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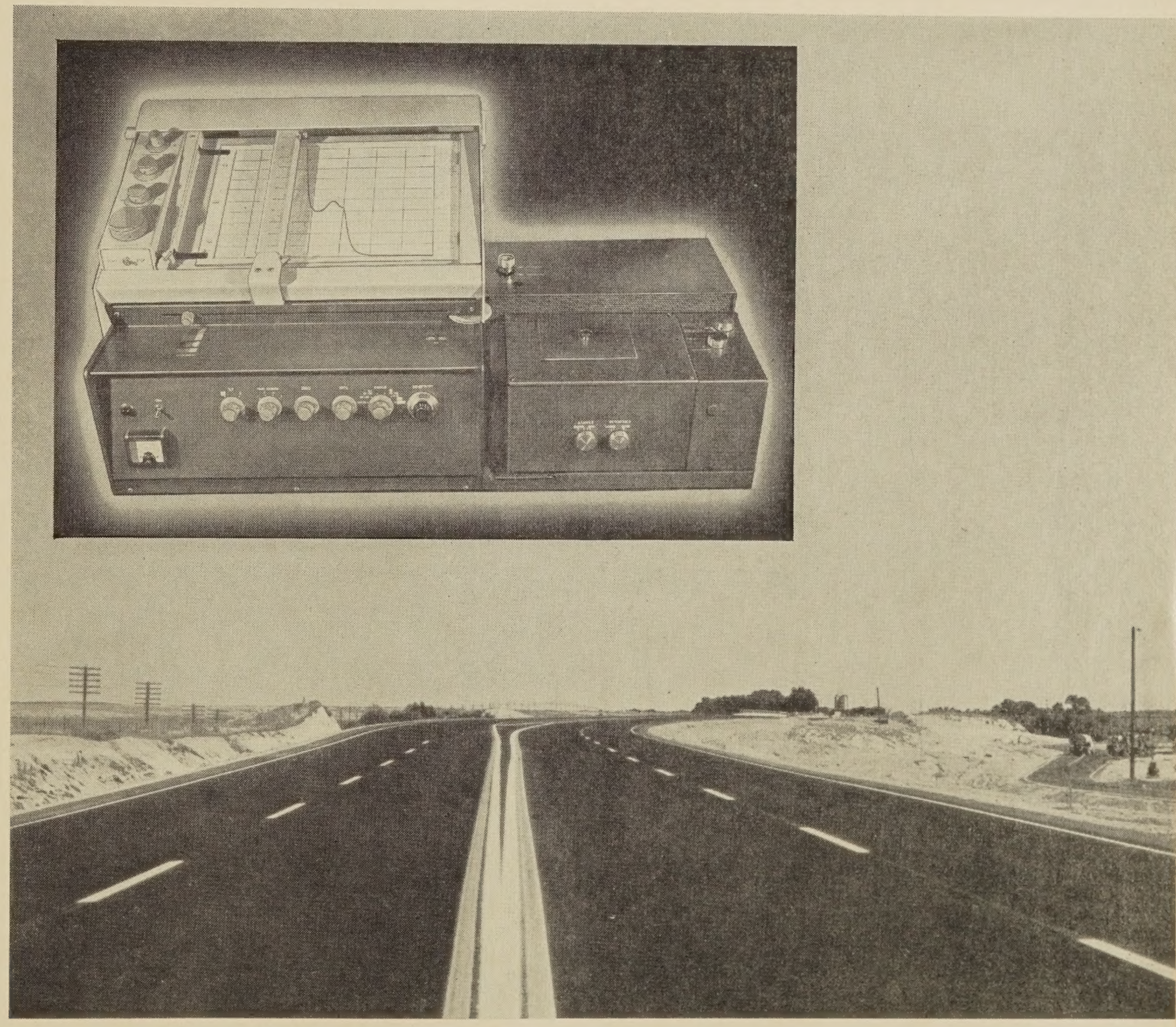

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Ultraviolet Spectrophotometric Detection of Adulteration in Traffic Paint Vehicles

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

Reported by[1] LEONARD BEAN, Research Chemist, and BERNARD CHAIKEN, Principal Research Chemist, Materials Division

Based on the materials investigated in a research study by the Bureau of Public Roads, an ultraviolet spectroscopic method for detecting adulteration of traffic paint vehicles in amounts as small as 2 to 5 percent by weight of the vehicle solids is reported herein. The method is applicable to the monitoring of purchased lots of traffic paint after a reference sample has been road tested and accepted for use. In the detection method used, the paint pigment is removed by centrifuging. A separate determination of nonvolatile solids is made by heating at 105° C. The solvents from a separate test sample are removed from a weighed sample of the vehicle by means of a rotating flask vacuum evaporator. A spectral grade of cyclohexane is used as a solvent to quantitatively prepare solutions of the vacuum dried vehicle solids, and the absorbances of the resultant solutions are measured in a double-beam recording ultraviolet spectrophotometer. The spectral curves and characteristics of the vehicle solids from both the reference and the purchased paints are compared to establish uniformity or evidence of adulteration. In the study reported here an alkyd resin was used as it is the most representative of traffic paint vehicles in use today. Plots of percentage of each adulterant—wood rosin, hydrocarbon resin, fish oil, and tall oil—against spectral absorbance at 264 nanometers (nm.) (or millimicrons) show the effect of the adulterant. About 4 hours are required for a single determination. Modifications of the method developed appear to have potential applicability to protective coatings in general, as well as to traffic paints, where composition is specified.

Introduction

APPROXIMATELY HALF of the State highway departments purchase traffic paints on the basis of extended road performance tests. When the best performing and most economical paint in terms of cost per useful day of service has been selected, it is essential that the paint delivered for actual use have the same composition as the test sample used in the road performance test. Many instances have been reported in which the delivered paint failed to have satisfactory durability or drying time. Adulteration of the delivered paint vehicle was found to be the cause. Consequently, State highway officials and reputable paint suppliers have been increasingly concerned about the problem of traffic paint adulteration. Unfortunately, detection of certain types of adulteration is difficult, tedious, and sometimes impossible when the classical chemical means normally available are used. Therefore, interest has increased in the development and use of rapid instrumental methods to detect adulteration of paint vehicles.

Adulteration of the paint pigment now can be quickly assessed by means of X-ray diffraction (*1*)[2] and the paint volatiles can be rather easily analyzed by infrared spectrometry. However, the detection of adulteration of the third major component of the paint, vehicle solids, is more difficult and is the basis for the study reported herein.

Applicability of Infrared Analysis and Other Methods

Infrared spectral analysis is a rapid and reliable way of detecting gross adulteration of the paint vehicle solids or the substitution of a completely different generic type of vehicle solid for the one in the test or reference sample. Representative infrared spectra of various generic types of vehicle constituents are available in the literature (*2, 3, 4*). These

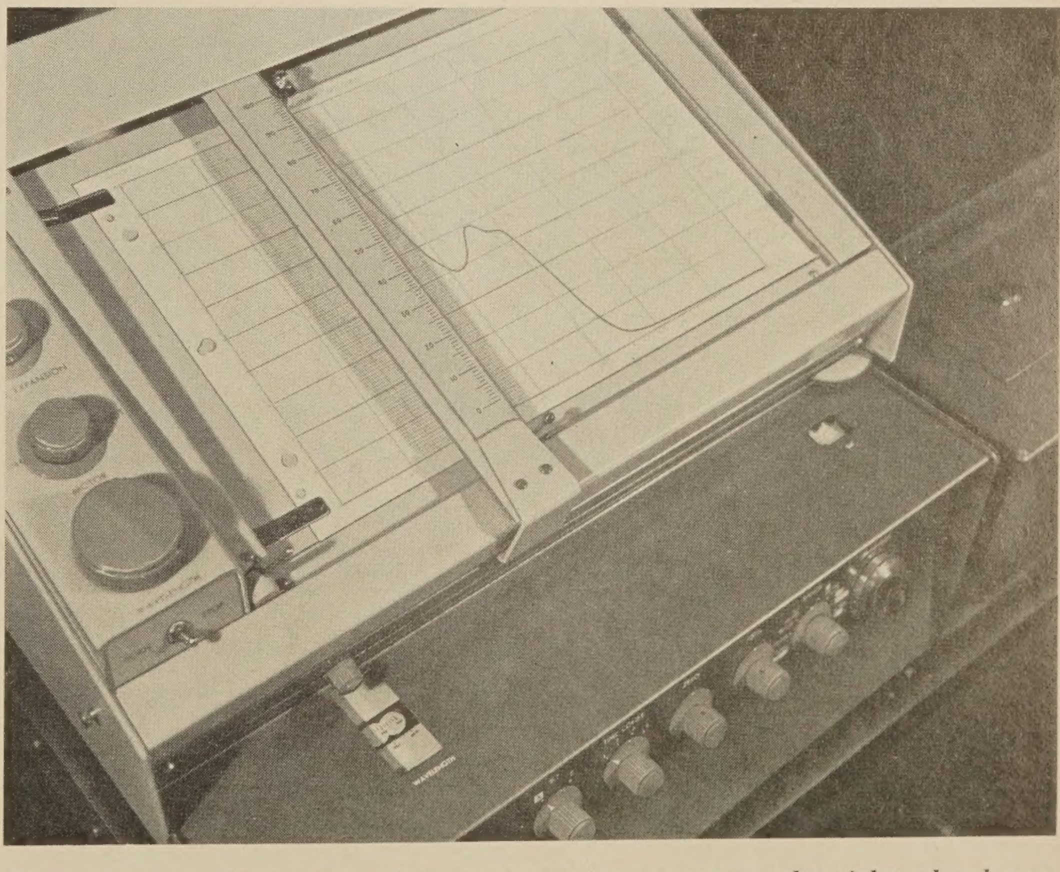

Figure 1.—Ultraviolet spectrophotometer used to measure ultraviolet absorbance.

[1] This article contains essentially the same material that was reported in *Materials, Research and Standards,* February 1967, published by the American Society for Testing and Materials.

[2] The italic numbers in parentheses indicate the references listed on p. 266.

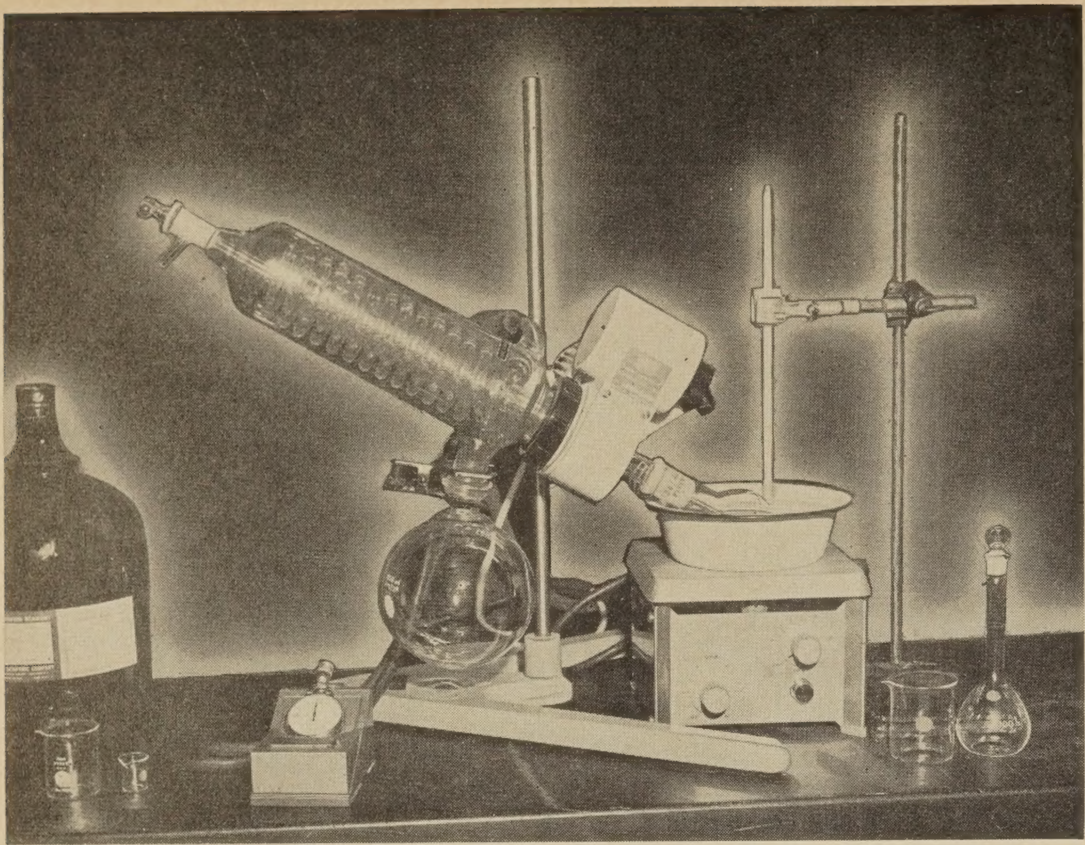

Figure 2.—Rotary-flask vacuum evaporator for removing solvents from paint vehicle solids.

spectra are usually adequate for identifying such adulteration or substitution. However, minor adulterations of some vehicle solids with less expensive raw materials such as fish oil, rosin, tall oil, and hydrocarbon resin are often difficult to detect by such means. These may and do have legitimate uses in some types of coatings. However, for the purpose of this study, they were considered adulterants in order to determine to what degree alien components could be detected in an alkyd paint vehicle. Recent cooperative investigations as yet unpublished by Subcommittee 44 on Traffic Paints of Committee D–1 of the American Society for Testing and Materials, have shown that additions of such extraneous substances to oil-alkyd paints, even up to the level of 20 percent by weight of the vehicle solids, cannot be clearly detected by infrared spectral analysis. Gas chromatography can be useful in detecting adulteration of the drying-oil portion of vehicle solids. However, the lengthy procedures required for gas chromatography and its limited application only to the drying-oil part of the vehicle solids indicated a need for other procedures for detecting adulteration in paint vehicles. As ultraviolet (UV) spectral analysis is known to be an extremely sensitive quantitative tool that rapidly reveals minor differences between organic substances, its potential was explored for detecting adulteration of vehicle solids commonly used in traffic paints.

In this study a comparison was made between UV spectral measurements of specially prepared solutions of alkyd resin containing no adulterants and spectral measurements of similar solutions containing known amounts of adulterants. A soya-alkyd resin was selected because it is a type of paint vehicle most frequently used by many State highway departments. Spectral absorbance curves of these solutions were obtained by means of a recording ultraviolet spectrophotometer.

Equipment and Materials

A recording double-beam ultraviolet spectrophotometer (see fig. 1) equipped with 1-centimeter matched silica cells was used to obtain spectral curves and measure the UV absorbance. The light source was a hydrogen discharge lamp and the detector was a photomultiplier tube. A rotary-flask vacuum evaporator of the type shown in figure 2 was used for removing the solvents from the vehicle solids.

Materials used in the study are identified as follows:

- *Alkyd resin solution.*—A 1-gallon sample of a medium oil length soya-alkyd resin having the following specification description: Acid value, 4–10 (solid basis); color (Gardner), 9 maximum; Stoke viscosity, 5.5 to 8.8; viscosity (Gardner-Holdt), T to V; solids, 49 to 51 percent; average weight per gallon, 7.60 pounds.
- *Wood rosin.*
- *Hydrocarbon resin.*
- *Fish Oil.*—A sample of liquid material labeled, *Product, Light Cold Pressed Fish* having the following specification description: Acid value, 8 maximum; color (Gardner), 12 maximum; cold test, 2 hours at 32° F., clear; average weight per gallon, 7.69 pounds.
- *Tall oil.*
- *Spectral grade cyclohexane.*

Experimental Procedure

In some preliminary experiments the pigment from an oil alkyd paint was removed by centrifuging. Total nonvolatile solids were determined by heating for several hours at

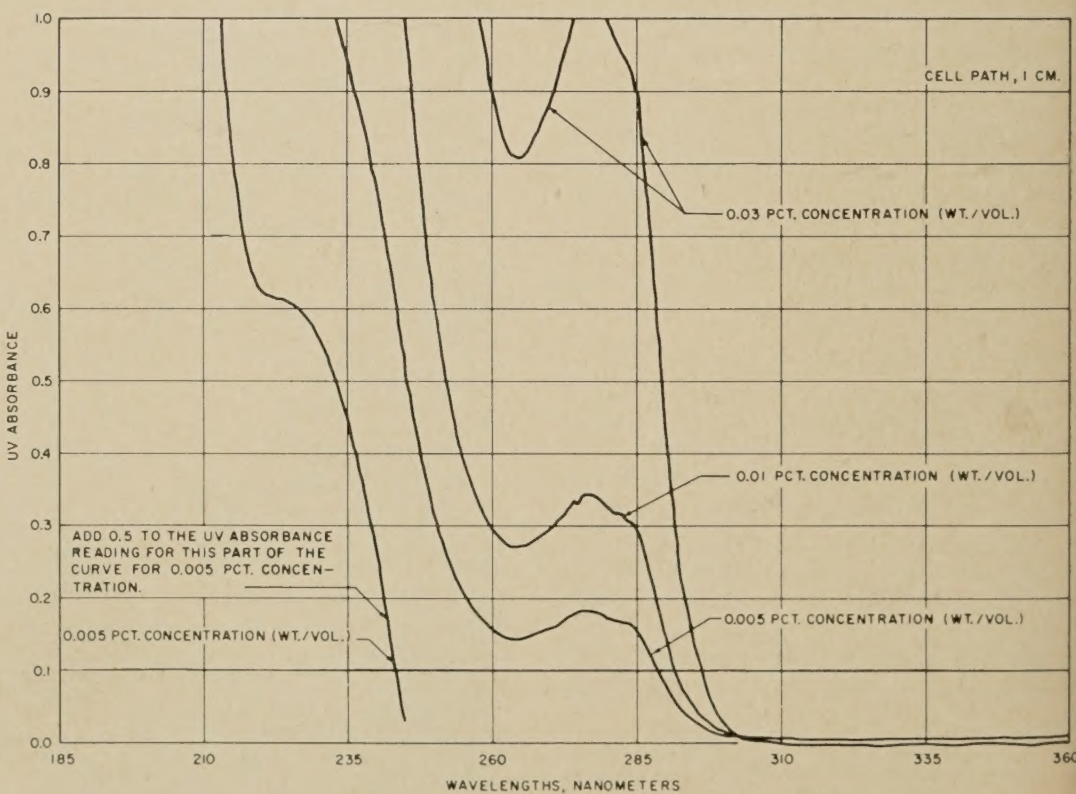

Figure 3.—Ultraviolet absorbance curves for different concentrations of alkyd resin solutions in cyclohexane.

