environmentally compatible and have good physical properties. Carbon dioxide is preferable due to low cost and wide availability, but nitrous oxide is more environmentally compatible because it decomposes into nitrogen and oxygen, which are normal elements of air. The volatile solvents that are replaced by these supercritical fluids are largely fast-evaporating solvents such as 1,1,1-trichloroethane, an air toxic solvent. More recent developments of this new technology indicate that the coatings appearance and performance actually improve due the superior atomization characteristics of the spray produced by the decompressive release of supercritical carbon dioxide.

Innovative advances has been made by Ciba-Giegy in modifying the pigment surface to increase the interactions between pigment particles and stabilize the dispersion in paint. This will make it easier to achieve lower VOC emissions by decreasing the solvents and increasing the solid content consisting of binder and pigments.
The paint film concept is an alternative coating method that covers metal and plastic parts with a preformed, multilayer film that performs the functions of traditional coatings. Paint films are applied on a line coater, which allows the paint to be applied to a continuously moving carrier web instead of painting each individual odd-shaped part. Painting a flat, flexible, continuously moving surface of low mass would enable the paint to be applied at a high rate from a fixed apparatus and require smaller curing ovens of lower heat capacity. These paint films can be applied in three ways: to a flat substrate which is subsequently formed into its final shape, to a part during molding or other methods of forming, and to a part that is already in its final shape. This approach moves the paint film formation process from parts and assembly plants to a line coater at considerable savings of equipment, cost, and time, as well as a reduction in VOC emissions³⁵.

Automotive manufacturers and suppliers are being pressured into making changes to conventional painting and achieve evidently conflicting purposes due to regulatory requirements to reduce VOC emissions, consumer demand to match the surface quality of Japanese and European cars that are finished with high-VOC finishing systems, and economic pressures to reduce cost so as to remain competitive in the international market. While there has been much progress in reducing VOC emissions, a great deal remains to be done with increasingly stringent regulatory requirements and a more competitive global market in the automotive industry. Continuous efforts to achieve
environmental compliance has become a way of life in finishing facilities and will be for a long time to come. In addition to VOC emissions, paint sludge is another issue of concern that automotive manufacturers must deal with, and we will examine that in detail in the next chapter.
Chapter 7  Waste Treatment in Automotive Painting

During automotive painting, some of the paint material sprayed in a booth lands on the walls, windows, robots, fixtures, floor grates, and other components of the paint booth. Since the primer-surfacer, basecoat, and clearcoat cure only in the oven at higher temperatures, the paint overspray generated becomes a sticky residue in the booth, which is the major source of solid waste in automotive painting.

Paint sludge is generated during the application of sealer, primer-surfacer, basecoat and clearcoat. Fig. 7.1 shows the sources of paint sludge in a painting process where the body-in-white is painted with a solventborne primer-surfacer, a waterborne basecoat, and a solventborne clearcoat. Fig. 7.2 is an equivalent chart except a solventborne basecoat is applied. In both cases, the basecoat is the largest source of paint sludge, which is influenced by transfer efficiency and paint consumption. The waterborne basecoat is a greater source of paint sludge in comparison with the solventborne alternative, which can be attributed to lower transfer efficiency and higher paint consumption. While transfer efficiency is dependent upon the type of paint used and the paint application technology, factors that influence paint consumption include paint film thickness, transfer efficiency, and solid content. Solid content is the percentage of paint solids in the paint, which forms the finish on the vehicle.
Fig. 7.1 Sources of paint sludge in painting process: waterborne basecoat

Fig. 7.2 Sources of paint sludge in painting process: solvent basecoat
Fig. 7.3 Sensitivity Analysis of paint sludge to clearcoat transfer efficiency

Fig. 7.4 Sensitivity Analysis of paint sludge to clearcoat film thickness
Fig. 7.5 Sensitivity Analysis of paint sludge to basecoat transfer efficiency

Fig. 7.6 Sensitivity Analysis of paint sludge to basecoat film thickness
Figures 7.3 to 7.6 graph how the amount of paint sludge generated changes with varying transfer efficiencies and film thicknesses for the clearcoat and basecoat. Under equivalent conditions, the solventborne coating generates less sludge than its aqueous or powder counterparts, but the difference in paint sludge generated diminishes with increasing transfer efficiency or decreasing film thickness. However, while improving application techniques to increase transfer efficiency or decrease film thickness will reduce paint sludge at the source, end-of-the-pipe measures such as recycling and incineration should also be taken into consideration.

