NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 392

Pavement Marking Materials: Assessing Environment-Friendly Performance

Transportation Research Board
National Research Council

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Pavement Marking Materials: Assessing Environment-Friendly Performance

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report describes the development of a semiquantitative process for measuring the engineering performance; the environmental performance, including the impact of volatile organic compounds (VOCs); and the health concerns, including an evaluation of the hazardous air pollutants (HAPs), of various classes of conventional pavement marking materials used for highway stripes. The report is especially timely because the United States Environmental Protection Agency (U.S. EPA) is expected to regulate the permissible amounts of VOCs in paints and coatings as early as January 1998. This regulation might proscribe the use of most presently available solvent-borne paints and some water-based paints. Prior to this research, information concerning VOCs and HAPs was not readily available to state departments of transportation (DOTs). The contents of this report are, therefore, of immediate interest not only to highway materials and maintenance personnel, but also to state and local government management and policymakers, environmental personnel, and those concerned about environmental and health law.

The Research Triangle Institute was awarded NCHRP Project 4-22, *Pavement Marking Materials: Health, Environmental and Performance Assessment,* to develop a pavement marking materials-selection methodology that would compile, evaluate, and quantify the benefits and liabilities of VOC-compliant materials, the hazards they may cause to workers and the environment, and their engineering performance. The research evaluated the most common categories of commercially available pavement marking materials used in the United States. These materials include (1) solvent-borne paints; (2) water-based paints; (3) thermoplastic markings; (4) tapes; (5) raised pavement markers installed using an adhesive; and (6) several field-reactive marking systems.

Using the process developed in this report, DOT personnel can investigate each pavement marking system under consideration by subjecting it to an objective test of selection criteria based on conventional factors such as retroreflectivity, durability, and cost, as well as criteria based on environmental compatibility. The report describes key characteristics of marking systems which, based on reliable data generated in the geographic area of interest, can be measured, estimated, or rated in some manner. By assigning user-determined weights to these characteristics, DOTs are able to select a marking system to fit the requirements of specific locations, usage, and other DOT-determined constraints. The tables and templates developed in this study allow the DOT to calculate the engineering, environmental, and health parameters of interest using linear combinations of these user-weighted values. This methodology, using data and weights based on local experience, should produce an accurate ranking of alternative pavement marking systems. For those DOTs that do not have an adequate database of pavement marking material performance, the report has included default data developed from regional testing programs of the Southeastern Association of State Highway and Transportation Officials and the Northeastern Association of State Highway and Transportation Officials.

The National Cooperative Highway Research Program is developing a software package to assist users in applying this technology without the manual computations currently required by this methodology.

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ACKNOWLEDGMENTS

The research reported here was carried out under NCHRP Project 4-22 by the Division of Chemistry and Life Sciences, Research Triangle Institute, Research Triangle Park, North Carolina. Dr. Anthony L. Andrady was the Principal Investigator on the project, and Ms. Song Ye carried out the compilation of chemical data and performance information on marking materials. The Institute research staff in the Center for Survey Methods Research, the Center for Environmental Analysis and the Division of Analytical and Chemical Sciences contributed to the research described in this report. Consultant Ken Agent (Kentucky Transportation Center) also provided guidance and information in support of this effort.

The author and the Institute wish to acknowledge the cooperation of and encouragement from numerous professional employees in various departments of transportation in different states and jurisdictions who promptly responded to the survey as well as to additional requests for information. This effort would not have been entirely successful if not for the cooperation of the numerous manufacturers of pavement marking materials who were contacted during the course of this study. Their generosity in sharing nonproprietary details of the chemical composition of the marking materials and in-house information on their performance was crucial to the success of this research effort. Finally, the author would like to thank the NCHRP Program Officer, Lloyd Crowther, for his guidance and support throughout this research effort.

PAVEMENT MARKING MATERIALS: ASSESSING ENVIRONMENT-FRIENDLY PERFORMANCE

SUMMARY

Selection of pavement marking materials used in highway delineation is generally made on the basis of conventional considerations of retroreflectivity, durability, and cost. While these are valid measures of their performance, additional factors will have to be taken into account when such selections are made in the future. The United States Environmental Protection Agency (U.S. EPA) is expected to regulate the permissible amounts of volatile organic compounds (VOCs) in paints and coatings as early as January 1998. The Draft Rule currently under review limits the VOC content of traffic paints at 150 g/L (1.26 lb/gal). This limit will preclude the use of most presently available solvent-borne paints and some of the water-based paints as well. The design of compliant paints, particularly as water-based formulations, is feasible. This VOC limit is likely to be revised in the future to an even lower value, making the strategy of switching to marginally compliant systems to be of limited value. A second consideration is the potential hazard posed by volatile constituents or hazardous air pollutants (HAPs) in the formulation to striping crews (and even motorists) routinely exposed to them. The U.S. EPA intends to regulate the HAP content of paints and coatings at a future date. Given these developments, the selection of marking materials should consider not only the conventional engineering performance (inclusive of cost) but also the environmental performance of marking materials. This latter category includes the VOC content relative to regulatory limits, the potential health impacts via inhalation exposure to marking materials, and other safety factors of concern.

A survey of user agencies carried out as a part of this project showed paints to be the single-largest category (an estimated 78 percent) of markings for longitudinal lines on U.S. roadways. A switch from solvent-borne paints to water-based paints will reduce the annual VOC emissions by 50 to 90 percent depending on the specific paints used. On the basis of collected data, the annual VOC emissions from both types of paints from only a single centerline in marked highways nationwide was conservatively estimated to be about 40 million pounds. A breakdown by state was studied but, no strong regional patterns were found. Most other types of markings are expected to have a negligible VOC content associated with them. Tapes that are adhered to the pavement use VOC-containing adhesives, and some of the solvent-borne types may not be permitted

under the U.S. EPA regulations. The low-VOC primers typically have about half the VOC content of water-based paints.

Measures of toxicity are based on the volume of air needed to dilute a unit weight of the marking material to a level where the concentration of volatiles will be at the threshold level. At this air concentration, routine exposure of workers to the HAPs is expected to have no serious health effects. Using this measure, solvent-borne paints were found to present the highest potential hazard of any class of marking material, with water-based paints only slightly lower in efficacy. However, the lack of reliable field data on the kinetics of evolution of the volatile components from the stripe, their air concentration while applying the marking, and their distribution around marking vehicles was a serious drawback in this study. No reliable estimates of inhalation-related damage are possible without this crucial information.

In this project, the researchers have examined the different classes of conventional pavement marking materials used in continuous stripes in an effort to develop semiquantitative measures of both their engineering performance and environmental performance. The performance of each type of material based on six measures of engineering attributes related to visibility, durability, ease of use, and lifetime cost was established. For the same types of markings, the environmental performance was established using the attributes of VOC content, toxicity and safety. The semiquantitative estimates were expressed in terms of the common unit of utility to obtain two parameters, $U_{engineering\ (eng)}$ and $U_{environmental\ (env)}$, for each type of marking material. In obtaining these, a specific set of weights was assumed to take into account the differences in the relative importance of these various attributes to the overall engineering or environmental performance. The researchers proposed reasonable utility functions to convert test data on key marking properties into values of utility while allowing the user the flexibility of adopting different functions and weights. This is important in that weights and utility functions should reflect the priorities and constraints relevant to individual jurisdictions (and thus should not be generalized). The two parameters plotted on a two-way grid allow the user to compare a given marking with others in terms of overall performance.

This methodology requires a reliable set of data generated in the locale of interest. The researchers illustrated the methodology using data from the Southeastern Association of State Highway and Transportation Officials (SASHTO) and the Northeastern Association of State Highway and Transportation Officials (NASHTO) Regional Testing Programs and the set of weights proposed for this project. Subject to the assumptions and the validity of the data set employed, four classes of pavement marking materials were identified as yielding superior overall performance taking into account the environmental as well as conventional considerations. These are listed in no particular order as follows: thermoplastics, polyester, preformed thermoplastics, and epoxy systems. Under testing conditions different from those employed in the SASHTO and NASHTO exposures, the present methodology may indicate different candidates to rank highly.

CHAPTER 1

INTRODUCTION

The effective and safe use of roadways by the public, particularly drivers, requires delineation of the pavements clearly indicating the different operating areas under a variety of use conditions. These include wet-night conditions, which are particularly important to older drivers. Delineation with markings is specially important in nighttime driving when other visual guides might be of limited value. Computed on a mileage basis, the accident rate at nighttime is about three times that associated with daytime driving (*1*). Pavement markings represent the most used and most cost-effective means of delineation when used alone or as supplements to other devices (*2*). These markings, used since the 1920s, are now recommended on all pavements wider than 3.9 m. Conventional markings primarily act as visual guides (*3*) but visual/tactile pavement markings are also used and benefit visually impaired (*4–6*) and older drivers. As might be expected, the driver's visual capabilities deteriorate with age (*7*), and consequently the perception-reaction time continuously increases (*8*). With older (or otherwise impaired) drivers, high-performance pavement markings might be needed to achieve the same level of safety (*9*). Anticipated benefits of channelization and centerlines in terms of safer driving patterns have been clearly established (*10–12*). In a 1978 study, the percentage of reduction in accidents attributed to the presence of centerlines alone was estimated to be about 29 percent for U.S. roadways (*13*). A benefit-cost analysis of the practice of lane marking was recently reported by Miller (*14*). Standards relevant to roadway delineation are presented in detail in the *Manual of Uniform Traffic Control Devices* (MUTCD; Revision 3, 1993), and delineation practices were recently discussed in the *Roadway Delineation Practices Handbook* (*15*).

In 1993 the annual expenditure for maintaining marking programs for the nearly 795,000 mi of U.S. roadways was estimated at about \$353 million (*16*). A majority of the markings were paints, particularly solvent-borne types. A 1993 study (*17*) estimated that 35 percent of jurisdictions responding to the survey use solvent-borne paints for center lines, edge lines and channelization on new asphalt pavements for high-volume traffic conditions. The corresponding figure for open-graded asphalt pavements was 69 percent. With newer pavements, thermoplastic and tape markings were also used by 20 to 25 percent of responding states. With Portland cement concrete (PCC) pavements, the corresponding percentages were 48 and 62 percent for pavements in good and poor conditions, respectively. The predominance of solvent-borne paints is even more pronounced in the data for low-volume roads reported in the same study. A 1993 survey found 62 percent of the pavement marking funds nationwide was spent on bead and paint systems. Not surprisingly, the annual use of traffic paints in the United States in 1988 was reported to be about 37 million gal (*18*).

The predominant use of solvent-borne paint as a marking material is not limited to the United States. The researchers found several countries also use a high percentage of solvent-borne paints, among them Australia (over 90%), Germany (75%) and Norway (60%). Interestingly, however, other countries such as the United Kingdom (1.5%) or Sweden (< 1%) use insignificant amounts of these paints. Most of their pavement markings are based on thermoplastics. The percentage of thermoplastic use was particularly high in Argentina (80%), United Kingdom (94%) and Sweden (98%). Of the eight countries studied, none with the exception of the United States used a marking material other than solvent-borne paints and/or thermoplastics to any significant (> 5%) extent.

With the recent trend to moving away from marking materials containing volatile organic compounds (VOCs), it is interesting to determine the present usage patterns of marking materials in the nation. Volatile organic compounds are regulated under the Clean Air Act Amendments (CAAA) of 1990 and include compounds that lead to an increase in trophosperic ozone and smog. User agencies across the United States were surveyed in 1995 in to obtain this information. The initial survey (Appendix A) had a response rate of 81 percent; the researchers later contacted most of the non-respondees to get answers to specific questions on the types of marking materials in use. A key question was on the percentage breakdown of pavement marking materials presently used in each jurisdiction. The format of the question required the numerical percentages provided by the respondees to add up to 100 percent to improve the reliability of the information gathered. The simplest means of analysis of data collected in such a survey is on the basis of frequency of responses, an approach successfully used in a 1993 study (*17*). A drawback to this approach, however, is that it does not take into account the wide variation in road miles available in different jurisdictions. A weight is needed to adjust the data to reflect the road miles marked; for instance, about 6,000 mi in Rhode Island as opposed to nearly 300,000 mi in Texas. A weight based on the total mileage of roads (excluding the very small roads) in the jurisdiction was, therefore, used to adjust the data.

The adjusted data in Figure 1 show both water-based and solvent-borne paints to be the dominant marking materials for longitudinal lines. Thermoplastic was the only other material used to a significant extent. For transverse lines and markings, thermoplastics was the most popular choice; water-based paints, solvent-borne paints, and tape also were used to a significant extent. While the present data cannot be directly compared with that reported in 1993 by Clark et al. (*17*), a reasonable qualitative observation is the decreased use of solvent-borne paints in the more recent survey. Solvent-borne paints generally contain 20 to 30 percent by weight of organic solvent that volatilize into the environment during the drying process. Most of these are classified as VOCs by the CAAA, and their use will be regulated in the near future. Impending restrictions on the use of high-VOC formulations by the U.S. EPA have apparently encouraged this trend in the recent years. While the water-based paints have benefited from this trend away from conventional (solvent-borne) paints, thermoplastic marking systems are also likely to capture a substantial market share. In spite of their higher cost relative to both polyester and epoxy, thermoplastics ranked high in usage for longitudinal line applications. Figure 2 shows the 1995 U.S. usage levels of solvent-borne, pavement marking formulations by jurisdiction. A substantial number of jurisdictions continue to use conventional solvent-borne paints at this time. In view of the cost advantage of paints relative to more durable substitutes (such as thermoplastics, polyester, epoxy, methyl methacrylate resin, tapes and raised pavement markings), this is not surprising. Driven by regulatory pressure, however, these jurisdictions are currently considering other options or are changing over to more environmentally acceptable marking systems.

A second issue addressed in the survey was the ease of application and removal of a stripe. Paints—both water based and solvent borne—were rated by users in the present survey as being the easiest to apply; thermoplastics and tape rated about twice more difficult to use than paints. As expected, two-part systems that require mixing at the site, such as polyesters, were rated as being even more difficult to apply. Often, existing stripes have to be removed in response

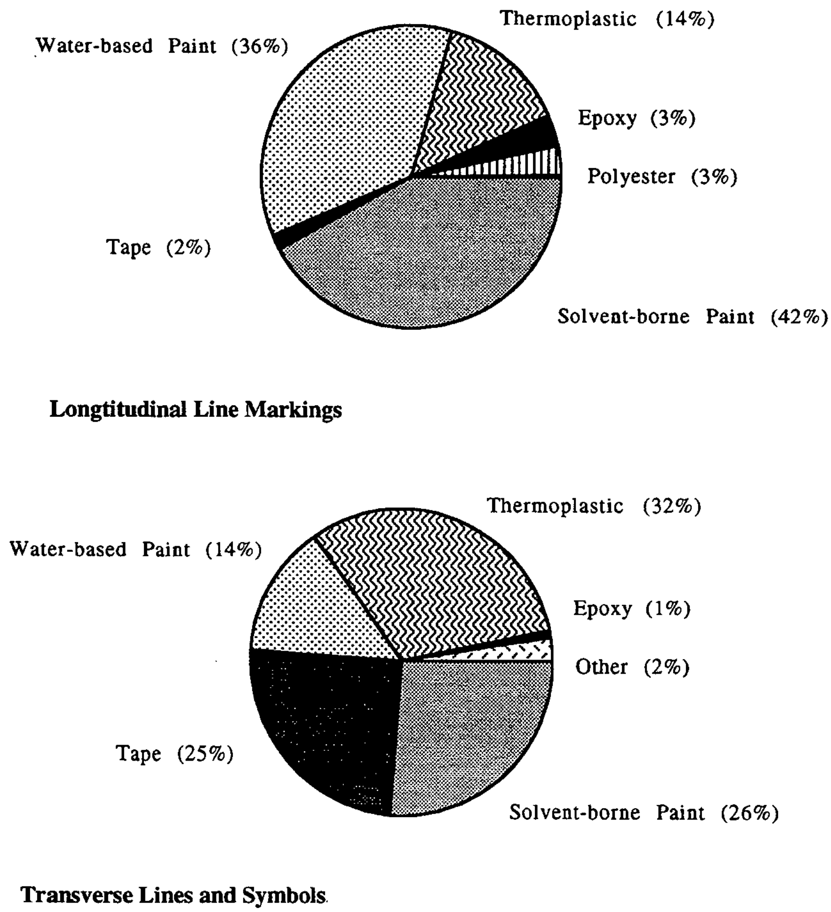

Figure 1. Use of different pavement marking materials in the United States in 1995 (from NCHRP Project 4-22 survey).

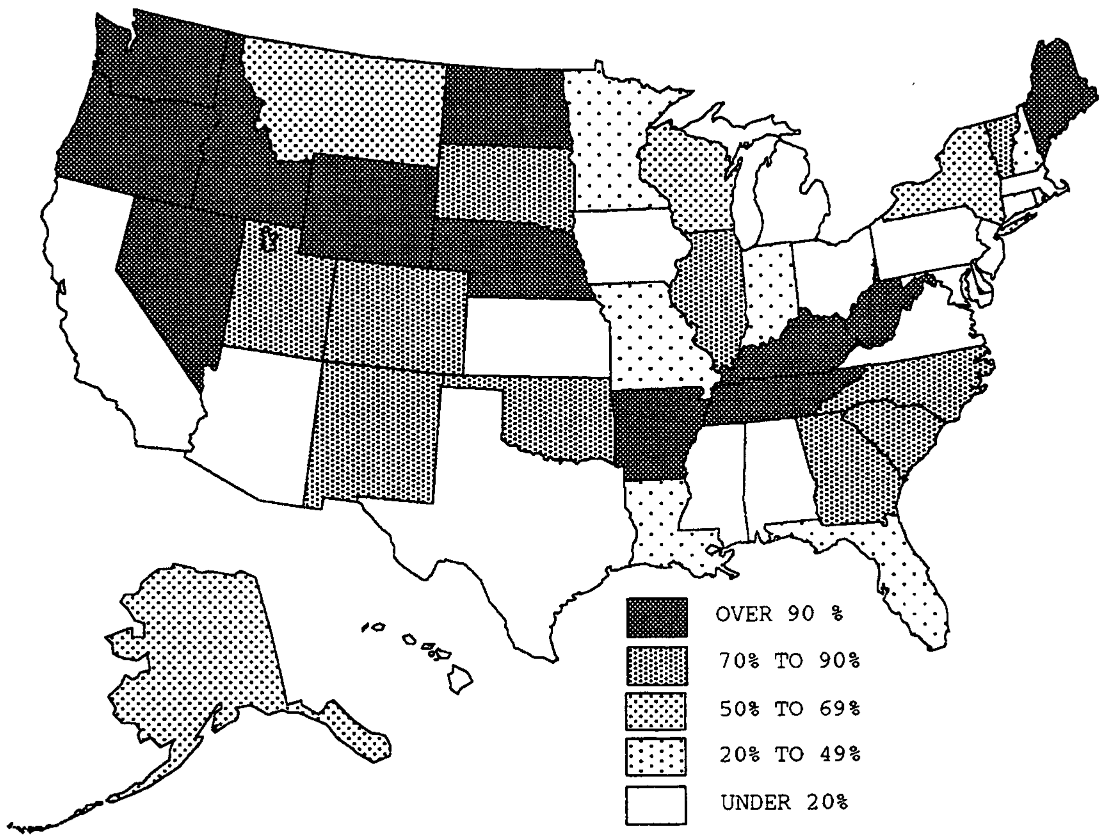

Figure 2. Solvent-borne paint use in the United States in 1995.

to changes in highway traffic routing. This is generally achieved by chemical methods, grinding or sandblasting, high-pressure water jet, or high-temperature burning of the marking (*19*). Removal of paints is expected to be much easier than that of durable markings, an expectation consistent with the findings of the survey. Of interest, however, is the perceived ease of removal of water-based coatings relative to solvent-borne coatings; the latter were rated as being about 50 percent more difficult to remove.

SELECTING PAVEMENT MARKING MATERIALS

In the selection of pavement markings, certain factors such as agency experiences and vendor influences may prejudice the user against certain marking materials. Therefore, an objective set of criteria is of obvious benefit. The FHWA in 1983 encouraged the development of such criteria presently used in many state agencies (e.g., Tennessee, Kentucky, Colorado, and Ohio). The selection is based on the type of road, its average daily traffic (ADT), and surface condition, as well as the expertise, vendors, and facilities available to the agency. The engineering performance, including the lifetime cost of the marking system, invariably guides the selection process. However, with increasing awareness of the environmental and health impacts of marking materials (to the user as well as to the general public) the selection process now has to address these additional concerns. These factors will be collectively referred to as the "environmental performance" of the marking material.

Engineering Performance

The engineering performance of a marking system refers to its initial retroreflectivity, its ability to retain an acceptable level of reflectivity throughout its lifetime, and the durability of the stripe. The cost of a marking system, while not an engineering consideration, is an important criterion and will be discussed under the same category of attributes. Information on the engineering performance of different marking materials can be obtained from several sources, including the NASHTO *Regional Testing Program, Evaluation of Pavement Marking Materials* (September 1993) and the SASHTO

Regional Testing Program, Summary of Results of 1993 (published in August 1994).

Retroreflectivity

Retroreflectivity is perhaps the single-most important quality of a pavement marking. Retroreflection is the redirection of light from automobile head lamps striking the marking surface directly back to the source of light. The beam is retroreflected and scattered toward the vehicle, enabling the driver to see the marking clearly at night. Retroreflectivity under wet conditions is particularly critical as adequate values measured on a dry pavement do not necessarily imply adequate performance under wet conditions (*20*). Assuming favorable dry driving conditions, several studies indicate a minimum retroreflectivity of a 100 millicandelas per lux per sq m (*21–24*) to be an adequate retroreflectivity rating. Daytime visibility is less important but can be easily achieved in asphalt pavements because of the high contrast (ratio of luminance) between the stripe and the background pavement. Restriping because of loss in visibility in spite of adequate retroreflectivity is a possibility. Establishing daytime visibility ideally requires an additional measurement of photometric contrast.

Durability

Durability is the second-most important consideration in selecting a marking material. Durability is generally understood in terms of the "service life" of the marking or the duration from the time the stripe is applied to the time it has to be reapplied. For painted stripes, most agencies consider 6 to 12 months to be a reasonable target (*15*). Service life of a given type of marking varies widely with the ADT levels (*18*) as well as the condition and type of pavement. Once applied, a combination of factors including abrasion by tires and weather-condition-related deterioration cause slow, uneven removal of the stripe. In the SASHTO regional study, durability was quantified as a tenth of the percentage of the stripe estimated to be remaining on the pavement. It is important to understand that durability of the stripe is not always an inherent property of the marking material. In a majority of the cases, the type of substrate or the condition of the pavement (*25,26*) heavily influence durability. Poor application practices also contribute to such failure.

Cost

A practical consideration in the selection of a marking material is cost, which includes pretreatment costs, materials, equipment and labor. Costs will vary depending on local labor rates as well as on market factors. Approximate installed costs (in dollars per 4-in.-wide linear foot) for different classes of marking systems were collected from the survey respondents of this study. In evaluating marking systems, it is the lifetime cost of marking rather than the initial cost that is important. The use levels reflected by the ADT determine the life of a paint stripe and therefore the frequency of restriping (*27*). A lower-cost option with a shorter lifetime will involve frequent restriping that can increase its lifetime cost significantly. For instance (*28*), conventional paints with initial installed costs of $0.03 to $0.06 per foot and lasting for a minimum of 4 months, have a 7-year life-cycle cost of $0.63–$1.26.

An attempt was made in the survey to understand user preferences for different types of marking systems in terms of their engineering performance. For those types of markings they were familiar with, the survey respondents indicated whether restriping was generally due to loss of retroreflectivity or the lack of durability of a stripe. With most categories of marking materials, the difference in score was marginal (a stripe is equally likely to be replaced due to either reason) and is of doubtful significance. However, solvent-borne paints were reported as being more often replaced because of durability limitations by about 70 percent of the respondents. The corresponding number for water-based paints was only about 55 percent. It is difficult to unambiguously interpret this result, as the population surveyed would have far more extensive experiences with solvent-borne paints compared with water-based paints. The other significant observation was that epoxy systems that generally last for 1 to 3 years were restriped mostly because of loss in retroreflectivity. Figure 3 summarizes the survey's findings on the leading causes for restriping and the ease of use of marking materials.

