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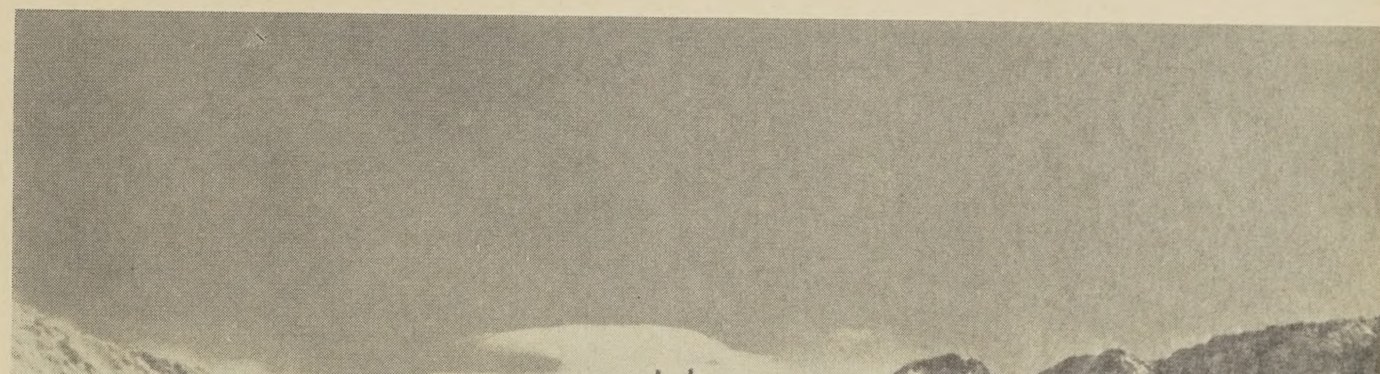

Snow removal operations on Fremont Pass, Colorado

Public Roads

A JOURNAL OF HIGHWAY RESEARC

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Snowdrift Control Through Highway Design

' THE
'REAU OF PUBLIC ROADS

Reported by **FREDERICK W. CRON,**
Regional Design Engineer,
Region 9, Denver, Colorado

In areas that are subject to large and frequent snowfalls, drifting snow on highways presents a serious maintenance problem. In the article presented here, the author discusses the research that has been accomplished in this field and presents recommendations for dealing with the problem of snowdrift control. In many areas of the country, particularly the northern States, the maintenance costs of highways during the snow season can be reduced considerably if the problem of drifting snow is considered when a highway is in the design stages. Research shows that where topographic conditions are favorable the sweep of the wind can be used to control the accumulation of snowdrift on highways. In areas where blowing snow is a problem, information on prevailing winds and drifting should be considered in the selection of a highway location. The profile and cross sectional design can also provide snow control by taking advantage of the wind and should be considered when a highway is initially planned or when reconstruction for snow control is planned. Appurtenances such as curbs, guardrails, fences, signs, etc., must also enter consideration for snow control because they are obstacles to the free movement of the wind and therefore contribute to the formation of drifts. By generally streamlining the area surrounding the highway, drifting is minimized, the esthetic qualities are enhanced, and the operational safety is increased.

Introduction

[THE NORTHERN STATES the drifting of snow presents a serious highway intenance problem and expenditures for wdrift control and snow removal run into millions every winter. In some places enditures are so large that attention uld be given to snowdrift elimination in design stage. The increased construction t of roads designed for snow control is to rge degree offset by decreased maintenance ts.

n Europe, North America, and Japan re is a considerable body of literature on control of drifting snow, most of which appeared since 1950. Mellor's bibliogra- of November 1965 (*1*)[1] is the most recent npendium of the available literature. neider (*2*) also cites an extensive list of rces extending back to work by Schubert 1903. E. A. Finney pioneered research in field at Michigan State College in the ldle and late thirties, using balsa sawdust l flake mica to simulate snow. He studied performance of various highway cross tions and snow fence designs in a wind nel. The practical validity of his findings never been seriously challenged (*3, 4*).

nclusions and Recommendations

Vith the information now available new hways can be designed that will, to a ge degree, use the sweep of the wind to vent drifted deposits of snow on the road- y. The maintenance expense thus saved l largely offset the increased construction t of the snow-control design. Some exist- highways can be reconstructed at moderate t to reduce drifting, primarily by flatten- and rounding slopes and removing drift- king obstacles on and near the right-of-way. many miles of existing highway, however, main defense against drifting from blow- snow will continue to be systems of snow ces, hedges, or windbreaks.

The author believes that additional re- rch is needed to determine ways to protect erchanges and their associated ramps and ictures from drifting snow. Control of the ground blizzards that occur in the Great Plains area should also be investigated, particularly the relationship between these blizzards and grazing. Reduction or elimination of grazing in a zone 500 feet wide upwind from the highway might help to control ground blizzards. Such zones could be established as scenic easements to the benefit of both esthetics and snow control. There is also a need for information on the cost of drift control and removal as related to highway design, particularly before and after cost figures such as those cited in this article for South Dakota. Such figures are needed to support the increased construction expenditures required to achieve built-in drift control by use of higher gradelines, flatter slopes, and streamlined cross sections.

Highway Location

In regions where blowing snow is a serious problem, snow control should be a prime consideration in locating the highway. Reconnaissance should be made during the winter months, as well as at other times of year, and in suspect areas all available information on prevailing winds and drifting should be collected and analyzed before the highway location is decided (*5*).

Where a choice of location is possible, considerable immunity from snowdrift formation can be achieved by proper selection of the road location. Valley locations through timber have few drift problems because the trees shelter the road from the wind and trap the snow (*4*). In rolling country the leeward side of natural slopes should be avoided, and the road should be constructed on the windward side or on the crest if possible (*4, 5*). For minor roads in heavy snow country considerable indirection of travel can be justified to stay on the ridges, as this may mean the difference between keeping the road open or having it closed for days awaiting the county snow plows. Many county roads in Wyoming deviate considerably from the usual section-line location to follow ridges and thus avoid severe drifting.

Drift Control by Profile Design

In open level country the wind can be used to sweep the highway clear of snow if the gradeline of the highway is raised above the adjacent ground level. The amount of elevation can be determined from snowfall records. To be effective, the finished grade should be higher than the depths of the snow deposits adjacent to the highway and higher than the prevailing adjacent vegetation (*4*). Michigan, Minnesota, South Dakota, and other States that have difficult snow problems try to elevate gradelines 3 to 5 feet above the adjacent ground.