Paint sludge and VOC emissions are important environmental concerns in automotive painting. These factors, in addition to costs, must be considered and evaluated in choosing paint technology and application techniques. The next chapter will be an evaluation of alternatives taking different factors such as cost, VOC emissions, and paint sludge into consideration in balancing tradeoffs and choosing feasible alternatives.
Increasing concern for the environment over the last two decades has had a significant impact on manufacturers and users of paints and coatings. This has resulted in the passing and implementation of numerous federal regulations as well as state and local laws, which have been the primary driving force behind the coatings industry's efforts to develop new products, equipment, processes, and chemistry. Sources regulated under these laws are largely categorized into mobile and stationary sources, the latter of which will be focused on in this study\textsuperscript{37}. Stationary sources include industrial facilities that emit pollutants in the refining and manufacturing process, and the paint shop in an automobile assembly plant is a classic example.

The general perception of consumer preference in the industry calls for a Class-A finish on the automobile, which is accomplished by applying an electrocoated primer, followed by a primer-surfacer and a topcoat consisting of a monocoat or a basecoat/clearcoat. To accommodate these preferences, automobile manufacturers have set up painting facilities whose costs account for approximately 50% of the capital equipment costs as well as a considerable share of the air emissions of the entire assembly plant. A major portion of these air pollutants are volatile organic compounds (VOCs), which are thought to be harmful to the earth's ozone layer and have been put under more stringent
controls under the Title VI of the 1990 Clean Air Act Amendments, which addresses the problem of regulating ozone-depleting chemicals\textsuperscript{38}. The paint sludge resulting from overspray and low transfer efficiencies also pose a significant environmental problem. But federal and state environmental regulations are proving to be a strong driving force for industry to come up with innovative ideas to resolve these environmental issues. The permits required to emit pollutants and the penalties imposed for non-compliance increases the costs of making and using products that cause pollution during manufacture and use. As a result, environmentally friendly products that meet environmental regulations are more competitive on the market because they are more attractive to the original equipment manufacturers (OEM) who need to meet these requirements within their facilities\textsuperscript{39}.

**Implementation Plans to Control Environmental Pollution**

Measures have been taken in an attempt to limit pollution. State and federal regulatory agencies have enacted regulations and taken steps to monitor industrial activities that emit pollutants and generate waste. Legislative initiatives addressing environmental concerns have also been implemented on the federal and state levels. These measures include enacting, implementing and enforcing environmental laws, setting up reporting requirements, requiring emission permits, and imposing penalties for non-compliance.
Reporting Requirements

State and federal agencies require companies to keep detailed records and report amounts of chemicals used and emitted to the environment.) This information is used to determine compliance with environmental requirements. Records and reports for the monitoring, usage, inspection, and inventory of hazardous waste, wastewater, and air pollution are kept for this purpose. In the past, records of the purchase and usage of chemicals, production figures, and environmental monitoring data were compiled on an annual basis to prepare the required reports. But today, state and federal regulatory agencies are now establishing new regulations that will require more frequent and detailed records and reports. An example is the Clean Air Act, which was amended in 1990 to require compliance with emissions limits on a daily, and in some cases, an hourly basis. These increasingly stringent and complex requirements have led to the need for companies to improve conventional compliance systems so that they can monitor pollution on an hourly basis40. One example of a complex reporting requirement is the EPA Toxic Chemical Release Inventory (TRI), mandated under Title III of the Superfund Amendments and Reauthorization Act (SARA)41.

Permits

An operating permit is becoming a common requirement in most manufacturing facilities. An example that will seriously affect painting facilities
and coatings manufacturers is the air-emissions permits required by Title V of the Clean Air Act Amendments of 1990 (CAA). These permits are required of all "major" sources of air emissions, which is defined by the severity of the nonattainment problem in the area. Emission thresholds are based on the potential to emit rather than on actual emissions. In addition to paying the mandatory permit fees, manufacturers will have to improve emissions monitoring, inspection, and record-keeping to achieve environmental compliance in the facility. The Environmental Protection Agency has established minimum requirements for state programs, which will be submitted to EPA for approval.