105° C. The residue after heating under these conditions was not suitable for ultraviolet absorbance measurements. As would be expected, the heat treatment and exposure to air had polymerized the material so that its re-solution was difficult in any usable spectral grade solvent. Also, the polymerization caused the UV absorption characteristics of the material to change considerably, and the amount of change varied in relation to the extent of heating. Some attempts were made to remove the volatile solvents from the vehicle by heating it at 60° C. in a bell jar under an inert atmosphere of carbon dioxide. The resultant spectral pattern varied with time of heating and was not repeatable to a satisfactory extent. Therefore, the use of a rotary-flask vacuum evaporator was investigated. Evaporation under vacuum of approximately 560 mm. of mercury for 20 minutes with the rotating flask partially immersed in a water bath maintained at a temperature of 56° to 60° C. gave resultant vehicle solids that were soluble in cyclohexane and had repeatable ultraviolet absorption characteristics suitable for quantitative purposes. Absorbance measurements on a solution of alkyd resin in cyclohexane made immediately after its preparation and after the solution had stood for 1 week showed no evidence of appreciable change or precipitation of the resin from solution.

Several different spectral grade solvents were evaluated. Some compromise had to be made between the dissolving power of the solvent for the dried test resin, and the solvent's UV absorbance characteristics from 210 to 360 nm., the range studied. Spectroanalyzed cyclohexane was selected for the work reported here. Although 20 percent of the wood rosin remained insoluble in cyclohexane, this solvent completely dissolved the other materials studied. Methanol dissolved all the wood rosin but it did not dissolve the alkyd resin and, therefore, was not applicable. Absorbance characteristics of the cyclohexane from 210 to 360 nm. were excellent. Other solvents tried were *p*-dioxane, *n*-butyl alcohol, isobutyl alcohol, *n*-heptane, acetonitrile, *n*-hexane, isopropanol, glycerine, and tetrahydrofuran. Only tetrahydrofuran completely dissolved all the materials studied. However, tetrahydrofuran usually contains hydroquinone or other substances that have been added to inhibit its oxidation. UV measurements made with this solvent indicated that either the tetrahydrofuran or the inhibitors were reacting with the dissolved alkyd resin, thereby affecting the spectral characteristics. When such solutions were allowed to stand, substantial changes occurred in UV absorbance.

After these preliminary experiments, a study was made of the repeatability of the results from the procedure tentatively selected. For these tests a portion of the alkyd resin solution was weighed, the volatile solvents in the sample were removed by evaporation under inert conditions in a rotating-flask vacuum evaporator, and the alkyd resin was redissolved in spectral grade cyclohexane. This solution was transferred to a volumetric flask; appropriate aliquots of this solution were taken to prepare solutions containing 0.03, 0.01, 0.005, and 0.001 percent concentrations of dry alkyd resin. For the purpose of this report, the percent concentration means the weight of solute per 100 ml. of solution; for example, a 0.03 percent solution means 0.03 grams of solids in 100 ml. solution. The UV absorbances for the various solutions containing different concentrations of alkyd resins were measured. Typical absorption patterns are shown in figure 3. The peak at 276 nm. is reported to be caused by phthalic acid (*5*). Within a 12-day period, eight replicate runs were made. The absorbances obtained at 276 nm. for 0.03, 0.01, and 0.005 percent solution concentrations of the alkyd resin in cyclohexane are given in table 1. Replicate ab-

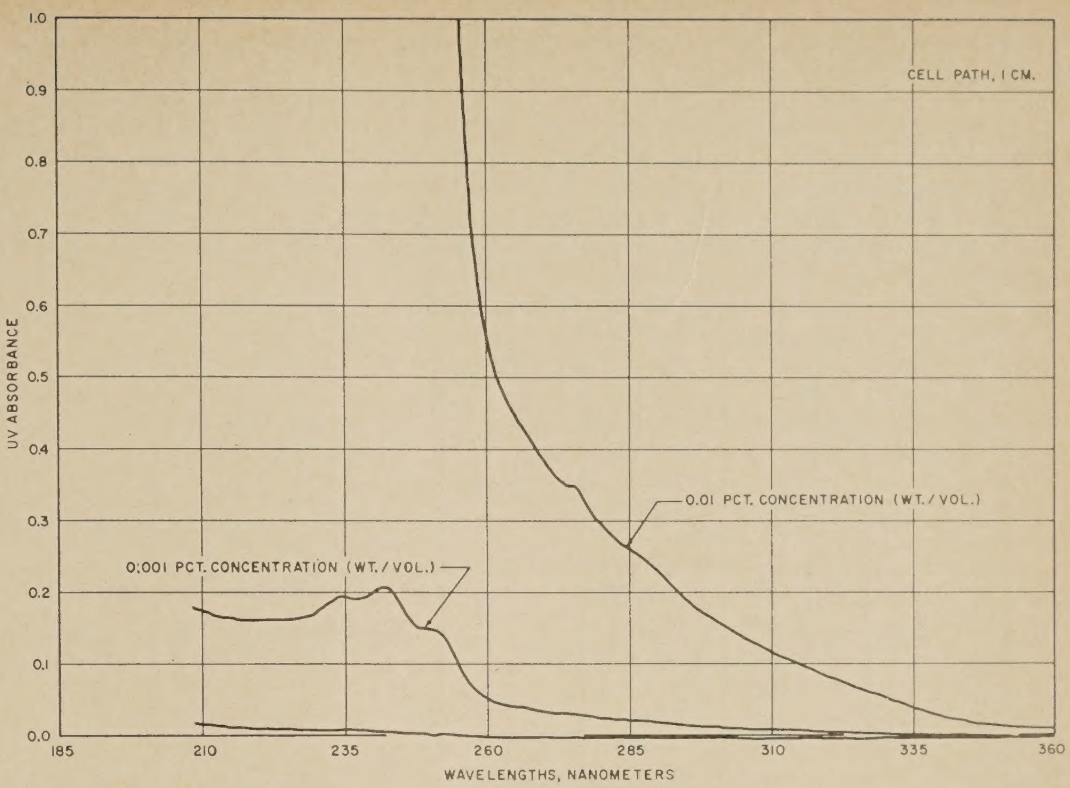

Figure 4.—Ultraviolet absorbance curves for different concentrations of wood rosin in cyclohexane.

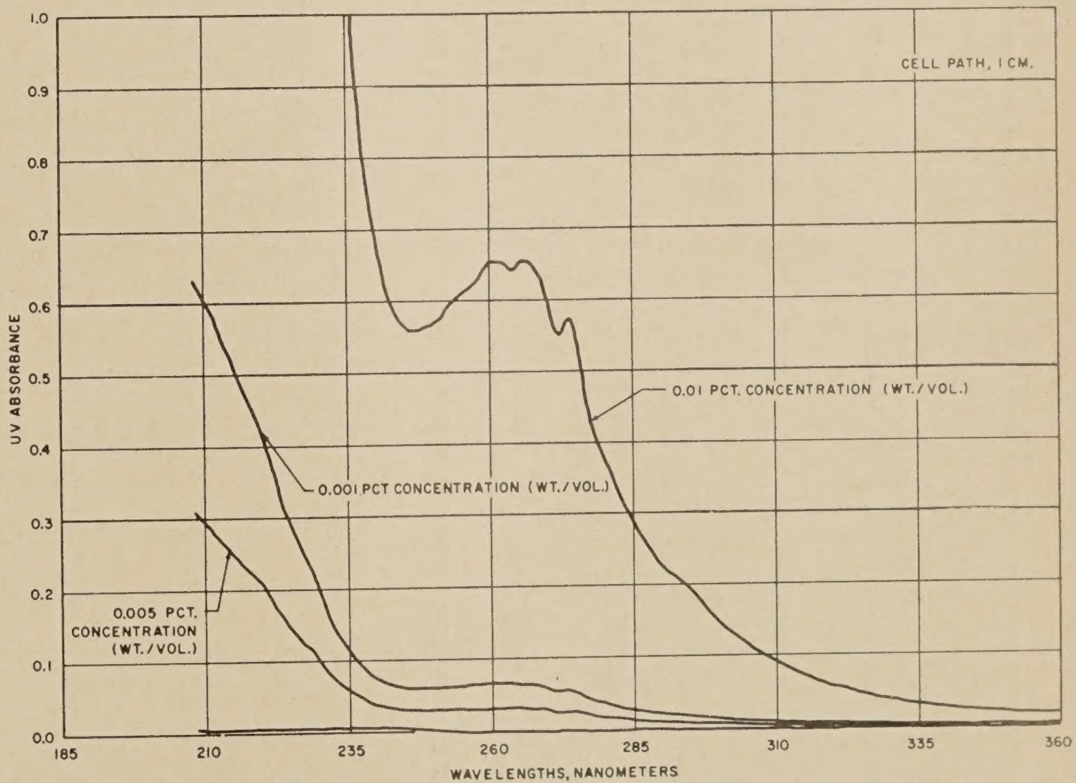

Figure 5.—Ultraviolet absorbance curves for different concentrations of hydrocarbon resin in cyclohexane.

sorbances obtained at 264 and 225 nm. are also given. In the spectrum of alkyd resin, a spectral trough occurs at 264 nm. and a shoulder occurs at 225 nm.

The calculated average, range, standard deviation, and coefficient of variation in the absorbance values for each of the wavelengths and concentrations studied are also given in table 1. Based on the results at 276 nm., the relative spectral repeatability was somewhat better for solutions containing the greater amount of resin.

After the absorbance patterns of the unadulterated alkyd resin solutions had been established, absorbance patterns were made of cyclohexane solutions of the adulterants to be used: wood rosin, hydrocarbon resin, fish oil, and tall oil. These patterns are shown in figures 4, 5, 6, and 7. It must be remembered that part of the wood rosin would not dissolve in cyclohexane. Consequently, solutions of wood rosin in cyclohexane were prepared and filtered through a bed of glass wool in order to remove the insoluble fraction before the stock solution was prepared, and the procedure of taking aliquot parts of the solution and measuring absorbances was continued. Glass wool was used as a filter because cyclohexane washed through ashless filter paper gave a definite ultraviolet absorption pattern.

By using a light box and superimposing the recorded spectral pattern of each adulterant over the pattern of the alkyd resin, and keeping in mind any differences in concentrations, a good idea of the effect of each of the adulterants on the resulting pattern of an alkyd resin-adulterant mixture could be obtained. Always, the overall spectral characteristics of each of the adulterants differed substantially from the alkyd resin and, therefore, an ultraviolet spectral approach to detecting alkyd resin adulteration seemed assured. The questions were then: How small an amount of adulterant could be detected, and how could quantitative measurements be made? A decision was made to focus upon the extent to which the alkyd resin absorbance peak at 276 nm., or its absorbance trough at 264 nm., would be changed by added increments of adulterant. These wavelengths were selected because sharp spectral peaks or troughs lend themselves more readily to quantitative treatment.

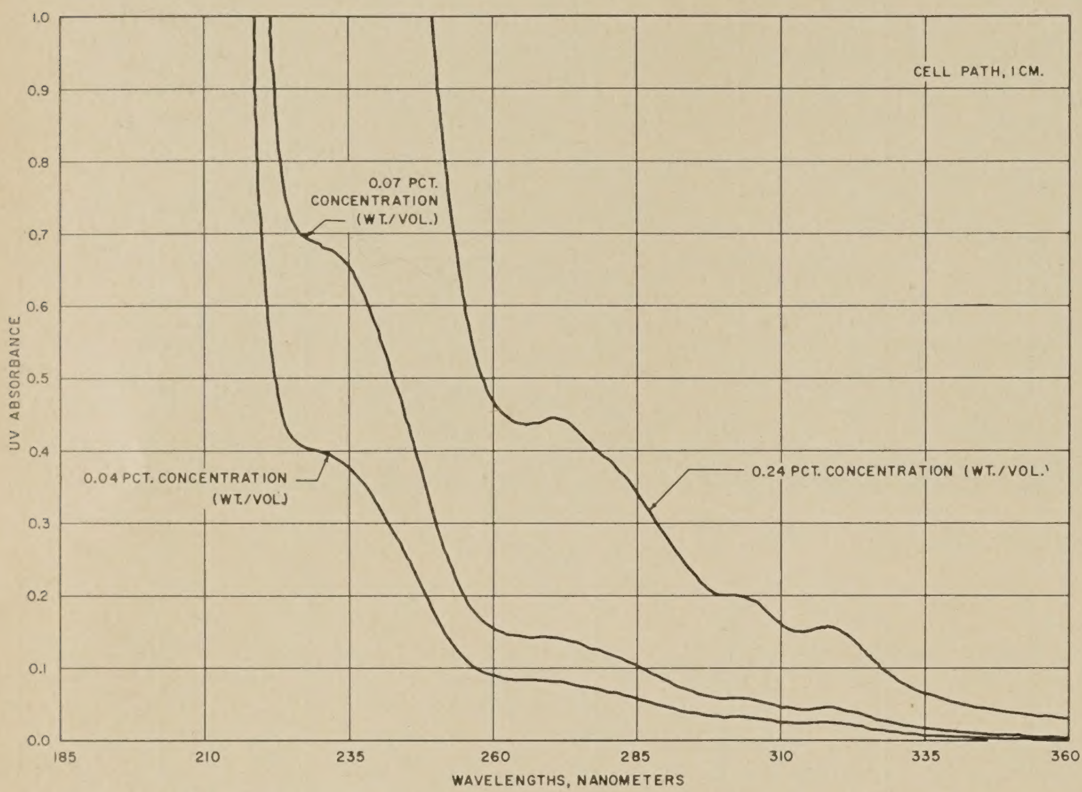

Figure 6.—Ultraviolet absorbance curves for different concentrations of fish oil in cyclohexane.

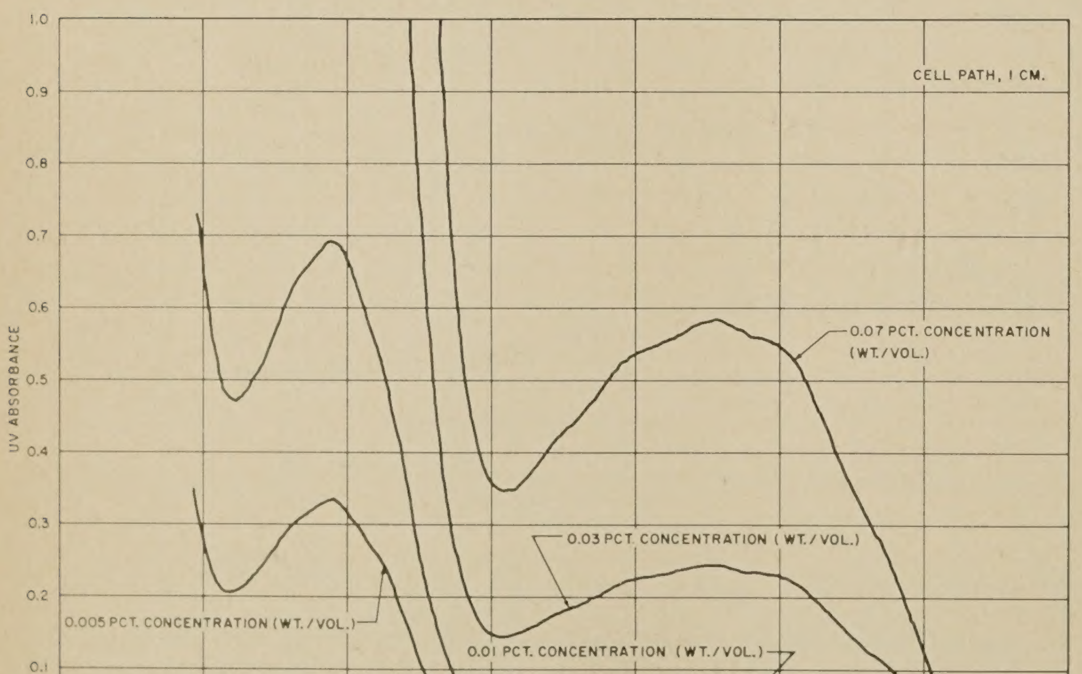

Figure 7.—Ultraviolet absorbance curves for different concentrations of tall oil in cyclohexane.

Effect of adulterants

From the comparison of the spectral patterns, it appeared that the effect of each of the adulterants studied would be to alter the alkyd resin absorbance at its trough at 264 nm., but the absorbance at its peak at 276 nm. would not always be altered. For example, the absorbance of wood rosin coincided almost exactly with the absorbance of the alkyd resin at its 276-nm. peak when the same concentrations were used. Referring to wood rosin in figure 4, the peak at 241 nm. is attributed to abietic acid, the shoulder at 250 nm. is attributed to isoabietic acid, and the shoulder at 276 nm. is attributed to dehydroabietic acid (*6*). The shoulder at 276 nm. coincides with the reported peak of phthalic acid in the alkyd resin (*5*). Therefore the alkyd resin absorbance *trough* at 264 nm., rather than the adjacent peak was used in order to preclude the possibility of permitting wood rosin adulteration to go undetected.

Sample preparation

Solutions of adulterated alkyd resin paint vehicles were prepared so that the vehicle solids part contained 5, 10, and 20 percent each of wood rosin, hydrocarbon resin, fish oil, and tall oil. Total nonvolatile solids content of each adulterated solution was determined by heating samples at 105° C.