Environmental and Health-Related Performance

At least two considerations broadly classified as "environmental factors" need to be taken into account in selecting a pavement marking material. These considerations are necessary partly because of future regulatory requirements relating to the composition of marking materials but more importantly to ensure that the striping crews and highway workers are not exposed routinely to hazardous pollutants associated with the marking process. They are as follows:

- The amount of VOCs in the marking material and
- Toxicity associated with the marking formulation, particularly the presence of hazardous air pollutants (HAPs) in the marking material.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are any components of carbon (excluding its oxides, carbonic acids, metallic carbides or carbonates and ammonium carbonate) that can

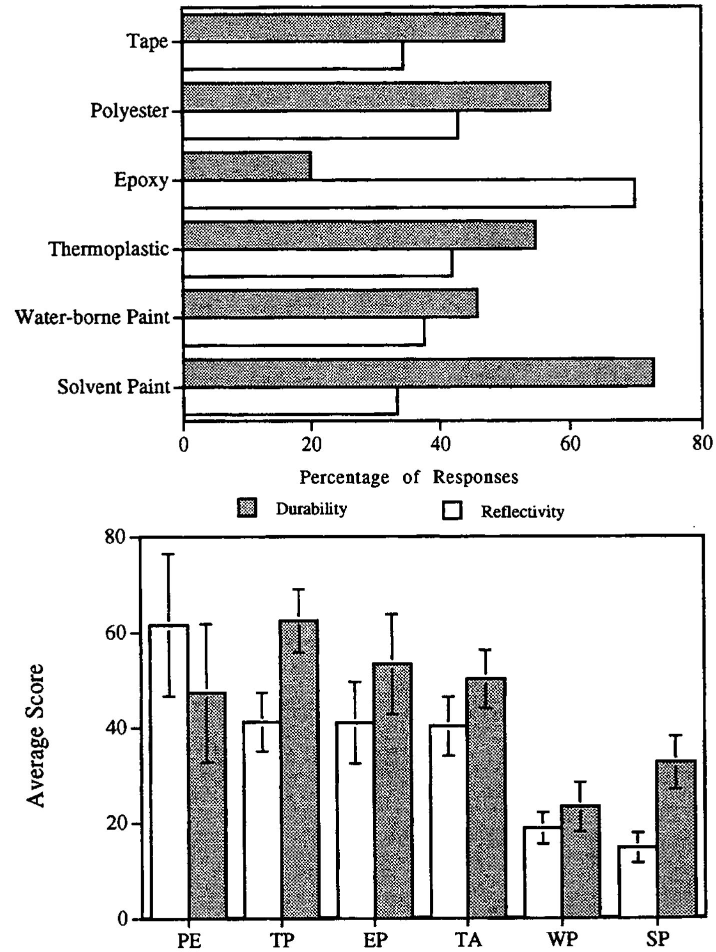

Figure 3. Survey findings on the percentage of responses on the leading cause of restriping (top) and on the average score for ease of use of the different marking materials (bottom). PE-Polyester, TP-Thermoplastic, EP-Epoxy, TA-Tape, WP-Water-based paint, SP-Solvent-borne paint.

participate in atmospheric photochemical reactions. Along with oxides of nitrogen and sulfur, VOCs released into the atmosphere interfere with the normal tropospheric photochemistry, resulting in ozone and smog formation (*29*) in urban areas. The presence of even low levels of ozone in the troposphere is associated with a variety of human health effects, agricultural crop loss and damage to ecosystems. Coatings account for about 9 percent of the VOC emissions from consumer and commercial product sources. In the interest of protecting the delicate chemical balance in the earth's atmosphere, the CAA (42 USC 7401 et seq. as amended) requires certain restrictions to be placed on industrial activities that result in the emission of large amounts of VOCs into the atmosphere. While a subset of VOCs determined to have only a negligible photochemical reactivity has been excluded from the regulatory definition [*Federal Register* 40 CFR Ch. 1, 7-1-94 Edition], many of these are separately regulated as ozone-depleting substances. Although VOCs are produced from natural sources such as vegetation and animal activity as well, at the present time it is the anthropogenic portion that is dominant. A recent U.S. EPA estimate places the non-methane VOCs released as a result of industrial activity (including pavement marking) to be 46 percent.

The pavement marking system of choice in the United States at this time, the conventional solvent-borne traffic paint, contains 25 to 30 percent by weight of VOCs. As all VOCs in the paint will be released into the atmosphere, this represents a significant load. In 1990 the approximately 12,387,000 gal of traffic paints used in the United States would have contributed an estimated 38,300,000 lb of VOCs into the atmosphere. An associated source of volatiles is the solvent used in cleaning pavement marking equipment. The full impact of this release of VOCs on global climate change and consequent health effects on the population is unclear.

From a chemical standpoint, the potential of different chemicals to produce smog and ozone via photochemical processes varies with their chemical structure. For regulatory purposes, however, all VOCs are regarded as being equally potent. For paints, potency is determined by a simple volatilization procedure described in ASTM D 2369-93, the Standard Test Method for Volatile Content of Coatings. Categories of pavement marking materials other than conventional paints have much smaller amounts of VOCs associated with them. Water-based paints, for instance, will have only a small percent of VOCs in them; the reduction in emissions by applying them in place of solvent-borne paints has been pointed out (*30*). Others, such as thermoplastics and tapes, have zero volatiles in them. However, in evaluating the VOC content in a marking material, the contribution from related sources, such as from priming adhesives used in the application of tapes, must be also taken into consideration. While adhesives are used at low levels, they can have much higher levels of VOC compared to solvent-borne paints. Although primers and undercoaters are allowed a higher level of 350 g/L of VOCs under the U.S. EPA Draft Rule, an adhesive (such as a popular tape adhesive) can typically have much higher levels of VOC. These too will be noncompliant under the new regulations.

The legal requirement to reduce the VOCs from industrial coating operations resulted in a regulatory negotiation exercise (called the "reg-neg" process) between the coating industry representatives and the U.S. EPA officials. After 2 years of discussion, in August 1994 the EPA terminated the process as it was clear that a consensus on policy was not achievable through the committee approach. The agency, however, developed its own recommendations on the issue in the form of a Draft Rule in June 1996. The final version of this rule is expected to be implemented in January 1998 (personal communication by U.S. EPA regulators to author). Pavement markings are expected to be affected by this regulatory exercise; and, after the rule is established, paint or marking material with more than 150 g/L (126 lb/gal) of VOCs will not be permitted. The special provisions to small manufacturers included in the reg-neg process documents are not included in the Draft Rule. It is certainly possible that this benchmark of 150 g/L will be revised downward at a later date. The language in the Draft Rule suggests the likelihood of such a revision in the future. The prudent response of the pavement marking community is, therefore, to examine options to reduce the VOC levels of marking materials by as much as possible below this level, rather than to merely comply with the present requirement. Presently available pavement marking materials can, therefore, be broadly classified into compliant and noncompliant systems, on the basis of this Draft Rule. Most water-based paints are expected to be compliant markings whereas most solvent-borne paints are not. However, a few compliant solvent-borne paints (using exempt solvents) are beginning to be available.

Toxicity Associated with the Marking Formulation

Some of the VOCs in marking formulations are also HAPs. These volatile compounds may potentially build up at high concentrations during striping operations, exposing the crew to a health hazard. The toxic reactions of the different volatiles vary widely from mild irritation of the respiratory tract to carcinogenicity. Unlike VOCs, all different types of HAPs cannot be regarded as being equally potent, and their regulation is expected to be far more complicated. The U.S. EPA has no immediate plans to introduce any rules pertaining to HAPs in pavement markings, but the issue is being discussed, and some regulatory activity by about year 2000 is a possibility. Pursuant to Section 112 of the CAAA, the EPA will formulate guidelines on HAPs; the first rule in this area was proposed in 1994 (40 CFR Part 63) and addresses the HAPs in coatings and paints in the shipbuilding industry.

Some HAPs commonly found in pavement markings at high levels include toluene, methanol, xylene, methyl ethyl ketone, and aromatics. These were identified by a comparison of the published lists of HAPs with formulae for different pavement marking materials collected from manufacturers or from literature. Low levels of methacrylate monomer, styrene, amines and phenols present in some formulations and these substances, when individually characterized, are known to pose various health hazards.

A second relevant toxicity issue is the use of lead chromate pigments in marking formulations. Both lead and hexavalent state of chromium are toxic. With the passage of Title X, the Residential Lead-Based Paint Hazard Reduction Act, lead-based pigments in paints attracted closer scrutiny. In mid-1994, the Office of Health and Environmental Assessment (OSHA) published the Interim Final Rule for Lead Exposure in Construction (29 CFR Part 1926), which reduced the permissible exposure level (PEL) for lead from 200 to 50 micrograms per cubic meter of air. Lead chromate pigment was widely used in yellow stripes in highway marking. Some use of lead chromate encapsulated in glass beads to reduce its toxicity has also been reported (*31*). The recent trend is to use increasing amounts of lead-free "organic yellows" in such formulations. The color stability and durability of these lead-free yellow formulations is reported to match or exceed that of the lead chromate formulations (*32*). Anecdotal accounts, however, indicate the organic yellow stripes to be somewhat inferior in retroreflective performance, especially wet-night conditions. This is possibly due to changes in hue undergone by the organic yellows under headlight illumination, and the need to change the color to bring it more toward the middle of the yellow range has been pointed out (*33,34*). In countries such as Norway, lead-free traffic markings have been in use for over a decade, suggesting that any technical difficulties involved in switching over to organic yellow pigments are certainly surmountable. As different marking materials can be compounded with different amounts of lead, the toxicity does not vary with the class of marking material but with the lead content in the formulation.

COMMERCIALLY AVAILABLE PAVEMENT MARKING SYSTEMS

From a technical standpoint, there are four basic approaches to pavement marking.

- Applying a solution or a latex of a polymer binder with necessary additives and subsequent evaporation of volatiles to obtain a marking (e.g., all traffic paints).
- Melting a solid polymer resin in the field and applying the melt directly onto the pavement (e.g., hot-applied plastics, thermoplastics).
- Applying a preformed plastic or other material onto the pavement using an adhesive (e.g., cold-applied plastics, raised pavement markings, tapes).
- Reacting monomers and other compounds (in the field) immediately prior to application to synthesize a resin or polymer directly onto the pavement (e.g., epoxy, polyester, and methacrylate systems).

The available pavement marking materials are classified into eight classes for convenience of discussion. As a prelude to the present analyses, the compositions and performance characteristics of each broad class are summarized below.

Solvent-Borne Paints

Most, if not all, of the solvent-borne paints available for pavement marking today will not comply with the maximum level of VOCs permitted by future regulations. However, it is possible that a solvent-borne paint might be formulated with less than the maximum permissible amount of VOCs along with other exempt solvents such as acetone. However, the use of such compliant solvent-borne paints may be restricted because of revised lower permissible VOC levels or possible HAP-related regulations in the future.

A paint generally consists of three basic components: a binder resin, pigments or fillers, and solvents/additives. The polymeric binder provides integrity and is the film-forming material. The pigments are used for desired optical properties such as high reflectivity in the case of titania and color in the case of lead chromate or Hansa Yellow. Fillers such as calcium carbonate are used to extend the paint composition. Optimum pigment volume concentration is in the range of 42 to 59 percent (*35*). Numerous other additives such as anti-settling agents, anti-skinning agents, stabilizers and biocides may also be included in the formulation. To enable the paint to be brushed, sprayed, or rolled onto a surface, its viscosity must be suitably adjusted with a solvent. The amount and type of solvent used controls the drying time of the paints, a property that is often used to classify paints as follows (*36*):

Conventional paints—Dry in > 7 min
Fast-Dry paints—Dry in 2–7 min
Quick-Dry paints—Dry in 30–120 sec
Instant-Dry paints—Dry in < 30 sec

Drying time is usually measured as the no-track time (often specified at 25° C [77° F] at a fixed thickness of coating). Solvents that tend to dissolve asphalt and are slow evaporating cannot be easily used in a paint formulation as they cause bleeding. Common solvents such as toluene or VM&P Naphtha evaporate fast enough to avoid bleeding.

An important additive in all traffic paints is the glass beads used to impart retroreflectivity to the stripe. The FHWA recommends their use at an application rate of 6 lb/gal of applied beads on stripes of 16-mil wet film thickness of paint (*15*). Other bead specifications have been used with success by different agencies (*37*). The size of the bead generally used falls within the 20 to 100 mesh range. The beads might be premixed or dropped on the marking. A full discussion of the role played by the beads and the variables that affect the reflectivity of glass beads is beyond the scope of this report. Some of the key variables include bead-related parameters such as size, refractive index, roundness, color or tint, chemical stability, and crushing resistance. Also important are installation-related variables such as level of beads, incorporation (premix versus drop-on), level of embedment in paint, thickness of paint film versus the size of bead, adhesion between the binder and bead, optical properties of the binder, and durability of binder used.

From a chemical standpoint, paints can be conveniently classified in terms of the resin binder used in the formulation. As the binder determines the nature and amount of solvent in the formulation, this classification is well suited for the present discussion.

Alkyd Paints. Alkyds, because of their low cost (*38,39*), are the most-used class of binder in solvent-borne paints. Alkyds are polyesters prepared from a polyol, a dibasic acid or the corresponding anhydride, and modifying oils. Glycerol and phthalic anhydride are the polyol and acid most commonly used for the purpose. Vegetable oils (soybean oil, safflower seed oil and linseed oil) or animal fat are used as modifying oils. The polyester so formed can be described in terms of the degree of unsaturation (drying oils that are the most unsaturated, semi-drying oils, and non-drying oils that are the most saturated) of the oil component. Alternatively, alkyds are also described in terms of the "oil length" or the oil content (short oils with < 50%, medium oils with 50%–70%, and long oils with > 70%). Oil length is important as it determines the solubility of the alkyd in different solvents; short-oil alkyds are soluble in aromatic solvents while the long-oil alkyds are soluble in aliphatic hydrocarbons. Alkyds crosslink by an oxidative mechanism yielding a tough film which, however, has limited durability, about 3–4 months under harsh conditions. They are generally applied hot at about 50° C (122° F) and dry in less than 5 min.

Hydrocarbon Paints. The C-5 aliphatic petroleum fraction is also used as the binder in solvent paints but to a much lesser extent than the alkyds. Hydrocarbon resins also tends to soften easily in contact with petroleum oils (motor oil).

Chlorinated-Polyolefin Paints. These include chlorinated rubber and chlorinated polyolefin type binders developed to compete with alkyds in durability. Chlorinated paraffin binders show improved durability by about 150 percent over the alkyds. In a study by NYSDOT, this category of paints lasted at least 9 months inclusive of a winter season (*40*). Chlorinated-rubber paints provided the best service lives in field studies and accelerated wear tests of traffic paints on both PCC and asphalt concrete pavements. The binder can be solubilized in methyl-ethyl ketone (a VOC) or a mix of solvents containing the ketone. Chlorinated resins are hot-applied and usually have a no-track time of 3–6 min (15 mils thickness).

Water-Based Paints

The interest in these formulations dates back to studies by Caltrans laboratories (*41*) and others (*42,43*) that found the water-based paints either matched or exceeded the service life and bead retention characteristics of solvent-borne paints. A recent study by Caltrans, however, found that none of the new water-based paints submitted by manufacturers for field evaluation met their current laboratory specifications, particularly the dry time and scrub resistance requirements (*34*). The newer water-based paints also showed some settling or gelling in containers.

The binder resin of choice in water-based formulations is a mixed acrylate-methacrylate copolymer available in the form of a 50 percent solid latex. The solvent is replaced for the most part by water, and additives are included in the formulation. These are different from those in solvent-borne paints and include non-ionic or ionic detergents to stabilize the latex, a dispersant such as polymethacrylate with acid functionalities, a coalescent to ensure rapid film formation and a thickener (such as hydroxyethyl cellulose) to maintain consistency. Usually some methanol (a VOC) is also present in the formulation.

As might be expected, using latex or emulsion paints drastically reduces the VOC levels in the formulation; reductions of over 80 percent are claimed in the literature (*18*). This coupled with its low cost is the major advantage of this type of marking material. Most water-based paints currently available are compliant with the maximum VOC requirement. Unlike solvent-borne paints, they are not flammable. The mixed reports from field studies on water-based paints suggest the efficacy of this class of marking system to be particularly sensitive to the type and quality of pavement and some striping practices. The switch from solvent-borne to water-based paints is complicated by the need to retrofit striping equipment as water can corrode conventional metal surfaces in pavement marking equipment (*22*).

Thermoplastics (Hot-Applied Plastic System)

This class of marking material is an excellent candidate to replace noncompliant traffic paints because of its moderate cost and good durability. These were once rated by some highway agencies as the marking material with best overall performance (*44*). Based on current evaluations, the extruded thermoplastic material is considered the most cost-effective material for crosswalk and stop bar installations (*45*). This marking system performs relatively better on asphalt compared to PCC pavements (*46,47*).

A thermoplastic stripe (*48*) is produced when a binder resin (compounded with pigments, fillers and additives) is melted and coated, sprayed, or extruded as a ribbon, onto the pavement surface. A small amount of preformed, precut, thermoplastic material is also used but mainly for symbols. The resin itself can be alkyd-based (for instance, a maleic-modified wood rosin) or C5 hydrocarbon-based. In spite of its marginally higher cost, the alkyd stripes have better retention of reflectivity (*49,50*) and are more durable. Thermoplastics retain good retroreflectivity for about 3.5 years and last even longer (*51*). Applied as a thicker stripe, they can be expected to last 3 to 15 times longer than conventional paint markings. In northern climates, snowplow activity and abrasion by studded tires can reduce the lifetime of thermoplastic stripes. An alternative installation method is by heat fusion; the thermoplastic sheet might be laid down on the pavement and heated with a propane torch to achieve bonding.

During application the slab or powder resin is melted at 193° to 232° C (380° F to 450° F) and screed-extruded or curtain-coated onto the pavement at a thickness of about 125 mil. At least two manufacturers also offer sprayable grades of thermoplastics applicable as a 60–90 mil stripe. Plasticizers are used to lower the melt viscosity to a point to enable spraying. Glass beads are premixed into the base material and also sprayed on the surface of the stripe. Depending on the condition of pavement, a primer (generally 2–5 mils of epoxy) may at times be needed to achieve good adhesion of the stripe. Alternatively, the pavement surface may be cleaned of all debris and markings prior to application of thermoplastic.

Hot-sprayed thermoplastic stripes placed correctly experienced no difficulty in a Kentucky study (*51,52*). Many problems associated with the material have been traced to the application process (*53*). Used properly, thermoplastics should last more than 5 years and provide reflectance of at least 130 millicandelas per lux per sq m. Available research data emphasize the importance of proper application of thermoplastics in order to obtain high durability. When comparing research data, it is important to take into account the different thicknesses of thermoplastic stripes. Thicker stripes are more durable and yield better visibility but will be more costly.

Composed of resin (about 20%), plasticizer, pigment and additives, the thermoplastics do not have measurable VOCs;

they are unlikely to have any significant levels of HAPs either. The only drawback in this regard is perhaps the hazard associated with dealing with high-temperature melts, and potential hazards due to hot aerosols and some fumes during application. Neither the composition nor the toxicity of such fumes is known at this time.

Tape

With tapes, the melt extrusion of the plastic into a ribbon and incorporation of glass beads is carried out in the factory, and the resulting preformed stripe (or a tape that is 30–90 mil thick) is adhered to the pavement using a glue. Thinner grades with adhesive backing are available for temporary marking of construction areas. In contrast with thermoplastics, tapes tend to have high initial cost and are therefore used in areas that require minimal marking that needs to perform under severe conditions. The composition of tapes is not unlike that of thermoplastics except that vinyl polymer (*54*) is often used. The formulation will have pigments and additives to allow proper extrusion processing. Glass beads may be incorporated into the bulk and also placed as a surface layer.

Freshly installed tapes provide excellent delineation with an initial retroreflectivity that is 4 to 6 times that of traffic paints. But they tend to lose their reflectivity rapidly (*49*), limiting their useful lifetime (*22*) that can be as low as 3 years (*55*). Tapes are more durable on asphalt pavements compared to PCC pavements (*46*). But a study in Kentucky found the thermoplastics to outperform tapes in crosswalk and stop bar markings (*39*). In general, inlaid installation of tapes outlasts the overlaid markings.

Inlaid installation on freshly laid asphalt pavements is done by pressing the pressure-sensitive, self-bonding tape onto the still warm, at least 54° C (130° F), pavement. No adhesive primer is generally used in this case; but the rate of application is slow, determined by the rate at which the pavement is being laid down. The inlaid tape is snowplowable and more durable than surface-applied tape. With older asphalt concrete surfaces, a contact cement has to be used even with tapes having an adhesive backing. Coating the adhesive on both the tape and the pavement surface is often necessary. As with preformed thermoplastics, tapes can also be installed by heat fusion.

Similar to thermoplastics, tapes are devoid of any VOCs or HAPs. However, when contact cement is used in its installation, the high VOC levels in the cement must be taken into account. As will be discussed later, the high-VOC cements can add a very significant VOC load (that is comparable to that associated with the use of solvent-borne paints) to some adhered tape systems. The high solvent levels may also present a fire hazard.

Polyester (Field-Reacted System)

Field-reacted marking systems differ from the marking materials discussed above in that a set of chemical reactions is needed at the field site to create the final form of the binder resin. This usually involves mixing two separate groups of reactants (often called Part A and Part B) immediately prior to application. It is best used with asphalt pavements (*56*) and can be applied over existing coatings. Polyester systems were identified as a durable marking material particularly suited for low ADT roads (*56*). Along with other systems tested, the polyester markings yielded about a 2.5-year life in a New York study (*57*). Much longer useful lifetimes are suggested by the data for polyester markings in NASHTO and SASHTO studies. Somewhat longer no-track times and difficulty of using polyester under snow conditions have been pointed out (*41*).

The binder resin is an unsaturated polyester liquid that is crosslinked on the pavement using styrene as a crosslinking agent. The reaction is catalyzed by a peroxide, generally methyl ethyl ketone peroxide, and an accelerator is also used. Equipment best suited for application sprays the polyester and additives at the desired width from one atomizer and the peroxide with accelerator package from a second. The two streams mix immediately above the pavement just before they contact the surface. Glass beads, typically 20 to 25 lb/gal, are dropped onto the surface of the wet, curing stripe. The typical 15-mil (no bead basis) stripe achieves tack-free condition in 8 to 12 min (takes longer with no beads). The pavement temperature should be at least 50° F for successful application, but higher temperatures yield shorter drying times. With new asphalts, an aging period of 30 days prior to striping is recommended. Spraying liquids onto a pavement always results in some aerosol generation as well as volatilization and may present a potential hazard to the striping crew.

While the polyester system is very low in VOCs, it uses styrene as a crosslinking agent. Styrene, used at a level as high as 30 percent of formulation, is mostly incorporated into the binder in polymerized form and is not available for volatilization. However, significant amounts of styrene must escape from the stripe laid on a hot pavement into the environment during application. As styrene is a hazardous substance, a HAP under Section 112 of the Clean Air Act (CAA), any significant inhalation of fumes by the crew will be of concern. No data on the air concentration of styrene during application of a stripe are available in the literature. The peroxide catalyst, usually methyl ethyl ketone (also a listed HAP under CAA) presents a limited fire hazard due to accidental spills. However, alternative peroxides (dibenzoyl peroxide) commercially available at 40 percent dispersion (in isodecyl benzoate-water) are free of this shortcoming. In spills, the high-boiling ester retains the solid in suspension reducing the risk of fire. The latter peroxide suspension is 10 to 100 times more viscous and requires a higher pressure to atomize and may require frequent cleaning of the spray head. The possible spillage of reactive chemicals in two-part systems (as well as methyl methacrylate monomer) also presents an environmental as well as a safety hazard.

Epoxy (Field-Reacted System)

The two-part epoxy paints are a durable marking material (*58*) that can be used on both asphalt and PCC pavements. They have moderate cost and yield a relatively high-service life of 3–6 years (*59,60*). However, recent studies have questioned the long-term performance of epoxy systems (*61*), and a tendency of white stripes to discolor with age has been reported (*62*). Equipment requirements for spraying epoxy formulations have been described (*63*). Generally applied at a thickness of about 15 mils, its cure time depends on the formulation. Fast-curing types that require no coning to slower varieties that dry in about 15 mins at 22° C (72° F) to 28° C (82° F) are reported (*64*). Glass beads are applied at the rate of 20 to 25 lb/gal.

Typical formulations consist of two parts: Part A consists of the binder resin, usually an epichlorohydrin-bisphenol A polymer, pigment and additives, while Part B consists of organic amine crosslinking agents. Because of the presence of resin, Part A is more viscous than Part B. When mixed in the appropriate ratio, usually 4:1, the system reacts hardening with little or no evolution of volatiles or fumes. Typical gel times measured in the laboratory are slightly over 2 min at 25° C for a 15-mil thick film. Most of the amine is nonvolatile and is incorporated into the binder film structure and is not volatilized subsequently. The nonvolatile nonyl phenol accelerator, however, is not so incorporated and resides in the stripe. The fully cured epoxy stripe has a hardness of over 80 on the Shore D scale. Part A of the formulation may contain a diluent such as a C-12 or C-14 glycidyl ether. Other diluents such as benzyl alcohol might be used in Part B of the formulation and act as an accelerator of the cure reaction. It has a boiling point of over 200° C and is not included in VOC estimates but is present as a free compound in the stripe. Formulations that do not use such diluents are 100 percent solid epoxy formulations. While the fully cured epoxy binder presents no hazard, the reactive chemicals used in the striping operation include hazardous chemicals.

Methacrylate (Field-Reacted System)

Methacrylate pavement markings have been used in Eastern Europe for years. This is also a two-part system with the first consisting of methyl methacrylate monomer, pigments, fillers, glass beads and silica. The second part consists of benzoyl peroxide dissolved in a plasticizer. The two parts are mixed immediately prior to application, generally at a 4:1 ratio, and the mix sprayed or coated onto the pavement and allowed to cure at ambient temperature. The curing proceeds via the polymerization of methacrylate monomer yielding poly(methyl methacrylate) and reaches a no-track state in about 20 min. The markings are durable, having a service life of 2–7 years depending on exposure conditions.

In a recent study in Alaska, methacrylate was rated higher than thermoplastics and tape as a durable marking material (*65*). The rating was based on durability, visibility, cost, and service life. In a study conducted by Caltrans (*62*), however, the material was found to have only limited uses in legend, stencil, and crosswalk applications. It is well suited for use on both asphalt and PCC pavements. Methacrylate can be applied at different thicknesses varying from 30 mil to 120 mil (even thicker in the case of raised profiles), and the thickness must be taken into consideration in evaluating performance. The marking rate with methacrylate is slower than with most other materials.

Methacrylate monomer, the main component in the formulation, is expected to be fully polymerized into the binder, leaving none to be volatilized. However, as with all reactive systems, the minimal volatilization during application of chemicals onto a warm pavement or via aerosols in spraying the formulation may present a health hazard to the striping crew.

Raised Pavement Markers

Raised pavement markers are becoming an increasingly popular and effective means of delineation (*66*). They have distinct advantages over most markings in terms of better wet weather retroreflectivity and better durability. The raised geometry provides a secondary tactile warning (rumble stripe) to drivers who may stray from traffic lanes. They are applied as a skip line and deliver exceptional lifetimes if left undamaged. Those states that use reflective or nonreflective raised pavement markings consider them to be a cost-effective method of delineation of pavements. The main drawback to using them is the high initial cost of installation. This has limited their use to delineation of major highways. Snowplow damage and some cracking under compression have also been reported. However, snowplowable models of markers are becoming available (*9*), but these are even more expensive.

