Vol. 35/No. 9

August 1969

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

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A JOURNAL OF HIGHWAY RESEARCH

Published Bimonthly

Harry C. Secrest, *Managing Editor* ● Fran Faulkner, *Editor*

August 1969/Vol. 35, No. 9

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Public Roads, A Journal of Highway Research, is sol by the Superintendent of Documents, Governmen Printing Office, Washington, D.C. 20402, at $2.00 pe year (50 cents additional for foreign mailing) or 4 cents per single copy. Subscriptions are available fo 1-, 2-, or 3-year periods. Free distribution is limited t public officials actually engaged in planning or constructing highways and to instructors of highway engineering. There are no vacancies in the free list a present.

Use of funds for printing this publication has been approved by the Director of the Bureau of the Budget March 16, 1966.

Contents of this publication may be reprinted. Mention of source is requested.

hird Generation estination Signing—An Electronic oute Guidance System

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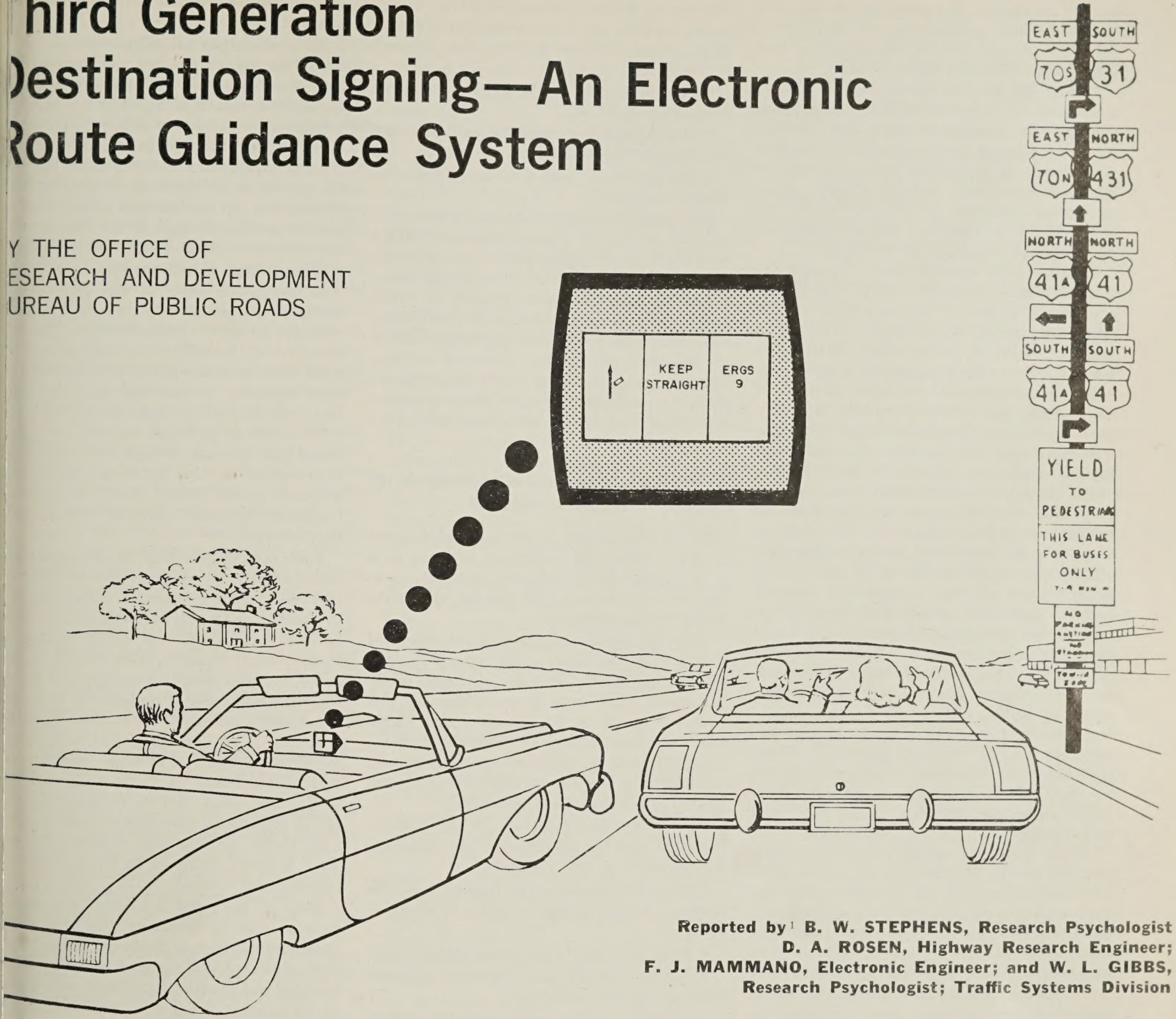

**Reported by[1] B. W. STEPHENS, Research Psychologist
D. A. ROSEN, Highway Research Engineer;
F. J. MAMMANO, Electronic Engineer; and W. L. GIBBS,
Research Psychologist; Traffic Systems Division**

The problem of routing an automobile driver safely and efficiently from his origin to his destination is analyzed and present highway routing and navigational methods are examined in the framework of a systems analysis of the highway routing subsystem. In this context, the functions, characteristics, normative operation, and constraints of the present routing subsystem are delineated. The analysis traces the implications of removing three major constraints from the present highway routing subsystem: Open loop communications with drivers, utilitarian rather than individualized communication, and treatment of the highway and the automobile as separate entities.

Techniques of communication that can remove system constraints are considered, and a route-guidance-system concept and a plan for implementing it are presented. The implementation plan for the concept, consisting of a multiphased research and development program currently underway, includes studies that will lead to the design of an electronic route guidance system, a prototype of which will be installed on an actual highway network to be thoroughly tested and evaluated.

If all highway route marking signs of the prefreeway era are considered first generation and those of the freeway era, second generation, then the new concept and routing system described here can be properly termed third generation destination signing.

Introduction

N this article, highway routing, or naviga- tional methods and procedures, as they exist day are analyzed; the functions, character- ies,- normative operation, and constraints routing methods are delineated; and several vel techniques for communicating direc- nal information to drivers are examined. research and development effort to trans- m into an operational system a concept of route guidance system is also examined. is system concept, which is now being plemented, is the outgrowth of synthesis of tain techniques combined with a funda- ntal analysis of routing. Considering all freeway route marking signs as first neration, and freeway signs of today as

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[1] Presented at the 48th annual meeting of the Highway search Board, Washington, D.C., January 1969.

second generation, the assembly of software and hardware components of the newly conceived system can be viewed as a third generation destination signing system.

During the current decade it has become fashionable to conduct analyses of existing man-machine systems to determine whether they can be made more efficient or whether man should be supplanted by mechanical or electronic functional analogs. Usually there are severe symptoms of disorder before the analyses are conducted or the solutions that have been developed are implemented.

Symptoms of disorder seem to exist for vehicular traffic operations. Many individuals are keenly aware of the degree of system disorder, including the infrequent traveler who journeys to major metropolitan centers, the traffic engineer who struggles from day-to-day with the movement of vehicles in and out of such areas, the weekend traveler who frequents his favorite recreation areas, and those who have observed aerially the minute-to-minute variations of traffic density. The evolution of highway transportation has been so gradual that the nation's more than 100 million drivers have adapted to the disorders with only an occasional discouraging word.

Such adaptation should not be unexpected, as the present highway transportation system and its associated methods of construction and control are the products of a gradual evolution dating back to the Roman Empire's Appian Way. Methods of routing and control for English and American personal transportation in the 19th century was astonishingly similar to present methods. During the mid-19th century in London, safety officers performed the functions of adaptive signals at high volume intersections, and in 1850, traffic congestion in New York City was often dissipated by the policeman's night stick.

About 1920, the motor vehicle became a practical means of extending the environs of most Americans, and the problem of finding one's way became a reality for many drivers. Signing devised by the automobile clubs and local governments became a solution, or rather, a myriad of solutions for route direction. Oil companies and automobile clubs served their customers and members by providing maps and road signs of different complexity. Various inventions, such as Jone's moving map, also provided guidance to drivers. Although the errors in planning and guidance were frequent, the penalties of the errors usually were minor.

Today, errors inflict penalties that are considerably greater, and only recently have drivers become aware of the costs resulting from congestion and from difficulty in finding one's way. Although the costs were intuitively perceived, they were seldom measured, and when they were measured, greatly simplified assumptions were made. Frequently, solutions to a tremendously complex set of problems have been seized upon without a knowledge of how to measure the efficiency of such solutions.

There is no attempt here to provide a solution to traffic congestion problems or to present a comprehensive theory of traffic movement. What is attempted is the tracing of the implications of removing the following three major constraints from the highway transportation system:

- Communication with drivers primarily exists as an *open loop*.
- Communication cannot be individualized but must be utilitarian.
- The highway and the automobile are separate entities.

The difficulties and benefits associated with removal of each of these constraints will be delineated in the following systems analyses. The most striking benefit of removing them, added to *real time* measurement of traffic proficiency, is the possibility of distributing vehicular traffic much more uniformly than is possible with the present system of routing. This strategy, which is mutually advantageous both to individual drivers and roadway authorities, has been labeled *route control* by Gazis (*1*).[2]

A Systems Engineering Analysis of Route Guidance

The specific system to be analyzed is a part of the highway transportation system. It is a collection of techniques, methods, procedures, and devices that will be referred to as the routing subsystem.

Although systems engineering activities will not be described here, some important steps will be delineated. Examples of several excellent books that serve as an outline for this endeavor are those by Chestnut (*2*); Flagle et al. (*3*); and Goode and Machol (*4*). Questions that will be addressed in this analysis, and which will serve as an outline for analyzing the routing problem, are as follows:

- What are the functions of the system?
- How can we characterize the operating environment of the system?
- What information do we possess about the system's current operation, and how should it operate?
- What constraints on system design exist?
- What tradeoffs exist between different proposed system solutions?

The functions of the highway routing system are the provision of *course and routing* information that is available to the driver at appropriate roadway nodes, and the provision of error signals when an improper course is selected or of other adaptive controls when improper maneuvers are made at junctures. These should not be considered independent functions as will be shown later for the proposed design.

The functions can be further delineated by specifying the operations, or tasks, that are inherent in trip generation—trip planning, path control, choice point path selection and control, and terminal or destination recognition. Each of these tasks, demanded of the driver at present, becomes more important as the trip becomes longer, as congestion is more variable, and as the perceptual and cognitive capabilities of the driver become low or stressed.

At present, trip planning requirements are served by human memory, previous transferable experience, and the ability of the driver to make accurate decisions on relative distances and durations of different routes. Distance and duration are derived primarily from maps that also can serve to prepare the driver for certain static elements of the trip. Other information on construction activity or congestion on various links of the trip usually is not reliably available to the driver during the planning stages of *trip making*.

In congested areas of the trip, frequent changes in routing may be necessitated by different levels of traffic demand. The driver who is very familiar with the highway network that he is traversing has comparatively little difficulty in selecting alternate routes. But even in such an environment, he is faced with situations in which his memory may be taxed, his decision process rate exceeded, or information on the state of congestion on alternate routes simply is not available. He frequently becomes what has been labeled a *local stranger*.

Path control primarily involves perceptual information processing and psychomotor control tasks that are related to judgments about overtaking, following, steering, accepting gaps between vehicles in the traffic stream, and passing other vehicles. The degree of interaction between uncertain routing decisions and vehicular control still remains to be resolved empirically, although some data have been obtained. It has been suggested in Brown and Poulton's analysis (*5*) of spare capacity under various conditions of traffic load and intersection frequency and in Sender's technique (*6*) of calibrating information load of drivers that traffic density and highway geometry have a strong influence on the variability of psychomotor control.

More to the point is a simulation study of time sharing by Stephens and Michaels (*7*). This study, although conducted in the laboratory, indicated that the proficiency of a simple tracking task similar to steering was influenced by the amount of signed information along the roadway and by the subject's expectancy for such information.

Field studies that directly measure speed and lateral variability as a function of the amount of destination information to be *stored in the human memory* are now being conducted by researchers of the Bureau of Public Roads.

Further, environmental uncertainty will aggravate increased stress or decreased alertness brought about by alcohol, fatigue, or other causes. It is remarkable that accident rates, which are compounded by destination information that is preserved in the driver's imperfect memory and by his difficulties in locating and recognizing signed information, are not higher than those that have been currently reported.

Proficiency of executing tasks associated with driving differs among drivers. Persons who have a great deal of difficulty in processing

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[2] Italic numbers in parentheses identify the references listed on page 200.

nformation about the highway environment pace these tasks by decreasing driving speed, which consequently, increases the variability of relative velocities of vehicles on the highway (6). Empirical relations between vehicular elative velocity and high accident rates for ural highways have been established by olomon (8). Speed differences as low as −10 m.p.h. were reported to perpetrate about six imes the accident involvement rates as situations in which the vehicles did not vary from he average speed of traffic. Recently Cirillo (9) reached essentially the same conclusions n the Interstate Highway System, although he results were more dramatic. An interesting oint about this relationship between speed eviation and accident involvement rate is hat it is not symmetrical about the mean peed of traffic; the minimum involvement rate ccurs when vehicles operate at speeds somewhat above the mean speed of traffic.

Choice-point path selection and vehicular ontrol in the vicinity of highway junctures lso seem to be strongly affected by the river's difficulties with information processing, decisionmaking, and psychomotor response changes. Mullins and Keese (10) indicated that for freeway ramps, 0.72 accidents er million vehicle miles (APMVM) occurred t off-ramps, and 3.91 APMVM at on-ramps. The converse was reported for California roadways by Lundy (11) who indicated that off-ramp accident rates vary from 0.62 to 2.19 APMVM, and on-ramps from 0.40–0.93 APMVM. Different geometrics, signing, and raffic volumes probably accounted for these ifferences.

According to Cirillo, a rapid escalation in ccident rates occurs as one approaches the ecision point at interchanges. From 2 to 4 miles before the juncture, on urban Interstate ighways, the accident rate is approximately alf the rate in areas between the gore and .2 mile immediately preceding it. Comparable rural Interstate sections yield only about n increase of ½ as one moves closer to the ighway juncture.

Covault et al. (12) attempted to determine he effects of lateral dispersion and speed hanges in the vicinity of interchanges as a unction of the redundant destination information provided by both audio and visual gns. Because of the redundancy of presentation, the probability of directional information eaching drivers increased, and the lateral tability and speed constancy also increased.

As the driver finally approaches his destination, how does he know he has arrived? There a rapid sequence of decisions associated with ocating the specific goal sought by the driver. He must park, usually to minimize the walking istance from his vehicle. In parking lots, on ity streets, and in the vicinity of shopping reas, the demands upon judgment are many. ubjective estimates of the distances involved uring location and parking maneuvering are markedly poor, probably owing, in part, to he fact that the driver infrequently has to make these judgments. There is a cascading f decisions that both demands rapid judgments and consumes a substantial part of most rips. In current studies at the Bureau of Public Roads, the scaling accuracy and judgments associated with turning maneuvers and distance judgments, such as those required in parking lots, are being dealt with.

As approximately 60 percent of trips are 5 miles long, or less (13), final selection of a specific parking spot can occupy from ½ to 2 minutes—a considerable portion of the travelers time. It has been estimated that from 2 to 24 percent of travel time is devoted to parking, and for the driver whose trips are almost exclusively less than 5 miles long, the parking time approaches 40 percent. It is not implied that the terminal phase of travel is constrained by routing information alone; parking availability is undoubtedly much more important in reducing the terminal part of travel time.

For the driver who is unfamiliar with the characteristics of the terminal, the problem is much more critical. The driver must search for cues, that may or may not be prominent, to locate his destination and these cues should indeed tell him when he has arrived. However, there is a period of intervening activity between assimilation of the cues and turning off the motor that requires an empirical analysis, which is planned by Public Roads researchers who will use the information-calibration technique devised by Senders (6).

The effectiveness of fulfilling the tasks that compose the highway routing subsystem depends largely on the specific characteristics of the environment in which drivers negotiate their trips.

Characteristics of the operating environment

The environment in which individual trips are generated is characterized by roadway segments that frequently consist of multiple parallel paths connected at junctures directly or by intervening roadway segments. For traffic assignment, this complex structure comprises the simpler notions of roadway segments (links) and intersections (nodes). When treated this way, a variety of techniques can be applied to solve shortest-route problems (14). Unfortunately, historical data on averages of travel patterns has little applicability to demands on particular roadways, except possibly at times when operation is near saturation.