Separate samples of the adulterated solutions were weighed and heated in the rotating flask evaporator under line vacuum to remove the solvent in the test sample. The resultant solids were redissolved in cyclohexane, and solutions containing 0.03, 0.01, 0.005, and

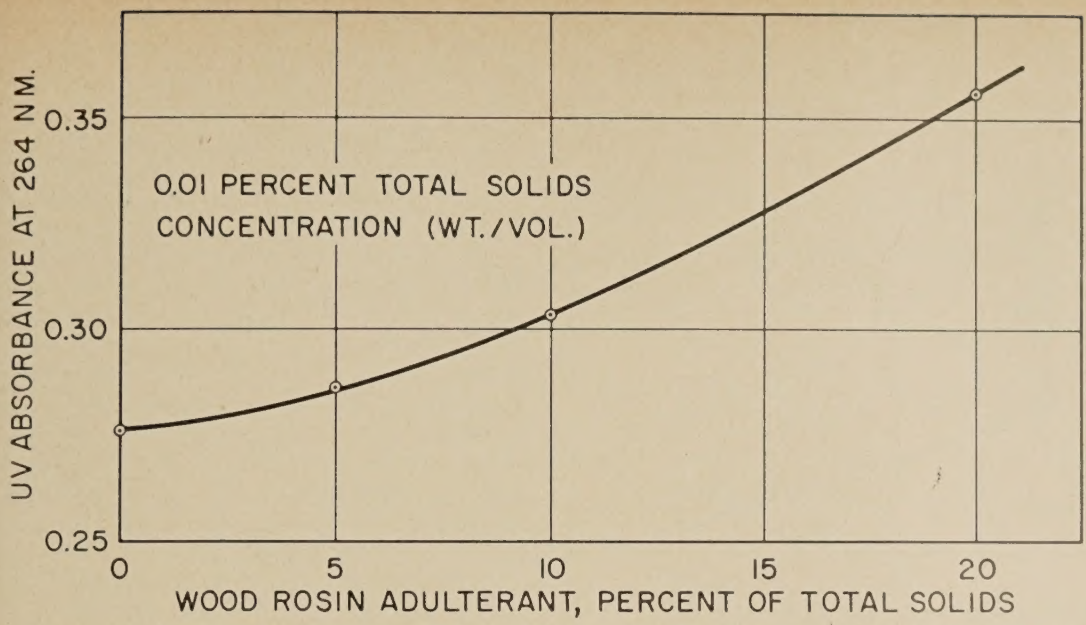

Figure 8.—Effect of wood rosin adulteration of alkyd resin on its UV absorbance.

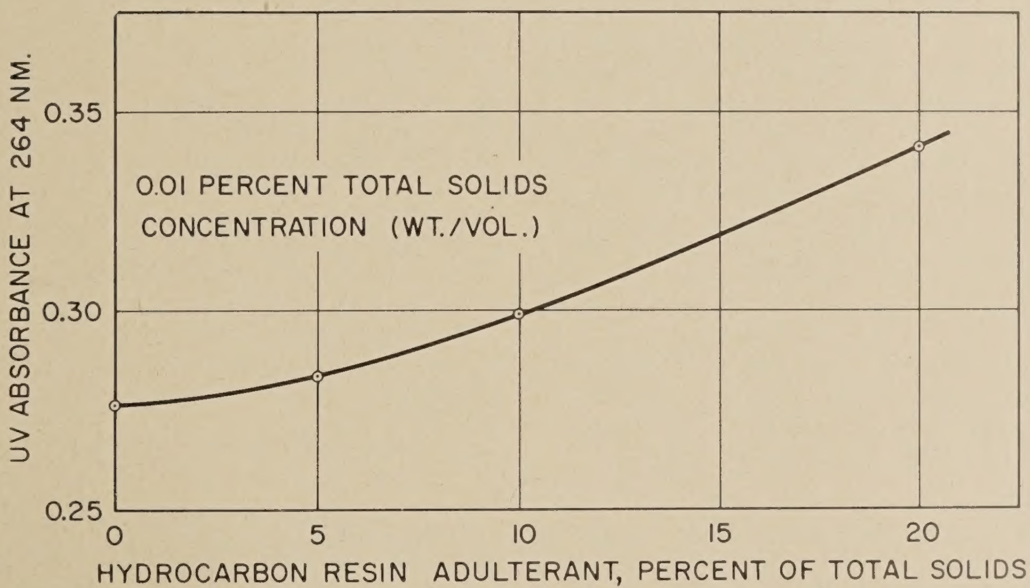

Figure 9.—Effect of hydrocarbon resin adulteration of alkyd resin on its UV absorbance.

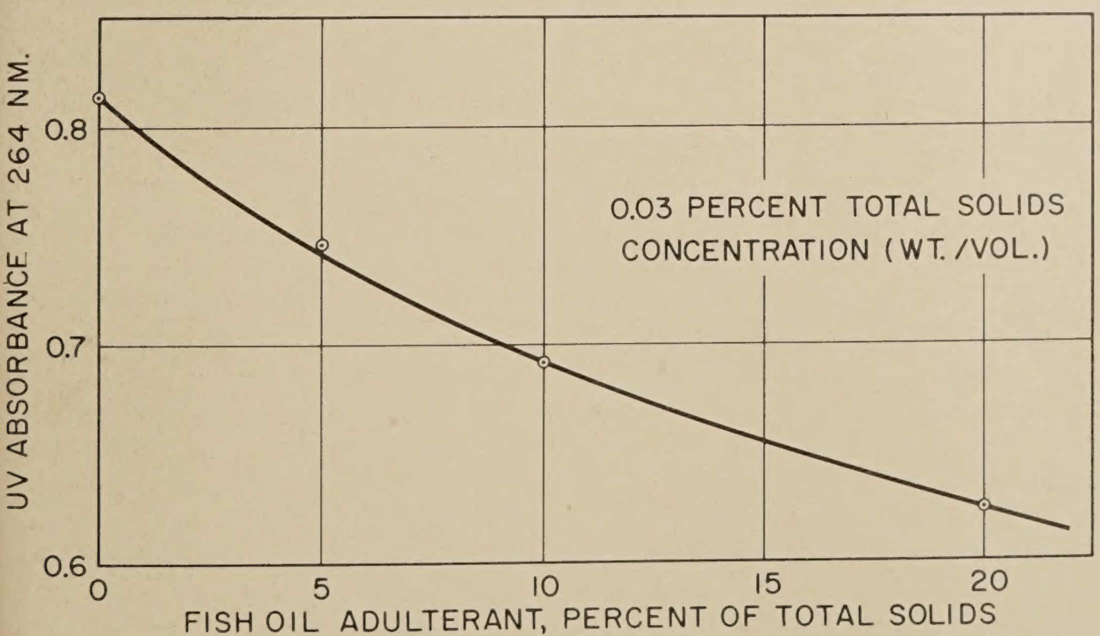

Figure 10.—Effect of fish oil adulteration of alkyd resin on its UV absorbance.

0.001 percent concentrations of nonvolatile solids were prepared by taking aliquot parts. UV absorbance measurements for each of the solutions were then made.

The effects of each added adulterant on the absorbance of the alkyd resin at the 264-nm. trough are shown in figures 8, 9, 10, and 11. Each of the points shown was obtained from a single determination. The superimposed patterns of 0.03 percent concentrations of the alkyd resin mixed to contain 0, 5, 10, and 20 percent fish oil respectively, on the basis of vehicle solids, are shown in figure 12 for the spectral area near 264 nm.

Four runs were made on the alkyd resin sample that had been mixed with 10 percent tall oil to check further the repeatability of the method. For a total solids concentration of 0.03 percent, a coefficient of variation of 1.35 percent was obtained. This is within the repeatability previously obtained from eight runs on the unadulterated alkyd resin at the same total concentration and wavelength.

From consideration of the results obtained on the adulterated samples with the calculated variability for unadulterated alkyd resin as given in table 1, minor adulteration of alkyd resins can be expected to be detected by ultraviolet spectroscopy. Allowing for a 2-sigma deviation within any single set of determinations at a single wavelength of 264 nm. (for the reference paint vehicle and test paint vehicle) the following levels of adulteration should be detectable at a 95 percent confidence level: tall oil, 2 percent; fish oil, 2 percent; wood rosin, 5 percent; and hydrocarbon resin, 5 percent. These detection limits, especially for wood rosin and hydrocarbon resin, can be reduced considerably by spectral changes at other wavelengths. For example, for wood rosin and hydrocarbon resin, large spectral differences exist between each of these materials and the pure alkyd resin in the area of 210 to 235 nm. (figs. 3, 4, and 5). By judicious use of these spectral differences and other parts of the spectrum, the detection limits for adulteration can be reduced considerably.

Figures 8 through 11 show that adulteration with wood rosin or hydrocarbon resin increases the absorbance of the alkyd resin trough at 264 nm., and the presence of fish oil or tall oil reduces the absorbance value at that same wavelength. Presumably, a combination of two adulterants could be calculated and added to alkyd resin so that UV absorbance measurements at only one wavelength might not be sufficient to show that adulteration had occurred, if conclusions were based on this characteristic only. However, as previously stated, a comparison of the entire curves of reference and test materials provides qualitative information that helps to identify such a combination of adulterants. For example, an appreciable spectral difference was noted in the curves for 0.005 percent solutions of each of the following: pure alkyd resin, alkyd resin mixed with 10 percent tall oil, and alkyd resin mixed with 10 percent wood rosin.

The unadulterated alkyd resin curve reached an absorbance of 1 at about 233 nm. while the curve for 90 percent alkyd resin and 10 percent

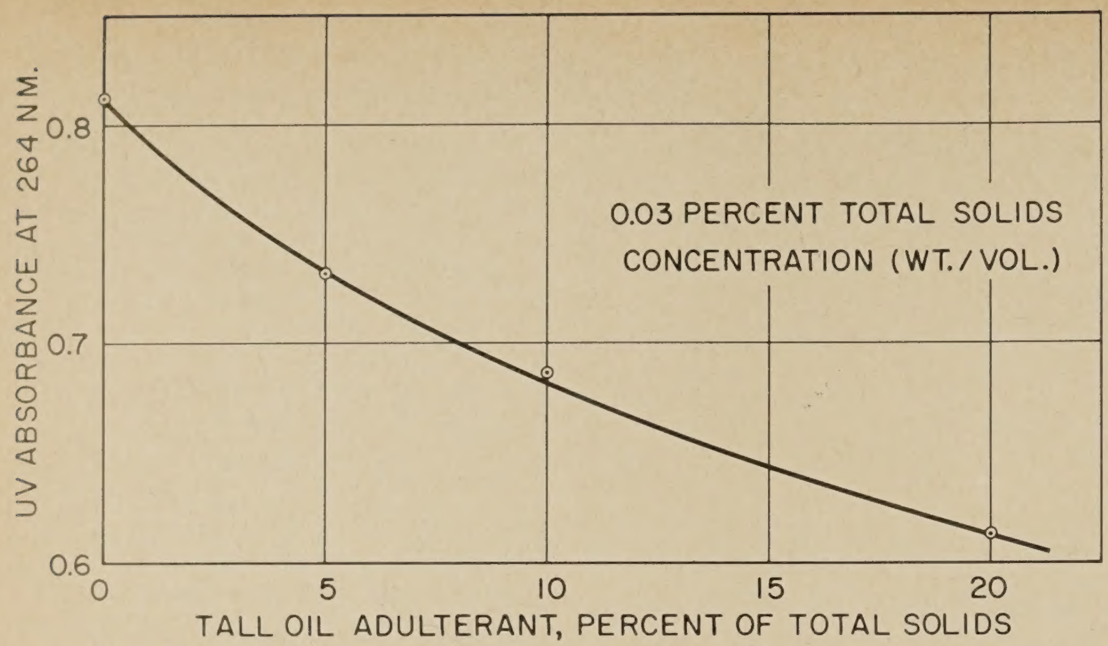

Figure 11.—Effect of tall oil adulteration of alkyd resin on its UV absorbance.

wood rosin reached an absorbance of 1 at 231 nm. In contrast, alkyd resin with 10 percent tall oil, reached this absorbance between 216 and 223 nm. in the case of the four runs made in this adulteration. Presumably, sophisticated adulteration with a combination of tall oil and wood rosin could be detected from a significant wavelength shift of the spectral curve where it reaches the higher absorbance values.

Because of the time required to conduct the study, the stability of the test resin on storage was of interest. Tests showed that a small change in absorbance characteristics of the unadulterated alkyd resin had occurred after a 3-month period. A slightly greater change occurred in the solution of alkyd resin, as obtained from the manufacturer, that was left in a clear glass jar exposed to the light of the laboratory than occurred in the main supply of the resin that had been stored in a gallon container in a dark cabinet. The absorbance of the trough at 264 nm. did not change as much on storage as did the peak at 276 nm. Refrigerated storage in a full container under a blanket of inert gas, such as nitrogen, would prevent such changes.

The protection afforded by the inert atmosphere was demonstrated by tests in which part of the solution of alkyd resin used in the study reported here was stored under an atmosphere of nitrogen for 50 days in a refrigerator. The procedure recommended subsequently was used on samples taken before and after the 50-day storage period. Absorbances for 0.03 percent solutions at 276 and 264 nm. differed by 0.000 and 0.005 absorbance unit, which is well within one standard deviation for replicate tests as given in table 1.

Recommended Procedure

The recommended procedure for determining whether a paint vehicle has been adulterated is described in the following paragraphs.

Remove the pigment from the paint by centrifuging and place the separated vehicle in a well-stoppered amber bottle. Determine the nonvolatile solids content of the vehicle by the procedure described in method 4041 of Federal Test Method Standard No. 141 (*7*). Weigh by difference in the following manner: Pour several grams of paint vehicle into a small screw-cap dropping bottle equipped with a medicine dropper. Weigh the sealed bottle and contents. Transfer about 1 gram of the vehicle to a weighed aluminum dish, quickly replace the cap, and reweigh the dropping bottle. Avoid sucking the vehicle up into the rubber bulb of the dropper.

Heat a water bath of appropriate size on a variable-control hotplate to a temperature of 56° to 60° C. Weigh by difference from a dropping bottle, a sufficient amount of the paint vehicle to provide about 0.4 gram of nonvolatile solids into a 100-ml. standard-taper, round-bottom Pyrex flask. Stopper the flask immediately.

Set up a rotary-flask evaporator without any lubrication on any of the ground glass joints. The rubber O-ring occasionally needs to be lubricated with a few drops of high-vacuum pump oil. Provide water connections to cool the condenser. Connect the outer jacket with pressure tubing to the stopcock of an unopened vacuum line. Remove the stopper from the flask and attach the flask to the evaporator; hold it in place with the clip provided. Close the glass stopcock at the top of the evaporator. Turn on the vacuum connection and start the rotation of the flask. A vacuum of about 560 mm. of mercury, or more, is satisfactory (absolute pressure of 200 mm., of mercury or less). Place the water bath and hotplate under the flask. Lower the flask until it is about one-half immersed in the water but so that it does not scrape the bottom of the water bath. Start timing at this point; keep the temperature of the bath between 56° and 60° C. If the temperature reaches 60° C. it can be reduced quickly by pouring in a little cold water.

At the conclusion of 20 minutes all of the solvent from the test sample should be evaporated. Then dissolve the dried alkyd resin in cyclohexane. A convenient way to do this is to pour approximately 45 ml. of spectral grade cyclohexane into a 50-ml. beaker and transfer about 4.5 ml. of this into a 5-ml. beaker. At this point turn off the vacuum, remove the pressure tubing from the vacuum line, and

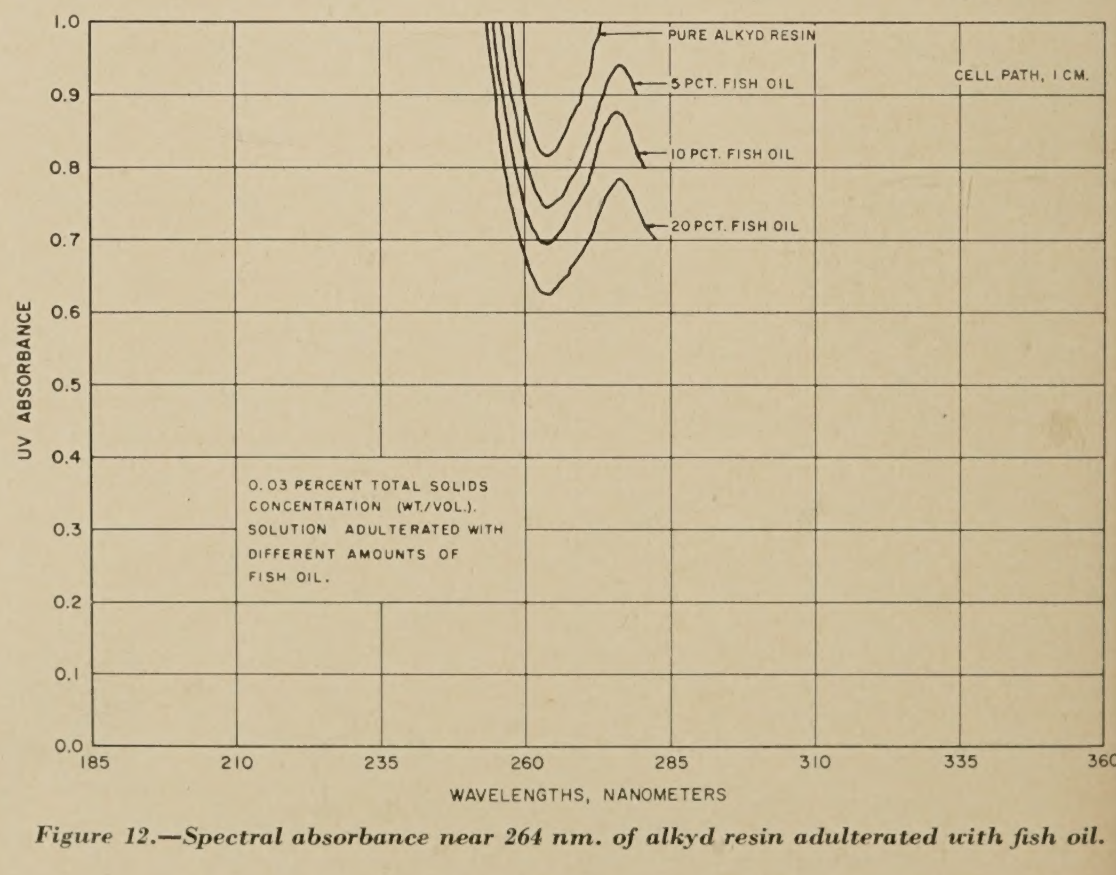

Figure 12.—Spectral absorbance near 264 nm. of alkyd resin adulterated with fish oil.

then reopen the vacuum line. Immediately turn the top ground glass stopcock of the evaporator so that it is open to the air. Hold the 5-ml. beaker under the glass inlet tube and with the other hand push the end of the pressure tubing up against the vacuum-line stopcock opening. This causes the cyclohexane in the 5-ml. beaker to be sucked through the center glass tube and into the evaporating flask. Repeat this procedure until the contents of the 50-ml. beaker have been transferred to the evaporating flask. Then close the ground glass stopcock at the top of the evaporator. Shut off the vacuum line stopcock and leave the pressure tubing disconnected. Continue rotating the flask in the water for 5 minutes to effect complete solution of the residue in the flask. Any convenient procedure for admitting the cyclohexane is acceptable as long as the dried resin is kept under inert conditions insofar as possible.