Raised pavement markers are made of ceramic, metal or plastic and are designed either with or without a reflecting surface. Some designs have replaceable reflectors. Those made of plastics are molded from ABS resin. A few types are self-adhesive with a pressure-sensitive butyl backing. It is more common to use a strong epoxy adhesive to hold the marker firmly on the pavement. The two-component epoxy systems used for the purpose are not too different in composition from the epoxy paints discussed above. Rapid set formulations that work well at temperatures as low as –2° C (30° F) are presently available. An alternative adhesive system gaining in popularity is based on bitumen. A study on the performance of these newer adhesives found them to be more compatible with the softer asphalt pavements that are recently constructed (*67*). Hot thermoplastics can also be used as adhesives (*68*). None of the adhesives presently used contain very high levels of VOCs and are therefore unlikely to be regulated in the future. With heavy use, the raised markers lose their reflectivity (*69*) and may get cracked or debonded and lost. Because a significant factor leading to loss of reflectivity is the obliteration of reflector by accumulation of grime and tire tracks, increased lifetimes should be obtained by periodic cleaning of markers.

Table 1 summarizes the different categories of pavement marking materials commonly used in the United States.

APPROACH TO ASSESSMENT OF PAVEMENT MARKING MATERIALS

The objective of this project was to develop a methodology for assessing the overall performance of pavement marking materials. This methodology could then be used as a comparison tool for selection of marking materials for particular applications. Because a number of different characteristics of the marking material need to be taken into account in selecting one for a particular application, a tool capable of making unbiased comparisons is useful.

Historically, selection was made on the basis of the engineering performance and the cost of marking materials. This approach has already changed with the U.S. EPA placing regulatory controls on the amount of VOCs permitted in paints. In addition, there is a growing concern about hazardous pollutants present in these formulations. Thus, increased public awareness of the health impacts of markings, both to striping crews as well as to motorists, necessitates an assessment that includes at least these two environmental considerations in addition to engineering performance. This makes the selection process relatively more complicated and the methodology developed here even more useful.

A useful assessment tool for pavement marking materials must be at least semiquantitative to be of value to decisionmakers. The approach adopted here will be to evaluate and express the engineering performance and the environmental performance of marking materials separately, using two different parameters (U_{eng} and U_{env}). The symbol U stands for the utility of the material with regard to its performance in each category. It is inappropriate to combine these as their relative importance to the overall performance of a marking material is difficult to determine; different users might weight the engineering and environmental properties differently in selecting marking materials. The two parameters (U_{eng} and U_{env}) can be used to locate any marking material on a two-dimensional grid where the vertical axis quantifies conventional engineering performance and the horizontal axis quantifies environmental performance. (Figure 5 illustrates data for the engineering and environmental performances of two hypothetical marking materials plotted in this manner.)

Basic Features of the Methodology

Performance of a marking material is judged in terms of several key characteristics of the system called **attributes**. These include conventional considerations such as "How quickly will the marking loose retroreflectivity to a point it is of little use?" or "What is the annual cost of using this marking material?" Also included are attributes related to environmental performance, particularly the VOC level in the formulation and the health implications of the material to striping crews. Ideally, the selected set of attributes will completely describe the engineering and environmental performance of the marking. In practice, however, only the more important of these attributes can be used for the evaluation purpose. A set of *six* attributes will be used here to quantify the engineering performance, and a set of *three* attributes will be used to quantify the environmental performance of a marking material. The development of the particular set of attributes used in the present study will be discussed in detail in Chapters 2 and 3. The selected attributes, however, are shown in Figure 4.

Each attribute of a marking can be measured, estimated or rated in some manner to provide a **measure** of that attribute. The attribute of cost of a marking, for instance, might be measured in terms of "annual cost of a 4-in. stripe per mile in U.S. dollars." The attribute of the extent to which VOCs are present may be measured in terms of "pounds of VOCs per gallon" of marking. There are several available measures that can be used with a single attribute, and the best one expressed in the most convenient units is selected for the present analysis. The selection of these measures will be discussed in Chapters 2 and 3.

These different measures of the nine key attributes of a marking material are not equally important in selecting a marking material for a particular application. Some attributes such as "durability" are considered universally to be more important than others such as "ease of use." To take into account this disparity in the relative significance of different attributes, the measures are weighted using a factor called the **weight**. The weight is a fraction and is used as a multiplier of the measure to reflect its relative importance. Figure 4 also shows a **set of weights** assigned to the nine measures. The choice of the numerical value of the weights can change depending on the decisionmakers' perception of what attributes are more important. The relative importance of other attributes such as the "annual cost" or the "storage stability" may depend on the jurisdiction or even the time of year at which the selection process is carried out. In any event, this set of nine measures must be assigned a set of nine weights. A set of weights is proposed here to illustrate the concept.

Different measures are expressed in a range of different units. Some of these are ratings and are therefore dimensionless. Others may have units such as dollars or pounds per gallon. A set of measures having these different units cannot be compared with each other, combined or manipulated mathematically. The development of a quantitative parameter requires these measures, appropriately weighted to take into account their significance, to be multiplied or added. The only meaningful way of achieving this is to convert each of

TABLE 1 Major categories of pavement marking materials

Type	Material	Lifetime[a]	Thickness[a]	Advantages	Disadvantages	VOC[b]
1. Solvent-borne Paint	Alkyd Hydrocarbon Chlorinated rubber	1-1.5	8 mils	* low cost * Good visibility and retroreflectivity *Fast drying * Well established * Equipment available	* High VOC levels * Possible health hazards *Poor wet-night visibility * Short lifetime * Solvents needed to clean-up equipment	6-9
2. Water-based Paint	Acrylic emulsion	1-1.5	8 mils	* Low cost * Good visibility and fair retroreflectivity * Clean-up with water * Equipment can be easily retrofitted	* Poor wet-night visibility * no-track time of 2 - 30 mins * Short lifetime. * Some weather restrictions on use * Newer material.	1-3
3. Two-part systems	Polyesters	2 - 3	16 mils	* Moderate cost * Relatively long service life * Good visibility and retroreflectivity	* No-track time is long (5 - 20 min) * Uses hazardous peroxides. * Lifetime in snow areas can be short	Negl.
	Epoxy	3 - 6	15 mils	* Relatively long lifetimes. * Good visibility and retroreflectivity	* Moderate cost * No-track time is long (5-20 min) * Special equipment needs	Negl.
	Methacrylate	3-10	40-120 mils	* Long lifetimes in some locations * Snowplowable * Applied at ambient temperature (safe)	* No-track time is long ~ 20 min. * Solvents used in clean-up * Needs special equipment	Negl.
4.Thermoplastics	Alkyds Hydrocarbons	3.5-6	90-120 mils	* Relatively long service life * Good visibility and retroreflectivity * No-track time is short ~0.5 - 1 min for sprayed stripes	* Special equipment needs. * Solvents needed for clean-up * For extruded stripe no track time is ~15 min	0
5. Tape and preformed thermoplastic	Vinyl	1-3	60-90 mils	* Convenient to use. * Inlaid tape is snowplowable * No emissions of VOC's or HAP's if in-laid	* The adhered tapes require primers with VOC/HAP's. * High Cost * Variable night visibility	0
6. Raised Pavement Markers	Ceramic Plastic (ABS) Metal	variable	na	* Durability is high *Good visibility and retroreflectivity * Need not be applied as a continuous marking	* High cost. * Requires adhesive that may contain VOC's * Failed markers have to be replaced individually	0

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[a] Lifetime in years is the estimated durability of the marking from reference 17. The no-track times and the reflectivity information in columns 5 and 6 are also from the same source.

[b] The VOC estimates expressed in lbs of VOC's per mile-year per 4-in.-wide strip are taken from reference 30

na - not available

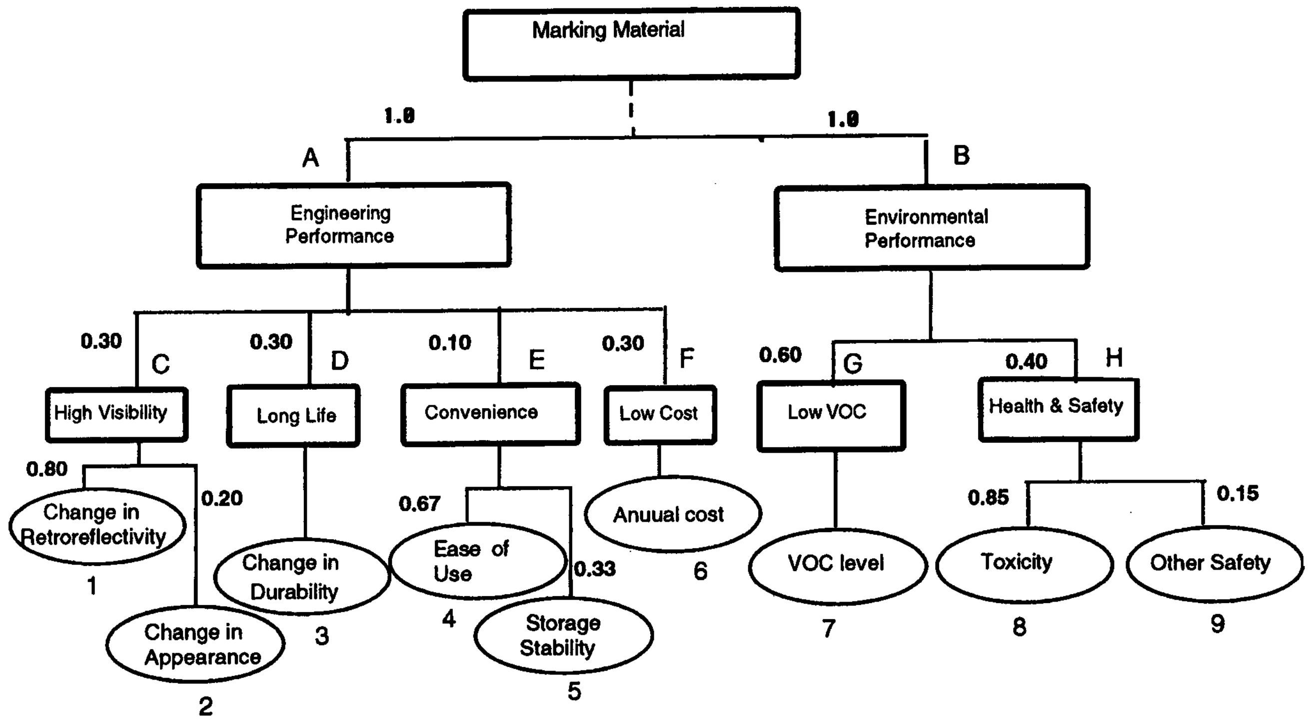

Figure 4. Attributes, measures, and weights used to quantify the performance of pavement marking materials.

the measures into a common quantity having the same unit. This quantity is called **utility**, a measure of the level of satisfaction derived from (or the level of desirability of) a given attribute. Each of the nine measures will have to be converted into values of utility using a simple conversion procedure. Any simple mathematical operation might be performed on the nine resulting utility values. The set of simple equations used to convert measures into utilities is called **utility functions**. In the following chapters, the selection of these utility functions will be discussed in detail.

The present methodology uses linear combinations of weighted utility values to calculate the two parameters of interest, U_{eng} and U_{env}. Once the user is accustomed to the concept of utility as a common unit for expressing all different measures, the process is mathematically simple and straightforward. The values of U_{eng} and U_{env} might be plotted on the two-way grid and reflect the relative performance of the marking. This type of plot is illustrated in Figure 5.

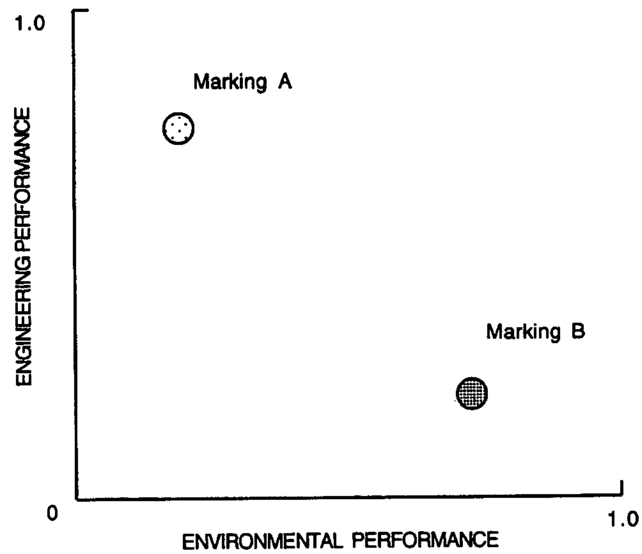

Figure 5. Schematic of the presentation of performance data.

CHAPTER 2

FINDINGS

As a prelude to developing a methodology for assessment of the performance of pavement marking materials, specific measures that quantify their main attributes need to be developed. Two sets of such measures, one pertaining to engineering performance and the other to environmental performance, were developed as a part of the present study.

ASSESSMENT OF ENGINEERING PERFORMANCE

The usefulness of pavement markings depends entirely on their visibility under all driving conditions. To ensure adequate visibility of a marking against a dark asphaltic surface or even a PCC pavement surface is not difficult. Ensuring retroreflectivity for nighttime driving, particularly under wet conditions, on roadways with no supplementary lighting is more of a challenge. The performance of a marking material should, therefore, be primarily quantified in terms of its ability to maintain an adequate level of retroreflectivity over a long period of time. Two other relevant conventional measures of performance that are often used are durability and cost. The durability of a marking must be high enough to obtain the full benefit of the duration during which retroreflectivity is maintained at an adequate level. An incomplete (or displaced) marking with adequate retroreflectivity,caused by a loss of integrity of a stripe, will be as confusing to the motorist as an intact stripe with inadequate retroreflectivity during nighttime driving. The lifetime cost of a marking is the key practical consideration that often limits the choice of marking systems available for use for a specific project.

In addition to these three primary attributes broadly referred to as the engineering performance, it is possible to identify a host of others. The more important of these are as follows.

- The useful lifetime of a marking in terms of maintaining retroreflectivity above a minimum required level.
- Retroreflectivity under wet-night conditions.
- Daytime visibility of the stripe against the asphalt or other pavement background.
- Durability of the marking as measured by the rate of physical loss of the marking with use.
- Ease of application of the marking, taking into consideration factors such as storage needs, equipment needs, manpower needs, traffic disruption levels, and clean-up procedures.
- Ease of application of markings in terms of prevailing weather conditions and sensitivity to installation under a range of temperatures and humidities.
- Where applicable, ease of removal or of overstriping an existing marking with the same or with a different marking material.
- Predictability of service life at the location where the marking is installed and the reliability of that prediction.
- Availability of in-house expertise or local contractors with the ability and experience to install the type of marking system in question.
- Annual lifetime cost of the marking.
- Ease of acquisition of new and disposal of worn-out marking stripes.

In spite of their importance, most of these attributes cannot be used in the present attempt to obtain a composite quantitative measure of engineering performance. In most instances, reliable data needed to quantify these attributes are simply not available.

The particular set of attributes to be used in the present study was selected by considering the properties of an ideal marking material and expressing them in terms of several well-defined, quantifiable properties. The rectangles in the mid-level of the tree diagram in Figure 4 show these four key properties: high visibility, long life, convenience of use and low cost. Each of these was then expressed in turn by one or more of the attributes from the above list. The researchers selected the following six attributes, based on the above criteria.

1. Maintains retroreflectivity in use for a long period of time.
2. Maintains high daytime visibility and overall marking quality in use.
3. Is not damaged, debonded or deteriorated easily during use.
4. Is easy to apply and to remove.
5. Is stable (does not settle, gel or biodegrade) during storage.
6. Is economical to use.

These attributes and their corresponding measures are shown in Table 2. A critical criterion in selecting useful attributes was the availability of reliable field test data generated in a study where several pavement marking systems were simultaneously tested using a sufficient number of typical members from each category of marking material. Without reliable data to validate it, the usefulness of the developed methodology will be limited.

Two sets of data on marking materials somewhat suitable for the present purpose were reported by the SASHTO Regional Testing Program and the NASHTO Regional Testing Program. The SASHTO study was carried out in Alabama (I-65 near Greenville on northbound lanes near milepost 140, with an ADT of 9135). The NASHTO site was in Huntingdon County, PA (on a three-lane undivided highway, US 22, EB, west of Huntingdon, PA). Both the SASHTO and NASHTO data cover a long enough period of observation to establish the useful lifetimes of markings. Markings, however, were mostly transverse lines and are therefore likely to have lifetimes significantly different from those for longitudinal markings. Of the data reported in these two studies, the following are pertinent to the present analysis.

SASHTO Study
- Mirolux 12 measurements of retroreflectivity of markings
- The durability of stripes on a scale of 1–10
- The appearance rating of on a subjective scale of 1–10

NASHTO Study
- Erickson measurements of retroreflectivity of markings
- The durability of stripes on a scale of 1–10

The differences between the SASHTO and NASHTO data for a given marking material must evidently reflect the differences in the test locations. Only the NASHTO exposure site, for instance, was subjected to any snowplowing and the SASHTO site in Alabama was routinely exposed to relatively higher levels of solar irradiation and higher temperatures. In any event, a direct comparison of the two sets of data is not valid because of the variability in pavement surfaces, ADT patterns, and installation practices (of the markings) used in the different studies. The particularly bad weather at the time of installation of markings on the NASHTO bituminous test deck required higher than average amounts of snowplowing and use of anti-skid materials. Conditions under which a marking is applied have a marked effect on its lifetime and may in part explain the high failure rates of some types of markings in the NASHTO study.

A few other studies, notably that entitled "Service Life and Cost of Pavement Marking Materials" reported in 1990 by the Pennsylvania Transportation Institute (PTI), also contain data that can be useful for the present assessment. The present discussion, however, will be based mainly on the NASHTO and SASHTO data.

Quantifying Visibility

Nighttime Visibility: Retroreflectivity in Terms of T_{100}

The objective here is to develop a simple quantitative measure of the duration for which a marking installed on a pavement will retain its retroreflectivity, *R*, at a level above an acceptable minimum level. In the absence of a nationally implemented minimum level, use the value of 100 millicandelas per lux per sq m for the present purpose. This value of

TABLE 2 Attributes and corresponding measures selected to quantify the engineering performance of a pavement marking material

ATTRIBUTE	MEASURE
1. Maintains retroreflectivity in use for a long period of time.	1. Estimated time in months for the marking to be reduced to a retroreflectivity value of 100 millicandelas per lux per square meter, T_{100}.
2. Maintains high daytime visibility and overall marking quality in use.	2. Appearance rated on a scale of 1-10 of the marking after 12 months of use.
3. Is not damaged, debonded or deteriorated easily during use.	3. Durability of the marking (the percentage of the marking material retained on the pavement surface) after about 12 months of use.
4. Is easy to apply and remove.	4. Rating on ease of application and removal based on results from a survey.
5. Is stable (does not settle ,gel or biodegrade) during storage.	5. Rating on storage stability based on the chemical composition and physical form of the marking material.
6. Is economical to use.	6. Annualized lifecycle cost (in U.S. $ per mile per year) of a marking system, assuming a 4" stripe.

Andrady 1996

retroreflectivity is suggested by reported research (*21–24*) to be the minimum acceptable level. The duration in months for the retroreflectivity of a new stripe of any given initial retroreflectivity to reach a value of 100 units, T_{100}, can be obtained directly if the available field data cover the full useful lifecycle of the marking material in question. However, this is generally not the case and extrapolation of short-term retroreflectivity data is often necessary to obtain an estimate of T_{100}.

Provided periodic measurements of retroreflectivity of a stripe are available for a given location, T_{100} can be readily estimated as follows. The retroreflectivity versus time data for numerous marking materials published in SASHTO and NASHTO studies and elsewhere (*21,28*) agree well ($r^2 > 0.85$) with the following empirical equation (see Figure 6 for examples).

$$\text{Retroreflectivity } R = -b(\text{Log duration in months}) + R_o \quad (1)$$

where the parameter b is the gradient of the semilogarithamic plot of retroreflectivity time data. The negative value indicates that the retroreflectivity decreases with time and the magnitude of b indicates the rate of loss of retroreflectivity. The constant R_o is an estimate of the initial retroreflectivity value. As the maximum loss that can be tolerated is (R_o – 100) units, the duration for reflectivity to reach a value of 100, T_{100}, is

$$T_{100}\text{ (months)} = 10^{(R_o - 100)/b} \quad (2)$$

For each category of marking material, the mean values of b and R_o were calculated from Equation 1 using the data published in NASHTO and SASHTO reports to obtain realistic

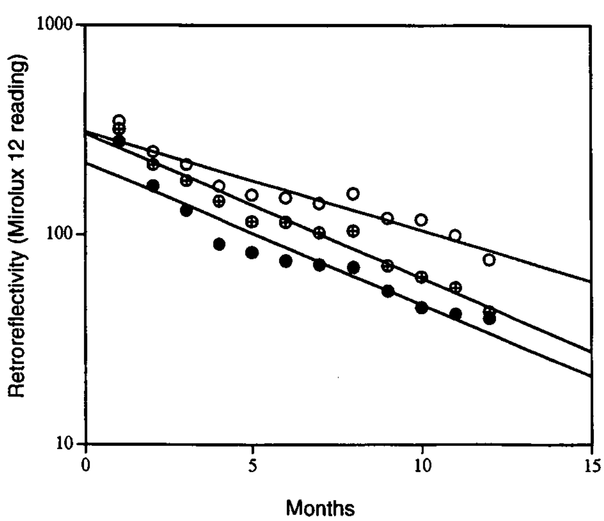

Figure 6. Change in retroflectivity of three solvent-borne paints during use (from SASHTO data).

ranges of values. The estimated values of T_{100} (months) based on this data, calculated using Equation 2, are shown in Table 3. These are strictly applicable only to the location (the type, condition, usage level of the pavement, and local weather conditions), application, and traffic conditions under which the data were generated. In fact, the correlation between the values of T_{100} obtained for NASHTO and SASHTO data for the same types of marking materials is only moderate (r = 0.71) indicating the importance of these variables. At best, the T_{100} values in Table 3 serve as an approximate guide to typical values to be expected from different markings in the two regions where tests were carried out. An estimate of the gradient b can also be made, using Equation 2, from a single determination of R, provided the value of R_o and the age of the stripe are known. This latter estimate will of course be less reliable.

This dependence of T_{100} values on the geographic location where the data were generated is illustrated by a comparison of the NASHTO or SASHTO data with published data for other geographic locations. Retroreflectivity data over a 35-month period were published in a recent report from the Alaska DOT (*28*). Their data for 3M Starmark 380 Tape and for sprayed 40-mil methacrylate showed the tape to have a useful lifetime that is about 25 percent shorter than that of the methacrylate stripes. In both NASHTO and SASHTO data, however, the lifetime of tape is significantly higher than that for methacrylate markings. A study by the PTI (*21*) reported service life data for various categories of marking materials observed over a longer period (>3 years) of exposure. As they selected a mirolux measurement of 100 units as the failure point, T_{100} values can be easily derived from their data. Data for alkyd paints (yellow and white), water-based paints (yellow and white), and preformed thermoplastics from NASHTO findings could be compared with their data. The estimates of T_{100} for the same categories of markings in the two studies were highly correlated (r^2 = 0.92). When their Florida data were compared with SASHTO data, however, the correlation was low (r^2 = 0.51). In both SASHTO and NASHTO data, white polyester paint displayed the longest lifetime, while solvent-borne paint displayed the shortest. These examples illustrate the importance of using estimates of T_{100} values that are relevant to the location of interest.

Daytime Visibility: Appearance Rating

Appearance of a marking refers to the total impression conveyed by it when viewed at a distance of at least 10 ft and is expressed in terms of satisfactory or unsatisfactory appeal to the observer. The subjective assessment of the appearance of a marking is included as an attribute in the present analysis to underscore the importance of daytime visibility of the delineation. Compared with retroreflectivity, daytime visibility is easier to achieve in a stripe and depends on the nature and quality of the pavement surface. The brightness, which

TABLE 3 Measures of the rate of deterioration in retroreflectivity of pavement markings

Marking Material	b value NASHTO	n	b value SASHTO	n	R_o Value NASHTO	T_{100} (mos.)	R_o Value SASHTO	T_{100} (mos.)
1. Tape - white	357.5 [76.1]	7	339.0 [48.1]	8	511.3 [10.9]	14.1	606.5 [79.9]	31.2
- yellow	217.8 [16.2]	7	269.5 [51.3]	7	338.4 [20.9]	12.4	499.5 [62.1]	30.4
2. Polyester paint - white	195.8 [18.9]	9	164.7 [23.3]	6	413.1 [22.8]	39.7	465.6 [72.2]	165.9
- yellow	129.6 [32.5]	6	155.6 [21.8]	7	179.2 [23.3]	4.0	360.5 [45.7]	47.2
3. Water-based paint - white	175.2 [18.4]	9	188.6 [12.7]	11	352.6 [24.2]	27.7	397.9 [23.9]	38.0
- yellow	110.0 [7.4]	8	143.9 [10.9]	11	255.9 [11.0]	26.1	278.9 [16.0]	17.5
4. Thermoplastic - white	174.2 [79.4]	9	-		299.1 [13.8]	13.9		
Hydrocarbon type			250.4 [17.8]	4			378.8 [29.3]	12.98
Alkyd type			246.0 [34.2]	6			495.7 [36.4]	40.6
Thermoplastic - yellow	98.0 [13.3]	7			187.5 [17.0]	7.8		
Hydrocarbon type			136.3 [7.0]	5			223.2 [21.4]	8.0
Alkyd type			152.2 [22.8]	6			293.0 [25.3]	18.5
5. Methacrylate paint	147.0 [7.7]	4	186.8 [34.5]	4	252.0 [17.3]	10.8	335.7 [45.6]	18.3
6. Preformed thermoplastic	137.0 [27.7]	3	239.1 [38.8]	5	250.7 [47.2]	12.6	239.1 [38.8]	3.8
7. Solvent Paint - white	123.9 [17.6]	9	201.5 [16.8]	10	234.5 [24.6]	12.2	293.5 [15.0]	9.1
- yellow	65.2 [7.8]	9	198.7 [19.6]	8	131.7 [12.5]	3.1	271.1 [21.5]	7.2
8. Epoxy paint	131.8 [25.9]	6	-		267.9 [32.9]	18.8	-	-

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Standard error of the mean of n samples is given in square brackets [ ]. The values of b are expressed as retroreflectivity units per month.

is a function of the contrast ratio (*21*), measured with a photometer, can be used to quantify this attribute of appearance. However, from the SASHTO study only a subjective rating of appearance on a scale of 1–10 is available for different classes of marking materials. Higher values indicate better appearance. In most jurisdictions, photometric measurements of stripes are not made routinely. (An experienced marking engineer is often able to estimate the appearance of a stripe after about a year of use well enough for the present purpose.)

