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FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

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CONTENTS

COVER

Interstate Highway 75 in Michigan between Vanderbilt and Indian River—part of the Ohio-to-Soo Freeway.

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Quality Assurance in Highway Construction

BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

Part 1— Introduction and Concepts

eported by THURMUL F. McMAHON,
rincipal Quality-Assurance Research Engineer,
nd WOODROW J. HALSTEAD,
hief, Materials Division

The disintegrated bituminous pavement shown above and patched concrete pavement shown below are examples of failures that may result from improper control of construction rather than from poor design.

Beginning with this issue and continuing in several succeeding issues, he Public Roads Research staff will present an interpretative summary of he progress in its research program for the statistical approach to qualty assurance in highway construction. This presentation will consist of he following six parts: 1.—Introduction and Concepts (in this issue), .—Quality Assurance of Embankments and Base Courses, 3.—Quality ssurance of Portland Cement Concrete, 4.—Variations of Bituminous onstruction, 5.—Summary of Research for Quality Assurance of Agregate, and 6.—Control Charts.

Statistically based quality-control methods have been used successully in industry, particularly in the defense program, for many years. ccording to research results, statistical quality-assurance methods lso should be adaptable to highway construction, provided that govrning specifications are properly written and sampling and testing ariations established to conform to the conditions of the locality in hich they will be applied.

QUALITY assurance in its broad application relates to the overall problem of btaining the quality of construction necessary r a product to perform the functions tended. It encompasses design, production, mpling, testing, and decision criteria.

The quality of the highway product has lways been a major concern to highway ngineers and contractors. Traditionally, uality has been attained primarily through kills of individual engineers. When such kills are properly applied, satisfactory highay quality is obtained. However, as the speed construction and the volume of materials to handled increased, the traditional system ecame subject to breakdown. Breakdown ccurs when the speed of testing does not eep pace with the speed of construction. dditionally, engineering duties have increased the extent that engineers must spread their lents over broad areas, and many quality ssurance activities have been delegated to ose whose skills and experience are often adequate for on-the-spot judgments. Morever, legal requirements for documented idence of specification compliance create roblems.

As the Interstate program moved into its full construction phase, it became evident that the traditional quality assurance procedures were subject to criticism and that new concepts were needed. Accordingly, in 1963, the Public Roads Director of Research and Development appointed a task force to study the problem and develop a cooperative State-Public Roads research effort to improve quality assurance methods in highway construction.

The discussions and data presented here are an interpretative summary of the research progress in this area; some of the discussions already have been released by the Office of Research and Development (*1*).[1] The reader should be aware that this article pertains to a Research and Development program—not to Public Roads policy. All the proposals presented will be carefully evaluated and only those proven to be workable under actual highway-construction conditions will be adopted as parts of State or Public Roads specifications and policy.

[1] Italic numbers in parentheses identify the references listed on p. 134.

Basic Problems of Quality Assurance

Reduced to its simplest terms, quality assurance of highway construction requires proper answers to the following three questions: (1) What do we want? (2) How do we order it? (3) How do we determine that we got what we wanted?

Answers to the first question encompass the total body of research, development, engineering technology, and experience. All these combine to define needs with respect to materials, properties, and design characteristics of the highway component.

Answers to the second question depend on the manner in which the details are spelled out in specifications—specific characteristics that must be controlled, needs with respect to qualitative level, and uniformity of the product from item to item.

Answers to the third question depend on the precision and accuracy of test methods as well as on the time required to perform the tests. Testing time often controls the number of measurements that can be made available for use in decisionmaking. More importantly, the relation of the characteristic, or property, measured by the test to the service performance of the completed component is a major consideration, which often is known only empirically, if at all.

Traditional Quality Assurance

Many specifications used today in highway construction are, in fact, recipes rather than specifications. They spell out in detail the operations of the contractor, the equipment he must use, and the desired end product he must produce. These traditional specifications have come about because adequate quality definitions and test methods pertaining to quality of the end product are lacking. When specifications do attempt to define required quality, the specified values for characteristics are often those obtained through judgment and experience. Tolerances for such characteristics seldom reflect the true needs and capabilities of the construction process or of the available materials.

When traditional specifications are combined with the skills of engineers, the complete cooperation of contractors, and the desire of everyone to do a good job, there is no doubt that a good highway can be built. However, inspectors and engineers must be capable of recognizing good materials and construction, without relying solely on quality measurements. Under most of the present procedures, one periodic sample is taken. This sample—assumed to be representative of the material or construction—is tested, and the test result is recorded as the value of the measured property, or characteristic. If the test result is within the stated tolerances, the material *passes* and is accepted. If the test result is not within the stated tolerances, the material or construction fails to *pass*. Engineering judgment must then be applied and a decision made as to whether the material should be retested or whether it may be said to *substantially comply* because the specification deviation will cause little impairment of performance.

Even though a quality assurance system that is based on engineering judgment is workable under proper conditions, the practice is difficult to define in legal or contractual terms. *Substantial compliance* has not been quantitatively defined, and the degree of acceptable variation will differ from engineer to engineer and from job to job.

To further complicate the problem, sampling and testing errors are often so large that the true variations of the materials or construction may be obscured. Some tests may not truly measure quality of the finished highway.

Improvement in quality assurance of highway construction accordingly entails:

- Development of realistic quality criteria.
- Development of valid quality tests.
- Development of valid decisionmaking rules.
- Quantification of substantial compliance.

New Developments in Quality Assurance Procedures

Statistical concepts are the most promising tools for the solution of many quality-assurance problems in highway construction. Other industries have been using statistical concepts in process control and acceptance. In fact, much of the development in this field was pioneered by the Department of Defense in its procurement program during World War II. Because of the nature of the highway industry, some of the methods must be modified, but the concepts are basic to any industry.

The science of statistics is a versatile tool. In situations requiring decisions concerning contractual items that are based on samples, statistical concepts allow varied acceptable solutions. Rules for each decision must be carefully defined and followed, but different rules can be formulated for each of the many conditions encountered. Decisions can be made with an established degree of confidence. The degree of confidence required for each decision can be correlated with the criticalness of the decision to the quality of the end product, and the rules formulated accordingly.

Test methods are continually being developed for better and more rapid measurement of quality. The greatest advance in new methods of testing has been in the nuclear field. The nuclear moisture-density gage (figs. 1 and 2) has been proved to be a fast, accurate method of measuring the moisture and density of compacted materials. Nuclear methods (fig. 3) of measuring density and asphalt content of bituminous pavements are showing considerable promise. Seismic methods of measuring compaction are also being developed. Sonic equipment is being used to test welds, and sonic methods of measuring the moduli of concrete have been in use for several years, but have not been widely accepted. Electronic equipment, using the principles of resistivity and magnetism, has been developed to check the placement of steel in concrete and to measure the thickness of pavement components.

Rapid nondestructive tests such as those cited will provide better quality control and make quality measurements available in the future.

Through the work of its different committees, the American Society of Testing & Materials (ASTM) is advancing the state of the art of quality measurement by developing precision statements for standard tests. These statements will provide a basis for evaluating the work of inspectors and laboratory technicians and should decrease testing errors.

Other aids to better quality products are automated processing plants with direct output printout. These plants provide not only automatic control, but also adequate documentation to check output for pay quantities. However, automated control is no guarantee of a quality product. One must know what to control and how precise the control must be before the benefits of automation can be attained. One area in which automation is producing dramatic results is that of surface-variation control. The *Stringline* (fig. 4), a wire guidance system to control vertical variations in concrete placement, and other guidance methods (fig. 5) have greatly improved the riding quality of pavements.

Figure 1.—The nuclear ROADLOGGER used for moisture-density determinations in compacted embankments.

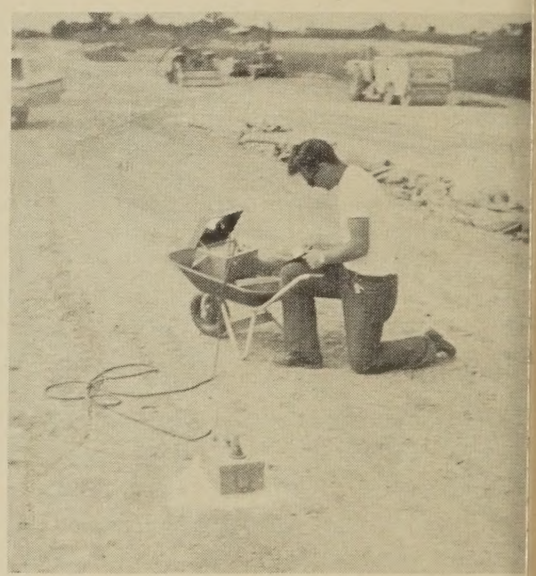

Figure 2.—Moisture-density determination in compacted embankment using portable nuclear gage.

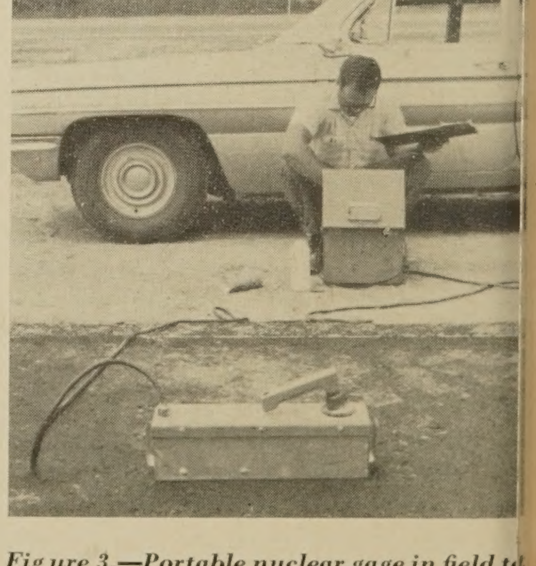

Figure 3.—Portable nuclear gage in field test to determine density of bituminous ba-

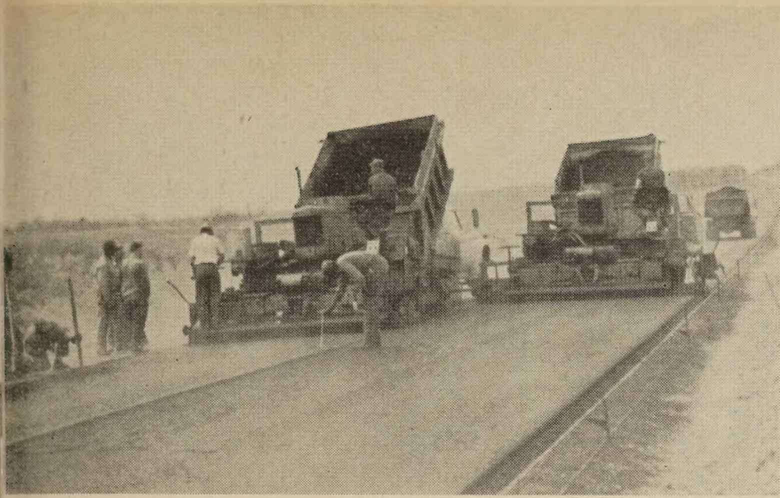

Figure 4.—STRINGLINE wire guidance system for controlling the placement of bituminous material.

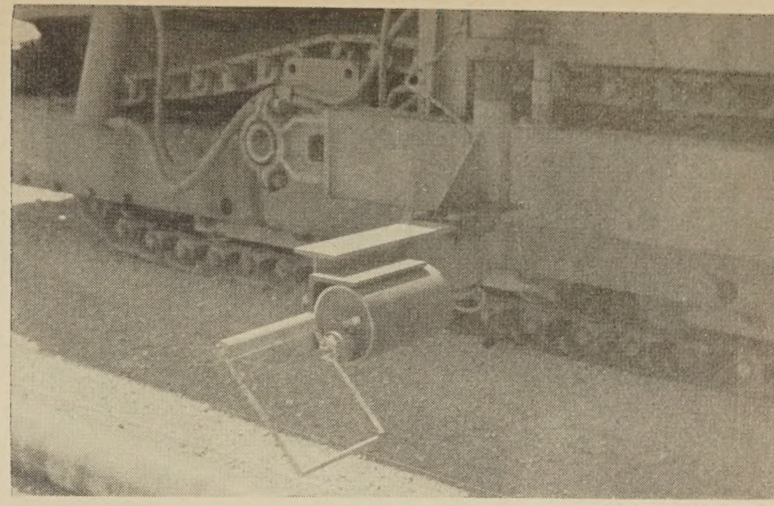

Figure 5.—SKI and wire guidance control used to provide smooth placement of pavement.

Advantages of Statistical Concepts

One significant problem in quality assurance ; that of communication. Definite instructions oncerning the materials and construction esired, methods to be used for determining ompliance, and conditions under which payent will be made, must be given to contracors. These instructions must be explicit so hat contractors, engineers, lawyers, and uditors can interpret them in only one way. 'he Office of Research and Development, 3ureau of Public Roads, recommends that tatistical concepts be incorporated in the pecifications for highway construction to nprove communications.

The proper use of statistical concepts will rovide the following requisites:

- Statement of concise quality requirements.
- Development of valid tolerances based on ıe capabilities of process, sampling, and esting methods.
- Delineation of responsibility for process ontrol and acceptance.
- Development of valid sampling plans as basis for decisionmaking.
- Establishment of precise decision criteria.
- Development of valid proportional-payient schedules.

tating quality requirements

In the writing of specifications, statistical ›ncepts can be used to express quality requireents as target values for which contractors e to aim, and to specify compliance requireents as plus and minus tolerances. Tolerıces from the target value, prescribed by esign needs, can be based on statistical analys of the variations in materials, processes, mpling, and testing existing in current conruction practices. Such tolerances are realic and enforceable. They take into account l the normal causes of variation and allow r the expected distribution of test results ›out the mean. Provisions can be made both r control to the stated level and for control the variation from this level.

Research by the States is being undertaken to define realistic tolerances on quality requirements. From this research, it is known that test measurements on characteristics of highway materials or construction form a definite pattern grouping around a central value called the mean. The grouping indicates that test measurements in highway construction can be described in the same terms as test measurements in other industries. The measurements group around the central value in a symmetrical pattern, thereby allowing the use of statistics based on the familiar bell-shaped *normal curve.* Although some slight variation from the symmetrical curve may occur, especially when the number of test results is small, the error in assuming normal distribution of population measurements usually will not be large. If the curve is decidedly asymmetrical, skewed to the right or left, then something other than normal distribution theory must be used in the analysis.

Even though curves are normal, they may not look alike. Those with a small standard deviation will be tall and narrow, whereas

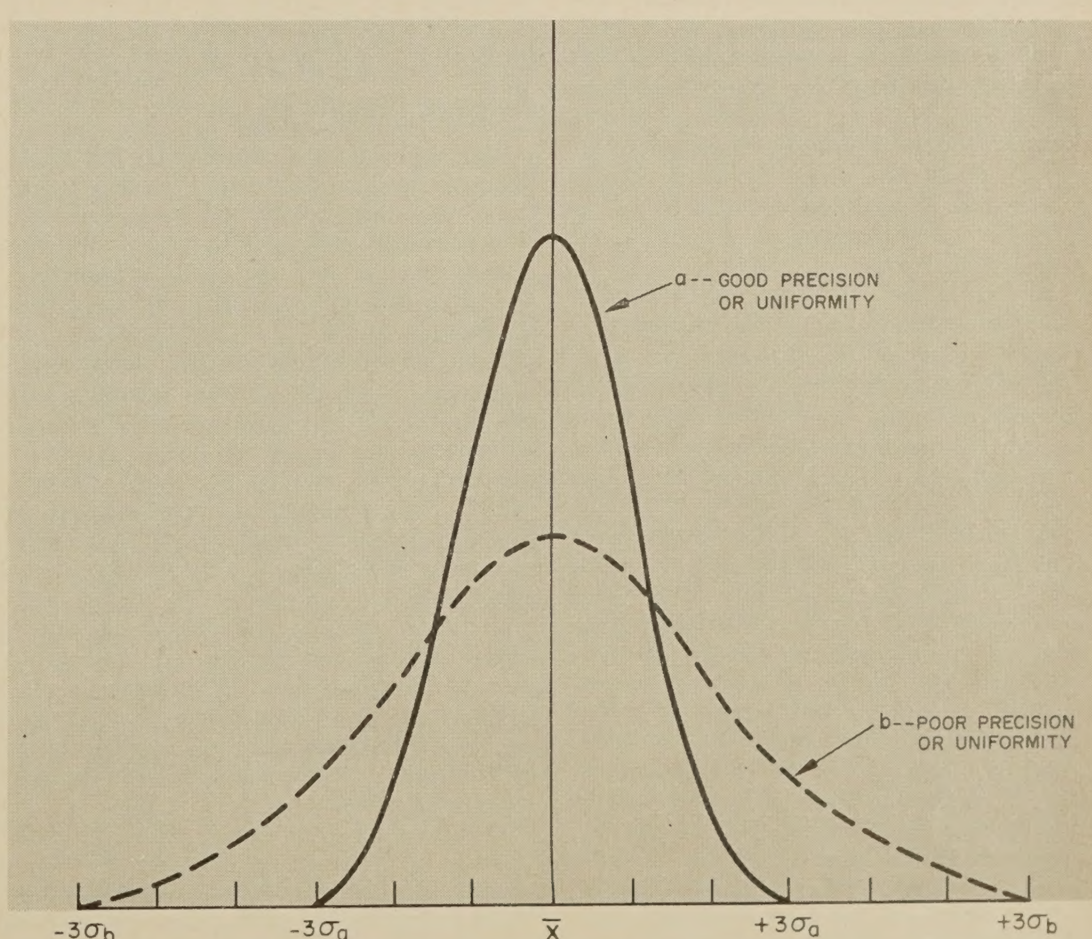

Figure 6.—Normal distribution curves.

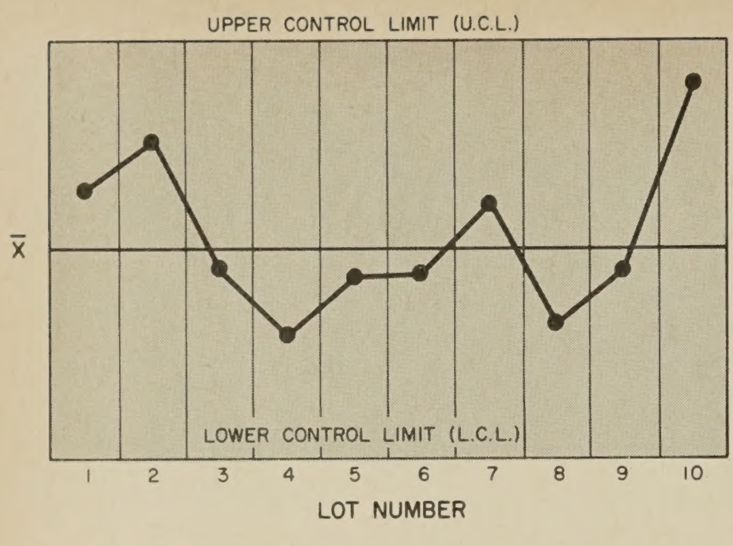

Figure 7.—Average, $\overline{X}$ control chart for n samples per lot.

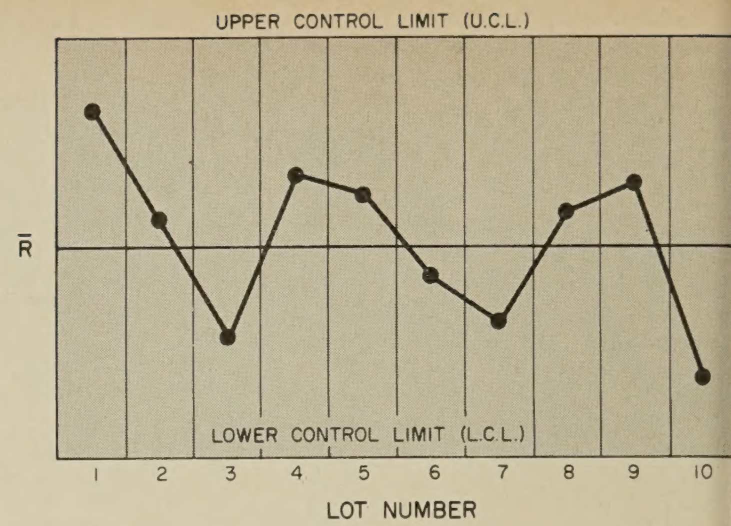

Figure 8.—Range, R, control chart for n samples per lot

those with a large standard deviation will be short and broad. (See fig. 6.) The tall narrow curve indicates good product uniformity or measurement precision; the short broad curve indicates poor uniformity or precision.

The assumption of a normal distribution when warranted, permits the use of estimated relationships of mean and standard deviation to establish realistic specification tolerances for selected sample sizes. Such tolerances can be established by statistical analysis, together with engineering judgment, according to the degree of control needed for permissible construction risks and the economics of testing. The number of test results on which the compliance decision is based directly influences the latitude that must be given to the contractor. Often, because of the small number of tests that can be made economically, the tolerances must be wider than would seem desirable.

These relations may be stated as follows:

$$T_s = \frac{Z}{\sqrt{n}}$$

Where,

T_s is the tolerance to be allowed on each side of the target value.

Z is a standardized factor equal to $(X - \overline{X})/\sigma$ that relates to the area under the normal curve for the desired confidence of decision.

n is the number of tests to be made (sample size).

Statistical concepts for quality assurance of highway construction are based on the laws of probability; consequently, these laws must be allowed to function. One of the most important requirements for proper functioning is that the data be selected by random sampling. A true random sample is one in which all parts of the whole have an equal chance of being chosen for the sample. A table of random numbers is the best device for achieving a strictly random sample, but another method of chance, such as dice, the tossing of several coins, or a wheel of chance, often will suffice in highway work. The principal requirement is that the sample not be biased by a set selection pattern or by an inspector seeking either good, bad, or representative parts for sampling.