Significant decreased winter maintenance expenditures have resulted from proper design. In South Dakota, Route U.S. 83

[1] talic numbers in parentheses indicate the references d on page 234.

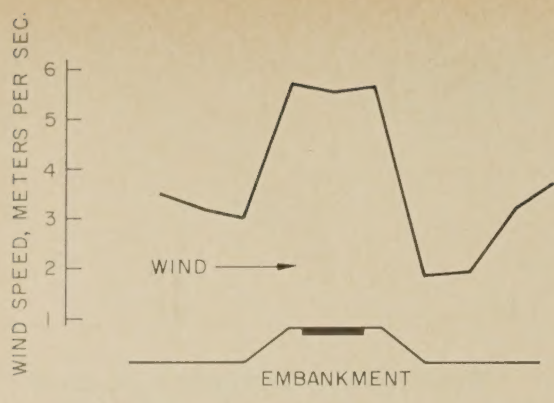

Figure 1.—Distribution of wind speed across an embankment (Benterud, 1947).

between Vivian and Fort Pierre was reconstructed in 1960 to provide an elevated profile and streamlined cross section. Before reconstruction it had a low profile, sharp slopes, and small ditches, and the snow removal costs averaged from $488 per mile in a severe winter to $203 per mile in a moderate winter (*6*). In the 6-year period since reconstruction the average annual snow removal cost for this highway has been only $68 per mile.

Such savings can repay in a few years the cost of the additional earthwork required for snow control. On one 4-lane Interstate highway project in South Dakota, snow control was achieved at an increased construction cost of only $6,000 per mile (*6*).

In Colorado an elevated gradeline did not entirely eliminate drifting on wide-median divided highways when both roadways were constructed at the same level. However, by elevating the downwind roadway slightly above the upwind roadway the self-clearing properties of the highway cross section were restored. This design was used for Interstate Highway 80S from Brush to Sterling, Colo., completed in 1965.

Cross Sectional Design

An elevated roadway or embankment is a barrier to the free sweep of the wind and causes eddies to form on both the windward and leeward sides of the road. The wind velocity in these eddies is less than that of the main airstream, permitting deposition of some of the suspended burden of snow to form drifts as shown in figure 1. Since the wind's power to transport snow varies as the cube of the velocity, even small decreases in velocity will cause snow to be deposited in drifts. The size, shape, and location of the drifts are influenced by the cross sectional shape of the roadway. Finney determined that the major eddy occurs on the leeward side of an obstacle, that the length of the eddy is about 6.5 times the height of embankment, and that wind velocity has no effect on the shape or length of the eddy. Further, the boundary of the eddy area is constant for all embankment slopes up to about 6½:1 at which ratio the eddy almost disappears as shown in figure 2. Finney also learned that when the windward slope of a highway embankment is steep the airstream is deflected upward at the shoulder line and creates a slight eddy over the roadway which could cause drifting. This eddy disappears when the side slopes of the highway embankment are 4:1 or flatter as shown in figure 3.

The findings of Finney were supported by similar findings obtained from full-scale tests in Michigan by the U.S. Army Snow, Ice, and Permafrost Research Establishment in 1955 and 1956. Test embankments were 6 feet high with 2:1, 3:1, and 4:1 side slopes. Drifts accumulated on all embankments until the effective side slope was reduced to 9: shown in figure 4, after which no fu drifting occurred. At this time the level of snow in the adjacent fields was 21 in A 3-foot embankment at the test site wa completely self-clearing when 27 inche snow lay on the adjacent fields, illustratin importance of an adequate differenc elevation between the embankment grade the general level of the snow cover on side (*1*).