Enforcement

Historically, environmental enforcement starts out as a civil action and evolve into a criminal investigation only if extreme situations are involved. This has changed in that enforcement now starts out criminal and only turns civil if the facts will not support a criminal conviction. As a result, environmental criminal enforcement has increased dramatically in recent years. To meet the increased demand for stepping up enforcement, additional lawyers were hired by the Justice Department to prosecute environmental crimes, and the 1990 Environmental Crimes Prosecution Act required the Environmental Protection Agency increase the number of criminal investigators in the agency.
When violations occur, the regulatory authority must determine the responsible party to prosecute. In many situations corporations are liable for the acts of its employees and can be fined, but the general trend today is to prosecute individuals who are responsible for these violations as well. Individuals can be criminally liable as a result of active participation, negligent supervision, or even general responsibility over a polluting facility. About 33% of federal criminal enforcement action has been against company presidents/owners, 15% against supervisory personnel and 20% against hourly employees\textsuperscript{43}. This trend has made it necessary for management and employees with environmental compliance responsibilities to become more aware of the enforcement of environmental laws.

Many federal environmental acts such as the Clean Air Act, the Clean Water Act, and the Resource Conservation and Recovery Act, provide criminal sanctions for environmental violations. For example, pertinent provisions under the Clean Air Act are willful endangerment and negligent endangerment. These violations are considered criminal and are punishable by fines and imprisonment\textsuperscript{43}.

**Environmental Law Statutes**

Environmental law is almost wholly dominated by federal legislation, much of which affect industry and manufacturing. Federal laws set limits on allowable pollution levels, which are the minimum standards for all states,
which can choose to have stronger pollution controls. In many cases, states develop state implementation plans (SIPs) to effect the general structure outlined in the federal regulations\textsuperscript{37}. These statutes provide a regulatory framework and guide for manufacturers developing environmentally compatible products or building environmentally safe facilities. Most of the relevant federal legislation passed in recent years is summarized below.

**Toxic Substances and Control Act of 1976 (TSCA)**

The Toxic Substances and Control Act permits "cradle to grave" regulation of chemical hazards, giving the Environmental Protection Agency (EPA) broad authority to regulate toxic substances, requiring industry to test chemicals, exercising regulatory control over introduction of new chemicals and instituting wide-reaching recordkeeping and reporting requirements\textsuperscript{44}.

**Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)**

The Comprehensive Environmental Response, Compensation and Liability Act, also known as Superfund, is a comprehensive federal mandate regulating the cleanup of hazardous waste. It provides for a fund, created in part by a tax on oil and chemicals, for reimbursement of costs incurred by Federal and State agencies in the clean-up of hazardous waste sites and releases. Except in the case of an imminent danger to health or the environment, in order
to collect from the fund for immediate removal and longer-term remedial costs, the Federal or State agency must first make a claim against the responsible parties, if known. If the responsible parties are not known or if settlement can not be reached, then a claim can be made against the fund. Generators of hazardous waste releases are liable for damages and responsible parties may be liable for as much as triple the original amount if they fail to comply with Federal cleanup orders\(^45\).

**Solid Waste Disposal Act (SWDA), Resource Recovery Act, and Resource Conservation and Recovery Act (RCRA)**

These environmental statutes deal with the problem of solid wastes. The Solid Waste Disposal Act, enacted in 1965, recognized the growing problem of solid waste disposal and tried to find better ways of disposal through federal leadership and assistance. The Resource Recovery Act shifted the federal emphasis from disposal to resource recovery, recycling of materials and conversion of waste to energy. The Resource Conservation and Recovery Act of 1976 expanded on the earlier legislation and identified another goal: conservation of resources. However, EPA has chosen not to play a leading role in the municipal solid-waste problem, preferring to concentrate on hazardous waste. As a result, efforts to control the solid-waste problem is mostly on the state and local levels\(^46\).
Clean Air Act Amendments of 1990 (CAA)

The Clean Air Act was amended by Congress and signed into law in 1990. These amendments tackles important issues such as attainment, emissions tracking, and integrating the federal permit system into existing state and local pollution permit programs. The law establishes more stringent pollution offsets for stationary sources according to the area classifications made on the basis of the degree to which emissions standards are exceeded. The bill also enacts stricter tailpipe emissions standards for vehicles, regulates toxic air emissions and acid deposition, and sets phase-out schedules for chlorofluorocarbons (CFCs). The Clean Air Act Amendments is the most significant and comprehensive air pollution legislation enacted in history.47

