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FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

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BUREAU OF PUBLIC ROADS
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U.S. Highway 22—322 in Perry County, Pa., hugs the Juniata River (left) from Amity Hall to Lewistown. The controlled access highway replaces the old narrow road seen between the river and the new road. (Photo courtesy Pennsylvania Dept. of Highways)

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FEDERAL HIGHWAY ADMINISTRATION
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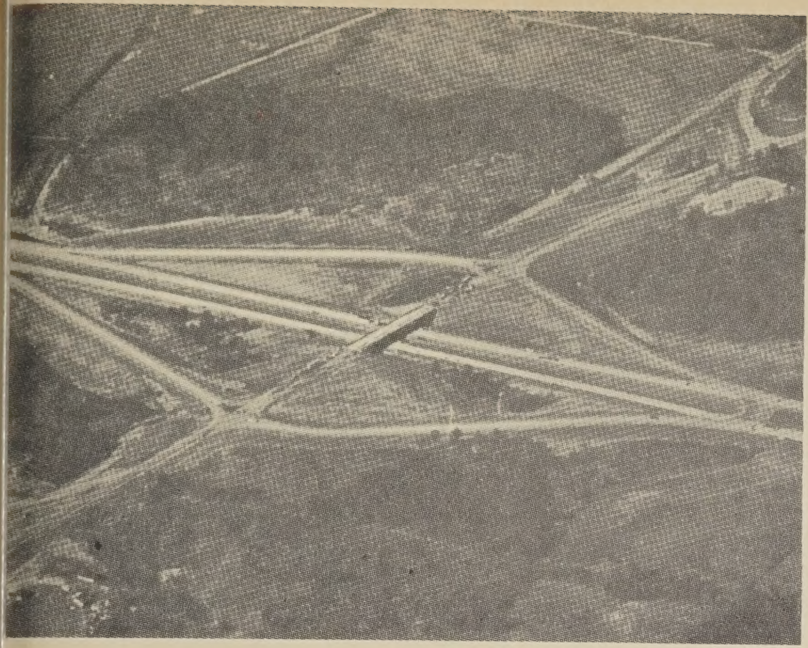

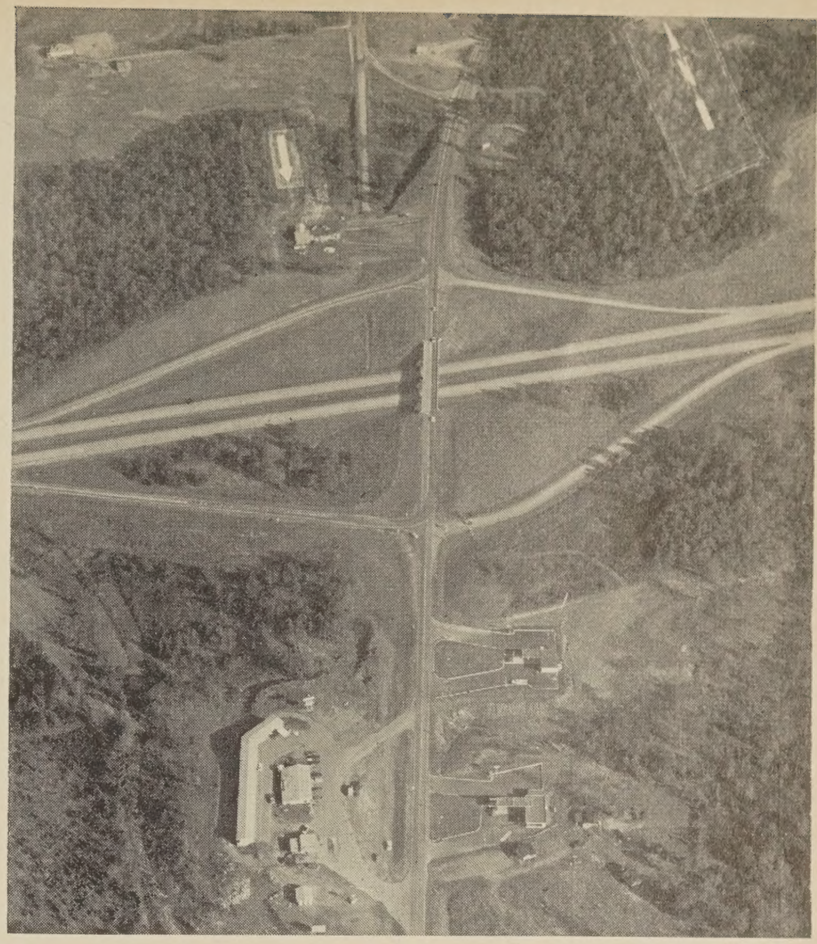

Highway-oriented land use at interchange areas is illustrated by these before-after photographs of the interchange near Lincoln, Alabama, where highways I-20 and U.S. 231 intersect. Photograph at left was taken in 1964, shortly after construction of the interchange was completed. In photograph at right, taken in 1968, new businesses—motel, 3 service stations, cafe, and fruit stand—that had located near the interchange are shown. Arrow points to most recent addition, a service station.

Highway Interchange Area Development—Some Recent Findings

Reported by
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BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

By combining data on 332 interchanges in 16 States, the author has shown that interchange land development is affected both by the type of intersecting highway and by the relative accessibility of the interchange quadrants. According to his review of Alabama interchanges, a large part of development near predominantly rural interchanges consisted of highway-oriented businesses like motels, service stations, and restaurants. In contrast, a windshield survey of the Capital Beltway around Washington, D.C., disclosed that rapid growth in the numbers of apartment houses, churches, schools, shopping centers and industrial parks occurred at predominantly suburban interchanges subsequent to highway construction.

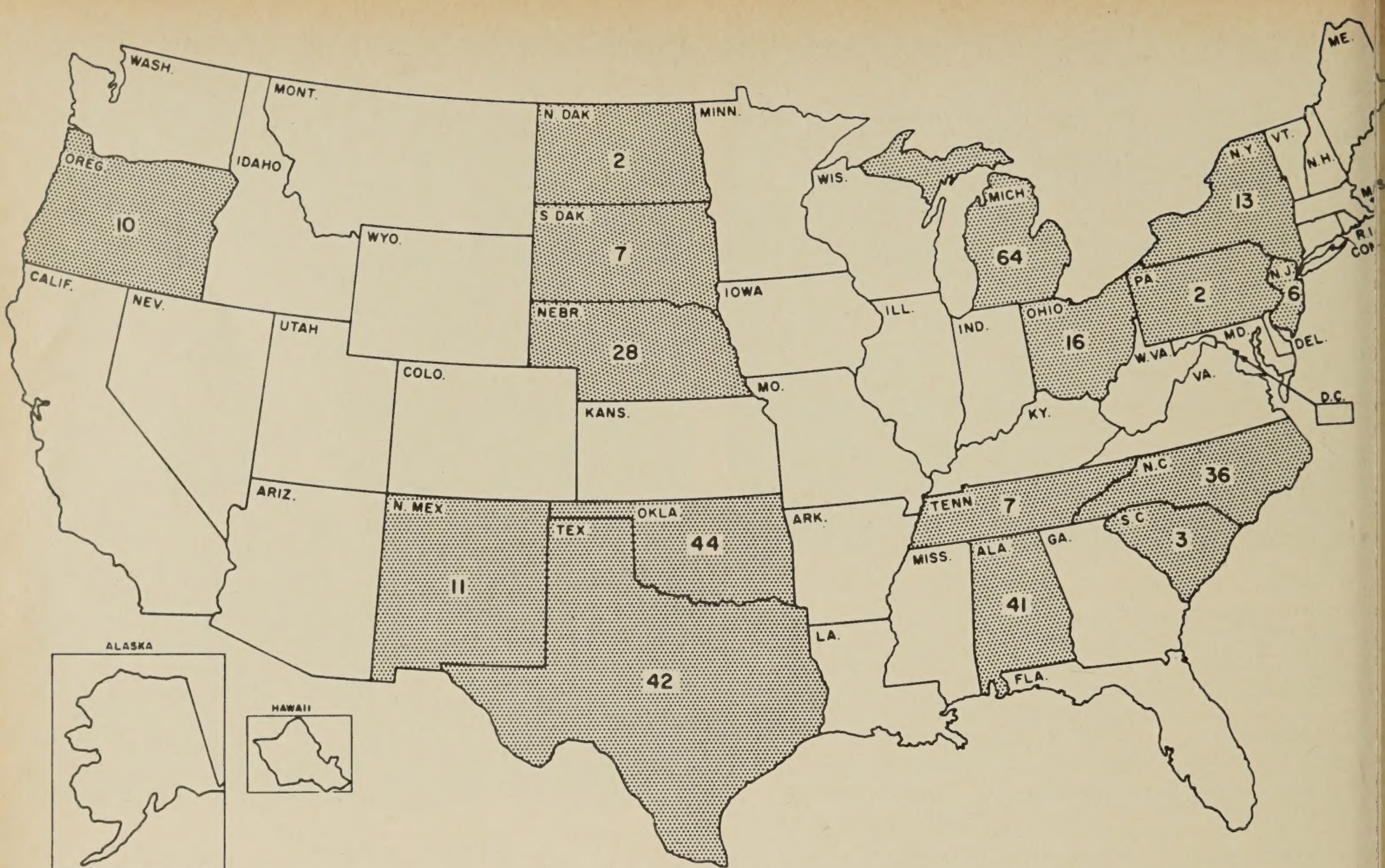
In other recent studies on interchanges, multilinear regression analysis and simultaneous linear models were used to predict interchange land development and to show that important factors of land development at an interchange are traffic volumes, distance to the nearest urban center, and populations of the nearest urban center.

Interchange research can assist highway planners and other officials to recognize potential interchange problem areas. The development of more precise analytical research tools and the formulation of a complete interchange planning process would facilitate the optimal economic development of highway interchanges and, simultaneously, protect their traffic capacities as vital components of an efficient transportation network.

A RELATIVELY large part of future intercity traffic is expected to use the Interstate Highway System, and many highway-related businesses can be expected to desire locations near interchanges. Industries that rely on motor carriers to obtain raw materials or distribute finished products are likely to seek plant sites close to Interstate highways. Even though interchanges in urban areas are spaced only about a mile apart, demand for the abundant nearby land is increased by the many land uses—commercial businesses, apartment houses, and institutions—that are attracted to interchange locations.

The many economic and social activities that locate near interchanges create a planning[1] problem. As one function of interchanges

[1] Planning is used here to describe the highway planning and design process that relates to specifying interchange design type, location, and design volume, and to effecting land-use and traffic-control techniques to maintain design capacity.



TOTAL NUMBER OF INTERCHANGES -- 332. DATA OBTAINED FROM INTERCHANGE LAND-USE STUDIES AND PUBLIC ROADS SEVERANCE DATA.

Figure 1.—Distribution of interchanges surveyed, by State.

Table 1.—Interchanges in survey, by year of survey[1]

Year of survey	Interchanges in survey	
	Number	Percent
1960	5	1
1961	15	4
1962	23	7
1963	24	7
1964	119	36
1965	19	6
1966	115	35
1967	12	4
Total interchanges in survey	332	100

[1] Date of construction for each interchange is not available.

is the provision of access to cross routes, the increased economic and social activity often produces traffic that exceeds original design estimates, and a spiral of activity develops possibly to impair freeway operation or cause serious traffic congestion on cross routes. Naturally, because interchange traffic consists of turning movements, any traffic congestion not only will increase accident potential near the interchanges, but also will impose another form of economic cost to the highway user—increased travel time. Each interchange represents a large investment, and careful planning is needed to maximize potential economic benefits to the community by providing locations with improved accessibility while minimizing impairment to efficient highway operations.

Interchange Land Development

Bureau survey of 332 interchanges

An awareness of potential problems at interchanges has prompted studies in nearly half the States (*1*).[2] Several of these studies and some severance studies, both of which describe interchange land use, have been combined to isolate general characteristics of land development and economic activity near interchanges. In the survey reported here all recent studies that contained information about interchange land uses were considered.[3] The distribution by State of the 332 interchanges surveyed in this manner is shown in figure 1, and the year that each interchange was surveyed is given in table 1. Aer[ial] photographs and graphic and verbal descr[ip]tions were used to subjectively evaluate ea[ch] interchange quadrant to determine predo[m]-

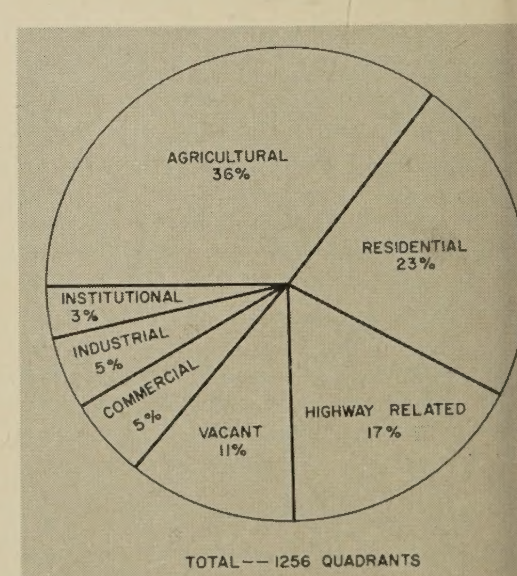


Figure 2.—Proportion of predominant la[nd] uses by quadrant—based on Public Roa[ds] survey of 332 interchanges in 16 Stat[es].

[2] Italic numbers in parentheses identify the references listed on page 249.

[3] Except for a few interchanges in urban areas, the interchanges surveyed in the study reported here were in rural areas, and an analysis of urban-interchange characteristics would not yield statistically significant findings.

nant land use within a one-half mile radius of the interchange center. For example, in this analysis, a motel, service station, and restaurant in a quadrant would be considered predominantly highway-related land uses, whereas a school and a church in a quadrant would be considered predominantly institutional land uses. Shopping centers and other retail outlets were classified commercial uses, and factories and warehouses industrial uses. As shown in figure 2, agricultural, residential, and highway-related land uses were the three types of land uses most frequently recorded. The vacant category represents land that was being held for speculation, was undergoing construction, or did not exhibit evidence of economic activity.

Researchers compared general land development according to the types of highways forming the interchanges. Interchanges formed by the intersection of non-Interstate highways, such as a U.S.-numbered highway and a State-numbered highway, were found to have a much greater proportion of commercial, industrial, and institutional land uses, possibly because Interstate highways were constructed more recently and have not yet attracted as many of these activities, or because different design standards were used for non-Interstate interchanges. As data on construction dates were not available for all interchanges, the time factor could be considered only for the Capital Beltway and Alabama analyses to be discussed later. As shown in table 2, non-Interstate interchanges had more than twice as many commercial, industrial, and institutional quadrants as those with at least one Interstate highway.

According to individual evaluations highway-oriented land uses did not locate randomly

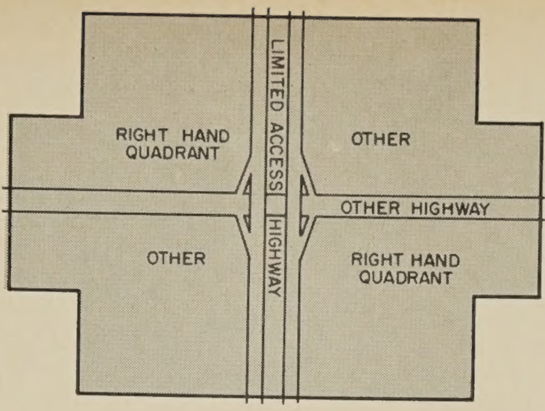


Figure 3.—Interchange quadrants

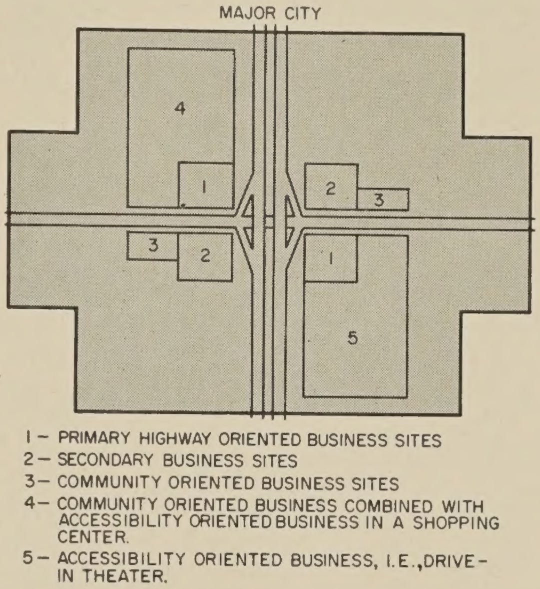


Figure 4.—Interchange development, preferred quadrants—adapted from Ohio report (4).

at the various types of interchanges (table 3). Twenty-eight percent of the motels were located near interchanges of two non-Interstate highways, which represented only 4 percent of the total number of interchanges in the survey. In contrast, 32 percent of the motels had locations near interchanges of Interstate highways and local or county roads, although these interchanges represented 50 percent of those in the survey. Moreover, 28 percent of the service stations were located near interchanges of Interstate and U.S.-numbered highways, even though this type of interchange comprised 21 percent of the total number of interchanges in the survey. Other tourist-oriented businesses, like souvenir stands, also seemed to prefer Interstate and U.S.-numbered highway interchanges, as 56 percent of those surveyed occupied sites near them. Preliminary statistical analysis has indicated that these variations are significant at the 95-percent level of confidence.