In addition to the laws of probability, another concept, *lots*, is essential to the proper application of statistics to quality control and acceptance sampling of highway construction. A *lot* is a uniquely identified, homogeneous portion of material or construction about which a decision is to be made. The size of the *lot* may vary depending on the economics of rejection and on sampling and testing costs. The lot size must not impose a severe hardship on the contractor who encounters a rejection—the smaller the *lot* the better the contractor's position. However, small *lots* entail more sampling and testing by the State—the larger the *lot* the better the State's position. Therefore, *lot* size must be a compromise equitable to both.

Production quality control

The application of statistical concepts to highway construction allows a definite assignment of responsibility for product quality. The contractor strictly is responsible for providing quality materials and construction; the State has the prerogative of acceptance sampling and testing.

Each contractor or supplier should have a statistical quality control program that will assure his meeting the acceptance requirements of the State. Such a quality control program can be patterned after the control currently exercised by the State or it can be considerably different. Much of the control of materials and construction can be accomplished by tests, usually called indicator tests, that are somewhat simplified. These tests are less precise but more rapid than the standard tests. When proper correlation has been established, a sufficient number of indicator-test results will provide control that is as good as fewer results from more precise tests.

Control charts are among the most useful tools in production quality control. These charts, on which test results are plotted, are simple line graphs of the required quality level and of the allowable variations from this level. They pictorially present data so that everyone concerned can see the results and readil observe trends that may affect quality.

Control charts depict data in several way and they can be of a simple design in whic the target value is used as the axis and th specification limits as the control limits. Suc charts show the variation of individual valu or averages with respect to the actual specific tions. However, when the mean, standa deviation, and the range of the material process can be computed from a sampl average and range charts should be used.

The average, $\overline{X}$, chart shows variations the averages of test results. A central line a upper and lower control-limit lines are use The range, R, chart shows variations in t ranges of test results. It also has a cent line and upper and lower control limi Construction of these charts is described any good quality control text.

If the average, $\overline{X}$, chart is being used control current production, a sample of items is taken from the process at rando intervals and a quality measurement made each item. The average of these measureme is then computed and plotted on the cha As long as the sample averages neither f outside the control limits nor show any n random variation within the limits, t process is deemed to be in control with resp to its central tendency or *target value.*

When a range, R, chart is being used control current output, the range of a sam of n items is computed and plotted on the chart. If the sample ranges neither fall outs the control limits nor show any nonrand variation within the limits, the process considered to be in control with respect its variability. The $\overline{X}$ and R charts must used together to assure control of both le and variation of quality. Examples of Avera $\overline{X}$, and Range, R, charts are shown in fig 7 and 8.

Acceptance procedures

For highway construction, the State m elect to use the results of supplier's or c tractor's quality-control programs to acc material or construction. However, the us procedure in buyer-seller relations is for buyer to establish independent acceptance plans for each item of material or construction. An acceptance plan designates lot size; where and when to sample, on a random basis; numbers of samples to be taken; method of test to be used in the quality measurement on each specified characteristic of the sample; and, based on the test results, procedure for making a decision. An acceptance plan may be a simple statement or a complicated system in which many steps must be taken before a decision can be made. Examples of sampling plans will be included in subsequent installments of this article.

When decisions are based on a sample, a basic truth must be accepted: There is a certain risk that the decision is incorrect because the sample does not truly describe the total of the material. One advantage of the statistical approach is the ability to design a sampling plan in which the probabilities of acceptance of poor material, the β risk, and the rejection of good material, the α risk, are known. When *good* and *bad* materials have been defined and the risks to be taken agreed upon, the number of samples required to make a decision compatible with the risk probabilities can be calculated. These relations and the methods for establishing an operating characteristic curve, which denotes the probability of acceptance for intervening qualities of a product, can be found in any good quality control text.

Summary of Research Effort

During the past 4 years, the Office of Research and Development, Bureau of Public Roads, has actively promoted the following five-point program of research in quality assurance in highway construction:

- Awakening the highway industry's interest in the utility of the statistical approach to quality control and acceptance testing.
- Developing guides for research that would yield statistical data for writing acceptance specifications.
- Planning and coordinating a nationwide program of research in applying statistical methods to highway construction.
- Gathering and analyzing data and disseminating research findings.
- Designing and implementing projects by which the findings of the research program can be evaluated.

This effort is basically State research financed with Highway Planning and Research (H.P. & R.) funds. Many of the studies have been conducted according to guidelines established by Public Roads Task Force; others have followed plans developed by State personnel.

Early in the research program it was realized that little data were available for use in establishing quality levels and variations in highway construction on a statistically valid basis. Therefore, a concerted effort was initiated to measure quality and its variations in terms of existing criteria. Participating State highway departments have been measuring the level and variability of quality in their construction. To date, 28 States have conducted studies funded under H.P. & R. contracts and seven others have been investigating construction in State-funded studies.

The objective in the formulation of all studies was to produce compatible information that could be used throughout the Nation. A booklet of guidelines (*2*) was prepared and distributed to the States for use in planning their projects. A method of obtaining statistically valid data for an analysis of variance to isolate the components of variance was outlined in a suggested research plan. The plan permits overall variance to be divided into material or process variance, sampling variance, and testing variance.

According to the research data received from the States, 50 percent or more of the overall variance could be attributed to sampling and testing in some of the studies. Results showing this magnitude of sampling and testing error indicate that a concerted effort should be exerted by each highway department to train inspectors and laboratory technicians.

Also, according to the research data, which has been statistically analyzed to determine the percentage of present construction that complied with the levels and limits of current specifications, a considerable portion of the construction is shown to be outside the limits defined by the specifications. In fact, as much as 30 percent of some construction, considered to be completely acceptable under current control procedures, may be outside the stated limits. This variation from the specifications, in part, reflects the errors of sampling and testing, but there are indications that many of the present limits do not reflect valid allowances for the variable materials and processes used in highway construction.

Supplementing the State research effort, the Public Roads Office of Research and Development began a contract-research program in 1963 to further the development of statistical quality-control applications to highway construction. Many aspects of the task force's research plan were based on the results of the initial study in which the contractor evaluated the choice of concepts available and pointed to the priority areas for study. The study conclusions were presented in an unpublished report entitled *A Plan for Expediting the Use of Statistical Concepts in Highway Acceptance Specifications*. Two subsequent contracts provided valuable information concerning the level and variation of quality in base and subgrade construction.

A review of the Public Roads Standard Specifications for *Construction of Roads and Bridges on Federal Highway Projects* (FP–61) was conducted by another contractor. The final report on the contract was later used to develop a *futurized* revision of FP–61—the first attempt at writing complete specifications using statistical concepts wherever feasible.

The *Futurized Revision of Federal Project Specifications* was never intended for use in highway construction, and distribution of the document has not been widespread. However, it has been reviewed by many outstanding highway engineers and by committees of the American Road Builders Association (ARBA) and other organizations. Most of the comments received have been favorable to the concepts incorporated in the specifications, but some disagree with methods of accomplishment and with items other than those that were treated statistically. The statistical applications embodied in the *Futurized Revision of Federal Project Specifications* have been proved to be sound and are the basis of many specifications now being written.

Subsequent information obtained from the States' research studies and Public Roads' in-house research has been used in the development of statistically based research specifications for construction of embankments, bases, and bituminous pavements. These specifications have been studied and discussed by many engineers associated with highway construction. It is evident from the comments received that some of the ideas presented are still not completely acceptable to the industry. Objection has been voiced to the complete delegation of quality control responsibility to the contractor and to the reduced payment schedules for nonconforming materials and construction. Primarily, the differences of opinion concern the degree of responsibility and the amount of reduced payment.

Undoubtedly, changes in present contractor-State relations are needed to fully implement the statistical approach to specifications. These changes must establish end-result requirements that can be measured by the States. Practical considerations such as inadequately trained manpower, equipment availability, and lack of adequate end-result tests in some instances prevent an immediate, complete changeover from the *traditional* specifications. However, a number of States already are assessing the degree to which they are involved in the process control and are shifting as much of the responsibility to the contractor that is possible under present circumstances. Where adequate tests to measure finished quality are available, there is no evidence that ultimate responsibility for process quality would present a hardship to the contractor. Increased contractor responsibility coupled with proper flexibility by the State should result in better and more economical construction and provide incentive for the equipment industry to produce equipment that is capable of high-quality work as well as high production.

For certain operations, reduced-payment schedules for out-of-limits construction seems to be a necessity. The designation of really *good* material or construction and really *bad* material or construction is relatively simple. However, there is usually a grey area in which the out-of-limit material or construction may be usable, and removal and replacement operations are not warranted because of delays or other hindrances to traffic. For such material or construction the concept of partial payment is not new. In current practice, payment to the contractor is arbitrated in after-the-fact negotiations. If schedules are established before the contract is let, the contractor will be aware of the risks involved and after-the-fact penalties probably will not be necessary.

Although objections have been raised to some concepts advocated in the research program, the basic idea of adapting statistical concepts to highway construction is being well received. Research data are being used by many States to revise specification limits to allow for sampling and testing errors determined through the research studies. Only one State has progressed sufficiently to include a complete statistical approach in its standard specifications. At least five States are known to be incorporating special provisions that were calculated on a statistical basis. Five other States have written statistically based specifications for some facet of their construction, but have not used them in contractual work.

Rapid progress is being made in the adoption of control charts for displaying and analyzing data. Control charts can be used under present specifications if the inherent limitations are well understood. Their use will be greatly enhanced as more information on quality requirements and measuring techniques are developed.

Optimum use of statistics in quality assurance can come only through the adoption of end-result specifications. End-result specifications will allow the proper designation of responsibility for control and acceptance, and they are the only means through which quality measurement of a completed segment of construction will ever evolve. End-result specifications require knowledge of end requirements and must be based on measurements made on the end product. The highway industry's present inability to adequately define performance requirements and to measure performance quality dictates a major redirection of the research program.

Discussion of Research Results

Information, data, and analyses obtained through research by the States, Public Roads, and others are presented in subsequent parts of this report. These data provide support for many of the statements in this introductory section.

The indicated variation in materials and construction is, in fact, often attributable to variation in sampling and testing rather than to the materials or the construction itself. It is essential, therefore, that each State determine the sampling and testing variation associated with its current methods and personnel, and that it make a concerted effort to reduce test variations to a minimum.

Many current specifications do not adequately allow for sampling and testing variations in the presently prescribed limits. Where such inadequacy exists, and it is impossible or uneconomical to further reduce these variations either by improving the procedure or increasing the number of tests, the specification limits should be relaxed.

When random samples are taken in sufficient number to adequately measure quality, it has been shown that a surprisingly large portion of currently acceptable construction does not comply with present limits. It may not be economically feasible to make sufficient tests for accurate measurement of quality during the control and acceptance process, but as stated earlier, the use of statistical concepts will make it possible to select the sample size in accordance with the importance of the decision being made and the economics of sampling and testing. It is therefore important that the validity of current tests as indicators of quality be studied, and that new tests be developed that will better measure the performance of the end product.

The variability of materials and construction is emphasized by the data. Present procedures usually are concerned with the average level of characteristics; however, even when the target value is met, it is shown by statistical analyses that a large portion of the materials or construction may be outside specification limits. Accordingly, variation, as well as the level of quality, should be controlled. To accomplish this control, a method of random selection of samples must be used. The adoption of random sampling by industry will significantly improve quality assurance in highway construction.

The research program has produced many other findings that will be discussed in subsequent sections. However, additional data are required before the results can be established as facts. Some of the data being received are not sufficiently complete to firmly establish the necessary basic relationships.

Discussions and findings for specific items of construction will be included in the next and subsequent issues.

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(*1*) *Quality Assurance Through Process Control and Acceptance Sampling,* reported by the Statistical Quality Control Task Group, Office of Research and Development, Bureau of Public Roads, April 1967.

(*2*) *The Statistical Approach to Quality Control in Highway Construction,* Research Guide, The Statistical Quality Control Group, Office of Research and Development, Bureau of Public Roads, April 1965.

Thermoplastic striping material on southbound lane of Atwells Avenue Bridge, Interstate Highway 95, Providence, R.I.

Comparison of the Performance and Economy of Hot-Extruded Thermoplastic Highway Striping Materials and Conventional Paint Striping

Reported by BERNARD CHAIKEN, Principal Research Chemist, Materials Division

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

In the survey reported here, the comparative durability, performance, and economy of hot-extruded thermoplastic traffic-marking materials and conventional paint striping were evaluated. All State highway departments, major toll road agencies, and several larger cities and county road authorities were included in the survey, in which it was shown that the relative durability and long-term economy of hot-melt thermoplastic striping materials were greatly affected by type of pavement, snowplow activity, and traffic density. It was also shown that, to a lesser extent, other factors also affected the relative merits of these materials. A guide chart was developed to facilitate selection of the more economical of the two marking materials. Selection parameters include pavement type, traffic density, and mean annual snowfall—snowfall being an indirect measure of potential snowplow activity. The chart permits selections on the basis of direct comparative costs alone, as well as on the basis of additional indirect costs such as traffic delays and potential accident hazards attributable to frequent conventional maintenance striping.

Hot-extruded thermoplastic was found to be more economical than traffic paint under conditions of high traffic density and limited snowplow activity; otherwise standard traffic paint was the more economical of the two methods of striping. Bituminous pavements showed the thermoplastics to better advantage than did portland cement concrete surfaces.

Introduction

FOR more than a decade, many highway agencies have been developing an interest in the use of hot-extruded (hot-melt) thermoplastic traffic striping materials as an alternative to conventional paint striping. This type of thermoplastic differs from the cold-flow preformed type, as well as from the hot-spray type, in that it is extruded onto the pavement in a molten state. The hot-extruded material is applied by first heating the solvent-free solid product to its molten state, at approximately 425° F., and then extruding the molten material directly onto the pavement through a die. The produced traffic stripe, about ⅛-inch thick, solidifies within minutes, and can be exposed to traffic much sooner than conventional paint stripes.

During 1965, the State highway departments reportedly used almost 5 million linear feet of hot-extruded thermoplastic striping, which is equivalent to about 900 actual stripe miles of the material (*1*).[1] Its growing popu-

[1] Italic numbers in parentheses identify the references listed on p. 154.

larity has been attributed to its rapid drying, or set, compared with traffic paint as well as to its superior durability, which thereby obviates the need for frequent stripe maintenance. Thus, compared to conventional striping the material potentially offers advantages of long-term economy and traffic safety. Major limitations to a wider use of the material have been the initial installation cost—15 times the cost of ordinary striping—and premature failures caused by loss of adhesion to the pavement surface. In reports on two surveys conducted by the author several years ago, the advantages and limitations of this material were discussed (*2*, *3*). Several other reports on the performance and merits of such thermoplastic striping are available and still others will be published soon (*4*, *5*, *6*, *7*).

In general, evidence to date has shown that:

•Thermoplastics are much more durable on bituminous pavements than on portland cement concrete pavements.

•The newer the concrete surface the poorer the adhesion; the material, after hardening, is somewhat subject to blistering, especially when applied to concrete.

•The thermoplastic is subject to snowplow damage.

•Thermoplastics may be more economical than conventional paint striping only when high traffic volumes are prevalent.

Except for these generalities, no clear-cut broad geographical criteria have ever been established to define precisely where and how such materials may be used to economic advantage. Moreover, the technology of applying thermoplastic striping has been improved in recent years; therefore, it seemed desirable to conduct an up-to-date investigation of the performance and economics of thermoplastics, and, in 1967, a survey was initiated by the Bureau of Public Roads to evaluate new developments and performance data. The objective of the survey was to develop, if possible, clear criteria on the relative long-term economics of thermoplastic and paint striping for any given location. The re sults of that survey are reported here.

Agencies Surveyed and Informatio Sought

The type of information requested in th survey is listed under the heading *Data R quested in Survey*, page 155. In requesting th information, emphasis was placed on recen installations where quantitative informatic and conclusions were available. The requeste information was formulated to yield quant tative data on the comparative long-ter economics of paint and thermoplastics, well as to obtain criteria used in differe localities to select one material over the oth

The inquiry was sent to all the State hig way departments, to the highway depa ments of the District of Columbia and Puer Rico, to most of the toll road agencies, a to some of the larger cities and counties. T number and type of agencies surveyed, t replies received, and the number of agenci

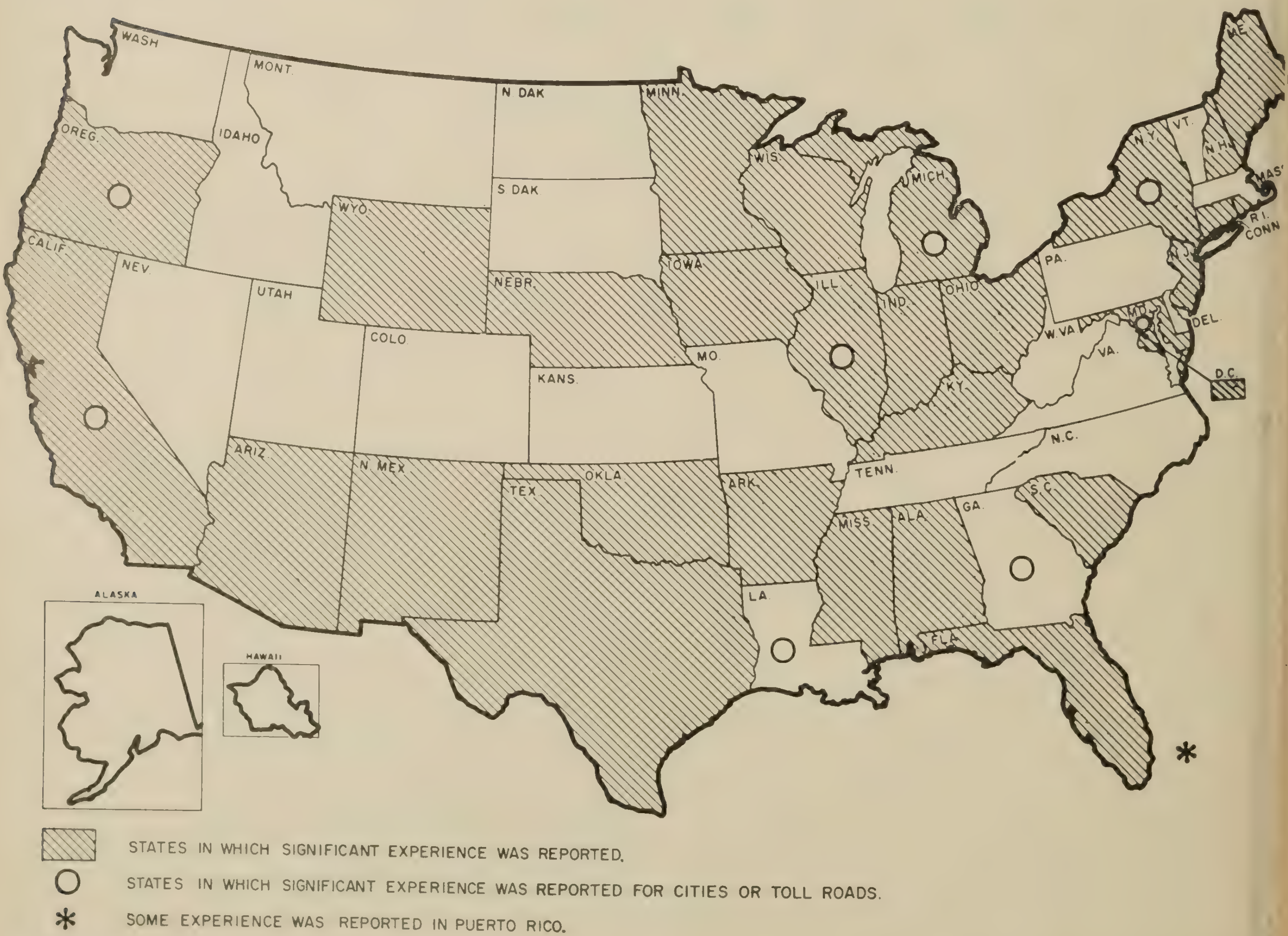

Figure 1.—States in which highway agencies reported significant experience in use of hot-extruded thermoplastic striping.

Table 1.—Summary of responses to questionnaire

Highway or bridge agencies	Number surveyed	Replies received	Number reporting significant experience with thermoplastic
States, District of Columbia, and Puerto Rico	52	48	31
Toll-road and bridge authorities	[1] 17	16	4
Cities and counties	[2] 16	13	8

[1] Included: Delaware River and Bay Authority, Florida State Turnpike Authority, Illinois State Toll Commission, Indiana Toll Road Commission, Kansas Turnpike Authority, Massachusetts Turnpike Authority, New Jersey Highway Authority (Garden State Parkway), New Jersey Turnpike Authority, New York State Thruway Authority, Ohio Turnpike Commission, Oklahoma Turnpike Authority, Pennsylvania Turnpike Commission, Port of New York Authority, Richmond-Petersburg Turnpike Authority, Triboro Bridge and Tunnel Authority, Texas Turnpike Authority, West Virginia Turnpike Commission.

[2] Included: Atlanta; Baltimore; Boston; Chicago; Dallas, Detroit; Los Angeles; Los Angeles County; Newark, New Jersey; New Orleans; New York; Philadelphia; Portland, Oregon, Providence; San Francisco; San Francisco County; and Seattle.

reporting significant experience with hot-extruded thermoplastics are summarized in table 1. Approximately half of the road agencies surveyed reported some recent significant experience with the material.

In figure 1, a map of the continental United States, the areas that reported significant recent experience with thermoplastic striping are shown; the major areas of the country were well represented by thermoplastic installations.

Tabulation of Survey Results

The responses of all the road agencies reporting substantial experience are summarized in tables 2 and 3, as well as in the section *Comments by Agencies Surveyed*, page 155.