Federal Water Pollution Control Act (FWPCA)

The Federal Water Pollution Control Act, also known as the Clean Water Act, authorizes the EPA to adopt effluent standards. National goals were established which include prohibition of toxic pollutant discharges, achievement of "fishable" and "swimmable" waters by July 1, 1983, and elimination of pollutant discharges by 1985. Pollutants were classified in three categories: toxics, conventionals, or non-conventionals. Industry was required to meet EPA toxic pollutant regulations requiring at least "best available control technology economically available" (BAT). The Clean Water Act also provides effluent
standards as well as specific provisions for monitoring, reporting, recordkeeping, and citizen suits\textsuperscript{45}.

**Superfund Amendment and Reauthorization Act of 1986 (SARA)**

Congress amended CERCLA, the federal hazardous waste clean-up law, more commonly known as the Superfund statute in 1986 with the Superfund Amendment and Reauthorization Act (SARA). During this process, Congress took a significant step toward reducing the likelihood of future hazardous waste contamination by enacting a comprehensive federal right-to-know program under Title III of SARA called the Emergency Planning and Community Right to Know Act (EPCRTKA), implemented by states under EPA guidelines\textsuperscript{7}. Under Section 313 of the EPCRTKA, facilities that store, manufacture, or use toxic substances are required to submit EPA Form R, the Toxic Chemical Release Inventory (TRI) Reporting Form for each toxic chemical manufactured, processed, or otherwise used. Facilities must report the quantities of both routine and accidental releases of listed toxic chemicals, as well as the maximum amount of the listed toxic chemical on-site during the calendar year and the amount contained in wastes transferred off-site\textsuperscript{11}. The EPCRTKA also mandates that most of the information reported must be made available to the general public upon request\textsuperscript{44}.
Pollution Prevention Act of 1990 (PPA)

The Pollution Prevention Act was established in 1990 with the purpose of encouraging businesses to reduce or prevent pollution at the source through cost effective changes in production, operation, and raw materials use. It called for the establishment of source reduction programs nationwide and matching grants to state agencies to set up these programs. Under the PPA, a source reduction clearinghouse was established to compile information on management, technical, and operational approaches to source reduction. Its purpose was to serve as a center for source reduction technology transfer, mount active outreach and education programs to further the adoption of source reduction technologies, and collect and compile information report by states receiving federal grants under this statute, and make information on source reduction available to the public. The PPA also added reporting requirements to Form R detailing the toxic chemical source reduction and recycling of each facility in addition to the information required under Title III of the Superfund Amendment and Reauthorization Act48.

Automotive Painting and the Regulatory Environment

Enforcement of environmental regulations on the federal and state levels have had a significant impact on industries involved in the finishing process and the manufacturing of paints. The following table sums up the ways in which each law affects all aspects of automotive painting..
### Environmental Law Statutes that Impact Automotive Painting

<table>
<thead>
<tr>
<th>Environmental Law Statute / Regulated Element</th>
<th>Air</th>
<th>Land</th>
<th>Water</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxic Substances and Control Act of 1976 (TSCA)</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Solid Waste Disposal Act (SWDA)</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resource Recovery Act</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resource Conservation and Recovery Act (RCRA)</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean Air Act Amendments of 1990 (CAAA)</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal Water Pollution Control Act (FWPCA)</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Superfund Amendment and Reauthorization Act of 1986 (SARA)</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Pollution Prevention Act of 1990</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

The price of environmental compliance includes the costs involved in installing abatement equipment, implementing improved paint and/or application technologies, operating permit fees for the facilities, as well as penalties incurred for non-compliance. These costs have become a significant part of production cost in recent years, and are unavoidably passed on to the consumer. Therefore, escalating environmental costs should be taken into account when generating cost data for automotive painting.

Environmental concerns have had a great impact in pressuring the move towards environmental compliance in industry, and the regulatory environment
is an important driving force behind the development and improvement of new products, equipment, processes, and chemistry. Consequently, regulatory changes have and will continue to have significant impacts on the automotive painting process, and should be incorporated as an externality in our overall analysis of feasible choices in paint technologies.
Chapter 9 Evaluating Alternatives: Choices and Tradeoffs

In today's environmentally conscious society, the objectives of manufacturing are no longer solely focused on cost and efficiency. Environmental factors such as air pollution, water treatment, and solid waste must also be taken into account. Paint technologies being developed today strive to achieve the most advantageous balance of these factors.