A much more microscopic analysis of trip distribution and the highway environment would consider at least the following roadway-related characteristics to successfully model the transition of vehicles from one set of roadway segments to another, or from the origins of the trips to the respective destinations:

- Highway lane during the vehicle's approach to each roadway junction.
- Conspicuousness of the junction including signing, roadway delineation, and highway alinement, as a function of distance from the junction.
- Geometric channeling near the juncture.
- Signaling and other control techniques.

The extent to which each of these characteristics facilitates or inhibits the flow of traffic depends largely on the following modulation characteristics:

- Traffic—the density and flow characteristics.
- Pedestrian flows.
- Weather restrictions.
- Vehicle handling characteristics.
- Driver perceptual sensitivities and response capabilities.

Several microscopic models, incorporating various combinations of parameters, already have been developed (15, 16, 17). To say that microscopic analysis of intersection and interchange operation is required is not to say that network operation and corridor operation analyses are not required.

As pointed out earlier, the objective of route control is to distribute vehicles on the roadway network and increase traffic flow throughout the network. To achieve this objective it is necessary to ascertain the diversity of trip origins and destinations, the time distribution of departures and arrivals, and the existence of parallel routes in different corridors. A discussion of anomolies of traffic operation caused by various stressors is beyond the scope of this article; it suffices to say that inclement weather, poor vehicular acceleration characteristics, high vehicular density, and driver capabilities all can influence traffic operation to a considerable degree. Perhaps a more salient question is, "How should traffic operate on the highway network?"

Normative system operation

In the preceding discussion, many characteristics of the traffic environment, as they affect distribution of vehicles on the network, were considered. It is now necessary to define the highway system in general operational terms to subsequently consider the effects of certain constraints on the traffic environment.

Perhaps the most general characteristic of total highway-system operation is the degree of entropy that the system has. Entropy in the context here can be viewed as the variation of traffic flow on the totality of all roadways, or links, within the system. Hence *Traffic Systems Entropy* can be defined as the sum of the variances of traffic flow which, obviously, is conditional and depends on the time period over which measures of flow are gathered. Accordingly, reference can be made to yearly, monthly, daily, *rush hour*, or entropy for any time period, depending on the purpose of the inquiry. For example, if it were necessary to determine whether several signal strategies for different daily time periods were warranted, flows would be measured on a base of one hour or less.

Of the several advantages to defining entropy in information-theoretical terms, the major advantage is the partitioning of information without regard to metrics (but not without regard to logic). The same measure of information can be arrived at in several ways, including the speed variability of pairs of vehicles, of individual vehicles, etc. Shannon's classic on information theory (*18*) has shown that, logically, variance can be transformed into information (or uncertainty or entropy).[3] Using the same types of formulation, throughput can be calculated for individual intersections or extended to broader networks. Other formulations, including conditional flow, can also be developed.

It is beyond the scope of this article to demonstrate analytically the relations between different microscopic measures of information for vehicular traffic flow. It suffices to state that once the transformations between flow and vehicular-speed and acceleration patterns are made, different equivalent operations should provide equivalent results, although some estimation processes are more efficient than others.

Treated in such a context, the capacity of a highway arterial or network section can be considered as a maximal-transmission or bandwidth problem, requiring decision-rules for recommending alternate routes when flow approaches theoretical capacity. Nearly all improved routing techniques are developed to increase the existing level of service so that it approaches theoretical capacity.

The proposed method of routing drivers through highway networks has been based on a partial analysis of flow data, as sufficient data exists to effect detailed analytic solutions. Network efficiency, as it is now determined, is a macroscopic measure that does not treat minute variations in the system. It is meaningful to planners, designers, and officials who are operating a traffic control system, but not to the individual driver who is primarily concerned with completing his trip quickly and reliably (*19*). As long as there is a monotonic relation between these two criteria, no difficulty exists. Otherwise reconciling the two becomes an optimization problem.

An important step in the development of the proposed routing system was a study by Carter et al.,[4] in which an attempt was made to develop a conceptual scheme for measuring the effectiveness of highway networks. Their approach was reductionistic and strongly oriented toward driver benefits rather than to total network advantages. The following excerpt from this unpublished report illustrates hypothetical relations between certain of these measures:

"The criteria for effective operation of a highway network must be operationally defined in terms of level of service of the network, safety, and comfort, and convenience to the operators. Values must accordingly be assigned to each of these criteria and finally alternate systems evaluated in such terms. One of the most difficult problems associated with such evaluation is how to optimize among criteria measured in differing terms. The evident answer lies in devising a common measure, or metric, to ascertain whether certain criteria which seem really important to the planner are actually important to the user. For example, a number of researches have indicated that drivers appear to choose routes which provide time savings even though drivers might have to drive much greater distances. Hence it would appear reasonable to employ time savings in place of or in some weighted combination with physical distance over the network as a criterion of network performance, at least for a number of types of travel.

"Michaels (*20*) has suggested an even more comprehensive formulation which provides a common index of subnetwork usage. This measure incorporates branch distance (in miles), relative distances on high-design facilities and low-design facilities and average travel speeds and distances. An equivalency measure can be established between these values and the level of stress impinging upon the operator. This provides for a scaling method relating certain of the variables associated with comfort and convenience.

"For various levels of this measure, both the effect upon traffic operations (primarily in-steam turbulence and turbulence at junctures or nodes) and upon safety (the probability of collisions weighted for severity) must be determined. . . .

"The level of traffic or vehicular performance can be operationally dealt with at a molecular level. Turbulence has been operationally defined for the branch situation by a number of investigators. 'Acceleration Noise' (standard deviation of acceleration) has been employed for the in-stream case by several investigators. While this measure is gross it is becoming widely employed to differentiate various levels of traffic operation. Rocca (*21*) has developed a more comprehensive analytic technique for evaluating the effects of particular disturbances introduced into the traffic stream (e.g., the effects of a stopped vehicle on the road shoulder upon in-stream speed variations). . . .

"Molecular operation of vehicles at nodes has also been explicitly considered by Bureau of Public Roads personnel while at least two contractors, Covault (*12*), Mace, et al. (*22*), have explicitly developed criteria for effective juncture operation. These criteria include operator-vehicluar performance in the traffic stream prior to the diverging operation as well as performance on the ramp itself."

Although there is little assurance that the measures presented here are relevant, the absence of data necessitates, as a guide for further research, the development of certain hypothetical relations between driver efficiency and network efficiency. If driver benefit is considered the percentage of drivers taking the shortest temporal routes from origins to destinations, it is more meaningful to talk about the impedance of the highway system, I(S), because of the difficulty of prescribing upper bounds for obtainable speeds on different highway segments.

Network impedance can be taken as the difference between highway capacity, or maximum flow, and the actual flow on each highway link summed over all the links in the network. If an upper speed bound, V(S), could be prescribed, then system efficiency, E(S), might be taken as that speed less I(S), or simply $E(S)=V(S)-I(S)$. Although the scales are mixed—one ordinal, the other ratio—the relations between network impedance, as defined here, and the percentage of drivers taking the shortest routes as shown in figure 1.

It is suggested by these relations that, when *free flow* conditions are maintained, *familiar* drivers are not obliged to change or reduce their velocities substantially; they will traverse a route because of its intrinsic benefits. The route is simply a preferred one. As capacity is approached on a particular link, average speed decreases, and the driver *scans memory,* receives radio communication about traffic conditions, or employs passenger knowledge and preference or maps to choose alternate routing *rationally* and improve his route selection. The *unfamiliar driver* who has not previously traversed the route has little to facilitate his travel. Hence, there seems to be a monotonically increasing function between driver benefit and network efficiency for *unfamiliar drivers,* but network efficiency would be less than maximal when *unfamiliar drivers* choose shortest temporal routes.

At least one more concept should be introduced into a generic analysis of network operation: the notion of the degree of adaptation afforded by the system dynamics. Traditionally this concept contributed little to the development of routing systems, although within the last few years, many dynamic operations have been reported in connection with traffic operations—freeway surveillance and control systems (*23*), helicopter communication to drivers (*24*), and adaptive signalization techniques (*25*).

It is expedient to develop some notions of relative benefits when the system is treated either in a static context, with infrequent updating—during a.m. or p.m. rush hours—or in a dynamic context with *real time* data provided for updating *best route* solutions. A routing system in which instructions to drivers are based on *best route* solutions derived from

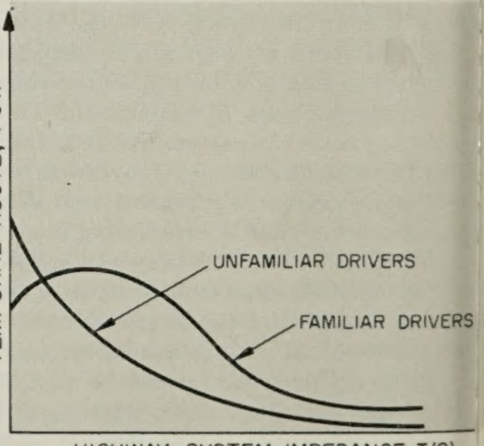

Figure 1.—Relation between driver benefits and highway system impedance.

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[3] Each sample should be taken over a fixed time period, for example a 5-minute interval. Maximum correlations might be obtained by applying auto-correlation techniques that permit estimation of the delay associated with each juncture. The use of such a technique is open to question, however, as stationarity should be assumed. The delay itself probably should be treated as a random variable.

[4] *Systems Analysis Study for a Highway Coding and Route Recognition System,* by A. A. Carter, R. E. Emery, B. W. Stephens, J. M. Wright, and F. J. Mammano, Bureau of Public Roads, September 1966 (Unpublished).

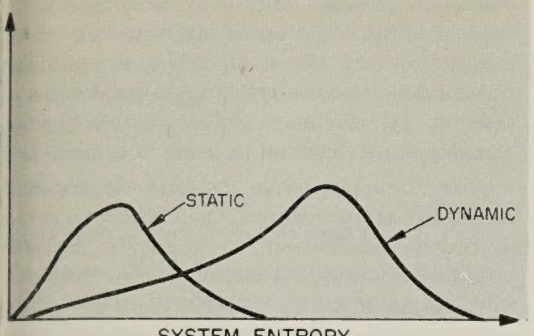

Figure 2.—Roadway system value relations.

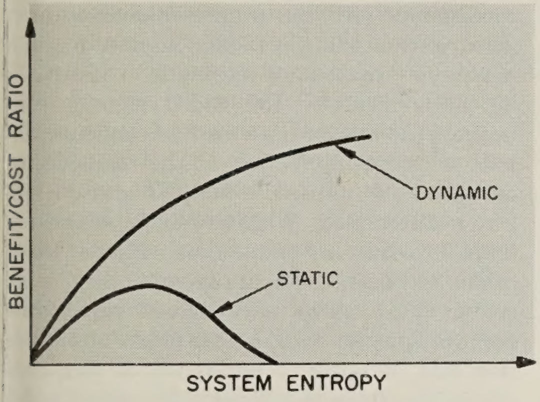

Figure 3.—Individual value relations.

istorical data will be called a *static routing ystem*. A routing system in which instructions o drivers are based on data supplied by air nd ground observers and by other surveillance techniques, with solutions updated frequently, will be called a *dynamic routing system*. At resent there is little reason to provide routing nformation, as it could be used only for signalization schemes. But if it is assumed that routing information could be used to increase the throughput at highway junctures, as well s to direct drivers, its provision attains practical significance apart from theoretical ignificance.

One approach to the problem of providing suitable system is to map system entropy nto a measure of a benefit-cost ratio for each ype of system. Total system entropy must be stablished, or evaluated for subnetworks. Obviously each benefit and cost must be made perational and reflect an extrapolation for ome period beyond the initial installation. Benefits are assumed to be weighted cost-functions or another common metric, such as that discussed in Michaels' article (*20*). Such scale is of little value unless it is either the nterval type or the ratio type.

A number of tradeoffs in selection of benets must be made. In the transportation of eople, the *bread and butter* is the level of service afforded by the different highway sections. Construction of additional freeway lanes is an expensive proposition with costs in some urban reas as much as several million dollars per mile. Deployment of guidance aids usually is ssumed to develop linearly with system entropy, although stepwise implementation seems to be a better extrapolation of the historical trend.

To highway officials, the salient benefits from any guidance system would be safe and efficient operation of the highway plant translated into reduced construction costs, fewer hazardous appurtenances, and lowered operating and maintenance costs. At present, when levels of service fall below established criteria, costs usually increase, as highway lanes, interchanges, parallel roadways and signalization systems are added to the system. To the driver, the salient benefits of a guidance system would be stopped delays, decreased travel time, lowered fuel costs, and less stress.

A cumulative logarithm function for benefits has been assumed and is expressed as:

$$B=a\left(1-\int_0^x e^{-gx}dx\right)$$

Where,

a, g are weighting values

x is the number of aiding units

B is the measure of benefit

The costs have been assumed to be of the same form, except that the weighting constant associated with the exponent is larger—becomes asymptotic more rapidly. The limit, then, of benefit-cost (B/C) ratio is a constant. When the B/C ratio is compared to system entropy, returns begin to fall off beyond some maximum value.

But such routing strategies do not permit responsiveness to changes in traffic demand, unless routing is altered according to historical data or operation is responsive to the minute-to-minute alterations in demand. There is no obligation to be responsive to low-flow, high-concentration conditions, because such persistent, obvious, bottleneck conditions could be alleviated by new construction.

The initial costs of a dynamic system undoubtedly would be high, but there would be a decrease in cost as engineering production increased, although the decrease would be less dramatic. The benefits for a low entropy system should be about the same as those for a static system, but as entropy and impedance increase, the benefits should increase as a logarithmic relation. These conditions suggest more gradual increase toward a maximum when the B/C ratio is taken relative to system entropy. These system and individual-value relations are plotted in figures 2 and 3.

Benefits to individual drivers mainly continue to increase as a system of routing aids are implemented unless they actually have an adverse effect on travel. For the individual driver, direct costs are fixed and indirect costs are nominal. Functions for static and dynamic systems are inverted-U shapes; however as system entropy increases rapid obsolescence would be expected. Only in areas with persistently small populations would a truly static system be expected to be useful.

Maximum B/C ratio for a programed routing system undoubtedly lies somewhere in between the two prototypes described here. A truly static system will not have practical utility unless it would be applicable to only one time period—non-rushhour—or it would be employed only in areas where prohibitions do not change for daily time periods. Subsequent discussion deals only with the programed-type or dynamic system.

System constraints

Historically there have been many constraints on methods to provide good-quality, reliable highway navigational aids. These constraints might be loosely classified as either technological or socio-economic. While many socio-economic constraints markedly affect system effectiveness, they will not be discussed explicitly; rather, principal technological constraints will be examined.

Previously, it was hypothesized that the reliability and efficiency of traffic networks can be enhanced by making the system dynamically responsive to individual user requirements. Also, favorable benefit-to-cost ratios were depicted for a dynamic system deployed on a high entropy network. Now, the major technological constraints on our present highway navigational system, which must of course be removed to provide a dynamic, user-responsive system, can be examined. As indicated earlier, these constraints are as follows:

- Open loop communication.
- Utilitarian, rather than individualized communication.
- Separation of roadway and vehicle components of highway transportation.

Communication is *open loop* in the sense that information flows in one direction only—from the highway sign to the vehicle operator. There is no provision for the driver to make his destination known to the system. In other words, there is no feedback channel in the system.

In any control system the consequence of open loop operation, with no feedback, is that very careful calibration of the system is required. In the present route guidance system this calibration is accounted for by the design of the sign message, which leads to another major constraint—nonindividual or generalized, presentation of routing information.

Information conveyed by signs must be designed for the traffic stream at large. Consequently, it is inherently impossible with sign messages to convey precise meanings according to individual driver's needs or destinations.

If a sign message does not conform to a driver's expectations or if he lacks good orientation, the result is hesitation and indecision at crucial decision points. Consequently, accident potential is increased at decision points, and turbulence can be introduced in the traffic stream with resultant adverse effects on capacity. A wrong decision means extra travel and driver frustration. Also, there are documented cases of drivers backing down freeway exit ramps and performing hazardous weaving maneuvers after they had decided that the wrong decision had been made (*26*).