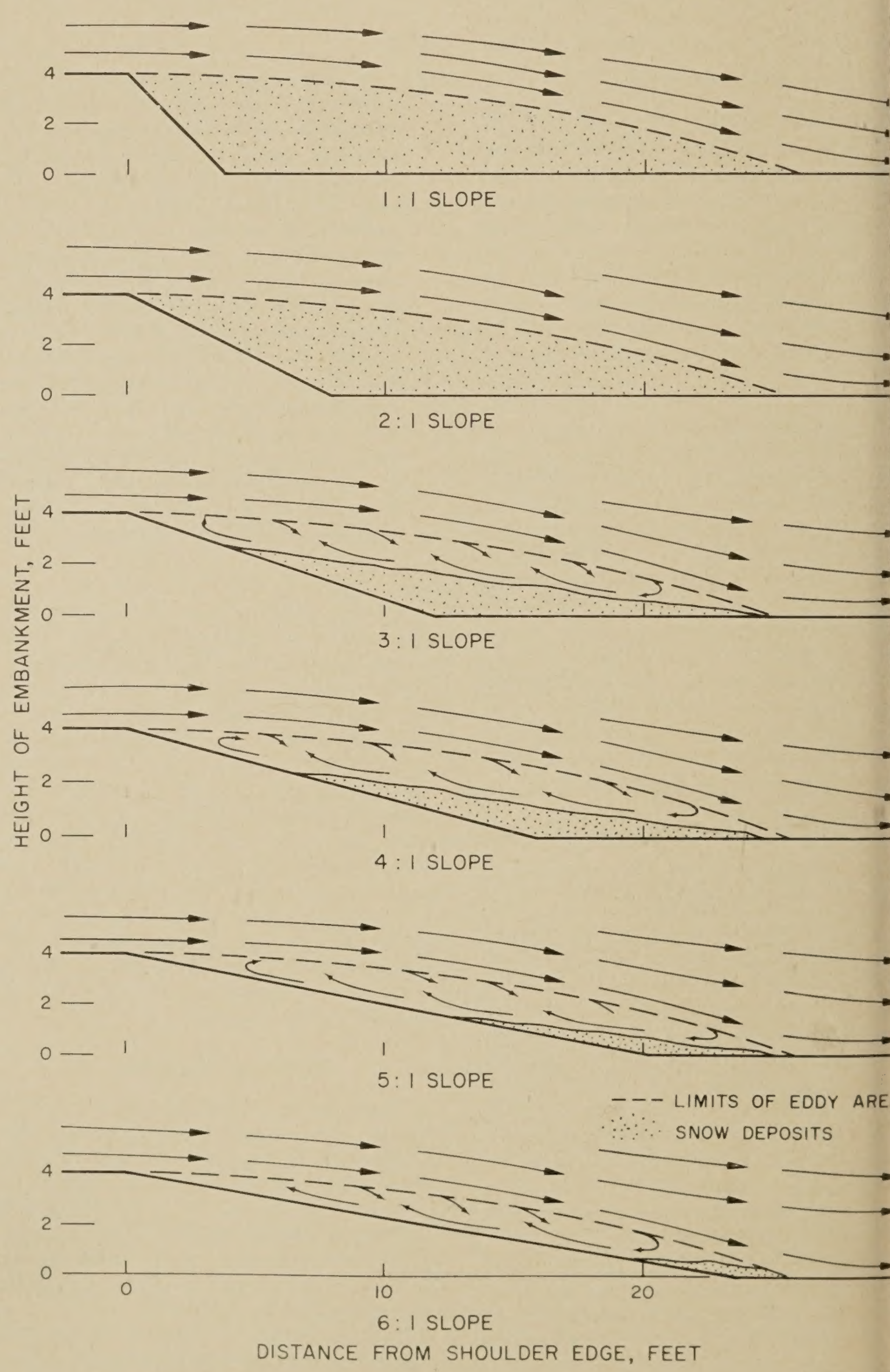

Figure 2.—Effect of embankment slope on drifting (Finney, 1939).

Rounding the intersection of the slope line the shoulder and toe of the fill does not ange the size or shape of the eddy area, but es cause the drift to form nearer to the toe the slope as shown in figures 5 and 6. ien the fill is rounded the eddy area starts the point where the vertical curve is tangent the shoulder plane, but in a cut the eddy rts at the point where the vertical curve is gent to the original ground slope (*4*).

The conditions observed on the leeward e of a highway embankment also exist where highway is in cut, except that the eddy a is above the highway grade and upwind m it, as shown in figure 7. The length of eddy area is approximately 6:5 times the oth of cut. Where the cut slope approxi- tes the boundary of the eddy area, the wind eam sweeps the slope area clear and snow- fts do not form. If, however, the slope is eper than the boundary of the eddy, the ly area is eventually filled solid with owdrifts, and no further drifting occurs. us, for the pavement and shoulders to nain free of snowdrifts, the horizontal tance from the shoulder edge to the top cut must be at least 6:5 times the depth cut, as shown in figure 8, (*4*). Where the w supply is ample, unwidened cuts can be ckly filled by drifts, the characteristic pe of the final surface being 8:1 on the wind side of centerline and 6:1 downwind, shown in figure 9, (*2*). Cuts more than out 25 feet deep are less vulnerable to fting than shallower cuts because there is re room on the side slopes to hold the idborne snow deposits (*2*), as shown in ire 10.

There is general agreement that shallow s should be graded with backslopes no eper than 6:1 and flatter if possible. ehill cuts should be daylighted on the ver side. Depressed medians should have pes no steeper than 10:1 to facilitate the eeping action of the wind.

Deep cuts should have wide ditches to vide storage not only for windborne snow also for snow plowed from the roadway. iere snow-bearing winds are predominantly m the same direction, most of the extra ch width should be placed on the upwind e of the road. Finney suggests that all cuts routinely widened and the resulting terial be used to raise embankments and ten fill slopes (*4*). Some of the snow tes, notably South Dakota, obtain borrow widening cuts on the upwind side, thus providing snow storage space and embankment material in one operation. If the grading is skillfully handled and ample rounding provided, such borrowing can be accomplished with a satisfactory overall appearance. Usually, however, extra right-of-way width is required.

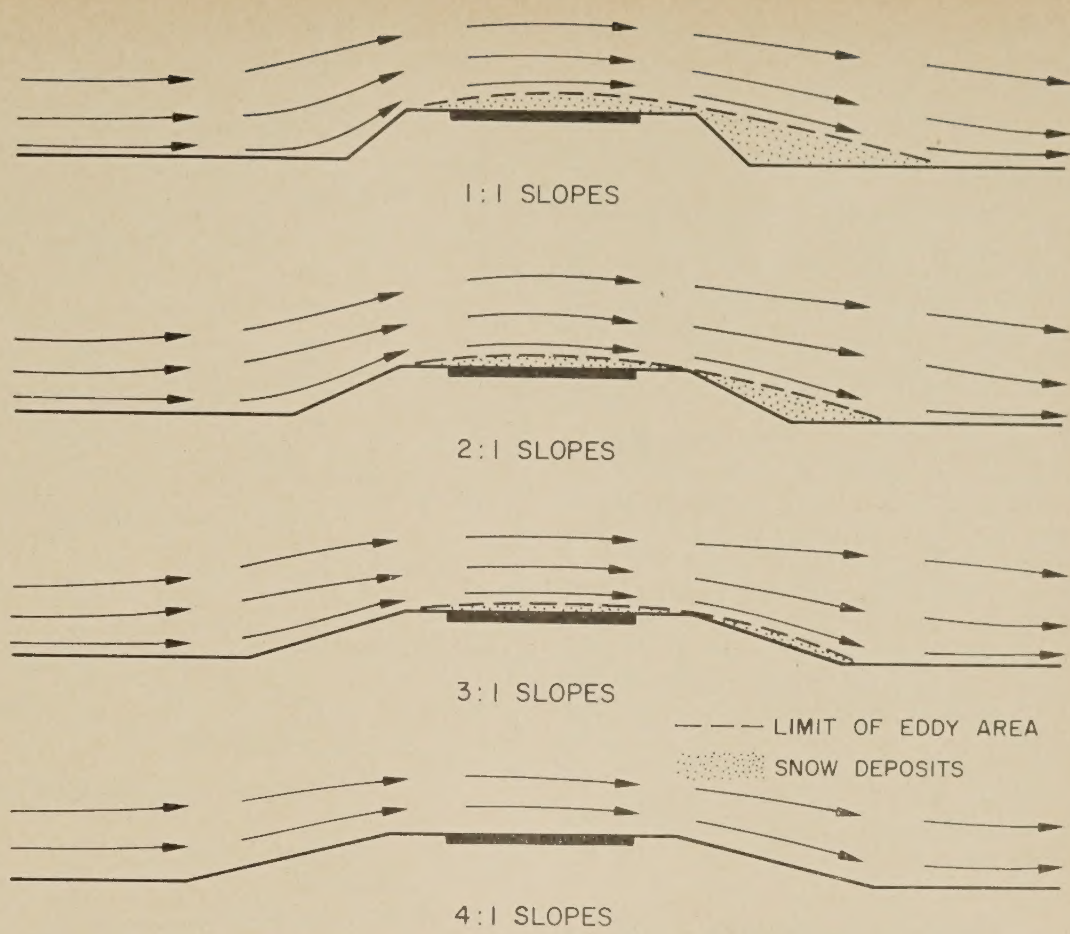

Figure 3.—Airflow across embankments with different slopes (Finney, 1939).