Industrial or institutional land uses—factories, warehouses, and golf courses—were also disproportionately distributed at interchanges of two Interstate highways. For example, 17 percent of the warehouses and factories in the survey preferred this type of interchange, which was 2 percent of the total number of interchanges analyzed. All of the interchanges in this group were of the directional type and did not provide direct access to adjacent land; nevertheless, they can be attractive to those who seek a location near two major intercity highways.

Most preferred quadrants

For interchange planning, it is important to know the preferred location of highway services on the interchange. Several studies have indicated that the most desirable location for highway services is the first quadrant on the motorists right as he approaches the interchange (*2*, *3*)[4] (see figures 3 and 4). Right-hand quadrants ordinarily can be reached more easily than other quadrants and are prominently visible—two factors that are important to the location of highway-oriented businesses. Accordingly, the interchange quadrants in the survey were divided into two groups—right quadrants and other quadrants—to test the hypothesis that right quadrants are preferred by highway-related businesses. (A significant variation was noted here at the 90-percent level of confidence.) Although 59 percent of the quadrants containing predominantly highway-related businesses were right-side quadrants, only 43 percent of those containing predominantly industrially related land uses were. (see figure 5).

Quadrants that lack accessibility to the interchange attract fewer land uses that depend on motorists for existence. For this reason directional interchanges do not seem to attract the same proportion of highway-related services as other types of interchanges (fig. 6). Eleven percent of the directional

Table 2.—General land development at interchanges, by highway classification
[Public Roads analysis of 1,256 interchange quadrants in 16 States]

Type of highway interchange	Interchange quadrants	Type of land development			
		Agricultural and/or vacant	Residential	Commercial, industrial, institutional	Total
	Number	*Percent*	*Percent*	*Percent*	*Percent*
Interstate highway—local road	628	43	27	30	100
Interstate highway—State-numbered highway	296	60	14	26	100
Interstate highway—U.S.-numbered highway	260	48	26	26	100
Non-Interstate highway—non-Interstate highway	52	15	23	62	100
Interstate highway—Interstate highway	20	55	25	20	100
Total	1,256	----------	----------	----------	-------

Table 3.—Distribution of highway-related land uses at interchanges, by highway classification
[Public Roads analysis of 332 interchanges in 16 States]

Type of highway interchange [1]	Service stations	Restaurants	Motels	Other tourist-oriented businesses
	Percent	*Percent*	*Percent*	*Percent*
Interstate highway—local road	49	48	32	44
Interstate highway—State-numbered highway	23	21	19	----------
Interstate highway—U.S.-numbered highway	28	22	21	56
Non-Interstate highway—non-Interstate highway	----------	9	28	----------
Total	100	100	100	100

[1] No highway-related land uses were recorded at interchanges of 2 Interstate highways.

[4] Unpublished paper presented to the North Central Land Economics Research Committee also provided land value data (see acknowledgments).

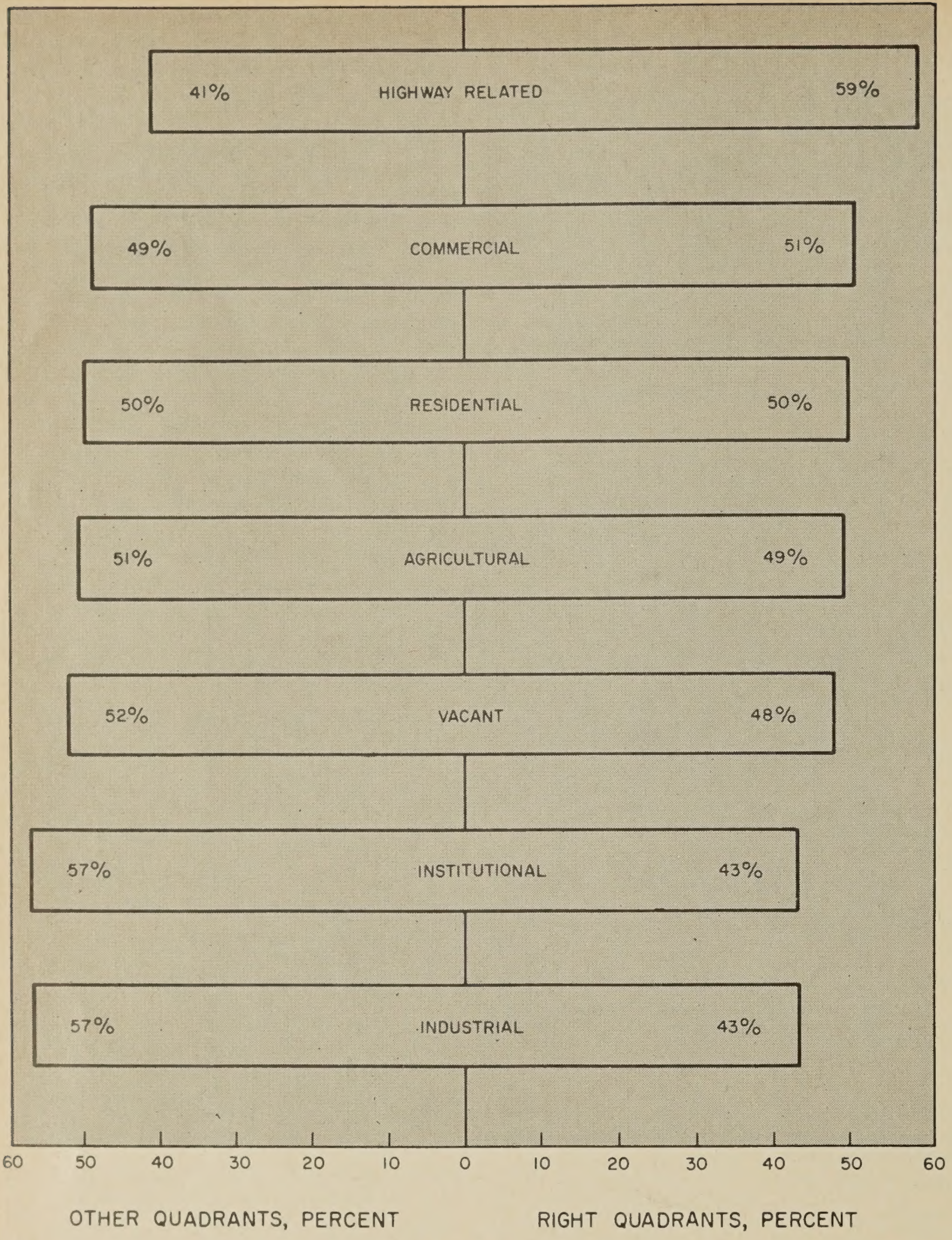


Figure 5.—Distribution of general land uses by quadrant—based on analysis of 1,256 interchange quadrants.

interchange quadrants surveyed were classified highway related whereas the proportion for partial cloverleaf interchange quadrants was 19 percent.

Free access and restricted access interchanges

The importance of access to the potential of land development is generally recognized. This access can be provided either by a free access crossroad or by a frontage road along the freeway. Frontage roads often provide good locations for highway-oriented services. Of the full-cloverleaf interchanges surveyed, 25 percent of the quadrants served by frontage roads were used for highway services. Interchanges without freeway or frontage-road access to the abutting properties—restricted-access interchanges—had no highway related uses. Other commercial uses also appear to gravitate to free-access interchanges (fig. 7).

Alabama interchanges

A good source for analysis of the growth o land uses near interchanges was provided b data on 57 Alabama interchanges (*4*), whic showed interchange development from 1964 t 1968.

Land uses were recorded more frequentl after highway construction had been com pleted (fig. 8). The greatest increase, in bot absolute and relative terms, was in highway related land uses. Although both commercia and industrial land uses exceeded highway related uses before highway construction highway-related uses were predominantly in tensive in 1968, approximately five years afte highway construction. As shown in figure 9 the increase in the highway-related land us was primarily a result of the increased numbe of service stations. In 1964, 27 percent of th 57 interchange areas had at least one servic station. By 1968, the percentage had increase to 67 (fig. 10).

Predicting interchange land development

Data collected on land development a interchanges can be useful to both highwa planners and local communities because i not only indicates the past economic growth but also can be used to estimate future growth One simple method of anticipating shifts i land use near interchanges is through ob servation. As shown in figure 11, eight Alabam interchanges that contained motels also con tained a service station or a restaurant, o both. Often these uses occurred during mote construction or immediately after constructio had been completed. As motels are usuall associated with other highway-oriented busi nesses, interchange development can be pre dicted by noting the locations of motels or o their planned constructions. This may the serve to initiate a more thorough investigatio of the interchange, which could includ evaluation of travel time to the nearest urba center and of the center's population; traffi counts; and surveys of local officials, planners businessmen, or developers.

Another method of predicting which inter changes will experience rapid development i to compare the proportions of specific inter change land uses that are occurring. Severa ratios of service stations and restaurants t motels, are given in table 4. Some of th differences in these ratios may be due to th fact that motels locate more frequently nea

Table 4.—Ratios of service stations and restaurants to motels at interchanges

	Service stations	Restaurants	Motels
	Ratio	*Ratio*	*Ratio*
Alabama [1]	8.5	1.6	1.0
Michigan: [2]			
Major city interchange	2.7	1.9	1.0
Secondary city interchange	9.2	3.1	1.0
Composite	4.3	2.4	1.0
Pennsylvania [3]	2.7	1.9	1.0
National [4]	2.7	1.0	1.0

[1] Ratios derived from Alabama report (*5*).
[2] Ratios derived from data collected in report, *Interchange Development Along 190 Miles of I-94*, Michigan State Highwa Department, 1964.
[3] Ratios are estimates used in Pennsylvania report (*6*).
[4] Ratios derived from Public Roads survey of 332 interchanges.

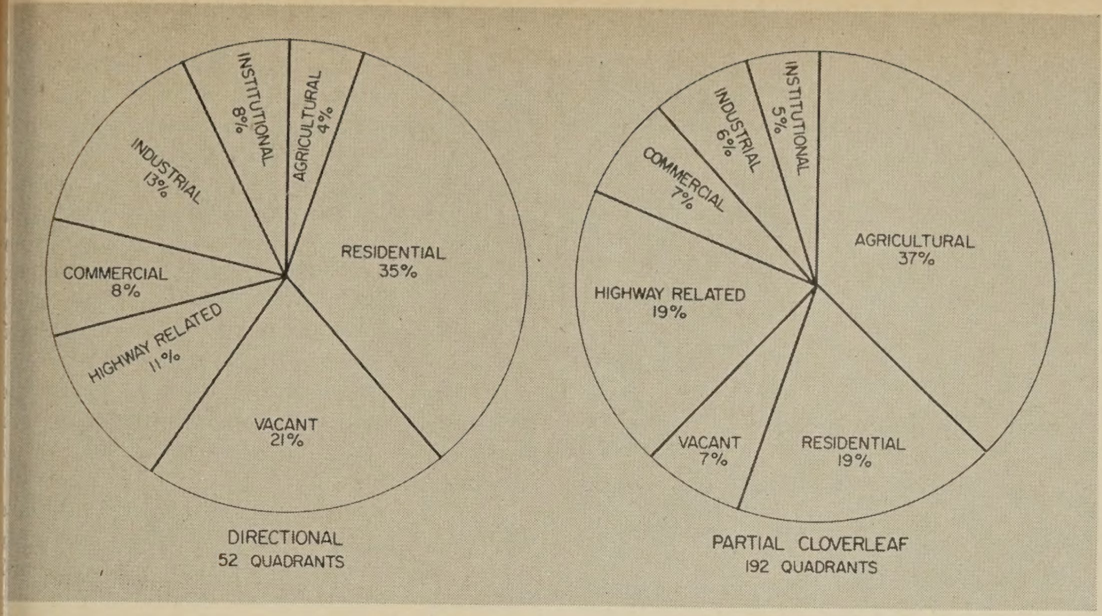


Figure 6.—Interchange land development by interchange design.

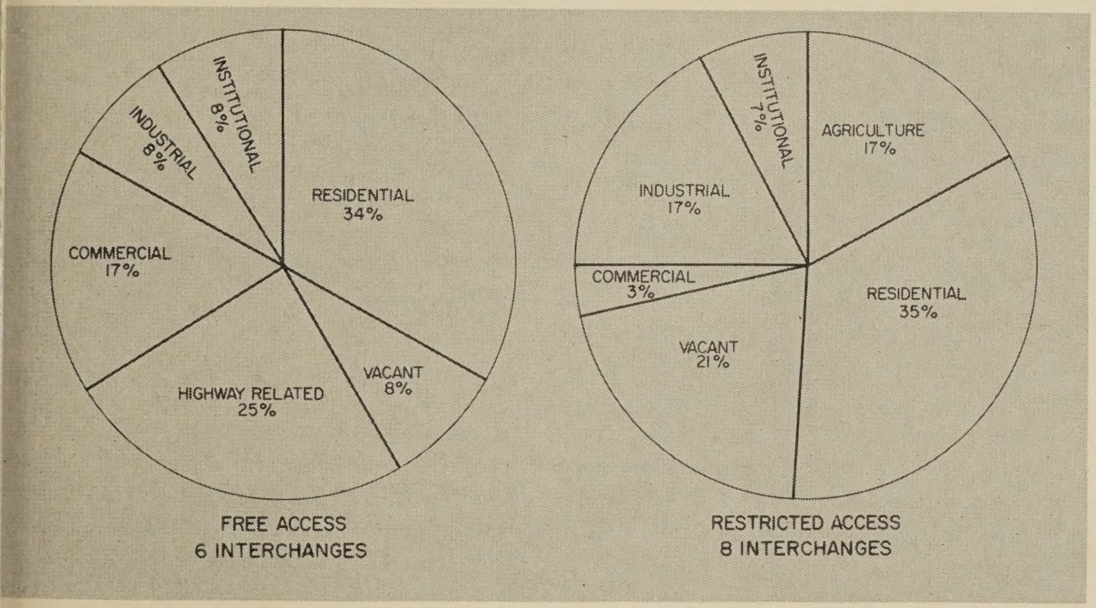


Figure 7.—Land development at full cloverleaf interchanges, by type of access—based on 14 full cloverleaf interchanges.

areas of large population concentration and service stations more frequently in areas of sparse population.

The value of ratios of this type was shown by researchers of the Institute for Research on Land and Water Resources at Pennsylvania State University (*5*) who used them to help predict the economic impact of interchanges on the economy of Clinton County, Pennsylvania. The researchers predicted that four interchanges located in the county would result in the construction of a new 100-unit motel, two new restaurants, one trucking terminal, and four service stations, and that these new businesses would increase the county's total economic activity (estimated through the use of an input-output model) by $5 million, or 2 percent. This figure included a 3-percent increase in annual government receipts of $230,000.

A multilinear regression analysis performed in a study by the West Virginia University Center for Appalachian Studies and Development for the West Virginia State Road Commission (*6*) tested with selected variables the relation of the number of gasoline pumps, restaurant seats, or motel rooms at 79 interchanges in nine States. Factors considered in that study included the number of years the interchange had been open, distance from the interchange to the center of the nearest city, and the population of the nearest city. The strongest statistical relationship was found between motel rooms and the population of the nearest city.