Table 2 is a tabulation of the data received. In column R of table 2, the average useful life of the thermoplastic stripe reported by each agency is shown, either on the basis of fully achieved life or on an estimated basis wherever the stripe was still considered to be serviceable at the last inspection. Results shown in parentheses were estimated by the author when the agency failed to report the estimated life and sufficient data were supplied. These estimates were calculated from the percentage of stripe lost up to the time of the last observation and were extrapolated on the assumption that the material would reach its terminal point when 40 to 50 percent of the stripe was lost—an approximation of the terminal point criteria used by several surveyed States and of that mentioned in a separate survey conducted by the Institute of Traffic Engineers.[2]

Related data on conventional paint striping for the same or comparable locations as those used for thermoplastic striping are shown in columns S and T of table 2. The relative long-term economics of thermoplastics and paint are presented in column U. The data in column U were calculated by dividing the unit annual maintenance cost of thermoplastic striping by that for conventional paint striping. Values greater than one indicate that conventional paint striping has a long-term economic advantage over thermoplastics; values less than one indicate the reverse situation. Here again, values shown in parentheses reflect calculations based on the author's estimates. More than one numerical entry in any column of the table reflects the data for more than one type of stripe, as shown in column O. The first numerical entry is for the first type of stripe listed in column O, etc. Where a single numerical entry is shown in column U or preceding columns, and more than one type of stripe is shown in column O, the numerical entry refers to the first type of stripe listed in column O—usually a lane line.

The policies or criteria reported by the various agencies as to the conditions under which they permit or justify the use of hot-extruded thermoplastics striping are summarized in table 3. In those agencies with established policies, the use of thermoplastics is generally restricted to areas of high traffic density and excluded from locations subject to heavy snowfall. A few agencies use the material only on bituminous pavements because of its somewhat erratic performance on concrete pavement. The few agencies reporting numerical criteria in terms of average daily traffic (ADT) show a considerable variation in this requirement; this will be discussed more fully later.

A summary of the qualitative and subjective remarks by the agencies reporting experience with hot-melt thermoplastics is presented in the section *Comments by Agencies Surveyed*, page 155.

General Observations From Survey Data

Some general observations are evident from the data shown in tables 2 and 3 and in the section *Comments by Agencies Surveyed*, page 155. These observations are discussed in the following paragraphs and, unless otherwise indicated, the remarks are applicable to data on 4-inch-wide longitudinal striping—either center lines or lane lines rather than edge or transverse markings.

Installation costs of paint striping and hot-melt thermoplastics

The reported costs for conventional paint striping varied from as little as 0.9 cent to as much as 10 cents per linear foot of 4-inch stripe. All reported costs reflect the entire installation cost—materials, labor, expendable supplies, equipment depreciation, etc. The 10-cent figure, much higher than the other reported costs, was reported by authorities in New York City with the explanation that the city's high traffic-control expenses accounted for much of the cost. In general, the reported costs for conventional striping were based on installations made by the agency itself rather than by a contractor. From the data reported, the average cost of paint striping for open highways was calculated and determined to be 2.2 cents per linear foot of 4-inch longitudinal striping. This average cost seemed to compare reasonably well with a detailed cost analysis of paint striping made by one agency, the New York Department of Transportation, which reported an average cost of 1.7 cents per linear foot of paint stripe for the year 1963 after an intensive study of this aspect alone (*8*). It was shown that approximately 36 percent of the cost, 0.6 cents, was for paint, and that the remainder, 1.1 cents, was for other items—glass beads, labor, fuel, supplies, equipment depreciation, etc. Assuming the normal inflationary rise between 1963, the time of the New York study, and the time of the survey reported here, 1967, the two cost figures are comparable. A few agencies reported contract costs for paint striping, which were approximately one and one-half to three times as high as when the agency did the striping with its own forces.

The reported costs of thermoplastic installations ranged from a low of 17 cents to a high of 63 cents a linear foot of longitudinal 4-inch stripe. Generally, the few agencies reporting extremely low costs had either performed the work themselves or stated that the contract price was the same as the contractor's cost or below it because the contractor had taken a loss to demonstrate the merits of the material. In general, extremely high costs were reported only for very small installations or for city installations in which the cost reflected expensive traffic control and slow application rates. The average cost of all 4-inch longitudinal thermoplastic striping was calculated to be 32.7 cents a linear foot, and generally represented the average contract price for large installations on open highways. This calculated cost is similar to that reported in another survey (*2*) in which it was pointed out that the installation cost is very much affected by the quantity installed and the extent of the performance guarantee provided.

Pavement precleaning prior to thermoplastic application

The type of pavement precleaning reported by the highway agencies differed. Some agencies did not preclean the pavement; others precleaned by one of the following methods: Sandblasting, brooming, air blasting, buffing, or acid etching. Many agencies did not know the exact nature of the precleaning performed. The most prevalent practice, especially on bituminous pavements, was no precleaning at all. There seemed to be no significant trend in the type of precleaning with respect to pavement type, except that sandblasting and acid etching were restricted to concrete pavements. Agencies having extensive, recent experience with thermoplastic materials prefer special precleaning methods for concrete surfaces. For example, the

[2] *Model Specifications for Thermoplastic Pavement Marking Materials*, Institute of Traffic Engineers, Committee 7M (66), Sept. 30, 1967. (Unpublished draft of standard under review.)

Agency	Project and location	ADT [2] Total	ADT [2] Per lane	Pavement Type [3]	Pavement Age [4]	Snowplow activity	Approximate mean annual snowfall [5]	Date striped	Pavement pretreatment [6]	Primer used	Name of thermoplastic [7]
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)
											STATE
		Thousands	*Thousands*		*Years*		*Inches*	*Month-year*			
Alabama	U.S. 231, between Tennessee River and Huntsville.	15-30	4-7	B	New	Negligible	4	3-59	None	None	Perm, Ca
Arizona	I-17, Phoenix	50	8.3	C	4	None	0	10-62	do	Rubber	Perm
Arkansas	I-30, S. of Little Rock	12	3	C	0.3		4	4-63		Pliobond	do
California	I-80, 5,000 ft. elevation			C, B		Heavy	100+	?-60	sbl [19]	do.[20]	Perm, Ca
	Routes 20, 49, and 149, Grass Valley, 2,500 ft. elevation.		5	B		Light [21]	60	9-65	do	do	([22])
	04-Ala. 24, Berkeley		8	B		None	0	12-58			
	04-SF-101, San Francisco		9	B		do	0	?-61			
	04-SF-101, Bayshore Freeway, San Francisco.		20			do	0	7-58			
	F-071-1(1), Los Angeles		3.5			do	0	?-64			
	I-605-2(76)127, Los Angeles		10			do	0	?-64			
	Summary and general observation	([25])		B	New and old	do	0	?-60	None	None	([22])
		([25])		C	do	do	0	?-60	sbl [20]	Pliobond	do
Connecticut	I-91, Rocky Hill to Hartford	42	7	C	New	Heavy	50	11-63	None	Epoxy [26]	Perm
Florida	Gainesville, NW 3, 5 and 7 and University Ave.	17	4	B		None	0	3-60			do
		17	4	B		do	0	3-60			Cat
	IP-506-A, Gainesville, Waldo Road.	6	1.5	B		None	0	7-63		None	
	IP-506-C	8.6	4.2	C		do	0	7-63		Unidentified.	
	I-95, Dade Co., Miami	87	11	C		do	0	3-65	abr	Epoxy	Perm
Illinois	FAI-55, Stevenson Expressway, Chicago.		13	C	1	Heavy	36-60	11-65		do	do
	Edens Expressway, Chicago	90	15	C	6	do	36-60	?-57	brm	Pliobond	do
	General observations (Chicago area).	High				Heavy	36-60				
Indiana	SR-53, Gary		9	C	Old	Light	60	7-63	None	Epoxy	Perm
	U.S. 27, Fort Wayne		8.8	B	do	do	36	7-63	do	do	Cat
	U.S. 31, Franklin		4.2	B	New	do	12-24	6-64	do	do	do
Iowa	I-235, Des Moines Freeway	44	11	C	do	Moderate	24-36	6-64	Acid	do	Perm
Kansas	I-70, Topeka		2	C	1	do	12-24	1-62	brm	Rubber	do
	U.S. 50, Kansas City		7	B		do	12-24	11-59	do	None	Cat
	U.S. 69, Kansas City		4.3	B		do	12-24	7-59	do	do	Perm
Kentucky	I-264, N. U.S. 60, Louisville (Site 1).	19	5	C	1	Medium	12	11-62	None [36]	Pliobond	do
		19	5	C	1	do	12	11-62	do	do	Cat
	I-264, S. U.S. 60, Louisville (Site 2A).	55	14	B	2	High	12	11-62	do [36]	do	Perm
		55	14	B	2	do	12	11-62	do	do	Cat
	I-264, S. U.S. 60, Louisville (Site 2B).	48	12	B	2	do	12	11-62	do	do	Perm
		48	12	B	2	do	12	11-62	do	do	Cat
	I-264, U.S. 60, Louisville (Site 2C).	43	11	B	2	do	12	11-62	do	do	Perm
		43	11	B	2	do	12	11-62	do	do	Cat
	I-64, Franklin-Shelby Co. (Site 3).	10	2.5	C	1	Medium	12-24	10-62	do	do	Perm
		10	2.5	C	1	do	12-24	10-62	do	do	Cat
	I-64, Clark Montgomery Co. (Site 4).	5.8	1.5	B	2	Low	12-24	11-62	do	do	Perm
		5.8	1.5	B	1	do	12-24	11-52	do	do	Cat
	U.S. 60, Frankfort-Versailles Road (Site 5).	9.7	2.4	C	5.5	Medium	12-24	6-65	Air	Epoxy	Perm
	I-64, S. Frankfort (Site 6)	8.8	2.2	C	3.5	do	12-24	6-65	do	do	do
	I-64, E. of I-264, E. Louisville (Site 7).	15	4	C	0.6	do	12	6-65	do	do	do
	I-65, N-S Expressway, E. Louisville (Site 8).	52	13	C	2-8	High	12	6-65	do	do	do
	I-264, SE. of Louisville (Site 9)	59	15	B	9	do	12	6-65	do	None	do
Maine	Augusta, State St		6	B	Old	Heavy	60-100	8 66	None	do	Cat
Maryland	Baltimore Beltway	55	7	C	New	do	12-24	6-65	Unknown	Epoxy	Perm
	Md. 193, Conn. Ave	40	10	C	Old	do	12-24	5-65	do	Unknown	Cat
		40	10	B	do	do	12-24	5-65	do	do	do
	U.S. 40, Flintstone Bypass	3.2	1.6	B	New	do	12-24	?-59	None	do	Unknow
Michigan	U.S. 127, S. of Lansing			B	Old	Heavy	36-60	?-58			do
				C	do	do	36-60	?-58			do
	I-75 & I-375, Chrysler Freeway, Detroit.	30	5	C	New-1	Light [37]	36	6-64	sbl	Epoxy [38]	Perm
Minnesota	I-494-4(65)231, near Minneapolis	58	10	C	2-4	Heavy	36-60	9-63	Buff	Synthetic rubber.	do
		58	10	B [39]	2-4	do	36-60	9-63	do	do	do
	I-35W-3(81)112, Minn.-St. Paul	26	4	C	2	do	36-60	5-66	None	Epoxy [40]	do
		26	4	B	2	do	36-60	5-66	do	do	do
	I-35-6(82)205, near Willow River	3	1	B	1	do	60	9-66	do	do	do
Mississippi	I-55-4(23)240, N. of Batesville	5.3	1.3	C	New	Slight	2-4	9 62	Clean [41]	Pliobond [42]	Cat
		5.3	1.3	B	do	do	2-4	9-62	do	do	do
	F-008-2(9), N. of Hattiesburg, Highway 49.	7	1.8	C	New	None	0	11-61	do [41]	do [42]	do
	F-008-1(8), S. of Hattiesburg, Highway 49.	6	1.5	C	Old	do	0	4-62	do	do	do
	F-018-3(2), Starkville (MSU), Highway 12.	2.8	0.7	C	New	do	2	12-64	do	do	do
Nebraska	I-80-9(106), near Lincoln		3.5	C	1	Moderate	24-36	?-63	None	Synthetic rubber.	do
	I-80-9(107), near Omaha		8.1	C	5	do	24-36	?-63	do	do	do
	I-280-9(108), near Omaha		5.6	C	6	do	24-36	?-63	do	do	do
New Hampshire	I-93-2(20)39, Concord to Canterbury.		3.0	B	New	Heavy	60-100	11-59	do	None	Perm
New Jersey	U.S. 1, N-S Freeway, Trenton	20	5	C	Old	Moderate	12-24	?-60		Unknown	Perm,
New Mexico	I-25, Albuquerque		4.2	C	0.25 and 4	None	12	5-63	do	None	Perm

See footnotes at end of table.

Thermoplastic-striping data—Continued										Standard paint-striping data [1]					
Amount of striping		Type of stripe [8]	Installation cost per linear foot of stripe [9] (P)			Amount of stripe lost (Q)		Average useful life (R)		Materials and installation cost per linear feet [10] (S)			Average useful life	Ratio of long-term cost, thermoplastic/paint [11] (U)	
(M)	(N)	(O)	4-inch width	6-inch width	8-inch width	First year	Total lost	Actual [12]	Estimated [13]	4-inch width	6-inch width	8-inch width	(T)	Determined	Estimated [14]
TERRITORY															
Miles	*Thousands of linear feet*		*Cents*	*Cents*	*Cents*	*Percent*	*Pct./No. of yrs.*	*Years*	*Years*	*Cents*	*Cents*	*Cents*	*Years*		
28		L	40			0	8/0		[15] 12	2.5			[15] <1		<1.3
1		L	40			0	0/5		8	4			0.5		0.6
2.5		L, E, T	[16] 35		85		[17] 8/2		3	[18] 5		[18] 9	0.5		1.2
						>50	50/0.25	1/4						>1	
	14		[23] 27				1/2		4	3			0.25		0.63
1							50/9	[24] 9							
1.6						0	0/6		8						
								>8							
							20/3		5						
									6						
		L, etc.	[23] 24		[23] 5	0	0/7		>8	3		15	0.75–2	<1	
		L, etc.	do		do	5	35/7		5	3		15	do	1.6	
	132	L, E, G	32	48	64	10	?/4	>4.5	6	[27] 3	[27] 3.5	[27] 6	0.3	<1	
		L, T	24		48								0.2		
		L, T	42										do		
		T						>4					1.8		
		T						>4					0.9		
1		L	[28] 35			([29])				2			>0.2		
	670	E, L, G	[30] 25	[31] 35	56		15/2		4	[30] 0.8	[31] 4.5	5.4	0.33		1
		L						4					0.25	[32] 0.6	
		L, G		[31] 35	56		50/4	4			[31] 3.1	5.4	0.33, 0.50	1, 1.3	
	31	L	33			30	45/1.5	1.5		2			0.33	3.7	
	2.5	L	35			Minor	Minor		7	2			0.5		1.2
	11	L	31			do	do		7	2			1		2
	29	L	[33] 46		64	[34] 70	50/3		3	[33] 1.2			0.5		(6)
	9	L	39	55	72		[34] 25/2	3		1.7			1	8	
	19	L		[31] 38		0		[35] 2			[31] 1.7		0.15	1.7	
	17	L		[31] 40		Much		3			[31] 1.7		0.15	1.2	
	12	L, E, T	39			1	7/4			1.6			1, 2		
	12	L, E, T	39			1	13/4	5		1.6			1, 2	5, 10	
	20	L, E, T	39			0	0/4		>8	1.6			2, 3		
		do	39			0	17/4		8	1.6			2, 3		
		L, E, T	39			0	0/4		>8	1.6			2, 3		
		do	39			0	17/4		8	1.6			2, 3		
		L, E, T	39			0	0/4		>8	1.6			2, 3		
		do	39			0	17/4		8	1.6			2, 3		
	100	do	39			6	35/4	4		1.6			1, 2	6, 12	
	100	L, E, T	39			9	65/4	4		1.6			1, 2	do	
	99	do	39			6	1/4		>8	1.6			2, 3		
	99	L, E, T	39			1	2/4		>8	1.6			2, 3		
	7	L	35			16			3	1.6			1, 2		
	9	L	32							1.6			1, 2		
	12	L	32							1.6			1, 2		
	186	L, E	32		57										
	310	L, E	32		57										
	15		28						5	1.5			1		4
1		L	33				25/2		4	3			0.4		(1)
2.6		L	27			>10	>25/2		3	3			0.4		(1.2)
2.6		L	27							3			0.4		
	1	L	35				10/8	>8	12	3			1		(1)
		T, E						9							
		T, E				Failed			1						
	44	L, E	32			5	13/3		5	3			1		2
	25	L	40		80	27	34/2	3.7		[27] 7		[27] 10	0.3	0.5	
	85	E, R	39							do			0.3		
5.7		L, R	42		80	25	25/1		4	2.5			0.8		4
1.1		L	42			0	0/1		10	2.5			0.8		1.4
9.4		L, E, R	36		70	0	0/1		10	2.5			0.8		1.2
0.8	1.5	L	49						8.5	[43] 6			0.9		0.9
		L	49						8.5	do			0.9		0.9
	16	L	37			Some	7/6		8.5	[43] 6			0.6		0.5
	20	L	28				11/15		8.5	do			0.6		0.3
	2.7	L	30				3/3		8.5	do			0.9		0.5
11.3	40	E, L, R	36	[31] 47	66		10/4	>4		0.9	[31] 1.1	1.7	0.5		
1.8	20	E, L, R	36	do	66		do	>4		0.9	do	1.7	0.5		
1.9	9.5	E, L. R	36	47	66		10/4	>4		0.9	[31] 1.1	1.7	0.5		
29	146	L	[44] 19			Minor			10	[27] 2			1.25		1.2
2	10	L, E	25					4		1.25			0.5	2.4	
0.5	2	L	43		53		50/4	2		0.8		1.6	0.5	10	

Agency	Test-site data							Thermoplastic-striping data			
	Project and location	ADT [2]		Pavement		Snowplow activity	Approximate mean annual snowfall [5]	Date striped	Pavement pretreatment [6]	Primer used	Name o thermoplastic [7]
		Total	Per lane	Type [3]	Age [4]						
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)
STATE OR TERRITOR-											
		Thousands	*Thousands*		*Years*		*Inches*	*Month-year*			
New York	I-81, Jefferson Co. (FIM 61-4)	5	1.5	B	New	Heavy	60–100	10-61		Synthetic rubber.	Crys
	I-81, Jefferson Co. (FIM 61-4)	5	1.5	B	New	do	60–100	10-61		Synthetic rubber.	do
	Southern State Parkway, Suffolk Co. (SSP 62-3).	55		C	2–24	Moderate	24-36	10-63	Air	Epoxy [26], [45]	do
	Heckshеr State Parkway, Suffolk Co. (HSPM 63-2).	42		C	1–3	do	24-36	10-63	do	do	Perm
	Meadowbrook State Parkway, Nassau Co. (MSP 62–3).	38		C	Old and new.	do	24-36	9-64	do	do [45]	do
		38		B	do	do	24-36	9-64	do	Synthetic rubber.	do
	Fire Island Inlet Bridge, Suffolk Co. (FIIB 64-1).	4.2		C	New	Moderate	24-36	10-64	do	Epoxy [45]	do
		4.2		B	do	do	24-36	10-64	do	Synthetic rubber.	do
	Northern State Parkway, Suffolk Co. (NSP 65-2).	60		C	Old	do	24-36	9-65	do	Epoxy [45]	do
	I-81, Jefferson Co. (FIRCM 65–134).	6		B	New	Heavy	55	10-65	brm	Synthetic rubber.	Cat
	U.S. 20, W. of Albany	12.5		C	19	do	60–100	5-60	do	do	do
	I-81, Oswego Co., (FIM 61-1)	10		C	1–3	do	60–100	7-61	do	do	Perm
	I-87, Saratoga Co., (FIM 61-2)	7		C	0.25–1	do	60–100	11-61	do	do	Crys
	I-490, Monroe Co., (FIM 61-3)	36		C	0.25–2	do	60–100	10-61	do	do	do
Ohio	Akron, Youngstown, Ravenna	High		B, C	Old and new.	do	36–60	11-64	Clean	None	Cat
Oklahoma	I-35-3(30)126, Oklahoma City		7	B	New	None	6–12	8-61	None	Epoxy	Perm
	SAP-16(9), U.S. 62 in Lawton		4	C	New	do	6–12	8-66	None	do	do
	I-440-4(26)154		5	C	do	do	6–12	4-61	do	do	do
	I-35-4(47)142, S. of Guthrie		2.8	C	do	do	6–12	10-61	do	do	do
Oregon	I-5, Minnesota Freeway, Portland		8.5	C	1	do	12	9-65	do	Pliobond	Cat
	U.S. 99E, Salem		4	B	Old	do	12	9-65	do	do	do
	U.S. 99E, Salem		4	B	New	do	12	9-65	do	Pliobond	do
	U.S. 20, Santiam Pass		1	B	Old	Heavy	100–300	9-65	do	do	do
Rhode Island	I-195, East Providence		5.2–11.5	B	New	do	36	10-59	do	None	do
			5.2–11.5	B	do	do	36	10-59	do	do	do
	I-95, Providence		13.3	B	do	do	36	10-63	do	do	Perm
	I-95, Providence		13.3	B	New	do	36	10-63	do	Pliobond	do
	I-95, Cranston, Providence		11–14.3	B	do	do	36	10-65	do	do	do
	I-95, Providence, Warwick		6.7–11.3	B		do	36	9-66			do
South Carolina	I-26-4(24) 175, Harleyville to Ridgeville.	3.8	1	B,C	New and 0.5.	None	9	9-62	Buff	Synthetic rubber.[48]	Cat
	I-385-2(28) 58, Greenville	7.5	1.9	B	.04	1 per yr	4	9-62	do	do	do
Texas	I-45, Gulf Freeway, Houston (District 12).	87.6	14.9	C	10	None	0	4-59	brm	None	Perm
		87.6	14.9	B	10	do	0	4-59	do	do	do
		87.6	14.9	C	10	do	0	3-60	do	Unknown	Cat
		87.6	14.9	C	10	do	0	4-59	do	do	do
		87.6	14.9	B	10	do	0	4-59	do	do	do
Wisconsin	I-94, East-West Freeway, Milwaukee.	72	12	C	3–4	Moderate	36–60	8-66	None [50]	Epoxy	Perm [50]
		72	12	B	4	do	36–60	8-66	do	do	do
	I-894, Milwaukee	32	8	C	New	do	36–60	8-66	sbl	do	do
Wyoming	Casper (City Street)		2.3	B	Old	Unknown	72	9-65	None	Unknown	Unknow
	I-25, Casper		2.2	B	Old	do	72	9-65	do	do	do
District of Columbia.	Wisconsin Ave., NW		5.2	B	New	Medium	12-24	9-60	do	None	Perm
			5.2	B	do	do	12-24	9-60	do	do	do
	Georgia Ave., NW		4.2	B	do	do	12-24	9-62	do	do	Crys
			4.2	B	do	do	12-24	9-62	do	do	do
Puerto Rico	PR-23, Rio Piedras, F. D. Roosevelt Ave.		8.4	B		None	0	3-64	do	do	Perm
	Fernandez Juncas Ave	36	9	B		do	0	11-66	do	do	Unknow
	Balderioty de Castro Ave	43		B		do	0	10-64			do
	Ponce de Leon Ave	37		B		do	0	1-65			do
	State Rd. 1, Rio Piedras to Caguas.	74	18	C		do	0	12-63		Epoxy Pliobond	Perm
T											
Illinois State Toll Highway Commission.	E W Tollway, Plaza 61		3	C	Old	Heavy	12-36	?-65	brm	Epoxy	Perm
	N-W Tollway, Plaza 19		3	C	do	do	12-36	?-66	do	do	do
	do Plaza 33		3	C	do	do	12-36	?-66	do	do	do
New York State Thruway Authority.	Roadway			C			36-100	6-60			Cat
	Ramp			C			36-100	6-60			do
Port of New York Authority.	John F. Kennedy Airport		9.7	C, B		Active	24-36	10-67	None	Epoxy	Perm
Triborough Bridge and Tunnel Authority.	General experience						24-36				

See footnotes at end of table.