The Effect of Highway Appurtenances on Drifting

Highway appurtenances, such as curbs, guardrails, right-of-way fences, traffic signs, delineators, lighting standards, and signal supports contribute to the formation of drifts because they are obstacles to the free movement of the wind. Eddies form behind each obstacle and some of the snow carried by the wind is dropped into the eddy areas as shown in figure 11.

Delineators and guideposts, to the extent that they interfere with plowing and result in windrows of snow on the shoulder of the roadway, contribute to drifting on the pavement and shoulders. Curbs also cause drifting on the pavement, particularly shoulder curbs on fills, because they interfere with the smooth flow of the wind over the fill contour and cause eddies to form.

Guardrails, especially those of the beam type, contribute to the formation of long continuous drifts along the roadway. At the same time the guardrail interferes with snow plowing and causes a continuous windrow of snow to accumulate against the rail posts, closing the opening under the beam. The guardrail then performs as a 3-foot solid snow fence creating an eddy zone downwind for a distance of about 45 feet, which may cause drifting over the entire width of a 2-lane road as shown in figure 12.

The best way to avoid drifting caused by guardrails is to eliminate the guardrails, and where fill slopes are as flat as 6:1 this can be

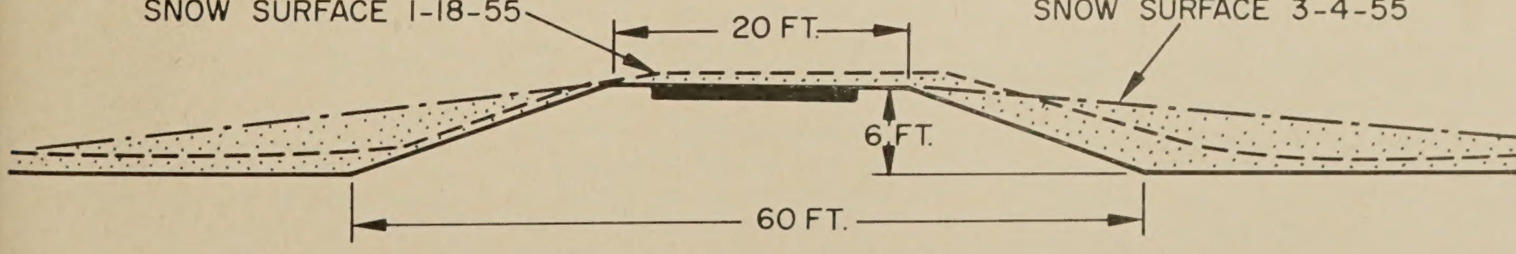

Figure 4.—Drift formation against a test embankment (Gerdel, 1960).

done without sacrificing operational safety. The current safety practice of moving sign supports, lighting standards, utility poles, and other fixed obstacles out from the roadway also contributes to reduction in drift formation.

Anything that contributes to the roughness of the surfaces exposed to the wind can cause snow accumulation. In South Dakota the surface roughness resulting from using a ¾-inch chip for surface treatment caused snow to deposit in the irregularities, which was then packed by traffic making the road extremely slippery. (*6*).

The most difficult problems with windblown snow occur at interchanges and grade separations. In snow country it is usually best to carry the more important highway over the crossroad, so the wind can sweep it clear of snow. However, much of the windblown snow will then collect around the bridge structure and in the depressed crossroad and ramps. Some relief from the snow accumulation may be provided by streamlining the interchange grading to avoid steep slopes and sharp angles; however, in many instances the most effective treatment will be to intercept the snow by snow fences, windbreaks, or hedges before it reaches the interchange.

Roadside Development and Landscaping

A generation ago the Bureau of Public Roads urged the adoption of a streamlined cross section for highways with comparatively flat slopes, rounded and warped to merge into the natural contours of the adjoining terrain, and with broad rounded ditches in place of the V-ditches used at that time (*7*). This cross section was promoted principally because of its esthetic advantages, but it also had improved properties for snow control. Grading for landscaping and grading for snow control complement each other because both result in desirable streamlining of the roadway cross section. Flat cut and fill slopes, desirable for snow control, are easier to stabilize by grass cover and easier to mow after the cover is established. Mowing in turn contributes to easier snow control in the winter. The streamlining of interchange grading improves appearance and reduces the eddy-forming angularities that cause snow to deposit. Both purposes are served by preparing contoured grading plans to control the field grading.

When it comes to plantings on or adjacent to the highway, landscaping should be closely coordinated with snow control to avoid the creation of maintenance problems. At one extreme are those sections of highways that lie in sheltered valley locations or through woodlands. Drifting snow is seldom a problem in these areas so cuts may be planted with shrubs and trees, glare shields may be planted in the medians, and accent planting may be used at structures and interchanges. At the other extreme are highways in the windswept grasslands of the high western plains where there is little or no vegetation other than grass. In most of these areas the planting of trees and shrubs on or immediately adjacent to the highway will cause or contribute to drifting and should be avoided. In particular, plantings should not be made in medians or on the slopes upwind from the roadway. Fortunately, in treeless areas restraint in planting is also good esthetics for such plantings are incongruous in the prairie setting. Between the extremes an infinite number of variations exist, and the decision to plant and what to plant should be made only after study of all aspects of operation and maintenance, including snow control and operational safety. The removal of trees from the immediate vicinity of the traveled way for safety reasons also reduces the possibility of drifts forming leeward from the trunks, and so contributes to snow control.

In some areas, notably Minnesota, windbreaks of trees or living snow fences have been planted to control drifting on the highways. Some of these windbreaks are so effective that they intercept practically all snow except that falling directly on the highway. Other States are also planning to make extensive use of shelterbelts located a safe distance upwind to control drifting snow.