Researchers at Pennsylvania State University continued the study of development at interchanges. In their report (*7*) they verified the feasibility of developing a predictive, interchange-development model of a

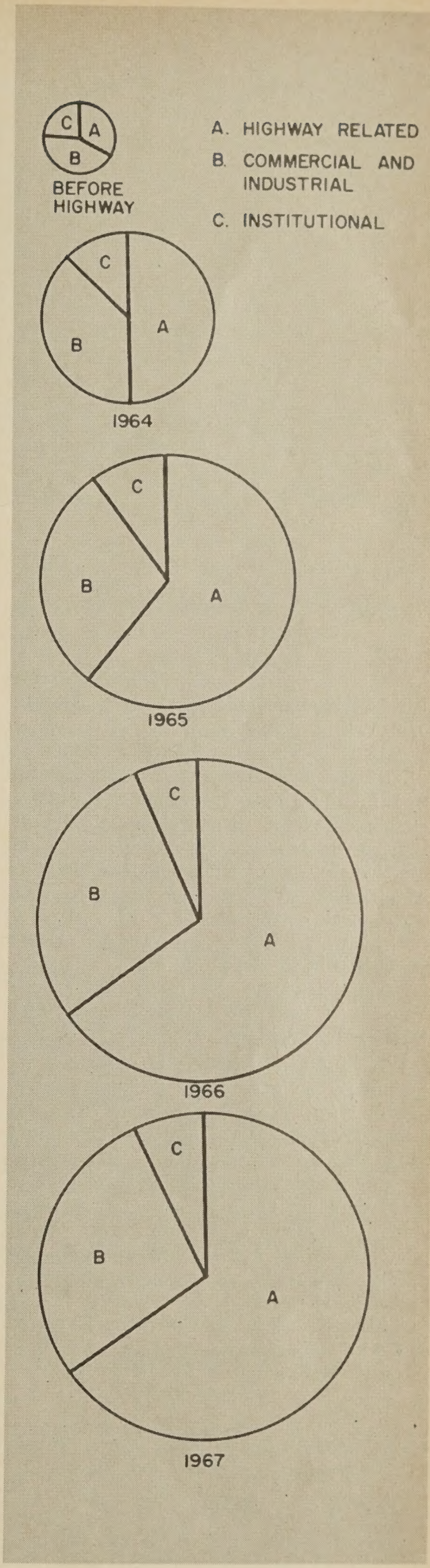


Figure 8.—Distribution of selected land uses at 57 Alabama Interstate interchanges. (Sizes portray growth in number of each of three uses in interchange area—not relative land area in use.)

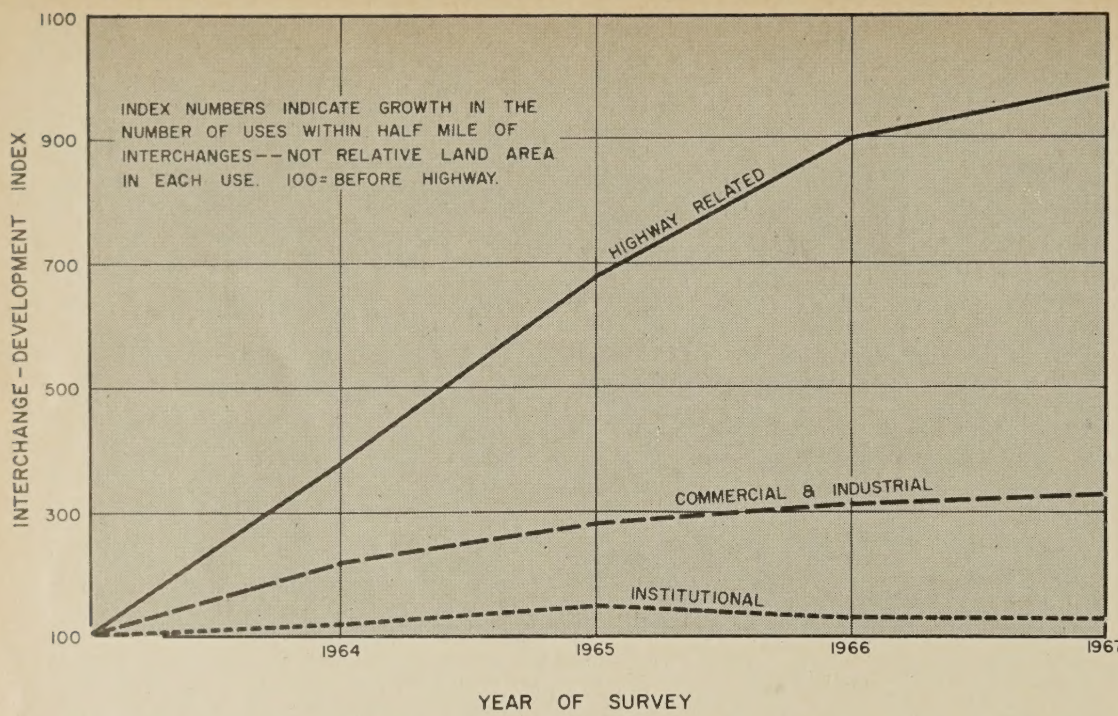


Figure 9.—Relative growth of selected land uses at 57 Alabama Interstate interchanges.

simultaneous-equation type. This model further developed in a doctoral thesis by Richard D. Twark at Pennsylvania State University in 1967, is described in a later progress report (*8*). A two-stage, least-squares technique was used in the thesis to estimate statistical parameters of the structural equations that describe interchange development at 105 interchanges. The researchers determined that average daily traffic on cross routes was the single most important factor in explaining new highway-oriented development. Other researchers at Pennsylvania State University developed a model that simulated spatial diffusion of land uses at interchanges and considered threshold size of population needed to support a given function (*9*).

Similarly, in a study of Oklahoma interchanges (*10*), traffic volumes and size and distance of the nearest urban area were noted to be primary factors in the development of highway-service-oriented establishments. Detailed land use maps were used to describe land development near interchanges. Aerial photographic observation, land-use maps, and simple charts provide a handy combination to evaluate interchange development. More sophisticated techniques can be implemented as the level of economic-development analysis warrants more complex analytical tools.

Interchange Land Development at Circumferential Highways

Capital Beltway, Washington, D.C.

Circumferential highways or beltways around urban areas have different characteristics from other types of limited-access highways. Even though one of their main functions is to divert intercity traffic, the origin or destination of which is not in urban areas, they serve many suburban residents and businesses.

The Capital Beltway, Interstate Highway 495, is a 66-mile freeway that encircles the most densely populated part of the Washington metropolitan area. Since its completion, several studies have been conducted to determine the impact of this highway on surrounding socio-economic development. In one study, a University of Virginia study (*11*), it was determined that nearly 48 percent of industrial employment in Northern Virginia was located within a mile and a half of the Beltway. According to officials of recently located firms, the Beltway was a prime factor in their site-selection decisions. It was noted in the study that since the Beltway was opened, more than 3,000 apartment units were built within a mile and half of the Beltway. When apartment residents were sampled, 50 percent stated that they used the Beltway to go to and from work.

In another study (*12*) conducted on the Maryland portion of the Capital Beltway similar economic attraction was discovered. The researchers in this study noted that the number of recreation trips between Virginia and Maryland suburbs increased after the Beltway had been constructed. Some of the social aspects of beltway-effect were studied in a Public Roads survey of churches that were located within a half mile of beltway interchanges (*13*), in which it was determined that many churches had located near the Beltway to take advantage of the improved accessibility and visibility provided by a beltway location (fig. 12).

After the Beltway was constructed, annual windshield surveys were conducted annually by the Bureau of Public Roads to provide an additional perspective of the beltway-effect on land development. Even though the Capital Beltway was completed in 1964, only 24 of nearly 40 interchanges had been opened and data on land use recorded for these interchanges were compared with subsequent surveys. Selected land uses at the interchange quadrants since 1964 are shown in figure 13. Churches were found at more Beltway interchange quadrants than any other type of land use. The next most frequent land uses, in order, were apartments, schools, and shopping centers. In contrast to the Alabama survey land uses for highway-oriented businesses were not predominant. Apparently, the tendency for residentially oriented land uses, such as apartments, schools, and shopping centers to locate at interchanges of circumferential highways may increase.

Because circumferential highways surround well-developed, populated areas, land uses adjacent to the highway will reflect the pattern outlined in the preceding paragraph. Apartments and churches can be located near other residential areas and are more dispersed than the highway-oriented businesses that tend to

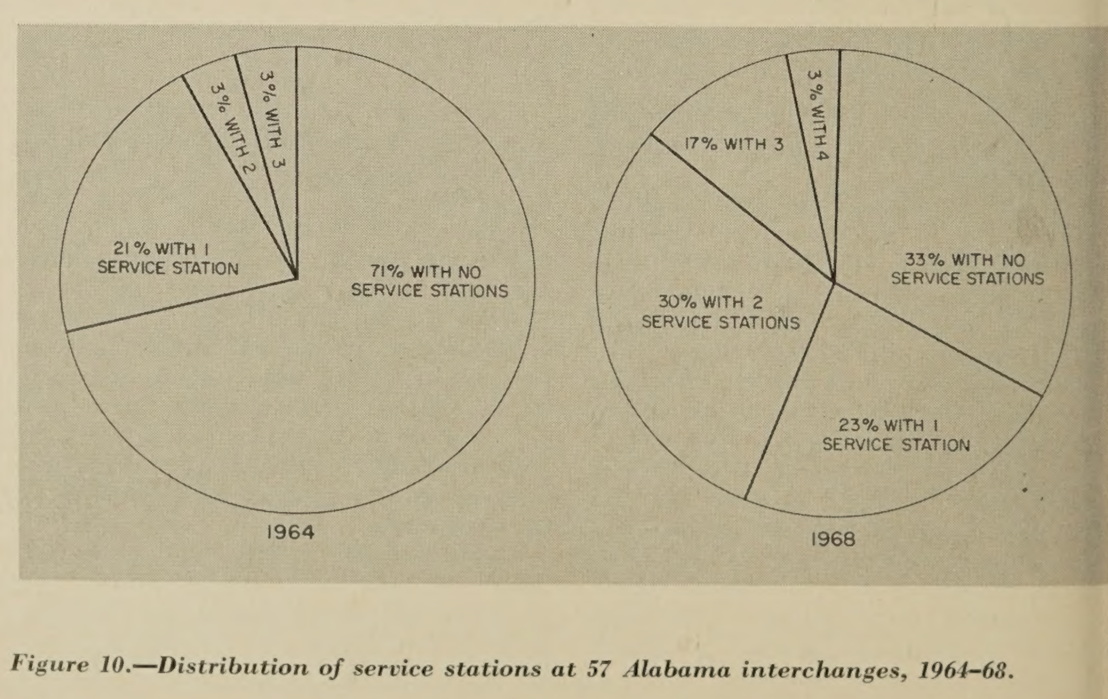


Figure 10.—Distribution of service stations at 57 Alabama interchanges, 1964–68.

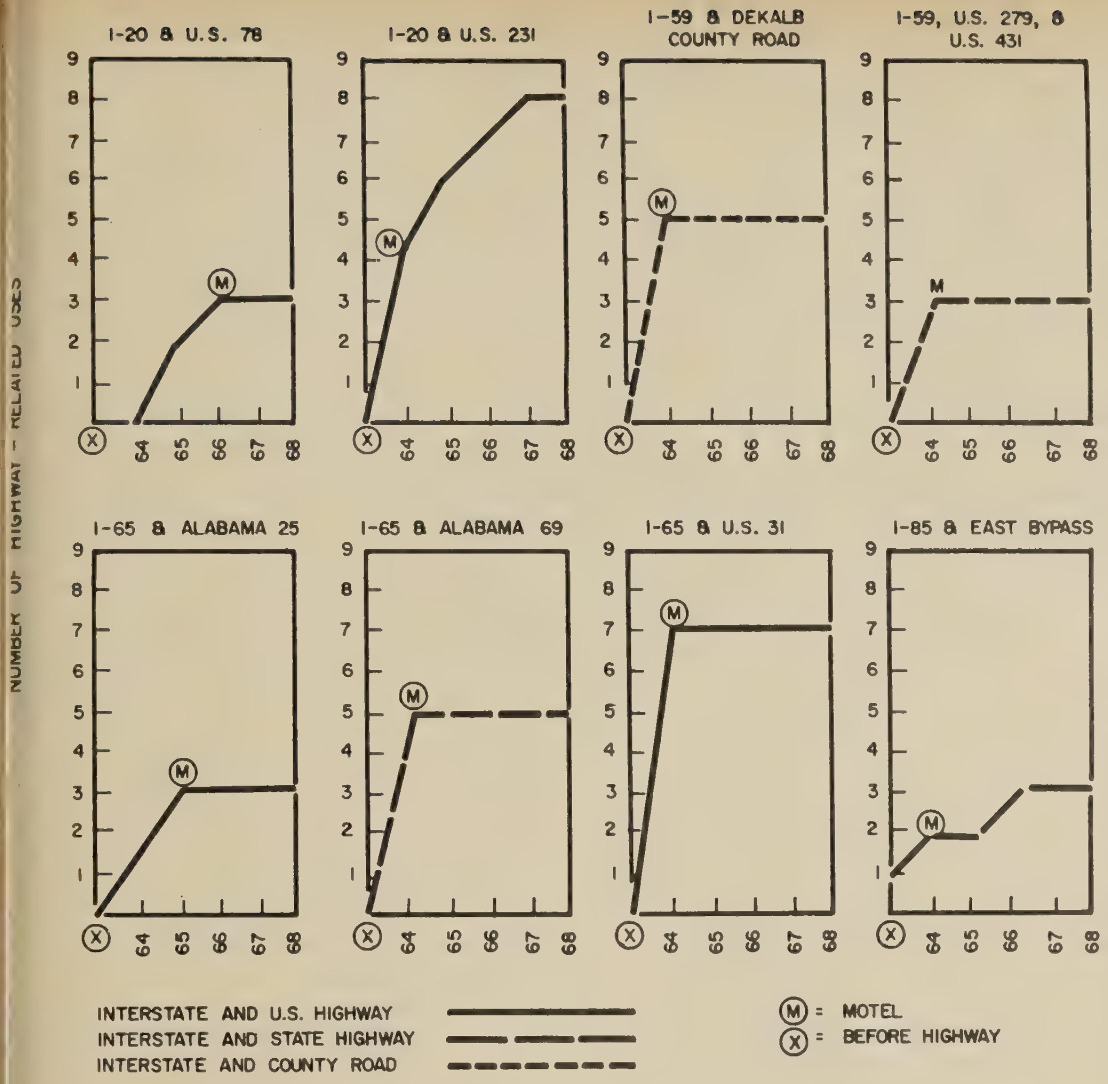


Figure 11.—Growth of highway-oriented uses at 8 selected Alabama interchanges—a profile of development.

prefer certain interchange areas that are most accessible to through traffic.

Another measure of development at interchanges is the number of driveways in each quadrant. Figure 14 shows a shift from quadrants with fewer than four driveways to quadrants with more than four driveways. Thus without land controls, the number of driveways connecting to feeder roads increases as demand for land at interchanges increases.

The Capital Beltway is only one example of the attraction that highway improvements have on economic development. But beltways around large urban centers are different from the usual highways because they attract residential, industrial, and commercial development. Thus the growth in the numbers of apartment projects, shopping centers and industrial parks at beltways is more rapid than highway-oriented land uses because of the proximity of large population centers.

Other beltways

The Massachusetts Beltway, Interstate Highway 495, which serves the Boston metropolitan area, was also analyzed (*14*) for its effect on police and fire-protection services. Researchers determined that this Beltway facilitated mutual-aid calls between suburban police and fire departments even though it caused an access problem when fires occurred between interchanges. They noted that traffic in local towns was reduced after completion of beltway construction because through travelers bypassed town streets.

The effect of this highway, also known as *Platinum Pike*, *Loot Route*, and *Silver Scimitar*, was discussed by Governor John A. Volpe, now Secretary of Transportation, in a seminar at Dean Junior College, Franklin, Massachusetts, in 1965 (*15*). The purpose of the seminar was to evaluate the impact of the beltway and determine the best way to maximize its potential contribution to the socioeconomic development of the area. One reason for interest in Interstate Highway 495, was the startling development along Massachusetts Route 128 where more than 340 industrial plants, with an annual payroll of more than $400 million, had located by 1965. Development along Route 128, once called the *Route to Nowhere*, was also studied by the Massachusetts Institute of Technology in a 1958 study (*16*).

In 1960, a study was conducted on portions of the Baltimore Beltway, Interstate Highway 695, by the Maryland State Roads Commission (*17*). According to the researchers, residents mentioned increased privacy and accessibility as advantages of beltway proximity.

In the Boston and Baltimore Beltway studies it was shown that land development increased near circumferential highways. Because these highways often are located in more densely populated areas than rural Interstate highways, they apparently experience different patterns of land development, which should be considered in future techniques for interchange research, planning, and control. Some possible land uses at beltway interchanges are commuter parking, mass-transit terminals, and motorist or tourist information centers. Research on one of these possibilities is now in progress to consider the problems caused by commuter parking at interchanges.