In Table 4, the data from the SASHTO report are summarized in terms of mean value of appearance at the end of about 12 months of use. As with retroreflectivity, appearance also depends on local conditions and ADT levels.

Quantifying Lifetime in Terms of Durability

The durability of a marking at any given time is expressed as a tenth of the percentage of the stripe material remaining on the pavement when a stripe is examined closely by the unaided eye. Values of durability of a marking at a given time can therefore vary between 0 and 10, with the higher values denoting higher durability. Test methods allow this quantity to be estimated in terms of the percentage of area where the underlying asphalt substrate is not exposed within the prescribed test area. This is a difficult estimation to perform when the stripe is unevenly deteriorated and discolored. For markings with drop-on beads, the vertical composition of the stripe is not the same and the early data include loss of beads in addition to that of matrix material. An estimate of the change in durability over a 12-month period is used as a measure of durability for the present purpose. The duration of about a year is perhaps not the best as durable pavement marking materials last much longer than a year of use. However, nondurable markings, particularly paints, last for less than a year, and the SASHTO or NASHTO data on the durability of different marking materials do not cover periods much longer than a couple of years.

As with measures of visibility, durability data are very dependent on the local climatic conditions, ADT levels, and other factors (such as pavement type, condition, and age). The need to obtain and use test data generated at the location of interest cannot be overstated. In Table 5, the data based on different pavement marking systems tested in NASHTO and SASHTO studies are summarized. There is no accepted standard or benchmark to interpret the durabilities obtained at the end of 1 year, and the closer the rating is to 10 at that time, the more durable the marking is assumed to be. The variation between different types of markings is not too large; solvent-borne and water-based paints are much lower in durability compared with tape, methacrylate, thermoplastic and two-component systems.

An important limitation of the data on durability needs to be pointed out. The NASHTO/SASHTO test data do not cover a period long enough to observe the loss of integrity of most durable marking materials. This would require a long-

TABLE 4 Average appearance ratings for various pavement markings on asphalt pavements after approximately 12 months of use (SASHTO data)

Marking Material	Mean Value	Std. Error	No. of Samples
1. Tape - white	9.2	0.39	7
- yellow	9.3	0.27	10
2. Polyester paint - white	7.2	0.61	9
3. Water-based paint -white	8.5	0.01	21
- yellow	8.6	0.07	46
4. Thermoplastic - white			
Hydrocarbon type	8.7	0.59	5
Alkyd type	9.2	0.09	4
- yellow			
Hydrocarbon type	9.3	0.21	4
Alkyd type	9.4	0.14	4
5. Methacrylate paint	8.8	0.34	10
6. Preformed thermoplastic	9.5	0.17	5
7. Solvent Paint - white	7.4	0.14	17
- yellow	8.0	0.06	22
8. Epoxy paint	9.1	0.22	3

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TABLE 5 Average values of durability of pavement marking materials after 10 to 12 months of use

	SASHTO DATA		NASHTO DATA	
	Durability in 11 months	n	Durability 10-12 months	n
1. Tape	9.4 [0.3]	13	note a	
2. Polyester Paint -white & yellow	7.1 [0.7]	9		
- white			8.5 [0.2]	15
- yellow			8.9 [0.2]	16
3. Water-based Paint - white	8.7 [0.1]	21	4.7 [0.5]	48
- yellow	7.4 [0.1]	41	5.0 [[0.4]	60
4. Thermoplastic (mixed) - white			8.1 [0.4]	27
Thermoplastic (mixed) - yellow			8.6 [0.3]	27
Hydrocarbon type	9.0 [0.4]	9		
Alkyd type	9.6 [0.1]	8		
6. Methacrylate Paint	9.0 [0.5]	7	10.0 [-]	20
8. Solvent Paint - white	7.1[0.6]	17	6.6 [0.4]	33
- yellow	7.7 [0.1]	22	6.5 [0.3]	37
9.. Epoxy Paint	9.1 [0.4]	9	10.0 [-]	6

Andrady 1966

Note a - Tapes at 10-12 month exposure were generally rated 0 or 10, probably depending on if it came off the pavement or was still retained. The mean of these values does not give a good representation of the performance of tape. A well-applied high-grade tape apparently can survive the exposure without any noticeable loss of material.
n = number of samples.

term observation (perhaps as long as 3–6 years) that allows the quantitative record of the change in integrity. Furthermore, the test data are for transversely applied markings that wear and deteriorate at a rate faster than the longitudinal markings. The estimates of durability of pavement marking materials reported in these as well as other databases address only the initial stages of the degradation process.

Quantifying Ease of Use of Marking Materials

Ease of Application and Removal

Ease of application of a pavement marking material is an important consideration because it has a direct impact on the level of experience needed to successfully install it. The ease of removal of the marking is also of interest as changes in the routing of traffic and channelization often require changes to existing pavement markings. This is also true of roadways under refurbishment or repair where temporary traffic lanes have to be created. Durable markings such as epoxy and thermoplastics have very high durability, but their removal from the pavement can be a labor-intensive and time-consuming operation.

In the project survey, information was requested on this attribute of pavement markings. Respondents were directed to assign a rating between 1 and 100 (1 signifying the easiest to use) for those marking materials with which they have had experience. The results showed both solvent-borne and water-based paints to be relatively easy to apply and to remove compared with other types of marking materials. This result may in part also reflect the long-term familiarity of the pavement marking community with conventional traffic paints as opposed to other types of marking materials. The findings from the survey are summarized in Table 6.

Given the errors likely to be associated with a subjective rating of this type, the above data can be simplified into several broad groups of marking systems. Paints are evidently the easiest to use category of markings, followed by tape and epoxy. The polyester and thermoplastics occupy a separate category having been rated the most difficult to either apply or to remove. These might be placed on an arbitrary scale of 0 to 5 (higher values for easier systems to use) according to ease of use. Based on the data in Table 6, paints are reasonably assigned a rating of 4 or 5; adhered tape and epoxy systems a value of 3 or 4; and polyester and thermoplastics a value of 2 or 3. Methacrylates are not included in the above list, but a rating of 3 is suggested. Raised pavement markers might also be assigned a rating of 3.

Storage Stability

The storage stability of marking materials, with liquid systems in particular, is an important property. Paint should not chemically deteriorate during storage causing changes in key properties such as dry time. It should exhibit good viscosity stability over time and should not cake, settle, gel, or change in color during storage. Once settled, it is difficult to reconstitute a paint to its original performance level. In addition, paint should not form a skin or be attacked by surface fungi or bacteria in partially filled cans. With systems such as polyesters and epoxy, storage of reactive chemicals is involved. The storage of toxic chemical compounds and peroxides is more difficult than storing conventional paints. The easiest to store are the very stable tapes and thermoplastics that are nonreactive and bio-inert. However, like all pavement marking materials (except for raised pavement markers), they, too, are flammable.

This attribute can be conveniently rated on a scale of 0–5, assigning 5 for thermoplastics and tapes and 2 for paints and two-component systems.

Lifetime Cost of Marking Materials

While not an attribute strictly related to engineering performance of a marking material, cost is obviously a crucial consideration in its selection. Cost can be the overriding consideration when choices of marking materials are made, especially in the case of low-ADT rural roadways. The cost of a marking material includes that of pavement pretreat-

TABLE 6 Summary of survey findings on the ease of application and removal of different pavement marking materials

Category	The mean score for Ease of Application	SE	The mean score for Ease of Removal	SE
1. Polyester	61.6	14.9	47.3	14.6
2. Thermoplastic	41.2	6.2	62.5	6.6
3. Epoxy	41.0	8.6	53.4	10.5
4. Tape	40.3	6.2	50.2	6.1
5. Water-based paint	18.9	3.2	23.2	5.1
6. Solvent-bome paint	14.8	3.1	32.6	5.6

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Note: A higher rating signifies increasing difficulty in application or removal of a marking.
SE is the standard error of the mean.

ment, application, maintenance and removal (where needed). As different pavement marking materials have different service lives, these costs are not directly comparable. An average annual lifetime cost needs to be calculated for each type of marking material for the purpose of the present analysis.

Developing lifetime costs requires good estimates of the initial cost of a marking material (the installed cost) as well as the lifetime of the marking under local climatic and traffic conditions. The latter varies with the region of the country and, in the case of certain types of marking materials, on how well it was installed.

For the present purpose, the national cost data collected in the project survey were used. The installed costs of a linear foot of a 4-in. stripe of marking materials were requested from survey respondents. The cost data collected for different pavement marking materials were analyzed statistically to determine the most frequent cost (the mode), listed as the average cost in the second column of the Table 7. It is useful to consider the range of costs for the purpose of this discussion. The two extreme cost values for each marking system were discarded and the range of costs obtained for different categories of marking materials listed in Table 7 (column 3). Using the average cost of a marking and its average estimated lifetime, a lifetime cost over a 6-year period was calculated. Also calculated was a range of lifetime costs based on the highest and lowest costs as well as the highest and lowest lifetimes expected of different markings. The methacrylates were not included in the survey but were included in the table using values from literature (*28*) to calculate the life-cycle costs. The analysis does not take into account incidental costs such as costs for conversion of existing equipment to allow the use of water-based paints. It also does not take into account the future cost of money through the use of a capital recovery factor. This level of sophistication is deemed unnecessary for the present analysis where the data are averaged over the whole of the United States and are, therefore, approximate in any event. The user may change the cost data for different markings to arrive at numbers that better reflect local cost scenarios.

ASSESSMENT OF ENVIRONMENTAL PERFORMANCE

The environmental performance of a pavement marking material includes two key aspects, the VOC content of the material and the extent to which HAPs in the marking can pose a health hazard to the striping crew. With the advent of regulatory controls on VOC limits and an increasing awareness of the health-related issues of paints by the user community, the environmental performance of pavement markings is receiving increasing attention. The possible future controls on the use of HAPs in coating formulations is also a good reason for paying closer attention to environmental aspects of pavement marking. The main goal here is to develop a quantitative measure of the environmental performance of pavement markings. Chemical formulations for typical pavement marking systems are shown in Appendix B.

The potential of traffic paints to pollute groundwater and soil environments, while not addressed in detail within the present methodology, can be significant. These solvents are likely to remain in water or soil only for a relatively short time period before evaporation and biodegradation. During this time, dissolved or floating solvents may present a hazard to biota in water or soil. Only very limited information is available on the ecotoxicity of solvents in the environment.

TABLE 7 Summary of survey findings on cost information and estimated life-cycle costs based on a 6-year cycle

Marking Type	Average Cost	Cost Range	N	Lifetime (y)	Average Lifetime (y)	*Lifecycle Cost (LC)	Average LC
Solvent-borne Paint	$0.03	$ 0.02 - $ 0.06	31	0.25 - 1	0.63	$0.48 - $0.12 $1.44 - $0.36	$0.29
Water-borne Paint	$0.06	$ 0.02 - $ 0.06	19	0.25 - 1	0.63	$0.48 -$ 0.12 $1.44 - $0.36	$0.58
Polyester	$0.10	$ 0.07 - $ 0.13	7	1 - 4	2.5	$0.42 - $0.11 $0.78 - $0.20	$0.24
Epoxy	$0.25**	$ 0.17 - $ 0.33	11	1 - 3	2.0	$1.02 - $0.34 $1.98 - $0.66	$0.75
Methacrylate[a]	$0.75	$0.25 - $1.25	-	2 - 6	4.0	$0.75 - $0.25 $3.75 - $1.25	$1.13
Thermoplastic	$0.30	$ 0.20 - $ 0.80	20	3 - 6	4.5	$0.40 - $0.20 $1.60 - $0.80	$0.40
Tape	$1.75	$ 1.04 - $ 2.25	21	2 - 6	4.0	$3.12 - $1.04 $6.75 - $2.25	$2.63

Andrady 1996

[a] Methacrylates were not included in the present survey, but cost and lifetime data from reference 28 were used in the calculation.
* Life-cycle cost calculated over a 6 -year period. The two ranges given are calculated using the low cost estimate (upper) and the high cost estimate (lower) form column 3.
** Unlike for other types of marking materials the cost data on epoxy were bimodally distributed. The histogram showed maxima in two cost ranges of $0.15 - $0.20 and $0.30 - $0.35. The average selected was $0.25.

However, regulations aimed at controlling the discharge of such solvents into aquatic environments are available in Europe. Best known is the WKG (water-endangering potential) classification of Germany. Common solvents such as toluene, xylene, and ethyl acetate have been assigned a rating of 2 (out of 3), identifying them as water-endangering chemicals.

The three attributes selected to characterize the environmental performance of pavement marking materials in the present study are as follows.

1. The VOC content of the marking material compared with the maximum level to be allowed under expected regulation.
2. The toxicity of hazardous volatile organic compounds present in a marking material.
3. Other safety concerns associated with a marking materials.

Regulation by the U.S. EPA of VOCs in Pavement Markings

The VOCs from traffic markings invariably find their way into the upper atmosphere where they can undergo photoreactions. In sunny climates, their reaction with nitrogen oxide can create photochemical smog (consisting of ozone, peroxides and oxidants). This has encouraged the United States and Western European countries to control and regulate VOC emissions. In the United Kingdom, recent legislative developments focused on the use of coatings. Most countries in Europe are guided by the UNECE VOC Protocol or the Geneva Protocol, which require the VOC emissions to be reduced by 33 percent by 1999 (1988 baseline year).

In the United States, Section 183(e) of the CAAA (1990) requires that the U.S. EPA control VOC emissions from certain categories of products, which include coatings. The definition of a VOC for regulatory purposes is any organic compound that can participate in atmospheric photochemical reactions; that is, any organic compound other than those that the Administrator of the EPA designates as having negligible photochemical reactivity. A list of such compounds, also referred to as exempt compounds, is given in 40 CFR 51.100. The "VOC content" means the amount of VOC in grams in 1 L of coating thinned to the manufacturer's maximum recommendation, excluding the volume of any water, exempt compounds, or colorant added to tint bases. For this purpose, the relevant test method will be the EPA Reference Test Method 24, "Determination of Volatile Matter Content, Water Content, Density, Volume Solids, and Weight Solids of Surface Coatings," found in 40 CFR, part 60, Appendix A. The regulatory language specifically refers to "traffic marking coatings" or a coating formulated and recommended for marking and striping streets, highways, and other traffic surfaces including, but not limited to, curbs, berms, driveways, parking lots, and airport runways. Primers used to pretreat pavement surfaces will also be covered by the same rule.

Effective January 1, 1998 (provided the present timetable holds), and thereafter, manufacturers and importers of coatings shall limit the VOC content of each traffic marking coating to the VOC level of 150 g/L (1.26 lb/gal). Primers and undercoaters are allowed a higher level of 350 g/L. At the present state of evolution, the U.S. EPA regulation has the following additional features.

- No extra compliance time will be available to small manufacturers and small importers of coating materials. An initial report on the product will be required of all manufacturers or importers by April 1, 1997.
- There will be additional labeling requirements for containers of pavement marking coatings.
- A variance might be granted on the basis of a written application showing inability to comply with the rule temporarily due to reasons beyond the control of the applicant.
- An alternative compliance mechanism in the way of an exceedence fee might be included in the rule.

In October 1992, the U.S. EPA established a regulatory negotiation committee consisting of EPA officials and representatives of affected parties including manufacturers of coatings, consumers, air pollution control agencies and environmental groups. From more than 2 years of negotiations emerged a draft regulatory framework, but the committee was unable to reach a consensus. With the breakdown of this negotiations process, the EPA proceeded to develop a rule by itself based on the information generated during the negotiations. The proposed rule on National Volatile Organic Compound Emission Standards for Architectural Coatings was published in the *Federal Register* of June 25, 1996 (Vol. 61, No. 123), for public comments. The public comment period was extended through November 4, 1996, in a *Federal Register* notice published on September 3, 1996 (Vol. 61, No. 171). By the closing date, the U.S. EPA had received about 200 public comments, and these are being reviewed at the present time. The Rule is expected to be implemented in January 1998. An update of the U.S. EPA regulatory activities pertaining top architectural coatings is available from the U.S. EPA office in Durham, NC, at (919) 541-5408.

Once enacted, these limits on VOCs are expected to reduce the emission from coatings (all architectural coatings) in the United States by over 100,000 tons annually. This is a very significant reduction, amounting to about 20 percent of the baseline VOC emissions estimated for 1990. The proposed limit of 150 g/L is, however, unlikely to be a fixed benchmark. Jointly, the U.S. EPA and the coatings industry intend to investigate the feasibility of adopting even more stringent VOC requirements in the future. A future phase of regulation in a 5- to 7-year time scale is envisioned.

VOC Content of Pavement Marking Formulations

Of the different classes of pavement marking materials available, paints are associated with the highest VOC content. Two-part systems may also have small amounts of volatiles in their composition, but thermoplastics or tape are unlikely to have any volatile components associated with them.

The data collected in the NASHTO study include the VOC content of various traffic paints provided by each manufacturer. None of the solvent-borne paints listed in the NASHTO report would have complied with the anticipated rule limiting the VOC level to 150 g/L (1.26 lb/gal). As there was no significant difference between the VOC levels reported for the white and yellow formulations, the data were combined to produce the histogram for solvent-borne paints, shown in Figure 7. Most of the solvent paints had a VOC level of about 3.00 to 3.25 lb of VOC per gallon (375 to 387 g/L); a few had values of over 3.75 lb/gal (446 g/L). Most of the water-based paints, however, showed VOC levels well below the anticipated regulatory limits. It is clear that compliant water-based traffic paints are available. (Note: Figure 7 is based on modified NASHTO data. The listing of VOC values for both solvent-borne and water-based paints in the NASHTO Report contains several errors. These were corrected using manufacturers data sheets when compiling the present data).

Assuming an application rate of 16 gal/mi (corresponding to a wet thickness of about 15 mils of paint excluding beads), the average annual VOC emissions per mile striped with solvent-borne paints is about 82 lb/year (see Table 8). The calculation is based on the mode value of VOC content solvent-borne and water-based paints given in the histograms in Figure 7.

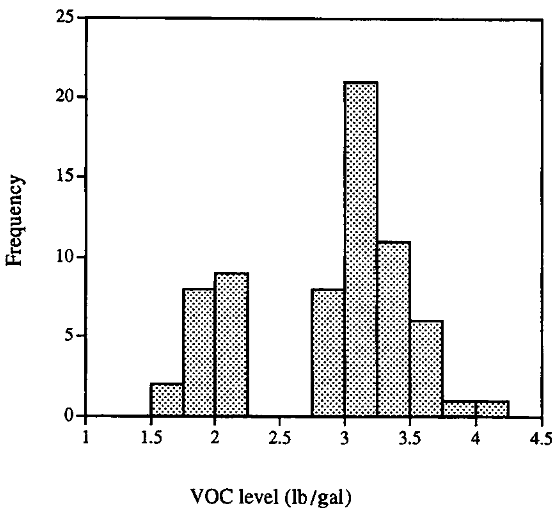

Figure 7. VOC content of solvent-borne paints tested in the NASHTO study.

Considering the number of miles of roadway annually striped in any jurisdiction, this is indeed a heavy VOC load on the atmosphere. On the average, replacing conventional solvent-borne paints with a water-based paint is estimated to reduce VOC emissions by as much as 78 percent. With the implementation of VOC regulations, the water-based paints are likely to be continually improved and formulated with even lower VOC levels than those available at the present time. The environmental advantage of using them can, therefore, be even greater than that implied here.

The two-component systems by comparison are expected to have very low levels of VOCs associated with them. However, the VOC determination methods for these systems must take into account the chemistry of the process by which the marking is produced in the field. Rather than the total VOCs in the formulation, only those available for release from the marking must be attributed to the marking material. Except for diluents present in the formulation, organic constituents of these systems, as well as those in methacrylate systems, polymerize or crosslink into a solid mass and are not available for subsequent volatilization. However, some minimal amount of loss of material as a vapor can take place when the hot mix, which is not as yet fully cured, touches the pavement surface. This minimal amount of VOC has never been reported as a field measurement and is generally assumed to be negligible (*30*). The operation of spraying liquid reactants onto the pavement must invariably involve the release of aerosols of individual reactants. These droplets may lack the two-part composition that causes curing and have the potential of being hazardous air pollutants. While all these compounds might not be specifically included in the lists of VOCs, their polluting potential cannot be ignored. However, the lack of any field measurements precludes the assessment of this important factor. Thermoplastics have no volatiles and can be assumed to have a zero VOC level for practical purposes. This is also true of preformed tapes in-laid into the pavement. However, with tapes that are affixed to the pavement with a contact adhesive, the contribution of the adhesive must be taken into account. Some adhesive primers are known to contain high VOC levels; contact adhesives available from a leading supplier of tape have 672 g/L (5.64 lb/gal) and 659 g/L (5.53 lb/gal) of VOCs for cements recommended for centerline and intersection marking applications, respectively. A low-VOC, water-based adhesive with only 37 g/L (0.31 lb/gal) of VOCs is available from the same source for centerline applications. It is not as widely used as the solvent-based cements (particularly in intersection marking), probably because of limited performance under shear forces. Currently available water-based adhesives can, therefore, be used only in some applications.

Assuming the average values of VOC contents of various categories of marking materials and their known application rates (miles per gallon), the VOCs emitted per mile of marking can be readily estimated. In the case of the two-part marking systems where data on VOC emissions are not

TABLE 8 Comparison of the average annual VOC emission from solvent-borne and water-based paints

Category	Average (mode) VOC level	VOC emitted (lbs/mile-year)
Solvent-bome Paint	3.2 lbs per gallon	82
Water-based Paint	0.70 lbs per gallon	18

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available, an arbitrary minimal value of 0.01 lb/gal was assigned on the basis of the discussion in the previous paragraph. The estimated values can also be expressed in units of pounds of VOCs per mile-year using estimated average lifetimes of the markings. Results of such calculations shown in Table 9 might be combined with the statistical data on usage of solvent-based and water-based paints nationwide collected in the project survey. This allows a very approximate and conservative estimate to be made of annual emissions of VOCs from paints used for traffic markings in different jurisdictions in the United States. All roadways are assumed to be marked solely with a single centerline, and other markings are ignored in this calculation. Furthermore, local roads are excluded from the computation resulting in a conservative underestimate of the VOC emissions. Yet, they are useful in recognizing patterns of VOC emissions from pavement markings in different states across the nation. These estimates also ignore the use of paints in crossbars and symbols. The map in Figure 8 shows the results from such a calculation. Based on these data a very conservative estimate of the national annual VOC load released from single centerline paint markings alone is 39.5 million lb.

It is convenient to use the VOC content (lb/gal or g/L) to quantify the potential of a pavement marking material to pollute the environment. This is advantageous as it allows the VOC content to be directly compared with the regulated level of 150 g/ L (or 1.26 lb/g). However, the true polluting potential of a marking material depends also on the rate of application (stripe-miles marked per gallon of marking material) of the marking material as well as the frequency of restriping with that material. Therefore, the pounds of VOC per mile-year better reflect the polluting load due to a marking material. However, as paints are applied at about the same rate, there is a very strong correlation ($r2 = 0.99$) between the VOC content of the paint in lb per gallon and the lb of VOC emitted per mile.

Health Impacts of Pavement Marking Materials

Solvents and other compounds in coating formulations can volatilize during mixing or application as well as immediately after marking on the pavement, causing a temporary increase in the air concentration of these compounds in the immediate vicinity. The striping crew is exposed to these volatiles on a routine basis. The most likely route of interaction is by inhalation of the volatiles and their absorption via the mucous membranes in the respiratory passage and in the lungs. Aerosols generated during the spraying of liquids and polymer melts may also pose an additional health hazard. Removal of markings, especially by abrasive techniques, generates fine dust that may be inhaled by workers.

This section addresses the health impacts on striping crews and motorists exposed to HAP compounds present in various pavement marking materials. For liquid systems, the impact of prolonged or repeated exposure to skin may also be a con-

TABLE 9 Estimated annual release of VOCs from different pavement marking materials

Marking Type	VOC (lbs/gal)	Application Rate (g/mile)	Average lifetime (y)	VOC emissions (lbs/mile)	VOC emissions (lbs / mile-year)
Solvent-bome Paint[a]	2.7 - 4.1	16	0.65	43 - 66	66 - 101
Water-based Paint[a]	0.26 - 1.24	16	0.65	4 - 20	6 - 31
Polyester	0.01*	16	2.5	0.16	0.1
Epoxy	0.01*	20	2.0	0.20	0.1
Methacrylate	0.01*	-	4.0	0.20	0.1
Thermoplastic	0	-	4.5	0	0
Tape (inlaid)	0	-	5.0	0	0
Tape (low-VOC primer)	0.31	12.6	5.0	3.91	0.8
Tape (high-VOC primer)	5.65	16.0	5.0	90.4	18

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a Based on NASHTO data.

* A value of 0.01 lb/gallon of VOCs is arbitrarily assigned to take into account any evaporative losses during application. The actual amount of VOCs will depend on the thickness of the stripe. In sprayed systems aerosols will be the primary route for VOC emission.