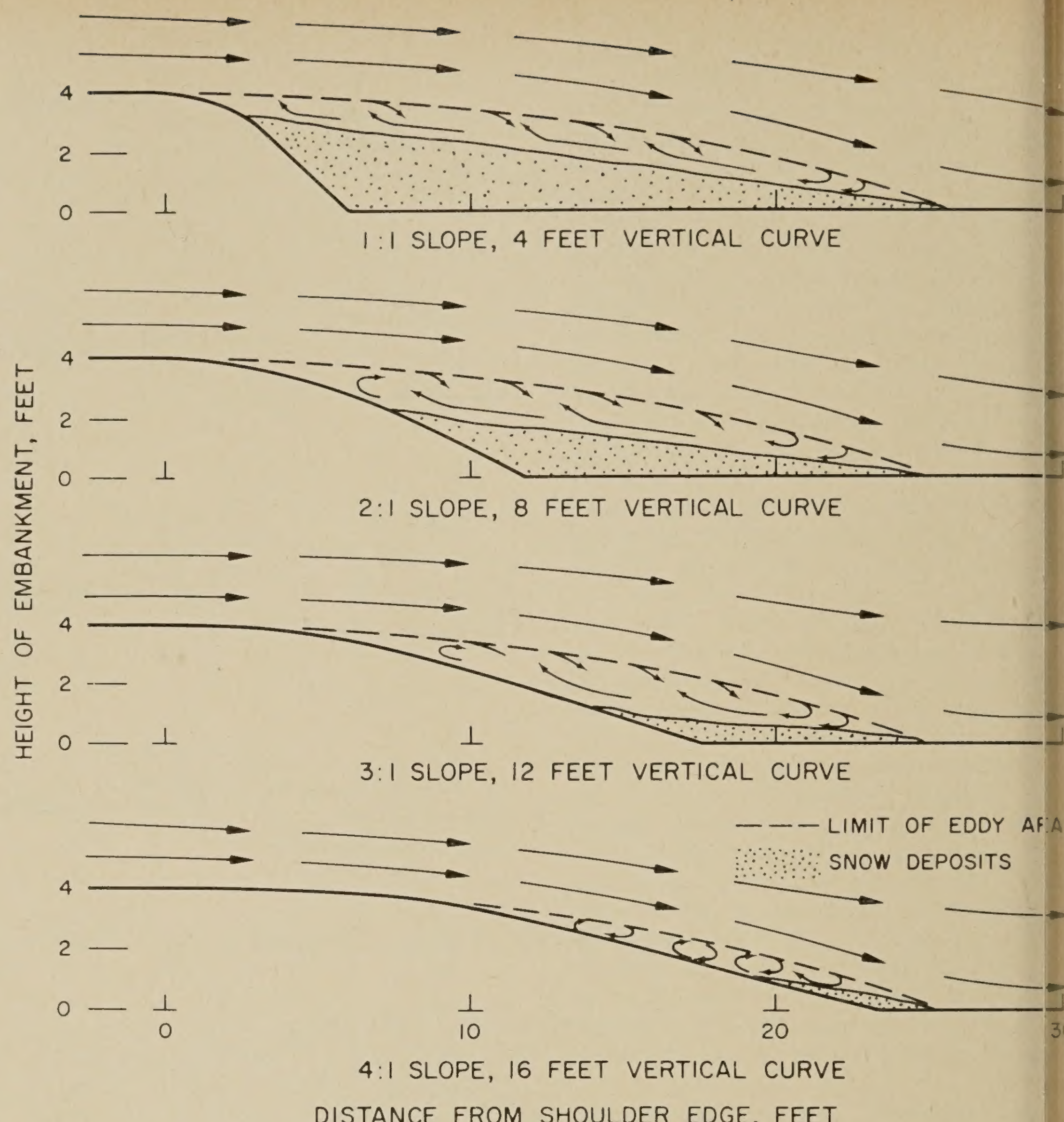

Figure 5.—Effect on drifting of rounding top of slope (Finney, 1939).

Snow Control and Operational Safety

The present trend in highway design is to clean up the roadsides by removing fixed obstacles that could cause damage if struck by vehicles out of control. Fill slopes are flattened wherever possible so the driver of a vehicle leaving the road may have an opportunity to recover control without capsizing. The flattened fill slopes provide a streamlined cross section and obviate the need for guardrails. It is becoming common practice to use 6:1 slopes for heights of fill up to 16 feet; in bad snow country 6:1 slopes could be justified for even higher fills.

The use of shoulder curbs for erosion control is a questionable practice for both snow control and operational safety. Not only do shoulder curbs cause eddies and drifting of snow on the pavement, but they can easily cause a vehicle to flip over if the vehicle strikes the curb at an oblique angle at high speed. Further, in semiarid regions shoulder curbs inhibit growth of vegetation on the slopes by intercepting water from the pavement and shoulders that would otherwise nourish plantlife.