Use of Interchange Research

Several States have attempted to implement the results of interchange-land-development analysis by formulating interchange controls. It was suggested in a report (*18*) by the Utah State Department of Highways that the installation of parks at interchange areas may help maintain interchange transportation efficiency, as well as provide recreational opportunities, and promote tourist trade. Recently, a proposal to establish a recreation-beautification project in the interchange area of the Dan Ryan and Stevenson Expressways was discussed at a meeting in Chicago, which was arranged by the Chicago Federal Executive Board and attended by representatives of State, municipal, and Federal agencies—Bureau of Public Roads; Federal Highway Administration; Department of Housing and Urban Development; Department of Health, Education, and Welfare; and the Department of the Interior.

In a report for the Illinois Department of Highways (*19*) it was suggested that State highway departments expand the role of interchange planning by coordinating this function with other community planning agencies and urban renewal programs, and thereby establish guidelines to assist developers and planners when land development near interchanges is being considered. As implied in figure 15, the intensity of planning will vary with the intensity of development. Additional control techniques can be adopted when warranted by projected development. Land development-projection techniques facilitate the recognition of potential problem areas.

Recommendations for Further Research

Many research techniques have been used to analyze land development at interchanges. Nearly 100 studies provide data on land development. The consolidation of several studies using some elementary statistical methods to present a nationwide summary of land development at interchanges has been attempted in the study reported here. The fact that some significant patterns of land development were found may indicate the need for more detailed and sophisticated research approaches, in which these additional factors should be considered:

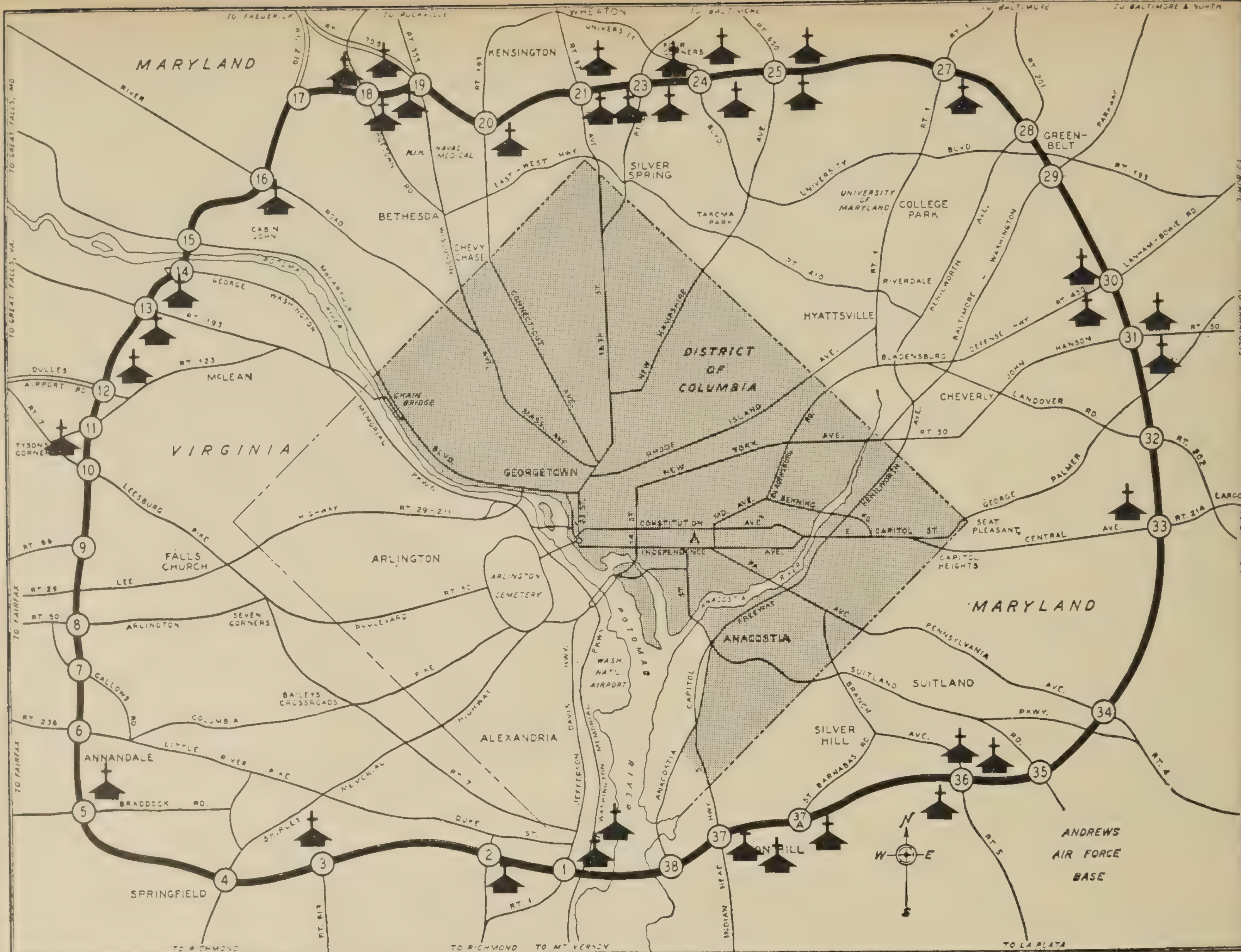


Figure 12.—Locations of 36 churches near interchanges of Capital Beltway, Washington, D.C. 1967.

• Interchange land development may differ according to type of interchange design and type of limited-access facility concerned.

• Land development at interchanges may be related to initial catalytic land uses that attract other related land uses.

• Interchange land-development research should not be separated from the interchange planning and control process problem.

Generalizations about interchanges can be made if the data are properly organized before the analysis is conducted. The studies that have group interchange land data in the early stages of tabulation produce the most significant findings. Analysis of interchange quadrants and specific land uses also reduces the level of aggregation and permits more careful analysis, which in turn, helps to increase the significance of the findings.

The appearance of a specific catalytic agent in land development is not evident immediately unless land development is measured over a period of time. Land-use planners generally recognize the ability of certain land uses to generate or attract other land uses.

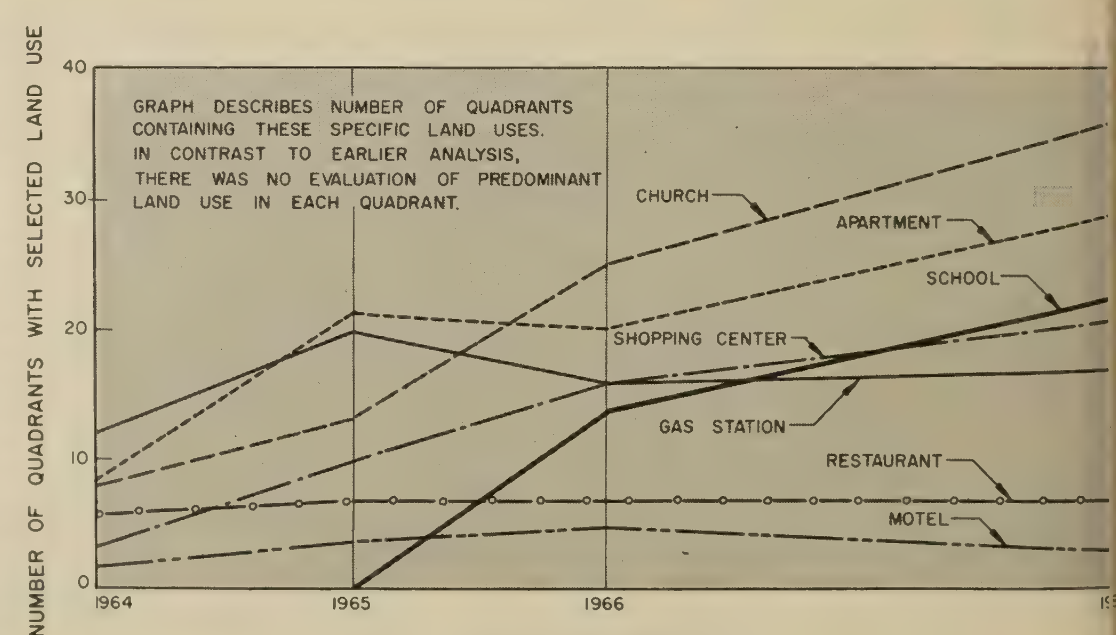


Figure 13.—Capital Beltway, selected land uses by number of quadrants, 1964–68—fro Public Roads windshield survey of 24 interchanges.

and near interchanges seems to experience atalytic growth as shown in the foregoing nalysis of land development at Alabama nterchanges. Future interchange research night find this type of growth to be responsible or some interchange development patterns. If ighway planners can predict which interhanges will attract the catalytic form of land se, they could design the interchanges to andle additional traffic volumes or apply and-use controls to reduce traffic pressure. A dynamic model of economic development t interchanges may be one approach to the olution of this problem.

Analysis of interchange land development nust be coordinated with interchange planing to permit maximum use of research ndings. Research findings can be useful to oth highway planners and local communities y indicating which interchanges will experience rapid land development. Because apid land development is often associated with increased trip generation, highway fficials can take immediate steps to preserve he efficiency of the interchanges as a transportation investment by considering possible lesign alterations to improve interchange raffic capacity.

On the other hand, local planning officials nay also wish to take land-use control measures that limit the density of land development near the interchange. Coordination of oth planning functions, land development and interchange planning, is required to permit optimal economic development and to void interchange traffic congestion, which not only creates a safety hazard but also reduces the efficiency of the entire highway network. The chart shown in figure 15 describes some of the factors that may be part of this process.

Summary

Land-use data at 332 interchanges in 16 States have been analyzed to determine land development patterns at interchanges. Land development at these interchanges was determined to be largely agricultural and residential, although more than 17 percent of the interchange quadrants had predominantly highway-related land uses—motels, restaurants, and service stations.

Although the majority of interchanges studied were those with at least one intersecting Interstate highway, the major land uses at non-Interstate interchanges were commercial, industrial, and institutional. The concentration of these uses at non-Interstate intersections may be influenced by the relatively recent construction of the Interstate System and may indicate that greater land development will occur at Interstate interchanges in the future.

Certain types of interchanges were observed to contain significantly larger proportions of certain land uses. Land uses generally associated with residential development were predominant near interchanges of Interstate highways and local roads. Highway-related land uses tended to concentrate near interchanges of Interstate highways and U.S.-numbered highways. In contrast, interchanges of two Interstate highways contained relatively larger portions of industrial land uses. Perhaps this was caused by the increased regional accessibility of the sites or by the lower land values resulting from the relative lack of access to nearby developments.

At Alabama Interstate-Highway interchanges, land development within a radius of one-half mile from the interchange centers consisted largely of highway-oriented businesses. Interchanges near population centers, such as beltway interchanges, included larger proportions of higher land uses, such as apartment developments and industrial parks.

Studies of interchange development can help planners predict which interchange areas will experience unusually rapid development. The coordination of interchange research and highway planning facilitates formulation of control techniques and planning methods that preserve the efficiency of the interchange and promote optimal economic benefits to the community.

ACKNOWLEDGMENTS

The author acknowledges the assistance and guidance of the Public Roads staff who contributed to this article. Floyd I. Thiel, Preston J. Moe, and Edward M. Nolan conducted the windshield survey of the Capital Beltway and designed the interchange analysis forms. Merritt D. Nolden and Edna Wolf helped prepare the charts and tables and performed the statistical calculations on which this report was based. Miss Ingrid Farquarson performed a thorough literature search of interchange studies.

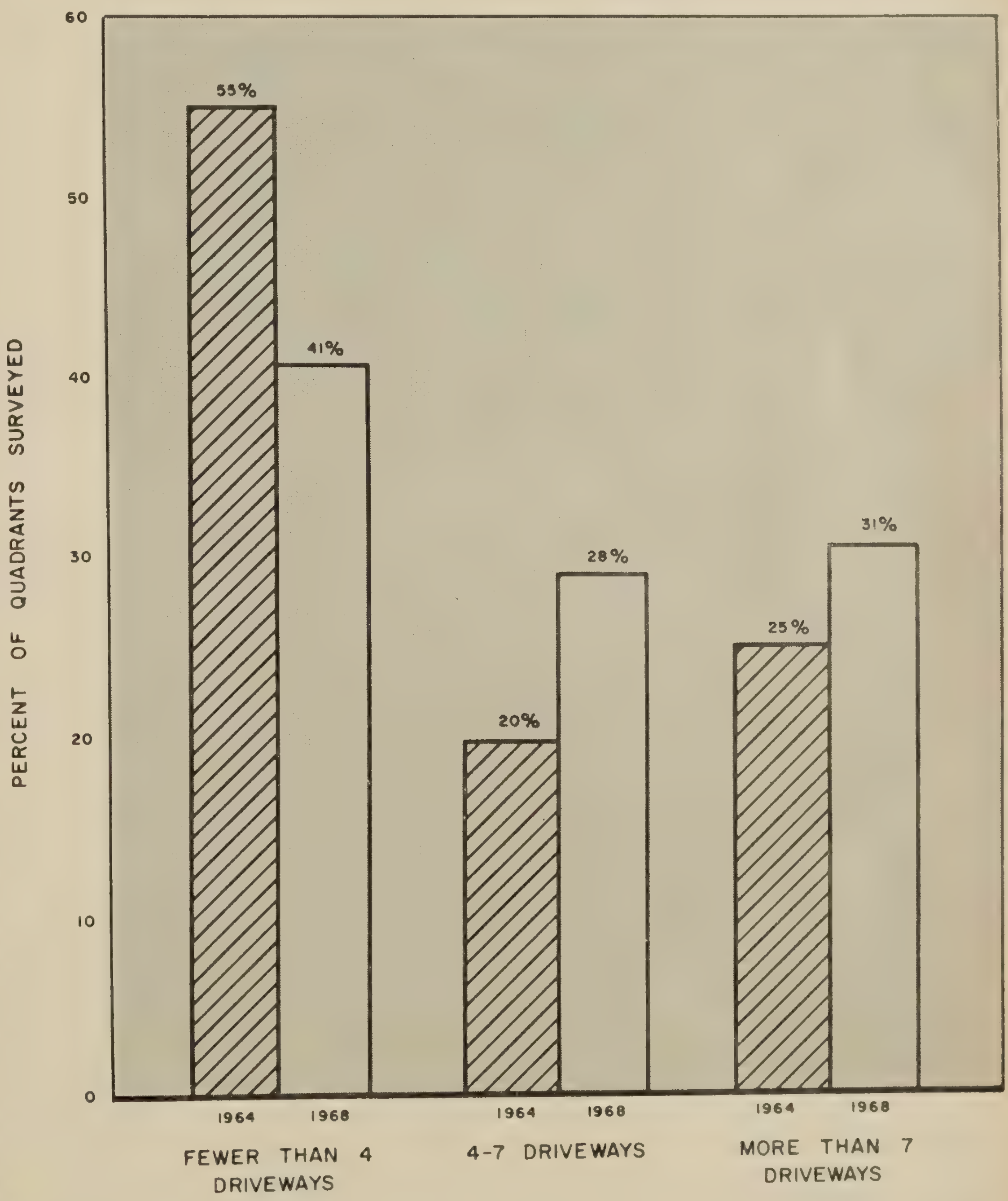


Figure 14.—Capital Beltway interchanges, number of driveways by quadrant, 1964–68—from Public Roads windshield survey of 24 Capital Beltway interchanges.