There is another constraint on our present highway system: vehicles operating in the system and the operators of the system—highway authorities—are relatively independent of one another. In today's highway system, this independence is manifested by the lack of direct communication links between the highway and the vehicle.

For example, Desrosiers (*25*) has shown that a considerable period elapses before vehicle operators adjust to a change in the speed of progression of a signal system. His research clearly shows the need for direct communication of the traffic signal setting to operators of vehicles using the system.

In summary, by removing the constraints on communications between vehicle and highway, many benefits, other than route guidance, could ensue. However, description here will concentrate on how a two-way communication system between the vehicle and highway can benefit the route guidance function.

Techniques and system solutions for vehicular routing

The number of techniques for communicating directional and guidance information to drivers has increased as technology has grown. Early constraints have become less compelling as the economics of electronic circuits have become less restrictive from the user's point of view. A brief look at highway-signing methods and routing-communication techniques permits a perspective that leads to solutions to highway routing problems that should be both economically feasible and socially acceptable.

Through the years, highway route signs and marking techniques have changed tremendously. From the era of makeshift local directional signing and colored bands on poles to identify routes, signing has progressed through the establishment of the U.S. and State route signing to the standardized Interstate system signing. Whether every change has been truly an advance is questionable. Color coding, currently being suggested in some quarters as a step that should be taken to promote smooth flow and safety, is characteristic of some of the earliest route markers. Following is a brief description of some of the most prominent methods of signing in use, or experimentally operated, today.

Static visual signing.—Static visual signs are attempts to provide the driver with destination and routing orientation. Occasionally, with the assistance of maps, the driver may choose, one, two, or three routes to a specific destination. Destination information, if it appears on the sign, does not necessarily relate to the driver's destination, but may be merely another milepost to the driver's ultimate destination. The routes given to the driver do not always take into account delays caused by congestion and other transient events. They could be selected for shortest travel time, for scenery, for business, etc. On high speed roadways, signs must be massive to accommodate the driver, but their size creates a driving hazard. In urban areas signs may tend to be very small and difficult to read even at low speeds. Sign designers, however, do not take into account the variable visual proficiencies among drivers or the complicated maneuvers that often have to be performed. Thus signs are frequently not placed in an optimum location to aid all drivers.

Variable message visual signing.—In recent years variable message signing has been used to a limited extent. This type of visual signing attempts to take into account delay owing to congestion. By proper sensing equipment or by use of a clock to indicate the beginning and end of peak periods, delays can be indicated by some figure of merit, and possible alternate routes transmitted to the driver by the variable message sign. Again, this type of signing is merely an intermediate aid to the driver and does not account for his ultimate destination.

Audio signs.—Studies of audio signs have shown that advisory information regarding approaches to exits, obstacles, maintenance operations, traffic accidents, etc., can be transmitted to vehicles as they proceed down a highway. This system uses a prerecorded audio message that is continuously repeated at preselected points on the road. A roadside antenna, trigger loop, and transmitter are employed, as well as an in-vehicle receiver. This type of signing is conceptually similar to static and variable message signing; however, the system could be portable and act as an early warning device for drivers as they approach hazardous situations. It is conceivable that alternate-route information could also be prerecorded.

Direct inquiry techniques and maps.—A driver today has several methods at his disposal for obtaining a routing to a destination. The familiar oil company maps as planning devices and tourist services offered by oil companies and automobile clubs are the most common assistances given to drivers. In some areas he may also call a travel service if he is equipped with Citizens Band Radio. All of these methods still require the driver to search out the appropriate signs of landmarks.

Passive communication systems.—In a passive communications system, the roadside equipment would continuously transmit coded signals concerning all destinations. The vehicle equipment would accept only the signal that corresponds to the encoded destination. The coded signal would also correspond to the type of maneuver to be performed at that particular intersection or trigger a particular message to be presented, either visual or aural, to advise the driver of the maneuver to be performed. This system would require that most of the equipment be housed in the vehicle. If a number of nodes instrumented are very near to each other, the problem of radio interference arises. Many frequency allocations would be necessary, and these are almost impossible to obtain because the spectrum at present is fairly well filled. Another disadvantage is that maintenance of complex equipment would be the responsibility of the driver or vehicle owner, if the logic equipment is housed in th
vehicle. From the condition of some of th
automobiles on the road today, it is difficu
to visualize communication equipment that
always in working order. Gumacos an
Cramer have reported on such a system (*27*

Active communication systems.—In an activ
communications system, the vehicle transmi
a coded destination to roadside decodin
equipment through a two-way, near-field con
munication link. On request from a decode
the in-vehicle transmitter is triggered to sen
the destination to the roadside equipmen
which *looks up* the destination in a prepr
gramed, *best route* solution matrix or set
tables and sends, through the same commun
cation link, the appropriate coded signal
correspond with the proper maneuver to b
performed at that particular intersection. Th
maneuver symbols, or messages, are activat
in the vehicle by the coded signal, whi
triggers the appropriate display elements. T
bulk of the equipment is at the roadside; t
in-vehicle equipment is simpler and requir
less maintenance. With a vehicle active sy
tem, benefits are numerous. For examp
origin and destination study capability, traf
count data, traffic surveillance capabiliti
etc. are built in. Also, a near field communic
tion link requires a minimum of frequen
allocations from the Federal Communicatio
Commission. The best example of such a sy
tem is described in the final report of a rece
Public Roads research project (*28*).

A Proposed Route Guidance Concep

About two years ago, the Bureau of Pub
Roads began to develop a new route guidan
concept. A number of studies that indicat
positive benefits from a system to overcon
some of the deficiencies of existing rou
guidance techniques, had been concluded
were nearing completion (*12, 22, 27*). Furth
more, there were proposals from a variety
groups to proceed with development of devi
for directing information to drivers by vario
means. Though none of the devices propos
were actually complete route guidance s
tems, many of them had features that possily
could be employed in a complete system. t
was becoming evident that a comprehens e
analysis and plan was needed to integr e
previous research and to guide future wo
From the integration of previous work and a
thorough analysis of the problem, a propo d
route guidance concept has evolved. Conc t.
testing of a closed loop, individualized, in
grated-highway-vehicle communication syst n
was carried out in the Washington, D.C. ar
The results indicated highly significant i
provements in travel time and stress red
tions (*29*). The essential features outlined n
the succeeding discussion characterized e
system concept.

Individual communication

To overcome the inherent limitations f
highway signs and their messages to e
traffic stream at large, it was deemed necess y
that the route guidance system communic e
information to individual drivers. This feat e

justified by studies[5] (*6*) that have shown at drivers' control performance is facilitated hen uncertainty is decreased and that have ggested that traffic operations should be gnificantly improved when individualized mmunication is employed at freeway exit mps.

ecific maneuver information

To bring drivers' decision-making requireents to an irreducible minimum, it was parent that information on the specific aneuver to negotiate a choice point must be nveyed, and that it be conveyed unamguously to individual drivers. Therefore, the ncept requires that the communication must rminate in the drivers' vehicles, which in rn, creates a need for an information display r the driver. The driver's display is the final k in the communication subsystem, and e information it emits is the basis for the iver's control actions. The design of the splay is critical, as it is the major informanal interface between the human operator d the highway-vehicular environment. A tailed analysis of requirements for relating splayed information to highway geometrics s been given by Eberhard et al. (*30*). uman factors analysis has indicated that the st display technique available is the *head-up* splay being used in low altitude aircraft. feasibility study was conducted and entuated in a vehicular head-up display ototype (*31*).

A parallel requirement to that of providing ecific maneuver information at a choice int is: the sequence of choice point decisions ust add up to a *best route* to a driver's stination.

ique codification schemes

The route guidance concept that has olved requires information coding schemes at are desirably efficient, flexible enough r other highway uses, capable of future pansion without disruption, and compatible th state-of-the-art of information-handling bsystems, both machine and human. A ding scheme for intersections, which is mpatible with *best route* solutions and ich is human engineered to reduce shortrm memory requirements, is described in e final report of a Public Roads study (*32*). Efficient machine code techniques and timum human usage is required in the terface between address machine logic and e operator during the process of encoding. me of these requirements have been dressed by researchers, and analysis is ing continued by the Bureau of Public oads.

According to analysis of the character of rectional codes, links, nodes, and link scalar antities are insufficient for high quality lutions of *best routes*. Solutions of large netrks having deterministic link scalars can be tained in reasonable periods using decomsition techniques, but most routing problems have relatively small stochastic link scalars as input data, which suggests more microscopic analysis would be fruitful.

Models of traffic flow using a combination of parallel links and sequential and conditional dependencies to select particular links at each node have not been formulated. High quality solutions will depend on a codification system yet to be devised. Further, as a result of coding work accomplished thus far, it is apparent that information coding goes beyond the route guidance concept and overlaps with several other important highway functions, including urban traffic control and urban transportation planning. The present coding scheme will be the subject of continuing review, and compatibility analyses will be made with other highway functions in mind.

Static to dynamic conversion capabilities

In the early stages of route-guidance-system development, it was recognized that a static system would have limited utility because a large part of highway travel consists of repeat trips over familiar routes. For the guidance system to be useful for these trips, it would be necessary to sense changing traffic and environmental conditions, and accordingly, change routings to provide *best routes* in a dynamic situation. Analysis presented earlier in this article provides the rationale for such a decision, and one of the design goals has been to develop coding and hardware that is capable of conversion to a dynamic system. Design of the system should provide for simple methods to update preprogramed stored tables at each instrumented roadway area.

Compatibility with existing signing

Another feature of the proposed route guidance system is its inherent compatibility with existing guidance techniques. Present signs would remain in place during conversion to the new concept and would not have to be changed in any way. After the new concept was widely implemented, they could be reduced to the minimum that might be required for back up if the system fails or for the fraction of vehicles or intersections that might not be equipped.

Warning and regulatory functions of present signs can also be handled by the proposed system, including some situations that are troublesome for existing signs. One example is the familiar *lane drop* situation at interchanges. The proposed system can give a driver an advisory lane-change-maneuver signal at any desired point along the highway. Properly placed for traffic and geometric design conditions, this signal could eliminate driver indecision and provide ample time for a merging maneuver. Moreover, the left hand exit ramp could be handled similarly. The one-way street situation is an example of a regulatory-sign function that could be served by the proposed system. One-way streets would be accounted for and drivers would get only signals for the proper direction. The problem is nontrivial for streets that are operated reversibly during peak hours; the roadside logic could respond to the change in direction and relieve the driver of reading and interpreting reversible one-way signs.

Programatic Development

No matter how superior the concept is, without a program of research and development studies with reasonable levels of support, the effort of identifying a desirable roadway navigational system is merely a mental exercise. Development of a program based on the findings of other investigators, as well as inventive attempts at communicating with vehicles from the roadside, has begun. What to communicate, when to communicate, how to communicate, and why we should communicate has been presented herein in considerable detail.

Guidelines were developed in an intensive study of the highway coding and route recognition problem conducted at the Bureau of Public Roads in 1966.[4] Within 6 months, a research and development plan that incorporated the following phases was developed:

- A detailed analysis of driver information needs and rules for the optimal transfer of such information.
- A coding requirement and format.
- Development of a programed routing system design for both roadway and in-vehicle hardware.
- Construction and installation of a limited amount of hardware for test and evaluation.
- Conduct of a test and evaluation plan.

The plan was to serve as the nucleus of major study, but could not be considered a program in itself. Time phasing and identification of the criticalness of each step ensued. Since that time 26 research and development functions have been identified.

Driver information requirements for route guidance

Development of a rational description of highway routing was the first logical step in providing a highway guidance scheme. There was no evidence that such a description had been developed for signing applications, despite the substantial costs of signs—estimated to be in excess of $3 billion.[4]

A generic language for highway routing applications was developed as part of an effort to define the navigational part of the driving task (*31*). Basically this was an information-requirements study, but it was developed at a fair level of detail.

A practical consideration has evolved from the question of where, spatially, should information be presented to drivers. An analysis of information lead-distance followed from work formerly conducted (*22*). Rules for decisions on where roadway hardware should be physically located with respect to highway choice points are being formulated. Most of this work is based on empirical analysis of the need for specific maneuver information, an analysis that is to be verified by use of vehicular stability measures.

Many factors influence the variability of responses elicited by different drivers, hence the influence of aging, stresses, and specific information requirements of traffic and highway geometrics all are being studied.

The task of establishing driver information requirements includes some prediction of human acceptance of a system in which design

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Additional Studies on Driver Information Processing, J. W. Senders and J. L. Ward, Final Report, Contract PR-11-5096, Bureau of Public Roads, 1968. (Unpublished).

parameters, hopefully, are optimized. Preference data are being collected from a substantial population representing a cross section of drivers. A unique form of questionnaire, basically a motion picture technique, is being used to obtain these data. All of this work will lead to development of a final routing configuration that is engineered for human use.

Attributes of network coding and best-route algorithms

As early as 1964, the Public Roads staff recognized the need to develop a national standard system of coding highway nodes that would be equally available to all potential designers of electronic routing and highway communication systems. A computerized technique was developed to solve the problem of routing an individual from any origin to any desired destination within a highway network (*27*). The uniqueness of the code and also the partitioning scheme for dividing up the highway network are shown by the following explanation:

Uniqueness.—A coding system and formatting technique has been developed for the unique identification of more than four million intersections in the United States. It is a logically consistent method for naming intersections and roads of a highway network.

Partitioned sets.—Owing to the size of the existing and projected roadway network, a certain procedure was used to develop the code. As the code had to properly identify the roadway network, a dual form of partitioning was established—geographic, to describe locality by the code; and hierarchial, to reduce the total information loading and handling requirements by selective transmission of hierarchial information. This is done by furnishing complete information about the network in the driver's immediate vicinity and less information about the network, at locations removed from his vicinity.

Rapid access and updating.—An algorithm (*27*) enables a solution of a matrix to determine *optimal routes* on a highway network. Optimal routes can be described by such criteria as travel time or distance. Use of such a code in a programed routing system requires three matrix solutions—one for each of the two peak and the off-peak periods. However, in a dynamic system, solutions are needed more frequently to account for delay, congestion, weather, etc. Therefore, a system for rapid updating and access must be developed for the dynamic system. Algorithms are yet to be developed to determine optimum real-time solutions for alternate routes in a network.

Hardware design

Based on the route guidance concept described and the *best* route algorithm and network coding, hardware to implement the system was designed. An engineering model, now operational was developed. The final report of the development project (*28*) gives details of the system design. Only the general features will be described here.

The system design includes both vehicular and roadside components. The vehicular components encode the driver's destination, transmit the destination to the roadside components at an intersection, and display the correct maneuver symbol or message received from the roadside.

The roadside component receives the driver's destination code, decodes the destination in terms of a specific maneuver symbol or message, and transmits the maneuver information back to the vehicle. Roadside decode logic is based on stored programs developed from solutions to the *best route* algorithms mentioned earlier.

Communication occurs through simple loop antennae mounted under the vehicle and buried in the pavement in each intersection approach lane. During the period (0.03 sec. or less) when the vehicular antenna is within the field of the buried road loop (generally corresponding to the physical boundaries of the road loop), destinations are transmitted and maneuver instructions received. Thus, each vehicle is specifically and individually serviced by the system.

Testing and evaluation of system effectiveness

The route guidance system described here is being proposed as a means to improve the safety and efficiency of the entire highway transportation system. The implementation of such a system would require large expenditures by highway authorities and road users, and before a decision to implement such a system is made there must be a sound and convincing demonstration that the expenditures can be justified; in other words, do the benefits justify the costs?

To provide inputs for a benefit-cost analysis, an elaborate test and evaluation program is being planned. The goal of the program is to evaluate the effectiveness of the system from the standpoints of both the driver and the highway authorities. Accordingly, the system evaluation plan consists of two distinct types of tests which can be classified as macroscopic and microscopic, as follows:

Macroscopic tests

Driver benefits:

- Time savings owing to *best routes* and fewer errors.
- Fuel savings.
- Fewer accidents.
- Fewer information stops.

Road benefits:

- Minimize overall travel time.
- Efficient use of network.
- Reduced congestion.
- Reduced air polution.
- Less congestion from accidents.
- Fewer roadside hazards.
- Fewer accidents.
- Improved aesthetics.
- Reduced signing requirements.

Microscopic tests

Driver benefits:

- Reduced operator stress.
- Improved vehicular control owing to uncertainty.

Road benefits:

- More efficient use of highway network because of decreased turbulence at decision points and higher overall speeds.