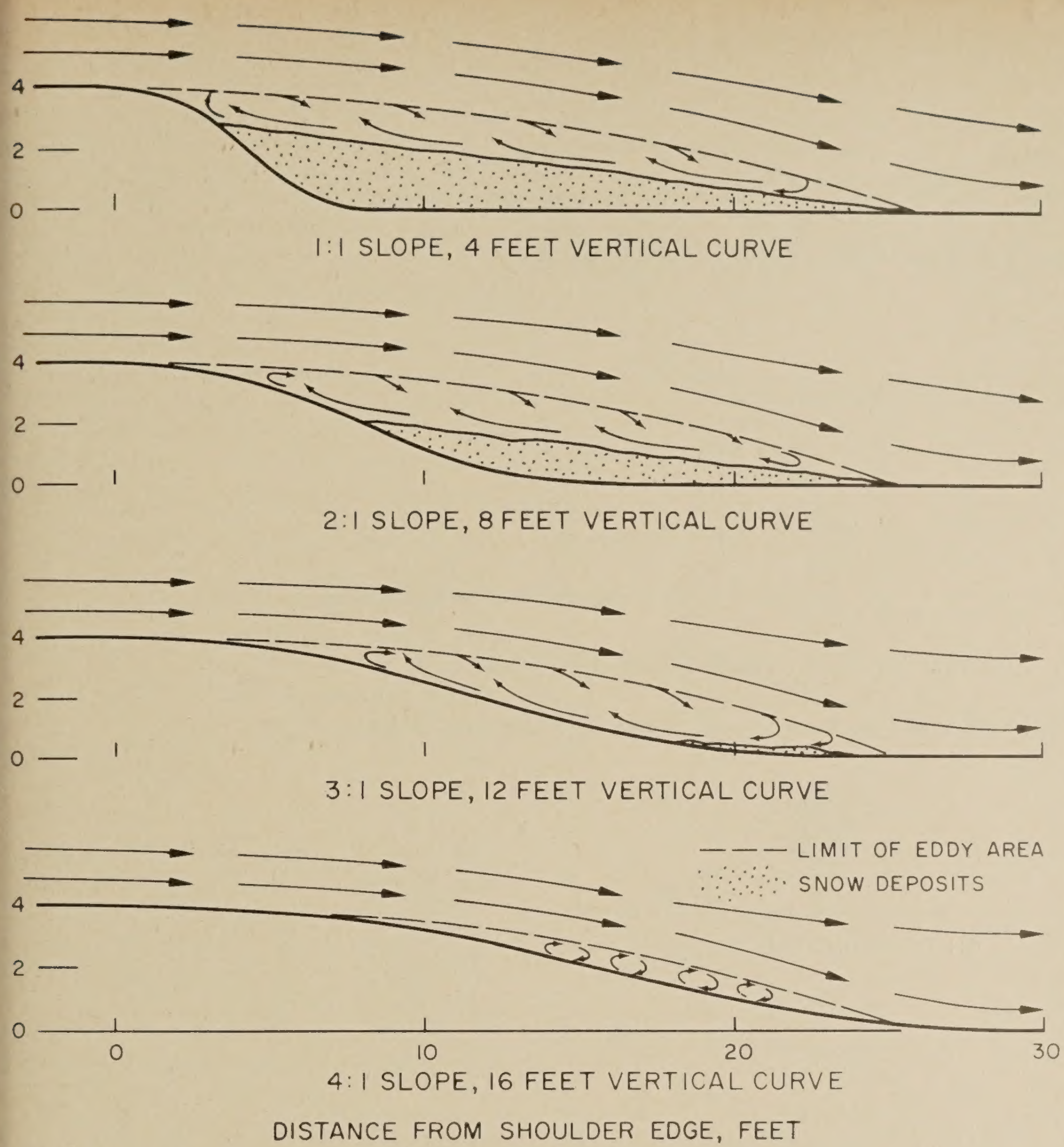

Figure 6.—Effect on drifting of rounding top and bottom of slope (Finney, 1939).

The removal of hazards such as large trees, gn supports, and light poles from the im- ıediate vicinity of the traveled way is esirable for reducing snowdrifts and may ırther contribute to safety by reducing shade ı the pavement that might cause icing.

Maintenance Practices

The most effective measures for snowdrift control use the wind to make the roadway self-clearing. However, because the wind does not always blow during a snowstorm, or from the same direction, or with uniform effectiveness, some deposits of snow must be plowed from the road. One pass of the snow plow can destroy the effectiveness of a streamlined elevated gradeline if the plow leaves windrows of snow on the shoulder of the road, especially the upwind shoulder; the windrows cause eddies and drifts rapidly form. To prevent the formation of these drifts the plowed snow should be scraped level with the top of the fill and wasted on the slopes. Shoulder curbs should be avoided because they interfere with clean snow removal. In cuts the plowed snow should be moved as far as possible from the shoulders. In areas particularly susceptible to drifting it may be advisable to pick the snow up with rotary equipment and blow it onto the slopes.

Much can be done before the first snowfall to prepare the highways for winter maintenance. Grass should be mowed as soon as the growing season is over, especially the grass adjacent to the right-of-way fences. Where blowing snow is a problem, ivy, honeysuckle, creeper, and other vegetation growing on the right-of-way fences should be removed so that wind can blow freely through the fences. In the West deposits of Russian Thistle, or tumbleweed, which collect upwind from the right-of-way fences and cause drifting, should be removed or burned. Turnrows caused by plowing adjacent fields should be smoothly leveled off. Maintenance materials stored on the upwind side of the roadway should be removed, transferred to the downwind side, or streamlined to eliminate eddying in their lee. Sand barrels should be placed on the downwind shoulder to minimize drifting. Piles of dirt from ditch cleaning should be spread in thin layers. All obstructions on the roadway that can interfere with the sweep of the wind and cause drifting should be eliminated or streamlined.

Obstructions Outside the Right-of-Way

Some obstructions that cause drifting on the highways are outside the right-of-way and beyond the control of the highway department. These include buildings, advertising signs, private hedges, windbreaks, and shelterbelts that are too close to the road. A natural

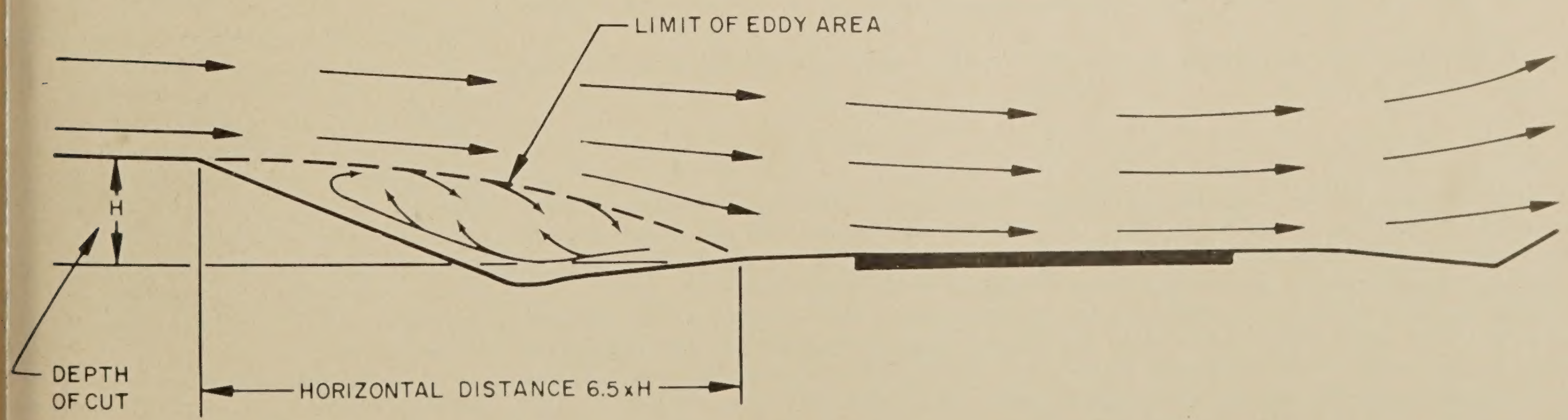

Figure 7.—Drift-forming eddies in a cut (Finney, 1939).