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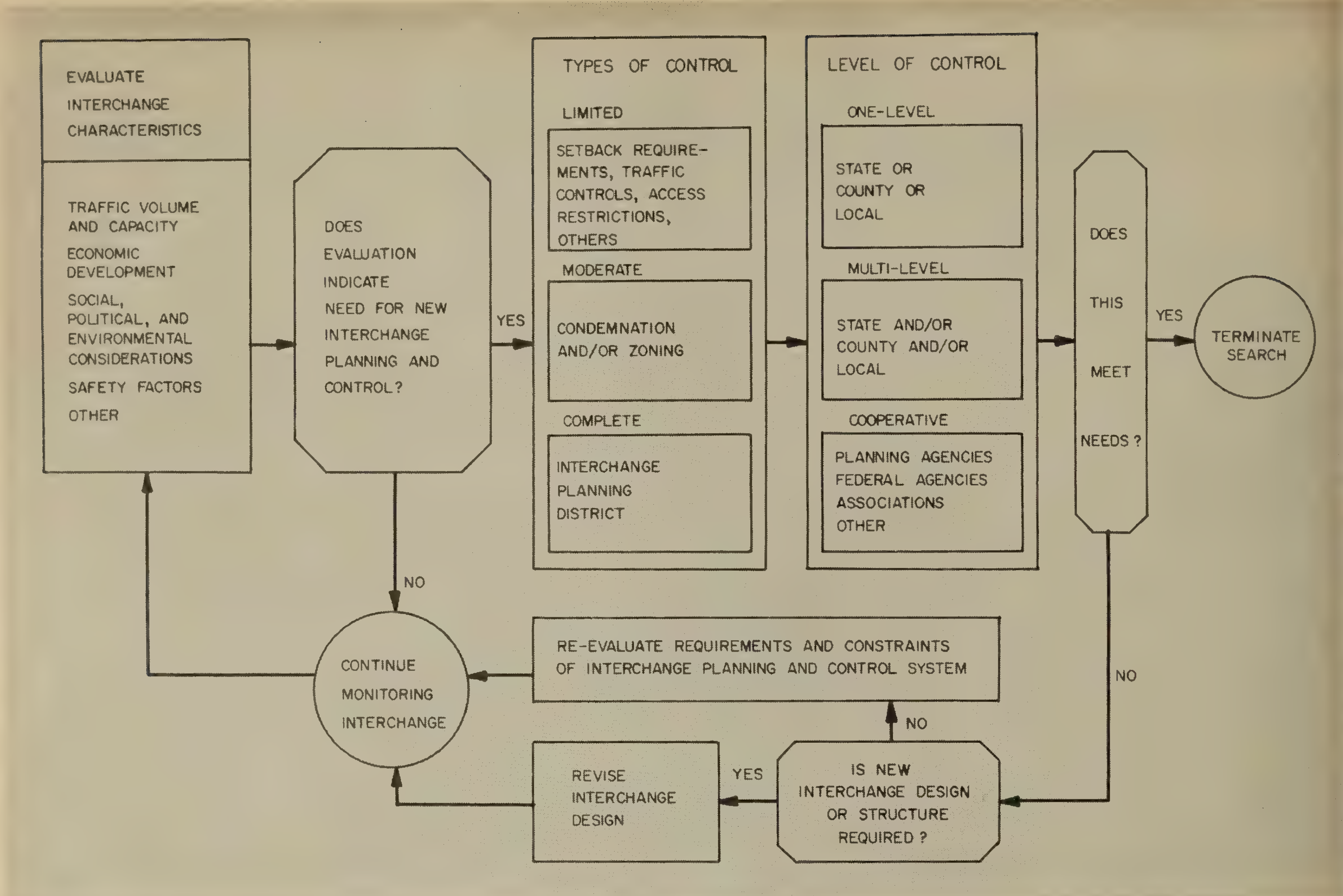

Figure 15—Suggested system for interchange planning and control.

The author also wishes to acknowledge the following unpublished paper, which provided background material for a part of this article: *Bureau of Public Roads Bank of Land Value Data—Its Status and Usefulness for Highway Related Developments*, by Floyd I. Thiel, Ruth B. Ross, and John Yasnowsky, presented to the North Central Land Economics Research Committee, Chicago, Illinois, 1965.

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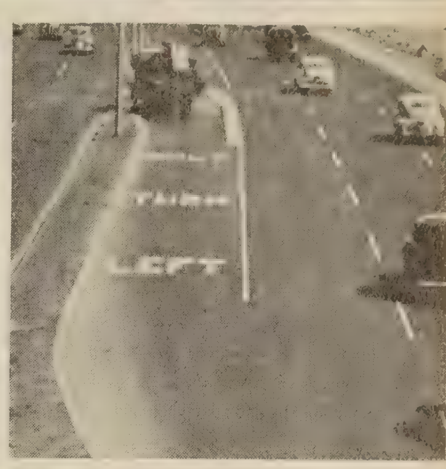

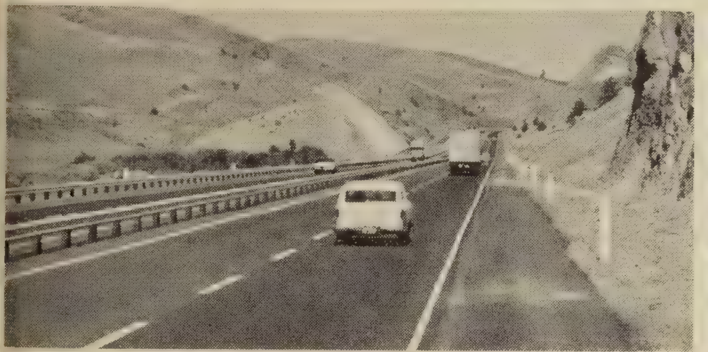

Traffic Marking Materials—Summary of Research and Development

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BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

Recent research in traffic marking materials is presented in this review to summarize the state-of-the-art since the last comprehensive bibliography published in 1952 by the Highway Research Board. It is intended not to present a complete bibliography on the subject since 1952, but rather, to point out the most pertinent research findings and developments in recent years. Research and development in the United States sponsored jointly by the State highway departments and the U.S. Bureau of Public Roads is emphasized and supplemented by information on other ongoing research by other agencies in the United States and throughout the world.

Many proprietary trade products are specifically mentioned to present a more complete account. Mentions of trade names are not to be considered endorsements of the products, nor are omissions of trade products, either overlooked or unknown to the author, to be considered inferences that such products are of lesser quality than those mentioned.

AS MOST highway engineers realize, traffic marking has become a sizable item in the maintenance budgets of many highway departments. In a published survey (*1*)[2], it was shown that throughout the United States, in 1965, 12 million gallons of conventional traffic paint were purchased by the States and an estimated additional 9½ million gallons by cities and counties. Thus city,

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[1] Presented at the 55th Annual Meeting of the American Association of State Highway Officials, Philadelphia, Pa., October 27–31, 1969.

[2] Italic numbers in parentheses identify the references listed on page 256.

county, and State governments nationally used more than 21 million gallons of conventional traffic paint. At average costs of $1.66 per gallon for white paint and $1.95 for yellow paint (*1*), the national cost for paint binder in 1965 alone was estimated at $38 million. It was also reported in the survey that approximately 107 million pounds of reflectorizing glass beads were purchased by these governments during the same year—66 million pounds by the States and an estimated 41 million pounds by cities and counties—at an estimated cost of about $12 million. Accordingly, the total cost of paint and beads during 1965 was approximately $50 million.

But these material costs are reported to be only about a third of the total cost of installed conventional striping (*2*). Thus the annual overall cost of striping with conventional paint in the United States is estimated to be at least $150 million. This estimate does not include costs of other marking systems like hot thermoplastics, preformed stripes, or raised button-type markers, which are known to be appreciable. Not only these exorbitant costs, but also the need for adequate lane delineation to enable safe driving during all seasons of the year and in inclement weather, have stimulated pavement-marking research and development. The significant trends and developments in this field since the last comprehensive bibliography on pavement marking materials, published by the Highway Research Board in 1952 (*3*), is summarized in this review, which is intended not as a complete bibliography, by any means, but as a current state-of-the-art report to point up to present researchers and potential producers the most pertinent research and development in recent years.

In gathering information for this review, research and development in this country, particularly through Federally-aided highway studies (*4*) and similar experimental projects, was emphasized. In addition, information on recent international research, obtained through the Highway Research Information Service of the Highway Research Board, as well as available literature, reports, and unpublished information on domestic and international developments, were reviewed. Many proprietary products, which may not have been fully evaluated by unbiased consumers or governmental agencies, are specifically mentioned in this review. The mentioning of any product to provide the reader with a broader scope of developments is not to be construed as an endorsement of that particular product. Similarly, the names of many deserving trade products unknown to the author probably have been omitted.

Conventional Solvent-Based Traffic Paints

The main objective of recent research and development in conventional traffic paints has been to improve durability and performance or to obtain more economical markings. Recent research activities include: studies of composition, as related to performance; special pavement pretreatments; accelerated laboratory tests to predict durablity; evaluation of the nature or cause of field failure; film thickness; and developments in reflectorizing glass beads. Each of these is discussed separately.

Composition

During the period from about 1940 to 1960, considerable research effort was directed at the pigment portion of traffic paint. In recent years, however, this aspect has received little attention from the State highway departments. Recent research and development effort on paint composition largely has been directed to the organic binder, commonly referred to by paint specialists as the nonvolatile vehicle. The most commonly used organic binder in conventional traffic paints purchased by State highway departments is the drying oil modified alkyd resin (*1*). Other vehicles used by these agencies in order of their decreasing prominence are: chlorinated rubber-alkyd, dispersion resins, phenolics, chlorinated rubber-petroleum hydrocarbon, and polyvinyl toluene polymer. A 1968 report by the Georgia Institute of Technology included results of laboratory and field tests on a wide variety of traffic paint formulations (*5*). The authors of that report concluded that oil modified alkyd, as well as chlorinated rubber-alkyd traffic paint, exhibited good performance—much better than most of the other types evaluated. In a separate report, it was shown by the New York Department of Transportation that, compared to a number of other conventional solvent-based paints, oil-modified alkyd paint gave the best performance (*2*). The New York Department of Transportation also conducted field tests and found that latex or emulsion-type paints did not compare favorably with their standard modified alkyd paint (*6*). The work in New York indicated that the latex paints had a useful life of only three or four months on either concrete or bituminous pavement. The latex paints performed poorly regardless of whether they were applied at ambient temperature or preheated and applied hot. Latex paints were also found to give poor adhesion in field tests reportedly conducted by the New Jersey State Department of Transportation (*7*).

Federally-aided research at North Dakota State University is currently being conducted on traffic paint vehicles that have the potential of reacting with the pavement substrate to provide good bond and durability. In this research, isocyanate-based paints are being studied for reaction with portland cement concrete pavement. At present, no significant trends have been reported. Current research at the Central Office of Public Roads in Poland is directed toward the development of polystyrene paints, but no conclusions are yet available.[3]

Special pavement pretreatments

In a 1957 study by Keese and Horn, it was reported that, compared to simple brooming or use of compressed air alone, sandblasting a portland cement concrete pavement to clean the surface prior to striping increased paint life substantially (*8*). In that study, sandblasting costs were reported to be 10 cents per linear foot. Regular cutting sand with an airflow of 210 cubic feet per minute and 110 p.s.i. compression was used for blasting. In a report issued by the New York Department of Transportation in 1969 (*2*), it was determined that neither acid etching nor synthetic rubber primer increased the durability of traffic paint on either concrete or bituminous surfaces regardless of the ages of the surfaces. It was also reported that preheating the paint and applying it hot did not increase durability. According to a 1966 study by the Corps of Engineers, adherence of paint to portland cement concrete pavement can be improved by pretreating the pavement with a 50-50 mixture of boiled linseed oil and mineral spirits (*9*). It was shown in their field tests that, compared to an untreated test section, adhesion to the pretreated pavement was superior. This finding should be of value to northern States where concrete bridge decks are pretreated with linseed oil to prevent damage by deicing salt.

Laboratory tests and cause of traffic paint failure

For a great many years an urgent need has existed for an accelerated laboratory wear test that would accurately predict field durability and properly rank traffic paints according to their field performances. Over the past several decades, much research has been directed to developing such laboratory-wear or abrasion tests. Simulated traffic wheels, Taber abrasion tests, falling sand tests, and other methods have been tried, but none has gained universal acceptance because of poor correlation with field results. A recent additional effort by the Georgia Institute of Technology to develop a laboratory wear test that would correlate well with field performance (*5*) was unsuccessful. During 1968, research reportedly was underway at the Federal Institute of Road Research in Germany to develop an accelerated laboratory durability test.[4]

Apparently, some traffic paint specifications that are based solely on physical tests are unable to adequately assure good paint performance on the road. This fact was confirmed by a 1964 report by the U.S. Naval Civil Engineering Laboratory (NCEL) in connection with Federal Specification TT-P-85b (*10*), which is for reflectorized traffic paint for airfield runway markings. The NCEL report stated that mere conformity with the requirements of Federal Specification TT-P-85b did not guarantee a paint with good field service, nor did the test results obtained on a wide variety of conforming paints correlate well with field service. In particular, NCEL reported that the laboratory bleeding test was of little value in predicting field bleeding behavior. Specification TT-P-85b also stipulates a falling sand abrasion test to assure good

[3] Highway Research Information Service, Highway Research Board, Washington, D.C.

[4] Highway Research Information Service, Highway Research Board, Washington, D.C.

durability, but the merits of this test are rather questionable on the basis of the NCEL findings.

Perhaps the major reason that abrasion-type laboratory tests have never become fully reliable or firmly established is that actual field failure involves a different mechanism. According to recent research results from an ongoing study by the State Highway Commission of Kansas, chipping or loss of adhesion, rather than abrasion loss, is a major cause of traffic paint failure on portland cement concrete. This observation, particularly with respect to concrete surfaces, was also noted by the Texas Highway Department and was reported in the literature by others some years ago (*11*). Work currently underway in Colorado confirms that traffic-paint chipping is a prominent cause of failure (*12*).

Paint film thickness

The most predominant wet film thickness of traffic paint used by most State highway departments is 15 mils (*1*). Use of this thickness may have become a general practice as a combined result of field experience and published research results. More than 10 years ago, the Michigan Department of State Highways, investigating the field performance of various wet film thicknesses from 12 to 21 mils (*13*), reported that the thicker films were more durable but that the additional life of paint thicker than 16 mils was not directly proportional to the additional thickness used. Accordingly, it was concluded that to increase the wet film thickness beyond 16 mils was not economical. Thus, the general practice of applying a wet film of 15 or 16 mils seems to have some substance. This practice is keyed to the use of conventionally graded glass beads.

In more recent work reported in 1965, researchers at the Georgia Institute of Technology reported that paint durability, and even night visibility, was improved as wet film thicknesses within the range of 10 to 20 mils (*5*) were increased. They specifically noted that wet film thicknesses of 10 mils were generally incapable of properly binding drop-on beading, presumably of conventional gradation. Their field work included a two-coat application of 15 mils each, which provided superior performance. However, it was postulated in the report that, for single-coat applications, 20 mils would seem to be the practical upper limit for the types of paints investigated. The Kentucky Department of Highways, experimenting with multiple film applications of 15 mils each, reported informally that multiple coats provided improved durability over a single 15-mil thickness, but that the comparative economics had not been fully established.

On the other hand, some of the research now being pursued seems to contradict part of these findings. For example, researchers at North Dakota State University, conducting a traffic paint study supported financially by the North Dakota State Highway Department and the Bureau of Public Roads, have stated that wet films much thinner than 15 or 16 mils are required for good paint adhesion and subsequent durability. This contention is based on limited field tests and on the premise that traffic paint fails more often through lack of adhesion than through abrasion. However, only limited field evidence has yet been presented to support this hypothesis. In an interim report on a study by the State Highway Commission of Kansas it was stated that both reflectivity and durability were increased when paint film thickness was reduced from 15 to 10 mils (*14*). This work is being performed in conjunction with an investigation of reduced bead application rates.

Hence, at present, evidence as to the optimum film thickness seems to conflict. Perhaps test conditions and even the bead application rate are some reasons for the different findings. The work in Kansas on films thinner than 15 or 16 mils was conducted on previously striped areas where remnants of the old stripe still remained under the newly applied stripe. Consequently, the thicker the new stripe, the more the older paint remnant lost its adhesion to the pavement. Moreover, where larger accumulations of old paint were evident, it was determined that chipping losses increased. The Kansas work also included an investigation of reduced bead application rate, which will be more fully considered in the next section.

The optimum film thickness of traffic paint may therefore depend on whether striping is applied to a previously unstriped area or to an area on which remnants or accumulations of old paint still exist under the new striping. In addition, it is becoming apparent that optimum film thickness is closely related to bead gradation and bead application rate.

Reflectorized beads

Small glass beads not only provide night visibility for traffic stripes but are reported to contribute as well to the overall durability of the paint binder (*5*). Within the last several years, considerable attention has been given to the role of traffic paint beads. A recent article by J. M. Dale, based on theoretical considerations, raised many questions about the adequacy of current State highway specifications for bead gradation and application rate (*15*). The parameters of glass beads, including the best index of refraction, are controversial factors, which fortunately are under intensive investigation at present.

In most State highway departments, the present practice is to use beads of a standard refractive index—1.50+ as opposed to 1.65 or more—and an application rate of about 6 pounds of drop-on beads per gallon of paint (*1*). Generally, the bead-size gradations range from a maximum of 20 mesh to a minimum of about 100 mesh (*15*). These common practices will now be examined in the light of recent research and development findings.

Regarding refractive index, the New York Department of Transportation reported that although the special 1.65+ index bead, measured instrumentally, gave slightly better initial reflectivity, the improvement was hardly noticeable to the driver, and the measured quantitative difference diminished and finally disappeared as the stripe exposure time increased (*16*). It was concluded that use of the standard index bead, 1.50+, at a savings of 2 to 3 cents per pound, was preferable. The results in New York were applicable to both concrete and bituminous pavements. In a recent report by the Colorado Department of Highways, similar results were cited (*12*).