Thermoplastic-striping data—Continued										Standard paint-striping data [1]					
Amount of striping		Type of stripe [8]	Installation cost per linear foot of stripe [9] (P)			Amount of stripe lost (Q)		Average useful life (R)		Materials and installation cost per linear feet [10] (S)			Average useful life	Ratio of long-term cost thermoplastic/paint [11] (U)	
(M)	(N)	(O)	4-inch width	6-inch width	8-inch width	First year	Total lost	Actual [12]	Estimated [13]	4-inch width	6-inch width	8-inch width	(T)	Determined	Estimated [11]
ontinued															
Miles	Thousands of linear feet		Cents	Cents	Cents	Percent	Pct./No. of yrs.	Years	Years	Cents	Cents	Cents	Years		
	150	L	26			1	50/5.5	5.5		1.7			0.5	1.4	
		E	26				15/5.5		10	1.7					
	304	L	30			1	10/4.5		10	1			0.4		
	250	L	30			1	5/4.5		10	1			0.4		
	34	L	35				13/3.5		8	1			0.4		
		L	35				1/3.5		12	1			0.4		
	49	L	35				5/3.5		10	1			0.4		
		L	35				1/3.5		12	1			0.4		
	174	L	34			1	5/2.5		10	1			0.4		
	600	L, E	32.5			0	[46] 5/2.5		10	1.7			0.6		
	3	L				100		0.5		1.7				>26	
	111	L	22.5			10–20	69/3.2	3		1.7			1	2.4	
	248	L	26			60	95/3	1		1.7			1.5	23	
	88	L	26			70–80	95/2.3	1		1.7			0.8	12	
	17	L, G	49		82		20+/2		3.5	3		13	0.5		2.3, 0.9
	90	L, E, G, T	30				6/3		7	[27] 3			0.33		0.5
	35		28			0	0/1		6	[27] 3			0.4		0.5
	9	L, E, G	30				17/4		7	do			0.4		0.5
	92	L, G	30				6/3		7	do			0.9		1
	13	L	33				1/2		5.5	1.5			0.25		1
	11	L	33				15/2		3.5	1.5			1		6
		L	33				1/2		>8	1.5			1		
	10	C	33				40/2		2.5	1.5			0.5	4	
	82	L	29	48	60		?/8	8		[47] 1.8			0.5	1	
		E	29	48	60		?/8		12	do			0.5		0.7
	118	E	31	48	60				8	do			0.5		1
	118	L	31	48	60				>8	[47] 1.8			0.5		<1
	302	E,L	31	48	60				7	do			0.5		1.3
	358	E,L	31	48	60					do					
	24	L	33							1.5			1.9		
	8	L	33							1.7			1.6		
	19	L	[49] 23				42/6	4		1.7			0.33	1	
		L	do				13/6		>8	1.7			0.33		
	18	L	[49] 29				35/5	4		1.7			0.33	1.4	
		L	do				21/6	4		1.7			0.33	1.4	
		L	do				8/6		>8	1.7			0.33		
	132	L,G	32		60	[34] 27			2	[51] 4		[51] 6	0.5		
		L,G	32		60				>5	do		do	0.5		<1
	8.4	L	32		60					do		do	0.5		
	0.2	L	63					>2		6			0.1		<0.5
	0.1	L	63						4	6			1		2.5
4.3		C,L	25				40+/7	7	4+	[31] 3			0.4	1	
4.3		T	28				25/2.5	6		[31] 5			0.25	0.4	
4.7		C,L	22				40+/5	5		[31] 3.3			0.4	0.7	
4.7		T	25					4		[31] 6			0.25	0.3	
	13.7	L	32				22/3.5		6	3.7			0.33	0.5	
		L					2/1		>10						
							15/3		8						
							2/2		>10						
		C,L					70/4								
OADS															
	4.8	T			65		8/2	2				3	0.5	5.5	
		T			65		8/1		2			3	0.5		5.5
		T			65		8/1		2			3	0.5		5.5
		L				100		<1							
		G				100		<1							
	19	L	[52] 42						4.5	2.4			0.25		1
		L	37					3		5			0.5		1.2

Table 2.—Tabulation

Agency	Project and location	Test-site data: ADT[2] Total	Test-site data: ADT[2] Per lane	Pavement Type[3]	Pavement Age[4]	Snowplow activity	Approximate mean annual snowfall[5]	Thermoplastic-striping data: Date striped	Pavement pretreatment[6]	Primer used	Name of thermoplastic[7]
(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)
CITIES AN											
		Thousands	*Thousands*		*Years*		*Inches*	*Month-year*			
Atlanta, Ga.	General observations, Central Business District.			C, B	New, old		1-2	?-64	None	Epoxy[53]	Perm
				C, B	do		1-2	?-54	do	do	do
Baltimore, Md.	do						12-24				
Detroit, Mich.	(See Mich. State Highway Department, Chrysler Freeway).										
Los Angeles County, Calif.	General observations		3-12	C, B	New, old	None	0	?-61	brm[55]	Pliobond	Perm
New Orleans, La.	do						0				Cat
New York, N.Y.	do		13	C			24-36	?-58		Epoxy	Perm
			13	B			24-36	?-58		None	do
Portland, Oreg.	N.E. 33rd Ave		7	B	New	None	12	9-65	None	Epoxy-Ply	Cat
San Francisco	General observations, city streets	5-10					0				
	General observations, downtown	15-40					0				
	General observations, downtown, heavy turning.	15-40					0				
	Van Ness Ave	35	6				0	5-62			

[1] Under same or equivalent conditions of exposure as thermoplastic.
[2] Average daily traffic during time of stripe exposure.
[3] B=bituminous, C=concrete.
[4] At time of thermoplastic installation.
[5] Obtained from reporting agency and Weather Bureau records, or estimated for location from Climatic Maps of the United States, U.S. Department of Commerce, Revised 1966 (fig. 11).
[6] sbl=sandblast, air=air blower, abr=abraded, acid=acid etch, brm=broomed.
[7] Perm=Permaline, Cat=Catatherm, Crys=Crystallex, unkn.=unknown.
[8] L=lane line, C=center line, E=edge line, T=transverse and stop lines, R=ramp edge line, G=gore or channelizing line.
[9] Contract basis unless otherwise stated. Generally includes material, labor, equipment depreciation, profit, etc.
[10] Unless otherwise stated, installed by agency forces and include cost of materials, labor, equipment depreciation, etc.
[11] From data on cost per linear foot per year of useful life for thermoplastic and paint.
[12] Terminal point reached in test section.
[13] Estimated from still serviceable stripe.
[14] Where useful life of still serviceable thermoplastic has been estimated under column
[15] For the lower density section averaging 4,000 ADT per lane.
[16] Cost was actually 45¢ per linear foot but estimated to be 35¢ in larger applications.
[17] Last observation made in 1965.
[18] Contract price. Cost if done by State was estimated to be about 1.4¢ per linear foot 4-inch width.
[19] On new portland cement concrete only.
[20] On portland cement concrete only.
[21] Salt and sand used but only light plowing.
[22] State composition specification material supplied by DeSoto Chemical.
[23] Applied by State forces.
[24] Pavement to be resurfaced.
[25] *High* traffic density.
[26] Adhesive Products Corp. material marketed as ADOPOX. Two parts ADOPOX Re T-243 R-2 plus one part Hardener T-166 H-1.
[27] Contract prices.

California Division of Highways required that all new concrete be given a light sandblasting and estimated that the cost of this practice was about $100 a stripe-mile. The Minnesota Highway Department, which had considerable recent experience, indicated that concrete should be given some sort of light grinding to promote better adhesion of the thermoplastic.

Use of primers before thermoplastic application

Different types of primer pretreatment were used by the various agencies for both bituminous and concrete surfaces, including synthetic-rubber and epoxy treatments; some agencies used no primer at all. In many instances the agency did not know the type of primer used, or even whether any was used at all.

On bituminous surfaces, the most common practice was to apply thermoplastic striping to unprimed pavement. Some synthetic-rubber primers and even some epoxy resins were used. The New York Department of Transportation reported no difference in the performance of thermoplastic on bituminous pavements, regardless of whether synthetic-rubber or epoxy solutions were used. According to a report by the Georgia Institute of Technology, priming is not an essential prerequisite for bituminous surfaces (*5*). In summary, the omission of a primer did not seem to affect the durability of thermoplastic when it was applied over bituminous surfaces.

On concrete surfaces, the most prevalent primer used in recent years has been epoxy resin solutions. Synthetic rubber has been used to a lesser extent in recent years. In only a very few installations was no primer used at all on concrete surfaces, and early failure was reported for at least one of these. The need for adequate priming of concrete was stressed by the Arizona Highway Department and in the above-mentioned Georgia Tech report (*5*). It was reported that epoxy primers provided greater adhesion than the rubber-based primers, as was evident in the survey replies from the States of Kentucky, New York, Connecticut, and others (*5*). In a few installations—in Minnesota and Puerto Rico—epoxies, when compared to rubber-based primers, did not significantly improve adhesion. Only the State of Nebraska reported that rubber-based primers provided bett service than epoxy primers. On the who the survey results indicated that epoxy res primers were preferable for concrete pav ments, but that much more improvement needed in the entire technology to assu proper adhesion.

Application rate of primers

The amount of primer used prior to therm plastic striping may be a factor in go bonding, especially on concrete surfaces. T most prevalent application rate for rubb based primers was 50 sq. ft. per gallon. several States it was believed that adhesi could be improved if the amount of prin were increased.

For epoxy primers, the approximate app cation rate was about 320–420 sq. ft. p gallon, which is roughly equivalent to 80 1,200 lin. (linear) ft. per gallon for a 4-in stripe. This amount of primer provides wet film thickness of approximately 4–5 m In one State a much lower application r of 4,000 lin. ft. per gallon, or roughly 1 wet thickness, gave a poorer bond on c

Thermoplastic-striping data—Continued										Standard paint-striping data [1]						
Amount of striping		Type of stripe [8]	Installation cost per linear foot of stripe [9] (P)			Amount of stripe lost (Q)		Average useful life (R)		Materials and installation cost per linear feet [10] (S)			Average useful life	Ratio of long-term cost, thermoplastic/paint [11] (U)	
(M)	(N)	(O)	4-inch width	6-inch width	8-inch width	First year	Total lost	Actual [12]	Estimated [13]	4-inch width	6-inch width	8-inch width	(T)	Determined	Estimated [14]
COUNTIES															
Miles	Thousands of linear feet		Cents	Cents	Cents	Percent	Pct./No. of yrs.	Years	Years	Cents	Cents	Cents	Years		
25		L, C	[54] 17						4	3.1			0.5		0.7
		T		[54] 25				1.8			?		0.25		
	40				[56] 70			4				[56] 7.2	1	2.5	
			25						6	2			0.5		1
			28							[57] 10				0.5	
	1,000	L	28							do.					
	4.6	L	28			<1			10	0.9			1		3
		L, T								1.3		[56] 13	2		
		L, T								1.3		[56] 13	1		
		L, T								1.3		[56] 13	0.5		
		L, T	60		[56] 60				>5	1.3		[56] 13	1		

28 Plus additional installation cost.
29 Deterioration began in 2 months with blistering and adhesion loss.
30 3-inch width.
31 5-inch width.
32 Based on State's estimate of thermoplastic: paint cost ratio of 10:1 and performance ratio f 16:1.
33 4½-inch width.
34 Replaced by warranty in June 1966.
35 Failed because of movement of bituminous overlay on portland cement concrete.
36 Occasional brooming but not definite.
37 Only plowed once in winter of 1966–67.
38 Preceded by prime of synthetic resin compound.
39 Paved shoulder.
40 Permaseal III H (Cook Paint & Varnish Co.) applied at rate of 4,000 linear feet per gallon.
41 Removal of obvious dirt only.
42 6 to 8 gallons per mile of actual stripe.
43 Contract price. Average cost by State forces is 3.5¢.
44 State advises that this is a very low bid but real. Probably done at or below cost to get striping in for demonstration purposes.
45 Maximum thickness of 6 mils.
46 50% loss on bituminous section without synthetic rubber primer. Only 1% loss on edge line.
47 5¢ by contract.
48 50 sq. ft. per gallon.
49 Excludes State labor for traffic control.
50 Thermoplastic placed over existing paint.
51 Includes application of black paint in skip zone.
52 Unconditional guarantee for 3 years. Believed that this guarantee contributed to higher cost.
53 Permaseal 1 and 2 used in equal proportions on portland cement concrete surface.
54 Done by city forces with leased equipment.
55 Hand broom. Grind to remove old paint. Sandblast to remove curing agent on fresh portland cement concrete.
56 12-inches wide.
57 Paint cost is 2¢, remainder of cost is 8¢.

rete than the higher application rate. How ver, when the primer was applied to bitu inous surfaces, a high application rate of 000 lin. ft. per gallon caused the thermo astic to *slide* over the primer resulting in oor adhesion to the pavement. Therefore, e lower rate of 4,000 lin. ft. per gallon was eferred for asphalt surfaces.

One thermoplastic producer held the opin n that the proper application rate of epoxy imer to concrete had to be different for fferent concrete; that is, 500 lin. ft. per llon for new, more absorptive concrete, d about 1,000 lin. ft. per gallon for older, ss absorptive surfaces. From the survey sults it appeared that the optimum appli tion rate of epoxy primer to concrete is far om resolved, and depends on the age, po sity, and texture of the pavement as well as the active solids content of the epoxy lution used. To provide good bonding to e thermoplastic and yet not be so thick as limit the escape of solvents and, thereby, terfere with the epoxy-catalyst reaction or ntribute to the phenomenon of blistering, optimum film thickness of primer apparently ust remain on the pavement surface after l absorptive effects have taken place.

Time interval between primer and thermoplastic application

On concrete surfaces especially, the time interval between the application of epoxy binder and the application of thermoplastic seemed to be a factor in the adhesion and blistering of the marking. This interval differed considerably in the few replies that included such information. In New York State, for example, the practice was to permit the primer to dry about 15 minutes before the hot thermoplastic was applied, which allowed sufficient time for the solvent in the primer to volatilize. Shorter time intervals had a tendency to enhance the blistering of the thermoplastic so often noted in New York and other States when the striping was applied to concrete. A developing preference of contractors is the application of both the epoxy primer and thermoplastic from the same vehicle, and the use of an infrared heater to speed drying of the primer. Thus the time interval between the application of primer and the application of thermoplastic is reduced to substantially less than a minute. On the basis of subjective observations by several agencies, this practice may contribute to excessive blistering and poor adhesion. One State stipulated a maximum time interval of 30 minutes. A few States noted that blistering of the thermoplastic seldom occurred on bituminous pavements, regardless of the primer used or the extent of the subsequent drying period.

Reflectance and color properties

Information on the relative reflectance and visibility of thermoplastic and paint varied considerably. Daylight reflectance of thermoplastic decreased noticeably with age and, although still satisfactory, the thermoplastic was not as bright as fresh paint. On the other hand, several agencies noted that the night visibility of thermoplastics was somewhat better than paint, especially under wet conditions. However, no definite pattern was evident from the reports received.

Effect of pavement surface and underlying traffic paint

According to the survey, the durability of thermoplastic striping was much better on bituminous surfaces than on concrete surfaces. One exception was noted for an installation with a bituminous overlay on portland cement concrete. The shifting of the overlay by traffic caused premature cracking and failure of the thermoplastic striping.

Several agencies noted that thermoplastic performance was much better on older concrete than on new concrete. Some agencies recommended against the use of thermoplastics on new concrete, whereas a few resort to sandblasting the concrete surface to improve bonding. Evidently, both the surface laitance layer and some curing compounds can seriously interfere with good bond to new concrete.

Several agencies noted that poor adhesion resulted when old traffic paint was not removed prior to the application of thermoplastic striping. From the limited evidence available, good practice would dictate the prior removal of built-up layers of old paint.

Special problems with edge lines

Both the New York and Kentucky highway departments observed that continuous edge lines of thermoplastic tend to impound rain water and thereby perpetrate skidding hazards. They recommend cutting transverse channels at intervals in order to permit drainage of entrapped water.

Effect of snowplows on thermoplastics

Reported snowplow damage to thermoplastics was widespread in northern States having an appreciable amount of snowfall. Several agencies reported that the material is not economically feasible in mountainous areas. A few agencies reported that snowplow damage could be reduced by feathering the leading edge of the skip line; this part of the stripe was most affected by plows. Less damage was noted where the plows were fitted with shoes and raised slightly above the pavement surface.

Terminal point of thermoplastic striping

A few of the survey replies made available the agency's criteria for assessing the terminal point in the useful life of thermoplastic striping. The majority of these replies indicated that the agencies consider the terminal point to be reached when only about 40–60 percent of the material is still intact on the pavement. It would seem that when 50 percent or more of the stripe is lost, the terminal point of the stripe has been reached or exceeded—an assumption that conforms to the findings in another survey(*2*).

Table 3.—Policy of agencies with significant experience in use of hot-applied thermoplastics

Agency	No policy stated	Thermoplastics not authorized for standard use	Criteria for use of thermoplastic in preference to conventional paint
STATE HIGHWAY DEPARTMENTS			
Alabama	X		
Arizona	X		
Arkansas			Where ADT exceeds 6,000.
California			Where ADT per lane exceeds 7,500 (urban) cr 5,000 (rural); not acceptable in heavy snow areas.
Connecticut			Roads with high traffic density.
Florida			Urban intersections with high traffic density.
Illinois			On high-volume freeways.
Indiana			On new bituminous surfaces with more than 6,000 ADT and with estimated minimum surface life of 4 years, or where excessive paint wear is experienced. Not used on portland cement concrete.
Iowa		X	
Kansas		X	
Kentucky	X		
Maine		X	
Maryland	X		
Michigan	X		
Minnesota			Economically justified on bituminous pavement.
Mississippi			Economically justified on high density roads.
New Hampshire			For stop lines and parking areas.
New Jersey		X	
New Mexico		X	
New York	X		
Ohio	X		
Oklahoma	X		
Oregon			Either: (a) 4-lane highways with ADT of more than 20,000 and 2-lane highways with ADT of more than 12,000, requiring painting 3 times yearly. Sandblast to remove old paint. Not in mountainous area. (b) Restricted or hazardous to paint area.
Rhode Island			High speed expressways.
South Carolina		X	
Texas		X	
Wisconsin			Bituminous surfaces.
Wyoming			Under consideration.
District of Columbia			Crosswalks.
Puerto Rico			High-traffic-density bituminous roads.
TOLL ROAD AUTHORITIES			
Illinois Toll Highway Commission.	X		
New York Thruway Authority	X		
Port of New York Authority			All transverse lines and longitudinal lines where economically justified.
Triborough B. & T. Authority			Material is justified even at higher cost.
CITIES AND COUNTIES			
Atlanta, Ga			For crosswalks.
Baltimore, Md			Lane lines in high-traffic-density areas.
Los Angeles County, Calif			New or recently resurfaced roads.
New Orleans, La			High-traffic-density areas.
New York, N.Y			Do.
Portland, Oreg	X		
San Francisco, Calif	X		

Development of Criteria for Use of Thermoplastics

The information obtained in the survey seems to warrant the development of more sharply defined criteria than the currently available and diffuse criteria shown in table 3. Suitable criteria are needed to show when thermoplastic markings instead of conventional paint striping might be used to economic advantage. The criteria must be based on the original cost and life expectancy of each type of striping and also on any other economic factors inherent in the use and maintenance, such as the traffic delays and safety considerations in highly congested areas caused by frequent maintenance striping with conventional paint. Each of these contributing parameters is analyzed separately in the following paragraphs and are subsequently integrated to provide new, sharply defined criteria. To simplify the development of this information, lane and center lines of 4-inch width, as they apply to divided highways of the Interstate type, are considered primarily. As will be shown later, the integrated criteria also will be applicable to other roadways.