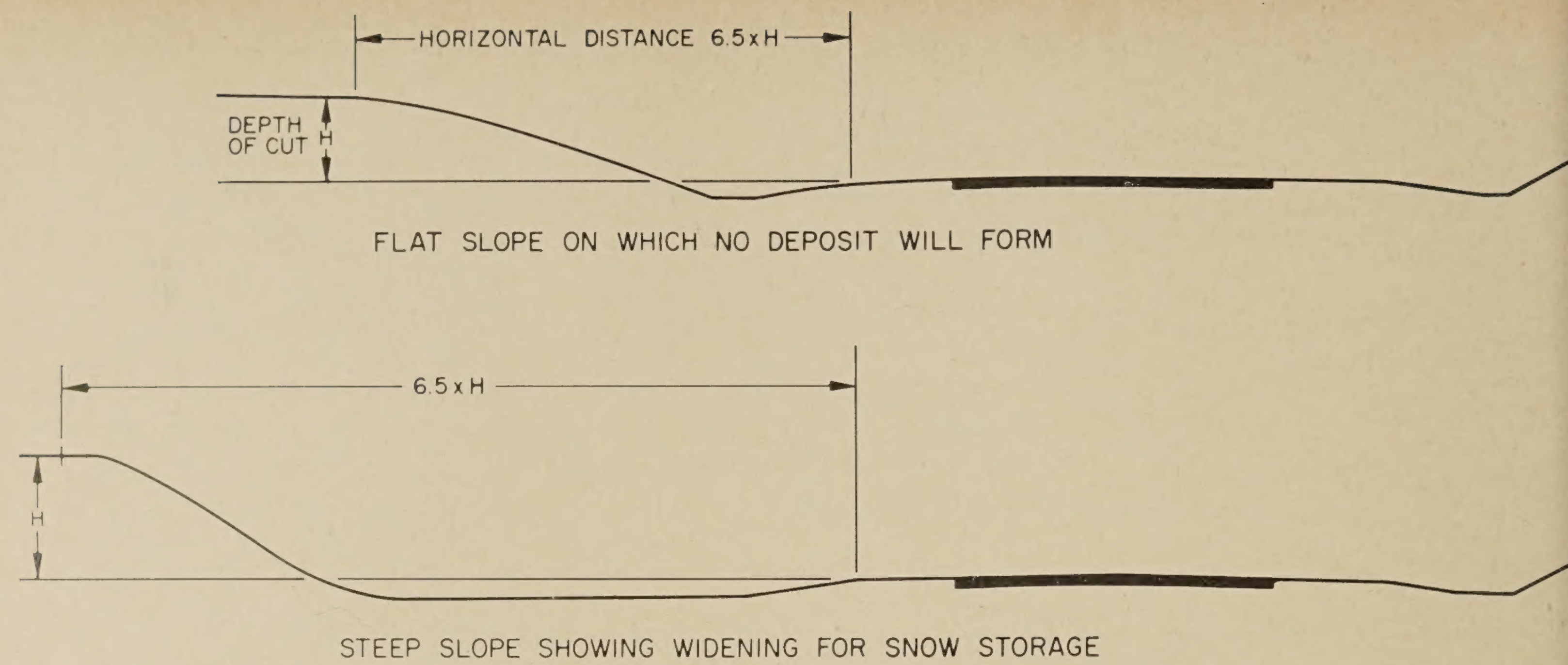

Figure 8.—Typical highway cross sections for minimum snow deposits (Finney, 1939).

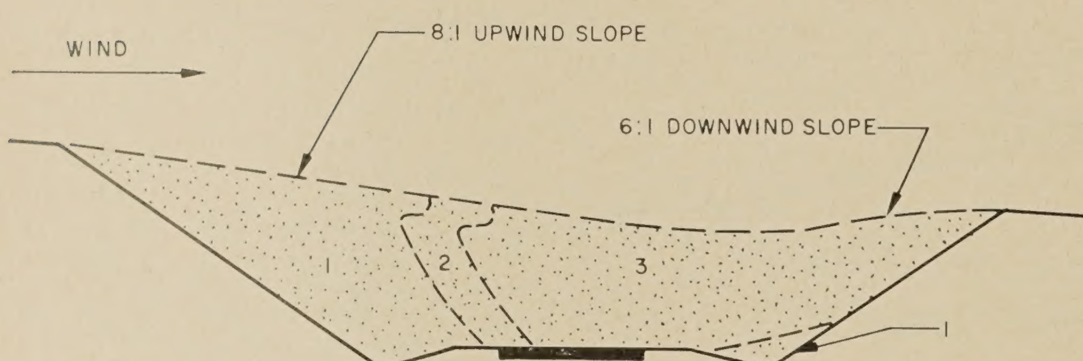

Figure 9.—Successive stages of snow deposits in a deep cut according to Schubert (1903).

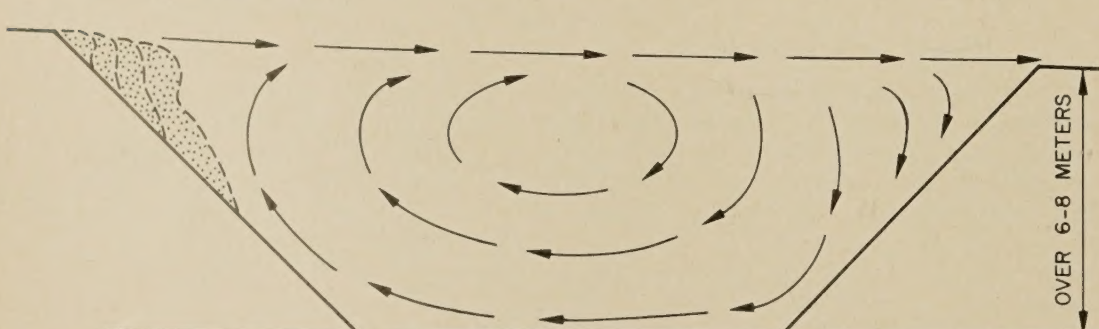

Figure 10.—Successive formation of snow deposits in a deep cut according to Petersen (1942).

topographic ridge upwind from the highway on private land may cause large drifts to form on the road. Generally, little can be done to remove these obstructions from existing highways, but as the roads are reconstructed or upgraded, efforts should be made to correct the worst conditions. Sometimes relocation of the highway is required and usually additional right-of-way width must be acquired. In many counties a systematic program of cleaning and resloping road sides in cooperation with the adjacent landowners will return its cost many fold in reduced winter maintenance (*8*).

Sometimes, the conditions on adjacent private land tend to reduce snow drifting on the highway. For example, the stubble from some crops, especially corn, acts as a reservoir to prevent the movement of snow. A strip of unplowed corn stubble 200 feet wide or wider upwind from the highway will greatly reduce the quantity of blowing snow reaching the highway (*3*). Windbreaks and shelterbelts, if they are far enough upwind, will also prevent large quantities of snow from drifting on the highway (*9, 10*).