The application rate of drop-on glass beads to traffic paint is another parameter that is receiving current research attention. On the basis of an ongoing research study, being conducted in conjunction with the study of films thinner than 15 or 16 mils, the State Highway Commission of Kansas reports that the beading rate could be reduced from 6 pounds per gallon of paint possibly to 4 pounds per gallon with no loss in reflectivity or durability and with resultant economic savings (*14*). According to theoretical considerations and practical laboratory tests, an intermediate bead application rate provides better reflectivity than either a very high or very low rate (*17*). In a recent report by the Colorado Department of Highways it was also shown that an application rate of 4 pounds per gallon was both more economical and more effective than a rate of 6 pounds per gallon (*12*). However in that work, other special parameters, such as special gradation and specially coated beads to afford a flotation feature, were involved.

Bead gradation is also undergoing research consideration. The current gradation specifications used by the State highway departments differ considerably. Generally the sizes specified range from a top size of 20 mesh (100 percent passing) to approximately 100 mesh size (*15*). Highway engineers are interested in obtaining an optimum gradation and more uniformity between the gradation specifications of the State highway departments. In the previously cited article by Dale (*15*), it is suggested that fewer than 30 percent of the beads of current conventional gradation for drop-on applications are effective when they are first applied. It is claimed that many of the beads of the small size fraction are immediately submerged in the paint and therefore are not initially effective. It can be argued that these submerged beads never become effective if the paint fails by chipping. On the other hand, if the paint wears out mainly through abrasion, the initially submerged beads become effective later in the life of the film. Previously cited research supports the theory that adhesion or chipping failure is a significant factor in the life of the paint film.

Field test results, reported some years ago for special gradations of glass beads obtained from a single source (*18*), indicated that coarse beads, 20 to 40 mesh, initially gave much higher reflectance than either fine beads, 40 to 100 mesh, or conventionally graded beads, 20 to 100 mesh. However, this superiority was not maintained for a long period. After about six months exposure, the reflectivity of the coarse gradation dropped below that of the other two gradations, indicating that the coarse beads ultimately are removed from the binder by traffic action, even though they are initially more effective because a greater proportion is exposed at the surface. In recent studies it has been shown that coarse beads, 40 mesh or larger, are lost by the binder soon after installation because they are poorly anchored (*12, 14*). Conversely, the extremely fine beads, 80–100 mesh, sink into the paint and never become effective reflective units when the paint fails from chipping or lack of adhesion. Accordingly, without considering cost factors, the optimum gradation should be one that is between a maximum size of 40 mesh and a minimum size of about 80 mesh, provided that a conventional wet film thickness of 15 or 16 mils is used.

The Colorado field experiment cited earlier is now being conducted on uniformly graded beads of a narrower gradation range than conventional gradations (*12*). The beads contain a coating that gives them a flotation property that is claimed to make them float but be partially immersed in the paint film. Presumably this property allows more reflectorizing units to be available at the paint surface. In interim reports from the Colorado experiment, it is shown that the special beads applied at a rate of 4 pounds per gallon provide reflectance equal to or greater than that of the conventional beads normally used by the States, which are applied at a rate of 6 pounds per gallon. According to the Colorado report, use of the special beads at the reduced application rate provided significant cost advantages. After 10 months, field tests indicated no evidence of any serious reversals in reflectance or of poorer durability. These findings have been confirmed by the Nebraska Department of Roads which informally observed the performance of such beads. The Nebraska observers stated that the flotation feature seemed more important than closer grading, as beads of the same grading but without the flotation property did not provide the same high degree of reflectance.

One predominant factor for good reflectivity seems to have been established by the results of past and current research—a bead must be slightly more than one-half immersed in the paint binder to obtain maximum retroreflectivity at high incidence angles (*17*).

Rapid-Dry Traffic Markings

There has been a recent upsurge of interest in rapid-dry traffic markings among State highway departments. One reason for this interest is the desire to disrupt traffic flow as little as possible during striping operations on existing highways where traffic densities are increasing. Another reason is economics; the cost of placing and removing the traffic cones needed for conventional striping can be partly offset by using the more expensive quick-dry markings, which do not require protective cones.

Several years ago a study was conducted on the use of microwave energy to heat and quickly dry traffic paint after its application to the pavement (*19*). The method was adjudged technically unfeasible because it was difficult to maintain a sufficient high-energy intensity in the paint film owing to its dissipation into the pavement itself.

The use of plasticized sulfur, which is melted in a flame or kettle and hot-sprayed onto the pavement, is being investigated as a quick-set marking by the Phillips Petroleum Company. Another material that seems somewhat similar, called *Sullarzan*, was reported in the British literature (*20*), in which the following properties were claimed: It is obtained by polymerizing sulfur (it may, in fact, be a mixture of polysulfide polymer and unpolymerized sulfur); it is available in solid granular form; it was developed by the Société Nationale des Petroles d'Aquitaine and is being introduced for trial in France and England; it is available in any color, presumably is applied in molten form, and dries, or sets, to a no-pick-up condition in 15 seconds; it contains glass beads and may even be applied to *wet* or *icy* roads (the latter claim is rather difficult to believe) and its covering rate is 400 grams per square meter. Its producer claims high durability—"6 times the durability of existing road marking materials." No evidence of rigorous and conclusive field research on the merits of sulfur-based markings by highway agencies is known to the author.

Several fast-dry, solvent-based paints were introduced in the last decade, one of which is the *Nite-Line* paint produced by Prismo Universal, Inc. Claimed to dry in 3 minutes or less, the paint is heated to 165°F and is applied by spray from special equipment. Glass beads are blown by compressed air into the wet binder. Application speed is said to be 8 m.p.h., and no traffic cones are used when the material is applied to the pavement. A follow-up truck about 500 yards behind the application truck temporarily keeps traffic off the wet stripe until it dries. The cost of the material, including glass beads, is about $6 per gallon. Reportedly, this product has been used in New York City and Baltimore, as well as in Pennsylvania, Florida, and Arkansas. In a recent article, it was reported that the Michigan Department of State Highways used a heated fast-dry paint, which may be similar to the above-mentioned product (*21*), except that the dry time claimed in the Michigan application was 1½ minutes rather than 3 minutes.

A similar fast-dry paint product, called *Green-Lite Liquid Striping Compound*, is being sold by the 3M Company. This solvent-based paint has a high solids content and is heated to 250°F and applied by airless spray. Dry time is claimed to be only 2–20 seconds, or an average of 10 seconds. The striping equipment can be purchased. The material contains pre-mixed beads and is applied at a wet-film thickness of 15 mils, which provides a dried film of about 11 mils. The producer claims that the material reacts with the air immediately when it is sprayed and that this aids in speeding up the dry time. Again, no protective cones are required for application. The durability of the paint is said to be equal to that of conventional striping, and material costs are about $8 per gallon. The maximum speed of the striper is 10 m.p.h. The company states that this material is being tried out in Florida, Michigan, Missouri, California, and Colorado.

Similar heated, fast-dry proprietary paints such as *Hot Line* produced by the Baltimor Paint and Chemical Corp., are also availabl from other producers. Within the last yea or two, the Texas Highway Department ha been experimenting with a fast-dry, heate paint based on chlorinated rubber, chlor nated paraffin, and alkyd resin. The pain has a low solvent content and requires onl moderate heating. The needed heat can b obtained from the liquid cooling system of the engine on the striping truck, thereb eliminating the need for special auxiliar heaters like those used for some of the oth proprietary fast-dry, heated paints. This ma terial is applied by airless spray and reportedl dries in 2 minutes when heated to abou 120°F, or alternatively dries in 4 or 5 minute when applied without heating. Material co of this paint is estimated to be about $2.3 per gallon. This material may be fairly simila to the British product called *Clearlane*.

Several other types of proprietary product have a rapid, almost instant, setting property These include the hot-extruded thermoplast striping and hot-sprayed plastic materia that are applied as rather thick coating However, because such materials were pr marily developed to provide long-lastin stripes, they will be discussed more fully i the following section.

Semi-Permanent Markings

Materials that have been developed t serve as semi-permanent markings incluc preformed glue-down plastic stripes, ho extruded and hot-sprayed thermoplast stripes, and plastic or ceramic raised butto type markers. Compared to conventiona stripes, they were developed mainly to provic long-range economic benefits, although th raised button-type markers are also intende to provide improved visibility in rain or fo

Preformed glue-down plastic stripes contai an adhesive backing and are mainly used o bituminous pavement in high-density urba areas—usually for crosswalks and stop line Their use on open highways has been rath limited. A report by the Arkansas State High way Department indicated that such materia do not provide adequate durability, mainl because their adhesion to concrete surfaces poor (*22*). Somewhat better performance wa reported when the material was applied t bituminous surfaces. Installed costs on a co tract basis were stated to be 55 cents p linear foot of 4-inch-wide stripe. A researc report by the New York Department o Transportation similarly indicated poor dura bility on open highways because the materi was quickly dislodged and destroyed b traffic and snowplows (*23*). Proprietary prod ucts of this type produced in this countr include *Plastix* and *Neff-Slabs*. An apparentl similar material, called *Verynl*, was invest gated by the New Zealand Transport Depar ment in 1968. This material is claimed t have good wear and to be more economic than paint for pedestrian cross-walks. *Veryn* contains polyvinyl chloride, is 2.5 mm. thic and is applied with standard mastic. It wa eportedly tried out in this country in Los ngeles.

There has been considerable research in this ountry on hot-extruded thermoplastic stripes, hich are applied at a thickness of about ne-eighth inch. Such materials are sold under he trade names of *Permaline* and *Catatherm*. . comprehensive survey and report on these naterials, prepared this year by the Bureau of 'ublic Roads (*24*), was based on the results f a large number of installations throughout he United States. The major conclusion and ecommendations in that study were as ollows:

- Hot-extruded thermoplastic materials were nuch more durable on bituminous pavement han on concrete pavement. The material is nore durable on older concrete than on new oncrete.
- Snowplow activity dislodged the material rom the pavement, particularly on concrete.
- A factor limiting the economic value of hermoplastic striping on bituminous pavement is the limited maintenance-free life of he bituminous surface.
- Unremoved layers of old paint adversely ffect the adhesion of thermoplastic striping o the pavement.
- Under conditions of little or no snowplow ctivity, thermoplastics were found to be more conomical than paint striping, provided the raffic density was appreciable. For bituminous avements, the daily density should exceed ,000 vehicles per lane; for concrete pavements, he density should exceed 9,000 vehicles per ne. Under conditions of moderate snowplow ctivity, the use of thermoplastics could be ustified, provided that traffic density levels re high enough. Finally, under conditions of evere snowplow activity, there is little economic justification for the use of hot-extruded hermoplastics.
- Guidelines in the report enable the selection of the most economical material—paint r thermoplastic—for different traffic densities nd degrees of snowfall.

An interesting sidelight to investigations of hermoplastic striping materials is a 1965 eport by California (*25*). Contrary to some eliefs, it was shown that thermoplastic triping presented no substantially greater kidding hazards than conventional striping.

Thick coatings of hot-sprayed plastic material for semi-permanent markings is a comparatively new development, exemplified by he proprietary product called *Hot Spray Plastix*. This hot-sprayed material, applied t a thickness of 90 mils, costs approximately 21 to 26 cents per linear foot for 4-inch-wide tripes and hardens in seconds. At present, xperience has been more limited with this naterial than with hot-extruded thermoplastics. The product is being tried in Philadelphia, on the Penn-Lincoln Parkway near Pittsburgh, on I-495 near Washington, D.C., nd on various expressways in and around New York City.

Raised button-type markers are also a form of semi-permanent marking, but because they lso serve to improve night-wet visibility, hey are discussed in the following section.

Markings for Improved Night-Wet Visibility

Raised button-type markers, used widely in some of the far western States, notably Washington and California, actually serve two purposes: they are long-lived and therefore economical, and they provide excellent night-wet visibility. Their use has been limited largely to areas that are free from snow and snowplow activity. Raised markers are used extensively in the snow-free areas of California (*26*). Patterns of four white nonreflective markers placed 3 feet apart are separated by 15-foot gaps. One reflective-type marker is placed in each gap on curves and in alternate gaps on tangents. According to the California Department of Public Works, the best reflective marker in use is an acrylic or ABS plastic-encased corner cube reflector. The Department's experience indicates that the raised marker is much more durable than conventional paint. The Washington Department of Highways also has reported good experience with raised markers in snow-free areas (*27*). Raised markers were reported to be superior to standard traffic paint in terms of durability, driver preference, and night-wet visibility, and their cost for a 10-year period was claimed to be compatible with the cost of standard paint striping. The annual cost of marker maintenance was one-fourth that of paint-striping maintenance. The California Department of Public Works recently reported on the development of a rapid-set epoxy adhesive for raised markers (*28*), which is based on the use of a polymercaptan curing agent that cures epoxies in thin films at a rate that is 7 to 10 times faster than the conventional curing rate of epoxies. The new adhesive can be used at temperatures lower than 30° F.

Raised markers perform poorly in snowy areas that are subjected to snowplow activity, as proved by experiments in Arkansas (*22*) and California (*29*), in which raised buttons failed badly. In California, failure occurred even when precast markers were inset in the pavement to obtain a lower profile. Poor performance in snow areas was also evident when epoxies were cast and cured-in-place in cut-out pavement sections that were finally finished off flush with the pavement surface.

When applied in snow-free areas, raised button-type reflective markings have substantially solved the problem of good night visibility under wet weather conditions. Present emphasis in research is to extend this solution to the snow-belt area of the country and also, if possible, to develop more economical and durable systems. In an interesting research study just completed in the State of Washington, regular raised markers were used in a snow-belt area, and snowplow blades were equipped with neoprene rubber bits to prevent marker damage. During two winter seasons at three separate test sites, the synthetic rubber bits were effective in removing snow except when the temperatures consistently remained below freezing. When semi-thawing conditions existed or could be induced by deicing chemicals, the rubber-tipped plows were very effective. Although initial costs were higher, the rubber bits did not wear out as quickly as steel bits and actually cost less per mile plowed. The most interesting part of this experiment was that few raised markers were lost at the test sites. At one site with concrete pavement, marker loss attributed to the rubber-tipped plow blades was from 1 to 2 percent during one winter season. At another site with bituminous pavement, marker losses were from 3 to 5 percent for a single winter. At the third site, no definite count was made, but the State reported from informal observations that little marker loss occurred in one winter.

Another development to obtain night-wet visibility in northern States where snowplow operations are extensive is the so-called *snow-plowable*, raised, reflective marker under investigation in both Pennsylvania and Texas. The reflective element is a high strength acrylic plastic that is based on corner-cube retroreflection and is contained in a steel casting with two keels. The keels are cemented with epoxy resin into grooves cut into the pavement. The casting also contains protective runners that direct snowplow blades over the marker, presumably without damage. The marker is installed in the skip zone between dashed stripes, generally in every other skip zone on tangents and each skip zone on significant grades and on horizontal curves. The estimated installed cost of each marker is approximately $4, and the replacement cost of each reflective element is estimated at 25 cents. The Texas project was recently initiated but the Pennsylvania installation on the Schuylkill Expressway in Philadelphia has been in progress since 1967. Informal reports on the latter investigation indicate that although very little snowplow damage occurs to the steel castings, the plastic reflectors have been badly damaged.

Other ideas for more economical, snowplow-resistant systems for night-wet visibility are being investigated in an ongoing study at the Georgia Institute of Technology that is sponsored jointly by the State Highway Department of Georgia and the Bureau of Public Roads. Researchers are looking into the possibilities of a corrugated or textured hot thermoplastic stripe containing beads. The thought behind this work is that the peaks of the corrugated thermoplastic stripe will not be immersed in water during heavy rains and, thereby, will provide retroflection in wet weather. The study also includes use of reflectorized aggregate chips in a suitable binder to obtain the same results. Two test sites, one snow-free and the other subject to snowplow activity, will be used in the investigation. Performance will be compared with conventional raised markers.