At the conclusion of the 5-minute period, raise the evaporator so that the water bath and hotplate can be removed. Dry the flask, stop the rotation, and lift the center tube of the evaporator so that it no longer protrudes into the flask. Carefully remove the flask and its contents.

Quantitatively transfer the contents of the flask to a 100-ml. volumetric flask; rinse the evaporator flask well with cyclohexane and collect the rinsings. Repeat the washir g procedure until the contents of the volumetric flask are slightly below the mark. After the flask has stood a few minutes and cooled to room temperature, carefully add cyclohexane to the volumetric flask until the contents reach the 100-ml. mark. Make final adjustments dropwise by means of a small pipet—do not use a rubber bulb on the pipet. Mix the contents of the volumetric flask thoroughly.

From this stock solution, appropriate concentrations can be made by putting aliquot parts into 25-ml. volumetric flasks and diluting these to the mark. A convenient equation to use in calculating the milliliters of aliquot to be taken is given in the following example. To make a 0.03 percent solution use:

$$\frac{0.03 \times 25}{\text{Weight of sample} \times \text{nonvolatile fraction}} = \text{milliliters of stock solution}$$

For other concentrations, substitute the percent of concentration desired for the figure 0.03. A 2-ml. pipet graduated to 0.01 ml. is convenient for transferring. To prepare a solution as dilute as 0.001 percent, it is advisable to transfer a 2.50-ml. aliquot of a 0.01 percent solution to a 25-ml. volumetric flask and dilute to the mark. It is well to estimate to the nearest 0.001 ml. when using the pipet in order to insure an accuracy in measurement of about one part in 100.

Obtain absorbance curves with the spectrophotometer using a scanning rate of about 20 nanometers per minute. Before each run, establish a baseline that shows the relative absorbances of the two cells containing only cyclohexane. This procedure provides evidence of cleanliness of cells and how well they are matched. In the work reported here, the alkyd resin coating on the cells could not be removed completely with any of the organic solvents or detergents that were tried. The cells, therefore, were cleaned by immersing them in freshly prepared chromic acid cleaning solution after each day's use (30-ml. beakers were used). After being rinsed thoroughly with distilled water, the cells were dried at 105° C. The instructions for operating the spectrophotometer are contained in the instruction manual provided by the manufacturer of the instrument (*8*).

A convenient method for pouring solutions into the 1-centimeter ultraviolet cells is to transfer about 3 ml. of each solution into a 5-ml. beaker and then to the cell. After the absorbance has been measured, if the solution to be discarded is poured out of the cell, it tends to run over the clear outside surface. Wiping or washing these sides during a test leaves them in such a condition as to cast doubt on subsequent absorbance measurements. This difficulty can be avoided in the following manner: Pull out a length of glass tubing to a small diameter and fire polish at both ends. Connect the tubing to a vacuum line through a safety flask. With the vacuum turned on, the smaller diameter part of the bent tube is very effective in removing solutions from the cells. Lower the tube down one of the frosted sides of the cell but do not allow it to touch the clear-glass windows through which the ultraviolet radiation passes.

Use this described procedure on the original road test sample of traffic paint submitted and on samples from the purchased lots of paint. It is desirable that the final spectral test solution be such that the more pronounced spectral peaks and troughs will occur at absorbance values near or below 1. The purchaser can be assured that the purchased paint vehicle has not been adulterated if the following criteria are met: (1) The pronounced spectral peaks and troughs for identical concentrations and wavelengths are within 2 to 3 parts in 100 of the same absorbance value. (2) Qualitative examination of the ultraviolet absorption patterns indicates the comparison spectrum is not shifted significantly in wavelength or otherwise different. If these criteria are not met, it can be assumed that the purchased lot has been adulterated. It is possible to complete the solvent removal and obtain the patterns for two determinations within an 8-hour day, including time required for cleanup.

Table 1.—Repeatability of absorbance measurements made on alkyd resin solution [1]

Absorbance measurements	at 276 nm.			at 264 nm.		at 225 nm.
Concentration, percent [2]	0.03	0.01	0.005	0.03	0.01	0.005
Replicate runs:						
1	1.055	0.353	0.172	0.818	0.276	1.058
2	1.043	0.347	0.174	0.805	0.270	1.069
3	1.032	0.345	0.176	0.798	0.267	1.063
4	1.046	0.350	0.175	0.812	0.274	1.068
5	1.033	0.345	0.186	0.798	0.271	1.094
6	1.017	0.338	0.167	0.781	0.264	1.011
7	1.016	0.337	0.172	0.782	0.263	1.047
8	1.015	0.334	0.168	0.786	0.263	1.039
Average	1.032	0.344	0.174	0.798	0.268	1.056
Range	0.040	0.019	0.019	0.037	0.013	0.083
Standard deviation	0.014	0.007	0.006	0.014	0.005	0.023
Coefficient of variation, percent	1.35	2.04	3.44	1.75	1.87	2.18

[1] In spectral grade cyclohexane using a 1-cm. cell.
[2] Weight per volume basis of alkyd resin in solution.

Conclusions and Applications

From the results obtained in the research reported here, it is concluded that the adulteration of traffic paint vehicle solids can be detected by the absorption of ultraviolet radiation in the range 210 to 360 nm. A rotating-flask evaporator operating under line vacuum of 560 mm. of mercury can remove volatile solvents without noticeably affecting the ultraviolet pattern of an alkyd resin. Cyclohexane was determined to be satisfactory for ultraviolet spectral analysis because it adequately redissolved the vehicle solids and also had satisfactory ultraviolet absorption characteristics. On the basis of materials investigated, it is concluded that adulteration in amounts as low as 2 to 5 percent by weight of the vehicle solids can be detected.

The techniques described and principles involved seem to be applicable to vehicles and adulterants other than those included in this report. Modifications of the method developed would also seem to be applicable to paint vehicles in protective coatings for steel. Even when composition is specified, the ultraviolet spectral characteristics may be useful as a rapid method for determining compliance with specifications. Some of these other applications of ultraviolet spectral analysis are being investigated by the authors.

ACKNOWLEDGMENT

Some of the early exploratory work in this study was conducted by R. Cherwinski and L. B. Hayes. The authors also wish to acknowledge the cooperation of the Archer-Daniels-Midland Co., the Hercules Powder Co., and the Velsicol Chemical Corp., in supplying some of the materials used in this investigation.

(*Continued on p. 266*)

Effects of Volume Controls on Freeway Traffic Flow—A Theoretical Analysis

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

Reported by EDMUND A. HODGKINS, [1] **Highway Research Engineer, Traffic Systems Division**

Traffic congestion on urban freeways is a major concern of traffic engineers faced with the problem of maintaining traffic flow, and in this article several methods for reducing peak period congestion are discussed. Methods are presented for calculating metering rates for certain ramp metering systems, queue lengths, delays, and lengths of congestion period. A hypothetical ramp metering problem illustrates the benefits to be gained by eliminating congestion from the freeways.

There are several methods of regulating freeway demand, and their use either individually or in combination can be an effective tool for transportation engineers. Ramp metering techniques have been effective in decreasing travel time, increasing average speeds, and reducing the number of accidents. Of the several methods of ramp metering, ramp closure and fixed time metering have been useful in eliminating recurring congestion. Dynamic ramp metering may eventually provide a major contribution to the elimination of congestion. Current systems have reduced congestion a great deal but have not completely eliminated it. Economic constraints may be effective in regulating demand, but their effect on traffic flow has not been determined and they could adversely effect economic development of the areas where they are used. Dynamic diversion of traffic—monitoring traffic conditions and informing the driver of alternative congestion-free routes—can prevent congestion in sections of a network and improve overall system utilization. Even the staggering of hours can be effective in regulating demand under certain circumstances.

Introduction

PEAK PERIOD CONGESTION on urban freeways is a problem that is growing to alarming proportions. Various methods of controlling demand on a freeway, a freeway system, or the whole urban area street-highway system, have been suggested by those concerned with the problem, but the methods currently being emphasized are freeway traffic surveillance and control. The primary objective of most surveillance and control projects is the reduction or elimination of congestion, and the methods used are designed to limit the flow of traffic into a section of freeway (ramp metering) or to distribute traffic throughout a system so that all links in a network operate at or below capacity. Although there are several freeway control projects now in operation throughout the country, none has yet succeeded in eliminating freeway congestion; however, congestion has been greatly reduced at some locations.

Several methods of reducing peak period congestion on freeways are discussed in this article and include ramp metering (ramp closure, fixed time ramp metering, dynamic ramp metering, gap availability metering, and system demand capacity metering); dynamic diversion of traffic; the concept of staggered hours; and the concept of economic constraint. In addition to the discussion of different methods of control, methods are formulated for calculating (1) metering rates for time-based metering systems, (2) maximum queue length, (3) total delay, and (4) length of congested period or ramp-metering period. These methods are then applied to a simple hypothetical ramp metering situation and an economy analysis is performed. The hypothetical ramp metering situation serves as a conservative example of the benefits to be obtained from eliminating freeway congestion.

In order to provide a facility that operates smoothly, it is necessary to design a system free of traffic bottlenecks. A bottleneck has been defined as a location at which the demand can exceed the capacity, *(1)* [2] or the point at

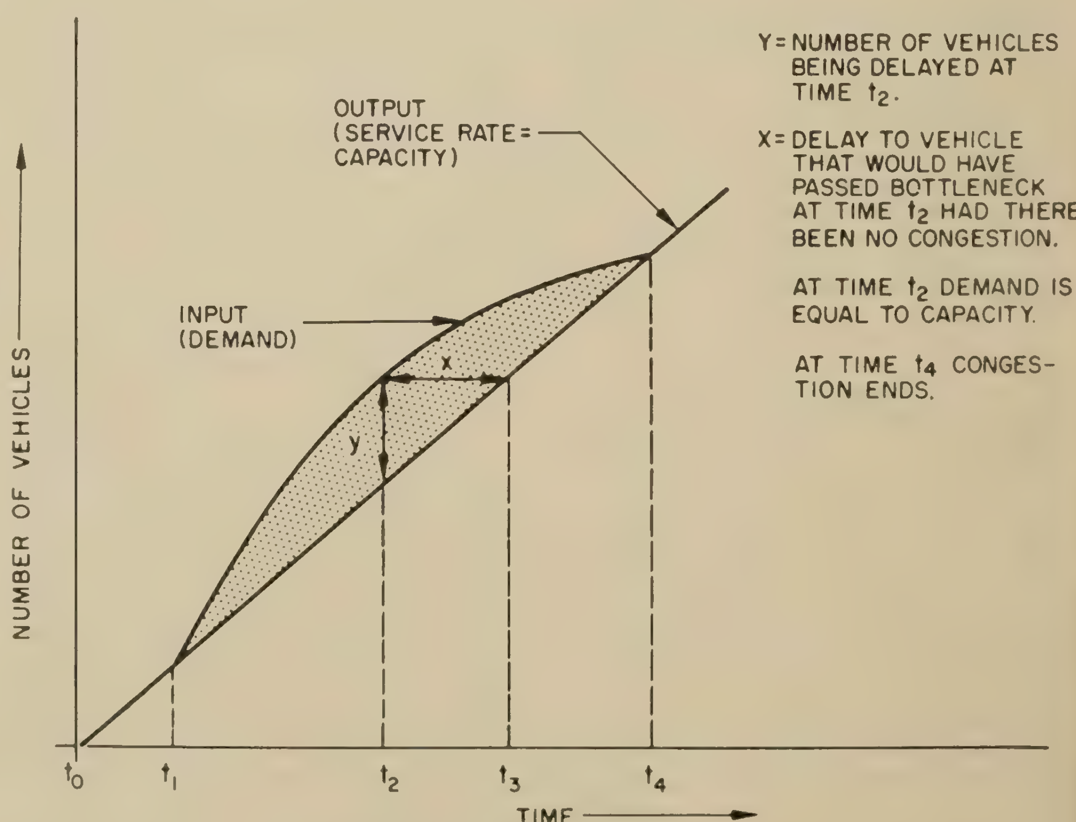

Figure 1.—Flow rate at a bottleneck.

[1] Mr. Hodgkins is the leader of the Stream Flow Task Group, a Public Roads research group concerned with the formulation and evaluation of traffic flow theory, the development of area traffic surveillance and control systems, and the evaluation and development of automatic highway systems.

[2] References indicated by italic numbers in parentheses are listed on page 266.

which the capacity decreases and/or the demand increases. The capacity of most highway facilities is not uniform. Conditions such as adverse grades, reduction in the number of lanes, short radius curves, heavy weaving movements, or heavy ramp movements (either on-ramp or off-ramp) will tend to reduce the capacity at given points on the facility. If the volume of traffic approaching a point of restricted capacity is larger than the capacity of that point, congestion will result.

or demand is less than capacity, but the congestion lasts until time t_4. The shaded area represents total delay. Any abscissa (x) represents delay to an individual vehicle, and any ordinate (y) represents the number of vehicles being delayed at a point in time. To eliminate the delay, it is necessary either to increase the capacity at the bottleneck or to decrease the rate of flow into the bottleneck. Most of the methods of volume control discussed in this paper are those designed to limit the rate of flow entering the system.

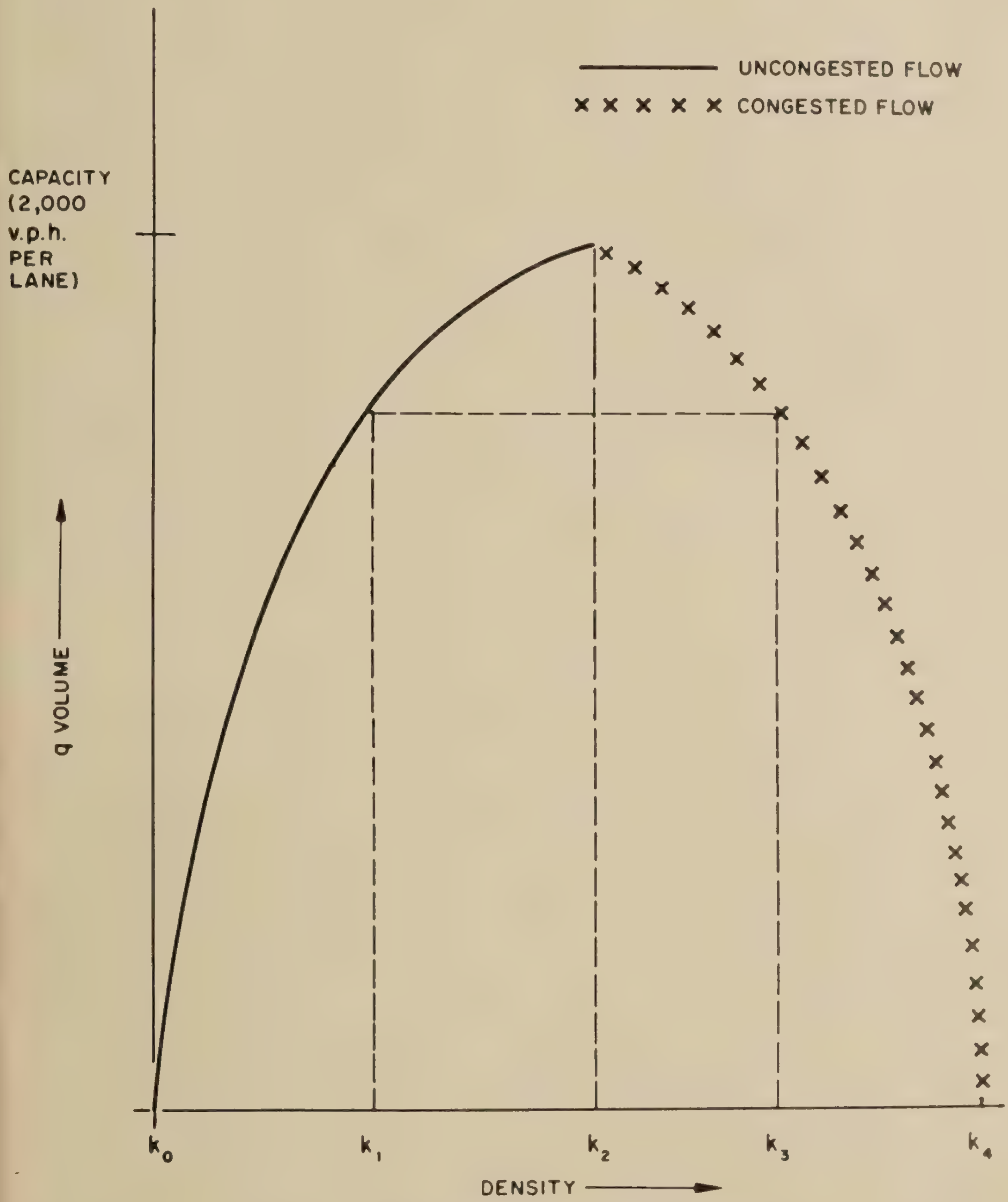

Figure 2.—Typical volume-density relationship.