Aqueous and powder alternatives to conventional solventborne coatings have been improved to such an extent that they are now cost-effective alternatives for painting automobiles. Options presently available and actually being used in production facilities include solventborne, aqueous, and powder primer-surfacers; solventborne and aqueous basecoats; and solventborne and powder clearcoats. Choosing a different paint technology for each automotive coating presents twelve possible alternatives for automotive painting. An environmental and economic accounting of these alternatives are listed in the table below. This chart lists the types of primer-surfacer, basecoat, and clearcoat used, as well as the costs incurred, VOCs emitted and the paint sludge generated when the alternative is chosen. Each alternative is a balance of tradeoffs between cost, VOC emissions, and paint sludge generation. Improvement in one factor is generally offset by an declination in the others and vice versa.
Environmental and Economic Accounting of Paint Alternatives

<table>
<thead>
<tr>
<th>Alternatives /Paint type</th>
<th>Primer Surfacer</th>
<th>Basecoat</th>
<th>Clearcoat</th>
<th>Cost ($/car)</th>
<th>Emissions (lbs/car)</th>
<th>Paint Sludge (gal/car)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solvent</td>
<td>Solvent</td>
<td>Solvent</td>
<td>$352</td>
<td>9.7</td>
<td>0.64</td>
</tr>
<tr>
<td>2</td>
<td>Solvent</td>
<td>Solvent</td>
<td>Powder</td>
<td>$401</td>
<td>7.8</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>Solvent</td>
<td>Aqueous</td>
<td>Solvent</td>
<td>$358</td>
<td>8.1</td>
<td>1.08</td>
</tr>
<tr>
<td>4</td>
<td>Solvent</td>
<td>Aqueous</td>
<td>Powder</td>
<td>$406</td>
<td>6.1</td>
<td>1.36</td>
</tr>
<tr>
<td>5</td>
<td>Aqueous</td>
<td>Solvent</td>
<td>Solvent</td>
<td>$351</td>
<td>9.2</td>
<td>0.77</td>
</tr>
<tr>
<td>6</td>
<td>Aqueous</td>
<td>Solvent</td>
<td>Powder</td>
<td>$399</td>
<td>7.2</td>
<td>1.05</td>
</tr>
<tr>
<td>7</td>
<td>Aqueous</td>
<td>Aqueous</td>
<td>Solvent</td>
<td>$356</td>
<td>7.6</td>
<td>1.21</td>
</tr>
<tr>
<td>8</td>
<td>Aqueous</td>
<td>Aqueous</td>
<td>Powder</td>
<td>$405</td>
<td>5.6</td>
<td>1.49</td>
</tr>
<tr>
<td>9</td>
<td>Powder</td>
<td>Solvent</td>
<td>Solvent</td>
<td>$392</td>
<td>8.8</td>
<td>0.61</td>
</tr>
<tr>
<td>10</td>
<td>Powder</td>
<td>Solvent</td>
<td>Powder</td>
<td>$441</td>
<td>6.8</td>
<td>0.89</td>
</tr>
<tr>
<td>11</td>
<td>Powder</td>
<td>Aqueous</td>
<td>Solvent</td>
<td>$398</td>
<td>7.2</td>
<td>1.05</td>
</tr>
<tr>
<td>12</td>
<td>Powder</td>
<td>Aqueous</td>
<td>Powder</td>
<td>$446</td>
<td>5.2</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Alternatives 1 and 12 are the extreme alternatives in this table. In comparison with other alternatives, alternative 1 incurs a relatively low cost, emits the highest level of VOCs, and generates a comparatively low amount of paint sludge. On the other hand, alternative 12 incurs the highest cost, emits a relatively low level of VOCs, and generates a comparatively high amount of paint sludge. Fig. 8.1 shows that a strong correlation exists between costs and VOC emissions for the paint alternatives, while there is very little or no correlation between costs and paint sludge, as graphed in Fig. 8.2. This can be attributed to the fact that recent improvements in paint technology such as aqueous and powder coatings have focused on the reduction of VOC emissions to meet the increasingly stringent regulatory requirements on air emissions at
the federal and state levels, even at the expense of increasing the generation of paint sludge in many cases. This explains the inverse correlation between VOC emissions and paint sludge generation, which is plotted on Fig. 8.3.