Another approach to the night-wet visibility problem is under study in the National Cooperative Highway Reaserch Program managed by the Highway Research Board. This study, NCHRP Project 5-5 entitled *Nighttime Use of Highway Pavement Delineation Materials*, is in progress at the Southwest Research Institute. It deals with the use of quarter-inch-diameter glass beads that are dropped into a cast-in-place epoxy marker, which is then allowed to set and harden. The large-bead concept was developed in a preliminary phase of the same study (*30*). The researchers had developed the concept that one-quarter-inch diameter beads half-imbedded in an appropriate binder will provide a profile that will not be completely inundated by a film of rain water and, thereby, will provide adequate night-wet visibility. The researchers believed that this concept would be less expensive than commercial raised markers and that the lower overall profile would be subject to less damage by snowplows. In the current phase of the study, a road machine that casts the epoxy, deposits the beads, and then moves on to the next marker location was developed. Installations of this type have been placed in Texas, California, New Jersey, North Carolina, and Florida. The study is to be completed shortly and the final report is under review.

In another novel experiment to obtain improved night-wet visibility now being conducted by Utah State Department of Highways (*31*), small longitudinal grooves are cut into concrete pavement to an overall width of 4 inches. At intervals, transverse grooves are cut across the longitudinal grooves to provide positive rain water drainage away from the longitudinal grooves to the low side of the crowned pavement surface. The longitudinal grooves generally are a quarter-inch deep. The grooving is then striped with conventional reflectorized traffic paint. Theoretically, the grooved striping will be more durable than conventional striping, as it is recessed and not subjected to traffic and snowplow abrasion. More importantly, the stripe should be more visible in rainy weather than conventional striping because rain water is drained away from the reflectorized grooved surfaces. The study is still in progress and no data are yet available on the relative economics of such striping, although recent indications are that the life of the grooved striping is better than that of conventional striping. One important development so far is that the grooved striping is more visible than standard striping during a rainstorm—either at night or during the day. The study will include several different grooving designs to determine the one that gives optimum performance. In addition, the State highway department has suggested that grooves be formed in a newly placed pavement—either fresh concrete or hot bituminous pavement—and has offered appropriate plans. There is considerable interest in this experiment from the standpoint of a snowplow-resistant marking that can provide night-wet visibility. As a result, at least two other States, New York and California, plan to investigate this approach.

Temporary Lane Markings

Temporary lane markings for construction detours are of interest to many State highway departments. In 1961, a machine used by the Missouri State Highway Commission to erase temporary stripes was described in the literature (*32*). Containing a 9-horsepower engine equipped with 92 steel cutters, the machine cost $758. It could operate at speeds as high as 10 feet per minute. The cost of each steel cutter was 20 cents and each could last as long as four working hours.

More recently, in 1965, the Michigan Department of State Highways reported an evaluation of temporary removable lane marking tape (*33*). It was claimed that grinding equipment to remove temporary paint was not fully effective and that paint residues remained to confuse the driver. The evaluated tape is 20 mils thick and is available in 4- to 6-inch-wide rolls. The core is soft aluminum and the top is a white or yellow beaded vinyl material. The backing contains a pressure-sensitive asphaltic adhesive and is used in conjunction with a pavement primer to promote good adhesion. It is recommended for use as a temporary marking instead of conventional paint, which is both difficult and costly to remove. The Massachusetts Department of Public Works, as a result of its own study completed in 1968, also recommended use of removable tape for temporary lane markings. The tape was compared with a water-based temporary paint and determined to be much more preferable.

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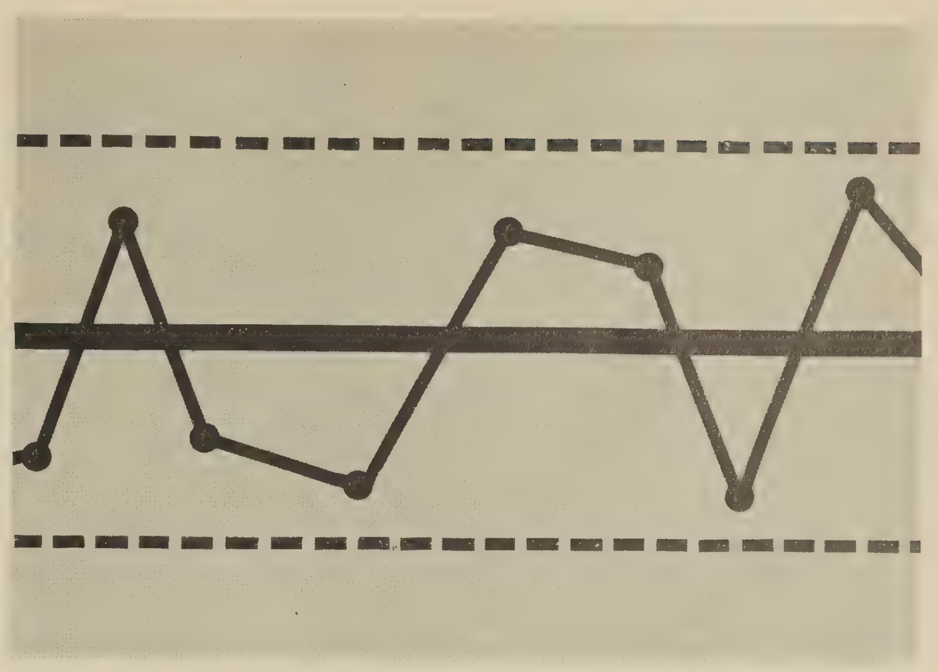
(*Continued on p. 264*)

Quality Assurance in Highway Construction

BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

Part 6— Control Charts



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This is the final 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, Part 3.—Quality Assurance of Portland Cement Concrete, Part 4.—Variations of Bituminous Construction, and Part 5.—Summary of Research for Quality Assurance of Aggregate were presented in previous issues of PUBLIC ROADS.

Introduction

TEST MEASUREMENTS portrayed graphically demonstrate the familiar adage, *a picture is worth a thousand words.* One type of graphical portrayal, the control chart, is used extensively by industry in quality-assurance procedures. Many of the industrial control-chart principles are just as applicable to process control and acceptance inspection in highway construction as they are to industrial techniques.

Control charts show cumulative trends in dimensional or physical properties within maximum and minimum limits that denote acceptable production. They not only indicate when established limits have been exceeded, but also provide the means to anticipate and correct causes that tend to promote the production of defective products. Thus, the use of control charts is an application of the principle that an ounce of prevention is worth a pound of cure.

In industrial statistical quality control methods, certain variations in product quality are classed as *chance* variations. Such variations obey the laws of probability as inevitably as the flipping of a coin. Little can be done to change these variations except to revise the control process.

In addition to these chance variations other variations in quality, systematic variations, can be attributed to *assignable causes,* such as differences among equipment, workers, materials, time, etc., and the interrelations of each to the others. Knowledge of the behavior of chance variations is the basis of control-chart analysis. If data vary in a pattern that conforms to the applicable statistical distribution, an assumption is made that no assignable causes exist. These data are said to be *in control.* If the data do not follow the statistical distribution, it is considered that assignable causes are at work and that the process is *out of control.* When the process is *in control,* the distribution of variations for large numbers of items are predictable.

According to Duncan (*1*), [1] ". . . a control chart is a device for describing in concrete terms what a state of statistical control is; second, a device for attaining control; and, third, a device for judging whether control has been attained."

The construction and use of a control chart can be explained simply. Samples of a given size are taken randomly from a process at more or less regular intervals and tested. If no assignable causes exist, these test values will be distributed in a definite pattern. If the distribution is normal, the pattern will assume the shape shown by the normal curve in figure 1. These data from the tests on the samples can be used to construct the control chart shown in figure 2. Actually, the normal curve has been tipped on its side and the values plotted in the horizontal plane on a time or unit of production basis. If a significant number of average ($\bar{X}$) values are plotted and all of them fall within the control limits and are randomly distributed about the average, that is, show no trends, then it can be said that the process is in a state of statistical control. If the data do not conform to this pattern, but show cycles or runs above or below average or outside the limit lines, the process should be investigated and the assignable causes ascertained. If all points fall within the control limits and are randomly distributed, assignable causes are not necessarily absent. However, the conclusion that chance causes alone are at work is acceptable, and a search for assignable causes would be unprofitable.

Types of Control Charts

Control charts now in use fall into two categories: Charts of attributes and charts of variables. Usually, control charts of attributes are associated with the *go* or *no go* discipline. They show one of two types of information: (1) The fraction defective or percent of items conforming or nonconforming to specifications, or (2) the number of defective items. Although the attributes may

[1] Italic numbers in parentheses identify the references listed on page 260.

often be measurements, mostly they are visually inspected properties like finish, scratches, missing parts, cracks, or functional ability. On the other hand, control charts of variables are used for values such as p.s.i. density, thickness, length or other such units reported from testing.

Whether to use plans for attributes or variables to control a process in highway construction cannot be answered here. The use of either will be dictated by the process or product to be controlled, and each will provide an effective tool to guide the State and the contractor. The only requisites are that the process be continuous, that the chart be visibly displayed, and that the charts be available to everyone concerned and correctly interpreted. Only control charts for variables will be considered in the remainder of this article.

Control charts can be constructed from test data in the form of individual measurements, averages, standard deviations, and ranges, either singly or in combinations. Again, the form to use will be dictated by the process to be controlled and the economics of the project.

Variables charts fall into two categories: (1) standards given and (2) standards unknown. The usual way to develop a control chart for the standards-given category is to analyze past data and use the information obtained to set up the charts for present and future production. Analysis of the past data will provide values of the average, $\bar{X}$,′ the range R,′ and the standard deviation σ, of the population for calculating the midpoint and limit-line positions on the chart. Usually, the charts are used in pairs—$\bar{X}$ and R or $\bar{X}$ and σ.

Computation of Limit Lines

To determine the respective limit lines for a normal population, when standards are known, the following formulas (*2*) are used:

$\bar{X}$ Chart:

$$\text{Center line} = ℄ = \bar{X}'$$
$$\text{Upper control limit} = \text{UCL} = \bar{X}' + A\sigma'_x$$
$$\text{Lower control limit} = \text{LCL} = \bar{X}' - A\sigma'_x$$

R Chart:

$$℄ = d_2\sigma'_x$$
$$\text{UCL} = D_2\sigma'_x$$
$$\text{LCL} = D_1\sigma'_x$$

σ Chart:

$$℄ = C_2\sigma'_x$$
$$\text{UCL} = B_2\sigma'_x$$
$$\text{LCL} = B_1\sigma'_x$$

Where the constants A, B_1, B_2, D_1, D_2, C_2, and d_2 for different sample sizes are given in tables of control chart constants like table 1.

Sometimes control charts must be constructed when historical data are not available for analysis and, consequently, the parameters (standards) are unknown. If the standards are unknown, data from 20 to 25 samples, consisting of four to five measurements each, are needed to compute the limits for the charts. Averages, ranges, or standard deviations of measurements on each sample are averaged to give $\bar{\bar{X}}$, $\bar{R}$ or $\bar{\sigma}$, respectively. Again, the charts are used in pairs—$\bar{X}$ and R or $\bar{X}$ and σ. The following formulas can be used to compute the center lines and the control limits for the charts:

If $\bar{X}$ *and* R *charts are used:*

$\bar{X}$ Chart:

$$℄ = \bar{\bar{X}}$$
$$\text{UCL} = \bar{\bar{X}} + A_2\bar{R}$$
$$\text{LCL} = \bar{\bar{X}} - A_2\bar{R}$$

R Chart:

$$℄ = \bar{R}$$
$$\text{UCL} = D_4\bar{R}$$
$$\text{LCL} = D_3\bar{R}$$

If $\bar{X}$ *and* σ *charts are used:*

$\bar{X}$ Charts:

$$℄ = \bar{\bar{X}}$$
$$\text{UCL} = \bar{\bar{X}} + A_1\bar{\sigma}$$
$$\text{LCL} = \bar{\bar{X}} - A_1\bar{\sigma}$$

σ Charts:

$$℄ = \bar{\sigma}$$
$$\text{UCL} = B_1\bar{\sigma}$$
$$\text{LCL} = B_3\bar{\sigma}$$

The values of constants A_1, A_2, B_3, B_4, D_3, and D_4 are listed in table 2.

Limits established by use of the factors from tables 1 and 2 are based on statistical probability and will satisfy the statistician but not necessarily the engineer. Usually the engineer wants the product to meet specification requirements that are based on engineering considerations, and he may not care whether the process is in statistical control. Many engineers prefer that the specification be used to develop the control chart. This can be done, for example, on a two-way specification by using the target as the centerline and the tolerances as the upper and lower limits. If the test results show nonconformance, either the process needs to be changed, sampling and testing techniques altered, processing improved, or the specifications changed to meet existing conditions. The engineer is thus faced with two alternatives: either change the specifications or insist that the requirements be met.

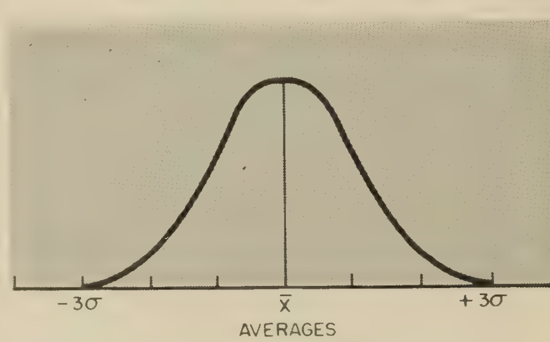

Figure 1.—Distribution of chance variations in a test sample measure of quality.

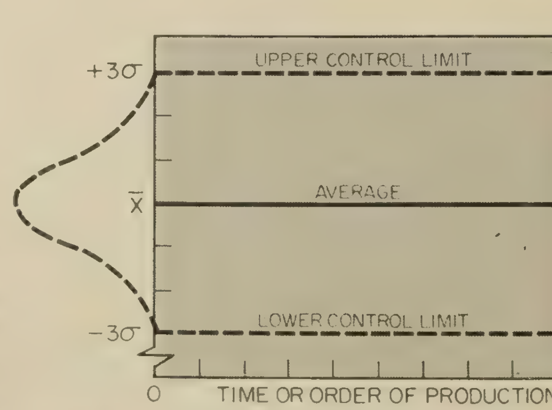

Figure 2.—Theoretical basis for a control chart.

How the Chart Works

The average, $\bar{X}$, chart shows shift of process average. The range, R, or standard deviation σ, charts show process dispersion or spread. Usually, the range, R, chart rather than the standard deviation, σ, chart is used to measure subgroup dispersion. Although both present similar trends, the range values for the R chart are much easier to compute and explain. Charts of individual test values can be used to depict both the shift of average and the dispersion, though not as efficiently as the combination of average and range charts.

Following are a few of the many warning signals that have been developed to indicate out-of-control processes (*3*):

Individual charts

- 1 test value greater than 2.33 standard deviation from centerline.
- 3 consecutive test values greater than one standard deviation above or below the centerline.
- 11 consecutive test values on same side of centerline job mix target.

Average and range charts

- 1 average or range value outside control limit lines on R and $\bar{X}$ chart.
- 2 consecutive averages outside 2 σ limit above or below the centerline.
- 7 consecutive values on either side of centerline for $\bar{X}$ charts or above centerline for R charts.

These signals are based on statistical probabilities; however, a 3- or 4-point consecutive trend toward either limit or above or below the centerline should be considered a warning. Diagnosis of the reason for the process being out of statistical control is an engineering consideration. The chart can only point out that something is wrong.

Examples of Use

At present, several States are experimentally using variables control charts on several items of construction.

In 1967, the South Carolina State Highway Department (*4*) used specification-based control charts to control and accept production of bituminous hot mix on an Interstate job. A chart on which extraction test results were plotted as individual measurements, average f 5 per lot, and range of 5 per lot, was used. harts were also prepared for bitumen content nd each of the following sieves: ¾ in., ½ in., in., No. 4, No. 8, No. 30, No. 100, and No.)0 for each 2,000-ton lot. A facsimile of a con- ol chart used on the South Carolina project r controlling percent passing the No. 30 eve is shown in figure 3. Similar charts were sed both for the remaining sieves and for itumen content. Control limit lines for dividual measurements, averages, and ranges ere superimposed on each chart. Limits for verage and range were computed from stand- ds known, using appropriate values from ble 1 multiplied by a factor of (2.33/3.00) times e standard deviation to reduce them to 98 ercent probability intervals. Limits on the art for the No. 30 sieve were developed om a standard deviation of 2.5 percent, hich had been determined in previous search. The limits were computed as follows:

ndividual measurements at 98-percent level

$$\text{Job mix tolerance} = (2.33) \times (2.5) = 5.8$$

$$\text{UCL} = 38.0 + 5.8 \text{ or } 43.8 \text{ percent}$$

$$\text{LCL} = 38.0 - 5.8 \text{ or } 32.3 \text{ percent}$$

verages of 5 per lot

$$\text{Job mix tolerance} = \left(\frac{2.33}{3.00}\right) \times (A) \times (2.5) = (0.78) \times (1.34) \times (2.5) = 2.6$$

$$\text{UCL} = 38.0 + 2.6 \text{ or } 40.6 \text{ percent}$$

$$\text{LCL} = 38.0 - 2.6 \text{ or } 35.4 \text{ percent}$$

Control limits for ranges were not estab- shed on this particular project. However, e central value and upper limit for 5 per t would be computed as follows for the 99 ercent level:

ange of 5 per lot

$$\text{Central value} = (d_2) \times (\text{standard deviation}) \times (\text{reduction factor}) = (2.326) \times (2.5) \times \left(\frac{2.33}{3.00}\right) = 4.5 \text{ percent}$$

$$\text{Upper control limit (UCL)} = (D_2) \times (\text{standard deviation}) \times (\text{reduction factor}) = (4.918) \times (2.5) \frac{2.33}{3.00} = 9.5 \text{ percent}$$

Statistically, the control chart for averages ig. 3) was out of control as seven consecutive oints were above the job mix target. How- ver, on this job nothing was done; the situa- on probably was one of engineering dgment.