Cost and life expectancy of conventional paint striping

As discussed earlier, calculations from the survey data showed that the average cost of a 4-inch-wide longitudinal stripe of conventional paint is 2.2 cents per lin. ft. of actual stripe. This cost includes all the obvious and inherent costs of striping—materials, labor, other expendable supplies, equipment depreciation, etc.—and is based on installations and mai tenance striping performed by the road agenc itself. It is generally applicable to open hig way striping rather than to the striping congested city streets.

The life expectancy of conventional lon tudinal paint stripes was determined to directly related to the amount of traffic e posure, as is evident in figures 2 and 3, which the reported paint life is plotted again the average daily traffic (ADT) per lane. T data reported for bituminous pavements a shown in figure 2, and that for portla cement concrete pavements are shown figure 3. Numerical entries at some of the da points represent mean annual snowfall, inches, and are shown only where snowf was significant and considerable snowpl activity expected. There was no significa correlation between the effect of snowpl operations measured by annual inches snowfall, and paint life. In figures 2 and 3, t

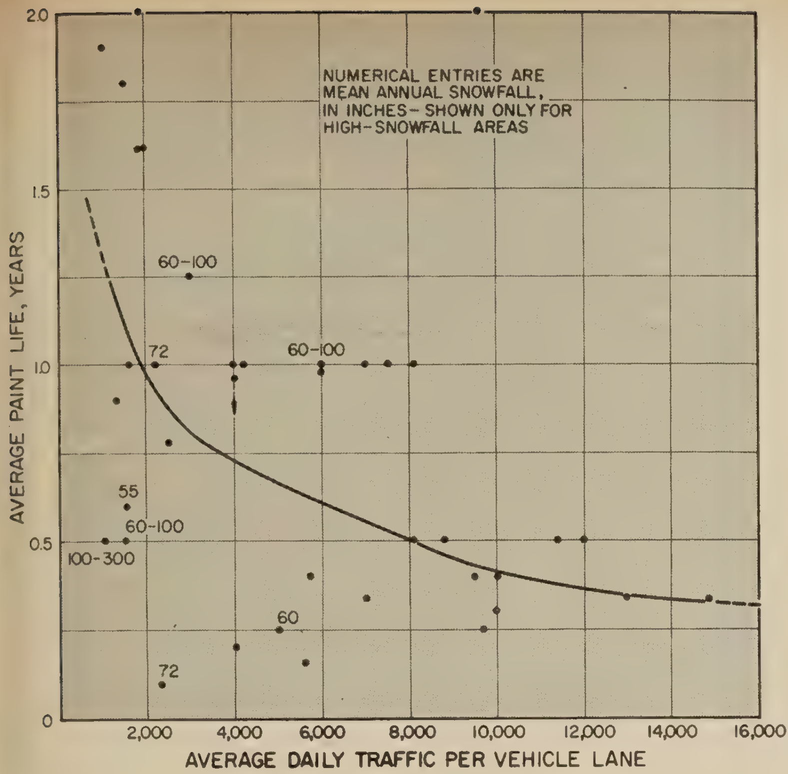

Figure 2.—Useful life of paint striping as affected by traffic density—bituminous pavement.

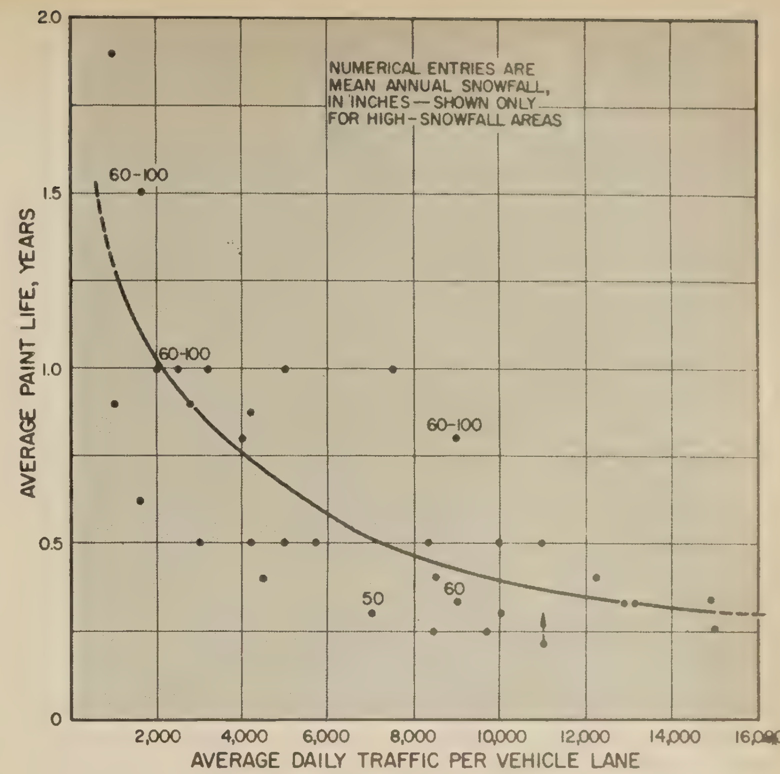

Figure 3.—Useful life of paint striping as affected by traffic-density—concrete pavement.

directional arrows pointed upward and those pointed downwards respectively represent data points reported to have the indicated minimum and maximum life expectancy. A line that best represented the average of all results plotted was drawn on each of the figures. There is very little difference in the locations of these lines on the two figures. Consequently, an average of the two lines is show in figure 4 to represent both concrete and bituminous pavements.

As previously mentioned, figures 2, 3, and 4 represent the situation for center and lane lines only. The bulk of the information received in the survey dealt with these longitudinal lines. Data obtained on other line types was insufficient to develop adequate relationships. Moreover, in the few installations for which such data was supplied, it appeared that edge lines lasted about one and one-half times as long, and transverse stripes about one-half as long as center or lane lines under similar road exposure conditions. This difference was to be expected, considering the difference in actual traffic exposure of such lines on a given highway or city street.

From the data in figure 4 and from the calculated average cost of conventional striping, 2.2 cents per lin. ft. of 4-inch-width striping, it was possible to calculate the average cost of a 1-foot length of a 4-inch wide paint stripe for a full year of useful service. The calculation was done for various traffic density levels, and the results are shown in the first three lines of table 4. As is evident in entry A, the annual cost of maintaining a paint stripe varies considerably with traffic density and can be very sizable in highly congested areas.

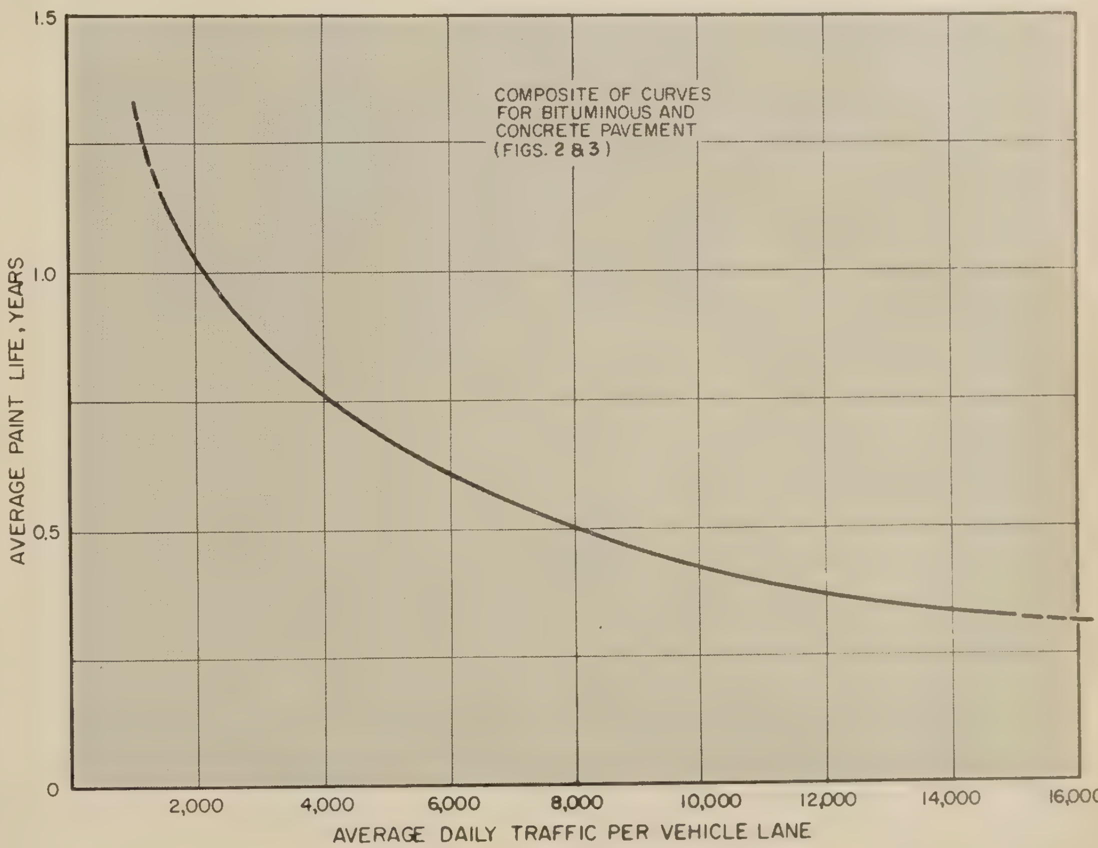

Figure 4.—Average useful life of paint striping as affected by traffic density—both bituminous and concrete pavement.

Effective costs of traffic delay during conventional maintenance striping

A significant factor in favor of long-lasting hot thermoplastic striping is that the frequency of maintenance striping is considerably reduced. Thus, the thermoplastic yields potential economic benefits in terms of reduced traffic delay caused by striping operations. As part of this study, an attempt was made to evaluate this factor and to determine the

Table 4.—Annual cost of conventional paint striping [1]

[Costs given separately and collectively for basic installation, traffic delay, and potential accidents]

	Average daily traffic (ADT) per lane—No. of vehicles															
	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000
Useful paint life [2] ...years..	1.32	1.02	0.87	0.75	0.67	0.60	0.55	0.50	0.45	0.42	0.38	0.36	0.35	0.33	0.32	0.31
Annual striping frequency [3]	.76	.98	1.15	1.33	1.47	1.67	1.82	2.00	2.22	2.38	2.63	2.78	2.86	3.03	3.12	3.22
Annual basic paint striping cost, per linear ft. per year (A) [4] ...cents..	1.67	2.16	2.53	2.93	3.28	3.67	4.00	4.40	4.88	5.24	5.79	6.12	6.29	6.67	6.86	7.08
Annual costs of paint striping on 4-lane divided highway:																
Cost of traffic delay, per linear ft. per year (B) [5] ...cents..	.02	.05	.11	.16	.23	.31	.39	.49	.61	.73	.89	1.02	1.14	1.30	1.43	1.58
Cost of potential traffic accidents, per linear ft. per year (C) [6] ...cents..	.00	.01	.01	.02	.03	.04	.05	.06	.08	.10	.12	.13	.15	.17	.19	.21
Total annual cost, per linear ft. per year (A)+(B)+(C) ...cents..	1.69	2.22	2.65	3.11	3.54	4.02	4.44	4.95	5.57	6.07	6.80	7.27	7.58	8.14	8.48	8.87
Annual costs of paint striping on 6-lane divided highway:																
Cost of traffic delay, per linear ft. per year (D) [5] ...cents..	.03	.07	.16	.25	.34	.46	.59	.74	.92	1.10	1.33	1.54	1.71	1.96	2.16	2.39
Cost of potential accidents, per linear ft. per year (E) [6] ...cents..	.00	.01	.02	.03	.04	.06	.08	.10	.12	.14	.17	.20	.22	.25	.28	.31
Total annual cost, per linear ft. per year (A)+(D)+(E) ...cents..	1.70	2.24	2.71	3.21	3.66	4.19	4.67	5.24	5.92	6.48	7.29	7.86	8.22	8.88	9.30	9.76

[1] Applicable to longitudinal striping of 4-inch wide center and lane lines, excluding edge lines, on open highways as typified by Interstate roads.
[2] Interpolated from figure 4.
[3] Calculated from data on *useful paint life.*
[4] Basic materials, labor, and installation costs calculated from: annual striping frequency × 2.2¢ (average cost per linear foot of 4-inch stripe per installation, as explained in text).
[5] Calculated from: $7.65 \times 10^{-6} \times$ total ADT $\times$ annual striping frequency (equation 1 in text).
[6] Calculated from: Total ADT $\times 10^{-6} \times$ annual striping frequency (equation 2 in text).

degree to which it contributes to the overall cost of conventional striping. Some of the reasoning presented in an unpublished report [3] was used for this purpose.

It was assumed that for each mile of conventional maintenance striping on an Interstate highway, about 1 hour is required for striping, drying, and the removal of the traffic cones used to protect the fresh paint. It was also estimated that, during this time, all passing vehicles on a one-directional roadway would experience a speed reduction of approximately 20 m.p.h. Assuming a speed decrease from 55 m.p.h. to 35 m.p.h., a delay of 0.6 minutes would be imposed on each passing vehicle for each mile of striping. If this delay time is calculated in terms of linear foot of actual stripe, then the delay time becomes:

$$\frac{0.6}{5280} = .000114 \text{ min. per vehicle per linear foot of stripe.}$$

Most conventional striping is done during off-peak daylight hours. Under such conditions, one-directional traffic on urban sections of an Interstate highway has been shown to be 2.6 percent per hour of the total ADT (*9*). Thus, the *total delay, in hours,* for all vehicles affected by one linear foot of conventional on-going maintenance striping becomes:

$$\frac{.000114 \times .026 \times \text{ADT}}{60} = 4.94 \times 10^{-8} \times \text{ADT (in hours)}$$

Based on $1.55, the total hourly time cost of all the occupants in a single vehicle (*10*), the total cost of such a single delay in *cents per linear foot of striping* becomes:

$$4.94 \times 10^{-8} \times \text{ADT} \times 155 = 7.65 \times 10^{-6} \times \text{ADT (in cents per lin. ft. of striping).}$$

The annual delay cost, given by the following expression, would depend on the frequency of restriping:

$$7.65 \times 10^{-6} \times \text{ADT} \times \text{annual striping frequency (in ¢/lin. ft./year)} \quad (1)$$

Using the above expression, equation (1), the additional annual costs of stripe maintenance attributable to traffic delays were calculated for both 4-lane and 6-lane divided highways. The results are shown in table 4 as entries B and D.

Effective costs of increased accident potential during conventional striping

Traffic-safety-benefits are an often cited intangible advantage of the more durable hot-melt thermoplastic striping. Such benefits could accrue by virtue of reduced striping frequency, thereby decreasing the accident potential that might otherwise exist because of frequent maintenance striping and its potentially hazardous effect on traffic.

An effort was made to derive some quantitative economic measure of this potential hazard and apply it to the overall cost of conventional striping. Consultation with several prominent traffic accident researchers, as well as a formal search of the available literature through the Highway Research Board's Information Service, failed to disclose any definitive literature relating to the increased accident potential that exists during a road maintenance or striping operation. However, several reports were available that did permit an empirical derivation to be made of the increased accident potential. This derivation and other considerations in the development of an economic measure of accident potential are discussed in the following paragraphs.

It has been established that the speed variance of individual vehicles from the mea speed of traffic contributes to accident in volvement on Interstate highways, as well a on other main rural roads (*11, 12*). During conventional paint striping operation, it i customary to require a speed reduction on th highway, which is usually accomplished b warning and speed-reduction signs placed i advance of the actual work. Regardless of th advance distance or number of signs; th starting point of deceleration, deceleratio rate, and actual extent of vehicle speed redu tion depends largely on the individual driver Although no measurements are known to exi for such a situation, general experience ind cates that a greater-than-normal variation i speed among vehicles does prevail under su circumstances. A brief empirical analysis w made to determine what effect this increase speed variance might have on the accide involvement potential. Data from a publish report (*11*) were used for this purpose.

Results of an earlier study (*9*) indicate th the standard deviation of speed on betwee interchange mainline units of Interstate hig ways is 7 m.p.h. In the vicinity of a stripi operation, it was assumed that the standa deviation of speed would be somewhat high perhaps from 10 to 15 m.p.h. Using the spe data in table 1 of Interim Report II (*11*), t involvement rate relating to accidents w computed for these situations.

From these computations it was found th the theoretical increase in accident involv ment rate over that for normal traffic oper tion with a standard deviation of 7 m.p.h. 3.5 if the standard deviation is assumed be 10 m.p.h., and 22.8 if the standard dev tion is assumed to be 15 m.p.h. Thus, in t vicinity of a pavement-marking operati the involvement rate may increase from to 22.8 times the involvement rate duri normal traffic operations. From this range value of 10 times the normal involveme rate was arbitrarily selected as an approxim tion of the potential increase in involveme

[3] *Study of Warranting Conditions for Use of Thermoplastic Lane Markings*, Bureau of Traffic, Ohio Department of Highways, 1967. (Unpublished.)

As most striping operations occur during off-peak daylight hours, the normal accident involvement rate was calculated for this period. From table 1, Interim Report II (*11*), the average or normal involvement rate during daylight off-peak hours was calculated to be 54.4 per 100 million vehicle miles (MVM)[4] on an Interstate highway. This rate is applicable only to accidents involving two or more vehicles traveling in the same direction and does not include single vehicle run-off-the-road type accidents. However, from a previous Interstate study, it was established that about one-third of all accidents involved two or more cars traveling in the same direction, and that the remainder involved only a single vehicle (*13*). Thus, if 54.4 is the involvement rate for accidents with two or more vehicles, single vehicle accidents excluded, then 54.4 (or less) is the additional involvement rate attributable to single car accidents. This additional rate gives a total *normal* accident involvement rate of no more than 108.8, which should account for all one-directional traffic during off-peak daylight hours on Interstate roads. From previous considerations, the theoretical involvement rate attributed to a striping operation should be about 10 times this value—10 × 108.8 or 1,088. The net difference in involvement rate between normal operations and traffic striping operations accordingly is 1,088−108.8, or roughly 979—say a round figure of 1,000. Thus, an involvement rate of 1,000 can be used as an expression of the additional potential hazards owing to conventional paint striping on an Interstate highway. From data in an Illinois report (*14*), the average cost of a single involvement was calculated to be about $200. Hence, the dollar cost per 100 MVM for an accident involvement rate of 1,000 is:

$$1{,}000 \text{ (per 100 MVM)} \times \$200$$

If it is assumed that the hazardous area is mile of directional roadway just preceding, alongside, and following the striping operation, and that this length of roadway will be hindrance to traffic for 1 hour, as previously discussed under traffic delays, the traffic density as well as the number of vehicle-miles this hazardous area are given by the following single expression:

$$.026 \times \text{ADT (during off-peak daylight hours)}$$

The potential accident cost, in dollars per mile of stripe during a single striping operation is obtained by combining the two preceding expressions, and is given by X in the equation:

$$\frac{X}{.026\times\text{ADT}}=\frac{1{,}000\times\$200}{100\text{ MVM}}$$

Where,

ADT = average daily traffic
MVM = million vehicle miles

Therefore:

[4] Involvement rate is the number of involvements per 100 million vehicle-miles, and implies a vehicle involved in an accident. Thus, one accident involving two vehicles is counted as two involvements.

$$X=\frac{1{,}000\times\$200\times.026\times\text{ADT}}{100\text{ MVM}}$$

Potential accident costs, expressed in cents per linear foot of conventional striping during an entire year, then become:

$$\text{Accident cost (¢/lin. ft./yr.)}=\frac{1{,}000\times 20{,}000¢\times.026\times\text{ADT}\times\text{yearly striping frequency}}{100\text{ MVM}\times 5{,}280\text{ lin. ft.}}$$

or:

$$=\frac{10^3\times 2\times 10^4\times 2.6\times 10^{-2}\times\text{ADT}\times\text{yearly striping frequency}}{10^2\times 10^6\times 5.28\times 10^3}$$

or approximately expressed as:

$$\text{Accident cost (¢/lin. ft./yr.)}=\text{ADT}\times 10^{-6}\times\text{yearly striping frequency} \qquad (2)$$

Using equation (2), the potential accident cost for conventional striping was calculated for various ADT's and is shown in table 4, entries C and E. From a comparison of these values with those in entries B and D, it is readily apparent that the additional cost of standard paint striping attributable to potential accidents is negligible, compared to the other economic factors, despite the fact that the empirically derived value for the increase in potential involvement rate over normal operations—10 times 108.8—is a rather liberal allowance, according to the subjective estimates of several accident researchers who were consulted.

Summation costs for all contributing economic factors were calculated and are shown as entries A+B+C and A+D+E of table 4. The cost analysis presented in the table will be used in a subsequent section to develop information on the comparative cost effectiveness of hot-extruded thermoplastic striping.

One additional factor, advantageous to the use of longer-lasting thermoplastics, is the reduced exposure of maintenance forces to traffic hazards during restriping operations. It was not possible to obtain quantitative data or develop empirical considerations that could be used to translate the advantage into

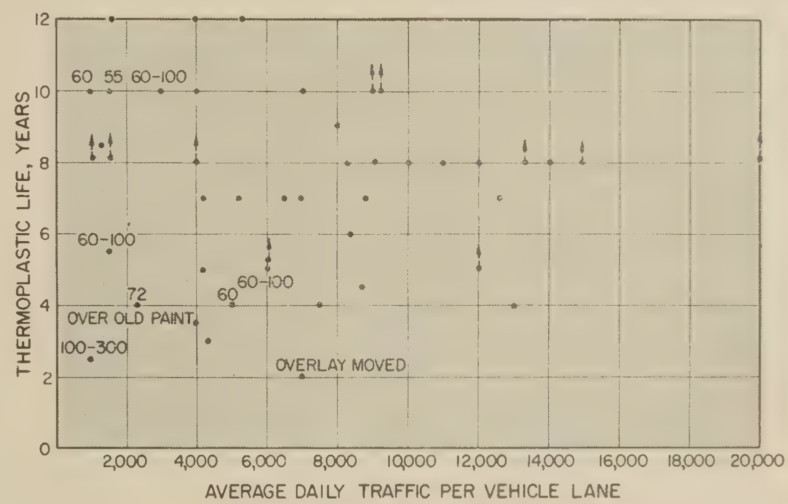

Figure 5.—Relation between thermoplastic durability and traffic density—bituminous pavement.