Plans for conducting these tests call for network of about 100 intersections in a secti of a large metropolitan area and a fleet f about 50 instrumented test vehicles. So tests will be conducted entirely on the instrumented network; others may consist of t runs in other noninstrumented portions of t area. Network and driver characteristics a driver population will be selected to make t tests as representative as possible. Tra characteristics, such as trip length, trip p pose, and time of day, will also be consider in the formulation of the experiments.

The test and evaluation program is bei designed to produce definitive data on bene that can be expected from a static rou guidance system. The test network is bei selected to provide several configurations which dynamic system concepts can be eva ated. The costs of equipping and program the network and the test vehicles will also established.

It is hoped that the results of the test a evaluation program will serve as inputs t comprehensive benefit-cost analysis. The u mate objective of the test and evaluat program is to determine the feasibility wide-scale implementation of the syste which would, of course, take into acco developments of related systems for aid the driver.

REFERENCES

(*1*) *Mathematical Theory of Automo Traffic*, by D. C. Gazis, Science, vol. July 21, 1967, pp. 273–81.

(*2*) *Systems Engineering Tools*, by Har Chestnut, John Wiley and Sons, 1965.

(*3*) *Operations Research and Systems E neering*, C. D. Flagle, W. H. Huggins, R. H. Roy, editors, The Johns Hopkins Pr 1960.

(*4*) *Systems Engineering*, by H. H. Go and R. E. Machol, McGraw-Hill, 1957.

(*5*) *Measuring the Spare Mental Capacit Car Drivers by a Subsidiary Task*, by I. Brown and E. C. Poulton, Ergonomics, vo 1961, pp. 35–40.

(*6*) *The Attentional Demand of Automo Driving*, by J. M. Senders, A. B. Kristoffer W. H. Levison, C. W. Dietrich, and J Ward, Highway Research Record 195, 1 pp. 15–32.

(*7*) *Timesharing Between Two Driving T —Simulated Steering and Recognition of I Signs*, by B. W. Stephens and R. M. Micha PUBLIC ROADS, A JOURAL OF HIGH RESEARCH, vol. 33, No. 5, December 1964, 81–88.

(*8*) *Accidents on Main Rural High Related to Speed, Driver, and Vehicle*, by D Solomon, Bureau of Public Roads, 1964.

(*9*) *Interstate System Accident Rese Study II, Interim Report II*, by Julie A Cirillo, PUBLIC ROADS, A JOURNAL HIGHWAY RESEARCH, vol. 35, No. 3, Au 1968, pp. 71–75.

(*Continued on p. 212*)

Samples being taken from bituminous pavement for testing—coring a 6-inch diameter sample (left) and sawing a square sample (right).

Quality Assurance
n Highway Construction

Part 4—
Variations of Bituminous Construction

ported by EDWIN C. GRANLEY,
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aterials Division

BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

This is the fourth part of an interpretative summary of the progress in Public Roads research program for the statistical approach to quality assurance in highway construction. Part 1.—Introduction and Concepts, Part 2.—Quality Assurance of Embankments and Base Courses, and Part 3.—Quality Assurance of Portland Cement Concrete were presented in previous issues of PUBLIC ROADS. The remaining parts, to be presented in succeeding issues, are 5.—Summary of Research for Quality Assurance of Aggregate, and 6.—Control Charts.

Introduction

N 1879, a natural asphalt from Trinidad was used on a street project in Washing- n, D.C., marking the first modern use in ts country of a bituminous material in road nstruction. The practice of treating the permost surface of roads with a thin uminous overlay, such as that used on this eet project, continued. The advent of the tomobile, bringing with it the production gasoline and its byproduct, bitumen, ought the material into widespread use, st as a dust preventative and later as a nder for asphaltic concrete.

In the early stages of bituminous mixture velopment, many of our present specifica- ns and tests were developed to guide con- ctors and to provide rules for acceptance. itially, one of the major functions of a speci- ation was to supply technological instruc- ns to the contractor and field engineer. It was necessary to specify exactly how to produce the mixture, how to place it, and how to compact it. Now, the industry has progressed so well that the States soon should be able to specify characteristics of the final product in terms of measurable parameters and to accept it when test results indicate that desired characteristics have been obtained. Before this goal can be reached, however, some problems must be overcome and the ultimate degree to which *end result* specifications can be used in bituminous construction must be determined. Nevertheless, progress is being made in changing from the contractor-State-control construction team to the true contractor-control and State acceptance concept. In shifting responsibilities it is important that acceptance plans protect both the contractor and the State.

To determine the quality characteristics of current construction, many States have been measuring variations in accepted bituminous production. Most of them have followed the guidelines developed by the Bureau of Public Roads Quality Assurance Task Force. The studies patterned after these guidelines not

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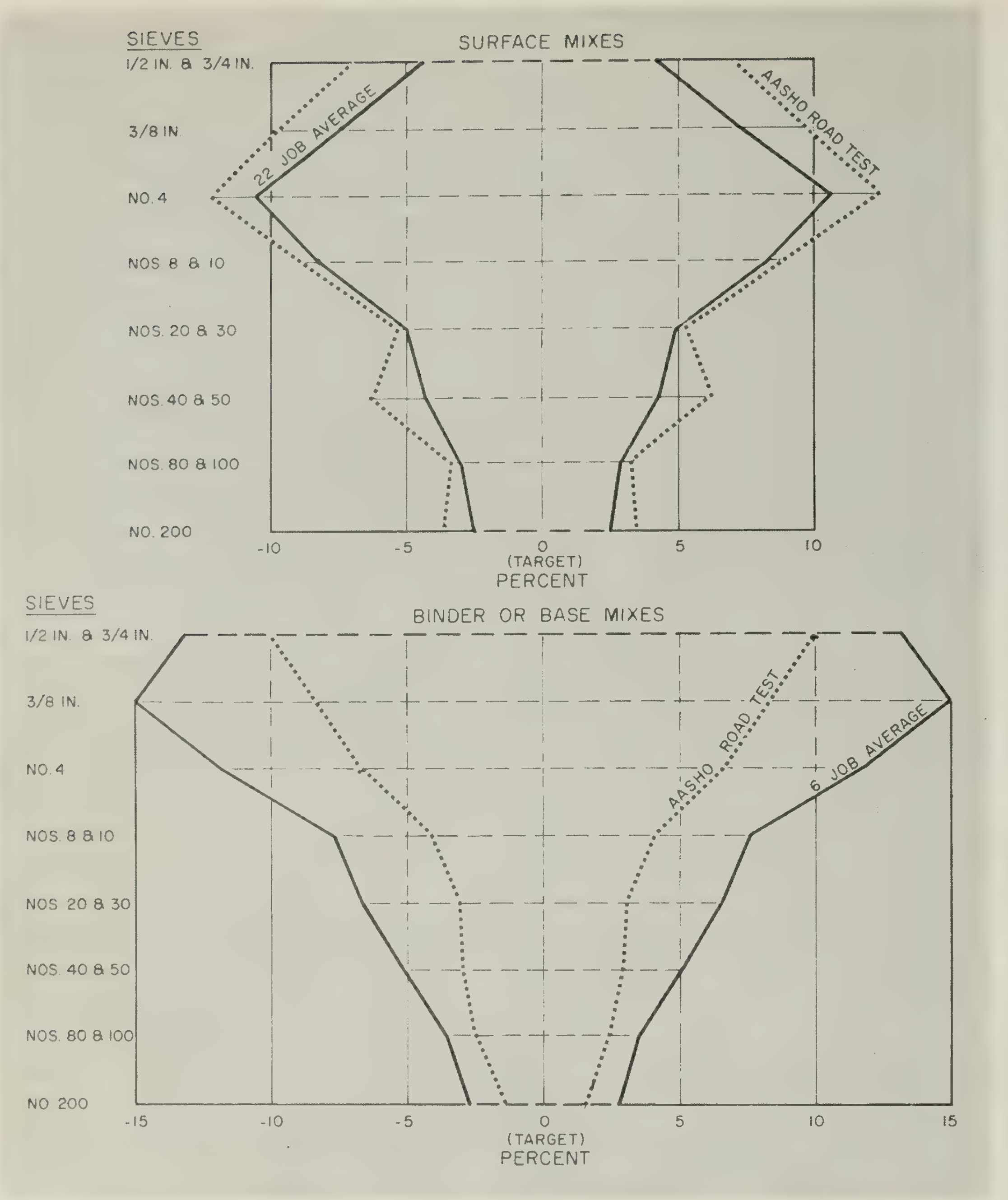


Figure 1.—Computed 3$^{\sigma}$ limits on target values of job mix formula for aggregate gradation—surface and binder or base courses.

only are providing estimates of the quality of construction, but also are isolating causes of variation.

Data from these studies are revealing the following significant results:

- Variability, indicated by the standard deviation, σ, is itself a variable, and a set value for a standard deviation applicable to the process cannot always be assigned.
- Calculations of the amount of material, or construction component, within present tolerance limits often indicate a considerably lower percentage within the tolerance limits than is expected.
- Test variation, or test error, is often an important factor affecting acceptance or rejection of the material.

Many laboratory-designed tests and sampling plans now being used for on-the-job control and acceptance are inadequate. These devices, developed for 1940 production rates, are still being used to attempt to control and accept bituminous production that exceeds 4,000 tons a day.

Research results obtained in studies f construction variations by several State hig-way departments have been summarized i this part. Compiling data from bituminc s hot-mix projects throughout the country s like putting together a jigsaw puzzle in wh the pieces never quite fit and even some e missing. Certain editorial privileges a l mathematical manipulations were used b present data uniformly. Sometimes statisti l rules were not strictly adhered to. Ir example, standard deviations, σ, were p-sented as an arithmetic *average* of individ l project results. Components of variance we similarly handled. The term *averages* for da of this type was used to avoid ambiguity wh other averaged data. Properly, variance da, in which the square root is directly or -directly involved, should be *pooled*.

Pooling consists of summing the squa d standard deviations (variance) multiplied y the number of test results per project, n, l s one $\sum[(\sigma^2)\ (n-1)]$, dividing by the t l number of test results from all the proje s, n, less the number of projects, N, ($\sum n-\sum$), and extracting the square root. The *poo d* standard deviation for the No. 4 sieve n table 1 was 3.56 percent, compared with 3 1 percent obtained from an arithmetical avera . From an engineer's standpoint the differe , 3.56−3.51 (=0.05) is considered insignifica t. Similar comparisons for other *average* stand d deviations, σ, showed a similar differe e. This insignificant difference is to be expect , as each project value was obtained fr n approximately 200 test values and a stand d test procedure.

Aggregates

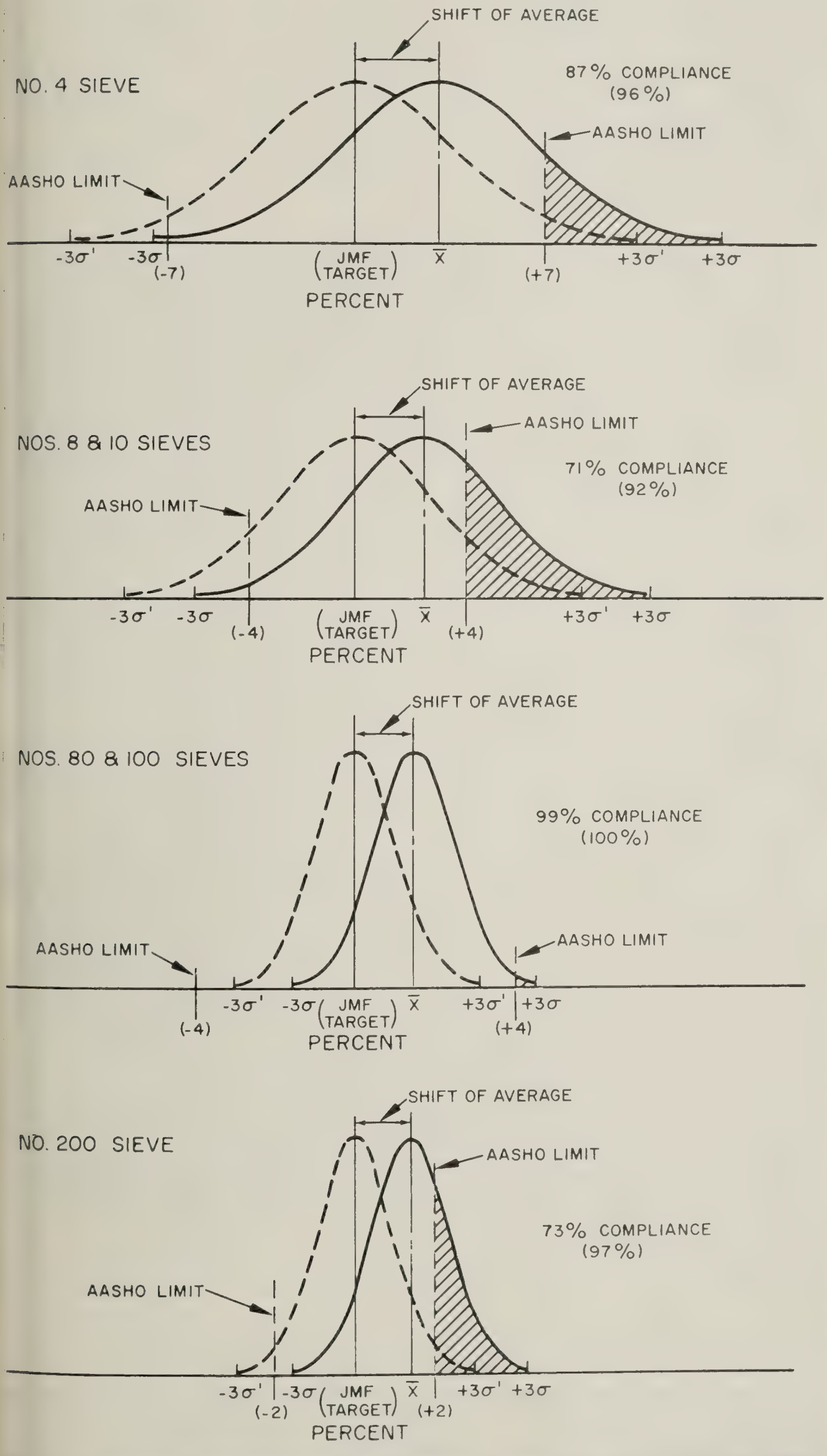
Aggregate represents the largest percent e of any ingredient in a bituminous mixt e; consequently, aggregate characteristics g-nificantly control the characteristics of e pavement mixture.

Laboratory research and field experie e indicate that, although gradation within e

Table 1.—Averages of aggregate gradation data from extraction tests

Sieve size	Average standard deviation ($\bar{\sigma}$) of percent passing	Shift of average ($\bar{X}$) from job mix target	Average variance components as a percent of total variance (σ_0^2)			Compute average complianc with job mix tolerance
			Testing	Sampling	Material	
Surface mixes, 22 projects						
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
¾ in. or ½ in.	1.43	1.70	72	4	24	99
⅜ in.	2.49	1.73	29	31	40	93
No. 4	3.51	2.95	12	18	70	78
No. 8 or 10	2.81	2.45	10	15	75	77
No. 20 or 30	1.74	2.10	13	18	69	87
No. 40 or 50	1.37	1.72	18	15	67	87
No. 80 or 100	1.00	1.44	17	11	72	82
No. 200	0.94	1.43	21	14	65	74
Average pct	1.91	1.94	24	16	60	85
Base or binder mixes, 6 projects						
¾ in or ½ in	4.33	1.66	65	13	22	83
⅜ in	4.93	5.88	55	30	15	60
No. 4	3.92	2.03	46	17	37	76
No. 8 or 10	2.53	1.81	19	13	68	50
No. 20 or 30	2.17	2.22	25	28	47	81
No. 40 or 50	1.67	1.63	23	31	46	84
No. 80 or 100	1.15	1.23	30	30	40	97
No. 200	0.88	1.02	21	14	65	74
Average pct	2.70	2.19	36	21	43	76

nfines of a rather wide grading band is ecessary to produce a high-quality product, single gradation can be adopted as the al one for bituminous mixtures. The adation to be specified depends on the type of surface desired. The maximum size stone used in the pavement is also influenced by the availability of aggregates. The best combination of various sizes then becomes a design problem leading to the establishment of a job-mix formula. The job-mix formula also includes the desired asphalt content.



gure 2.—*Theoretical-frequency-distribution curves of gradation data for selected sieves.*

Under present practice, the State often accepts responsibility for determining the job-mix formula. Once the job-mix formula is established and approved by the engineer, it becomes the target or central value for process control. A tolerance is usually included to account for normal variability of materials or processes.