Several other States have or are proposing) use control charts. The Vermont Depart- ent of Highways, for example, plots all field st data on charts. The California Division of Highways is proposing to use a moving aver- age of five as the basis for corrective action. Trends are more apparent with the moving average chart than with the average chart. Decisions on conformance of the sublot are based on individual-tolerance requirements for the test and on reduced-tolerance requirements for averages of the preceding four sublots plus the one under consideration. On the other hand, the Virginia Department of Highways proposes to plot only individual results and rely on individual probability trends for judgment of conformance. Initially, this ap- proach is being applied experimentally to asphalt mixes. Kansas also plots individual bituminous extraction data and is starting to plot averages of the same data.

For the past 5 years, the Mississippi State Highway Department, the forerunner in the use of control charts, has been using a progres- sive-step chart to accept and control density of stabilized bases. The 1967 specification extends this use to other bid items. This seemingly complicated plan allows acceptance to be based on as few as two tests per lot, but a minimum of six tests are usually required for rejection. The plan has a built-in safeguard for excluding wild test results. In addition, the test results of the lot are averaged with all test results from the previous five lots, and

Table 1.—Factors for computing control chart lines—standards given

Number of observations in sample, n	Chart for averages	Chart for standard deviations			Chart for ranges		
	Factors for control limits	Factors for central line	Factors for control limits		Factors for central line	Factors for control limits	
	A	c_2	B_1	B_2	d_2	D_1	D_2
2	2.121	0.5642	0.000	1.843	1.128	0.000	3.686
3	1.732	0.7236	0.000	1.858	1.693	0.000	4.358
4	1.500	0.7979	0.000	1.808	2.059	0.000	4.698
5	1.342	0.8407	0.000	1.756	2.326	0.000	4.918
6	1.225	0.8686	0.026	1.711	2.534	0.000	5.078
7	1.134	0.8882	0.105	1.672	2.704	0.205	5.203
8	1.061	0.9027	0.167	1.638	2.847	0.387	5.307
9	1.000	0.9139	0.219	1.609	2.970	0.546	5.394
10	0.949	0.9227	0.262	1.584	3.078	0.687	5.469
11	0.905	0.9300	0.299	1.561	3.173	0.812	5.534
12	0.866	0.9359	0.331	1.541	3.258	0.924	5.592
13	0.832	0.9410	0.359	1.523	3.336	1.026	5.646
14	0.802	0.9453	0.384	1.507	3.407	1.121	5.693
15	0.775	0.9490	0.406	1.492	3.472	1.207	5.737
16	0.750	0.9523	0.427	1.478	3.532	1.285	5.779
17	0.728	0.9551	0.445	1.465	3.588	1.359	5.817
18	0.707	0.9576	0.461	1.454	3.640	1.426	5.854
19	0.688	0.9599	0.477	1.443	3.689	1.490	5.888
20	0.671	0.9619	0.491	1.433	3.735	1.548	5.922
21	0.655	0.9638	0.504	1.424	3.778	1.606	5.950
22	9.640	0.9655	0.516	1.415	3.819	1.659	5.979
23	0.626	0.9670	0.527	1.407	3.858	1.710	6.006
24	0.612	0.9684	0.538	1.399	3.895	1.759	6.031
25	0.600	0.9696	0.548	1.392	3.931	1.804	6.058
Over 25	$\frac{3}{\sqrt{n}}$	------------	(1)	(2)	------------	------	-----

[1] $1-\frac{3}{\sqrt{2n}}$. [2] $1+\frac{3}{\sqrt{2n}}$.

Table 2.—Factors for computing control chart lines—standards unknown

Number of observations in sample, n	Chart for averages		Chart for standard deviations			Chart for ranges		
	Factors for control limits		Factor for central line	Factors for control limits		Factor for central line	Factors for control limits	
	A_1	A_2	c_2	B_3	B_4	d_2	D_3	D_4
2	3.760	1.880	0.5642	0.000	3.267	1.128	0.000	3.267
3	2.394	1.023	0.7236	0.000	2.568	1.693	0.000	2.575
4	1.880	0.729	0.7979	0.000	2.266	2.059	0.000	2.282
5	1.596	0.577	0.8407	0.000	2.089	2.326	0.000	2.115
6	1.410	0.483	0.8686	0.030	1.970	2.534	0.000	2.004
7	1.277	0.419	0.8882	0.118	1.882	2.704	0.076	1.924
8	1.175	0.373	0.9027	0.185	1.815	2.847	0.136	1.864
9	1.094	0.337	0.9139	0.239	1.761	2.970	0.184	1.816
10	1.028	0.308	0.9227	0.284	1.716	3.078	0.223	1.777
11	0.973	0.285	0.9300	0.321	1.679	3.173	0.256	1.744
12	0.925	0.266	0.9359	0.354	1.646	3.258	0.284	1.716
13	0.884	0.249	0.9410	0.382	1.618	3.336	0.308	1.692
14	0.848	0.235	0.9453	0.406	1.594	3.407	0.329	1.671
15	0.816	0.223	0.9490	0.428	1.572	3.472	0.348	1.652
16	0.788	0.212	0.9523	0.448	1.552	3.532	0.364	1.636
17	0.762	0.203	0.9551	0.466	1.534	3.588	0.379	1.621
18	0.738	0.194	0.9576	0.482	1.518	3.640	0.392	1.608
19	0.717	0.187	0.9599	0.497	1.503	3.689	0.404	1.596
20	0.697	0.180	0.9619	0.510	1.490	3.735	0.414	1.586
21	0.679	0.173	0.9638	0.523	1.477	3.778	0.425	1.575
22	0.662	0.167	0.9655	0.534	1.466	3.819	0.434	1.566
23	0.647	0.162	0.9670	0.545	1.455	3.858	0.443	1.557
24	0.632	0.157	0.9684	0.555	1.445	3.895	0.452	1.548
25	0.619	0.153	0.9696	0.565	1.435	3.931	0.459	1.541
Over 25	$\frac{3}{\sqrt{n}}$	------	-------------	(1)	(2)	-------------	------	-----

[1] $1-\frac{3}{\sqrt{2n}}$. [2] $1+\frac{3}{\sqrt{2n}}$.

this average must not deviate by more than a specified amount from the target value.

Summary

The use of control charts to regulate and accept highway construction is still in a fledgling stage. Up to now the industry has existed and expanded with the single test, retest, and engineering-judgment concept. The use of control charts will not alter the fact that the engineer has the final decision in accepting construction. The charts, however, are effective tools to visually forewarn that undesirable trends may be developing and to help both the engineer and the contractor decide *when to take action* and *when not to take action.*

The adoption of control-chart use by the highway industry would provide a significant technological advance in ascertaining adequacy of construction. Almost anyone can spot large changes, but successive small changes that develop as trends are not easily detected, even by experienced people. The picture portrayed by the control charts would highlight the trends and motivate the use of such charts as a decision tool.

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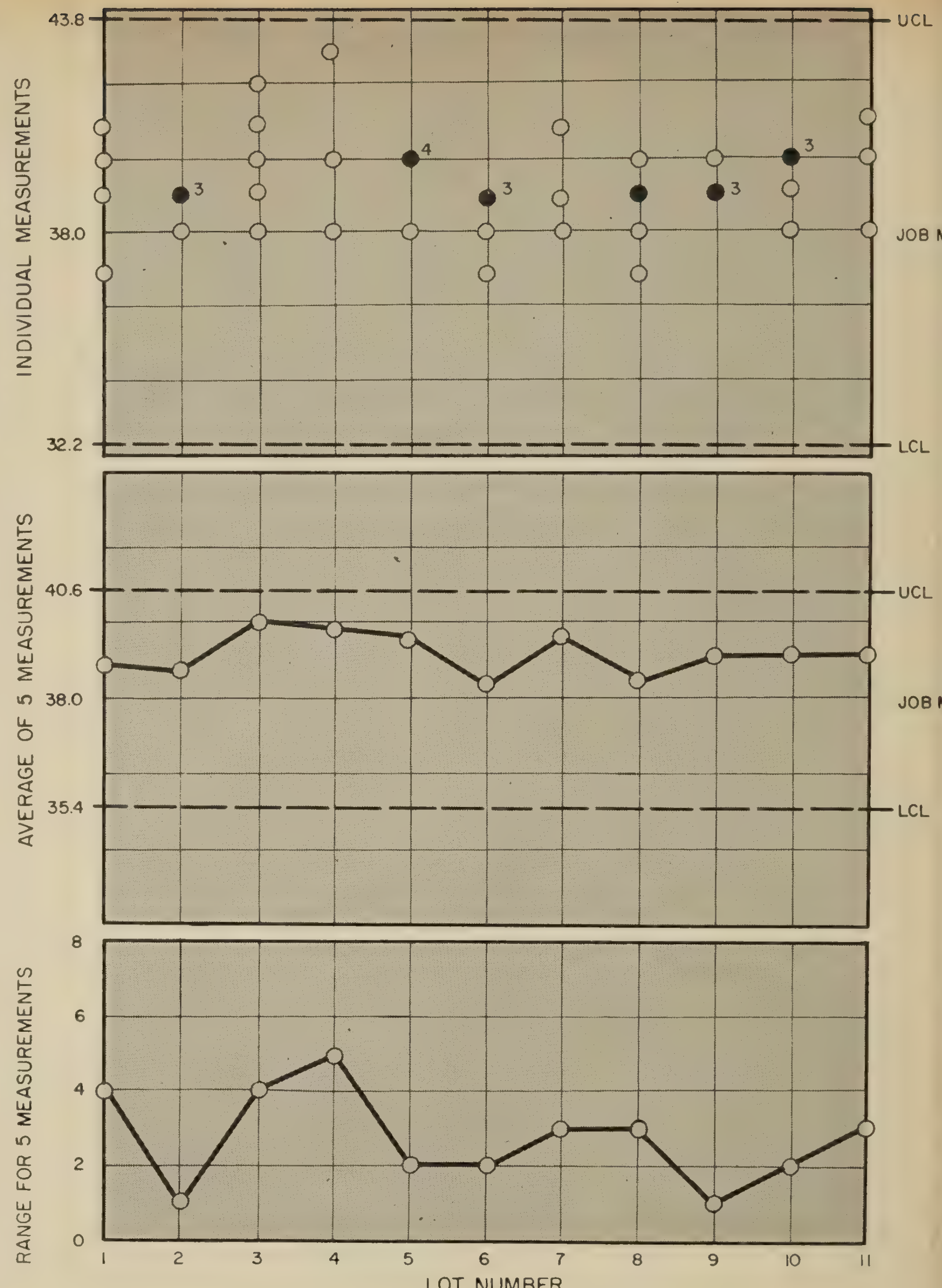

Figure 3.—Control chart used by South Carolina.

Fatal Accidents Involving Tractor-Trailer Combinations in Rear-End Collisions on Completed Sections of the Interstate System, 1968

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The article *Fatal Accidents on Completed Sections of the Interstate System, 1968,* in the October 1969 issue of PUBLIC ROADS presented a general summary of the characteristics and circumstances of fatal Interstate-Highway crashes. Differences in the types of accidents and in the vehicles involved produce rather widely divergent patterns, and in this supplementary report one accident type, rear-end collisions involving tractor-trailer combinations, is examined in more detail.

In the general summary it was noted that tractor-trailer combinations were involved in rear-end collisions relatively more frequently than other types of vehicles, particularly passenger cars. Almost a third (31.6 percent) of the tractor-trailer combinations primarily responsible for fatal accidents were involved in rear-end collisions, compared with only 12.6 percent of the passenger vehicles. This comparison is based on the assignment of primary responsibility for the collision to one of the two or more vehicles involved, as determined by analysis of police investigators' reports. It does not necessarily imply any legal responsibility for the accidents. Vehicles considered to be primarily responsible for rear-end collisions are usually, but not always, the striking vehicles.

In the general summary, vehicles involved in the rear-end collisions, but not primarily responsible for them, were not discussed. A supplementary analysis of the detailed accident reports provides two additional types of information on these collisions: (1) the characteristics of the collisions for which drivers of tractor-trailers were primarily responsible, and (2) data on the rear-end collisions involving tractor-trailers for which the drivers of other types of vehicles were primarily responsible.

As indicated in the accompanying table, tractor-trailer drivers were primarily responsible for 80 or approximately one-fifth of the total rear-end collisions. Fewer than half of these involved passenger vehicles, and almost a third involved two or more tractor-trailers. This seems somewhat unexpected as tractor-trailers constitute only about 10 percent of the total traffic volume on the Interstate System. However, tractor-trailers tend to travel more frequently at night, and to the extent that this occurs, the proportions of these vehicles in the total traffic stream at night would be increased above the general average. Of all the fatal rear-end collisions on the Interstate System in 1968, 61 percent occurred in hours of darkness as compared with 53 percent for all types of fatal accidents on this system. Also, indications are that tractor-trailer drivers sometimes tend to travel in queues.

Of the 88 fatalities, 31 were occupants of the tractor-trailers responsible for the accidents, and another four were occupants of the combination vehicles struck. Property damage to vehicles, cargo, and roadside appurtenances averaged $10,916 per accident. This figure is affected somewhat by the fact that, in a few collisions, more than two vehicles were involved.

Investigating officers reported that seven of the 80 tractor-trailer drivers were fatigued or dozing and that two had been drinking—one of whom was obviously intoxicated. In seven of the 26 accidents involving two or more tractor-trailers, tailgating, or following the vehicle ahead too closely, was reported as a significant contributing factor.

Accidents in which another type of vehicle was responsible for rear-end collisions involving tractor-trailer combinations outnumbered by a substantial margin—113 as compared with 80—those for which tractor-trailer drivers were responsible. In four-fifths of the accidents in the former category, the drivers of passenger vehicles were primarily responsible for the collisions. Only three of the 139 fatalities were occupants of the tractor-trailers that were struck. Property damage averaged $4,106 per accident.

More than a fourth of the 113 drivers of vehicles that struck tractor-trailers were reported to be asleep or fatigued. Another 31 were described as having been drinking—eight of them obviously intoxicated. Speeding was reported in 52 of these accidents; half of them involved speeds in excess of legal limits—a few as much as 100 m.p.h.

Of course the investigating officers' reports of driver conditions and violations differ widely with respect to quality of reporting and completeness. Nevertheless, it seems significant that driver condition was reported to be a contributing factor in half the accidents in which drivers of passenger vehicles collided with tractor-trailers, compared with one-fifth of the collisions for which tractor-trailer drivers were primarily responsible.

Fatal accidents involving tractor-trailer combinations in rear-end collisions on completed sections of the Interstate System, 1968

Type of collision [1]	Total accidents	Fatalities			Property damage	
		Vehicle 1 [2]	Vehicle 2	Total	Total	Per accident
	Number	*Number*	*Number*	*Number*		
Tractor-trailer—passenger vehicle	35	4	48	52	$226,600	$6,474
Tractor-trailer—tractor-trailer	26	22	4	26	522,200	20,077
Tractor-trailer—single-unit truck	14	5	--------	5	116,000	8,286
Tractor-trailer—pickup or panel	5	--------	7	7	9,300	1,860
Total collisions, tractor-trailer responsible	80	31	59	88	873,300	10,916
Passenger vehicle—tractor-trailer	93	111	3	114	337,500	3,629
Single-unit truck—tractor-trailer	5	5	--------	5	11,600	2,320
Pickup or panel—tractor-trailer	15	20	--------	20	73,800	4,920
Total collisions, other vehicle responsible	113	136	3	139	422,900	4,106

[1] The vehicle listed first is the one primarily responsible for the accidents.
[2] Vehicle primarily responsible for the accidents—that is, the striking vehicle with a very few exceptions.

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