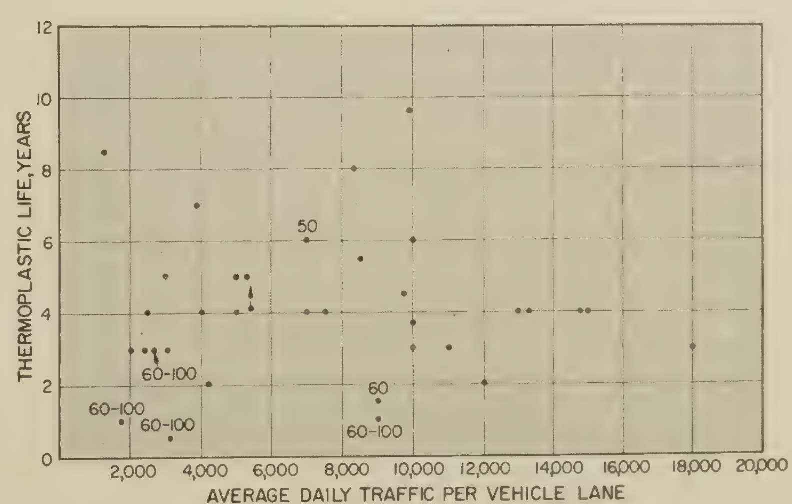

Figure 6.—Relation between thermoplastic durability and traffic density—concrete pavement.

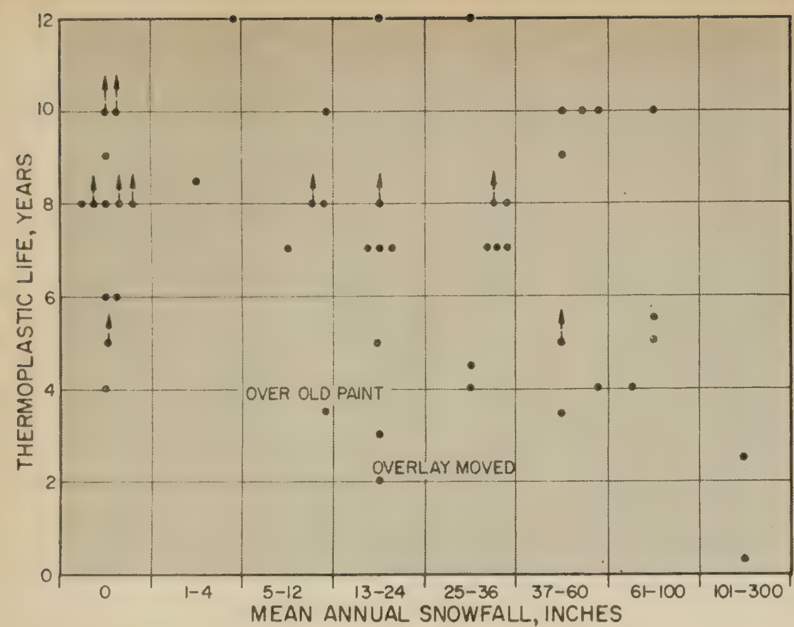

Figure 7.—Relation between thermoplastic durability and annual snowfall—bituminous pavement.

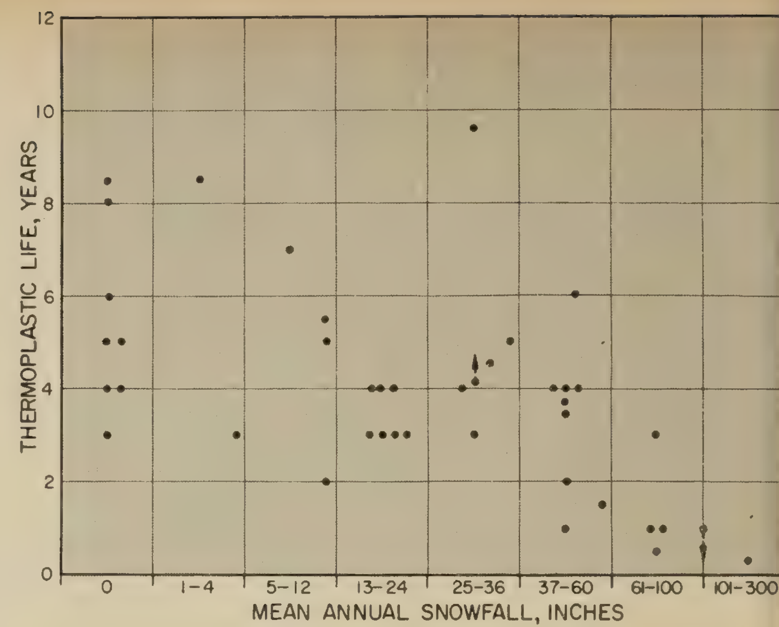

Figure 8.—Relation between thermoplastic durability and annual snowfall—concrete pavement.

potential economic value with quantitative dimensions. Therefore, the economic considerations must remain a subjective factor at this time. It should be remembered however, that although thermoplastic striping is required less frequently, this advantage is somewhat offset by the fact that it is a much slower operation than conventional striping, and exposes the striping crew to traffic hazards for a period two to three times as long as that required for paint striping during any single striping operation.

Cost and life expectancy of hot-melt thermoplastic striping

As stated earlier the average cost of thermoplastic striping reported in this survey was 32.7 cents per linear foot of 4-inch stripe. In general, this cost is for installations performed on a contract basis, the most prominent method of installation.

No correlation could be found between theromoplastic life expectancy and traffic density, as was evident in conventional striping. This lack of correlation is shown in figures 5 and 6 for bituminous and concrete surfaces, respectively. Theoretically, some relation would be expected, but so many other variables affected performance that such a relation was obscured. Interfering variables that possibly affected durability of the thermoplastic were snowplow operations, pavement pretreatment, primer type and application rate, and pavement age. Of these, the only single parameter that showed some independent correlation with thermoplastic durability was the intensity of snowplow operations as measured by mean annual snowfall. Plots of annual snowfall data against the reported useful life of thermoplastics are shown separately for bituminous and concrete pavements in figures 7 and 8. These relations are more clearly evident in figure 9 in which individual data for each snowfall grouping was averaged, and the average plotted. Numerical entries within each box (bituminous pavement) or triangle (concrete pavement) indicate the number of individual data points that were averaged to obtain the plotted result, and the curves were carefully weighted to reflect these values. It is apparent from figure 9 that a correlation does exist between thermoplastic durability and mean annual snowfall for each type of pavement. It is also evident that thermoplastics are much more durable on bituminous pavements than on concrete. On both types of pavements, durability was decreased in high-snowfall areas. These results agree completely with the individual observations reported by many of the highway agencies.

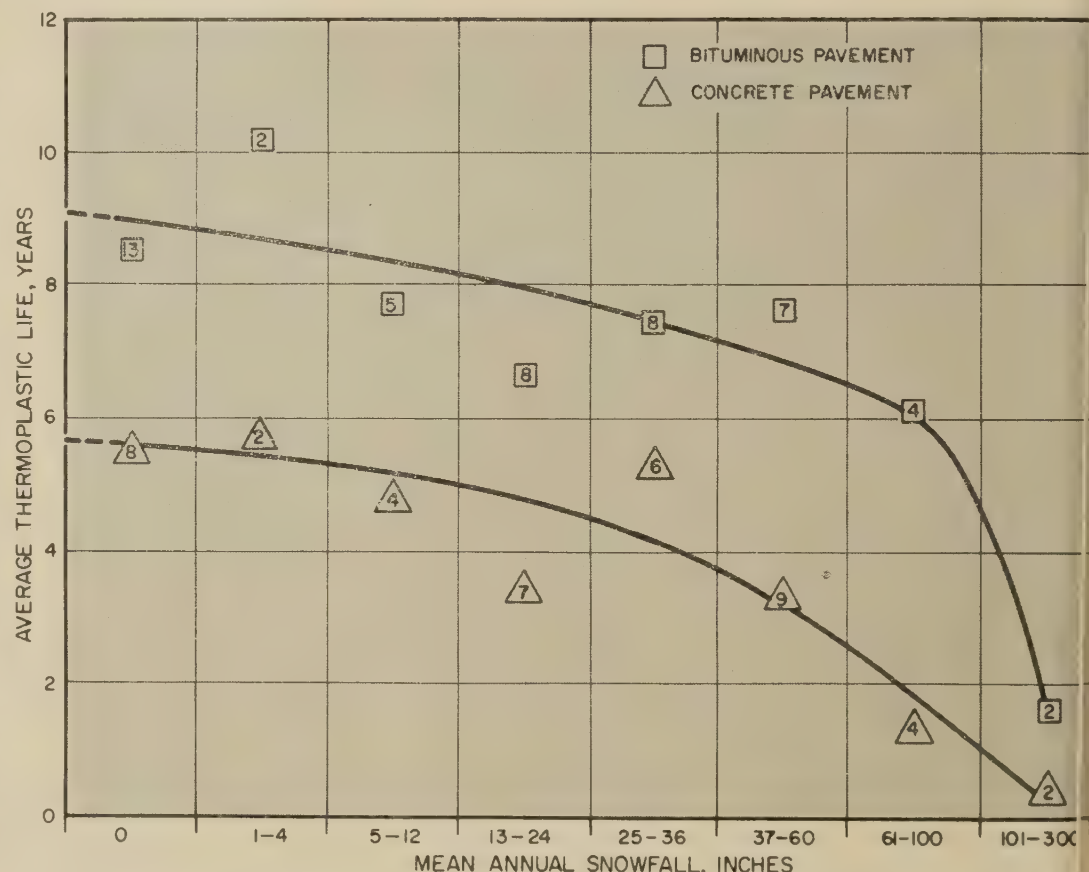

Figure 9.—Relation between average thermoplastic life and annual snowfall.

The curves in figure 9 apply mainly to center and lane lines. Where additional data were available, it seemed to indicate that edge lines lasted about one and one-half times as long as the indicated durabilities and transverse lines about one-half as long.

Guide for selecting the most economical material

On the basis of the data already presented, it was possible to develop criteria for selecting the most economical striping material—either paint or hot-extruded thermoplastic.

Data on the annual unit cost of paint striping, as it was affected by traffic density is provided by table 4. Cost data are given for the installation alone as well as for additional economic factors caused by frequent maintenance striping—traffic delay and traffic safety. The objective was to determine those conditions under which thermoplastic striping had costs comparable to conventional striping, as well as lower and higher costs. The average life of thermoplastic striping was interpolated from figure 9 for each pavement type at the midpoint of each incremental snowfall grouping. From these interpolated values and the average cost of the thermoplastic installation, 32.7 cents per linear foot, the unit costs per year of service were calculated for each pavement type and degree of snowfall. These costs were matched against interpolated costs for paint for the various traffic densities (table 4). It was then possible to establish equal cost *matches* for paint and thermoplastics, and the exact conditions under which they were operative—ADT, snowfall, and pavement type.

As a result of this calculation, a new chart, shown in figure 10, was constructed to show the conditions under which the long-term cost of painting and thermoplastic striping were equivalent. Points along curves C and F of the figure represent conditions conducive to equal costs of the two materials when the actual installation costs are considered alone and the economic effects of traffic delays and potential accident hazards are disregarded. Curves A and D are lines of equivalent costs for 6-lane divided highways, and curves B and E are for 4-lane divided highway. Any combination of snowfall and traffic density conditions that falls to the left of an appropriately selected demarcation curve would be an indication that paint is more economical than thermoplastics. The opposite is true for a combination of conditions that are to the right of the selected curve. The lower portion of the three curves for bituminous pavement—A, B, and C—have dashed vertical segments which are *cut-off points* that were determined as described in the following paragraph.

A number of road agencies reported that after the thermoplastic stripe had been used for some period, the bituminous surface required overall maintenance, necessitating the thermoplastic striping, which was still serviceable, to be covered over by a bituminous topping. The value of any long-lived stripe is governed by the maintenance-free life of the bituminous pavement. The following comments of the various agencies were selected as illustrative of the expected maintenance-free life of bituminous pavements.

Alabama—"Bituminous pavement required resurfacing after 8 years."

Arizona—"Use thermoplastics with caution on bituminous pavements because of limited maintenance-free life expectancy of such surface."

Kentucky—"Estimate maintenance-free life expectancy of bituminous pavements not to exceed 8 to 10 years."

Oklahoma—"4 to 5-year-old bituminous surface was resurfaced resulting in the obliteration of the thermoplastic marking."

Los Angeles County—"With road maintenance and utility work, the useful life of the pavement surface is not much more

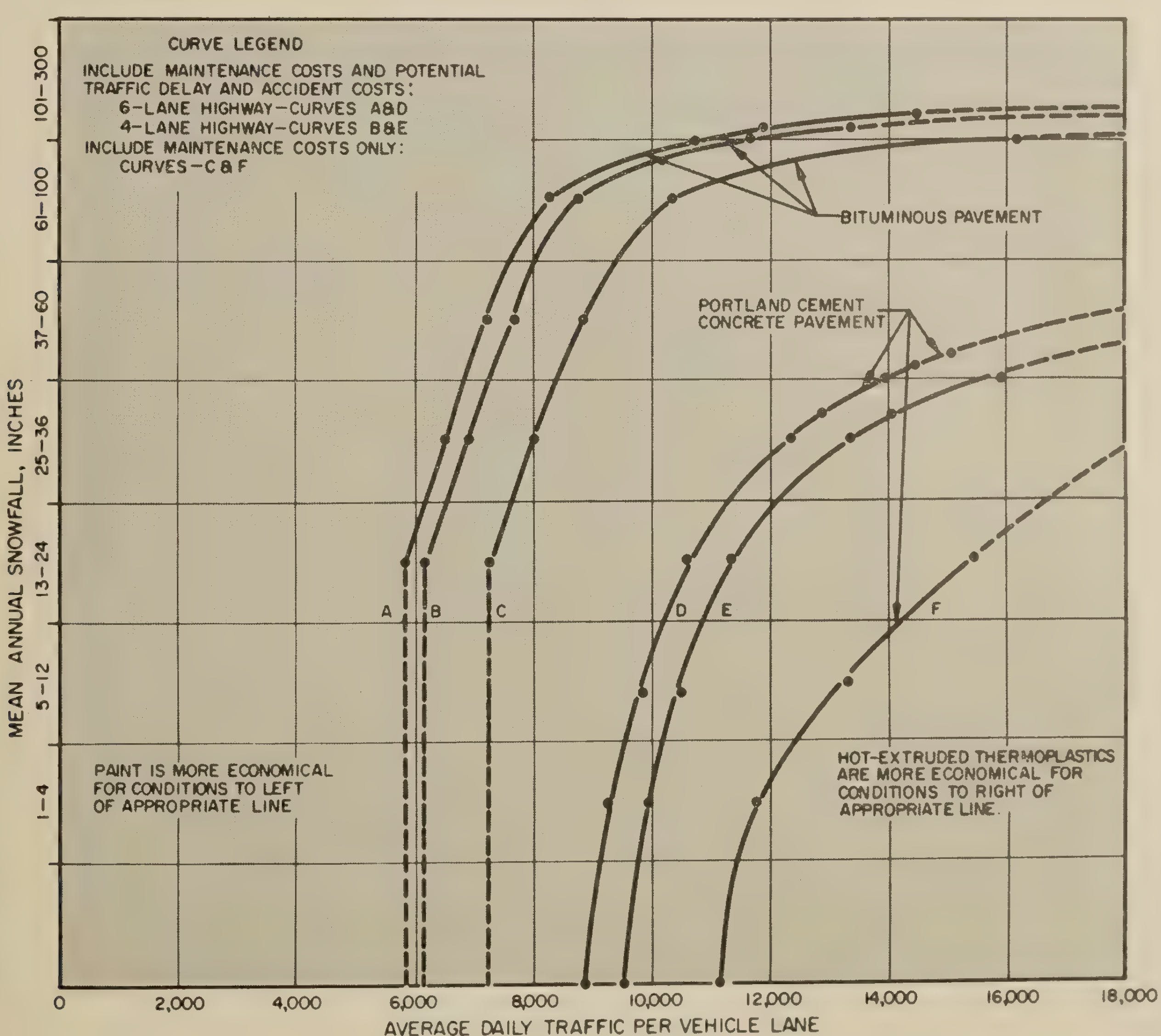

Figure 10.—Guide for selecting the most economical striping material, paint or thermoplastic.

Figure 11.—Mean annual snowfall, in inches, in the United States (prepared by the Department of Commerce, Revised 1966).

than 4 years, and thermoplastics are therefore limited to this."

Public Roads' specialists were also consulted on the durability of bituminous pavement surfaces. According to the information obtained from all sources, the best approximation of the average maintenance-free life of a bituminous surface was about 8 years. Therefore, this period was established as the nominal maximum useful life of thermoplastic striping on bituminous pavement and was the basis used to calculate the lowest possible annual unit cost applicable to thermoplastic striping, thus establishing the limiting value shown by the dashed vertical segments of figure 10.

Applicability and use of guide chart

Figure 10 can be used as a guide to determine whether conventional paint or hot-melt thermoplastic is the most economical striping for a given location. This chart is based mainly on data obtained on 4-inch-wide longitudinal lane and center lines on open highways and is essentially applicable to installations in which such lines are used. However, these criteria should be applicable to other stripe widths, provided that the ratio of installation costs for paint and thermoplastic remain the same as found in this survey. The criteria should also be applicable to edge markings, provided that the ratio of useful paint life to thermoplastic life is similar to that for lane or center striping.

To use the criteria for a given location, the following information is required to judge the relative economics of the two striping materials:

- Estimated or actual ADT per vehicle lane.
- Type of pavement surface—concrete or bituminous, and number of vehicle lanes.
- Mean annual snowfall in inches.

Mean annual snowfall can be obtained from local Weather Bureau officials, or from the snowfall contour lines shown on the Climatic Maps of the U.S., published by the U.S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service. A reproduction of such a map is shown in figure 11.

Using the above information and the guide chart, figure 10, plot the appropriate values for mean annual snowfall (in inches) against the ADT per vehicle lane. Select a demarcation line to denote both pavement type a[nd] whether installation costs only or the ad[di]tional economic factors of traffic delay a[nd] safety considerations are to be consider[ed]. Curves C and F are used to compare on[ly] direct tangible costs—installation and maintenance. Curves A, B, D, and E are used to compare overall costs that include traffic del[ay] and potential accident costs. Curves A and B apply to bituminous surfaces—curve A f[or] 6-lane, curve B for 4-lane roads. Curves D and E apply to concrete surfaces—curve D f[or] 6-lane, curve E for 4-lane roads. Data poi[nts] falling to the right of a selected demarcati[on] line indicate that thermoplastics are m[ore] economical than paint for the conditions to [be] encountered. Points falling to the left indic[ate] that paint is more economical than thermoplastics. When thermoplastics are selected [for] use under these criteria, their applicati[on] should be considered carefully. The installation of thermoplastic on new concrete with[out] precleaning or sandblasting the concrete [sur]face is a risky operation. For older bitumin[ous] pavements, the remaining years of maintenance-free service expected of the pavem[ent] surface should be determined and this pe[riod] balanced against expected stripe life.

The guide chart is applicable when the ratio of total installed cost of thermoplastic to paint is approximately 15:1, as determined in the reported survey. A cost ratio that differs substantially from 15:1 should be taken into account by appropriate modification of the described criteria. The guide chart does not consider the hazard to maintenance crews during restriping operations. This is a subjective factor to be weighted in favor of thermoplastics.

Comparison of Developed Criteria With Other Available Guides

The proposed criteria for the selection of :he most economical striping material, developed in the study reported here and illustrated ın figure 10, were compared with the limited guides suggested by several agencies in their esponse to the survey. (See table 3.) The agencies' guides, essentially, are qualitative guides that limit the use of hot-melt thermoplastics to high density roads and/or bituninous surfaces. For such installations, the proposed quantitative criteria are compatible vith these qualitative restrictions. The guides offered by the Arkansas and Indiana highway lepartments are much more liberal than those leveloped here. They permit the use of hermoplastics, at least on asphalt pavements, vhen the *total* ADT is at least 6,000. A ninimum limit of 6,000 ADT *per vehicle lane* s suggested by the proposed criteria. The riteria of California and Oregon are more in ine with the proposed criteria. In these States, he minimum ADT per vehicle lane conducive or the best economic use of thermoplastics is pproximately 5,000 to 6,000.

An important feature of the proposed set of uides is that it provides for continuous uantitative criteria which cover a wide range f snowfall and traffic conditions and type of avement surface.

ypical Specifications and Warranties for Thermoplastic Materials

Incidental to the primary information deeloped from the survey, some data were btained on typical specifications and warran- es used for hot-melt thermoplastics. This ıformation, summarized in tables 5 through is incomplete and is not representative of l practices, but it does provide an adequate ımpling of what is generally available and use.

A summary of typical specifications for nthetic rubber primers used in conjunction ith hot-extruded thermoplastics is given in ble 5. These primers had been used largely r portland cement concrete surfaces but ırrently are being gradually replaced by ooxy primers. According to the data in the ble, the critical components are either a ixture of neoprene and butadiene-styrene bber or of nitrile rubber (Buna N) and ıenolic resin. These materials usually are pplied and used in solution form containing oout 10 to 20 percent solids by weight.

Information on typical specifications for o-part epoxy primers, which have begun to place the synthetic rubber primers, is listed in table 6. Generally, each of the two components is used in solution form containing about 50 percent reactive solids.