Variations in aggregate gradation

According to the research studies being conducted, randomly selected samples, taken independently of control samples, usually show deviations in gradations that often are larger than the specification tolerances. Summaries for each aggregate gradation in presently accepted construction and their relations to specified tolerances are shown in tables 1 and 2 and in figures 1, 2, and 3. Data for surface course mixes are included from 22 projects in eight States and for binder or base mixes from six projects in five States.

A consolidation of gradation data for aggregates from extraction test results is shown in table 1. These data were obtained on samples taken independently of those used for job control and acceptance. Departure of averages, $\bar{X}$, from the job-mix formula for individual jobs were about evenly divided below and above this target.

An analysis was conducted to determine the components of variance that could be attributed to sampling, σ_s^2, testing, σ_t^2, and materials, σ_a^2. For surface material, combined testing and sampling variances $(\sigma_t^2+\sigma_s^2)$ are shown to be in the range of 25–35 percent of the total variance, (σ_o^2), for sieve No. 4 and smaller sieves. For the larger sizes of either surface or base course materials, the combined sampling and testing error was a significantly larger proportion of the total variance. For the base course materials, even smaller sizes showed large sampling and testing variances. The statistically computed average percent compliance to States' job-mix formula and tolerances are also shown.

Further analysis of the data from the construction projects for surface course materials is given in table 2. These data provide a summary of variations from the least variable one-third, and the most variable one-third of the projects, as well as the average for the total. Also, statistically computed percent compliances with suggested tolerance limits of the AASHO Guide are shown instead of computed conformance to job-mix tolerances. In general the most variable projects show average standard deviations, $\bar{\sigma}$, of about twice the corresponding values for the least variable projects.

The plus or minus three average standard deviations, $\pm 3\ \bar{\sigma}$, (table 1) for both surface and binder or base courses are plotted in figure 1. The bulged shape, or the largest spread, emerges at the No. 4 sieve for surface courses, and at the ⅜-inch and larger sieves for binder and base courses. Average variations for base and binder courses are about ⅓ larger than those for surface courses. Superimposed on each diagram are $\pm 3\ \sigma$ values for each

Table 2.—Averages of surface course aggregate data from extraction tests on 22 projects

Sieve size	Average standard deviation ($\bar{\sigma}$) of percent passing			Deviation of average ($\overline{X}$) from job mix target			Suggested AASHO tolerance limits	Computed compliance with suggested AASHO tolerance limits		
	⅓ of jobs having least variable σ	All jobs	⅓ of jobs having most variable σ	⅓ of jobs having least variable σ	All jobs	⅓ of jobs having most variable σ		⅓ of jobs having least variable σ	All jobs	⅓ of jobs having most variable σ
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
¾ in. or ½ in.	0.81	1.43	2.32	0.53	1.70	2.62	±7	100	100	95
⅜ in.	1.71	2.49	3.46	1.06	1.73	2.36	±7	100	98	91
No. 4	2.33	3.51	4.52	2.22	2.95	4.83	±7	98	87	68
No. 8 or 10	1.90	2.81	3.85	1.68	2.45	4.04	±4	89	71	49
No. 20 or 30	1.32	1.74	2.24	1.70	2.10	3.06	±4	96	86	66
No. 40 or 50	0.93	1.37	1.82	1.41	1.72	1.23	±4	100	95	94
No. 80 or 100	0.65	1.00	1.36	0.65	1.44	1.48	±4	100	99	97
No. 200	0.51	0.94	1.45	1.43	1.43	1.74	±2	87	73	57
Average pct.	1.29	1.93	2.64	1.33	1.94	2.67		96	89	77

type of mix from the AASHO Road Test (*1*).[1] Because the construction of the AASHO Test Road was very carefully controlled, these data are considered a solid base with which to compare research data. For average surface course data, almost perfect agreement is shown with the AASHO Road Test results. There is no apparent reason why AASHO Road Test gradation data show less variation (smaller standard deviation) for base courses than for surface courses.

Both the standard deviation and the shift of the average, $\overline{X}$, from the job-mix target affect conformance to specifications. The effect of $\overline{X}$ shift from the target value is shown in figure 2, in which values from table 1 were used to compute theoretical normal frequency distributions of four selected sieve size groups. Darkened areas of the tips of the curves represent noncompliance with suggested (*2*) AASHO Guide Specifications. The dashed line curves, which are the same distributions shown by the solid curves, are superimposed on the job-mix target values. The percent compliance with AASHO limits of the superimposed curves are usually much larger than that of the solid curves, as is indicated by the figures in brackets.

Many consider that a reasonable conformance to a specification is met if tests indicate that 95 percent of the material is within the stated tolerance. For a normal distribution this 95-percent conformance level approximates the two standard deviation limits. For the 22 surface course projects, the relation of the spread of gradation represented by $\pm 2\sigma$ from the average to the suggested limits of the AASHO Guide Specification (*2*) is shown in figure 3. The $\pm 2\sigma$ range is also shown for the ⅓ of the jobs with the largest standard deviation. Except for No. 8 and No. 10 sieve group, the $\pm 2\sigma$ range of all jobs are within the AASHO Guide Limit. The $\pm 2\sigma$ ranges for the third with the largest standard deviations are relatively close to the AASHO limits; the most significant deviation occurred again for the No. 8 and No. 10 group. There were also significant deviations for the No. 4 and the No. 200 sieves.

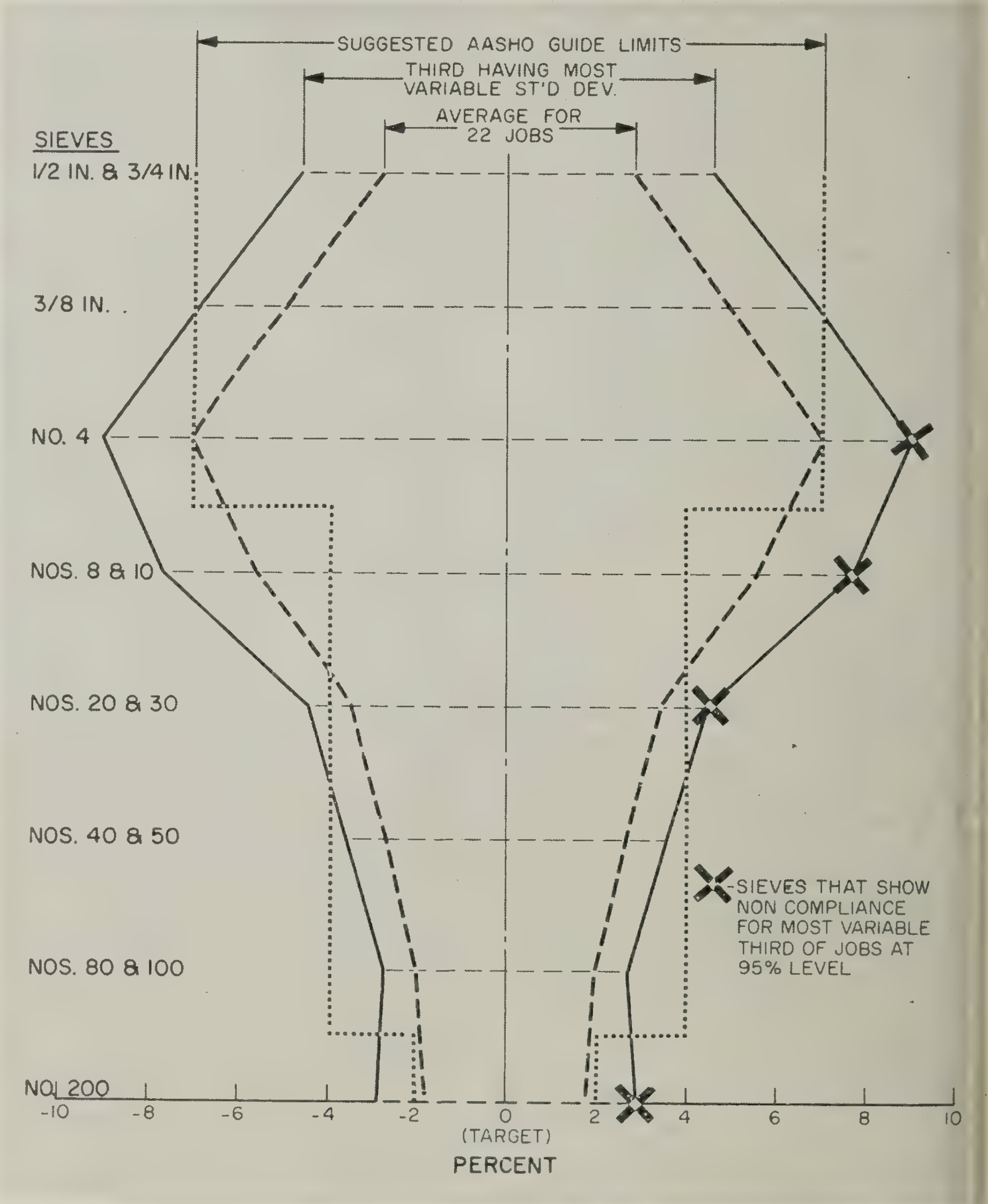


Figure 3.—Comparison of surface-course-gradation 2σ limits and suggested AASHO gu limits.

The relation of the standard deviation to the average percent retained on each sieve is shown in table 3 for the different groups of surface and base or binder mixes. It will be noted that the standard deviation for surface course mixes seems to be related to the amount of material retained on each sieve, as shown in figure 4.

Asphalt Content

The quality and quantity of asphalt i pavement mixture largely determines the ful life of the pavement, provided that pavement has been properly compacted.

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[1] Italic numbers in parentheses identify the references listed on page 211.

much asphalt in a mixture can cause flushing nd rutting of the pavement, and too little sphalt can cause cracking or raveling. Thus, a close control of asphalt content is desirable.

Asphalt content data from extraction tests n 26 surface course mix and seven base ourse or binder mix projects are arranged in able 4 according to size of standard deviaion. Also, the surface course mix projects are grouped by thirds to delineate those with the east variable standard deviation, the middle hird, and those with the most variable standrd deviation. Shown in separate columns are he plus or minus shift of the job average from ob-mix target and statistically computed ompliance with ±0.4, ±0.6, and ±0.8 ercent tolerances, respectively.

The average $\overline{\sigma}$ of extracted asphalt for surace mix projects was 0.28 percent. The verage for binder or base mix projects was .35 percent. The computed $\pm 3\sigma$ limits for 0 of the 26 surface course projects, in which he job-mix target value was reported, are hown in descending order in figure 5. Also hown in figure 5 is the shift of the average rom the target value. The asphalt content or Project No. 1 was on the target; it was lso the only project to show variations that ere less than the suggested ±0.4 percent mits of the AASHO Guide. The three tandard deviation limits for individual rojects ranged from 0.36 to 1.59 percent. he computed 3 σ limits for AASHO (*1*) and ASHO (*3*) road tests were 0.54 percent and .20 percent, respectively. On about ⅔ of the bs, the job averages were lower than the rget (table 4). Only three surface mix jobs omplied 100 percent with assumed tolerances om the job-mix formula of ±0.6 percent, lthough half the total showed more than 95 ercent compliance. Increasing the tolerance ±0.8 percent did not appreciably increase e number of jobs having more than 95 ercent conformance.

Data for the surface course projects from ble 4 are shown in figure 6, grouped into ree sections according to standard deiation of asphalt content. The $\overline{\sigma}$ for each oup was used to construct the three normal rves, which show that the most variable rojects also had the largest shift of the $\overline{X}$ om the target value. This shift indicates a ck of job control that adversely affects both e average and the variance. The computed nformance percentages are based on the ASHO's suggested ±0.4 percent tolerance. parentheses, beneath the percent conrmance for each group, is the computed ercentage that would have been obtained if l projects averages had been on the target lue.

esting and sampling variance

Testing, sampling and material variances asphalt content for both surface and binder base-course mixes are shown in figures and 8, respectively. These variations imply at results of a single extraction test are not reliable measure of asphalt content. Hower, the precision of the measurement can be proved by using the average of several

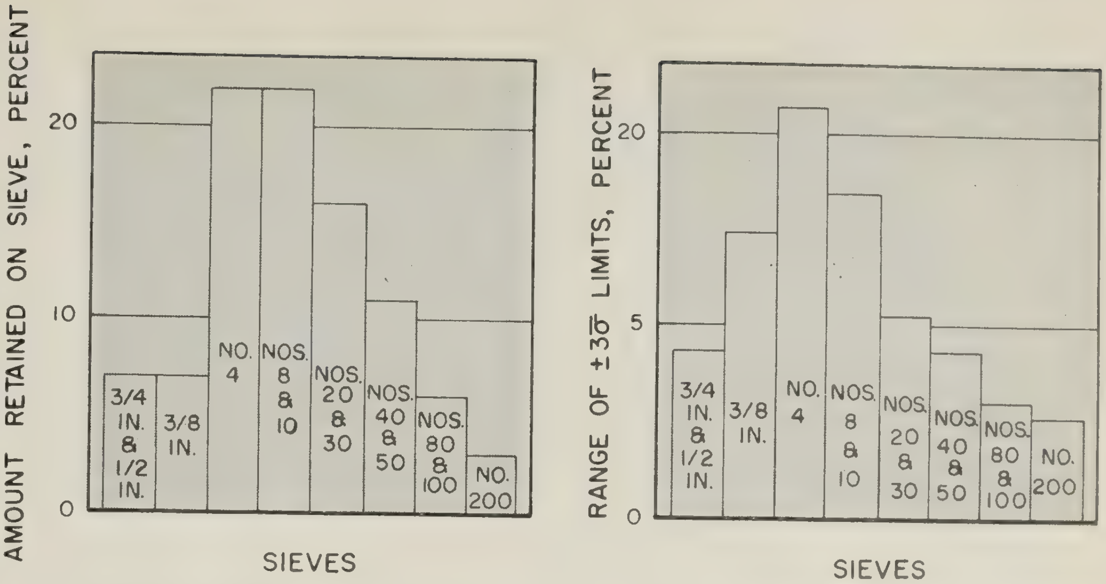


Figure 4.—Comparison of average amount retained on sieves and range of 3σ limits—surface course projects.

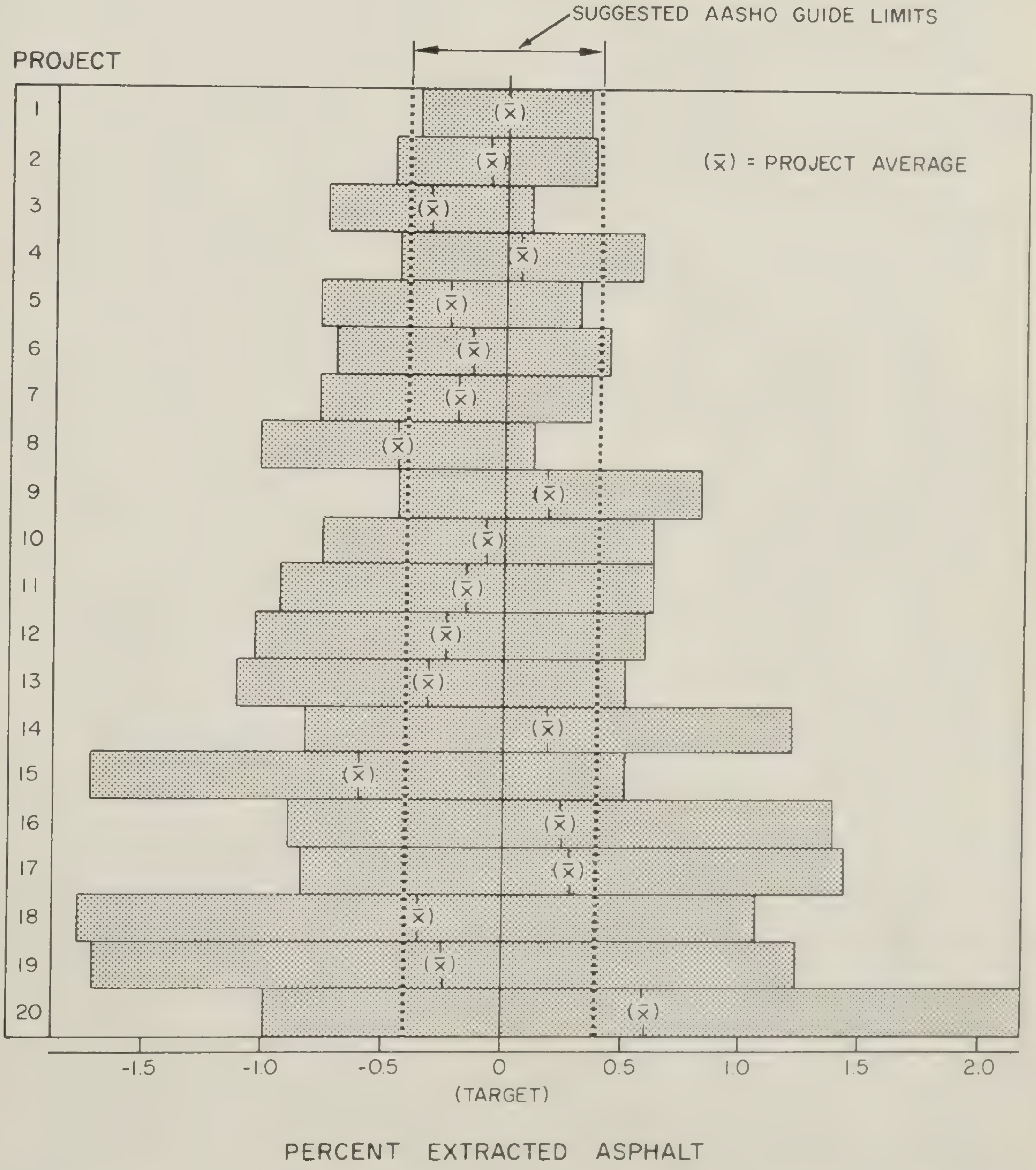


Figure 5.—Computed 3σ limits and shift of average from job-mix-formula target for extraction test data of asphalt content—20 surface course projects.