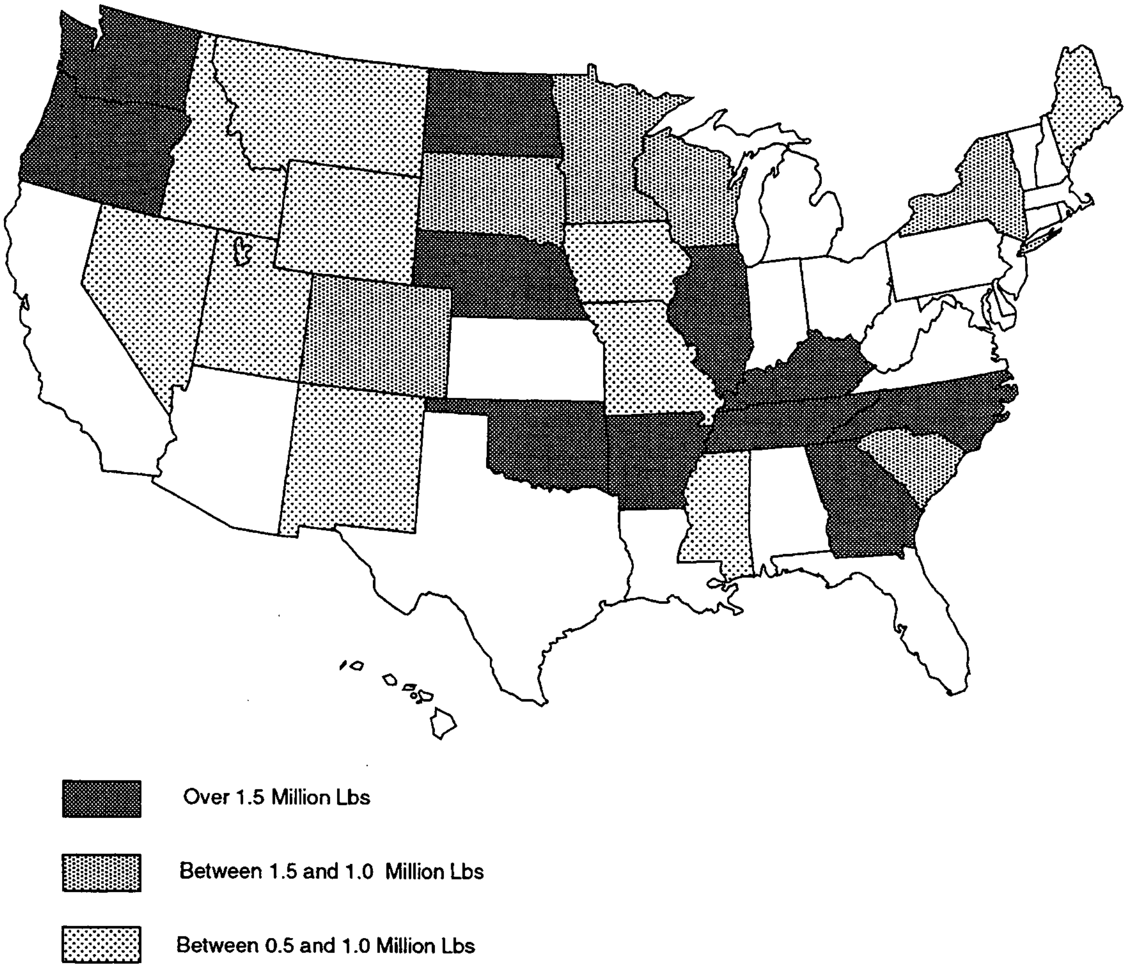

Figure 8. Estimated annual VOC emissions from the use of traffic paints in different states. This estimate does not include all paved roads, and it takes into account only a single longitudinal line marking. The blank states have estimated annual VOC emissions of less than 0.5 million pounds.

cern. This is particularly true of contact with eyes, particularly when contact lenses are being worn (contact lenses should not be worn by anyone while handling solvents). The objective here is to express the potential for health hazards semiquantitatively using a convenient parameter that can be used in the methodology to be discussed in the following chapter.

The regulation of HAPs in coating formulations is expected to be far more complicated than that of VOCs. The latter is treated as a single class of agents having a similar damaging influence on the environment; all VOCs controlled under the CAAA are considered equally potent pollutants (note, however, that this is not true of Europe, where the Geneva Protocol dealing with VOC reduction uses the concept of the "Photochemical Ozone Creation Potential [POCP]" of different VOCs.) With hazardous chemicals, however, each compound may not only affect different organs but will have different toxicity levels as well. Several databases addressing the toxicity of organic compounds are available for use in determining the health impacts associated with using these compounds. Two of these are particularly useful: the Integrated Risk Information System (IRIS), which documents the exposure levels as well as the background information on compounds; and the American Conference of Governmental Industrial Hygienists (ACGIH) database, which gives threshold limit values (TLVs) for different chemicals. These values pertain to air concentrations of the VOC and are related to the potential for health hazards in using a given marking formulation. Alternative databases exist; for example, the Maximum Allowable Concentration (MAK) values used in Germany.

Information in the IRIS2 System

IRIS2 was designed by OHEA for use by EPA employees. It is a compilation of detailed information on the toxicity of common organic compounds for use in environmental risk assessments. Volatile organic compounds that give rise to toxic end points other than cancer or gene mutation are referred to as systemic toxicants and affect the functions of various human organ systems. On the basis of current understanding of adaptive mechanisms, systemic toxicity is treated as if there were an identifiable exposure threshold below which these effects are not observable. Only systemic toxicants are treated in this manner. This concept of a threshold assumes the existence of a range of concentrations where the individual will not express any systemic toxic effects and is therefore important from a regulatory standpoint.

The assessment of risks associated with systemic toxicity is carried out by the EPA in a stepwise process involving hazard identification, dose-response assessment, exposure assessment and risk characterization. Hazard identification is based principally on human and animal studies but takes into account supporting data reported in the literature. In establishing the dose-response level, the EPA relies on one or more critical studies, preferably human studies that avoid the complications of extrapolating data from animals to humans. An exposure level where no adverse effect was observed in the exposed population compared to a valid control group is selected as the "no observed adverse effects level (NOAEL)." The process, however, is not all that clear-cut as toxicologists may disagree on what constitutes an "adverse effect." Statistically, NOAEL is a function of population size as well. Where several toxic endpoints are obtained with a single chemical, NOAEL is the lowest level at which any of the potential adverse effects were reported. A "lowest observed adverse effect level (LOAEL)" is similarly identified on the basis of available data. Based on the NOAEL values, a benchmark dose called the Reference Dose (R_fD) is derived as follows.

$$R_fD = \text{NOAEL}/(UF \times MF) \quad (3)$$

where UF and MF stand for uncertainty factor and modifying factor, respectively. UF is a factor that takes into account the order of magnitude of uncertainty associated with the critical studies, and MF (0 to 10) is a similar factor that reflects the uncertainty associated with the entire data set on that compound. R_fD is expressed in mg/kg-body weight/day. Doses lower than R_fD are not expected to be associated with any health risk. Where the inhalation of the toxicant is a possibility, an R_fC value (inhalation reference concentration) is also developed and expressed in units of mg per cubic meter.

The VOCs encountered in formulations of all pavement marking materials collected in the present study were checked against the IRIS2 database. For those VOCs listed in this database, all information pertaining to inhalation toxicity and carcinogenicity were retrieved and are included here as Appendix C. The key information in these chemical reports include the NOAEL values and R_fC values. Information on carcinogenicity of the compound, when available from the same source, is also included.

Table 10 summarizes the information available from this database. While the quality of studies used to establish these levels is high, most of the data available are for oral exposure rather than for inhalation exposure. The main drawback of the database is its incompleteness at this time. Detailed information was available for only several of the VOCs found in the different generic pavement marking systems. However, for those found in the database, excellent data and supporting documentation on toxicity assessment were found.

American Conference of Governmental Industrial Hygienists Database

The threshold limit values (TLV) published by the ACGIH were also obtained for the same set of VOCs found in pavement marking materials. This source is widely used in the practice of industrial hygiene as a guide to assist in the control of health hazards. They are not intended for regulatory use.

TLVs are airborne concentrations of substances to which the workers might be exposed daily without any adverse effects, based on the best information available from experience and research. As the amount of data on which a TLV is based varies with the particular VOC in question, the reliability and precision of the values are not the same for all compounds. Two values are generally reported: (1) the time-weighted average (TLV-TWA) concentration for a work week (8 hr days × 5 days) to which the workers can be exposed repeatedly day after day without adverse effect and (2) the short-term exposure levels (TLV-STEL) to which the workers can be exposed continuously for a short period of time without suffering health effects. The effects range from irritation, chronic or irreversible tissue damage, and/or narcosis and might be experienced (to a degree) to increase risk of accident, reduce work efficiency or impair the ability to self-rescue. STEL is defined as a 15-min TWA exposure that should not be exceeded at any time even when the 8-hour daily TWA levels are not exceeded. STEL should not be exceeded even for shorter periods of times more than 4 times per day or with a frequency of less than once in 60 min. The TLV-STEL values complement the TLV-TWA values and are used with compounds where toxic effects have been reported from short-term exposure in human or animal studies. These levels are often based on National Institute of Occupational Safety and Health (NIOSH) or on OSHA-permissible exposure limits, except where the ACGIH TLVs are more restrictive than these. While these threshold values are used in the control of potential health hazards in industrial environments and in the evaluation of air pollutant loads, they are not relative indices of toxicity. Table 11 summarizes the information from the ACGIH compilation (1995–1996 version) for the VOCs encountered in different marking formulations.

TABLE 10 Reference doses (mg per kg-day) for VOCs present in pavement marking paints (from IRIS database)

Compound[a]	NOAEL	LOAEL	Critical Effect	R_fD
1. Toluene 108-88-3	223	446	Kidney and liver weight changes	2E-1 M
2. Methanol 67-56-1	500	2500	Decreased brain weight. Increased SGPT and SAP	5E-1 M
3. Xylenes[b] 1330-20-7	179	357	Hyperactivity, decreased weight and increased mortality	2E+0 M
4. Styrene 100-42-5	200	400	Liver and red blood cell effects	2E-1 M
5. N-Hexane 110-54-3	none	73	Neurotoxicity and nasal epithelial lesions.	2E-1 M
6. Formaldehyde 50-00-0	15	82	Reduced weight gain and tissue damage	2E-1 M
7. Acetone 67-64-1	100	500	Kidney and liver weight increase	1E-1 L
8. Methyl Ethyl Ketone[c] 78-93-3	1771	3122	Decreased fetal birth weight	6E-1 L

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[a] CASRN number of compound is shown below the name.
[b] Mixture of m-xylene, p-xylene, o-xylene and ethylbenzene.
[c] Doses are for 1% solutions in 2-butanol.

Note: 1. All data except for hexane are for chronic oral exposure. The data on hexane are for inhalation exposure. Data for inhalation exposure of other compounds were not available in the database at the time of writing.

2. The letters M and L next to the R_fD values (in last column) indicate their reliability. M - Medium. L - Low.

The data are particularly pertinent to the present study as it deals with airborne chemicals. Even with the availability of reliable threshold level information, the use of this database is complicated by two serious limitations.

Lack of Data on Air-Concentration of VOCs. A valid assessment of health risks requires a knowledge of both the toxicity of the VOC in question as well as the anticipated level of exposure to that VOC. The main concern is toxicity via inhalation of the VOC by the striping crews. The inhalation doses obtained in the field will depend on a variety of factors, including the volatility of the compound, the ambient temperature, prevailing air movements, the rate of application of the stripe, the temperature of application and the type of equipment used. However, no controlled studies have been carried out to experimentally establish the levels of volatiles in the air during striping operations using different pavement marking systems. Even the extent of aerosol generation during spraying of liquid formulations is not reliably known. The VOCs as well as the aerosols are unlikely to be symmetrically distributed about the marking equipment; it is not known if most of it is concentrated behind the striper, perhaps limiting the exposure of workers in front of the striping equipment. The concentration of HAPs a striping-crew member is exposed to also depends on the kinetics of its evolution from the freshly applied stripe and the position of the worker in relation to the stripe.

Field measurements to establish HAP emission levels are not difficult to carry out and involve the sampling of air at the worksite in vacuum bottles and subsequent analysis using standard chromatographic methods. Continuous recording VOC-monitoring systems might also be used to obtain comparable data but with lower accuracy. Alternatively, the evolution and dissipation of volatiles from the marking system might be mathematically modeled using laboratory data on the volatile components. No such studies have been reported and no realistic assessment of the levels to which a striping-crew member is exposed in a typical work week can be estimated with any degree of reliability. The lack of these data is the weakest aspect of the present exercise and limits the usefulness of the methodology developed here.

Mixed HAPs in Formulations. With paint formulations, it is common to use a combination of solvents to ensure adequate coating performance. For instance, one of these might be used to dissolve the resin, another as a cosolvent to control the evaporation rate, and another to retain additives in solution. Where several HAPs are present in a mixture and they affect the same set of organs, their combined effect needs to be taken into account in assessing the risk. Assuming the volatilized concentration (or air concentration) of the mixture to be the same as that of the liquid, a composite TLV for the mixture of VOCs can be calculated as follows.

$$\{TLV\}_{\text{mix}} = 1/\{\textstyle\sum w_j/(TLV)_j\} \tag{4}$$

where w_j and $(TLV)_j$ are the weight fraction and the threshold value of each VOC component in the formulation. The

TABLE 11 TLVs of constituents in pavement marking formulations

Compound	Synonyms	TWA (ppm)	(mg/m3)	ST-TWA (ppm)	Target Organs
Toluene (XS52500000)	Toluol Methyl benzene	50	188	150	CNS, liver, kidney, skin
Methanol (PC14000000)	Wood alcohol Carbinol Methyl alcohol	200	262	250	CNS, eyes, GI tract, skin
Xylene (ZE21000000)	1,2dimethylben zene-o-xylol	100	434	150	CNS, eyes, GI tract, blood, liver, kidneys, skin
Heptane (M17700000)	Heptane	400	1640	440#	Skin, respiratory system
Methyl Ethyl Ketone (EL 6475000)	2- Butanone	200	590	300	CNS, lungs
Styrene (WL3675000)	Ethyl benzene styrol	50	213	100	Skin, resp.iratory system, CNS, eyes
Methyl methacrylate (OZ5075000)		100	410	-	Eye, Respiratory system, skin
Hexane (MN9275000)		50	176	-	Respiratory system, skin, eyes
Acetone (AL3150000)	2-propanone	250 / 750*	560/1780	1000	Respiratory system, skin
Formaldehyde (LP8925000)	Methyl aldehyde	0.01 / 1*	0.025/0.25	2	Respiratory system, skin, eyes
Amyl Acetate (AJ1925000) iso Amyl Acetate	Amyl acetic ester	100	532	-	Respiratory system, skin, eyes
VM&P Naptha**	Octanes Nonanes mixture	300 200	1400 1050	-	-

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* NIOSH and OSHA levels are different.

** VM&P Naptha (boiling range of 245°F to 290°F) is a mixture of C-8 and C-9 hydrocarbons, including paraffins, cycloparaffins and less than 1% of aromatics. The Ashland Chemicals product in this boiling range has about 60 percent normal paraffins and about 40 percent cycloparaffins.

- Ceiling concentration and "-" means no available data

CNS - Central nervous system. GI - Gastrointestinal tract

equation does not take into account synergistic effects of multiple volatiles. While it can be used to obtain a TLV for the volatile fraction of a coating composition, it assumes the different HAPs in the composition to pose similar health effects. Where the effect of individual volatiles is on different organ systems, this approach does not hold. The summary information in Table 10 indicates that many of the VOCs found in paints do in fact affect the same target organs. Assuming the above relationship to hold for pavement marking paints, the combined TLVs for the volatile fractions in paint formulations listed in Appendix B were calculated and are shown in Table 12. The composite TLV values expressed in mg per cubic meter ranged from 331 to 1,261 for the seven solvent-borne paint formulations studied. The average TLV was 604 mg/m³, and the average volatile fraction of a solvent-borne paint was 28.8 percent by weight.

Quantifying the Health Hazards Associated with Markings

Rather than relying on a rating or ranking system based on the subjective evaluation of the toxicity of different marking systems, an attempt was made to develop a parameter based on the TLVs discussed above. Each individual paint or other marking material composition will have a different complex TLV and a different VOC content. While the potential health hazard of these will vary with individual formulations, it is sufficient for the present purpose to consider the health impacts due to major categories of marking materials (as opposed to individual formulations).

A quantity of an HAP might be diluted with a sufficient volume of air v to bring its air concentration to a value below that at which it presents any health effects. The value of v (cubic meters of air needed to dilute 1 lb of the VOCs in a

TABLE 12 TLVs of the volatile fractions in selected traffic paint formulations

PAINT TYPE	Composite TLV of VOC mixture (mg/cubic meter)	Wt. Percent of VOC fraction	Air Volume in cubic meter / g paint[a]	Analysis of VOCs (%)
SP 1	434.7	27.7	0.637	Naphtha 16 Thinner 30 Toluene 12 MEK 42
SP 2	1261.6	30.1	0.239	Naphtha 73 Heptane 26 Methanol 1
SP 3	503.2	24.5	0.487	Toluene 28 MEK 68 Xylene 4
SP 4	424.3	29.9	0.705	Naphta 48 Thinner 52
SP 5	858.9	31.3	0.364	Naphtha 41 Toluene 23 Heptane 36
SP 6	331.6	29.9	0.901	Hexane 30 MEK 57 Toluene 13
SP 7	415.95	28.5	0.685	MEK 45 Thinner 40 Mixed Solvent 15
WP 1	262	2.0	0.076	Methanol
Adhesive primer for installation of Tape (High-VOC type)	536.0	78.5	1.47	Naphtha 39 Acetone 17 MEK 14 Hexane 14 Toluene 3 Amyl Acetate 8 Butyl Acetate 5
(Low-VOC type)	314.2	4.3	0.14	Toluene 55 Methanol 45

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Note: Thinner was assumed to be a mixture of hexane and cyclohexane in the ratio of 60:40. This was based on the published data for a "thinner" of boiling point comparable to that used in traffic paint formulations.
[a] The volume of air needed to dilute the total VOC content of 1 g of the paint to meet the compositeTLV level for that mixture.

marking material to a concentration equal to the TLV level for that mixture of VOCs) is therefore a reasonable guide to the toxicity of a given marking formulation. Figure 9 illustrates the interpretation of the measure v. As the lb per gallon of VOCs associated with different categories of marking materials is known, the value of v per gallon of marking material and per mile-year of marking material can be calculated. The latter is the air volume V needed per mile annually to dilute the VOCs to the TLV of the mixture and will be used to quantify health effects for the present purpose ($V = v \times$ (lb of VOCs per mile-year)). Larger values of V signify a higher potential for health hazards to the crew. Using the range of VOC levels reported for paints in the NASHTO study, the logarithm of V for solvent-borne paints ranges from 4.7 to 4.9 while that for water-based paints ranges from 4 to 4.7. While water-based paints have a relatively low level of VOCs, the types of VOCs often present (such as methanol) have a low TLV value. Their value of V is, therefore, only moderately different from that of solvent-borne paints. The field-reacted systems (epoxy, polyester and methacrylate) yield only a minimal amount of volatiles arbitrarily set here as 0.01 lb per mile-year. The corresponding value of V is 2 orders of magnitude smaller than that for conventional and water-based traffic paints. It is reasonable to assume zero emissions and no related health effects from in-laid tape or thermoplastic markings. Tapes requiring a low-VOC adhesive, however, are estimated to have a value of V, an order of magnitude higher than that for field-reacted systems. Using a high-VOC primer with tapes can increase the value of V to a value comparable to that of water-based paints. The values of V (expressed here in cubic meters air/mile-year) for different categories of marking systems are given in Table 13. However, the reader is cautioned that the rate of volatilization, the single most important factor that determines the health risk to striping crew, has not been considered in obtaining these estimates. The estimates also ignore the

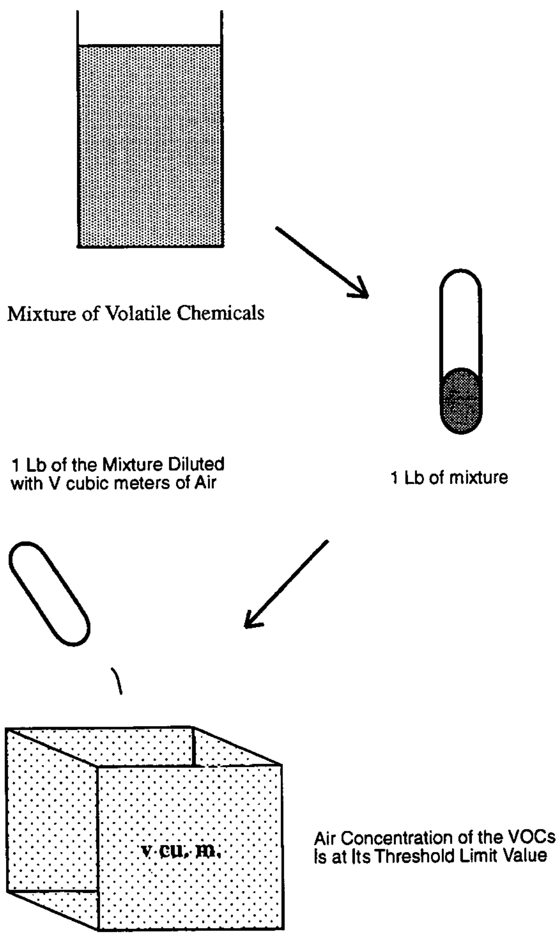

Figure 9. Interpretation of V as a measure of toxicity.

incidental use of solvents for cleaning solvent-borne paint equipment.

This treatment of mixtures in effect computes an overall or average threshold limit value for the mixture of VOCs present in the composition. While this is a valid approach with a lot of merit, different volatile compounds in paints do not volatilize at the same rate, and the most likely exposure of the striping crew is not to the total mixture but only to some fraction of it. Therefore, the more volatile compounds have a higher likelihood of posing a health hazard to workers. On this basis it is justifiable to identify those compounds in the paint mixture that have particularly high volatility as well as high toxicity. Figure 10 compares the TLV values of different solvents with their relative rate of evaporation (with that of n-butyl acetate = 1) from Solvent Property Chart published by Ashland Chemical Company. As high-TLV values and low rates of evaporation lead to lower potential hazard to striping crews, solvents such as heptane or VM&P Naphtha might be considered more desirable than solvents such as methylene chloride. This type of analysis focusing on the most undesirable component (as opposed to average effect of all VOCs) is useful, but requires accurate information on the composition and evaporation rates of the various constituents of the marking material. The evaporation rate of a single solvent is never a good indicator of the rate at which it will volatalize off a paint film containing a mixture of solvents as well as the resin. However, simple analytical techniques are available to obtain this information for any paint formulation. This approach is not pursued further in the present effort as no reliable analytical data for specific marking formulations are available.

METHODOLOGY FOR OVERALL ASSESSMENT OF PERFORMANCE

This section discusses the theoretical basis of the methodology developed here. An understanding of the concepts presented in this section is not necessary to be able to use the methodology for its intended purpose, the evaluation of pavement marking materials. Readers who are not interested in how the methodology was developed but only in its practical application may skip this section. The use of this methodology is discussed in detail and illustrated with examples in Chapter 3. For those who are interested in a detailed theoretical discussion, several excellent works are available (e.g., R.L. Keeney and H. Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs:* Cambridge University Press, Cambridge, MA [1993]).

In assessing the overall performance of a marking material, one needs to address all the key attributes of markings discussed earlier. This approach will be to carry out two separate assessment exercises: one based on the engineering performance and the other based on the environmental performance including the health impacts of the materials. This allows these two major sets of criteria to be considered independently for the time being, avoiding the difficult issue of the relative importance of engineering versus environmental performance.

Multiattribute Value Problems

In selecting a pavement marking, the user is faced with a set of key objectives such as high visibility of the markings, low lifetime cost and minimal risk of health hazards to workers. As no single marking will have all of these attributes optimized, the selection will involve tradeoffs of achievement in one objective against those of another. A selection methodology is merely a system for carrying off these tradeoffs in a structured, deliberate manner.

Previously, a fixed number of attributes of a marking material that represent its engineering as well as environmental performance were selected. The key considerations involved in the selection of a marking material might be ordered into a tree diagram or a *goals hierarchy* shown in Figure 4. The

TABLE 13 Estimates of the volume of air to dilute the VOCs to an allowable level for different marking systems

Marking Material	[a]TLV of the VOC mixture (mg/cu. m.)	VOC (lbs / mile - year)	[b]The Volume of Air v (cu. m.) per lb of VOC	[c]The Volume of Air V (cu. m.) per mile-year	Log V
Solvent-borne Paint	604	66 - 101	751	5.0 $\times 10^4$ - 7.6 $\times 10^4$	4.7 - 4.9
Water-borne Paint	262	6 - 31	1731	1.0 $\times 10^4$ - 5.4 $\times 10^4$	4.0 - 4.7
Polyester	213	0.1*	2129	21	1.32
Epoxy	400	0.1*	1134	11	1.04
Methacrylate	410	0.1*	1106	11	1.04
Thermoplastic	-	0	0	0	0
Tape (Inlaid)	-	0	0	0	0
Tape (Low-VOC primer)	314	0.8	1445	1.16 x 10^3	3.05
Tape (High-VOC primer)	536	18	846	1.53 x 10^4	4.18

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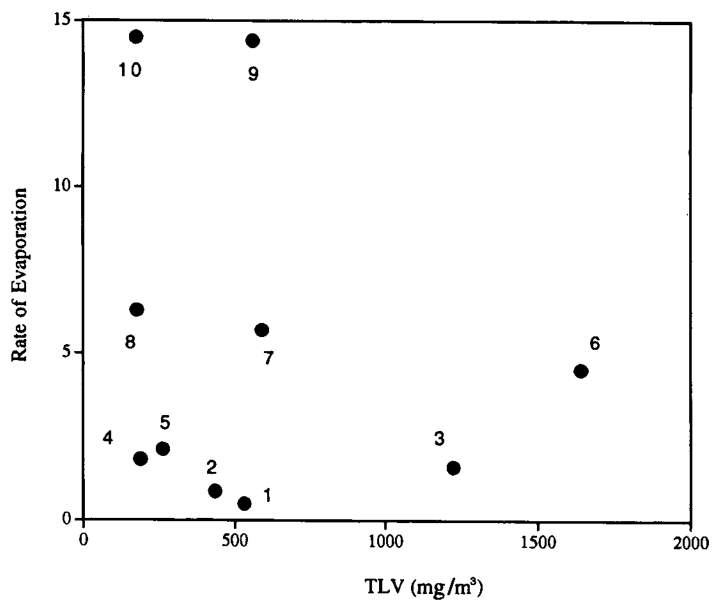
* VOC level assigned to take into account volatilization of unreacted chemicals during application.

[a] The TLV values of mixtures of VOC's were calculated using equation [4] for paints and adhesives. That for polyester and methacrylate markings were set at the TLV for styrene and methacrylate monomers, respectively. That for epoxy was assigned on the basis of the TLV values of typical constituents in formulation. See Table 12.