A tabulation of typical specifications for hot-extruded thermoplastic striping material is presented in table 7. The material, referred to as Crystallex, is apparently designed to meet British Standards, as is evident from the tabulation. The material, which is specified by the California Highway Department, is a specialized formulation that is somewhat different from the other materials listed. The

Table 5.—Typical specifications for synthetic rubber primer for thermoplastics

Agency or company	Goodyear Tire & Rubber Co.	Calif. State Highway Dept.	N.Y. State Highway Dept.	Conn. State Highway Dept.
Specification	*Technical Book Facts* PB-6.	63-F-40	White thermoplastic, Item 401.	Special Provisions, Federal-Aid Projects I-91-2(35)31 and I-91-3(53)36.
Specification date	Received May 1968.	1963	Apr. 18, 1968	July 15, 1963.
Name of material	Pliobond 20 [1]	Primer for traffic paints and thermoplastic traffic paints.[2]	Primer for bituminous concrete pavement.	
Composition (solids basis):				
Neoprene, percent			Required (or SBR).	Required (or SBR).
Butadiene-styrene (SBR), do			Required (or Neoprene).	Required (or Neoprene).
Buna N rubber, do		60–70		
Phenolic resin, do		30–40		
Synthetic rubber, do	Required [1]			
Synthetic resin, do	Required [1]			
Conform to standard infrared spectrum.		Required		
Solids, percent	20	9–11	10 [3]	10 [3].
Weight per gallon, pounds	7.2			
Solvents (based on total solvent):			Volatile, organic	Volatile, organic.
MEK, percent	Required	50		
MIBK, do		20		
DIBK, do		5		
Toluene, do		20		
Xylene, do		5		
Dry time, tack-free, minutes			Less than 5 (6 mil film at 70° F. and 60% R.H.[4]).	

[1] In qualitative infrared analysis by Public Roads laboratory, it was shown that this material is a Buna N-phenolic resin mixture similar to the standard spectrum in California State specification 63-F-40.
[2] Intended for use on new portland cement concrete surfaces prior to application of traffic paint and on portland cement concrete and asphaltic concrete surfaces prior to application of thermoplastic traffic marking material.
[3] Minimum.
[4] R.H. = Relative humidity.

Table 6.—Typical specifications for 2-part epoxy primer for thermoplastics

Agency or company	Adhesive Products Corp.	N.Y. State Highway Dept.	Cataphote Corp.	Perma-Line Co.
Specification		White thermoplastic, Item 401.		Concrete Sealer-Binder DX-1037.
Specification date	Sept. 7, 1967	Apr. 18, 1968	Nov. 22, 1967	Received May 17, 1968.
Name of material	Adopox	(1)	(1) (2)	Perma-Seal III.[3]
Epoxy component (A)	T-243R-2 Adopox			Bisphenol.
Reactive solids, percent	50		50 [4]	52.
Weight per gallon, pounds	8.095	8.095 [4]	8.10 [4]	8.35±1.
Epoxide equivalent (solids basis)	185–200	185–200	185–200	
Solvent(s)	Aliphatic			Aromatic.
Viscosity, No. 2 Zahn, 77° F, seconds				14±1.
Appearance and color				Clear, straw yellow.
Catalyst component (B)	T-1661I-1 Adopox Hardener.			
Type				Aromatic amine.
Reactive solids, percent	50		50 [4]	26.
Weight per gallon, pounds	7.405	7.405 [4]	7.40 [4]	7.47±0.1.
Solvent(s)	Aliphatic			Aromatic.
Viscosity, No. 2 Zahn, 77° F, seconds				14±1.
Appearance				Clear, red-brown.
Mixture of (A) and (B):				
Mix ratio (A:B), by volume	2:1	2:1	2:1	1:1.
Pot life (closed container at 72° F)	3–4 days	24 hours [4]	24 hours [4]	2–4 hours.
Dry time, to tacky, minutes	15 (5–7 mils wet at 40–110° F).			
Color of dried film	Clear			
Reactive solids content, pct. by weight		50 (A+B, 1:1 vol.).[4]		39–41 (A+B, 1:1 vol.).

[1] Primer for portland cement concrete.
[2] For application prior to thermoplastic, apply between 40–110° F. at 5–7 mils wet. Apply marking material after it is tacky, or approximately 30 minutes under normal conditions, 70° F. and 40% R.H.
[3] Apply at 50–100° F. Sandblast portland cement concrete where required.
[4] Minimum.

Table 7.—Typical specifications for hot-applied thermoplastic material

Agency or company	Perma-Line Co.	Cataphote Corp.	Constructex Overseas Ltd.	British Standard (B.S.)	California State Highway Department	Florida State Highway Department	Connecticut State Highway Department	New York State Department of Transportation	
Specification	Perma-Line	Catatherm	Crystallex [1]	B.S. 3262, Part 1, 1960.	White thermoplastic IR 353.	Special provisions to 1966 standard specifications, Item 611.	Special provisions for highway I-91.	White thermoplastic.	White thermoplastic.
Specification date	Revised Mar. 7, 1968 (long form).	Received Aug. 29, 1967.	Received May 17, 1963.		January 1964.	Nov. 21, 1966.	May 1964	Apr. 18, 1968.	Mar. 25, 1966.
LABORATORY PROPERTIES									
Composition:									
Pigment, for white thermoplastic percent by weight	6-10 (of pigment).[2]	10 minimum (of pigment).[2]		6-10 minimum.[2]	13.0 [2]		10 minimum (of pigment).[2]	10 minimum.[2]	10-15.[2]
Extender pigment do				10-14 [3]	41.6 [4]				
Aggregate do	([5])	([5])		38-42				38-49	32-48.
Beads (premixed) do	15-50	25-50		18-22	20.8	20 [6]	20-30	20-25	20-25.
Organic binder do	15-35	15-35		18-22				17-22	22-28.
Synthetic resins	([7])	([7])		Required					
Modified alkyd						Required			Required.
Hydrogenated ester gum do					9.8				
Pliolite ACl do					9.0				
Hydroabietyl alcohol do					5.8				
Rosin				Required					
Mineral oil				do					
Monohydric primary alcohol								Required [8]	
Modified maleic resin								Required	
Color:									
Yellow (FTMS 141, Method 4252), match standard color chip.	Required	Required [9]				Required			
White (ASTM E-97): Daylight reflectance (Rd) minimum. percent	70	70			75 [10]	70	70		
Redness-greenness, a	−5 to +5	−5 to +5				−5 to +5	−5 to +5		
Yellowness-blueness, b	−10 to +10	−10 to +10				−10 to +10	−10 to +10		
Color retention, no perceptible change:									
Yellowness index, maximum (FTMS 141, Method 6131).					0.12 [10]				
After heating to plastic state	4 hours [11]	4 hours [12]			([13])				
After ultraviolet exposure hours	([14])	100 [15]				100 [15]	([15])	100 [15]	100.[15]
Specific gravity (25° C./25° C.)	1.0-2.5	1.9-2.5	2			1.9-2.15		1.9-2.2	1.9-2.0.
No deterioration when heated to plastic state. do	4	4 [16]			4 [17]	4 [16]	([18])		
Toxic fumes, when heated to plastic state	None	None				None			
Volatile material							None		
Temperature-viscosity characteristics, the same after reheating. No. of reheatings	4	4			([13])	4			
Water absorption (ASTM D 570) maximum. percent	0.5	0.5				0.5			
Softening point (ASTM E 28, Ring and Ball) minimum. degrees C	90	90	([19])	40-50		90		90	90.
Impact resistance (ASTM D 256) at 77° F., 1- x 1- x 3-inch cast bars, minimum. inch-pounds	10								
Bond strength (ASTM C 321) between 3½- x 7-inch area of portland cement concrete. minimum p.s.i.	150 [20]	150 [21]			200 [10] [22] [23]				
Indentation resistance (ASTM D 1706), Shore Durometer Type A-2, reading after heating 4 hours at 400° F., cooled and held for 15 seconds at:									
115° F reading	60 [24]	65 [6]			47-57 [10] [25]				
77° F do	95 [24]	95 [6]							
40° F do		95 [6]							
Cracking, low temperature stress resistance (coating on portland cement concrete surface) no cracking, flaking or adhesion failure.					([26])	([27])			
Flowability, residue in can percent					13-17 [28]				
ROAD PROPERTIES AFTER APPLICATION									
Deterioration by deicing chemicals, pavement constituents or oil drippings.	None	None				None			
Deformation or discoloration under normal traffic	None [29]	None [30]				None [31]	None [32]		
Drying time, no impression or imprint by traffic:									
At 50° F minutes	2 [33]	2 [33]			2 [34]				
At 70° F do						15 [35]		15 [34]	15 [34].
At 90° F do	15 [33]	15 [33]			10 [34]				
Free from tack	Yes	Yes				Yes			
Chipping or cracking	None	None				None			
Slippery when wet	No	No				No	No		
APPLICATION REQUIREMENTS									
Temperature and environment degrees F				50 [36]		([37])	40 [38]	40 [6]	40 [6]
Pavement condition				Dry, no old paint.			No paint	Dry, oil-free.	Dry, oil-free.
Pavement precleaning, remove dirt, oil, grease	Yes [39]	Yes [39]					Yes [39]		
Primer	Required	Required				Required [40]			
For portland cement concrete pavement	do			Required [41]		do	Required [42]	Required [42]	Required
For bituminous concrete pavement	Required [43]	Required [43]				do [44]		do [45]	Do.[45]
Primer application rate (wet film) sq. yd. per gal				70-100					
Synthetic rubber sq. ft. per gal							50		50.
Epoxy do		([46])						429	230-320.

Table 7.—Typical specifications for hot-applied thermoplastic material—Continued

Agency or company	Perma-Line Co.	Cataphote Corp.	Constructex Overseas Ltd.	British Standard (B.S.)	California State Highway Department	Florida State Highway Department	Connecticut State Highway Department	New York State Department of Transportation	
APPLICATION REQUIREMENTS—Continued									
Time between primer and thermoplastic application:									
With synthetic rubber				After solvent evaporates.					
With epoxy, minutes		30 [47]					30–120	15 [48]	15 [48].
Thermoplastic application temperature, degrees F	375–475	380–420	280–350 [49]	250–280		380–420		360–420	360–420.
Thermoplastic application speed, m.p.h.	2 [6]						4 in.—17–171 ft/min.	15,000–20,000 lin. ft./8 hour.	15,000–20,000 lin. ft./8 hour.
Thickness of thermoplastic in place:									
Center, minimum, inch	1/8	1/8							
Edge, minimum, do	3/32	3/32							
Overall, do	3/32–5/32	3/32–3/16		1/8 [6]		3/32–3/16	3/32–1/8	1/8–3/16	1/8–3/16.
Drop-on beads, application rate, per 100 sq.ft. of line, pounds	3; 20 [50]					0.2	3	5	5.
Visibility				60 [51]					
CERTIFICATION OF TEST COMPLIANCE									
Certification of compliance by contractor						Required	Required		

[1] Crystallex specifications similar to B.S. 3262, Part 1.
[2] TiO_2.
[3] $CaCO_3$ or lithopone.
[4] $CaCO_3$.
[5] $CaCO_3$, white, 5,000 p.s.i. minimum.
[6] Minimum.
[7] Mixture (one must be a solid at room temperature).
[8] High boiling point.
[9] Federal yellow.
[10] After 4 hours at 450° F.
[11] At 395° F. and 4 reheatings.
[12] At 375° F. and 4 reheatings.
[13] Repeated reheatings.
[14] Prolonged exposure to sun.
[15] ASTM D 620.
[16] And 4 reheatings.
[17] At 450° F. and reheatings at 450° F.
[18] 4 reheatings.
[19] 45 for standard grade; 60 for tropical grade.
[20] ⅛-inch thick with binder.
[21] $\frac{1}{10}$–⅛-inch thick.
[22] Portland cement concrete blocks sandblasted and primed with 63-F-40 primer.
[23] $\frac{1}{16}$–⅛-inch thick.
[24] Minimum (2-pound weight).
[25] 2-kilogram weight.
[26] ⅛-inch layer on 1 square foot sandblasted and primed portland cement concrete, conditioned, to 77° F., 24 hours at 15° F., remove and examine within 5 minutes.
[27] 32-square-inch specimen, 1 hour in cold H_2O, 24 hours at −20° C., condition and test at ambient temperature.
[28] 20% residue after 4 hours at 450° F.
[29] Provided air and road temperature is between −20° and 120° F.
[30] Provided air and road temperature is between 0° and 120° F.
[31] Provided road temperature does not exceed 140° F.
[32] Provided air and road temperature is between −30° and 120° F.
[33] Maximum (maximum 70% RH).
[34] Maximum.
[35] Maximum (⅛–$\frac{5}{32}$-inch thick).
[36] Minimum pavement temperature.
[37] Articles 6.1, 6.2, 6.3, 6.10.
[38] Minimum (relative humidity 80% minimum).
[39] Where necessary.
[40] Epoxy (as recommended by thermoplastic manufacturer).
[41] 1 part asphalt, 1 part dichloromethane.
[42] Epoxy.
[43] If less than 8% asphalt.
[44] If less than 7% asphalt.
[45] Synthetic rubber.
[46] 5–7 mils.
[47] Or until tacky.
[48] Approximately, till tacky.
[49] 280 for standard grade; 350° for tropical grade.
[50] High intensity beads.
[51] Minimum (average luminance).

remainder of the specifications are somewhat similar, and appear to be patterned after the two most prominently used hot-melt thermoplastics in this country—Permaline and Catatherm. The specifications are presented under separate subheadings to show clearly the required laboratory properties, field properties, and application requirements for these materials.

Typical specifications currently in use for both premixed and drop-on type beads used in conjunction with thermoplastic striping are listed in table 8. Except for the British Standard, these specifications are similar, but do show some minor differences.

Some typical warranties furnished by the contractor or required of him in connection with the durability of thermoplastic striping are tabulated in table 9.

Conclusions and Recommendations

The principal findings and recommendations developed from the study reported here are summarized in the following statements:

- Hot-extruded thermoplastic striping is much more durable on bituminous pavements than on portland cement concrete pavements.
- Thermoplastic striping generally is more durable on older concrete pavements than on new concrete.
- Snowplow activity, as measured indirectly by mean annual snowfall data, greatly affects thermoplastic adhesion to the pavement, especially on portland cement concrete. The service life of thermoplastic striping is related more to snowplow activity than to traffic density. By contrast, the durability of conventional paint striping is related to the volume of traffic.
- A limiting factor in the economic value of thermoplastic striping on bituminous pavements is the maintenance-free life of the bituminous surface; this was estimated to be an average of about 8 years.
- Unremoved layers of old traffic paint may adversely affect the adhesion of thermoplastic striping to the pavement.
- A guide (fig. 10) was developed to assist in the selection of the more economical of the two materials, conventional paint or hot-melt thermoplastics, for specific conditions: pavement surface, traffic density, and expected snowfall in the area concerned.
- Under conditions of little or no snowplow activity, thermoplastics can provide economic benefits over paint striping on bituminous pavements when the traffic density is approximately 6,000 vehicles per lane or greater, or on concrete pavements when the density exceeds 9,000 vehicles per lane. Under moderate snow conditions thermoplastics can be justified at higher traffic density levels. Little economic justification exists for the use of thermoplastics under severe snow conditions requiring considerable snowplow activity.
- Although many such installations have performed well, the greatest deterrent to the wide use of thermoplastic striping is its sporadic, and sometimes unexplained, failure on concrete surfaces. Research to improve this situation should be sharply emphasized. Suggested for such investigation are the following parameters and their contributions to thermoplastic performance on concrete: surface cleaning and preparation, improved primer formulation, rate of primer application and its relation to the age and nature of the concrete surface, time interval between primer and thermoplastic application, and feathering of thermoplastic leading edges and sides to reduce snowplow destruction.

Table 8.—Typical specifications for glass beads for thermoplastic striping

Agency or company	Perma-Line Co.	Cataphote Corp.	British Standard	California State Highway Department	Florida State Highway Department	New York State Highway Department
Specification		Data Sheet	BS 3262, Part 1.	Thermoplastic Formula, IR 353.	Spec. Prov. to 1966 Std. Specs., Item 611.	White thermoplastic, Item 401.
Specification date	Revised Mar. 7, 1968.	Received Aug. 29, 1967.	1960	January 1964.	Nov. 21, 1966.	Apr. 18, 1968.
PRE-MIXED TYPE						
Index of refraction, liquid immersion at 25° C., minimum.	1.50	1.65		1.50	1.50	1.65.
Roundness (ASTM D-1155), True spheres, minimum. pct	70	90	80	75	70	90.
Air inclusions do		None		None		
Milky, black, amber, or colored particles. do		1 [1]				
Gradation (ASTM D-1214), passing Sieve No.:						
10 do			100 [2]			
16 do						100.
20 do						98–100.
30 do						75–90.
36 do			10 [1, 2]			
40 do	80–100	80–100		95 [3]	80–100	
50 do						15–40.
70 do				10 [1]	0–10	
80 do	0–10	0–10				
100 do						0–10.
200 do						0–5.
Chemical resistance (water, acid).	Required					
Crushing resistance (ASTM D-1213). pounds	40 [4]					
DROP-ON TYPE						
Index of refraction, liquid immersion at 25° C., minimum.	1.50, 1.90 [5]	1.65				1.65.
Roundness (ASTM D-1155), True spheres. pct	70 [3]	90				90.[3]
Milky, black, amber, or colored particles. do		1 [1]				
Gradation (ASTM D-1214), passing Sieve No.:						
16 do						100.
20 do	80–100 [5]	90–100				98–100.
30 do						75–90.
35 do		0–10				
40 do						
50 do	90–100					15–40.
70 do	0–10					
80 do	0–10 [5]					
100 do						0–10.
200 do						0–5.
Chemical resistance (water, acid).	Required					
Moisture resistance, cotton bag-funnel test.						Required.
Crushing resistance (ASTM D-1213). pounds	40 [4]					

[1] Maximum.
[2] British Standard (BS) sieve.
[3] Minimum.
[4] Average minimum.
[5] When high intensity stripe is specified.

Table 9.—Typical warranties for hot-applied thermoplastics

Agency or company	Perma-Line Co.	Cataphote Corp.	New York City
Specification	Perma-Line	Catatherm	Plastic Marking.
Specification date	Mar. 7, 1968	Received Aug. 29, 1967.	1968.
Crosswalks and stop lines, percent guaranteed for:			
1 year percent	90 [1, 2]	90 [1, 3]	100.[4, 5]
1½ years do			
2 years do	75 [1, 2]	75 [1, 3]	
2½ years do			
3 years do		50 [1, 3]	
Lane and center lines, percent guaranteed for:			
1 year do	90 [2, 6]	90 [3, 6]	100.[5, 7]
1½ years do			100.[5, 8]
2 years do	80 [2, 6]	80 [3, 6]	100.[5, 9]
2½ years do			100.[5, 10]
3 years do	60 [2, 6]	60 [3, 6]	100.[5, 11]

[1] Percent of the total installation at any single intersection.
[2] 25,000 ADT maximum.
[3] 30,000 ADT maximum.
[4] School crosswalks.
[5] When more than 20% failure occurs in a line within guarantee period, entire line must be replaced. Contractor not liable for damage caused by snowplow blades.
[6] Percent of a unit defined as 2,000 linear ft. of line of specific width.
[7] More than 40,000 ADT.
[8] 30,000–40,000 ADT.
[9] 20,000–30,000 ADT.
[10] 10,000–20,000 ADT.
[11] Less than 10,000 ADT.

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SURVEY ON PERFORMANCE OF HOT-EXTRUDED THERMOPLASTIC STRIPING MATERIALS FOR HIGHWAYS—DETAILED INFORMATION

Data Requested in Survey

- Location of controlled experiment.
- Length of installation (linear feet of thermoplastic or ›ther basis).
- Date initiated.
- Average daily traffic per vehicle lane.
- Pavement surface (asphalt or concrete, new or older urface).
- Pretreatment of pavement surface (other than primer).
- Primer applied, if any (synthetic rubber, epoxy, etc.).
- Brand name of thermoplastic used.
- Relative snowplow activity.
- Unit cost of thermoplastic stripe (contract cost or other asis)—cost per linear foot of actual stripe (indicate stripe vidth—4, 6, 8, etc., inches).
- Comparative unit cost of applying a similar width of onventional traffic paint stripe (either contract cost or cost ncluding materials, labor, and equipment depreciation).
- Average actual useful life of conventional paint stripe in rea under consideration.
- Average useful life of thermoplastic stripe in this same rea (indicate whether estimated on basis of performance of till useful stripes or whether terminal point was reached by his material).
- Estimates of percentage of thermoplastic line lost by dhesion failure.
- Cost of replacing thermoplastic (indicate basis of cost).
- Comments and specific conclusions on relative durabil- ty and long-term economy of these competitive materials n this specific area and for these circumstances. Include tatement of any special conditions that may have affected ehavior on this project.
- Present policy, practice and criteria employed relative to he use of hot-extruded thermoplastics in regular maintenance riping operations.

The following note was included in the survey question- aire: If general knowledge is available, based on experiences ith several installations that may not be included as parts f controlled experimental projects, please provide a general ummary of such knowledge.

Comments by Agencies Surveyed

tates, District of Columbia, and Puerto Rico

Alabama.—High traffic-volume portion of heavy duty bitu- inous concrete resurfaced after 8 years of service, covering ver thermoplastic and not permitting full life of thermo- astic striping. Limitations of conventional paint are minished crew safety because of more frequent maintenance d poor visibility during last half of paint's useful life. fter 8 years, 30 percent of original ⅛-inch thick thermo- astic remains on section with 4,000 average daily traffic r lane. No adhesion failures noted.

Arizona.—In 5 years of service, reflective properties of ermoplastic have deteriorated considerably and stripe does ot remain bright throughout its life. Material should be ed with caution on bituminous pavement owing to flexi- lity and shorter life expectancy of bituminous surface. aution in using on portland cement concrete with less than ear of service because of moisture, curing compounds, and tance. Earlier tests showed thermoplastic performed orly on portland cement concrete without primer.