The flow rate at a bottleneck is illustrated in figure 1. As shown, from time t_0 to time t_1, the input rate at this point on the highway is equal to the output rate. For this example the flow rate from time t_0 to t_1 equals the capacity of the facility. At time t_1 the demand (input) exceeds the capacity; the output or service rate cannot exceed capacity, therefore, a queue begins to form. At time t_2 the input

An important factor to be considered when discussing bottleneck capacity is the actual reduction in effective capacity that occurs when the freeway becomes congested. In figure 1 it is assumed that there is no reduction in capacity. Reduction in effective capacity can be partly attributed to a decrease in volume when the density in vehicles per mile exceeds a certain critical value (in the

range of 50 to 60 vehicles per lane-mile), as shown in figure 2.

The mathematical expression for the volume of a highway lane is:

$$q = kv$$

Where,

q = the flow rate in vehicles per hour.
k = the density in vehicles per mile.
v = the speed in miles per hour.

The effect of the terms of this equation is depicted in figure 2 in which it is shown that by decreasing the density from k_3 to k_1, an equivalent volume can be moved at higher speed and that by decreasing the density from k_3 to k_2 a larger volume can be moved at a higher speed. Density k_2 is the density at capacity in this illustration; when the density is greater than k_2 congestion will occur.

The reduction in effective capacity can be partly attributed to another phenomenon, which is reported in the Highway Capacity Manual 1965 (*2*), on pages 78 and 108. It is noted that, although the normal lane capacity of a multilane highway is 2,000 vehicles per hour, if the traffic flow is stopped, the flow rate leaving the point of interrupted flow usually will not exceed 1,500 vehicles per hour. This is an effective reduction in capacity of 500 vehicles per hour, a reduction which cannot be regained except by the addition of 500 vehicles per hour to the traffic downstream from the point of interruption. This phenomenon is illustrated in figure 3.

In figure 4, the effect of an effective reduction in capacity on the cumulative flow over a period of time is compared with the results shown in figure 1, where it is implicitly assumed that there is no effective reduction in capacity. As illustrated, the total delay will be larger, the delay to individual vehicles will be longer, the maximum queue length will be greater, and the freeway will be congested over a longer period of time.

Ramp Metering

For a long time, traffic engineers have thought of metering freeway traffic as a method of effectively controlling inputs to the freeway, thereby providing desirable operating conditions on the freeway system. In theory it is possible to prevent congestion by controlling the vehicular densities in the freeway system. In the introduction to this paper it was shown that the elimination of congestion results in an increase in speed, or a decrease in travel time, on the freeway, and could result in an increase in volume.

In a research report (*3*), David Solomon shows that a reduction in congestion results in fewer accidents. In other research studies it has been shown that a reduction in travel time, an increase in driver comfort, and an increase in the effective volume carrying capability of the facility can also be realized from reduced congestion. Ramp metering experiments at the Chicago Area Expressway Surveillance project have produced a 25-percent increase in volume, a sharp reduction in peak-period congestion, and a significant reduction in the accident rate.

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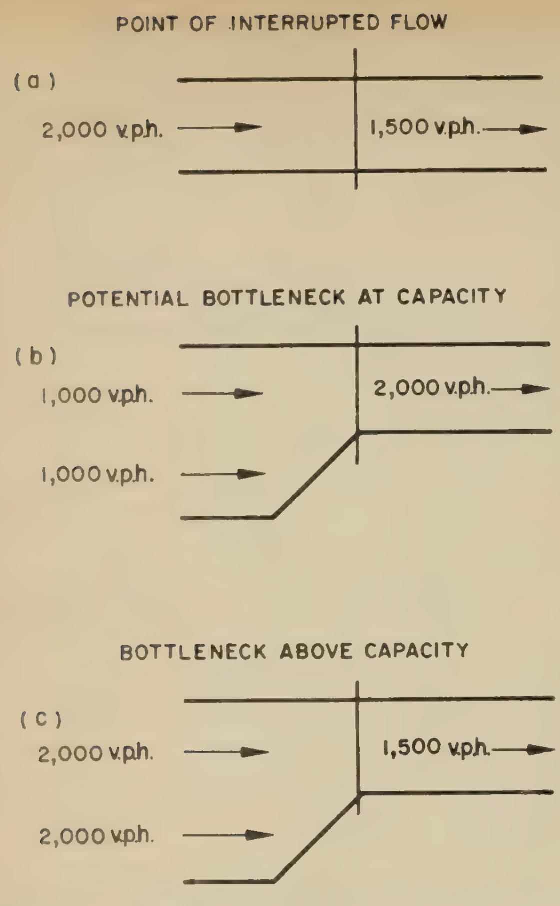

Figure 3.—Effects of interrupting the flow of traffic

To be completely effective and provide the most efficient use of the freeway system all entrance ramps should be controlled and all exit ramps should be monitored. The several methods of ramp metering include ramp closure, fixed time ramp metering, dynamic ramp metering, gap availability metering, and system demand-capacity metering. Each of these methods is discussed briefly in the following paragraphs.

Ramp closure (*4*) may be thought of either as a change in geometrics (elimination of a ramp) when a ramp is closed for the duration of the peak period or, as a special case of metering, when closure periods range from 5 to 15 minutes at a time during peak periods. Ramp closure can inconvenience drivers who usually use a ramp, and care must be taken to ensure that alternate routes are available to those drivers affected.

Fixed-time ramp metering is based on the premise that ramp and freeway demand is relatively predictable from day to day, and no attempt is made to account for unusual events such as traffic accidents. By using information gathered in origin and destination surveys, ramp and freeway demand are estimated, and signals are installed on the ramps to feed ramp traffic into the freeway flow at predetermined flow rates during peak periods. This type of system operation is based on historical data; it does not respond to traffic flow conditions on the freeway.

Dynamic ramp metering requires an analytic definition of freeway traffic flow to be used effectively. By measuring certain traffic-flow parameters at strategic points on the freeway and on the on-ramp, metering rates are varied incrementally using previously derived relations between the flow rate and the parameter being measured on the freeway. For example, metering rates on the Eisenhower Expressway in Chicago are based on a relation between lane 2 (middle lane) occupancy [3] upstream from the ramp and the freeway flow rate (see table 1), and metering rates on the Gulf Freeway in Houston are based on a relation between the speed in lane 1 (right shoulder lane) downstream from the nose of the ramp and the freeway flow rate. Queuing on the ramp is measured by different methods, and attempts are made to minimize storage on the ramps and frontage roads.

Both *gap availability metering* and *system demand capacity metering* are forms of dynamic ramp metering, but their application is slightly different from the general form of dynamic ramp metering in which the metering rate is based on a relation between a traffic flow parameter, measured on the freeway, and the freeway flow rate.

In *gap availability metering* the spacing in the traffic stream in lane 1 (right shoulder lane) upstream from the ramp is measured, and the signal at the ramp is programed to allow one, two, three or more vehicles to enter a gap in the stream that is based on a predetermined acceptable gap per vehicle. Occasionally vehicles may switch lanes and fill the gap prior to the arrival of the gap at the nose of the ramp, but a detector at the nose of the ramp indicates whether a vehicle or vehicles have managed to enter the freeway.

All of these metering systems except system demand capacity metering can be used at individual ramp locations with varying degrees of success. Generally, it is more practical to meter a series of ramps or all of the ramps in a controlled area to maximize the probability of eliminating congestion. *System demand capacity metering*, however, is an analytic method for metering the entire system rather than just individual ramps or a series of ramps. System demand capacity metering might be visualized in its simplest form as measuring the inputs and outputs of a system and controlling entrance to the system so that a predetermined optimum density can be maintained.

Research is now being conducted using combinations of all these ramp metering methods to provide more flexible, optimum metering rates in an effort to approach relatively high-speed, near-capacity operation.

Ramp metering has progressed a great deal in the last 6 years, evolving from a concept and advancing to the beginnings of an operational practicality. The ramp metering systems that have been designed to date are admittedly crude; but when a better understanding of the functional relationships of traffic flow has been achieved, the application of these analytic descriptions of traffic flow to ramp metering and to other types of control will provide greater sophistication in traffic surveillance and control, and current experiments in ramp metering will be recognized as highly valuable contributions to the total knowledge that enabled man to control his driving environment effectively.

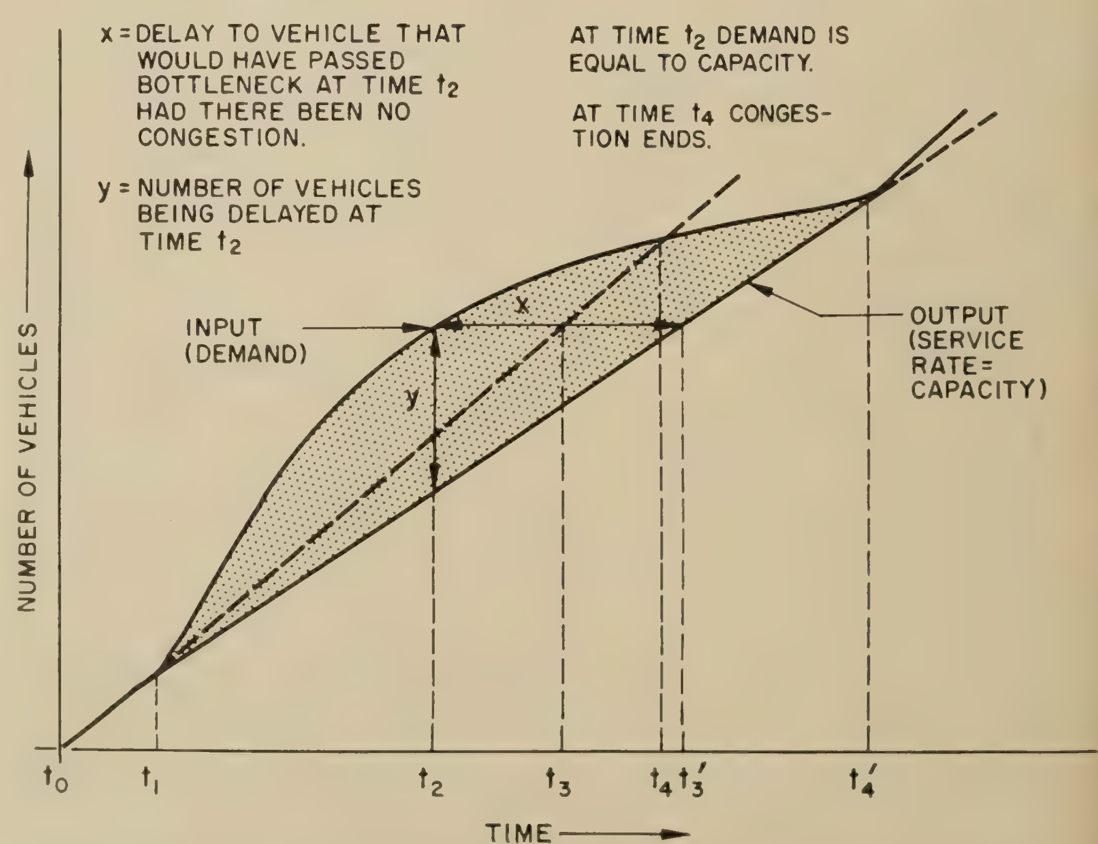

Figure 4.—Effect of a substantial reduction in capacity on the flow rate at a bottleneck.

[3] Occupancy is defined as the percentage of time that the space under a detector unit is occupied by a vehicle on the roadway.

Table 1.—Metering rates for various occupancy levels

Lane-2 occupancy	Metering rate
Percent	*v.p.m.*
15	12.0
16	12.0
17	12.0
18	8.5
19	8.5
20	8.5
21	7.5
22	6.5
23	5.0
24	5.0

Dynamic Diversion of Traffic

One concept for reducing system demand on links of freeway having insufficient capacity is dynamic traffic assignment—the assignment of traffic based on the operating conditions on any of the links of the freeway-highway network. By measuring traffic flow parameters on several different links of the freeway-highway network it should be possible to determine when the demand is about to exceed the service rate of any particular link. When this condition exists a computer system will activate the proper communication devices to inform the driver of all alternate routes which will provide better service and minimize his overall travel time in his home-to-work or work-to-home trip. To effectively use dynamic diversion of traffic, it is necessary to measure those traffic flow parameters that will adequately predict the current state of traffic dynamics at any point in time. In a sense dynamic diversion of traffic does not really reduce the system demand, but it does provide the means for optimizing use of the system to minimize travel time and to offset congestion. If the demands on the system as a whole exceed the system capacity, then it becomes necessary to reduce the inputs into the system. Traffic-flow models to prescribe the dynamic diversion of traffic throughout any freeway-highway network can be derived by using the same linear programing techniques that are currently used in assembling traffic assignment and traffic distribution models for highway planning purposes. It is possible that with a better knowledge of the economic and traffic flow parameters, models now used for traffic assignment and traffic distribution can be easily modified for use in programing the dynamic diversion of traffic.

An example of a crude though often effective technique of diverting traffic based on existing traffic-flow conditions is the traffic reporter in a helicopter communicating with the driver through local radio stations. More complicated and effective techniques for accomplishing the dynamic diversion of traffic would require an extensive system of detector units to measure the traffic-flow parameters, and a system to communicate these measurements to a central computer complex that would continually record the state of the traffic. This is essentially what has been done in Toronto and what is being done in San Jose and New York City in an attempt to provide a coordinated system of signals throughout the city-street network. Dynamic diversion of traffic, however, would be applied to the freeway-highway system; a central computer would analyze and record the effective traffic flow parameters and provide appropriate information to drivers so that they could follow the optimum route to their destination either by choice or by enforcement of more stringent routing controls.

Dynamic diversion of traffic has been experimented with in a very limited way on the John C. Lodge Expressway, Detroit, Mich.—the National Proving Ground for Freeway Surveillance, Control, and Electronic Traffic Aids. When an accident or heavy congestion occurs on the freeway, red X's over each lane light up and a green arrow at the exit ramps begins flashing. Drivers on the John C. Lodge Expressway have learned that this informational display indicates a blocked expressway that they should leave it at the next exit.

In Chicago, informational signs have been placed on city streets to alert the driver approaching an on-ramp of conditions on the Eisenhower Expressway and adjacent ramps. Changeable color arrows are used to indicate the traffic flow condition on the expressway and ramp. A red arrow indicates congestion has set in, an amber arrow indicates slow moving traffic and impending congestion, and a green arrow indicates free flow. Preliminary studies indicate that very little diversion can be attributed to these signs.

Other Methods of Volume Control That Have Been Proposed

In addition to ramp metering and dynamic diversion, several other methods of effectively reducing demand to a freeway system have been proposed. Two of these methods are staggered hours and economic constraints.

The concept of staggered hours

It is felt that by having people start work at different times of the day, the demand for use of the freeway-highway system could be spread over a longer period of time, thus relieving congestion and all its concomitant ills. However, there are several disadvantages to using the concept of staggered hours:

- Although it is no longer feasible from the standpoint of highway use, it may be essential in some areas of employment for everyone to work the same hours. Therefore, in staggering hours between different employees, it is necessary to account for the interrelations and interactions that take place during any normal work day.
- Staggered work hours tend to work against other factors that contribute to a more favorable demand-capacity relation; for example, the staggering of hours could adversely affect the formation of carpools and conceivably result in an increase in total vehicle miles of travel and a decrease in average vehicle occupancy.
- It is impossible to account for all vehicles in the system; traffic for shopping, business, school, social trips, etc., cannot be effectively regulated by staggering hours.
- The staggering of hours is directly affected by network configuration and land use.

The University of Arizona conducted a study to formulate a mathematical model for determining the extent to which traffic loads could be distributed over a longer period of time and for establishing the spread of hours needed to effect economies in the level of service (*5*). Results of this study indicated that staggering hours is technically feasible, but that the economic cost factors needed to use the model effectively were not completely known at the time. In general, it would seem that, to spread the demand over a long enough period to cause a significant reduction in the demand, and thus enable the highway system to operate at or below its capacity, would cause too long a spread in demand—perhaps too long in any single working day to be acceptable in a larger city. In medium-to-large cities, staggering hours would have to take place over a 2- to 3-hour period to accomplish significant reductions in demand during the peak hours.

The staggering of hours alone may not be one of the better methods of adjusting demand to match capacity, but this concept used in conjunction with dynamic diversion and ramp metering might prove to be an effective tool in regulating traffic flow.

The concept of economic constraint

Economic constraint, as a method for controlling volume and thus regulating demand so that the service rate of the facility is not exceeded, states that demand can be reduced through the imposition of a toll or other user charge that is so high that the user will attempt to find alternate modes of less expensive transportation. One disadvantage of this concept is that it seems to let the rich man use the roadway and force the poor man to use mass transportation facilities or at least reduce his flexibility by forcing him to form carpools.

Several methods have been proposed for imposing these economic constraints. One is simply to placing tollgates at all roadways leading into an urban area; another is to place detector loops in certain critical areas within the city and to require that all vehicles traveling within the city be equipped with meters that would measure the time each vehicle is operated or parked within these critical areas. The payment for this time would be directly proportional to the demand that these areas normally engender during peak periods. Still another method of economic constraint—one less stringent than the two just mentioned—is to provide free mass transportation facilities so that the driver has a choice of spending money to drive his own vehicle or traveling on a transit system (either bus or rail), which he is subsidizing.

All of these economic constraints should cause a reduction in demand for use of a facility or system and, if the constraint is stringent enough, enable the facility to handle flows within its capacity. In the long run, however, any urban area imposing such economic constraints as toll charges or exorbitant parking fees is likely to contribute to the decline of the central urban area and to promote even greater urban area decentralization than has heretofore been experienced.