None of the intermediate alternatives are dominated by another; since differences in one factor are offset by others. Therefore, each alternative may be the best alternative depending on the circumstances and the order of priority in reducing cost, VOCs, or paint sludge in the automotive painting process. A choice of technologies allows the decision maker to choose the alternative that offers the most in terms of the improving economic and environmental factors as judged to be necessary in each unique situation.

Fig. 8.1 Correlation between Painting Cost and VOC Emissions

92
Fig. 8.2 Correlation Between Painting Cost and Paint Sludge Generated

Fig. 8.3 Correlation between VOC Emissions and Paint Sludge Generated
The following table lists possible approaches to reducing costs, VOC emissions, and paint sludge. These are achieved by making changes in paint technology, color, transfer efficiency, and film thickness. In most cases these changes result in reductions in cost, VOCs, and paint sludge. Switching from conventional solvent paint technology to aqueous or powder coatings reduces VOC emissions, but generally increases cost and paint sludge.

**Approaches to Reducing Costs and Pollution**

<table>
<thead>
<tr>
<th>Changes/Affected Parameters</th>
<th>Reduction in cost ($/car)</th>
<th>Reduction in VOC Emissions (lbs/car)</th>
<th>Reduction in Paint Sludge (gal/car)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Primer-Surfacer Paint Technology Solvent Coatings ----&gt; Aqueous Coatings</td>
<td>$1.40</td>
<td>0.52</td>
<td>(-0.13)</td>
</tr>
<tr>
<td>Change in Primer-Surfacer Paint Technology Solvent Coatings ----&gt; Powder Coatings</td>
<td>(-$40.26)</td>
<td>0.92</td>
<td>0.04</td>
</tr>
<tr>
<td>Change in Basecoat Paint Technology Solvent Coatings ----&gt; Aqueous Coatings</td>
<td>(-$5.70)</td>
<td>1.62</td>
<td>(-0.44)</td>
</tr>
<tr>
<td>Change in Clearcoat Paint Technology Solvent Coatings ----&gt; Powder Coatings</td>
<td>(-$48.56)</td>
<td>1.95</td>
<td>(-0.28)</td>
</tr>
<tr>
<td>Change in Basecoat Color Red ----&gt; Black</td>
<td>$30.80</td>
<td>1.56</td>
<td>0.58</td>
</tr>
<tr>
<td>Change in Basecoat Transfer Efficiency 50% ----&gt; 100%</td>
<td>$35.23</td>
<td>1.14</td>
<td>0.8</td>
</tr>
<tr>
<td>Change in Clearcoat Transfer Efficiency 80% ----&gt; 100%</td>
<td>$18.89</td>
<td>0.5</td>
<td>0.12</td>
</tr>
<tr>
<td>Change in Basecoat Film Thickness 1.0 mil ----&gt; 0.5 mil</td>
<td>$31.99</td>
<td>1.14</td>
<td>0.4</td>
</tr>
<tr>
<td>Change in Clearcoat Film Thickness 2.5mil ----&gt; 1.0 mil</td>
<td>$54.35</td>
<td>1.51</td>
<td>0.07</td>
</tr>
<tr>
<td>Change in Clearcoat Film Thickness 2.5mil ----&gt; 0.5 mil</td>
<td>$72.49</td>
<td>2.01</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The color of an automobile plays an important role in determining how polluting the process of painting a body-in-white will be. In this study, data has been collected on basecoats in three colors, red, white, and black and the properties distinctive to each color are listed in the table below.