Table 3.—Average sieve data from extraction tests

Sieve size	Average amount passing [1]	Average amount retained on indicated sieve size [1]	Range of ±3 average standard deviation limits				Suggested AASHO guide (±)limits
			Surface course mixes			Base or binder mixes all jobs	
			Least variable third	All jobs	Most variable third		
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
¾ in. or ½ in.	93	7	[2] 2.4	[2] 4.3	[2] 7.0	13.0	7
⅜ in.	86	7	[2] 5.1	7.5	10.4	14.8	7
No. 4	64	22	[2] 7.0	10.5	13.5	11.8	7
No. 8 or 10	42	22	5.7	8.4	11.5	7.6	4
No. 20 or 30	26	16	[2] 4.0	5.2	6.7	6.5	4
No. 40 or 50	15	11	[2] 2.8	4.1	5.5	5.0	4
No. 80 or 100	9	6	[2] 1.9	[2] 3.0	4.1	[2] 3.5	4
No. 200	6	3	[2] 1.5	2.8	4.4	2.6	2

[1] For surface mixture only.

[2] Within AASHO guide recommended tolerance limits.

Table 4.—Bituminous content data from extraction tests

Job No.	Standard deviation (σ)	Shift of average from job mix target		Computed compliance with tolerances from job mix target		
		Below	Above	Suggested AASHO guide tolerance ±0.4%	Assumed tolerances ±0.6%	Assumed tolerances ±0.8%
Surface course mixes						
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Least variable third of jobs:						
1	0.12	0.00	0.00	100	100	100
2	0.14	0.31		74	98	100
3	0.14	0.04		99	100	100
4	0.17		0.07	97	100	100
5	0.18	0.22		88	98	100
6	0.19	0.44		42	80	97
7	0.19	0.13		92	99	100
8	0.19	0.20		85	98	100
9	0.21		0.20	83	97	100
Average, least variable third	0.17	0.18		84	97	100
Middle third of jobs:						
10	0.22					
11	0.22					
12	0.23	0.06		93	99	100
13	0.26					
14	0.26	0.15		83	96	100
15	0.27	0.22		74	92	98
16	0.27	0.30		64	87	97
17	0.27					
Average, middle third	0.25	0.18		79	94	99
Most variable third of jobs:						
18	0.33					
19	0.34		0.20	68	88	96
20	0.37	0.60		29	50	79
21	0.38		0.30	51	78	91
22	0.38		0.25	58	82	93
23	0.47					
24	0.47	0.35		50	68	83
25	0.49	0.23		54	73	86
26	0.53		0.20	52	71	84
Average, most variable third	0.42	0.30		52	73	87
Average, surface course mixes	0.28	0.22		72	88	95
Base or binder course mixes						
1	0.22					
2	0.27		0.33	60	88	96
3	0.28					
4	0.38					
5	0.38	0.24		62	81	93
6	0.43		0.13	63	82	93
7	0.50					
Average, binder or base mixes	0.35	0.23		62	84	94

results as the test value. Better precision ca also be obtained by improved sampling an testing procedures.

Testing Variations

Effect of sampling point

Engineers disagree as to whether th location at which a sample is taken affec test results. According to present practic extraction test samples usually are o tained from the truck at the plant so th results can quickly be made available. R search has been performed to evaluate t effect of the sampling location. Average te results of samples from the truck and tho of core samples from the pavement are list in table 5. These data from 10 jobs indicat no significant differences between core sampl and truck samples. The bar graphs in figure substantiate that the point of sampling do not significantly affect the variances f asphalt content.

Ash correction

The extraction test for determining asphalt content includes an ash correction for i- soluble material that passes through the filt. Because field laboratories do not always op ate under optimum conditions, it is thoug by some that the State should dispense wi running the ash correction in field laborator and substitute constant corrections det- mined by a central laboratory.

Several studies were conducted to determi ash correction variations in the field. In Florida report (*4*), field laboratories tes, when compared with central laboratory tes, were shown to be inconsistent. All fi laboratories weighed their ash correcti residue to the nearest 0.1 gram, instead f to 0.01 gram, apparently because of e sensitivity of available scales. Some correcti s were made on the basis of a constant fac r per 100 cc. of solvent used in the test. Fi d laboratories also used more solvent, and e quantities of solvent varied more from test o test than those of the central laboratory.

Central laboratory and field laborat y ash corrections were compared by test g split samples taken from surface and bin r mixes on 10 jobs. The results showed that e field laboratories had a smaller $\overline{X}$ ash corr- tion and were, on the average, less variab. On individual jobs, this trend was not o pronounced, as shown by the follow g tabulation.

Ash correction:	*Gra*
Surface mix, average ($\overline{X}$):	
Central laboratory	4.0
Field laboratory	4.0
Binder mix, average ($\overline{X}$):	
Central laboratory	4.5
Field laboratory	4.0
Surface mix, standard deviation (σ):	
Central laboratory	2.8
Field laboratory	1.4
Binder mix, standard deviation (σ):	
Central laboratory	2.8
Field laboratory	1.4

Table 5.—Average sieve data, aggregate residue and asphalt content—from extraction tests of samples obtained from same mix at two locations on 10 projects in three States

	Average standard deviation ($\bar{\sigma}$)		Average shift of average ($\bar{X}$) from job mix formula target		Average variance components as a percent of total variance (σ_o^2)						Average percent compliance with job mix formula tolerances	
					Testing		Sampling		Material			
Sample location	Truck	Core	Truck	Core	Truck	Core	Truck	Core	Truck	Core	Truck	Core
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Sieve:												
¾ in. or ½ in.	1.33	1.69	1.58	1.11	74	32	1	2	25	66	99	100
⅜ in.	2.34	2.42	1.16	0.87	37	39	22	14	41	47	98	98
No. 4	2.89	2.96	1.68	2.14	26	27	21	28	53	45	85	83
No. 8 or 10	2.53	2.58	1.81	2.50	19	21	13	24	68	55	84	87
No. 20 or 30	1.52	1.73	1.59	2.06	12	13	18	17	70	70	92	86
No. 40 or 50	1.45	1.66	1.80	2.00	22	16	6	8	72	76	84	79
No. 80 or 100	1.06	1.09	1.34	1.63	27	21	10	9	63	70	79	74
No. 200	0.98	0.97	1.05	1.26	27	24	11	10	62	66	74	70
Average	1.76	1.88	1.50	1.69	31	24	13	14	56	62	87	85
Asphalt	0.22	0.22	[1] 0.23	[1] 0.22	32	40	11	22	57	38	[1] 61	[1] 63

[1] From six jobs in one State only.

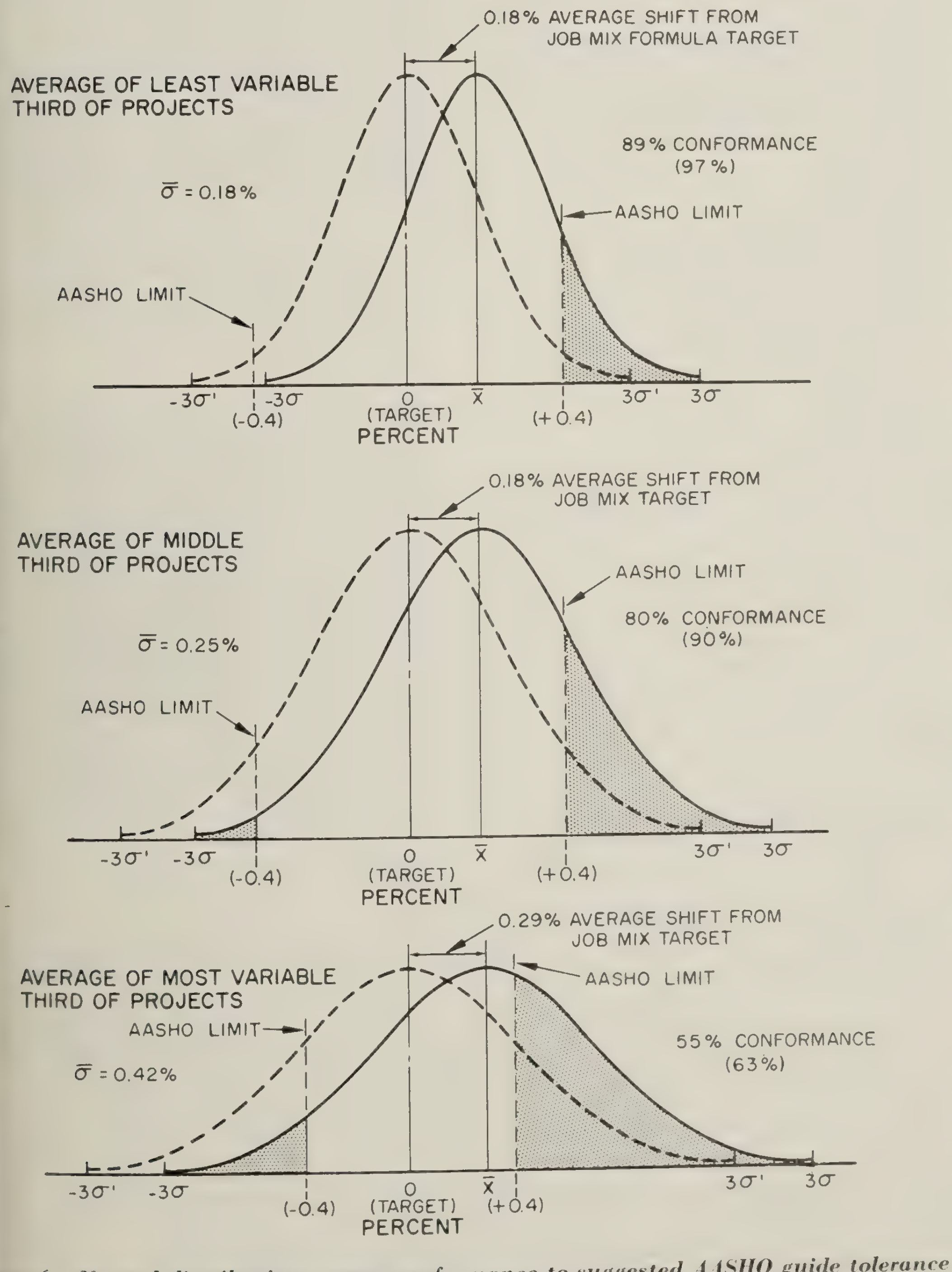


Figure 6.—*Normal distribution curves, conformance to suggested AASHO guide tolerance of ±0.4% for asphalt content—three groups of surface course projects.*

The lower values and less variability of the field tests do not necessarily indicate that the results are more accurate. In ash correction there is always a danger of not obtaining a true aliquot because of ash settlement in the container, which could cause indicated trends.

The variances obtained using both a constant ash correction factor and actual field correction factors were compared for binder and surface mixes using the chi square statistic, χ^2. Neither calculated value of χ^2 reached the critical 5-percent significance level. Statistically, from the Florida report (*4*), "it has not been demonstrated that any significant difference exists." This means both methods will produce the same results. The Florida report further states:

"At present the evidence seems to indicate that if the operation of the extraction test could be improved (specifically: uniformity in devices, amount of solvent used, number of washes employed, speed of rotation, etc.), there is a very good possibility that the running of the ash correction as a field test could be dispensed with and a system devised using a factor assigned by the central lab., which would give statistically as good, if not better results, than are being obtained under the present system. Periodic spot checks and inspections of equipment, procedures, etc., would undoubtedly have to be made to ensure that continued high standards of operation were continuously being obtained."

Effect of extraction test equipment, operators, and laboratories

Extraction tests on the 33 projects shown in table 4 were made with either Reflux or Rotorex test equipment. Except for those of two States, all extraction and sieve tests were performed at district or central laboratories. In New Jersey (*5*), half the extraction tests were made at the central laboratory, and available plant testing equipment and plant inspectors were used to test the remaining half to determine whether any significant testing variability or *variability of testing variability* existed. According to the data in table 6, which is from a report by Afferton (*5*), testing variance, σ_t^2, for determining asphalt content was more than 15 times greater in field laboratories than in the central laboratory. The statistical test for differences of σ_t^2, using the *F* ratio at the 5-percent level, showed a high significance of testing variance for both courses.

A comparison test on split samples using both Reflux and Rotorex test equipment was reported in a West Virginia study (*6*). On the basis of *t* and *F* statistical tests, no significant differences in standard-deviation var ability could be attributed to the type (test equipment. However, in companio studies, in which two sets of samples wit known asphalt quantities, two operators, an both sets of equipment were used, it wa shown that operator proficiency significantl affected the accuracy of the test result possibly enough to nullify the smaller standar deviation expected of the Reflux apparatu In another experiment, in which six operato each used Rotorex equipment to test tw samples with known asphalt content (unknow to operators), the operators retained the same numerical order of proficiency.

A Florida study (*4*) also statistically con pared field asphalt content determinatio

Table 6.—Tests for significant variance difference between field and laboratory testing, 5-percent level

Test property	Testing variance (σ_t^2)		Largest variance	*F* ratio		Is difference significant?
	Laboratory	Field		Computed	Critical	
Top						
	Pct.	*Pct.*		*Pct.*	*Pct.*	
Asphalt content	0.0088	0.1734	Field	[1] 19.70	1.75	Yes.
Stone content	1.5500	2.9040	Field	1.87	1.75	Yes.
Sieve analysis:						
Passing 1 in., retained on ½ in	0.7200	1.0358	Field	1.44	1.75	No.
Passing ½ in., retained on ¼ in	2.1600	6.2827	Field	2.41	1.75	Yes.
Passing ¼ in., retained on No. 10	0.9200	0.7246	Laboratory	1.27	1.75	No.
Passing No. 10, retained on No. 30	0.9000	0.3591	Laboratory	2.51	1.75	Yes.
Passing No. 30, retained on No. 50	1.6400	1.8232	Field	1.11	1.75	No.
Passing No. 50, retained on No. 80	1.1700	0.9429	Laboratory	1.24	1.75	No.
Passing No. 80, retained on No. 200	0.7600	3.0043	Field	3.95	1.75	Yes.
Passing No. 200	0.2900	0.5121	Field	1.76	1.75	Yes.
Bottom						
Asphalt content	0.0111	0.1658	Field	[1] 14.94	1.75	Yes.
Stone content	2.9700	7.9839	Field	2.69	1.75	Yes.
Sieve analysis:						
Passing 1½ in., retained on 1 in	13.8400	19.7247	Field	1.42	1.75	No.
Passing 1 in., retained on ½ in	17.1100	23.1702	Field	1.35	1.75	No.
Passing ½ in., retained on ¼ in	8.0100	9.3947	Field	1.17	1.75	No.
Passing ¼ in., retained on No. 10	3.0000	1.4930	Laboratory	2.01	1.75	Yes.
Passing No. 10, retained on No. 30	0.6200	0.3234	Laboratory	1.92	1.75	Yes.
Passing No. 30, retained on No. 50	0.5400	0.8708	Field	1.61	1.75	No.
Passing No. 50, retained on No. 80	0.4600	0.4770	Field	1.04	1.75	No.
Passing No. 80, retained on No. 200	0.8700	0.9584	Field	1.10	1.75	No.
Passing No. 200	0.3000	0.2867	Laboratory	1.05	1.75	No.