Arkansas.—Thermoplastic lane lines applied over 3-week- l paint stripe on portland cement concrete. Air bubbles med initially. Night visibility superior to paint. No bond lures in 2 years, but about 8 percent chipped at edges. tter service on bituminous pavement than on portland ment concrete pavement.

California.—New portland cement concrete should be dblasted (a cost of approximately $100 per mile). Thermo- astic lasts indefinitely on bituminous pavement owing to ion. Most failures on portland cement concrete occur from ipping because of poor adhesion. Although thermoplastic s better than paint in many areas, it is being replaced by sed markers in snow-free areas.

Connecticut.—Average life of paint reported as 2 months but actually repaint only 2 to 3 times a year. Ten percent loss of thermoplastic in last year on portland cement concrete replaced by contractor. More wear on horizontal curves. Section of portland cement concrete primed with synthetic rubber is much poorer than that primed with epoxy. Placement velocity of thermoplastic is 5 m.p.h., on long continuous lengths. Blistering still a problem over portland cement concrete pavement. Thermoplastic not subject to color fading as with paint. Unexplained isolated cases of failure still occur. Practice is to apply epoxy primer and thermoplastic from same moving truck using heater pass over the epoxy. May change this to allow more time for primer to dry.

Florida.—Gainesville (University Avenue)—Catatherm much softer than Perma-Line. Yellow Catatherm bleaches to lighter shade. Good to excellent night reflectivity, but poorer and dirty in day. Dirt accumulates in depressions but appears better after a rain.

Interstate 95 (Dade County)—In 2 months thermoplastic began to deteriorate over portland cement concrete but paint still satisfactory. Thermoplastic blistering and breaking away. Better durability on older bituminous pavement. *Northern* grade of thermoplastic in Miami failed because of shifting and softness. Thermoplastic on portland cement concrete showed air pockets and blisters.

Illinois.—Terminal life of thermoplastic is considered reached when only 50 percent remains.

Indiana.—Currently not using thermoplastic on portland cement concrete because of adhesion failures. Have had satisfactory experience on portland cement concrete in isolated cases.

Iowa.—Ninety days after installation, thermoplastic appearance was dull. First application on portland cement concrete failed within 9 months through adhesion loss. Replacement under warranty performing adequately. High cost cannot be justified, considering economics of standard paint over portland cement concrete.

Kansas.—Movement of bituminous overlay on portland cement concrete caused early thermoplastic failures.

Kentucky.—Suggest that feasibility of use of thermoplastic be estimated on basis of anticipated renewals of traffic paint during a reasonable period—not exceeding tenure of particular pavement surface and certainly not more than 8 to 10 years. Thermoplastic loss of more than 1 percent per year, or less than 90 percent terminal retention in line footage is intolerable. Thermoplastic performed better where greater application rate of Pliobond primer was used. Thermoplastic lost adhesion more quickly on new portland cement concrete than on older portland cement concrete. Epoxy-primed section on portland cement concrete more durable than Pliobond-primed section on portland cement concrete. Better performance of thermoplastic on bituminous pavement than on portland cement concrete.

Maine.—Considerable snowplow damage to thermoplastic on bituminous pavement; therefore not economically feasible in heavy snowplow areas.

Maryland.—After 18 months, thermoplastic lost considerable night visibility. In poor condition on portland cement concrete after 2 years. Condition good on bituminous pavement after 8 years at one location.

Michigan.—Better adhesion of thermoplastic on older portland cement concrete and on bituminous pavement. Needed early replacement on new section of portland cement concrete. Not recommended on portland cement concrete. Still usable after 8 years on bituminous pavement.

Minnesota.—Snowplow causes extensive damage to thermoplastic. Poorer adhesion to portland cement concrete may have been caused by application over existing paint stripe. Even with epoxy primer over unpainted area, thermoplastic still had approximately same loss in first year as installations with rubber primer and over paint. For future, recommend light grinding or sandblasting of portland cement concrete, improved epoxy primer, and increased rate of primer application and primer not applied more than 30 minutes before thermoplastic application. Thermoplastic justified on bituminous pavement; still excellent after 2 years. Epoxy applied to portland cement concrete and bituminous pavement at 4,000 linear feet per gallon. When rate increased to 1,000 lin. ft. per gallon thermoplastic began to slide on bituminous pavement but held fast on portland cement concrete.

At installation near St. Paul-Minneapolis, in 1967—15 percent loss in less than 1 year. Surface preparation of light grinding or sandblasting and increased primer application rate produced little improvement in adhesion to portland cement concrete. Very good performance on bituminous pavement. Performance on portland cement concrete variable between projects, also within a single project and even between adjacent lanes. Leading edge first to deteriorate mainly because of snowplows. Deterioration related to the number of snowplow operations. More failures noted when thermoplastic is placed over existing paint than when no paint previously existed.

Mississippi.—Thermoplastic more effective and cheaper than paint on road with high-traffic density over a 7-year period. Pliobond applied at 6–8 gallons per mile of actual stripe.

Nebraska.—Thermoplastic satisfactory at night where 40 percent or more of line still intact. Daylight appearance not quite up to new paint but performance satisfactory. By comparison, rubber-based primer seems to give better adhesion than epoxy.[5] Some damage by snowplows.

New Hampshire.—Good visibility of thermoplastic gave improved safety compared to paint and its associated degradation. Extensive cracking of thermoplastic owing to cold weather but performance not dversely affected. Minor damage by snowplows on several sections. Paint contract at 2 cents per linear foot is real. Present price now about 3–4 cents per linear foot. For thermoplastic, 19 cents per linear foot is real but low—this was an early installation, perhaps done at cost.

New Jersey.—Reflectivity of thermoplastic decreases with age. In 4 years, project terminated because all lane lines were worn off at curves and were therefore painted.

New Mexico—Thermoplastic may have lasted longer if surface had been sandblasted. No primer and surface preparation used at manufacturer's recommendation.

New York.—Thermoplastic discolors after 4–6 years. Some pinholing and blistering. Blistering over portland cement concrete ut not specifically noted over bituminous. Damage to leading edge of lane stripe. Suggest feathering leading edge. Much better adhesion to bituminous concrete than to portland cement concrete. On bituminous concrete, no difference in 1½ years whether placed over synthetic rubber or no primer. Adhesion failures in Long Island installations greatly reduced by use of epoxy primer on portland cement concrete.

After 5 years, thermoplastic still approximately as bright as fresh paint. Thermoplastic more economical than paint if on bituminous pavement with high traffic density. Synthetic rubber primer on portland cement concrete gives variable service—less than 1 year on new portland cement concrete to 50 percent retained in 2½ years on 2-year-old portland cement concrete. On new portland cement concrete with epoxy primer, thermoplastic appears satisfactory after 1 year. Thermoplastic seems more visible than paint under wet conditions.

Epoxy primer for portland cement concrete usually applied at 5–7 mils wet film (more recently 4–5 mils) and approximately 15 minutes before thermoplastic. An infrared heater may be used for shorter cure time. Synthetic rubber primer for bituminous pavement contains 10 percent solids applied at 100 linear feet (6-inch stripe) per gallon and allowed to become tacky before thermoplastic applied (sometimes more than 1 day before thermoplastic application).

Thermoplastic detached from portland cement concrete had thin laitance layer of portland cement concrete on bottom surface. Adhesion losses less if snowplow shoes used rather than no shoes. Edge stripes catch and pond water—should contain gaps or channels.

Long Island Parkways (SSP 62-2, MSP 62-3, HSPM 63-2, F118 64-1, NSP 65-2): Generally, precleaning for skip line

[5] This observation is contrary to reports by other agencies.

required air blower, whereas edge line required mechanical and hand brooming and blowing, depending on accumulation of debris. Maximum thickness of epoxy 6 mils. Amount of thermoplastic blistering decreased as thickness of epoxy decreased.

Specifications for chemical composition of binder recently changed to reduce bubbling of thermoplastic. Wet film of epoxy binder reduced to 4–5 mils to help prevent bubbling and to better cure epoxy prior to application of thermoplastic. Allow approximately 15 minutes for epoxy to cure before thermoplastic application. Infrared heater may be used to shorten epoxy cure time.

Ohio.—Thermoplastic failed mainly on portland cement concrete, not on bituminous pavement. Snowplows did not particularly disturb material.

Oklahoma.—Thermoplastic is favorable for highways with high traffic density. Faded significantly on Interstate 440—don't know why. Perhaps poor binder. Gores needed painting after 6 years of thermoplastic use. Failure mostly on curving ramps and on bridge decks sanded during ice storms. Bituminous pavement, 4–5 years old, needed resurfacing and therefore obliterated thermoplastic still in place.

Oregon.—Thermoplastic lasts longer when not applied over built-up paint layer on older bituminous pavement. Therefore, should remove old layers of paint by sandblasting. Better service when applied over paint film only 1-year-old. On U.S. 20, 40 percent of thermoplastic removed by snowplows—therefore not suitable for mountain passes.

Rhode Island.—Excellent performance over bituminous pavement. Avoid application over bituminous seams, which later crack and affect lane lines.

South Carolina.—Synthetic rubber primer applied at 50 square feet per gallon. Thermoplastic still in good condition, but extrapolating cost of thermoplastic and paint it would take 28 to 32 years of maintenance painting to overcome initial cost of thermoplastic. Therefore thermoplastic not economical under these conditions. On bituminous pavement paint more visible than thermoplastic on rainy day or on dry night, but on portland cement concrete thermoplastic more visible than paint on rainy day.

Texas.—Excellent durability of thermoplastic on bituminous pavement overlay on portland cement concrete, but average life was 4 years on portland cement concrete. Catatherm yellowed considerably while Perma-Line did better. Flaking action noted in winter.

Wisconsin.—On bituminous pavement, reflectance decreased in 1 year. On portland cement concrete, winter plowing destroyed some sections with more than 10 percent failure in first year. Reflectance low after 10 months probably contained less exposed beads than regular paint. Believe portland cement concrete should be sandblasted or acid etched, as thermoplastic performance is unreliable on portland cement concrete. Blisters (cause unknown) evident after 1 week and then break. This perhaps presents rough surface for snowplows to catch and destroy. Where thermoplastic adhered properly, it goes thru winter better than paint and has good daytime appearance. Snowplows catch leading edge of dashed stripe. In view of blister formation in recent replacements on portland cement concrete, relegate thermoplastic use to bituminous surfaces or to only experimental use on portland cement concrete. Originally no difference found whether thermoplastic placed over well adhered paint or over unpainted bare portland cement concrete pavement. Later found better adhesion on new portland cement concrete without paint than on older pavement with paint. On Interstate 94 all thermoplastic lane lines replaced in 1 year. Pavement sandblasted and epoxy-primed, let dry over weekend, and epoxy-primed again immediately prior to thermoplastic application. Blistering occurred again in 1 week. Inconsistent results on different portland cement concrete sections.

Wyoming.—Good results with thermoplastic on bituminous pavement—durability ratio of at least 10:1 over paint on city street and 4:1 on highway. Consideration given to further use.

District of Columbia.—Thermoplastic life on bituminous pavement equal to eight or more paint applications. Plan to use for crosswalks whenever feasible.

Puerto Rico.—Better adhesion on bituminous pavement. Use bonding agent over portland cement concrete and apply thermoplastic immediately over primer. Not recommended for secondary roads, with low traffic volume, requiring painting only once a year.

Unsatisfactory results in December 1963 over portland cement concrete with epoxy primer. Replaced in January 1964 using Pliobond primer. In August 1967 only 30 percent of stripe intact, needed immediate repainting. Bonding is still a problem on portland cement concrete. New installations on portland cement concrete, Perma-Seal II epoxy primer used but too new to determine results.

Toll roads and bridges

Illinois State Toll Highway Commission.—Applied as a rumble stripe in advance of toll plaza. Subject to heavy snowplow activity. No experience with lane and edge lines.

New York Thruway Authority.—Thermoplastic gore markings began to fail within weeks, and in several months, thermoplastic was virtually gone. On lane lines, excellent to beginning of first winter and then plows completely removed it.

Port of New York Authority.—Generally use thermoplastic for lane lines if costs are equal or slightly higher than paint. Smaller additional cost justified by reduced interruption and delays to traffic.

Triborough Bridge and Tunnel Authority.—Painted line i more economical but thermoplastic line is more effective.

Cities and Counties

Atlanta, Ga.—On bituminous surface, cost of thermoplast on crosswalk are fully recovered and justified. Usually g eight times life of paint with thermoplastic. Don't us thermoplastic for center and lane lines except on streets wit high traffic density.

Baltimore, Md.—Thermoplastic gives superior performan compared to paint. Center and lane lines provide 2–3 yea durability where paint lasts less than 1 year. Use therm plastic for center and lane lines for downtown, expressway and freeways.

Detroit, Mich.—(Chrysler Freeway—also see Michig State Highway Department report)—On bituminous pav ment, thermoplastic in good condition after 2½ years. O portland cement concrete, thermoplastic poor compared performance on bituminous pavement. Initial chipping aft 3 months, loss increased progressively. Generally starts leading edge, caused by plows. In 3½ years on portlan cement concrete, chipping and failing badly. Costwis satisfactory in bituminous pavement but poor on portlan cement—major repairs needed in 18 months. Need improv ment for applications on portland cement concrete.

Los Angeles County.—Ordinarily use hand brooming clean, grinding to remove old paint, or sandblast to remo curing agent on fresh portland cement concrete. Yell thermoplastic showed excessive color deterioration, fad and inability to remain self-cleaning in relatively dry clima. Thermoplastic requires life of 6–8 years to compare econo cally with paint. However, because of road maintenan program, permit work and utilities repair, useful life thermoplastic is impractical beyond 4 years. With 4 ye wear, appearance of thermoplastic is generally poor.

New York, N.Y.—Some damage of thermoplastic snowplows but not significant. Costwise, thermoplas cheaper than paint in long run. Durability of thermoplas over paint is approximately 6:1. Thermoplastic also exhib safety advantages over paint.

Portland, Oreg.—Thermoplastic should be applied o newly surfaced roadways to get assurance of maximum Plan to use more thermoplastic on high-traffic-volu streets.

San Francisco, Calif.—Thermoplastic crosswalks chea than paint on medium- and high-traffic-density stre. Work is done in conjunction with resurfacing program.

NEW PUBLICATIONS

The Bureau of Public Roads has recently published two documents. These publications may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, prepaid. The following paragraphs give a brief description of each publication and its purchase price.

A Study of Airspace Utilization

A Study of Airspace Utilization (75 cents a copy) deals with the general question of airspace utilization over and under freeways. The publication was prepared as the final report of a research study to provide policy and procedure guidelines for the State of California Legislature, the California Division of Highways, the U.S. Bureau of Public Roads, city and county governments and others interested in air rights. The objectives of the study were to identify the major issues and problems connected with freeway air rights; to analyze these issues, including the procedural, legal, technical, financial, aesthetic, and policy aspects of air rights; and to recommend guidelines and design a course of action for the utilization of airspace in California.

Such questions as, "Why are these rights significant," "what uses are desirable" and "under what circumstances will the use of freeway airspace be successful," are answered in terms of the impact upon local communi s, the California Division of Highways, he Bureau of Public Roads, and the airspce developer.

Highway Statistics, 1967

Highway Statistics, 1967 ($1.75 a copy) is he 23d issue of the annual compilation of st is- tical and analytical tabular matter pertai n- to Federal aid for highways. This 196- ge publication presents information, prim il in tabular form, on motor fuel, motor veh e- driver licensing, highway-user taxation, St and local highway financing, road and s e mileage, and Federal aid for highways.

U.S. GOVERNMENT PRINTING OFFICE: 1969

PUBLICATIONS of the Bureau of Public Roads

A list of the more important articles in PUBLIC ROADS *and title heets for volumes 24–34 are available upon request addressed to ureau of Public Roads, Federal Highway Administration, U.S. epartment of Transportation, Washington, D.C. 20591.*

The following publications are sold by the Superintendent of ocuments, Government Printing Office, Washington, D.C. 20402. rders should be sent direct to the Superintendent of Documents. repayment is required.

ccidents on Main Rural Highways—Related to Speed, Driver, and Vehicle (1964). 35 cents.

ggregate Gradation for Highways: Simplification, Standardization, and Uniform Application, and A New Graphical Evaluation Chart (1962). 25 cents.

merica's Lifelines—Federal Aid for Highways (1966). 20 cents.

apacity Analysis Techniques for Design of Signalized Intersections (Reprint of August and October 1967 issues of PUBLIC ROADS, a Journal of Highway Research). 45 cents.

onstruction Safety Requirements, Federal Highway Projects (1967). 50 cents.

orrugated Metal Pipe Culverts (1966). 25 cents.

reating, Organizing, & Reporting Highway Needs Studies (Highway Planning Technical Report No. 1) (1963). 15 cents.

ederal-Aid Highway Map (42 x 65 inches) (1965). $1.50.

ederal Laws, Regulations, and Other Material Relating to Highways (1965). $1.50.

ederal Role in Highway Safety, House Document No. 93, 86th Cong., 1st sess. (1959). 60 cents.

reeways to Urban Development, A new concept for joint development (1966). 15 cents.

uidelines for Trip Generation Analysis (1967). 65 cents.

andbook on Highway Safety Design and Operating Practices (1968). 40 cents.

ighway Beautification Program. Senate Document No. 6, 90th Cong., 1st sess. (1967). 25 cents.

ighway Condemnation Law and Litigation in the United States (1968):

Vol. 1—A Survey and Critique. 70 cents.

Vol. 2—State by State Statistical Summary of Reported Highway Condemnation Cases from 1946 through 1961. $1.75.

ighway Cost Allocation Study: Supplementary Report, House Document No. 124, 89th Cong., 1st sess. (1965). $1.00.

ighway Finance 1921–62 (a statistical review by the Office of Planning, Highway Statistics Division) (1964). 15 cents.

ighway Planning Map Manual (1963). $1.00.

ighway Research and Development Studies. Using Federal-Aid Research and Planning Funds (1967). $1.00.

ighway Statistics (published annually since 1945):

1965, $1.00; 1966, $1.25; 1967, $1.75.

(Other years out of print.)

ighway Statistics, Summary to 1965 (1967). $1.25.

ighway Transportation Criteria in Zoning Law *and* Police Power and Planning Controls for Arterial Streets (1960). 35 cents.

ighways and Human Values (Annual Report for Bureau of Public Roads) (1966). 75 cents.

Supplement (1966). 25 cents.

ighways to Beauty (1966). 20 cents.

ighways and Economic and Social Changes (1964). $1.25.

ydraulic Engineering Circulars:

No. 5—Hydraulic Charts for the Selection of Highway Culverts (1965). 45 cents.

No. 10—Capacity Charts for the Hydraulic Design of Highway Culverts (1965). 65 cents.

No. 11—Use of Riprap for Bank Protection (1967). 40 cents.

Hydraulic Design Series:

No. 2—Peak Rates of Runoff From Small Watersheds (1961). 30 cents.

No. 3—Design Charts for Open-Channel Flow (1961). 70 cents.

No. 4—Design of Roadside Drainage Channels (1965). 40 cents.

Identification of Rock Types (revised edition, 1960). 20 cents.

Request from Bureau of Public Roads. Appendix, 70 cents.

The 1965 Interstate System Cost Estimate, House Document No. 42, 89th Cong., 1st sess. (1965). 20 cents.

Interstate System Route Log and Finder List (1963). 10 cents.

Labor Compliance Manual for Direct Federal and Federal-Aid Construction, 2d ed. (1965). $1.75.

Amendment No. 1 to above (1966). $1.00.

Landslide Investigations (1961). 30 cents.

Manual for Highway Severance Damage Studies (1961). $1.00.

Manual on Uniform Traffic Control Devices for Sheets and Highways (1961). $2.00.

Part V only of above—Traffic Controls for Highway Construction and Maintenance Operations (1961). 25 cents.

Maximum Desirable Dimensions and Weights of Vehicles Operated on the Federal-Aid Systems, House Document No. 354, 88th Cong. 2d sess. (1964). 45 cents.

Modal Split—Documentation of Nine Methods for Estimating Transit Usage (1966). 70 cents.

National Driver Register. A State Driver Records Exchange Service (1967). 25 cents.

Overtaking and Passing on Two-Lane Rural Highways—a Literature Review (1967). 20 cents.

Presplitting, A Controlled Blasting Technique for Rock Cuts (1966). 30 cents.

Proposed Program for Scenic Roads & Parkways (prepared for the President's Council on Recreation and Natural Beauty), 1966. $2.75.

Reinforced Concrete Bridge Members—Ultimate Design (1966). 35 cents.

Reinforced Concrete Pipe Culverts—Criteria for Structural Design and Installation (1963). 30 cents.

Road-User and Property Taxes on Selected Motor Vehicles (1964). 45 cents.

Role of Economic Studies in Urban Transportation Planning (1965). 45 cents.

The Role of Third Structure Taxes in the Highway User Tax Family (1968). $2.25.

Standard Alphabets for Highway Signs (1966). 30 cents.

Standard Land Use Coding Manual (1965). 50 cents.

Standard Plans for Highway Bridges:

Vol. I—Concrete Superstructures (1968). $1.25.

Vol. II—Structural Steel Superstructures (1968). $1.00.

Vol. IV—Typical Continuous Bridges (1962). $1.00.

Vol. V—Typical Pedestrian Bridges (1962). $1.75.

Standard Traffic Control Signs Chart (as defined in the Manual on Uniform Traffic Control Devices for Streets and Highways) 22 x 34, 20 cents—100 for $15.00. 11 x 17, 10 cents—100 for $5.00.

Study of Airspace Utilization (1968). 75 cents.

Traffic Assignment Manual (1964). $1.50.

Traffic Safety Services, Directory of National Organizations (1963). 15 cents.

Typical Plans for Retaining Walls (1967). 45 cents.