[b] v = Cubic meters of air needed to dilute 1 pound of the VOC mixture in marking material to obtain a mixture of vapor that will contain the Threshold Limit Value (TLV) of the mixture of volatiles. At this low air concentration, routine exposure to the VOC fraction is not expected to pose a health risk.

Note: v (cu.m./lb of VOC) = $\dfrac{\text{cu.m.} \;\; 1000\text{ mg.} \;\; 453.5\text{ g}}{(\text{TLV})\text{ mg} \; . \; 1\text{g} \; . \; 1\text{ lb}}$ = 453.5 x 10^3 /TLV (mg/cu.m.)

[c] V = v . (VOC lbs / mile-year)



1 - Amyl Acetate 2 - Xylene 3 - VM&P Naphtha 4 - Toluene 5 - Methanol 6 - Heptane
7 - Methyl Ethyl Ketone 8 - Hexane 9 - Acetone 10 - Methylene Chloride

Figure 10. Comparison of the rate of evaporate (n-Butyl acetate = 1.0) to the TLV value (ACGIH) of common solvents used in pavement marking materials.

broader considerations at higher levels of the hierarchy or the *objectives* are eventually expressed as individual *attributes* at the lowest levels. In the simple hierarchy set up for the present purpose, the objectives are indicated in rectangular spaces in the diagram and the attributes are shown in oval spaces. Any attribute in the set can be quantified in terms of an actual measurement (e.g., the attribute of lifetime cost is measured in dollars) or in terms of an arbitrary rating (as with storage stability measured on a scale of 0–5). The selection of *measures* for various attributes was discussed earlier.

While the desirability of a more comprehensive hierarchy that includes additional objectives and attributes was recognized, it was not pursued because of the lack of data to justify its use. It is assumed that a given pavement marking is completely described in terms of the nine attributes at the lowest level of the goals hierarchy diagram. Table 14 lists the nine attributes, their measures, and the relevant units.

A valid minimal set of attributes has several important properties. The basic requirement is, of course, comprehensiveness; the selected attributes should cover the key considerations involved in assessing the performance of a marking material. The attributes must be operational and be useable in practice. At least some of the attributes are decomposable to a pair of measures while others are expressed in terms of a single measure. Lack of redundancy is important to avoid double-counting a characteristic. A pair of attributes in the present analysis, "long service life" and "low cost," are related as the latter is measured in terms of annual cost based on the life-cycle cost calculations. However, given the importance of lifetime to the selection process, this is not considered to introduce redundancy to the analysis.

The function used to reduce the different measures into comparable units is a single-measure, scalar-valued utility function. A measure of v_j for an attribute can be translated into a corresponding utility U_j such that

$$0 < U_j(v_j) < 1 \qquad j = 1 \text{ to } 9 \tag{5}$$

The nine measures in Table 14 require the identification of nine utility functions U_1 through U_9 to convert them into utility values. These might be a set of simple linear equations or more complicated expressions. Higher numerical values $U_j(v_j)$ for a given attribute need not always result in a higher utility or desirability; high life-cycle cost, for instance, is associated with low utility.

The calculation of multimeasure utility values is complicated by the fact that different attributes are not equally important in the selection process. For instance, retroreflectivity is regarded as a more important attribute compared to ease of use by most selectors. To reflect such inequities, a weight w_j is assigned to each attribute and/or measure. The features of the goals hierarchy (shown in Figure 4) require the following to hold for the set of weights so defined.

$$(w_1 + w_2) = (w_4 + w_5) = (w_7 + w_8) = 1 \tag{6}$$

$$w_3 = w_6 = 1$$

$$w_A + w_B + w_C + w_D = 1 \tag{7}$$

$$w_E + w_F = 1$$

These equations are determined by the form of the hierarchical diagram with the sum of weights associated with all branches at a node being equal to unity. The multimeasure utility for any given objective in the diagram might now be conveniently expressed in terms of weighted utility functions. For instance, the utility for objective of high visibility can be quantified as follows.

$$w_c U_c = w_1 U_1 + w_2 U_2 \tag{8}$$

with

$$w_1 + w_2 = 1$$

A similar expression might be written for any node at any level of the hierarchy. The most complicated of these will be for the highest level; for instance, for goal A the engineering performance of a marking. The corresponding linear equation is

$$U_{\text{eng}} = w_c(w_1 U_1 + w_2 U_2) + w_3 U_3 + w_E(w_4 U_4 + w_5 U_5) + w_6 U_6 \tag{9}$$

That associated with environmental performance can be similarly obtained.

$$U_{\text{env}} = w_H(w_8 . U_8 + w_9 . U_9) + w_G . U_7 \tag{10}$$

The solution to multiattribute problems is sensitive to the choice of weights and particularly to that of utility functions. Selection of utility functions is based on an appreciation of how increments in the measured values (or the rating) of an attribute will relate to the utility or the desirability of the marking material. The simplest are the linear functions where the utility either increases or decreases linearly with the attribute. Some of the attributes dealt with here will, however, have to be identified with nonlinear utility functions as well.

Assignment of Weights and Utility Functions

On the basis of historical data and the experience of the pavement marking community, it is possible to identify an appropriate set of weights for the present purpose. These weights, however, will change with factors such as the ADT values of the pavement, its age or condition, the local regulatory environment, and fiscal constraints at the time of evaluations. The proposed weights are therefore merely suggested reasonable values; actual weights to be applied in a given situation need to be arrived at by the user taking all relevant factors into account. One set of weights is better than another only in that it better reflects the priorities, political

TABLE 14 Attributes, measures, and their units used in the present analysis

Goal	Attribute	Measure	Units of Measure
Good Environmental Performance	1. High Visibility	Rate of loss of retroreflectivity	T_{100} (months)
		Rate of loss in appearance	Appearance rating at 12 m
	2. Long Service Life	Durability	Tenth of percent of the marking remaining at 12 m
	3. Convenience	Ease of Use	Rating
		Storage Stability	Rating
	4. Low Cost	Lifecycle cost	Annual cost in $
Good Environmental Performance	1. Low VOC content	VOC level	Lbs per gallon
	2. Safety	Health Risk	Logarithm of V
		Other	Rating

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realities, and experience of the particular user. A set of proposed weights is given below and in a hierarchical diagram (see Figure 4). These weights satisfy the additivity requirements described above.

$w_C = 0.30$	$w_D = 0.30$	$w_E = 0.10$
$w_F = 0.30$	$w_G = 0.60$	$w_H = 0.40$
$w_1 = 0.80$	$w_2 = 0.20$	$w_3 = 1.00$
$w_4 = 0.67$	$w_5 = 0.33$	$w_6 = 1.00$
$w_7 = 1.00$	$w_8 = 0.85$	$w_9 = 0.15$

To specify a utility function for a given attribute, the mathematical form of the function and the boundary values for $v_i : U_i(v_i) = 0$ and $v_i : U_i(v_i) = 1.0$ needs to be stated. Basically, there will be two types of functions: those where the utility increases with increasing numerical value of the measure and those where the utility decreases with increasing value of the measure. It is convenient to discuss different categories of utility functions separately.

Utility Functions for Ratings. Some of the measures are ratings as opposed to actual measurements of the property of a marking material. The measures of Ease of Use, Storage Stability, and Other Safety Considerations for different pavement marking materials can be conveniently expressed as ratings. All three are rated on a scale of 0 to 5.0 with larger numerical values indicating higher utility. It is reasonable to expect the desirability of the material to vary linearly with the rating, with zero utility when the rating is zero. The utility function, therefore, will have the form

$$\text{Utility} = 0.2X \qquad (11)$$

where X is the numerical rating.

The Appearance is also a rating expressed on a scale of 1 to 10 and can be handled similarly with an expression where the gradient is 0.1. Figure 11 illustrates these utility functions.

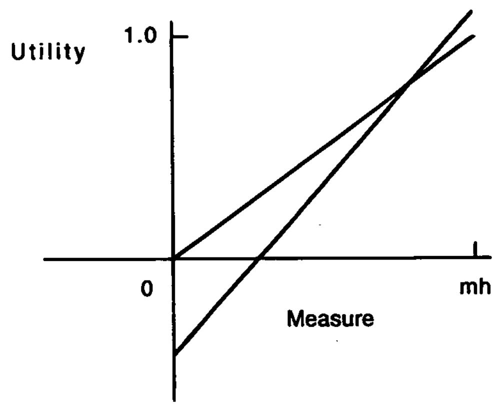
Retroreflectivity Measure of T_{100}. The worst possible case is a marking that takes less than a month of use to reach the minimum acceptable retroreflectivity (i.e., $T_{100} = 0$). It is reasonable to assign this case-zero utility. The longest value of the measure reported in SASHTO data for polyesters is 166 months for a white stripe! A maximum value of 150 months was arbitrarily selected as the "best" expected value. This was assigned a utility of unity. The utility is assumed to increase linearly with the duration in months to reach minimum acceptable retroreflectivity (T_{100}).

$$\text{Utility} = (T_{100})/150 = 1 \text{ for } T_{100} > 150 \text{ months} \qquad (12)$$

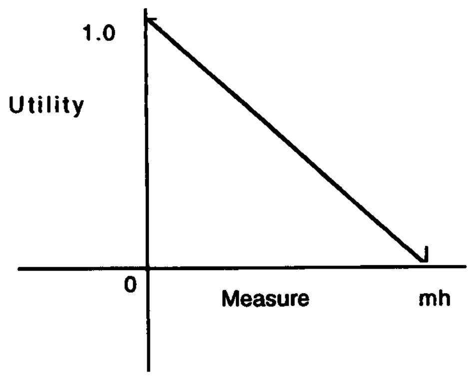
Cost. Life-cycle cost is an estimate that might also be expected to proportionately affect the utility, with lower cost yielding higher utility. With this measure of cost, a negative gradient and a positive intercept is expected. The maximum and minimum values for the range of costs (0 to $3.00) was based on the information collected in the survey and the reported average lifetimes of different marking materials.

$$\text{Utility} = -0.33\ \text{Cost}(\$) + 1 \qquad (13)$$

Durability. Durability of a marking is indicative of the physical lifetime of the stripe as opposed to the period during which it maintains acceptable retroreflectivity. Based on the data collected in the user survey carried out as a part of this project, restriping due to loss of reflectivity or due to loss of durability was found to be equally likely. Therefore, as with retroreflectivity, a simple linear utility function is appropriate for durability. The one proposed here ranges from values of 2 to 10 for durability based on the durability data for various markings reported in NASHTO and SASHTO studies. As most markings have high values of 12-month durability, a value of 2 (instead of 0) is assigned as the minimum durability (after 12 months use) and zero utility. No change



Utility increases from zero to 1 as the value of measure increases from 0 to mh.
Functions proposed for Reflectivity, Durability, Appearance, Ease of Use, Storage Stability, and Safety, fall into this category.



Utility decreases from 1 to zero as the value of measure increases from zero to mh.
Function proposed for Lifetime Cost of Markings falls into this category.

Figure 11. Illustration of several simple utility functions used in the assessment methodology.

in durability (i.e., a value of 10) is assigned the maximum utility of 1.

$$\text{Utility} = 0.125 \text{ Durability} - 0.25 \qquad (14)$$

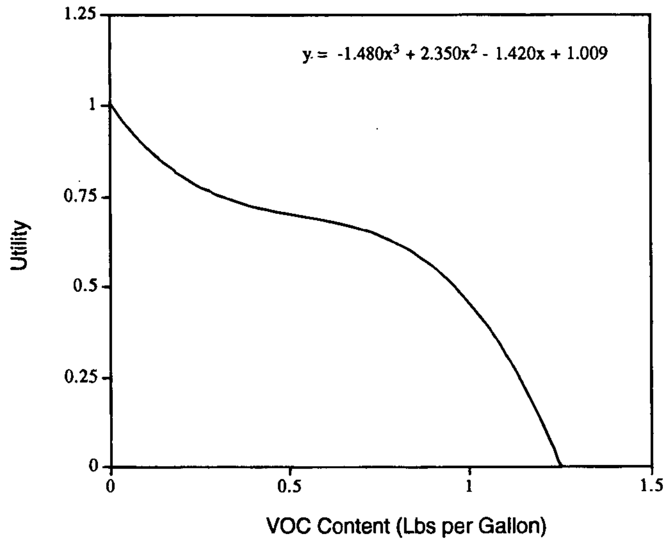
VOC Content. The two major attributes describing the environmental performance of markings are the VOC content and toxicity. With VOCs the upper limit is already established by regulation. As this maximum allowable VOC level is likely to be revised downward in the future, VOC contents lower than the stipulated regulatory limit are more desirable. Therefore, a non-linear utility function is proposed for this measure as opposed to using merely a "pass/fail" criterion to take into account this crucial property. The form of the function must recognize the desirability of even a moderate lowering of the VOC content of paint formulations used widely in pavement markings. The convex part of the curve takes this into account. A plot of the utility function proposed is shown in Figure 12 and a listing of values is given below it. This type of plot is well represented by the empirical polynomial equation below that might be used to calculate utility values from known values of durability after 12 months of use.

$$\text{Utility} = 1.48X^3 + 2.35X^2 + 1.42X + 1.009 \qquad (15)$$

Toxicity. The utility of using a low-HAP coating is determined by the likelihood of inhalation toxicity and the severity of the health impact. In the absence of data for a more complete analysis, the researchers developed V (the volume of air needed to dilute the VOCs in the formulation to TLV) as a reasonable measure of toxicity. A logarithm of V was used as a measure of the toxicity of the formulation and varies between 0 and 5.0 for most classes of marking materials. A simple utility function of the following form is proposed for the present purpose.

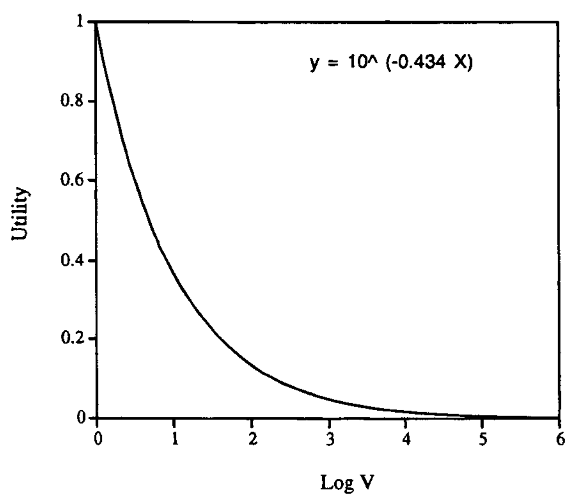
$$\text{Utility} = 10^{(-0.434 \text{ Log } V)} \qquad (16)$$

This function, shown in Figure 13, shows the utility to be relatively insensitive to V at higher values of Log V.



Lbs/Gallon	Utility	Lbs/Gallon	Utility	Lbs/Gallon	Utility
1.25	0.02	0.80	0.62	0.35	0.74
1.20	0.13	0.75	0.64	0.30	0.76
1.15	0.23	0.70	0.66	0.25	0.78
1.10	0.32	0.65	0.67	0.20	0.81
1.05	0.40	0.60	0.68	0.15	0.84
1.00	0.46	0.55	0.69	0.10	0.89
0.95	0.51	0.50	0.70	0.05	0.70
0.90	0.56	0.45	0.71	0.00	1.00
0.85	0.59	0.40	0.72		

Figure 12. Proposed utility function for VOC content of markings.



Log V	Utility	Log V	Utility	Log V	Utility	Log V	Utility	Log V	Utility
0.0	1	1.00	0.37	2.00	0.14	3.00	0.05	4.00	0.02
0.25	0.78	1.25	0.29	2.25	0.11	3.25	0.04	4.25	0.01
0.50	0.61	1.50	0.22	2.50	0.08	3.50	0.03	4.50	0.01
0.75	0.47	1.75	0.17	2.75	0.06	3.75	0.02	5.00	0.01

Figure 13. Proposed utility function for toxicity of markings.

As stated earlier, these proposed utility functions, while reasonable on the basis of assumptions made in this study, are open to modification. Such changes will in fact be needed to ensure that the pavement marking experience within a state agency and the priorities pertaining to pavement marking projects are properly taken into account in the analysis. This is also true of the attributes selected for inclusion in the analysis as well as of the weights assigned to them.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATION

This chapter discusses the application of the methodology developed and illustrates the procedure using data from the SASHTO and NASHTO studies. The methodology for assessment of pavement markings makes relative comparisons between two or more pavement marking systems for which adequate test data and compositional information are available. Its success depends on the selection of attributes to be included in the analysis and the choice of weights that reflect the constraints and priorities pertaining to the user agency. A typical use for the methodology would be to compare a relatively new marking material with an established material such as solvent-borne paints. This requires test data that are generated at the location of interest, or at least in the general region, for the two candidate materials. Initially the attributes and weights proposed here might be used to carry out a performance analysis. The result might then be refined where needed by modifying the weights or even the set of attributes used in the present analysis. The methodology is summarized in Scheme 1.

DESCRIPTION OF METHODOLOGY

1. Review the weights assigned to each attribute of the pavement marking materials indicated on the tree diagram A. If these weights do not correctly reflect the particular experience, priorities, and constraints in the jurisdiction of the user, they should be revised by the user. To help the user revise these weights while maintaining the mathematical relationships between them, a template (Template A) is provided.
2. Obtain the data needed for the two or more marking materials to be compared. This methodology requires nine data input values of various measures of the performance of pavement marking materials in question. This number of inputs (or measures) might be reduced if the user decides to disregard some of the inputs. Template B provides a convenient means of compiling the data in the required units.
3. Convert the collected data into corresponding values of utility, using the utility functions given in Table 15.
4. Calculate the values of U_{eng} and U_{env} using the multimeasure utility equation. Plot the result to graphically illustrate the performance. Template C guides the user through the calculations.

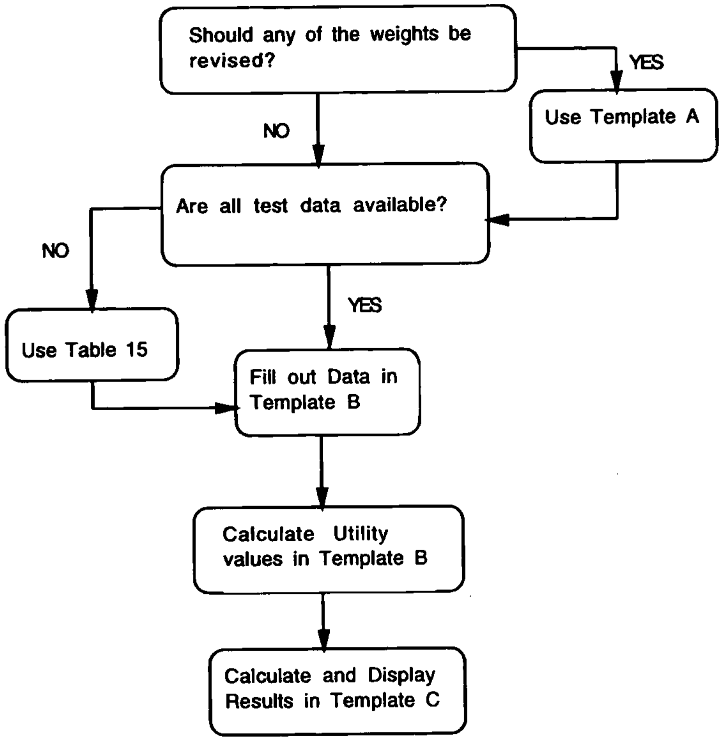
1. Review of Weights (Use Template A)

The review of weights is a crucial part of the evaluation process. The methodology involves value tradeoff decisions that cannot be made on technical grounds alone. The weights assigned to each attribute were carefully selected on the basis of opinions expressed by a panel of experts. However, these weights will not be universally suitable for use in all situations. Pavement marking projects in locations with different climatic conditions and roadway conditions or those experiencing very different ADTs may require different sets of weights. The weights may also be different for agencies operating under specific constraints such as budget limitations or the availability of in-house expertise with the application of a particular type of marking material. However, it is important to use Template A to revise the weights to ensure that the revised values meet the mathematical relationships.

2. Compilation of Data on Marking Materials (Use Template B)

The following nine inputs are required to carry out the evaluation. Some of these might be eliminated by the user by setting the respective weight at a value 0. For instance, if the value of weight w_2 is set to 0 (and $w_1 = 1$), then appearance rating can be dropped as an input. Where needed, a different attribute and a corresponding measure might be used in its place and the appropriate weight selected for it.

- A value for T_{100} expressed in months.
- A rating for appearance 12 months after installation (0 to 10 expressed to the first decimal place).
- A value for durability 12 months after installation (0 to 10 expressed to first decimal place).
- A rating for the ease of use (0–5).
- A rating for the storage stability (0–5).
- Estimate of the annual life-cycle cost of the material expressed in U.S. dollars to the nearest cent.
- The VOC content of the marking material in pounds per gallon. (Note: To convert lb/gal into g/L multiply by 119.05.).
- The hazardous potential of the material based on the value of *V*.
- A rating for other safety factors (0–5).



Scheme 1

All or some of these data might be provided by the users based on their experience with the marking material under local conditions. Such data, however, are not always available, and a user may have to rely on published information for some of the needed data. The test data reported rarely will be for the identical formulation of marking material of interest or for a comparable location. Therefore, one has to often rely on measures for broad classes of marking materials rather than for individual marking material such as a specific solvent-borne paint.

Default values are given for all nine inputs for each broad category of marking material, based on the SASHTO and NASHTO data, to be used in the event that user-provided data are not available. These values are listed in a Table of Default Values (Table 16) for each class of pavement marking materials for which data are reported. This allows a user with little or no available data to at least evaluate markings based on the performance in either the SASHTO or the NASHTO test program. Data relating to appearance are available only from SASHTO data. Default values from other published sources might be used in place of those indicated in Table 16, particularly where the alternate data were generated under conditions closer to those of interest to the user.

3. Conversion of Input Values into U-Values (Use Template B)

This is a simple mathematical transformation of the data based on the nine utility function equations derived previously. Most of these are simple algebraic operations. For toxicity and VOC content, the functions are nonlinear, and the tables of values provided in the Table 15 might be conveniently used. Alternatively, the empirical equations given in Figures 12 and 13 might be used to calculate approximate values of the utility.

4. Calculation of Performance Factors (Use Template C)

Based on data collected and tabulated in Templates A and B, a simple calculation of the total weighted utility is carried out in Template C. It is far more convenient to carry out these calculations in a spreadsheet program or using software specially written for the purpose. This allows an easy means of assessing the impact of changing the weights assigned to different measures and of different utility functions on the outcome of the analysis.

ILLUSTRATIONS ON THE USE OF METHODOLOGY

The methodology is illustrated using several comparisons of the performance of marking materials based on the NASHTO/SASHTO data. The examples shown use both the proposed set of weights as well as revised weights. The detailed procedure for carrying out the assessment using the Templates provided is given in Appendix D.

Example 1: Compare the overall performance of a typical solvent-borne and a water-based paint using NASHTO and SASHTO data to obtain default value inputs.

TEMPLATE A : REVISION OF WEIGHTS FOR ENGINEERING PERFORMANCE

OBJECTIVES	HIGH VISIBILITY	LONG LIFETIME	CONVENIENT TO USE	LOW COST	REVISED WEIGHTS MUST ADD UP TO 1.OO AS SHOWN.
PROPOSED WEIGHT	$W_C = 0.30$	$W_D = 0.30$	$W_E = 0.10$	$W_F = 0.30$	$W_C+W_D+W_E+W_F = 1.00$
REVISED WEIGHT					$W_C+W_D+W_E+W_F = 1.00$

ATTRIBUTES FOR OBJECTIVE C	CHANGE IN RETROREFLECTIVITY	CHANGE IN APPEARANCE	REVISED WEIGHTS MUST ADD UP TO 1.OO AS SHOWN
PROPOSED WEIGHT	$W_1 = 0.80$	$W_2 = 0.20$	$W_1+W_2 = 1.00$
REVISED WEIGHT			$W_1+W_2 = 1.00$

ATTRIBUTES FOR OBJECTIVE E	EASE OF USE	STORAGE STABILITY	REVISED WEIGHTS MUST ADD UP TO 1.OO AS SHOWN
PROPOSED WEIGHT	$W_4 = 0.67$	$W_5 = 0.33$	$W_1+W_2 = 1.00$
REVISED WEIGHT			$W_1+W_2 = 1.00$

TEMPLATE A : REVISION OF WEIGHTS FOR ENVIRONMENTAL PERFORMANCE

OBJECTIVES	LOW VOC	HEALTH AND SAFETY OF STRIPING CREW	REVISED WEIGHTS MUST ADD UP TO 1.OO AS SHOWN.
PROPOSED WEIGHT	$W_G = 0.60$	$W_H = 0.40$	$W_G+W_H = 1.00$
REVISED WEIGHT			$W_G+W_H = 1.00$

ATTRIBUTES FOR OBJECTIVE H	TOXICITY OF THE MARKING	OTHER SAFETY CONSIDERATIONS	REVISED WEIGHTS MUST ADD UP TO 1.OO AS SHOWN
PROPOSED WEIGHT	$W_8 = 0.85$	$W_9 = 0.15$	$W_8+W_9 = 1.00$
REVISED WEIGHT			$W_8+W_9 = 1.00$

TABLE OF REVISED WEIGHTS TO BE USED IN THE CALCULATION

	w_1	w_2	w_3	w_4	w_5	w_6		w_7	w_8	w_9
PROPOSED WEIGHT	0.80	0.20	1.00	0.67	0.33	1.00		1.00	0.85	0.15
REVISED WEIGHT			1.00			1.00		1.00		

The marking material evaluation sheet in Appendix D illustrates the use of the above three steps and shows step-by-step calculations to obtain the U_{eng} and the U_{env} parameters. The results are given below.

	Solvent-Borne Paint	*Water-Based Paint*
U_{eng}	0.59	0.59
U_{env}	0.06	0.45

The engineering performance of the two types of paints is about the same but the water-based paints evidently offer far superior environmental performance. This advantage is almost solely a result of adherence to the regulatory pressure for lower VOC contents in paints, a factor weighted heavily in the present analysis.