Properties of Color Basecoats

<table>
<thead>
<tr>
<th>Color/Properties</th>
<th>Paint Consumption (gal/car)</th>
<th>Transfer Efficiency (%)</th>
<th>Film Thickness (mils)</th>
<th>Solids Content (% volume)</th>
<th>VOC Content (lbs/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>1.6</td>
<td>50%</td>
<td>1</td>
<td>16%</td>
<td>1.4</td>
</tr>
<tr>
<td>White</td>
<td>0.7</td>
<td>55%</td>
<td>1.2</td>
<td>37%</td>
<td>1.8</td>
</tr>
<tr>
<td>Black</td>
<td>0.5</td>
<td>55%</td>
<td>0.6</td>
<td>28%</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The following table lists the costs, VOC emissions, and paint sludge for basecoats of these colors. It indicates that painting a car red incurs the greatest cost and generates the most VOC emissions and paint sludge during the painting process while the black basecoat is the least expensive and has the least environmental impact. While the color of an automobile is largely determined by consumer preference, it is necessary and useful to know the dissimilarities between different colors beyond its exterior appearance. The consumer may be persuaded to choose environmentally friendly colors for their cars if they are made aware of the differences. Another strategy might be to change the present practice of pricing cars only on the basis of vehicle model so that the price tag reflects the cost and environmental difference of painting vehicles in different colors.
VOC Emissions and Paint Sludge of Waterborne Basecoats

<table>
<thead>
<tr>
<th>Waterborne Basecoat Color</th>
<th>Basecoat Cost ($/car)</th>
<th>VOC Emissions (lbs/car)</th>
<th>Paint Sludge (gal/car)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>$91.78</td>
<td>2.27</td>
<td>0.8</td>
</tr>
<tr>
<td>White</td>
<td>$88.51</td>
<td>1</td>
<td>0.32</td>
</tr>
<tr>
<td>Black</td>
<td>$61.19</td>
<td>0.71</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Conclusions

There are two reasons for painting an automobile: to achieve a pleasing appearance and to protect the underlying panels from the harsh environment. However, the automotive painting process has great potential to cause adverse environmental impacts, and industry has been looking into ways to modify the paint chemistry and the application techniques so as to reduce the potential environmental damage while maintaining a consistent quality of finish in a cost-effective manner.

Present approaches towards improving paint technology has provided two alternatives to the conventional high-solid solventborne coatings, namely aqueous and powder coatings. Figures 8.4 to 8.6 plot the correlation between attributes of paint alternatives in ascending order of cost, VOC emissions, and paint sludge respectively. These graphs indicate the general trends of increases in cost and paint sludge generation with reductions in VOC emissions and vice versa. They also show a lack of correlation between costs and paint sludge. These plots point to the fact that the driving forces behind today's technological innovations in automotive painting are the environmental regulations industry is
required to comply with. For example, the Clean Air Act Amendments (CAAA) enact strong enforcement powers and imposes harsh penalties while laws that have been established to regulate the treatment and disposal of solid waste and water are comparatively more lenient. As a result, industry has responded actively to reducing VOCs by developing and improving paint technologies to achieve that objective while showing a relative apathy in resolving the issue of paint sludge abatement.

The problem of solid waste has not been dealt with as vigorously as the air emissions issue. The position industry has taken can be attributed to the fact that solid waste and landfills are not considered to be particularly urgent problems in North America, especially in comparison with the air emissions issue. However, in view of the strong influence of regulatory action on technological progress, the focus of industrial efforts will almost certainly shift to include paint sludge abatement if laws such as the Solid Waste Disposal Act (SWDA) and the Resource Conservation and Recovery Act (RCRA) start implementing stricter standards and imposing penalties comparable to laws regulating air emissions. And, as regulatory agencies begin to perceive the gravity of solid waste and landfill problems, the scope of environmental legislation will expand further to include implementation of more stringent measures regulating solid waste, which in turn will pressure industry into developing and improving paint technologies that will attain the dual objectives of reducing VOC emissions and paint sludge.
Fig. 8.4 Correlation Between Attributes of Paint Alternatives Ordered By Cost of Automotive Painting

Fig. 8.5 Correlation Between Attributes of Paint Alternatives Ordered By VOCs Emitted During Automotive Painting
Fig. 8.6 Correlation Between Attributes of Paint Alternatives Ordered By Paint Sludge Generated During Automotive Painting

The table below summarizes the pros and cons of each paint technology and how their relative capabilities in each aspect. Comparisons are made between different paint technologies with respect to these characteristics. This table indicates that there is a great deal of potential for improvement in many areas, including the transfer efficiency and film thickness of the powder clearcoat, solid content of aqueous coatings, and reducing the VOC content in paints. These steps, which require improvements in application techniques and paint chemistry, will accomplish the purpose of reducing VOC emissions and paint sludge. The question is if these goals can be accomplished in a cost-effective manner.
Pros and Cons of Choosing Different Paint Technologies