[1] Highly significant at 5-percent level.

Table 7.—Comparison of dry hot bin and extraction results [1]

Sieve size	Total percent passing			Standard deviation (σ)	
	Average hot bin	Average extraction	Average difference [2]	Pooled hot bin	Pooled extraction
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*
½ in	99.6	99.6	0.0	0.3	0.5
¼ in	78.6	77.8	0.8	2.5	3.7
⅛ in	47.5	46.2	1.3	3.0	2.3
No. 20	21.0	21.4	−0.4	3.7	2.3
No. 40	13.3	14.7	−1.4	3.3	1.3
No. 80	6.3	7.8	−1.5	1.9	1.3
No. 200	2.8	4.5	−1.7	1.0	1.0
Percent asphalt content		6.3			0.3

[1] Data based on 491 combined hot bin analyses and 491 extraction tests from 29 mix plants during 1962, 1963, and 1964.

[2] Difference is significant at 99 percent confidence level for all sieves except for No. 20, which is significant at 95 percent confidence level.

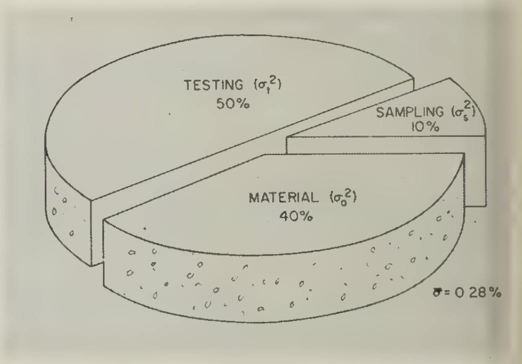


Figure 7.—Average percent of total varianc σ_o^2, attributable to testing, sampling, a material variances for asphalt conte extraction tests—23 surface course pro ects.

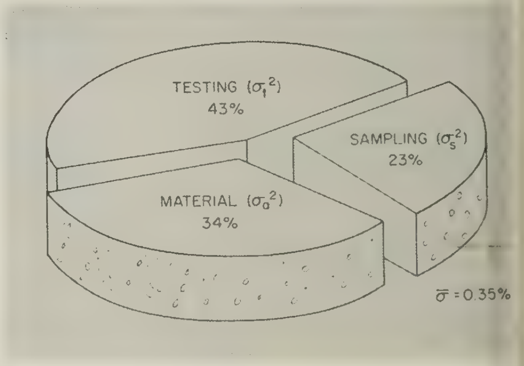


Figure 8.—Average percent of total varian σ_o^2, attributable to testing, sampling, a material variances for asphalt conte extraction tests—6 base or binder cou projects.

Table 8.—Average bituminous hot mix density data from research jobs

	Jobs	States	Average standard deviation ($\bar{\sigma}$)		Average ($\bar{X}$)		Average variance components as percent of total variance (σ_o^2)			Percent compliance with State specificatio
			Core	Loose sample	Core	Loose sample	Testing	Sampling	Material	
Percent of theoretical density (voidless):	*Number*	*Number*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Surface	15	6	1.57		93.1		5	19	77	78
Binder	3	2	2.90		94.2		33	16	51	88
Percent of Marshall density: Surface	12	5	1.53		96.0					
Marshall density percent of theoretical density: Surface	10	2		0.89		96.2	20	12	68	
Theoretical density (voidless):			*grams/cc.*	*grams/cc.*	*grams/cc.*	*grams/cc.*				
Surface	10	3	0.013	0.011	2.43	2.46	18	12	70	
Binder	1	1	0.029	0.013	2.48	2.48				

binder and surface mixes made by regular nt inspectors on 10 jobs with central oratory test results of duplicate samples d by percent of total variance from re- ssion lines for each. Essentially the same erators were rated good-to-fair and poor- very poor in both types of tests, indicating t operator training and constant sur- illance is necessary to achieve precise raction test results.

ntrol by hot bin sieving

From 1 to 2 hours are required to complete ld extraction tests now being used to deter- ne whether bituminous hot mix conforms the requirements of the job-mix formula. r this reason several State highway depart- nts have been seeking quicker means to ertain conformance so that remedial action n be taken quickly.

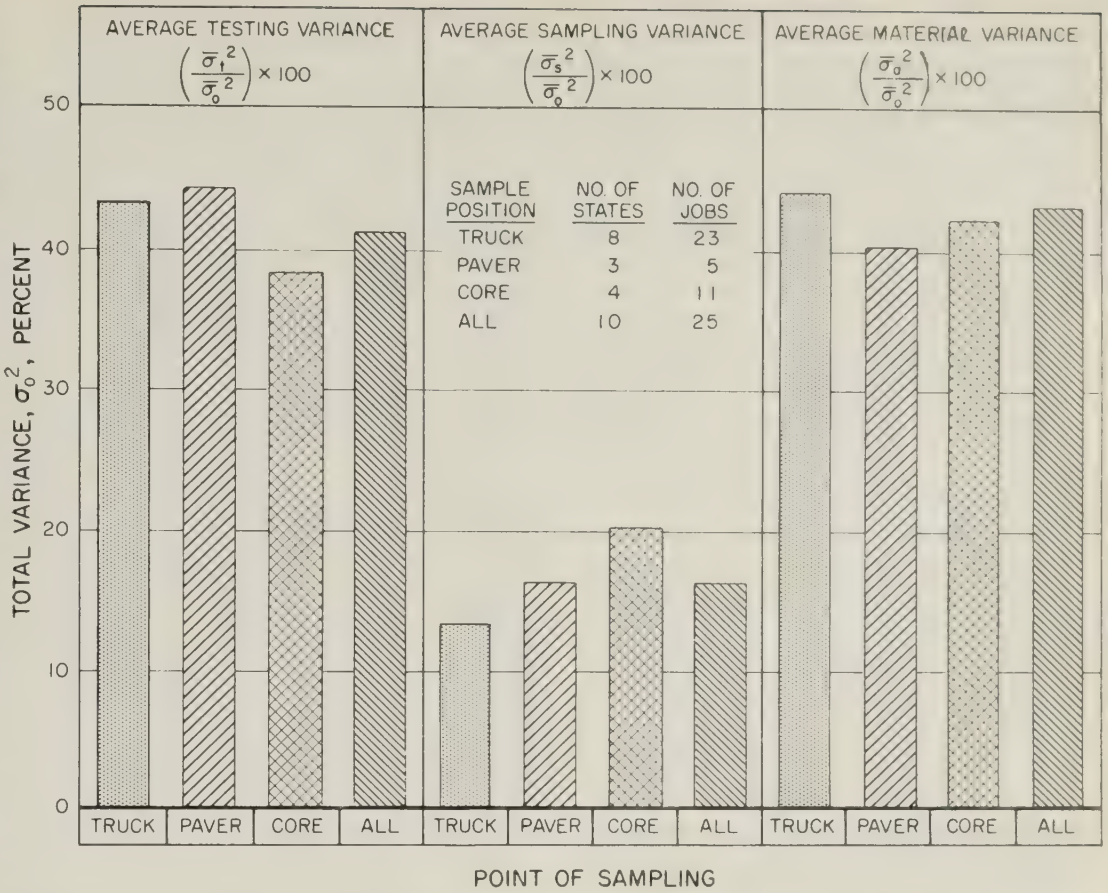
In a New York study (7), it was determined om research comparisons (see table 7) on dry t bin and extraction sieve tests that dry ving was more uniform for ½-in., ¼-in., and . 200 sieve sizes. The extraction test yielded re consistent results for the ⅛-in. thru No. sieves. As accurate printed weights of ma- rial used in each batch from each bin were tained, it was decided to use the more rapid t bin sieving to control the uniformity of the ix. This test was to be supplemented with a ily extraction test for aggregate passing the . 80 and No. 200 sieves. According to the t bin data from the 29 plants in which the sts were performed, anytime that the pri- ary size in the coarse bin—material passing in. sieve and retained on ½-in. sieve in No. 1 n, and passing ¼-in. sieve and retained on in. sieve in 1A bin—fell below 70 percent, e mix generally became nonuniform. By trial was determined that a 12-percent fluctua- n in this quantity from the last test was a actical limit to use in order to avoid ex- eding the job-mix formula limits. On the e aggregate bin, the same tolerance limit s applied to material retained on the No. sieve, because usually about one-half of e fine aggregate was retained on this sieve. Because of the relation of primary size to e overall conformance to the job formula, e New York State highway department is ing this correlation as an indicator of uni- rmity. The uniformity control test is supple- ented by complete hot bin analysis, usually ter every fourth test. Thus, one State has en able to shift dependence on extraction st results to a secondary role.

Their inspection manual states:

> "In general, production is accepted by ob- ining gradation test results within the limits a job mix formula. Hot bin analyses and iformity tests determine the gradation of aterial larger than the No. 80 sieve. The ex- action test is used to determine gradation of aterial smaller than the No. 80 sieve and so indicates the approximate bitumen con- nt. Actual bitumen content is determined by rifying batch quantities."

Density

Permanence of bituminous pavement de- nds largely on the degree of compaction ob- ined. The compaction value is usually ex-



SAMPLE POSITION	NO. OF STATES	NO. OF JOBS
TRUCK	8	23
PAVER	3	5
CORE	4	11
ALL	10	25

Figure 9.—Average percent of total testing variance, σ_o^2, attributable to testing, sampling, and material variances for asphalt content extraction tests—alternate sampling locations.

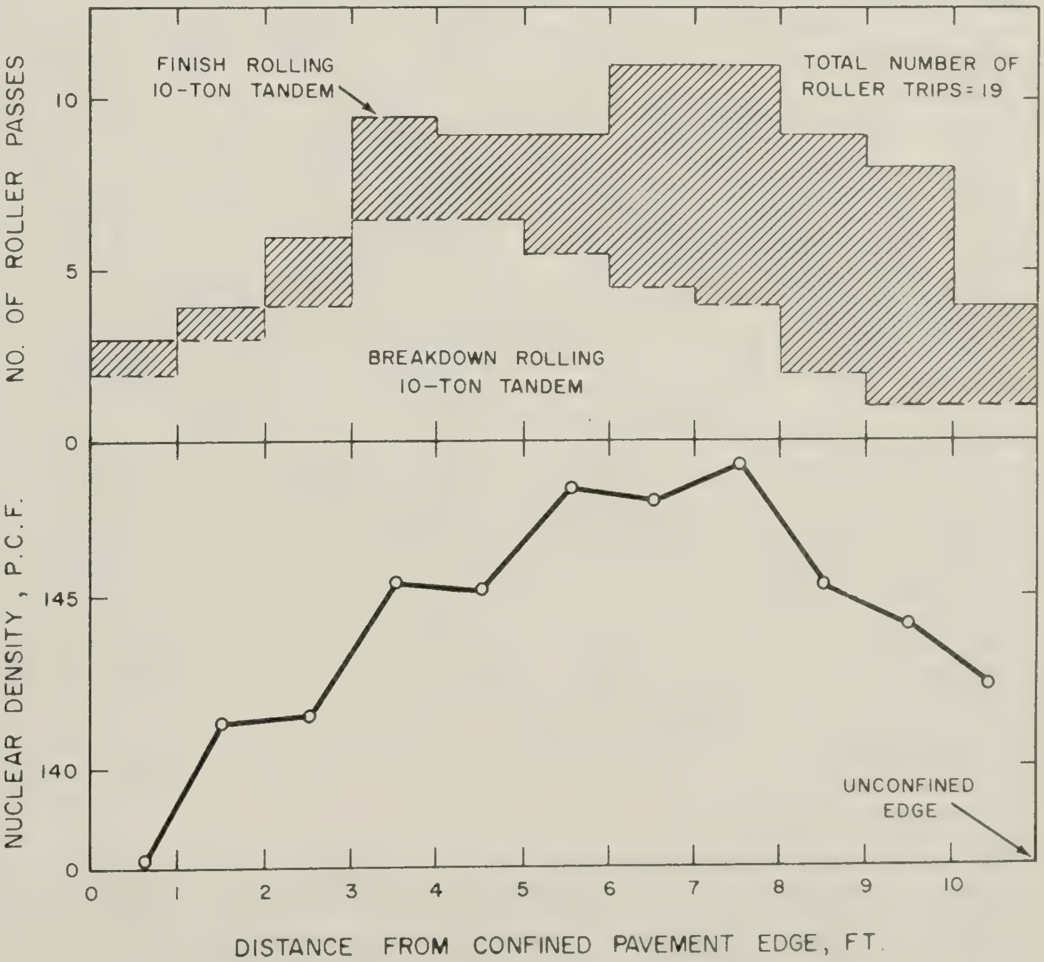


Figure 10.—Lateral variation in compactive effort and density.

pressed as a percentage of either theoretical (voidless) or Marshall density, determined by laboratory tests. Density data from several construction jobs are shown in table 8. It is quite possible that much below-specification density can be attributed to improper rolling patterns. Figure 10 was taken from a report by Kilpatrick and McQuate (*8*) who reported the following conclusions regarding effect of rolling pattern on density:

"Normal rolling procedures used by roller operators result in wide lateral variations in compactive effort. The number of roller passes applied in the center of the lane is usually from three to six times greater than at the lane edges.

"The lateral pattern of density is similar to the lateral pattern of compactive effort; i.e., high-in-the-middle and low-at-the-edges."

In figure 10, the density pattern across the lane approaches the shape of a normal curve. In a random selection of sample locations across the lane, sites at any distance from the edge have an equal chance of being selected.

Marshall Test Results

A number of State highway departments use the Marshall test and equipment to design the job-mix formula and control the ideal blend of aggregate, aggregate sizes, and bitumen, so that the mixture will be stable and durable when it is incorporated into the pavement. Marshall test data variations for stability, flow, and air voids from several State projects are shown in table 9. Testing and sampling variances for *stability* and *flow* values total *58* and *76* percent respectively. Variability of Marshall stability is shown in figure 11 for 3 groups of jobs: the third with the least variable standard deviation, the middle third, and the third with the most variable standard deviation. The computed $\bar{\sigma}$'s from these groups were used to plot the normal curves.