Example 2: Compare the performance of inlaid preformed tape versus tape that is adhered onto the pavement surface using either a high-VOC or a low-VOC adhesive. The VOC data for typical adhesives commercially available were used for the purpose.

TEMPLATE B : DATA COLLECTION AND CONVERSION

1. FILL IN THE REQUESTED DATA IN THE TABLE BELOW FOR EACH TYPE OF MARKING MATERIAL TO BE EVALUATED. ENTER DATA IN THE UNITS INDICATED.

2. WHERE DATA OR ESTIMATES PERTAINING TO YOUR OWN LOCATION ARE NOT AVAILABLE USE DATA FROM DEFAULT VALUES TABLE (TABLE I 6).

INPUTS	units	Marking 1	Marking 2	Marking 3	Marking 4	Marking 5
1. T_{100} in months	months					
2. Appearance (12 m)	1 to 10					
3. Durability (12 m)	1 to 10					
4. Ease of use rating	1 to 5					
5. Storage stability rating	1 to 5					
6. Annual cost	US $					
7. VOC content	(lbs/g)					
8. Hazard potential	Log V					
9. Other safety	1 to 5					

3. ALL NINE BOXES FOR EACH TYPE OF MARKING TO BE EVALUATED MUST BE COMPLETED BEFORE PROCEEDING TO THE NEXT STEP.

4. CONVERT EACH MEASURE (IN EACH OF THE BOXES ABOVE) TO UTILITY VALUES USING THE CONVERSION TABLE (TABLE I 5).
ALL NINE BOXES FOR EACH TYPE OF MARKING TO BE EVALUATED MUST BE COMPLETED BEFORE PROCEEDING TO THE NEXT STEP. COPY THE DATA INTO TEMPLATE C.

INPUTS		Marking 1	Marking 2	Marking 3	Marking 4	Marking 5
1. T_{100} in months	U_1					
2. Appearance (12 m)	U_2					
3. Durability (12 m)	U_3					
4. Ease of use rating	U_4					
5. Storage stability rating	U_5					
6. Annual cost	U_6					
7. VOC content	U_7					
8. Hazard potential	U_8					
9. Other safety	U_9					

	Inlaid Tape	*Adhered Tape (Low VOC)*	*Adhered Tape (High VOC)*
U_{eng}	0.47	0.43	0.43
U_{env}	0.99	0.50	0.04

The analysis yielded the above result. Having zero VOCs, inlaid tapes that can be used with new pavements show the best environmental performance of the three materials. The use of adhesive primers decreases this very high level of environmental performance to an extent depending on the VOC content of the primer. In spite of their low application rates, the high VOC contents of the primers lead to very large reductions in the environmental performance. The results of the analysis are shown in Figure 14.

Example 3: Compare the performance of thermoplastic markings with that of epoxy markings using default input values from SASHTO data. However, revise the weights to exclude the measure of appearance from the evaluation.

Appearance rating is excluded here as it is often difficult to find long-term data on the appearance of a marking. The revised set of weights will be as follows. Note that weights w_C through w_H remain the same, but both w_1 and w_2 are changed.

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9
Revised Weight	***1.0***	***0.0***	1.00	**0.67**	**0.33**	1.00	1.00	**0.85**	**0.15**

The results from the analysis are as follows.

	Thermoplastic	*Epoxy*
U_{eng}	0.57	0.60
U_{env}	0.97	0.76

TABLE 15 Expressions for converting the values of measures to values of utility

Measure (X)	units	Range of values.	Equation to convert the measures into utility values.
T_{100}	months	X: 0 to 150	U = X/150 U=1 for X > 150 m
Appearance	Rating	X: 0 to 10	U = 0.1X
Durability		X: 2 to 10	U = 0.125 X -0.25
Ease of Use	Rating	X: 0 to 5	U = 0.2X
Storage Stability	Rating	X: 0 to 5	U = 0.2X
Cost	$ per year	X: 0 to 3.00	U = -0.33X + 1
VOC content	lbs/gal	X: 0 to 1.25	See Table below {$y = -1.48X^3+2.35X^2-1.42X+1.01$}
Toxicity (LogV)		X: 0 to 5.0	See Table below {$U = 10^{(-0.43X)}$}
Other Safety	Rating	X: 0 - 5	U = 0.2X

TABLE FOR CONVERTING VOC CONTENT (LBS. PER GALLON) INTO UTILITY VALUES.

Lbs/Gallon	Utility	Lbs/Gallon	Utility	Lbs/Gallon	Utility
1.25	0.02	0.80	0.62	0.35	0.74
1.20	0.13	0.75	0.64	0.30	0.76
1.15	0.23	0.70	0.66	0.25	0.78
1.10	0.32	0.65	0.67	0.20	0.81
1.05	0.40	0.60	0.68	0.15	0.84
1.00	0.46	0.55	0.69	0.10	0.89
0.95	0.51	0.50	0.70	0.05	0.70
0.90	0.56	0.45	0.71	0.00	1.00
0.85	0.59	0.40	0.72		

TABLE FOR CONVERTING VALUES OF LOG V INTO UTILITY VALUES.

Log V	Utility	Log V	Utility	Log V	Utility	Log V	Utility	Log V	Utility	Log V	Utility
0.0	1.00	1.00	0.37	2.00	0.14	3.00	0.05	4.00	0.02	5.00	0.007
0.25	0.78	1.25	0.29	2.25	0.11	3.25	0.04	4.25	0.014	5.25	0.005
0.50	0.61	1.50	0.22	2.50	0.08	3.50	0.03	4.50	0.011	5.75	0.003
0.75	0.47	1.75	0.17	2.75	0.06	3.75	0.02	4.75	0.009	6.00	0.003

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The difference between the two marking materials is primarily in their environmental performance. Even the minimal VOCs associated with the field-reacted epoxy system make it somewhat less environmentally attractive than the thermoplastic. The values obtained are only slightly changed by dropping appearance as a measure; including it as a measure, the engineering performance of both marking materials would have been higher by about 0.05 units. The environmental performance is of course unaffected by changes to w_1 and w_2.

Example 4: Compare the performance of all different classes of pavement marking materials on which data are reported in the SASHTO report. Use the unrevised set of weights used in examples 1 and 2 above.

The procedure used in examples 1 and 2 was carried out on all types of marking materials using the default values from NASHTO study as the input data. Appearance data for all types of markings were taken from the SASHTO data. Details are not given for this example, but the data obtained are plotted to illustrate the relative performance of the marking materials (Figure 15).

The objective of the example is to illustrate the use of this new methodology in ranking several marking systems relative to one another. Choices suggested by this particular analysis based on reported data may not be applicable in a general sense. Wherever possible, the user needs to rely on valid test data rather than merely using the default values given here to obtain a meaningful result.

TEMPLATE C: CALCULATIONS

FROM TEMPLATE A COPY

	w_C	w_D	w_E	w_F	w_G	w_H
REVISED WEIGHT						

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9
REVISED WEIGHT			1.00			1.00	1.00		

FROM TEMPLATE B COPY

INPUTS	Index i	Marking 1	Marking 2	Marking 3	Marking 4	Marking 5
1. T_{100} in months	U_1					
2. Appearance (12 m)	U_2					
3. Durability (12 m)	U_3					
4. Ease of use rating	U_4					
5. Storage stability rating	U_5					
6. Annual cost	U_6					
7. VOC content	U_7					
8. Hazard potential	U_8					
9. Other safety	U_9					

CALCULATION

1. $P = w_C (w_1 . U_1 + w_2 . U_2)$
2. $Q = w_E (w_4 . U_4 + w_5 . U_5)$

$$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3$$

3 $R = w_H (w_8 . U_8 + w_9 . U_9)$

$$U_{ENV} = R + w_G . U_7$$

The result in Figure 15, though based on data specific to two locations, is informative and interesting. Various pavement marking materials are seemingly very different in their performance when quantified in the manner developed here. It is clear that the more desirable marking materials should fall in the top right-hand quadrant of the plot. Arbitrarily selecting a minimum level of engineering performance equal to or better than conventional solvent-borne paints, the choices of marking materials at different levels of environmental performance can be discerned from the diagram. The highest performers exceeding a utility of 0.75 for environmental performance are the thermoplastics and preformed thermoplastics. If the next lower level of environmental performance (utility > 0.50) is selected, polyesters might be added to the group. Small changes in the acceptable minimum values allow two more markings to be included in the category: the epoxy systems and the water-based paints. Subject to the assumptions used in the analysis, it is possible to rank the few marking materials that show high performance in both engineering as well as environmental performance, as follows.

Thermoplastics and Preformed thermoplastics > Epoxy and Polyester > Water-based paints

Example 5: Compare solvent-borne and water-based pavement marking material using the following revised set of weights. Note that all weights are revised to suit a specific user's experience.

	w_C	w_D	w_E	w_F	w_G	w_H
Revised Weight	**0.35**	**0.15**	**0.10**	**0.40**	**0.70**	**0.30**

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9
Revised Weight	***1.0***	***0.0***	1.00	**0.50**	**0.50**	1.00	1.00	**0.85**	**0.15**

Note that these weights are very different from those used hitherto in the analysis. The results obtained using these revised weights and the original set of weights are compared below to illustrate the sensitivity of the evaluation to the

TABLE 16 Default values for inputs (from NASHTO and SASHTO data)

INPUTS	Units	Solvent paints	Water paints	Thermoplastic	Tape	Tape (adhered)
1. T_{100} in months	months	12 white 3 yellow	26 to 28	14 white 8 yellow	14 white 12 yellow	
2. Appearance (12 m)	1 to 10	-	-	-	-	-
3. Durability (12 m)	1 to 10	7	7	8 white 9 yellow	9	
4. Ease of use rating	1 to 5	4	4	2	4	2
5. Storage stability rating	1 to 5	2	2	5	5	4
6. Annual cost	US $	0.29	0.58	0.40	2.63	
7. VOC content	(lbs/g)	3.2	0.7	0	0	5.65 High VOC 0.31 Low VOC (adhesive primer)
8. Hazard potential	Log V	4.50	4.04	0	0	4.0 High VOC 3.0 Low VOC
9. Other safety	1 to 5	4	4	2	4	3

Table of Default Values for Inputs Based on SASHTO Data

INPUTS	Units	Solvent paints	Water paints	Thermoplastic	Tape	Tape (adhered)
1. T_{100} in months	months	9 white 7 yellow	38 white 18 yellow	41/19* white 19/8 * yellow	30 to 31	
2. Appearance (12 m)	1 to 10	7.4 white 8.0 yellow	8.5	8.7/9.2 white 9.4 yellow	9.3	
3. Durability (12 m)	1 to 10	7 white 8 yellow	9 white 7 yellow	9.6 alkyd 9.0 hydrocarb.	9.4	

Data on thermoplastics are for alkyd on first line (white/yellow) and for hydrocarbon on second line (white/yellow) ANDRADY 1996

INPUTS	Units	Polyester	Epoxy	Preformed Plastic
1. T_{100} in months	months	white 39 yellow 4	19	13
2. Appearance (12 m)	1 to 10	-	-	-
3. Durability (12 m)	1 to 10	9	10	-
4. Ease of use rating	1 to 5	2	2	3
5. Storage stability rating	1 to 5	2	2	5
6. Annual cost	US $	0.24	0.75	0.40
7. VOC content	(lbs/g)	0	0	0
8. Hazard potential	Log V	2	2	0
9. Other safety	1 to 5	2	3	0

Table of Default Values for Inputs Based on SASHTO Data

INPUTS	Units	Polyester	Epoxy	Preformed Plastic
1. T_{100} in months	months	White 166 yellow 47	-	4
2. Appearance (12 m.)	1 to 10	7.2	9.1	9.5
3. Durability (12 m)	1 to 10	7	9	-

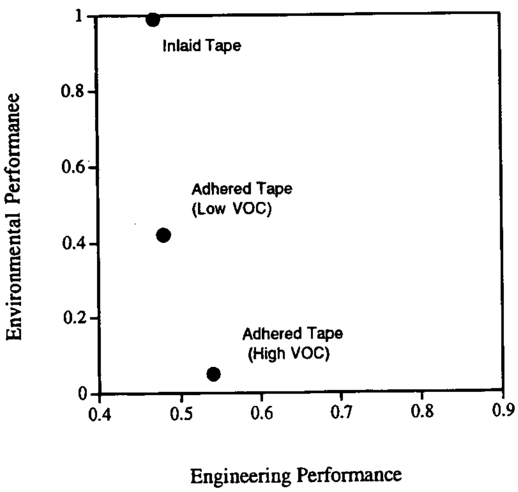

Figure 14. Comparison of the performance of inlaid tape and tape adhered to the pavement.

choice of weights. As seen from the table below, changing the set of weights results is a small but significant change in the engineering performance value as well as in the environmental performance values of the paints. However, the qualitative conclusion remains unchanged; based on NASHTO data, the two types of paints have comparable engineering performance but the water-based paints show far superior environmental performance compared to solvent-borne paints.

	Original Weights	*Revised Weights*
Solvent-borne Paint		
U_{eng}	0.59	0.54
U_{env}	0.06	0.05
Water-based Paint		
U_{eng}	0.59	0.54
U_{env}	0.45	0.50

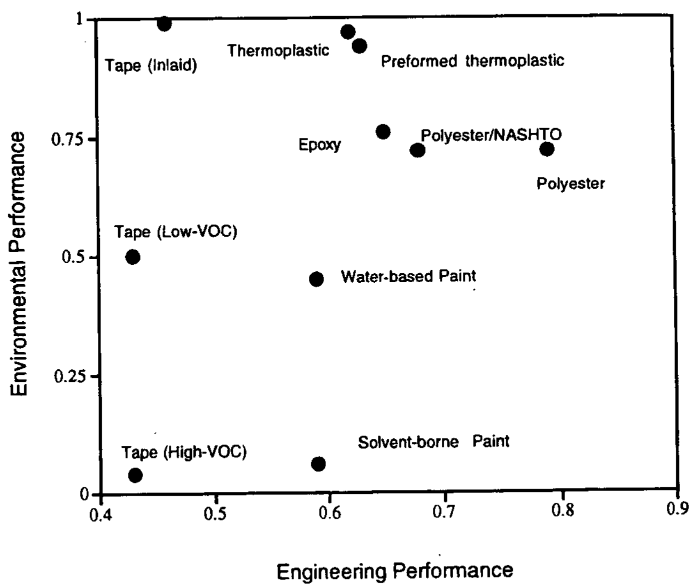

Figure 15. Performance of various pavement marking materials on the basis of NASHTO and SASHTO test data.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

1. Solvent-borne and water-based paints constitute the most-used category of pavement marking material in the United States. In longitudinal markings, it is estimated that paints account for more than all other marking materials combined. On the basis of data collected during the project, the annual VOC emission from the nation's centerline markings alone is conservatively estimated at about 39.5 million pounds.
2. An adequate assessment of the performance of a pavement marking material must include a study of both its engineering performance as well as its environmental performance. The latter evaluates the potential emission of VOCs from the markings as well as the impact of HAPs in the marking material on the health of striping crews and the public.
3. The U.S. EPA is currently in the process of drafting regulations on the allowable VOC levels in paints including compositions used in pavement marking. The expected maximum amount permitted in pavement marking compositions will be 150 g/L or 1.26 lb/gal of VOCs. According to information available at this time, the regulation should go into effect in January 1998.
4. The amount of reliable data pertaining to the performance of pavement marking materials available in the literature is rather limited and incomplete. Although data from NASHTO and SASHTO studies represent the best available source to date, they do not provide sufficient detailed information or an adequate analyses.
5. This inadequacy of data is particularly true of the environmental performance of pavement marking materials. Basic information, such as the kinetics of VOC emission from a stripe, the levels of operator exposure to VOCs, the ambient air levels of these chemicals in field-reacted systems, and the water extractibility of chemical residues from fresh markings, are all unknown at this time. This lack of key data presents a serious drawback for studies of this nature.
6. Solvent-borne paints emit more pounds of VOCs per mile-year of marking. Using water-based paints can result in a 50 to 90 percent reduction in the VOC emissions. Tapes that use high-VOC adhesive primers (containing 5–6 lb VOC per gallon) emit a pollutant load (lb of VOC per mile-year) close to that from water-based paints.
7. Health impacts and risks associated with the inhalation of VOCs in pavement marking compositions are not well known and can only be indirectly appraised using threshold limit values published for these chemicals. The volume of air needed to dilute the quantity of emissions released per mile-year of coating to an air concentration that is believed to be relatively safe for routine exposure was used as an approximate measure of negative health effects attributable to the material. In the absence of reliable experimental data, this rather approximate measure was used in the study.

   The value of this measure, V, is 1 to 3 orders of magnitude lower in non-paint marking materials compared to paints. The solvent-borne paints on the average show a higher value of V than water-based paints as might be expected, but the difference is smaller than might be expected on the basis of their fractional VOC content.
8. The engineering performance of pavement marking materials relies on a variety of factors including those related to pavement quality and traffic levels. Those factors that pertain directly to the marking material might be conveniently quantified using the ability of the marking to remain visible during the day as well as under night conditions, its durability, and its lifetime cost.
9. A quantitative measure of the overall engineering performance might be obtained in terms of (a) the duration over which the retroreflectivity of the marking is maintained above 100 millicandelas per sq ft per ft cdl, (b) the appearance rating after 12 months of use, (c) the durability after 12 months use, (d) the ease of use, (e) the storage stability, and (f) the lifetime cost. These different measures are of course not weighted equally.
10. A quantitative measure of the environmental performance might be obtained in terms of (a) the VOC content of the marking material, (b) the estimated toxic-

ity of the volatile fraction of the material, and (c) other safety concerns associated with the marking. Again, these are not weighted equally.

11. By adopting a set of weights that correctly reflect the relative importance of each of the above measures of a marking material, its overall performance might be expressed by two parameters: U_{eng} and U_{env}. These are simple functions of the utility of these various measures. This allows a given marking to be placed on a two-way grid to visualize its relative performance in terms of engineering and environmental attributes.
12. This simple methodology was applied to data generated in the NASHTO and SASHTO studies on pavement marking materials. The plot of the results shows several interesting features. Thermoplastics, polyesters, and even epoxy systems appear to be rated highly for SASHTO test sites when evaluated using the set of weights proposed here. The relative performance of different marking materials under any given set of conditions might be studied using this methodology provided the required data inputs are available.
13. The key finding of this research effort is the formal methodology previously discussed. Its effective use requires the input of field data for the location of interest as well as the selection of appropriate weights and utility functions that adequately describe the concerns, constraints and political realities involved. These vary from jurisdiction to jurisdiction. The analysis based on SASHTO and NASHTO data presented here is mainly to illustrate the potential of the methodology.

SUGGESTIONS FOR FURTHER WORK

1. Study the air concentrations of HAPs and particulates during the pavement marking operations.

   A realistic assessment of the environmental performance of a marking material must involve a study of inhalation of volatile material from the stripe by striping crew and possibly even by the motorists. The amount of volatile compounds available for inhalation at the operator location on striping equipment depends on several key variables including the kinetics of their release from the stripe, prevailing air movements, the operator location with respect to the freshly applied stripe, and the rate of application of the marking material. No experimental data are presently available on even the air concentrations of these volatile components at a marking site.

   A crucial contribution to the available information will be an experimental study of this phenomenon. This is conveniently achieved by collection of air samples in the field during striping operations followed by analysis in the laboratory by conventional analytical techniques such as gas chromatography-mass spectrometry. The study should also include paints as well as field-reacted materials such as polyesters where the possible emission of styrene is a concern. The analytical procedures for these particular chemicals are well established and are relatively straightforward to perform. Potential negative impacts that are related to the nonvolatile, more durable fraction of markings might also be addressed in such a study. The most important among these is the potential for contamination of groundwater and soil due to the marking being partially extracted by rain water.

   With this information, it is possible to carry out a meaningful analysis of the potential of a marking material to pose a health hazard to striping crews and motorists. It will also allow a test of the possibility that slower-evaporating solvents, in spite of their higher toxicity, may actually present less of a risk than a fast-evaporating solvent of lesser toxicity when present in a pavement marking composition. At this time when reformulation of marking materials to reduce the VOC content is of interest, this information may help the development and recognition of marking formulations less likely to pose health hazards.

   The potential hazards posed by factors other than airborne volatile chemicals were considered outside the scope of this report. Nevertheless, issues such as the contamination of potable water supplies by runoff, impact of water-borne extractives from markings on soil biota or freshwater ecosystems, and the effects of skin contact with chemical substances encountered in pavement markings can all be very significant. These topics need to be addressed in future work as well.
2. Improve implementation of the results from this study by developing a software package to assist the user in applying the methodology.

   While the methodology developed here is fairly simple, it involves repetitious calculations. A user might be discouraged from routine application of the methodology because of the tedium associated with these calculations and in collecting data from default value tables or other sources.

   This practical drawback can be effectively addressed by developing a software package to carry out these calculations. Furthermore, a computer database will be able to carry more extensive default value data for various inputs. The methodology encourages the presentation of results in a graphical format, a feature particularly amenable to computerization. Such a software package could include a database of health and safety information on particular VOCs of interest.
3. Develop a uniform label for paint and other marking materials intended for highway use.

   The anticipated U.S. EPA regulations on the VOC content of marking materials include a provision on labeling paints and coatings with several pieces of specific information including its VOC content in units of g/L.

The designed label, perhaps color coded, may carry not only the information required by law but also other additional data on the composition or safety of the material provided on a voluntary basis. This exercise can be carried out in consultation with the manufacturers as well as the pertinent committees in the American Society for Testing and Materials and the International Standards Organization.

4. Design a test method for VOC determinations that is applicable to two-part marking formulations.

The Draft Rule on VOC regulation requires that the VOC content of a marking material be determined using a specific U.S. EPA test method. While the method suggested is adequate as a general method, it is very likely to overestimate the VOC content of two-part formulations. In these, the bulk of organic reactants are polymerized or crosslinked in the marking and are hence unavailable as VOC emanating from the stripe. The volatile content of the separate parts (A and B) of the formulation (or even its mixture, depending on test conditions) when determined by common methods will be quite high. This may discourage or even preclude the use of some of these formulations that have superior performance characteristics.

There is a need to examine the different VOC determination methods available to determine those that might be suited for use with two-part systems. The identified or redesigned test method along with validation can then be presented to the U.S. EPA for consideration as an alternative test method for two-part systems. As the Draft Rule states that alternate test methods might be allowed on a case by case basis, the identification of a suitable method will have a direct and immediate impact on the use of these formulations.

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APPENDIXES A AND C

UNPUBLISHED MATERIAL

Appendixes A and C as submitted by the research agency are not published herein. For a limited time, copies are available for loan on request to NCHRP, Transportation Research Board, Box 289, Washington, D.C. 20055. The appendixes are titled as follows:

Appendix A: Survey Questionnaire
Appendix C: Toxicity Data for Volatile Chemicals Found in Markings

APPENDIX B
TYPICAL FORMULATIONS OF PAVEMENT MARKING MATERIALS

Solvent-Borne Paints

Formula SP-1: Typical Fast Dry Solvent-Borne Alkyd Paint.

MATERIALS		Weight in Pounds	
		WHITE	YELLOW
Titanium Dioxide		105	0
Medium Chrome Yellow	L	0	105
Zinc Oxide		20	20
Magnesium Silicate		260	270
Calcium Carbonate		250	260
Organo montmorillonite(20-30% MeOH)[1]	*	6	6
Methanol	*	2	2
Alkyd resins (60% non volatiles)[2]	*	135	135
Chlorinated Rubber (20 cps)		80	80
Chlorinated Paraffin		55	55
Soya lecithin		8	8
24% Lead Dryer	L	1.5	1.5
6% Cobalt Dryer		0.6	0.6
Antiskinning Agent		1	1
Epoxy Resin		2	2
Aliphatic thinner[3]	*	100	100
Methyl Ethyl Ketone	*	140	140
Toluene	*	40	40

Source: State of Illinois Dept. of Transportation M 123-88

Formula SP-2: Typical Slow Dry Solvent-Borne Alkyd Paint.

MATERIALS		Weight in pounds	
		WHITE	YELLOW
Titanium Dioxide		100.0	0
Hansa Yellow (11-2400)[4]		0	32
Magnesium Silicate		320	190
Calcium Carbonate		120	135
Antisettling Agent		6.0	6.0
Methanol (95% in water)	*	1.9	1.9
Alkyd resins (60% non volatiles)[2]	*	340.0	327.5
Soya lecithin		1.9	1.9
Naphtha	*	104.0	100.0
Heptane	*	87.0	84.0
12% Cobalt Drier		1.0	1.0
4% Calcium Drier		5.7	5.6
12% Zirconium Drier		2.9	2.8
Antiskinning Agent		1.4	1.4

Source: Wyoming Dept. of Transportation Bid No. C5916, Oct. 94

Formula SP-3 : Typical Solvent-Borne Alkyd Paint.

MATERIALS		Weight in Pounds	
		WHITE	YELLOW
Titanium Dioxide		100	25
Medium Chrome Yellow	L	0	85
Zinc Oxide		25	50
Talc		250	100
Feldspar - LU 390		0	125
Calcium Carbonate		275	250
Antisettling Agent[5]		5	5
Alkyd resins (75% non volatiles)[6]	*	130	130
Chlorinated Rubber (20 cps)		105	120
Chlorinated Paraffin		85	75
36% Lead Dryer	L	1.5	1.5
12% Cobalt Dryer		0.5	0.5
Antiskinning Agent		2	2
Stabilizer (Thermolite 813)		0.5	0.5
Methanol	*	5	6
Methyl Ethyl Ketone	*	207	270
Toluene	*	53	0
Xylene	*	10	0

Source: Oklahoma Dept of Transportation, Standard Specifications 1988 Ed.

Formula SP-4 : Typical Solvent-Borne Paint.

MATERIALS		Percent by Weight	
		WHITE	YELLOW
Titanium Dioxide (Type II rutile)		14 - 15	0
Medium Chrome Yellow (Type III)	L	0	17.5 - 18.5
Diatomaceous silica (Type B)		9.5 - 10.5	10 - 11
Magnesium Silicate		9.5 - 10.5	11.5 - 12.5
Calcium Carbonate (Type GC Grade 1)		13.5 - 15	17.5 - 18.5
Organo montmorillonite (in 20-30% methanol)	*	0.15 - 0.4	0.15 - 0.4
Alkyd resins (59 - 61% non volatiles)[2]	*	35.0	35.0
Petroleum thinner + other additives[7]	*	15.0	15.0

Source: Georgia Dept of Transportation, Standard Specifications. sec.870.03

Formula SP-5 : Typical Solvent-Borne White Alkyd Paint.