Development of a Method for Determining Time Based Metering Rates

As stated in the introduction, fixed-time ramp metering is based on the premise that ramp and freeway demand is relatively predictable, and this type of ramp metering can be used to prevent recurring congestion. A procedure to determine the fixed-time ramp-metering rates for a single on-ramp is developed in the following paragraphs. This procedure can be adapted to dynamic ramp-metering situations and, if necessary, extended to account for a series of bottlenecks. For the purposes of this article, however, the additional complexities required to adapt or extend these procedures for several bottlenecks would provide no better illustration of the use of ramp metering or other volume controls than that given for the single ramp.

The following notation will be used for the remainder of this article:

$f(t)$ = freeway demand (vehicles per hour) at the merge point as a function of time

$r(t)$ = ramp demand (vehicles per hour) at the merge point as a function of time

$d(t)$ = the total demand (vehicles per hour) at the merge point as a function of time

C_{m1} = the capacity (vehicles per hour) of the merge point before congestion occurs

C_{m2} = the effective capacity (vehicles per hour) of the merge point after congestion occurs

q_m = the output flow rate (vehicles per hour) at the merge point

$$q_m = d(t) \qquad (1)$$

Where, $d(t) \leq C_{m1}$

$$q_m = C_{m2} \qquad (2)$$

Where, $d(t) > C_{m1}$ and metering is not employed

$$q_m = C_{m1} \qquad (3)$$

Where, $d(t) > C_{m1}$ and metering is employed

$L(t)$ = the length of queue (number of vehicles) at time t

$D(t)$ = the total delay (vehicle-hours) at time t

t_o = the time when $f(t) + r(t) = C_{m1}$

t = the time (hours)

$r^c(t)$ = the ramp metering rate (vehicles per hour) as a function of time

It is obvious that:

$$d(t) = f(t) + r(t) \qquad (4)$$

In order to eliminate congestion at the bottleneck it has been shown that q_m must be less than or equal to C_{m1}.

The objective of ramp metering is to eliminate congestion at the bottleneck. Congestion is defined as the traffic flow condition that occurs when capacity is exceeded; therefore, the following equations can be derived:

$$r^c(t) = C_{m1} - f(t) \qquad (5)$$

Where,

$$d(t) > C_{m1}$$

and

$$q_m = f(t) + r^c(t) = C_{m1} \qquad (6)$$

Where,

$$d(t) > C_{m1}$$

The above procedure allows the freeway to operate at capacity. Freeways have been observed to flow at capacity; that is, 2,000 vehicles per hour per lane, for the entire peak period under the proper operating conditions. Ramp metering ensures that the proper operating conditions are maintained.

Without ramp metering the queue lengths and delays are calculated as follows:

$$L(t) = \int_{t_o}^{t} d(t)dt - \int_{t_o}^{t} C_{m2}dt \qquad (7)$$

$$D(t) = \int_{t_o}^{t} L(t)dt \qquad (8)$$

Equation (7) gives the total number of vehicles in a queue at any point in time. This total should be divided between the freeway and the ramp in a ratio proportional to the respective demands. The same procedure should be used for equation (8).

With ramp metering the queue lengths and delays are calculated as follows:

$$L^c(t) = \int_{t_o}^{t} r(t)dt - \int_{t_o}^{t} r^c(t)dt \qquad (9)$$

$$D^c(t) = \int_{t_o}^{t} L^c(t)dt \qquad (10)$$

The length of the period of congestion (or ramp metering) can be calculated by determining the time t at which the queue length is reduced to zero and then subtracting t_o, the time at which the congestion began.

This procedure allows the freeway to keep flowing at capacity at the expense of the vehicles using the ramp. In fact use of this procedure will result in ramp closure during those periods when the freeway is operating at capacity. It must be assumed that there is either ample storage at the ramp or an alternate route available for use by the ramp vehicles. If an alternate route is available, the delay to the vehicles normally using the ramp will, in all likelihood, be less than if these vehicles were to be stored in queues at the ramp. In the calculations and analysis that follow it is assumed that no alternate route is available, but that there is ample space for storage, thus the ramp vehicles will be penalized to allow optimum operation of the system as a whole.

Sample Calculations

The problem

In the preceding section the analytic procedures for calculating the metering rate, length of congestion time, length of queue, and total delay were developed. In the following paragraphs a solution of a simplified metering situation is completed to illustrate the use of these procedures.

The metering location of this example is a single on-ramp to a single-lane freeway. The following equations supply the information necessary to solve this problem:

$f_1(t) = 1,400 + 600t \qquad 0 \leq t \leq 1 \qquad (11)$

$f_2(t) = 2,600 - 600t \qquad 1 \leq t \leq 2 \qquad (12)$

$f_3(t) = 1,400 \qquad 2 \leq t \leq 24 \qquad (13)$

$r_1(t) = 200 + 600t \qquad 0 \leq t \leq 1 \qquad (14)$

$r_2(t) = 1,400 - 600t \qquad 1 \leq t \leq 2 \qquad (15)$

$r_3(t) = 200 \qquad 2 \leq t \leq 24 \qquad (16)$

$d_1(t) = 1,600 + 1,200t \qquad 0 \leq t \leq 1 \qquad (17)$

$d_2(t) = 4,000 - 1,200t \qquad 1 \leq t \leq 2 \qquad (18)$

$d_3(t) = 1,600 \qquad 2 \leq t \leq 24 \qquad (19)$

C_{m1} = 2,000 vehicles per hour

C_{m2} = 1,800 vehicles per hour

The problem is to find the following:

- The metering rate at which the freeway flow will not exceed C_{m1} (2,000 vehicles per hour).
- The maximum length of queue under uncontrolled conditions.
- The maximum length of queue under controlled conditions.
- The total delay under uncontrolled conditions.
- The total delay under controlled conditions.
- The length of time congestion lasts under uncontrolled conditions.
- The length of time metering is required under controlled conditions.

Figure 5 is a graphical representation of the problem and its solution.

Calculation of metering rate

The metering rate can be calculated using equation (5) in the previous section.

$r^c(t) = C_{m1} - f(t)$

$r_1^c(t) = 2{,}000 - (1{,}400 + 600t) = 600\ (1-t)$
$t_o \leq t \leq 1 \qquad (20)$

$r_2^c(t) = 2{,}000 - (2{,}600 - 600t) = 600\ (t-1)$
$1 \leq t \leq 2 \qquad (21)$

$r_3^c(t) = 2{,}000 - 1{,}400 = 600$ *v.p.h.*
$2 \leq t \leq t_3 \qquad (22)$

Where,

t_o = the time at which the total demand is first equal to 2,000 v.p.h.

and

t_3 = the time at which the queue length is reduced to zero.

Using equation (17) t_o can be calculated:

$$2{,}000 = 1{,}600 + 1{,}200t_o$$

$$t_o = 1/3 \text{ hour}$$

Calculation of maximum queue length

The queue length for uncontrolled conditions can be calculated using equation (7) of the previous section.

$$L_1(t)=\int_{t=1/3}^{t}(1{,}600+1{,}200t)\,dt-\int_{t=1/3}^{t}1{,}800\,dt$$

For any value of time in the given interval the following equation will give queue length:

$$L_1(t)=600t^2-200t \qquad \tfrac{1}{3}\leq t\leq 1 \qquad (23)$$

Because the function for flow rate is constructed from three separate continuous functions in time, the queue length at $t=1$ in equation (23) must be added to the calculation for queue length for the time period from 1 to 2 in figure 5. Thus

$$L_2(t)=400+\int_{t=1}^{t}(4{,}000-1{,}200t)\,dt-\int_{t=1}^{t}1{,}800\,dt$$

$$L_2(t)=2{,}200t-600t^2-1{,}200 \qquad 1\leq t\leq 2 \qquad (24)$$

Similarly

$$L_3(t)=1{,}200-200t \qquad 2\leq t\leq t_4 \qquad (25)$$

Using equation (25) t_4 can be calculated:

$$L_3(t)=0=1{,}200-200t_4$$

$$t_4=6 \text{ hours}$$

Using equations (18) and (24) the maximum queue length can be calculated. The maximum queue length occurs when

$$d(t)=C_{m2} \text{ at } t_2>t_o$$

$$C_{m2}=1{,}800=d_2(t)=4{,}000-1{,}200\,t_2$$

$$t_2=\frac{2{,}200}{1{,}200}=1\tfrac{5}{6} \text{ hours}$$

Using equation (24) the maximum queue length can be calculated to be:

$$L_2(t)=2{,}200\,t_2-600(t_2)^2-1{,}200$$

$$=2{,}200\left(\frac{11}{6}\right)-600\left(\frac{121}{36}\right)-1{,}200$$

Maximum Queue Length = 816 vehicles

This represents 682 vehicles on the freeway and 134 vehicles on the ramp.

The queue length for controlled conditions can be calculated using equation (9):

$$L^c(t)=\int_{t_o}^{t}r(t)\,dt-\int_{t_o}^{t}r^c(t)\,dt$$

$$L_1^c(t)=\int_{t_o}^{t}(200+600t)\,dt-\int_{t_o}^{t}(600-600t)\,dt$$

$$L_1^c(t)=600t^2-400t+67 \qquad \tfrac{1}{3}\leq t\leq 1 \qquad (26)$$

As three separate continuous functions are used to describe flow rate, the queue length at $t=1$ must be added to the calculation for queue length for the time period from 1 to 2 in figure 5. Thus

$$L_2^c(t)=267+\int_{t=1}^{t}(1{,}400-600\,t)\,dt-\int_{t=1}^{t}(600\,t-600)\,dt$$

$$L_2^c(t)=2{,}000t-600t^2-1{,}133 \qquad 1\leq t\leq 2 \qquad (27)$$

Similarly the calculation of queue length for the time period from 2 to t_3 results in the following equation:

$$L_3^c(t)=1{,}267-400t \qquad 2\leq t\leq t_3 \qquad (28)$$

From the above equation it can be shown that $t_3=3\tfrac{1}{6}$ hours.

The maximum queue length occurs when $r(t)=r^c(t)$ at $t_1>t_0$. Using equations (15) and (21), t_1 can be calculated:

$$1{,}400-600t_1=600t_1-600$$

$$2{,}000=1{,}200t_1$$

$$t_1=1\tfrac{2}{3} \text{ hours}$$

The maximum queue length which occurs at t_1 can be calculated from equation (27).

Maximum queue length $=2{,}000(\tfrac{5}{3})-600(\tfrac{25}{9})-1{,}133=534$ vehicles

These vehicles will be stored at the ramp.

Calculation of total delay

The total delay can be calculated using the equation:

$$D(t)=\int_{t_o}^{t}L(t)\,dt$$

It must be remembered that three separate continuous functions were used to describe flow rate; the calculations for cumulative delay result in the following equations for uncontrolled conditions:

$$D_1(t)=200t^3-100t^2+4 \qquad \tfrac{1}{3}\leq t\leq 1 \qquad (29)$$

$$D_2(t)=1{,}100t^2-200t^3-1{,}200t+404 \qquad 1\leq t\leq 2 \qquad (30)$$

$$D_3(t)=1{,}200t-100t^2-1{,}196 \qquad 2\leq t\leq t_4 \qquad (31)$$

To calculate the total delay t_4 must be substituted for t in equation (31). The total delay in the uncontrolled situation is 2,404 vehicle hours.

The calculations for total delay for controlled flow result in the following equations:

$$D_1^c(t)=200t^3-200t^2+67t-7 \qquad \tfrac{1}{3}\leq t\leq 1 \qquad (32)$$

$$D_1^c(t)=393-1{,}133t+1{,}000t^2-200t^3 \qquad 1\leq t\leq 2 \qquad (33)$$

$$D_3^c(t)=1{,}267t-200t^2-1{,}207 \qquad 2\leq t\leq 3\tfrac{1}{6} \qquad (34)$$

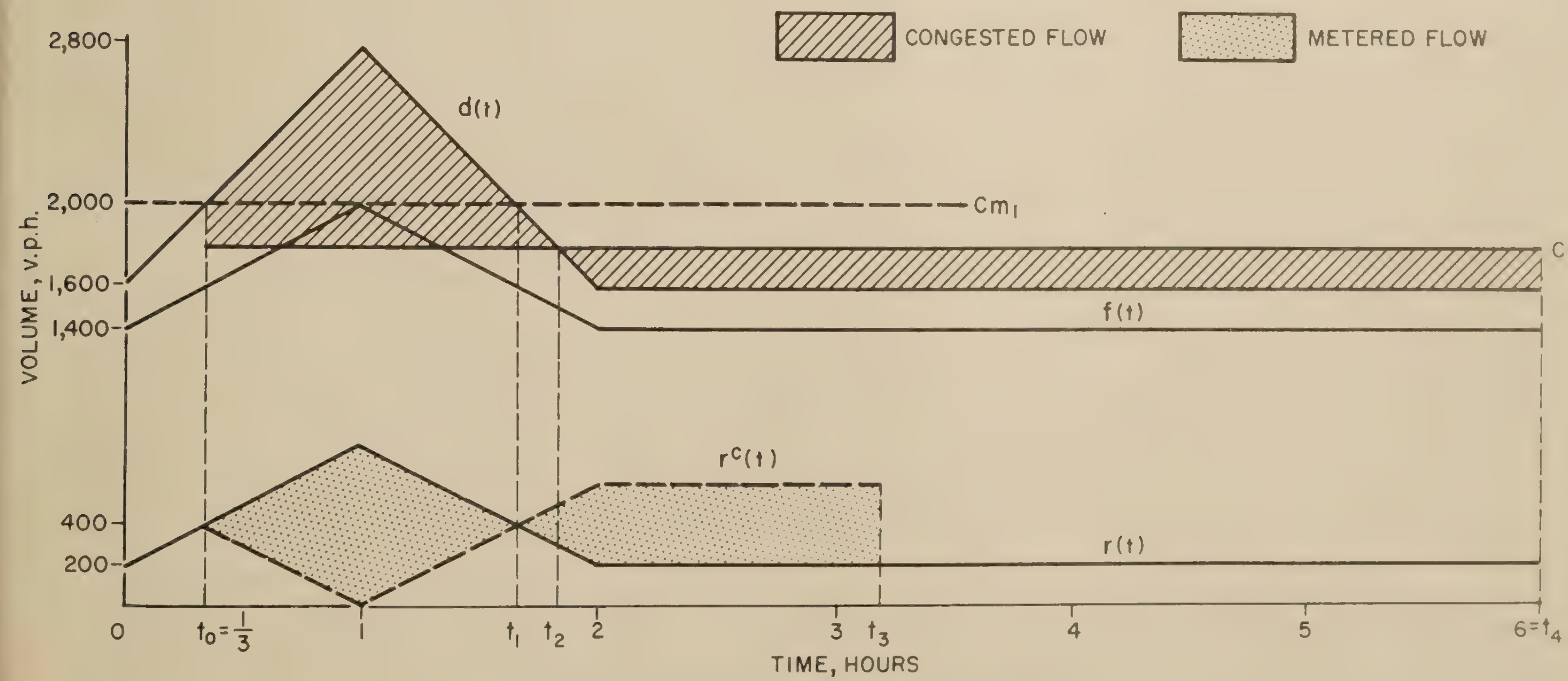

Figure 5.—Solution of ramp metering problem.

The calculated total delay is 799 vehicle-hours for the traffic flow situation where ramp metering is employed.

Calculation of length of congested period or ramp metering period

The length of the congested period is

$$t_4 - t_0 = 6 - \frac{1}{3} = 5\frac{2}{3} \text{ hours.}$$

The length of the period of ramp metering is $t_3 - t_0 = 3\frac{1}{6} - \frac{1}{3} = 2\frac{5}{6}$ hours.

Analysis of Economy of Sample Metering Scheme

The improvement conceived for the previous example of the benefits to be derived from volume controls was an isolated ramp metering location, and the formulated ramp metering scheme provided for penalizing the on-ramp flow to benefit the freeway flow. The analysis quantified the benefits to be derived from this type of installation in terms of vehicle-hours saved. The control philosophy used in the example was to allow the freeway to operate in an uncongested state at capacity, which means that the freeway was assumed to be operating at 2,000 vehicles per hour and that the average speeds would be in the range of 35 to 40 miles per hour.

As mentioned, the ramp traffic bore the full burden of the delay; however, this resulted in a substantial reduction in total delay, the capability for maintaining capacity flow, and higher average speeds on the freeway. It would be possible to set the metering rate to maintain a higher level of service on the freeway, but the benefits in terms of total delay would not be as evident.

Obviously there are no single-lane freeways, but an analysis for a single-lane situation actually errs on the conservative side. An analysis for a multilane highway under conditions in which the merge point capacity was exceeded would show even greater benefits from the application of this particular method.

For the example illustrated there are only two logical alternatives: One is to do nothing, and the other is to install equipment to implement the control procedures described. Peak period volume controls are not usually affected by the average daily traffic (ADT); highways that require metering installations or other volume controls are those on which demand regularly exceeds the capacity of the facility. It is not necessary to forecast growth rate, because there will be little opportunity for growth. In the example, the freeway operated at 1,600 vehicles per hour in the off-peak period (freeway and ramp flow combined). Increasing demand would require longer periods of control.

There are only three surveillance facilities in the country—those at Detroit, Chicago, and Houston—that have had appreciable experience in surveillance and control techniques. Although exact costs of the initial investment and of operations are not readily available for these projects, approximate costs were obtained to provide an accurate estimate. As a single facility is being dealt with, the cost of the total freeway is not needed; only the cost of the metering installation, the central control center, and related operating expenses have to be estimated. Similarly, only the differences in the road user costs caused by congestion need be considered.