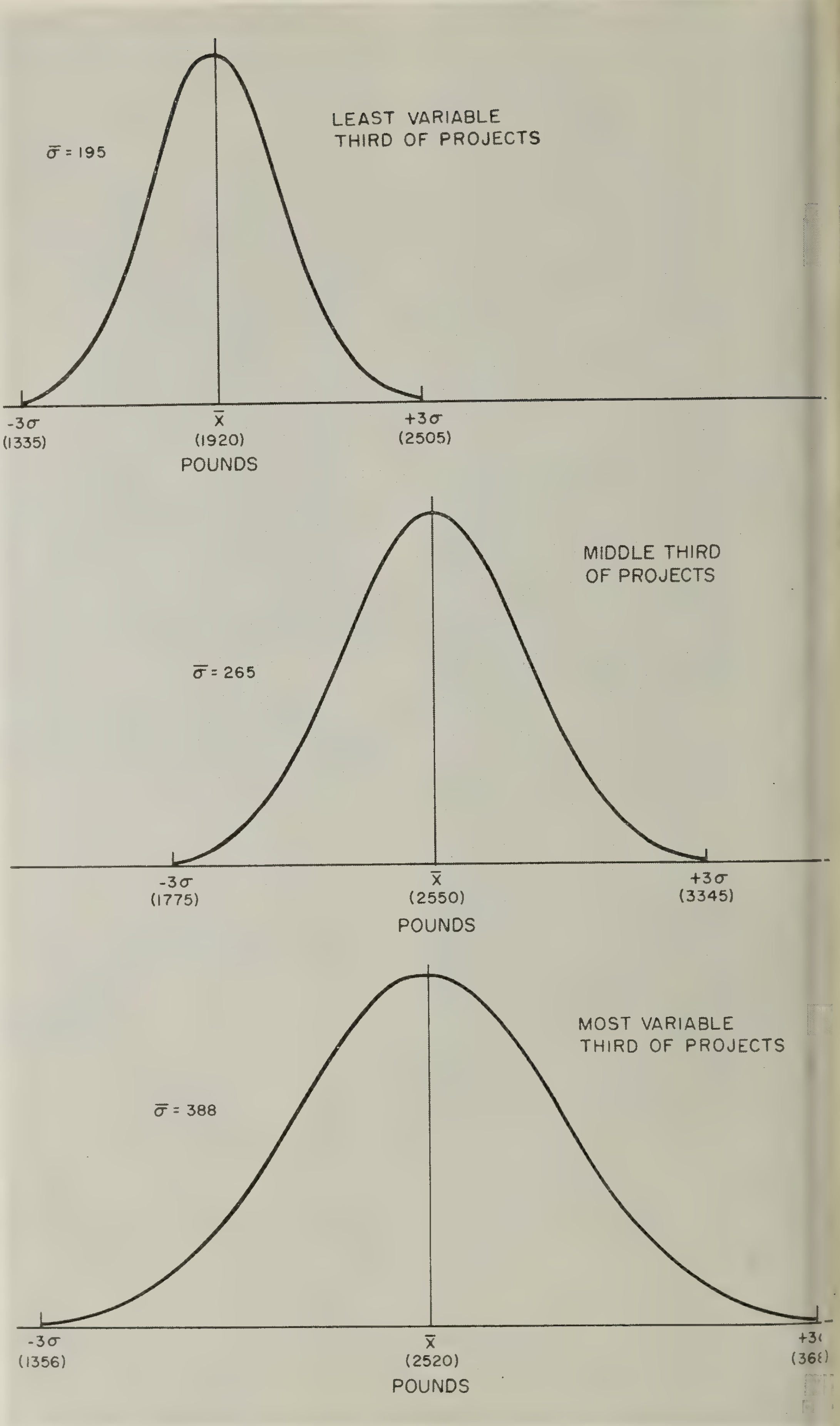


Figure 11.—Computed 3$\bar{\sigma}$ limits of Marshall stability for 18 projects grouped accordin to size of average standard deviation, $\bar{\sigma}$.

Temperature

Another physical characteristic of the mix that may effect final density is mix temperature during breakdown rolling. Kilpatrick and McQuate (*8*) concluded that: "Breakdown rolling, both steel and pneumatic, should be completed before the pavement temperature drops below 220° F. to achieve maximum density." It is probable that final rolling, when accomplished above this critical temperature, will also produce the best results. The average standard deviation of temperature at the paver for 10 research jobs was 15° F. the range was from 6° to 22° F. Consequently, a plant producing batches with an average temperature of 275° F. will have a number of batches in the 230°–250° F. range. With temperatures in this range, it is difficult to achieve proper breakdown before the pavement cools below the reported critical 220° F.

Pavement Thickness

Thickness is another attribute needed to achieve economy of construction. A pavement that is thicker than required for adequate performance needlessly increases cost. A pavement that is too thin reduces service life and increases maintenance cost. Ideally, design thickness for pavements can be used to provide the most economical construction. However, research indicates that the variations in thickness of presently constructed pavements may significantly influence such performance. Da from 12 jobs in four States show that accep surface courses have a $\bar{\sigma}$ of 0.26 inch. In o words, about 5 percent of the pavement ill have a thickness over ½ inch less than des

Table 9.—Hot mix Marshall test data variations for stability, flow, air voids

	Projects	States	Average standard deviation ($\bar{\sigma}$)	Average ($\bar{X}$)	Average variance components as a percent of total variance (σ_o^2)		
					Testing	Sampling	Material
	Number	*Number*					
Marshall stability___pounds__	18	4	283	2,305	38	20	42
Marshall flow_________100/in__	15	2	1.29	8.62	62	14	24
Marshall air voids______pct__	18	4	1.00	4.33	21	24	55

if the average corresponds to the specification. If concepts developed by Rex (*9*) are utilized, the computed expected service life for 5 percent of the area of a 3-inch pavement will be only ⅔ of the design life.

Conclusions

The production of high quality bituminous pavements requires the diligence of all concerned—the producer, the contractor and the contracting agency. The statistically measured variations (parameters) of accepted construction presented in this article indicate that much more variability exists than is revealed by the usual acceptance tests. Variations in excess of those normally expected for *good practice* were prevalent on almost every job studied. At present, the full significance of such variations cannot be assessed. Large sampling and testing errors virtually prevent a true evaluation of the material variation on a specific job. Also, it is difficult to assess the degree to which the variations affect actual pavement performance.

Because performance has not always been satisfactory, the need for improvement is obvious. Research results indicate that much improvement could be obtained and testing level reduced by the following changes:

- Adjust tolerance limits on gradation to conform to the principle of most tolerance on largest fraction retained on a sieve.
- Control the uniformity of gradation of the mixture by hot bin sieve tests, when a printed record of batch weights is available.
- Reduce to a minimum the number of sieves used for control testing.
- Exercise more diligence in the training and surveillance of operators performing control and acceptance tests.
- Require installation of automatic features on asphalt plants and finishers to reduce human error.
- Use random sampling to obtain all test portions.

REFERENCES

(*1*) *The AASHO Road Test Report No. 2, Material and Construction*, National Academy of Sciences, National Research Council, Publication 951, Highway Research Board Special Report 61-B, 1962, table 46, p. 82.

(*2*) *Guide Specifications for Highway Construction*, American Association of State Highway Officials, 1968.

(*3*) *The WASHO Road Test, Part 1: Design, Construction, and Procedures*, Highway Research Board Special Report 18, 1954.

(*4*) *A Study in the General Field of Quality Control Engineering*, State Road Department of Florida in cooperation with the Bureau of Public Roads, by Warden Engineers, Inc., Raleigh, N.C., September 1965.

(*5*) *A Statistical Study of Asphaltic-Concrete*, by Kenneth C. Afferton, New Jersey State Department of Transportation, Highway Research Record 184, 1967, pp. 13–24.

(*6*) *Determination of Statistical Parameters for Highway Construction*, Research Project No. 18, State Road Commission of West Virginia, by Materials Research and Development Inc., Miller Warden Associates Div., Raleigh, N.C., July 1966.

(*7*) *Realistic Job-Mix Formula Tolerances for Asphalt Concrete*, Research Report 66–3, by Malcolm D. Graham, William C. Burnett, Jerome J. Thomas, and Charles B. Fletcher, Bureau of Physical Research, New York Department of Public Works, January 1967, p. 21.

(*8*) *Bituminous Pavement Construction*, by M. J. Kilpatrick and R. G. McQuate, Bureau of Public Roads, June 1967, pp. 19–22, and figure 16, p. 23.

(*9*) *Effect on the Road of Variations in Thickness*, M-W Technical Paper No. 87, by Harry M. Rex, Miller Warden Associates, Raleigh, N.C., February 1964.

(*10*) *Procedures for Using Statistical Methods for Process Control and Acceptance of Bituminous Mixtures*, South Carolina State Highway Department, by Paguette-Mills, Consulting Engineers, Atlanta, Ga., February 1966.

(*11*) *A Statistical Analysis of Type 3 Plant Mix Bituminous Surfacing for Quality Control*, by Thomas P. Kostohris, State of Montana Highway Commission, 1966.

(*12*) *Bituminous Concrete Shoulder Study, Part 2—Analysis of Depth Variation Related to Two Base Course Materials*, by Fred E. Sternberg, Connecticut State Highway Department, November 1966, pp. 13a–22a.

(*13*) *Statistical Approach to the Quality Control of Plant Mix Pavement*, Wyoming State Highway Department, June 1968.

(*14*) *Statistical Parameters Research Quality Control Study on Asphalt Pavement*, Colorado Department of Highways, April 1967.

(*15*) *A Study of Variability in Production, Sampling and Testing Bituminous Concrete Base, Part II—the 1966–67 Study*, by Richard French and Bryce Edwards, Maine State Highway Commission, September 1967.

(*16*) *Tolerances for Asphaltic Concrete and Base Courses*, by Verdi Adam and S. C. Shah, Louisiana Department of Highways, November 1966.

(*17*) *Variations in Bituminous Construction in Nebraska*, Nebraska Department of Roads in cooperation with the Bureau of Public Roads, September 1968.

(*18*) *Bituminous Concrete Surface Course Analysis*, State Highway Commission of Wisconsin in cooperation with the Bureau of Public Roads, 1965.

(*19*) *Quality Control of Construction by Statistical Tolerances*, by J. H. David, Alabama Highway Department, May 1967.

(*20*) *Variability in an Asphalt Concrete Mix*, by Edward R. Oglio and Joseph A. Zenewitz, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 34, No. 1, April 1966, pp. 5–15.

(*21*) *Compaction of Bituminous Pavement and Base Courses*, Production Study Report No. 401, by Edwin C. Granley and Richard G. McQuate, Bureau of Public Roads, U.S. Department of Commerce, July 1965.

New Publications

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

Drainage of Highway Pavements

Drainage of Highway Pavements, Hydraulic Engineering Circular No. 12, March 1969 ($1 a copy), contains procedures for estimating storm runoff from pavement areas, computing flow in gutters, and designing and spacing inlets for removing water from the pavement surface. Typical inlet designs are given and tables and charts are provided for computing flow in gutters and the water intercepted by curb opening and grate inlets.

Other hydraulic publications available from the U.S. Government Printing Office are listed on the inside back cover.

Ultrasonic Testing Inspection for Butt Welds in Highway and Railway Bridges

Ultrasonic Testing Inspection for Butt Welds in Highway and Railway Bridges (40 cents a copy) is a 49-page manual prepared by the Bethlehem Steel Corporation in cooperation with the Bureau of Public Roads. It is a training and reference manual for inspectors using special techniques developed by Bethlehem Steel Corporation for butt weld inspection. It explains the theory and operation of ultrasonic pulse-echo, flaw-detection equipment and describes special procedures for using this equipment.

The use of ultrasonics as a nondestructive test method for weld inspection is steadily increasing, largely because it is less costly and less time consuming than the method now being used. In recognition of these advantages, the Bureau of Public Roads is issuing a *Specification for the Ultrasonic Testing of Butt Welds in Highway and Railway Bridges* that will be applicable to steel bridges constructed under Federal-aid projects. This specification is to be used in conjunction with the manual.

Third Generation Destination Signing—An Electronic Route Guidance System

(Continued from p. 200)

(10) *Freeway Traffic Accident Analysis and Safety Study*, by B. F. K. Mullins and C. J. Keese, Highway Research Bulletin 291, 1961, pp. 26–78.

(11) *The Effect of Ramp Type and Geometry on Accidents*, by Richard A. Lundy, Highway Research Record 163, 1967, pp. 80–119.

(12) *A Study of the Feasibility of Using Roadside Communications for Traffic Control and Driver Information: Report No. 2*, by Donald O. Covault, Turgut Dervish, and Andrew C. Kanen, Highway Research Record 202, 1967, pp. 32–66.

(13) *Automobile Facts and Figures*, 1968, Automobile Manufacturers Association.

(14) *Minimum Path Algorithms for Transportation Planning*, by B. V. Martin, Massachusetts Institute of Technology in cooperation with the Bureau of Public Roads, M.I.T. School of Engineering Research Report R63–52, 1963.

(15) *Computer Simulation of Driver Behavior During Car Following: A Methodological Study*, by Myron L. Braunstein, Kenneth R. Laughery, and John B. Siegfried, Cornell Aeronautical Laboratory, Inc., Final Report, Contract CPR 11-8686, Bureau of Public Roads, 1963.

(16) *Urban Intersection Study*, by Kenneth R. Laughery and Edwin A. Kidd, Cornell Aeronautical Laboratory, Inc., vol. I, Summary Report, Final Technical Report, Contract CPR 11-2856, Bureau of Public Roads, September 1968.

(17) *A Digital Computer Simulator of Driver Overtaking, Following, and Passing*, by G. M. Howat, Cornell Aeronautical Laboratory, Inc., in cooperation with the Bureau of Public Roads, C.A.L. Report VK-1938-V-1, Contract CPR-11-0637, 1965.

(18) *The Mathematical Theory of Communication*, by Claude E. Shannon, University of Illinois Press, Urbana, 1949.

(19) *National Survey of Transportation Attitudes and Behavior*, by Robert K. McMillan and Henry Assael, National Cooperative Highway Research Program Report 49, 1968.

(20) *Attitudes of Drivers Determine Choice Between Alternate Highways*, by R. M. Michaels, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 33, No. 11, December 1965, pp. 225–236.

(21) *Design of an Automobile Controller for Optimum Traffic Response to Stochastic Disturbances*, by William Bryan Rocca, Jr., Engineering Experiment Station Report 202-A9, Ohio State University, sponsored by Ohio Department of Highways and the Bureau of Public Roads, September 1965.

(22) *Information Requirements for Exiting at Interchanges*, by Douglas J. Mace, Robert S. Hostetter, and Edmund L. Seguin, HRB-Singer, Inc., Final Report, Contract CPR 11-2808, Bureau of Public Roads, September 1967.

(23) *Annotated Bibliography on Gap Acceptance and Its Applications*, by Fred S. White, Final Report, Contract CPR 11-2842, Bureau of Public Roads, 1966 (Texas Transportation Institute Gap acceptance and traffic interaction in the freeway merging process, vol. 7).

(24) *Traffic Surveillance and Means of Communicating with Drivers*, by Morton I. Weinberg, National Cooperative Highway Research Program Report 9, 1964.

(25) *Traffic Flow Responses to Unannounced Increases in Progression Speeds of Signal Systems*, by R. D. Desrosiers and C. H. Leighty, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 34, No. 1, April 1966, pp. 1–4.

(26) *Freeway Signing Concepts and Criteria*, Bureau of Public Roads, U.S. Department of Commerce, by Alan M. Voorhees & Associates, June 1966.

(27) *Optimal Route Recognition and Coding*, by C. Gumacos and B. G. Cramer, Philco Corporation, Final Report, Contract CPR 11-2621, Bureau of Public Roads, March 1966.

(28) *A Design for Experimental Route Guidance System*, General Motors Research and Delco Radio Div., Final Report, Contract FH-11-6626, Bureau of Public Roads, 19[illegible].

(29) *Driver Performance Using an Experimental Route Guidance System*, National Symposium on Information Display, 9th, Technical Session Proceedings, 1968.

(30) *Driver Information Requirements and Acceptance Criteria for ERGS*, by John W. Eberhard, H. H. Jones, G. S. Kolsrud, and D. W. Schoppert, Highway Research Record 265, 1969.

(31) *Experimental Route Guidance Head-Up Display Research*, by R. W. Benzinger and E. Bell, Highway Research Record 265, 1969.

(32) *Highway Coding for Route Designation and Position Description*, Philco-Ford Corporation Final Report, Contract CPR 11-[illegible]85, Bureau of Public Roads, July 1968.

Highway Research and Development Reports Available From Clearinghouse for Federal Scientific and Technical Information

The following highway research and develop-nt reports are available from the Clearinghouse Federal Scientific and Technical Informa-n, Sills Building, 5285 Port Royal Road, ringfield, Va. 22151. Paper copies are ced at $3 each and microfiche copies at cents each. To order, send the stock number each report desired and a check or money er to the Clearinghouse. Prepayment is uired.

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169494	Vol. II
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PB 169502	Management Improvement Project for the Indiana State Highway Commission.
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PB 169504	A Study of the Effectiveness of Highway Training Program for Graduate Engineers, Virginia Department of Highways.
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PB 169507	Operations and Maintenance Cost Study, Interim Report.
PB 169508	Alabama Highway Laws Study, June 1965.
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ighways and Human Values (Annual Report for Bureau of Public Roads) (1966). 75 cents.

Supplement (1966). 25 cents.

ighways to Beauty (1966). 20 cents.

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

ydraulic Engineering Circulars:

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

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

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

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

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

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

Landslide Investigations (1961). 30 cents.

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

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

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

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

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

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

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

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

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

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

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

Standard Plans for Highway Bridges:

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

Vol. IV—Typical Continuous Bridges (1969). $1.50.

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

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

Study of Airspace Utilization (1968). 75 cents.

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

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

Ultrasonic Testing Inspection for Butt Welds in Highway and Railway Bridges. 40 cents.

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