MATERIALS		Percent by Weight	
		Fast-dry	Reg. -dry
Titanium Dioxide (Type II rutile)		8.3	10.7
Kaolin Clay		8.3	
Bentonite Clay		0.06	0.06
Talc			19.7
Calcium Carbonate (Type GC Grade 1)		39.6	27.3
Polar solvent (methanol)	*	0.02	0.02
Alkyd resins (60% non volatiles)[1]	*	27.4	25.45
Heptane or Lactol spirits	*	9.4	14.9
Toluene	*	5.9	
Driers		1.02	1.87

Source: Provided by Manufacturer of Pavement Marking Material. 1995

Formula SP-6: Typical Chlorinated Rubber Paint.

MATERIALS		Pounds / 100 gal.	
		WHITE	YELLOW
Titanium Dioxide (rutile)		164.0	
Medium Chrome Yellow	L		208.0
Talc		72.1	72.1
Celite 281		90.8	90.8
Calcium Carbonate (Vicron 45-3)		235	235
Mica (English Mica C-1000)		71.7	71.7
Antisettling agent		7.0	7.0
Hydrocarbon Resin (Velsicol XL30)		15.0	15.0
Safflower Oil		18.5	18.5
Chlorinated Rubber (Parlon 10 cps)		122.0	122.0
Chlorinated Paraffin (Chlorowax 40)		41.1	41.1
Propylene oxide	*	1.8	1.8
Copper Phthalocyanine		0.006	0.006
6% Cobalt Naphthenate		0.4	0.4
24% Lead Naphthenate	L	0.6	0.6
Antiskinning Agent		1.1	1.1
Hexane (Chevron 5)	*	105	105
Methyl Ethyl Ketone	*	202	202
Toluene	*	47.9	47.9

Source: CALTRANS specifications Pt56A and Pt69 , 1975.

Formula SP-7: Typical Acrylic-Modified Alkyd Paint.

MATERIALS		Parts by Weight	
		WHITE	YELLOW
Titanium Dioxide (rutile)		75	0
Medium Chrome Yellow	L		75
Calcium Silicate		35	35
Magnesium Silicate		100	120
Calcium Carbonate		355	345
Antisettling agent[8]		6	6
Soya Lecithin		100	110
Alkyd Acrylic Copolymer[9]		100	100
Chlorinated Paraffin		55	55
Poly(α methyl styrene)		85	
Methyl butyl methacrylate copolymer		8	8
6% Cobalt Naphthenate		0.4	0.4
24% Lead Naphthenate	L	1	1
Methanol (95% in water)	*	2	2
Aliphatic thinner	*	140	140
Methyl Ethyl Ketone	*	155	155

Source: CALTRANS specifications 8010-21F-02 1992

1 - Antisettling agent (hydrous magnesium aluminum silicate)
2 - Resin dissolved in Naphtha
3 - Solvent with a minimum IBP 87.8 C and a maximum dry point of 110 C
4 - Organic non-lead yellow pigment
5 - Bentone 34 or Claytone 40
6 - Resin dissolved in toluene
7 - Includes driers, stabilizers and antisettling agents
8 - Organic derivative of a magnesium montmorillonite clay.
9 - Reichold #13-645 Volatiles 49 to 51%. Composition of volatiles: 20% paraffins and naphthenes, 12% toluene and ethylebenzene, 8% aromatics and hydrocarbons C8 or higher, and exempt oxygenates 60%.

* contributes a significant level of volatile organic compounds.
L contributes Lead

Water-Based Paints.

Formula WP-1: Typical Fast Dry Water-Borne Alkyd Paint.

MATERIALS		Weight in Pounds	
		WHITE	YELLOW
Titanium Dioxide (Ti-Pure R 900)		100.0	20.0
Hansa Yellow		0	32.0
Calcium Carbonate (Omyacarb 5)		760.6	750.0
Acrylic Emulsion (E-2706) 50%		460.1	460.1
Dispersant (Tamol 901)		7.2	7.2
Surfactant (Surfynol CT-136. surfactant)		2.8	2.8
Defoamer (Drew L-493)		5.5	5.5
Methanol	*	30.0	30.0
Coalescent (Texanol, a complex ester)		2.0	23.0
Thickener (Natrosol 250HR) 2% aq.		7.0	6.0
Water		11.6	12.7

Source:Wyoming Dept. of Transportation Bid No. C5916, Oct. 94
Lousiana Dept. of Transportation Specs. Jan. 1994

Formula WP-2: Typical Fast Dry Water-Borne Paint.

MATERIALS		Weight in Pounds	
		WHITE	YELLOW
Titanium Dioxide (Ti-Pure R-900))		100.0	40.0
Organic Yellow (Harshaw 1244)		0	50.0
Inorganic yellow (Iron chromate)		0	2.0
Calcium Carbonate (Miss. Lime M-60)		150.0	125.0
Calcium Carbonate (Huber Q-6)		430.0	450.0
Acrylic Emulsion[1] (DT 211NA 49.5-51.5%)		535.0	527.0
Dispersant (Colloids 226/35)		8.0	10.0
Triton CF 10(surfactant)		2.0	2.0
Defoamer (Drew L-493)		5.0	6.0
Methanol	*	29.0	28.0
Coalescent (Texanol, a complex ester)		24.0	23.0
Thickener (Natrosol 250HR) 2% aq.		0.5	0.30
Preservative (Dowicil 75)		1.5	0
Preservative (Troysan 192)		0	1.5
Water		16.0	23.0

Source: Missoui DOT formulation

* contributes a significant level of volatile organic compounds.

Formula WP-3: Typical Fast Dry Water-Borne Paint.

MATERIALS		Weight in Pounds	
		WHITE	YELLOW
Titanium Dioxide (Ti-Pure R-900))		100.0	21.0
Organic Yellow (Harshaw 1244)		0	32.0
Calcium Carbonate (Miss. Lime M-60)		150.0	150.0
Calcium Carbonate (Huber Q-6)		430.0	465.0
Acrylic Emulsion (DT 211NA 49.5-51.5%)		541.0	535.0
Dispersant (Colloids 226/35)		8.0	9.0
Triton CF 10 (surfactant)		2.0	2.0
Defoamer (Colloid 654)		5.0	5.0
Methanol	*	29.0	28.0
Coalescent (Texanol, a complex ester)		24.0	23.0
Thickener (Natrosol 250HR) 2% aq.		0.5	0.5
Preservative (Troysan 192)		1.5	1.5
Water		10.0	10.0

Source: Illinois Dept. of Transportation specification November 1994

Formula WP-4: Typical Water-Borne Paint.

MATERIALS		Percent by Weight	
		WHITE	YELLOW
Titanium Dioxide (Rutile Type II)		min. 8.2	21.0
Lead-free Yellow		0	min. 3.0
Calcium Carbonate (Type GC)		max 54.8	max. 57.3
Acrylic Emulsion (E-2706) 50%		31.5 -36.0	34.0 -36.0
Methanol	*	2.1 - 2.8	2.0 - 2.8
Coalescent (Texanol, a complex ester)		1.6 - 2.0	1.5 - 2.0
Other Additives		max. 2.0	

Source:Georgia Dept. of Transportation. Sec. 870 April 1993.

Formula WP-5: Simple Fast Dry Water Borne Paint Formulation.

MATERIALS		Weight %
Titanium Dioxide (Ti-Pure R-900)		7.4
Acrylic Emulsion (50% solids)		41.2
Dispersant + Surfactants		1.0
Calcium Carbonate		45.0
Defoamer		0.5
Methanol	*	2.1
Coalescent (Texanolor Butyl Carbitol)		1.8
Water		1.0

Source: Formulation provided by paint manufacturer

* contributes a significant level of volatile organic compounds.

Formula WP-6: Typical Fast Dry Water-Borne Paint.

MATERIALS		Weight in Pounds	
		WHITE	YELLOW
Titanium Dioxide (Ti-Pure R-900))		100.0	20.0
Organic Yellow (Englehardt 1250)		0	32.0
Calcium Carbonate (Omyacarb 5)		760.0	760.0
Acrylic Emulsion (50% solids)		453.5	453.5
Dispersant (Tamol 901)		7.2	7.2
Surfactant (Surfynol CT 136)		2.6	2.6
Defoamer (Drew L-493)		5.5	5.5
Methanol	*	30.0	30.0
Coalescent (Texanol, a complex ester)		23.0	23.0
Thickener (Natrosol 250HR) 2% aq.		0.12	0.14
Preservative (Dowicil 75)		0.5	0.5
Water		24.0	25.0

Source: Wyoming DOT formulation from Dow Chemicals

* contributes a significant level of volatile organic compounds.

Epoxy Formulations

Formula EP-1: Typical Epoxy Formulation

MATERIALS		Weight %
PART A		WHITE
Epoxy resin		51.8
Titanium Dioxide		27.0
Diluents and additives		21.2
PART B		
Hexamethylene diamine		23.6
Nonyl phenol		23.2
Polyamine hardner		38.7
Triethanolamine		14.5

Source: Manufacturer of epoxy pavement marking materials.

Formula EP-2: Typical Epoxy Formulation

MATERIALS		Percent by Weight	
PART A		White	Yellow
Titanium Dioxide (Type II rutile)		18 - 25	14 - 17
Organic Yellow			7 - 8
Epoxy Resin		75 - 82	75 - 79
PART B*			
Diethylene triamine		10 - 25	10 - 25
Nonyl phenol		20 - 50	20 - 50

Source: Manufacturer of epoxy pavement marking

NOTE: The marking material is generated by mixing TWO volumes of Part A with ONE volume of Part B. The percentage compositions given are for composition of each Part and not for total formulation.

Formula EP-3: Epoxy Compound used as an Adhesive for Raised Pavement Markers

MATERIALS		Parts by Weight
PART A		
Titanium D ioxide		7.68
Talc		36.64
Epoxy Resin (Epon 828)		100.0
PART B		
N-Aminoethyl piparazine		25.10
Talc		69.26
Malacco Black		0.23
Nonyl phenol		50.03

Source: NJ Dept. of Transportation.

Thermoplastic Formulations

TP-1

MATERIALS		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Binder resin		> 18.0	> 18.0
Titanium dioxide		> 10.0	
Yellow pigment			> 2.0
Calcium Carbonate (fillers)		< 42.0	< 50.0
Glass beads		30 - 40	30 - 40

Source: Thermoplastic Specifications. Kentucky DOT

TP-2

MATERIALS		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Binder resin		> 17.0	> 17.0
Titanium dioxide		> 10.0	
Yellow pigment			*
Calcium Carbonate (fillers)		< 42.0	*
Glass beads		30 - 40	30 - 40

Source:Thermoplastic Specifications Sec. 727-01 (Jan 1990). New York.DOT

TP-3

MATERIALS		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Binder resin		> 18.0	> 18.0
Titanium dioxide		> 10.0	-
Yellow pigment			*
Calcium Carbonate (fillers)		< 37.0	< 44.5
Glass beads		> 35.0	> 35.0

Source:Thermoplastic Specifications. Kentucky DOT

TP-4

MATERIALS		Percent by wt.
		WHITE
C-5 Hydrocarbon		15 - 18
Kraton polymer		2 - 4
Plasticizer (mineral oil)		1 - 3
Calcium Carbonate (fillers)		15 - 30
Titanium dioxide		3 - 10
Glass beads		15 - 20
Aggregate		30 - 40

Source: Hydrocarbon resin manufacturer

NOTE: Above formulations contain 1-3% of a plasticizer, usually mineral oil.
* Amount and type at the option of manufacturer

Polyester Formulation

Formula PE-1: Polyester Composition used in Pavement Marking.

MATERIALS		Parts by	Weight
		WHITE	YELLOW
Polyester resin		84 - 85	86 - 87
Acrylic (40%)		2 - 3	2 - 3
Styrene	*	12 - 13	10 -11
Titanium dioxide		18.9	2.8
Yellow pigment	L	-	5.0
Fumed Siilica		8.0 -10.0	8.0 - 10.0
Aluminum Silicate		19.0 - 20.0	76.0 -77.0
Calcium Carbonate		50.0 - 61.0	50.03
Polyethylene wax		1.4	1.0 - 2.0
Inhibitor		0.15	0.15
Promoter		0.3	0.3

Source: Manufacturer of Polyester Pavement Markings.

Tape Formulations

Formula TA-1: Preformed Tape.

MATERIALS		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Aluminum		30 - 60	30 - 60
Synthetic rubber		10 -30	10 - 30
Vinyl resin		5 - 20	7 - 13
Titanium dioxide		5 - 10	
Pigment Yellow 34			3 - 7
Bis(2-ethylhexyl) phthalate		0.5 - 1.5	0.5 - 1.5
Glass beads		5 - 40	5 - 40

Source: Literature from tape manufacturer.

Formula TA-2: Preformed High Performance, Intersection Tape.

MATERIAL		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Resins		10 -30	10 -30
Synthetic rubber		10 -30	10 - 30
Polyurethane*		1 - 5	1 - 5
Plastic binder		1 - 5	1 - 5
Titanium dioxide		10 - 30	1 - 5
Pigment Yellow 34			7 -13
Ceramic particle*		1 - 5	1 - 5
Glass beads		30 - 60	30 - 60

Source: Literature from tape manufacturer.

Formula TA-3: Preformed Intersection Grade Tape.

MATERIAL		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Resins		10 -30	10 -30
Synthetic rubber		10 -30	10 - 30
Polyurethane*		5 - 15	3 - 7
Titanium dioxide		10 - 30	1 - 5
Organic yellow pigment I			1 - 5
Organic yellow pigment II			1 -5
Ceramic particle		1 - 5	1 - 5
Glass beads		30 - 60	15 - 40

Source: Literature from tape manufacturer.

Formula TA-4: Preformed Removable Tape.

MATERIAL		Percent by wt.	Percent by wt.
		WHITE	YELLOW
Resins		15 - 40	15 - 40
Synthetic rubber		10 -30	10 - 30
Plastic binder		3 - 7	3 - 7
Titanium dioxide		1 - 5	1 - 5
Organic yellow pigment I			1 - 5
Aluminum		15 - 40	15 - 40
Ceramic particle		1 - 5	1 - 5
Glass beads		10 - 30	15 - 40

Source: Literature from tape manufacturer.

Formula TA-5: Contact Adhesive for Durable Tape Application

MATERIAL		CAS Number	Percent by wt.
Water		7732-18-5	40 - 50
Polychloroprene		9010-98-4	30 - 40
Phenol-α pinene resin		25359-84-6	1 - 10
Glycerol ester of hydrogenated rosin		65997-13-9	1 - 10
Zinc Oxide		1314-13-2	1 - 10
Toluene	*	108-88-3	< 3
Methanol	*	67-56-1	< 2.5
Tall-oil rosin		8052-10- 6	0.1 - 1
2,2 nethylenebis 6 tert-butyl-*p*-cresol		119 - 47 - 1	0.1 - 1

Source: Literature from tape/contact adhesive manufacturer.

Formula TA-6: Contact Cement for Durable Tape Application.

MATERIAL		CAS Number	Percent by wt.
Aliphatic Solvent Naphtha	*	64742-88-7	25.6 - 38.5
Acetone	*	67-64-1	11.3 - 16.9
Polychloroprene		9010-98-4	9.0 - 13.5
Methyl ethyl keone	*	78-93-3	8.4 - 12.6
Hexane	*	110- 54-3	6.4 - 9.6
Toluene	*	108-88-3	1.7 - 2.6
p-tert butyl phenol-formaldehyde resin		25085-50-1	5.3 - 7.9
n-amyl acetate		628-63-7	4.7 - 7.1
2-metyl butyl acetate		624-41-9	2.8 - 4.1
isoamyl acetate		123-92-2	0.5
Formaldehyde		50-00-0	0.2
Magnesium oxide		1309-48-4	3.5 - 5.3

Source: Literature from tape/contact adhesive manufacturer.

APPENDIX D
DETAILED CALCULATIONS RELATING TO PERFORMANCE ASSESSMENT

PAVEMENT MARKING EVALUATION SHEET 1

Example 1 : Compare the performance of a conventional solvent-borne paint and a water-based paint for use at the location where SASHTO test data were generated.

Comparing: **SP** = Solvent - borne Paint **WP** = Water-based Paint

1. TABLE OF REVISED WEIGHTS.**(not revised)**

	w_C	w_D	w_E	w_F		w_G	w_H
REVISED WEIGHT	0.30	0.30	0.10	0.30		0.60	0.40

	w_1	w_2	w_3	w_4	w_5	w_6		w_7	w_8	w_9
REVISED WEIGHT	0.80	0.20	1.00	0.67	0.33	1.00		1.00	0.85	0.15

2. TABLE OF INPUT DATA AND UTILITY VALUES

Note : All data used are from Default Values Table (SASHTO)

INPUTS	Units	Measure	Utility	Measure	Utility	
		SP	**SP**	**WP**	**WP**	
1. T_{100} in months	months	12	0.08	27	0.18	
2. Appearance (12 m.)*	1 to 10	7.4	0.74	8.5	0.85	
3. Durability (12 m)	1 to 10	7	0.63	7	0.63	
4. Ease of use rating	0 to 5	4	0.8	4	0.8	
5. Storage stability rating	0 to 5	2	0.4	2	0.4	
6. Annual cost	US $	0.29	0.90	0.58	0.81	
7. VOC content	(lb/gal)	3.2	0	0.7	0.66	
8. Hazardousness	0 to 5	4.5	0.01	4.0	0.02	
9. Other safety	0 to 5	4	0.8	4	0.8	

* Data on Appearance after 12 months of use are from SASHTO data.

3. CALCULATIONS

<u>**FOR SP** = Solvent - Borne Paint</u>

$P = w_C (w_1 . U_1 + w_2 . U_2) =$ **0.30 (0.80 * 0.08 + 0.20 * 0.74) = 0.06**

$Q = w_E (w_4 . U_4 + w_5 . U_5) =$ **0.10 (0.67 * 0.8 + 0.33 * 0.4) = 0.07**

$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3 =$ **0.06 + 0.07 + (0.30 * 0.90) + (0.30 * 0.63)**

$U_{ENG} =$ **<u>0.59</u>**

$R = w_H (w_8 . U_8 + w_9 . U_9) =$ **0.40 (0.85 * 0.01 + 0.15 * 0.8)=0.05**

$U_{ENV} = R + w_G . U_7 =$ **0.05 + (0.60 * 0.) = <u>0.05</u>**

<u>**FOR WP** = Water-based Paint</u>

$P = w_C (w_1 . U_1 + w_2 . U_2) =$ **0.30 (0.80 * 0.18 + 0.20 * 0.85) = 0.09**

$Q = w_E (w_4 . U_4 + w_5 . U_5) =$ **0.10 (0.67 * 0.8 + 0.33 * 0.4) = 0.07**

$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3 =$ **0.09 + 0.07 + (0.30 * 0.81) + (0.30 * 0.63)**

$U_{ENG} =$ **<u>0.59</u>**

$R = w_H (w_8 . U_8 + w_9 . U_9) =$ **0.40 (0.85 * 0.018 + 0.15 * 0.8) = 0.05**

$U_{ENV} = R + w_G . U_7 =$ **0.05 + 0.60 * 0.66 = <u>0.45</u>**

THE RESULT

	Solvent-Borne paint	Water-Based paint
$U_{ENGINEERING}$	0.59	0.59
$U_{ENVIRONMENT}$	0.05	0.45

PAVEMENT MARKING EVALUATION SHEET 2

Example 1 : Compare the performance of inlaid tape and conventional tape (using the high VOC adhesive).

Comparing: **TA** = Tape (inlaid) **TA1** = Tape (applied with adhesive)

1. TABLE OF REVISED WEIGHTS **(not revised)**

	w_C	w_D	w_E	w_F		w_G	w_H
REVISED WEIGHT	0.30	0.30	0.10	0.30		0.60	0.40

	w_1	w_2	w_3	w_4	w_5	w_6		w_7	w_8	w_9
REVISED WEIGHT	0.80	0.20	1.00	0.67	0.33	1.00		1.00	0.85	0.15

2. TABLE OF INPUT DATA AND UTILITY VALUES

Note : All data used are from Default Values Table (NASHTO)

INPUTS	Units	Measure	Utility	Measure	Utility	
		TA	**TA**	**TA1**	**TA1**	
1. T_{100} in months	months	14	0.09	14	0.09	
2. Appearance (12 m.)	1 to 10	9.3	0.93	9.3	0.93	
3. Durability (12 m)	1 to 10	9	0.88	9.4	0.88	
4. Ease of use rating	0 to 5	4	0.8	2	0.4	
5. Storage stability rating	0 to 5	5	1	4	0.8	
6. Annual cost	US $	2.63	0.13	2.63	0.13	
7. VOC content	(lb/gal)	0	1	1.25	0	
8. Hazardousness	0 to 5	0	1	4	0.05	
9. Other safety	0 to 5	4	0.8	3	0.6	

Note: The additional cost of adhesive is ignored here.

3. CALCULATIONS

FOR TA = Inlaid Tape

$P = w_C (w_1 . U_1 + w_2 . U_2) =$ **0.30 (0.80 * 0.09 + 0.20 * 0.93) = 0.08**

$Q = w_E (w_4 . U_4 + w_5 . U_5) =$ **0.10 (0.67 * 0.8 + 0.33 * 1) = 0.09**

$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3 =$ 0.08 + 0.09 + 0.30 * 0.13 + 0.30 * 0.88

= 0.47

$R = w_H (w_8 . U_8 + w_9 . U_9)$ = 0.40 (0.85 * 1 + 0.15 * 0.8) = 0.39

$U_{ENV} = R + w_G . U_7$ = 0.39 + (0.6 * 1) = 0.99

FOR TA1 = Tape using adhesive (high-VOC)

$P = w_C (w_1 . U_1 + w_2 . U_2) =$ **0.30 (0.80 * 0.09 + 0.20 * 0.93) = 0.08**

$Q = w_E (w_4 . U_4 + w_5 . U_5) =$ **0.10 (0.67 * 0.4 + 0.33 * 0.8) = 0.05**

$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3$ = 0.08 + 0.05 +(0.30 * 0.13)+(0.30 * 0.88)

U_{ENG} = 0.43

$R = w_H (w_8 . U_8 + w_9 . U_9)$ = 0.40 (0.85 * 0.05 + 0.15 * 0.6) = 0.04

$U_{ENV} = R + w_G . U_7$ = 0.04 + 0.60 * 0 = 0.04

THE RESULT

	Inlaid Tape	Tape (adhered)
$U_{ENGINEERING}$	0.47	0.43
$U_{ENVIRONMENT}$	0.99	0.04

PAVEMENT MARKING EVALUATION SHEET 3

Example 3: Compare thermoplastic markings with epoxy markings using SASHTO data to obtain default input values. However revise the weights to exclude measure of appearance from the evaluation.

Comparing: **TP** = Thermoplastics **TA** = Inlaid tape

1. TABLE OF REVISED WEIGHTS. **(revised)**

	w_C	w_D	w_E	w_F		w_G	w_H
REVISED WEIGHT	0.30	0.30	0.10	0.30		0.60	0.40

	w_1	w_2	w_3	w_4	w_5	w_6		w_7	w_8	w_9
REVISED WEIGHT	*1.0*	*0.0*	1.00	0.67	0.33	1.00		1.00	0.85	0.15

Note revision: $w_2 = 0.0$ $w_1 = 1.00$

2. TABLE OF INPUT DATA AND UTILITY VALUES

Note : All data used are from Default Values Table

INPUTS	Units	Measure	Utility	Measure	Utility	
		TP	TP	Tape	Tape	
1. T_{100} in months	months	41	0.27	14	0.09	
2. Appearance (12 m.)	1 to 10	-	-	-	-	
3. Durability (12 m)	1 to 10	9.6	0.92	9	0.875	
4. Ease of use rating	0 to 5	2	0.4	4	0.8	
5. Storage stability rating	0 to 5	5	1.0	5	1.0	
6. Annual cost	US $	0.40	0.87	2.63	0.13	
7. VOC content	(lb/gal)	0	1.0	0	1.0	
8. Hazardousness	0 to 5	0	1	0	1	
9. Other safety	0 to 5	2	0.4	4	0.8	

3. CALCULATIONS

<u>FOR TP = Thermoplastic</u>

$P = w_C (w_1 . U_1 + w_2 . U_2) = 0.30 (1.0 * 0.27) = 0.08$

$Q = w_E (w_4 . U_4 + w_5 . U_5) = 0.10 (0.67 * 0.4 + 0.33 * 1) = 0.06$

$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3 = 0.08 + 0.06 + 0.30 * 0.87 + 0.30 * 0.95$

$U_{ENG} = \underline{0.69}$

$R = w_H (w_8 . U_8 + w_9 . U_9) = 0.40 (0.85 * 1 + 0.15 * 0.4) = 0.36$

$U_{ENV} = R + w_G . U_7 = 0.36 + 0.60 * 1.0 = \underline{0.97}$

<u>FOR TA =Tape (inlaid)</u>

$P = w_C (w_1 . U_1 + w_2 . U_2) = 0.30 (0.80 * 0.09) = 0.03$

$Q = w_E (w_4 . U_4 + w_5 . U_5) = 0.10 (0.67 * 0.8 + 0.33 * 1.0) = 0.09$

$U_{ENG} = P + Q + w_F . U_6 + w_D . U_3 = 0.03 + 0.09 + 0.30 * 0.13 + 0.30 * 0.99$

$U_{ENG} = \underline{0.42}$

$R = w_H (w_8 . U_8 + w_9 . U_9) = 0.40 (0.85 * 1.0 + 0.15 * 0.8) = 0.39$

$U_{ENV} = R + w_G . U_7 = 0.39 + 0.60 * 1.0 = \underline{0.99}$

THE RESULT

	Thermoplastic	Inlaid Tape
UENGINEERING	0.69	0.42
UENVIRONMENT	0.97	0.99

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board

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