It was assumed that the useful life of the equipment is 15 years and that there would be no salvage value. Three vestcharge rates of 8, 10, and 12 percent were selected for use in the calculations. The cost of accidents was not considered in the analysis, and consequently, the benefits to be derived from a reduction in accidents were not determined. It was decided that the benefit-cost-ratio method would be used rather than the rate-of-return method. Computation of the road user cost required an estimate of the number of speed change cycles during the period of congestion, or metering period. This was computed by assuming conditions: the rate of acceleration and deceleration for a speed change cycle is 5.5 feet per second ^{2} (a speed change cycle is defined by Winfrey (*6*) as "reducing speed from and returning to an initial speed"); the speed before entering the congested section and after leaving it is 40 m.p.h.; traffic flow is stop and go in the congested area with the vehicle repeatedly accelerating to 35 m.p.h. and then decelerating to zero. Under these conditions, only the major and more prominent stoppages in the traffic flow were considered.

Using these assumptions and the computed total delay it is possible to compute the number of speed change cycles at 35 m.p.h. The number of speed change cycles at 40 m.p.h. is equal to the number of vehicles through the section in the period of congestion or ramp metering. It was also assumed that there were no commercial vehicles in the traffic stream. The results of these computations above are shown in table 2; the costs for the speed change cycles shown are taken from tables derived by Winfrey (*6*).

The vehicle-running costs shown in table 2 and the costs for delay in vehicle-hours shown in table 3 are daily costs. As the cost of time is a moot subject, the total costs for time were calculated at three different dollar amounts—$1.00, $1.55, and $7.20 per hour per person. The differences in costs between the uncontrolled merge and controlled merge were calculated and are shown in table 4. The costs of equipment and operations incurred on the different surveillance projects are shown in

Table 2.—Calculation of speed-change cycles and vehicle-running costs incurred

Type of operation	Vehicle delay per day	Time used per cycle per vehicle	Speed-change cycles	Cost	
				Per 1,000 cycles	Per day
	Vehicle hours	*Seconds*	*Number*		
Controlled:					
From 40 m.p.h.	7	23.34	1,133	$15.76	$17.86
From 35 m.p.h.	792	18.64	152,961	12.24	1,872.24
Uncontrolled:					
From 40 m.p.h.	64	21.34	10,800	15.76	170.21
From 35 m.p.h.	2,360	18.64	455,794	12.24	5,578.92

Table 3.—Cost of time delay caused by congestion or metering

Type of operation	Total time delay		Total cost		
	Vehicle delay	Person delay	@ $1.00 per hour	@ $1.55 per hour	@ $7.20 per hour
	Hours	*Hours*			
Controlled	799	1,200	$1,200	$1,860	$8,640
Uncontrolled	2,404	3,606	3,606	5,589	25,963

Table 4.—Differences in road-user costs between uncontrolled merging and controlled merging

Classification	Cost differences		
	Per day	Per year	Cumulative annual totals [1]
Cost of speed changes:			
From 40 m.p.h.	$152.35	$39,611	-----------
From 35 m.p.h.	3,706.68	963,737	-----------
TOTAL	-----------	1,003,348	-----------
Cost of time:			
@ $1.00 per person-hour	2,406.00	625,560	$1,628,908
@ $1.55 per person-hour	3,729.00	969,540	1,972,888
@ $7.20 per person-hour	17,323.00	4,505,980	5,509,328

[1] Totals obtained by adding annual time costs to annual total speed-change costs ($1,003,348).

table 5. It was decided that the Detroit project costs would be used to approximate the costs of the hypothetical ramp-metering installation considered here; actually a fixed-time metering installation could be installed and maintained at a much lower annual cost. Table 6 shows the benefit-cost ratios calculated for the various factors. It can be seen that the ramp-metering installation can be easily justified according to the benefit-cost analysis.

Summary

Several methods of ramp metering are currently being studied. Ramp closure and fixed time metering are relatively inflexible methods of control; however, these methods have proved to be useful in eliminating recurring congestion. Dynamic ramp metering including gap-availability metering and system demand-capacity metering would seem to require more definitive analytic descriptions of the traffic flow interactions than are available; current research in dynamic ramp metering indicates that ramp metering may eventually contribute in a major way to the elimination of freeway congestion. Metering systems have been developed to the extent, that congestion has been significantly reduced but not completely eliminated. In developing metering systems care should be taken to ensure that the storage requirements on ramps and frontage roads do not cause detrimental traffic conditions to develop in the flow of traffic on adjacent streets and highways. Ramp-metering techniques have been proved effective in decreasing travel time throughout the system, increasing volumes and average speeds and reducing accidents.

Economic constraints could prove to be effective in regulating demand; however, the effect of economic parameters on traffic flow has not been determined, and at present there is no way of predicting exactly how the imposition of toll constraints would affect traffic flow. It does appear that institution of the toll or high parking-fee type of constraint could adversely affect further economic development of those areas incorporating them.

Dynamic diversion of traffic consists of monitoring traffic conditions on the freeway networks and informing the driver of the alternate routes that he should use to prevent congestion in individual links of the network and to provide optimum and maximum utilization of the system.

The use of staggered hours as the sole means of regulating demand is not feasible in most instances, but there are some circum-

Table 5.—Annual costs of operating different surveillance projects

Facility or project	Initial cost	Vestcharge rate [1]	Capital recovery factor (15 years)	Annual cost
John Lodge Expressway, Detroit, Mich. (National Proving Ground):		*Percent*		
TV cameras and monitors	$140,000	8	0.11683	$16,356
		10	0.13147	18,406
		12	0.14682	20,555
Control cable [2]				22,500
Detectors and traffic-control equipment	310,525	8	0.11683	36,279
		10	0.13147	40,825
		12	0.14682	45,491
Computer [3]				36,000
Annual-power costs				9,700
Annual equipment maintenance costs				14,300
Personnel [4]				67,500
TOTAL @ 8-percent rate				202,635
TOTAL @ 10-percent rate				209,231
TOTAL @ 12-percent rate				216,046
Gulf Freeway, Houston, Tex.: Control center [3]				9,600
Television system [3]				108,000
Ramp-control equipment				60,000
Office costs				3,000
Personnel				30,000
Detector system [3]				23,000
TOTAL				233,600
Chicago area expressway [4]				250,000

[1] The cost of money (investment charge) for which a noncash benefit is realized, as in the public-works field. Term coined by Robley Winfrey, Group Leader, Engineering Economics Group, Bureau of Public Roads.
[2] Equipment leased.
[3] Equipment rented.
[4] Cost estimated.

Table 6.—Summary of economic analysis of a ramp-metering installation

Vest-Charge rate [1]	Time costs excluded			Time costs included								
				@ $1.00 per hour			@ $1.55 per hour			@ $7.20 per hour		
	Annual benefits	Annual costs	Benefit-cost ratio	Annual benefits	Annual costs	Benefit-cost ratio	Annual benefits	Annual costs	Benefit-cost ratio	Annual benefits	Annual costs	Benefit-cost ratio
Percent												
8	$853,348	$52,635	16	$1,478,908	$52,635	28	$1,822,888	$52,635	34	$5,357,328	$52,635	101
10		59,231	14		59,231	25		59,231	30		59,231	90
12		66,046	12		66,046	22		66,046	27		66,046	81

[1] The cost of money (investment charge) for which a noncash benefit is realized, as in the public-works field. Term coined by Robley Winfrey, Group Leader, Engineering Economics Group; Bureau of Public Roads.

stances in which the staggering of hours may be warranted.

Development of these methods and their use, either individually or in combination, promise to provide transportation engineers with effective tools for eliminating congestion.

A procedure was developed for calculating ramp-metering rates, length of queue, total delay, and the length of the period of congestion or ramp metering. This procedure was used to calculate the required metering rates and other factors for a simplified ramp-metering situation.

A benefit-cost analysis was performed to determine whether the ramp-metering alternative was a better choice than the uncontrolled-freeway alternative. The benefit-cost ratios developed range from 12 to 101.

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Edward F. Gervais, *Instrumentation Capabilities and Listing of Reports*, National Proving Ground for Freeway Surveillance, Control and Electronic Traffic Aids, Detroit, Mich., January 1966.

Kevin E. Heanue and Donald O. Covault, *The Development of Criteria for Closing a Freeway Ramp Using Linear Programing.* Unpublished paper presented to the Committee on Theory of Traffic Flow, Highway Research Board, Washington, D.C., January 1962.

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Ultraviolet Spectrophotometric Detection of Adulteration in Traffic Paint Vehicles

(*Continued from p. 257*)

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Travel by Motor Vehicles in 1965 and 1966

BY THE OFFICE OF PLANNING
BUREAU OF PUBLIC ROADS

by **THEODORE S. DICKERSON, JR., and W. JOHNSON PAGE,**
Highway Research Engineers, Current Planning Division

MOTOR-VEHICLE travel in the United States in 1966 totaled 930.5 billion vehicle-miles, an increase of 4.8 percent over the travel in 1965. The travel data were compiled by the Bureau of Public Roads from information supplied by the State highway departments and toll authorities. Total travel for 1967, based on information for the first 9 months of the year, is estimated at 967 billion vehicle-miles, a 3.9 percent increase over 1966.

The term vehicle-miles and the other technical terms used in this article are defined in the following statements:

Vehicle-miles.—Vehicle-miles refers to the amount of travel by one motor-vehicle traveling 1 mile and includes travel on all highways and streets in the United States.

Trailer combinations.—A trailer combination is a truck or truck tractor pulling one or more trailers and/or a semitrailer.

Motor-fuel comsumption.—Motor-fuel consumption is the total consumption of motor fuel by highway vehicles for the year, obtained from State records.

Motor-fuel consumption rate.—Motor-fuel consumption rate is the average rate of motor fuel usage in miles per gallon (m.p.g.).

Because of recent rapid increases in motorcycle usage, separate estimates of travel for this vehicle type are shown for the first time. Motorcycle travel is estimated to have increased 32.4 percent from 1965 to 1966. The estimates for motorcycles, which are less detailed and less reliable than for other vehicle types, are based on special counts obtained by the State highway departments beginning in 1965 and on very limited data on usage characteristics from industry and user sources.

The proportions of travel by road system and vehicle type changed little from 1965 to 1966. Of the 1966 travel, 35.2 percent was on main rural roads comprising 14 percent of the Nation's total of 3.7 million miles of roads and streets. Some 50.5 percent of the travel was on urban streets, which comprise 14 percent of the total mileage. Travel on local rural roads was only 14.3 percent, although these roads are 72 percent of the total mileage.

Passenger cars represented 82 percent of the vehicles registered and did 80 percent of the travel in 1966; motorcycles, 2 percent of the vehicles and less than 1 percent of the travel; trucks and truck combinations, 16 percent of the vehicles and 19 percent of the travel. Similar figures for buses were less than 1 percent.

Average vehicle performance in 1966 differed very little from that reported for 1965. The average motor vehicle traveled 9,698 miles in 1966, half of it in cities, and consumed 778 gallons of fuel at a rate of 12.47 miles per gallon. The average passenger car traveled 9,506 miles and consumed 679 gallons of fuel at a rate of 14.00 miles per gallon. In 1966, the average truck and the average commercial bus traveled a little more than in 1965, but their average rates of fuel consumption did not change appreciably.

The average annual travel for single-unit trucks, however, decreased from 10,003 miles in 1965 to 9,588 miles in 1966. Since these trucks are used extensively in the construction industry, substantial changes in construction activity are likely to affect single-unit truck travel. New construction placed in the United States in 1966, in constant (1957–59) dollars, decreased slightly from 1965.

The travel and related information for 1966 and revised information for 1965 are shown in table 1 by road system and vehicle type. Such data have been reported in PUBLIC ROADS, *A Journal of Highway Research*, for a number of years; the latest for 1965 appeared in vol. 34, No. 6, February 1967, pp. 132 and 133.

The comparable State-by-State estimates of 1965 travel, shown in table 2, became available as a byproduct of the preparation of the report to the Congress, *1968 Estimate of the Cost of Completing the National System of Interstate and Defense Highways.* Each State highway department prepared an estimate of actual travel in 1965, as a foundation for traffic forecasts needed for this report.

According to the State estimates, the traveled way of the Interstate System carried 147.2 billion vehicle-miles, or 16.6 percent of the total 1965 travel on all roads and streets. The traveled way consisted of 18,000 miles of Interstate System highways now in use and 23,000 miles of existing connecting highways; service for this total mileage will be provided by the completed Interstate System. From the State estimates it is expected that by 1975 the 41,000 mile Interstate System, comprising little more than 1 percent of the total road and street mileage of the United States, will carry more than 20 percent of the total 1,213 billion miles of travel estimated for 1975.

According to the State estimates of 1965 travel, all Federal-aid systems combined, which includes about 25 percent of all roads and streets, carried 65 percent of all travel. Because of their principal use in a report to the Congress, the State estimates of 1965 were made according to a system classification and rural-urban distinction directly related to the Federal-aid program. In the Federal-aid law, an urban area is "an area including and adjacent to a municipality or other urban place having a population of 5,000 or more . . . ." In the annual estimates reported in table 1, however, urban signifies the areas within the political boundaries of municipalities such as cities, boroughs, and villages. As a consequence, urban travel in 1965 as shown in table 1 was 50.5 percent of the total, but by the State estimates it was 48.6 percent.

In recent years the annual travel estimates reported in table 1 have been developed in part from trend indicators, extending from a base of comprehensive studies by the States of travel in 1957. The revised estimate of total travel in 1965 is only 0.02 percent more than the original estimate. One of the larger differences was in the proportion of urban travel, which was revised from 48.0 percent of total travel to 50.6 percent.

Table 1.—Estimated motor-vehicle travel in the United States and related data for calendar year 1966 and revised for 1965 [1]

Vehicle type	Motor-vehicle travel					Number of vehicles registered	Average travel per vehicle	Motor-fuel consumption		Average travel per gallon of fuel consumed
	Main [2] rural roads	Local rural roads	All rural roads	Urban streets	Total			Total	Average per vehicle	
1966										
	Million vehicle-miles	*Million vehicle-miles*	*Million vehicle-miles*	*Million vehicle-miles*	*Million vehicle-miles*	*Thousands*	*Miles*	*Million gallons*	*Gallons*	*Miles gallon*
Personal passenger vehicles:										
Passenger cars [3]	--------	--------	--------	--------	744,844	78,353	9,506	53,220	679	14.00
Motorcycles [3]	--------	--------	--------	--------	6,896	1,753	3,930	92	52	75.00
ALL PERSONAL PASSENGER VEHICLES	247,626	103,746	351,372	400,368	751,740	80,106	9,384	53,312	666	14.10
Buses:										
Commercial	941	196	1,137	1,871	3,008	84.5	35,598	637	7,538	4.72
School	712	798	1,510	334	1,844	238.7	7,725	259	1,085	7.12
ALL BUSES	1,653	994	2,647	2,205	4,852	323.2	15,012	896	2,772	5.42
ALL PASSENGER VEHICLES	249,279	104,740	354,019	402,573	756,592	80,429	9,407	54,208	674	13.96
Cargo vehicles:										
Single-unit trucks	57,143	26,774	83,917	56,976	140,893	14,694	9,588	13,636	928	10.33
Trailer combinations	21,277	1,507	22,784	10,228	33,012	823	40,112	6,779	8,237	4.87
ALL TRUCKS	78,420	28,281	106,701	67,204	173,905	15,517	11,207	20,415	1,316	8.52
ALL MOTOR VEHICLES	327,699	133,021	460,720	469,777	930,497	95,946	9,698	74,623	778	12.47
1965 REVISED										
Personal passenger vehicles:										
Passenger cars	--------	--------	--------	--------	706,386	75,252	9,387	50,206	667	14.07
Motorcycles	--------	--------	--------	--------	5,208	1,382	3,770	69	50	75.00
ALL PERSONAL PASSENGER VEHICLES	236,777	96,635	333,412	378,182	711,594	76,634	9,286	50,275	656	14.15
Buses:										
Commercial	932	194	1,126	1,893	3,019	85.0	35,518	645	7,588	4.68
School	687	758	1,445	318	1,763	229.3	7,689	249	1,086	7.08
ALL BUSES	1,619	952	2,571	2,211	4,782	314.3	15,215	894	2,844	5.35
ALL PASSENGER VEHICLES	238,396	97,587	335,983	380,393	716,376	76,948	9,310	51,169	665	14.00
Cargo vehicles:										
Single-unit trucks	52,771	28,177	80,948	59,169	140,117	14,008	10,003	13,504	964	10.38
Trailer combinations	20,459	1,382	21,841	9,478	31,319	787	39,795	6,431	8,172	4.87
ALL TRUCKS	73,230	29,559	102,789	68,647	171,436	14,795	11,587	19,935	1,347	8.60
ALL MOTOR VEHICLES	311,626	127,146	438,772	449,040	887,812	91,743	9,677	71,104	775	12.49

[1] For the 50 States and District of Columbia.
[2] Main rural roads include roads on the State highway systems, roads of the Interstate System, other mileage on Federal-aid systems, and major toll roads, which approximate in 1965 523,000 road miles and in 1966, 527,000 road miles.
[3] Separate estimates of passenger car and motorcycle travel are not available by highway category.