<table>
<thead>
<tr>
<th>Characteristics/Paint Technology</th>
<th>Solventborne</th>
<th>Aqueous</th>
<th>Powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basecoat Transfer Efficiency</td>
<td>+</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Clearcoat Transfer Efficiency</td>
<td>+</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Film Thickness (mils)</td>
<td>+</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Solids Content (% volume)</td>
<td>+</td>
<td>--</td>
<td>++</td>
</tr>
<tr>
<td>VOC Content (lbs/gal)</td>
<td>--</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Cost Savings ($/car)</td>
<td>+</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Reduction of VOC Emissions (lbs/car)</td>
<td>--</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Reduction of Paint Sludge (gal/car)</td>
<td>+</td>
<td>--</td>
<td>-</td>
</tr>
</tbody>
</table>

++: Excellent, +: Good, -: Mediocre, --: Inferior

Seeking a feasible alternative in automotive painting calls for modifying the conventional process to reduce pollution in a cost-effective manner. From an industrial standpoint, this can be achieved by switching to alternative paint technologies, modifying paint chemistry, or working on improving paint application techniques to improve transfer efficiency or reduce paint film thickness. From a market viewpoint, however, the consumer should be educated about the environmental impacts of painting alternatives so that the customer will make an informed choice when purchasing a vehicle. Also, the escalating costs of environmental compliance, hazardous waste permits, and non-compliance penalties will make conversion to improved and more environmentally friendly technologies necessary to stay competitive in the global market.
Future Work

In this study, the MSL automotive painting cost model was used to generate figures for the costs, VOC emissions, and paint sludge during the automotive painting process. This data is used to evaluate the feasibility of choosing between different alternatives and making tradeoffs.

Ideally, decisions and choices should be made based on available information, which in this case, are costs, VOC emissions, and paint sludge. However, this poses a dilemma for the decision maker. Valuation is an approach towards solving a multi-objective problem by arriving at a singular measure of performance\(^4\). The difficulty lies in determining the importance of each attribute relative to the others. These attributes are heavily dependent on the decisionmaker's perception of values and other external factors which are constantly changing. It would be difficult to set up a rigid system of valuation that would meet universal needs.

Methods of valuation that would come up with a "right" answer are subject to contention among different interest groups and require extensive modifications to keep up with changes. These methodologies can be divided into two categories: transformation and value measurement. Transformation involves translating objectives into a single common measure, which is usually money, a criterion that affects many important decisions. An example is the Swedish Environmental Priority Strategies (EPS), which attempts to monetize negative impacts on human health and the environment. Valuations are made by
assigning a value to a change in the environment and estimating which contribution a certain resource depletion, emission, or other activity gives to this value of the change in the environment. These impacts are valued on a relative scale in Environmental Load Units (ELU) according to the willingness to pay to avoid negative effects on human health and the environment\textsuperscript{50}. This method has the advantage of facilitating comparisons among attributes by monetizing environmental effects. However, it does have its drawbacks of being difficult to evaluate due to many factors, one of which is a lack of complete information regarding politics, the economy and the environment.

Value measurements rank the relative preference of sets of decision consequence. A method that evaluates decisions based entirely on preferences among attributes is multiattribute utility analysis. Attributes are weighted with respect to each other to determine an overall utility function, which is used to make decisions such as choosing technological alternatives by inputting measurable properties of these alternatives to calculate overall utility\textsuperscript{51}. However, the disadvantages of this approach are the difficulties in achieving consensus in groups and dealing with the varying preferences of individuals\textsuperscript{52}.

A less contentious approach might be a valuation system that provides general guidelines that the decision maker might adapt to specific situations and priorities. For example, a country with a landfill shortage might view the paint sludge problem to be as important, or not more, than the issue of reducing VOC emissions. This methodology can be used to determine viable alternatives in
automotive painting, and can also be utilized on a more comprehensive scale to analyze diverse attributes of automobile production as part of a lifecycle analysis. Developing such a methodology is a logical next step in following up on this study.

In the present day, industries bear additional responsibilities in that the goals to be achieved have been expanded beyond the financial aspect to include environmental, social, and other concerns. Today's manufacturers must not strive only to achieve monetary gains, but must also fulfill their obligations in protecting the environment.
References:

5. Lasko, T., Plant Description, General Motors Corporation, Orion Assembly Center.