Table 2.—Vehicle-miles of travel in 1965 on all roads and streets, free and toll, by State and highway system, estimated by State highway departments in 1967

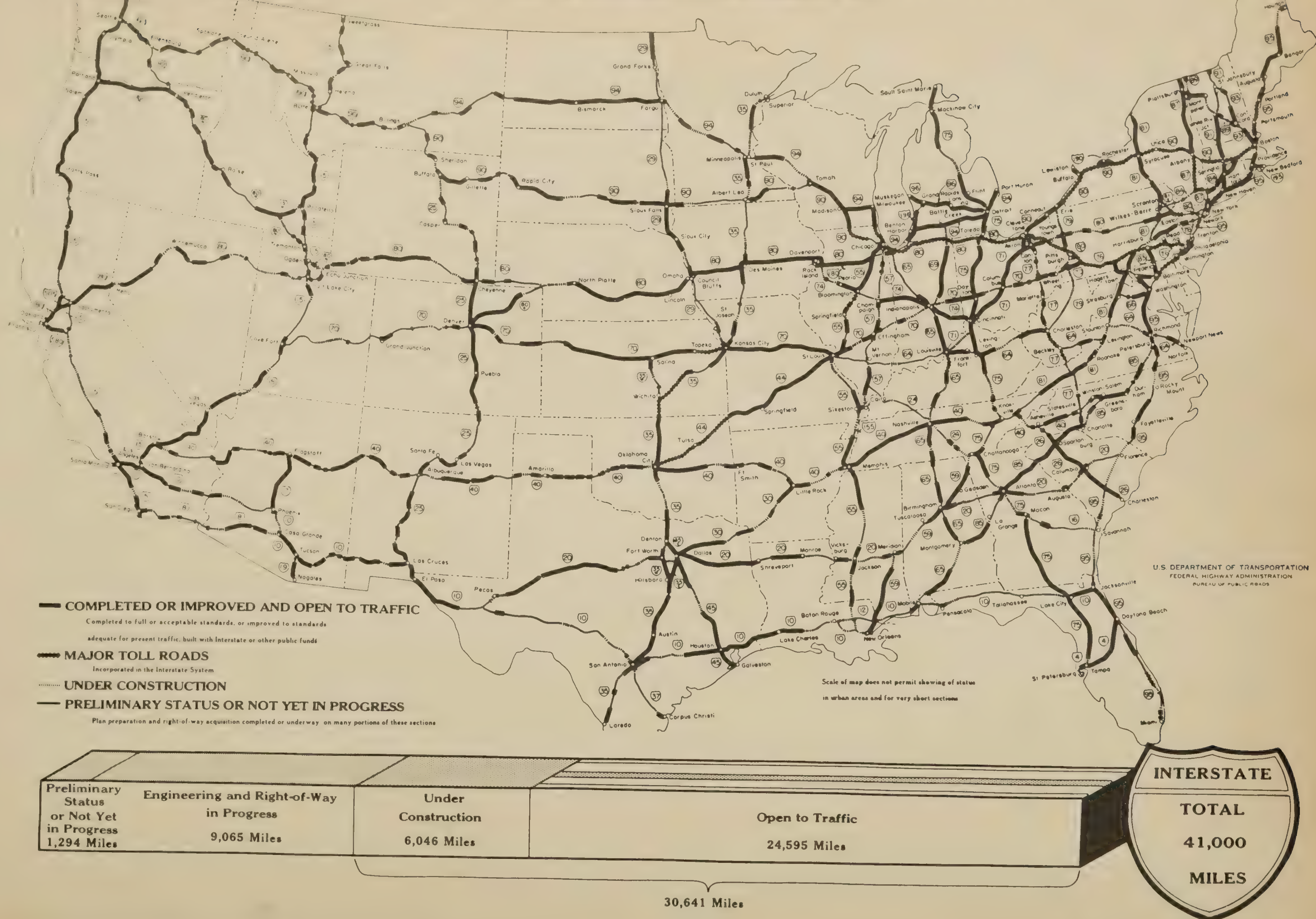
(Millions)

Division	State	Federal-aid highway system: Interstate rural: Final 01	Interstate rural: Traveled 1/ 31	Interstate rural: Total rural	Interstate urban: Final 02	Interstate urban: Traveled 1/ 32	Interstate urban: Total urban	Sub-total Inter-state	Other Primary: Rural 03	Other Primary: Urban 04	Other Primary: Total	Secondary: State rural 05	Secondary: State urban 06	Secondary: Local rural 07	Secondary: Local urban 08	Secondary: Total	Total Federal-aid rural	Total Federal-aid urban	Total Federal-aid	Not on Federal-aid systems: Other State rural 09	Other State munici-pal 10	Local rural 11	Local munici-pal 12	Sub-total rural	Sub-total urban and munici-pal	Total
New England	Connecticut	622	163	785	1,637	414	2,051	2,836	1,193	1,438	2,631	899	668	7	67	1,641	2,884	4,224	7,108	428	2,537	161	2,766	3,473	9,527	13,000
	Maine	413	129	542	53	71	124	666	1,243	420	1,663	792	121	-	-	913	2,577	665	3,242	743	284	238	338	3,558	1,287	4,845
	Massachusetts	951	154	1,105	996	1,071	2,067	3,172	2,384	4,273	6,657	529	475	1,067	1,463	3,534	5,085	8,278	13,363	158	1,208	835	5,737	6,078	15,223	21,301
	New Hampshire	322	52	374	54	48	102	476	952	320	1,272	680	81	4	3	768	2,010	506	2,516	237	59	262	401	2,509	966	3,475
	Rhode Island	13	85	98	308	154	462	560	488	757	1,245	172	171	22	177	542	780	1,567	2,347	70	146	18	1,236	868	2,949	3,817
	Vermont	131	192	323	23	59	82	405	643	119	762	259	1	136	16	412	1,361	218	1,579	7	*	188	198	1,556	416	1,972
	Total	2,452	775	3,227	3,071	1,817	4,888	8,115	6,903	7,327	14,230	3,331	1,517	1,236	1,726	7,810	14,697	15,458	30,155	1,643	4,234	1,702	10,676	18,012	30,368	48,410
Middle Atlantic	New Jersey	197	801	998	925	1,725	2,650	3,648	2,868	4,555	7,423	58	47	1,786	1,688	3,579	5,710	8,940	14,650	1,043	1,968	4,088	11,812	10,841	22,720	33,561
	New York	2,230	276	2,506	4,397	922	5,319	7,825	8,084	10,633	18,717	1,686	1,091	2,688	1,364	6,829	14,964	18,407	33,371	41	57	7,983	14,897	22,988	33,361	56,349
	Pennsylvania	3,167	1,361	4,528	1,828	964	2,792	7,320	7,571	5,258	12,829	5,300	3,081	46	90	8,517	17,445	11,221	28,666	3,062	3,785	3,912	9,840	24,419	24,846	49,265
	Total	5,594	2,438	8,032	7,150	3,611	10,761	18,793	18,523	20,446	38,969	7,044	4,219	4,520	3,142	18,925	38,119	38,568	76,687	4,146	5,810	15,983	36,549	58,248	80,927	139,175
South Atlantic (North)	Delaware	43	-	43	124	158	282	325	938	607	1,545	296	192	-	-	488	1,277	1,081	2,358	-	-	80	62	1,357	1,143	2,500
	Dist. of Col. 2/	-	-	-	134	167	301	301	-	980	980	-	-	-	486	486	-	1,767	1,767	-	-	-	714	-	2,481	2,481
	Maryland	544	332	876	1,043	968	2,011	2,887	2,600	2,030	4,630	1,428	763	400	376	2,967	5,304	5,180	10,484	567	68	2,890	2,265	8,761	7,513	16,274
	Virginia	1,997	1,568	3,565	338	887	1,225	4,790	4,695	2,021	6,716	2,331	416	1,723	367	4,837	12,314	4,029	16,343	69	322	1,450	2,538	13,833	6,889	20,722
	West Virginia	242	514	756	50	247	297	1,053	1,827	627	2,454	1,373	103	825	29	2,330	4,781	1,056	5,837	4	18	277	1,050	5,062	2,124	7,186
	Total	2,826	2,414	5,240	1,689	2,427	4,116	9,356	10,060	6,265	16,325	5,428	1,474	2,948	1,258	11,108	23,676	13,113	36,789	640	408	4,697	6,629	29,013	20,150	49,163
South Atlantic (South)	Florida	1,181	1,182	2,363	860	1,068	1,928	4,291	4,592	2,745	7,337	4,179	1,905	406	126	6,616	11,540	6,704	18,244	1,071	937	1,857	6,483	14,468	14,124	28,592
	Georgia	988	1,267	2,255	943	574	1,517	3,772	5,056	1,481	6,537	2,269	457	1,157	327	4,210	10,737	3,782	14,519	134	352	1,654	4,921	12,525	9,055	21,580
	North Carolina	1,036	1,091	2,127	292	231	523	2,650	3,929	1,352	5,281	4,371	727	3,603	867	9,568	14,030	3,469	17,499	64	236	1,338	2,724	15,432	6,429	21,861
	South Carolina	738	694	1,432	62	141	203	1,635	3,852	1,234	5,086	2,670	388	114	4	3,176	8,068	1,829	9,897	264	784	319	318	8,651	2,931	11,582
	Total	3,943	4,234	8,177	2,157	2,014	4,171	12,348	17,429	6,812	24,241	13,489	3,477	5,280	1,324	23,570	44,375	15,784	60,159	1,533	2,309	5,168	14,446	51,076	32,539	83,615
East North Central	Illinois	1,951	1,450	3,401	3,656	882	4,538	7,939	7,852	6,504	14,356	1,024	468	2,377	196	4,065	14,654	11,706	26,360	1,370	3,332	2,666	11,821	18,690	26,859	45,549
	Indiana	1,414	1,532	2,946	238	1,238	1,476	4,422	5,758	2,516	8,274	2,748	570	1,723	621	5,662	13,175	5,183	18,358	131	214	1,031	5,805	14,337	11,202	25,539
	Michigan	2,423	266	2,689	2,006	1,722	3,728	6,417	6,643	4,735	11,378	1,333	214	6,173	781	8,501	16,838	9,458	26,296	27	57	4,033	11,149	20,898	20,664	41,562
	Ohio	3,414	673	4,087	2,299	1,515	3,814	7,901	7,618	4,929	12,547	4,180	1,387	2,190	1,859	9,616	18,075	11,989	30,064	104	401	4,691	11,490	22,870	23,880	46,750
	Wisconsin	1,044	268	1,312	235	253	488	1,800	5,030	2,030	7,060	1,560	463	1,425	833	4,281	9,327	3,814	13,141	36	39	1,096	4,863	10,459	8,716	19,175
	Total	10,246	4,189	14,435	8,434	5,610	14,044	28,479	32,901	20,714	53,615	10,845	3,102	13,888	4,290	32,125	72,069	42,150	114,219	1,668	4,043	13,517	45,128	87,254	91,321	178,575
West North Central	Iowa	681	381	1,062	159	67	226	1,288	5,025	1,361	6,386	-	-	1,455	285	1,740	7,542	1,872	9,414	77	47	841	2,354	8,460	4,273	12,733
	Kansas	605	238	843	280	111	391	1,234	3,606	993	4,599	543	20	1,372	310	2,245	6,364	1,714	8,078	77	47	879	3,349	7,320	5,110	12,430
	Minnesota	194	724	918	512	830	1,342	2,260	4,741	2,000	6,741	1,013	32	2,411	145	3,601	9,083	3,519	12,602	3	115	1,253	3,207	10,339	6,841	17,180
	Missouri	1,252	1,006	2,258	1,158	568	1,726	3,984	4,961	1,849	6,810	2,249	376	20	34	2,679	9,488	3,985	13,473	158	488	1,850	5,894	11,496	10,367	21,863
	Nebraska	412	296	708	39	36	75	783	2,579	578	3,157	587	15	611	63	1,276	4,485	731	5,216	2	-	975	1,757	5,462	2,488	7,950
	North Dakota	255	171	426	18	49	67	493	1,188	113	1,301	181	3	429	14	627	2,224	197	2,421	1	2	641	374	2,866	573	3,439
	South Dakota	293	302	595	17	14	31	626	1,538	186	1,724	213	21	404	24	662	2,750	262	3,012	20	7	615	329	3,385	598	3,983
	Total	3,692	3,118	6,810	2,183	1,675	3,858	10,668	23,638	7,080	30,718	4,786	467	6,702	875	12,830	41,936	12,280	54,216	338	706	7,054	17,264	49,328	30,250	79,578
East South Central	Alabama	381	1,122	1,503	58	740	798	2,301	3,476	1,459	4,935	1,249	216	1,603	198	3,266	7,831	2,671	10,502	385	102	633	2,702	8,849	5,475	14,324
	Kentucky	824	849	1,673	478	394	872	2,545	3,326	1,075	4,401	2,939	381	410	90	3,820	8,348	2,418	10,766	813	510	970	1,695	10,131	4,623	14,754
	Mississippi	351	564	915	87	437	524	1,439	3,189	578	3,767	712	77	865	158	1,812	5,681	1,337	7,018	8	19	600	1,219	6,289	2,575	8,864
	Tennessee	348	1,557	1,905	419	837	1,256	3,161	4,052	1,840	5,892	967	222	625	38	1,852	7,549	3,356	10,905	53	5	1,665	3,417	9,267	6,778	16,045
	Total	1,904	4,092	5,996	1,042	2,408	3,450	9,446	14,043	4,952	18,995	5,867	896	3,503	484	10,750	29,409	9,782	39,191	1,259	636	3,868	9,033	34,536	19,451	53,987
West South Central	Arkansas	376	543	919	238	89	327	1,246	2,489	795	3,284	1,719	230	276	26	2,251	5,403	1,378	6,781	33	44	664	1,262	6,100	2,684	8,784
	Louisiana	393	1,104	1,497	239	562	801	2,298	2,367	1,128	3,495	3,069	482	11	1	3,563	6,944	2,412	9,356	408	450	610	2,130	7,962	4,992	12,954
	Oklahoma	954	264	1,218	431	414	845	2,063	4,318	1,221	5,539	916	193	676	207	1,992	7,128	2,466	9,594	197	91	964	3,042	8,289	5,599	13,888
	Texas	1,763	2,588	4,351	3,782	2,267	6,049	10,400	10,201	6,402	16,603	6,963	2,482	-	-	9,445	21,515	14,933	36,448	1,160	719	2,460	12,212	25,135	27,864	52,999
	Total	3,486	4,499	7,985	4,690	3,332	8,022	16,007	19,375	9,546	28,921	12,667	3,387	963	234	17,251	40,990	21,189	62,179	1,798	1,304	4,698	18,646	47,486	41,139	88,625
Mountain	Arizona	612	1,492	2,104	239	330	569	2,673	1,064	109	1,173	524	43	538	1,590	2,695	4,230	2,311	6,541	156	20	326	1,254	4,712	3,585	8,297
	Colorado	613	615	1,228	363	373	736	1,964	1,914	1,381	3,295	796	119	-	-	915	3,938	2,236	6,174	48	98	1,244	2,459	5,230	4,793	10,023
	Idaho	312	334	646	16	75	91	737	1,167	129	1,296	304	22	263	36	625	2,380	278	2,658	4	7	627	486	3,011	771	3,782
	Montana	200	556	756	8	69	77	833	1,220	178	1,398	366	48	-	-	414	2,342	303	2,645	-	-	665	390	3,007	693	3,700
	Nevada	395	314	709	-	143	143	852	624	183	807	244	59	71	163	537	1,648	548	2,196	24	20	90	490	1,762	1,058	2,820
	New Mexico	644	659	1,303	67	225	292	1,595	1,399	479	1,878	746	124	6	-	876	3,454	895	4,349	82	412	349	613	3,885	1,920	5,805
	Utah	136	913	1,049	134	359	493	1,542	736	390	1,126	499	408	92	122	1,121	2,376	1,413	3,789	33	117	375	582	2,754	2,112	4,866
	Wyoming	359	377	736	16	21	37	773	815	111	926	211	1	12	13	237	1,774	162	1,936	3	3	258	365	2,035	530	2,565
	Total	3,271	5,260	8,531	843	1,595	2,438	10,969	8,939	2,960	11,899	3,690	824	982	1,924	7,420	22,142	8,146	30,288	350	677	3,934	6,639	26,426	15,462	41,888
Pacific	California	1,597	5,109	6,706	7,663	4,293	11,956	18,662	9,500	12,916	22,416	2,020	976	3,902	3,328	10,226	22,128	29,176	51,304	531	1,296	13,443	29,210	36,102	59,682	95,784
	Oregon	1,030	281	1,311	486	110	596	1,907	2,069	1,224	3,293	994	260	647	393	2,294	5,021	2,473	7,494	3	12	1,210	1,796	6,234	4,281	10,515
	Washington	269	1,008	1,277	919	472	1,391	2,668	1,818	982	2,800	829	404	1,645	335	3,213	5,569	3,112	8,681	16	187	3,374	3,070	8,959	6,369	15,328
	Total	2,896	6,398	9,294	9,068	4,875	13,943	23,237	13,387	15,122	28,509	3,843	1,640	6,194	4,056	15,733	32,718	34,761	67,479	550	1,495	18,027	34,076	51,295	70,332	121,627
Total - All Divisions		40,310	37,417	77,727	40,327	29,364	69,692	147,418	165,198	101,224	266,422	70,990	21,003	46,216	19,313	157,522	360,131	211,231	571,362	13,925	21,622	78,648	199,086	452,704	431,939	884,643
	Alaska	-	-	-	-	-	-	-	267	96	363	78	30	-	-	108	345	126	471	-	-	100	204	445	330	775
	Hawaii	-	124	124	17	267	284	408	420	261	681	195	37	-	-	232	739	582	1,321	-	-	371	702	1,110	1,284	2,394
United States Total		40,310	37,541	77,851	40,344	29,631	69,976	147,826	165,885	101,581	267,466	71,263	21,070	46,216	19,313	157,862	361,215	211,939	573,154	13,925	21,622	79,119	199,992	454,259	433,553	887,812

1/ Traveled-way includes travel on highways in the Interstate System status of completion group 2. This group consists of mileage which is adequate for present traffic but will need further construction and improvement to bring it to full Interstate standards. In some instances these are divided highways with full control of access and in others they are two, three or four-lane undivided highways with no access control.
2/ Total vehicle-mile estimate provided by the District of Columbia Highway Department. Distribution of travel by highway system was estimated by the Planning Services Branch, Bureau of Public Roads.
3/ Bureau of Public Roads estimate based on data furnished by the Alaska Highway Department. Alaska has no interstate mileage and therefore did not prepare an estimate.
* Less than 0.5 million vehicle-miles.

THE NATIONAL SYSTEM OF INTERSTATE AND DEFENSE HIGHWAYS

STATUS OF IMPROVEMENT AS OF SEPTEMBER 30, 1967



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Supplementary Report, House Document No. 124 (1965). $1.00.
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