On the High Plains ground blizzards are a troublesome phenomenon. Snow carried along close to the ground by the wind may completely obscure the driver's view of the road, even on clear days. The supply of snow from adjacent closely grazed range lands seems inexhaustible and the blizzard continues as long as the wind is strong enough to move the snow. Delineators and guideposts are necessary to keep drivers from running off the road during ground blizzards, but these guideposts sometimes contribute to drifting on the road as previously described. Ground blizzards are difficult to control, but some measure of relief may be obtained by trapping as much of the snow as possible before it reaches the highway with snow fences, snow ridges, or shelterbelts.

Snow Fences

As previously explained, a large measure of drift control can be achieved on new highways by selection of the location and by cross sectional and profile design. However, the highway locator is seldom able to choose his location for snow control alone, nor can a favorable profile and cross section always be attained, owing to other restrictions such as right-of-way. Other measures, such as snow fences, windbreaks, shelterbelts, and even snowsheds, must therefore be used to control the drifting snow.

The design and placement of snow fences and windbreaks has been studied intensively for years, but a full discussion of them is beyond the scope of the study reported here.

resent practice seems to favor fences 4 to 6 et high of about 50 percent density, that is, 0 percent of the vertical area presented to ie wind is solid material. The length of the rift formed in the lee of the fence and the uantity of snow trapped in front of and ehind it are functions of the height of the ence, its density, and the free space between he ground and the bottom of the fence. ences are most efficient when placed at right ngles to the wind, as shown in figure 13.

Where space is limited it may be desirable o create snow ridges by successively raising he snow fences before they become buried. n Russia ridges or "ramparts" 10 meters high ere produced by using movable wooden anels, called snow shields, to form snow arriers (*2*). In the thirties drifts 27 feet high ere produced by the Bureau of Public Roads n this manner in the Colorado Rockies. he proper location of snow fences requires nowledge of the topography along the ighway, of the prevailing winds, and of ie past locations of drift-susceptible spots. now fence should be placed at all known rift spots as one or two bad spots left unpro-ected will decrease the effectiveness of the hole system. The horizontal distance from ie roadway to the nearest snow fence depends n the height and type of fence and varies om 10 to 15 feet per foot of fence height. There the supply of snow is large, two or iore parallel rows of fences may be required, ut the rows should be far enough apart that ie drifts do not overlap. In irregular terrain may be necessary to experiment for several inters with portable fences to establish the ost effective fence arrangement.

Because few rights-of-way are wide enough o permit the proper placement of snow fences, ermission is obtained to place the fences on private property upwind from the highway. When the private land is in cultivation the fences must be taken down each spring and re-erected in the fall, involving considerable expense for labor, breakage, and storage. Some States have therefore acquired additional right-of-way to accommodate windbreaks or living snow fences of trees and shrubs. Railroads in North America and Europe have used this form of protection for over 60 years in certain localities.

There is a considerable body of literature on the spacing, cultivation, and care of a variety of trees suitable for shelterbelts, windbreaks and snow hedges (*3, 9, 10, 11, 12, 13, 14*). Trees that retain a fairly high density during winter, such as evergreens, are generally best for snow hedges, but certain

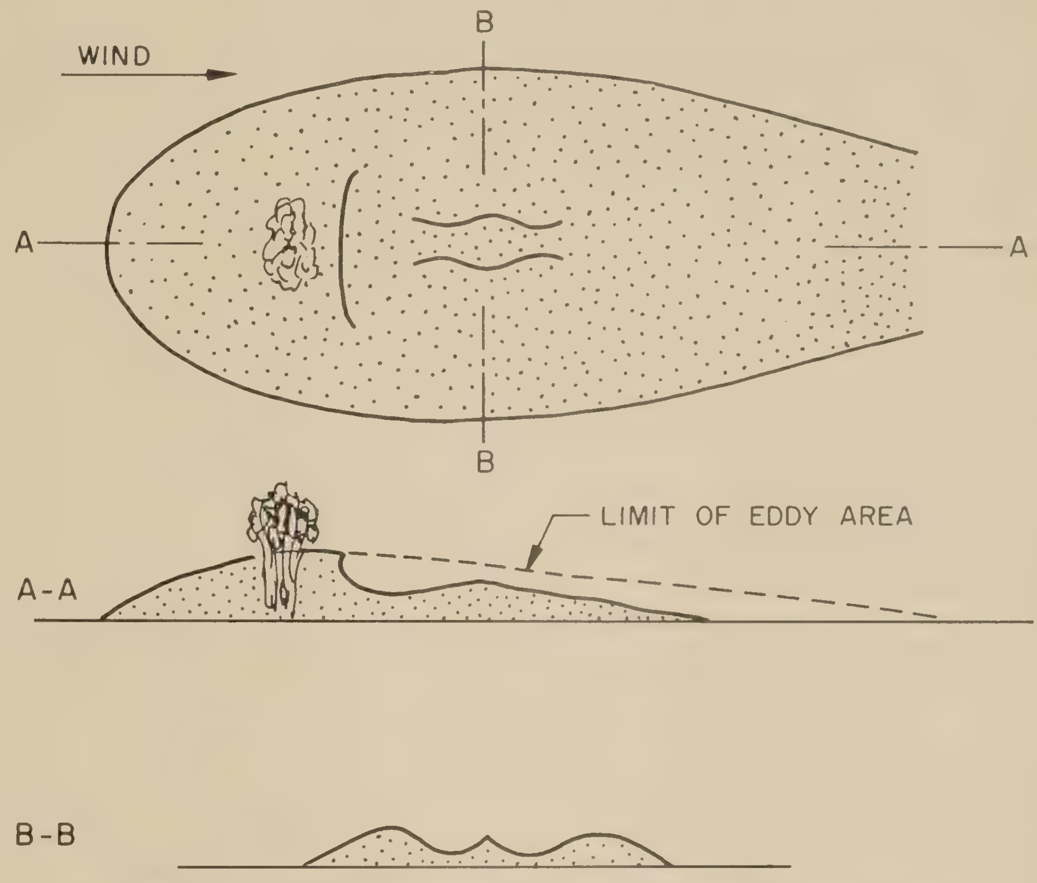

Figure 11.—Snow deposits caused by clump of bushes (Cornish, 1902).

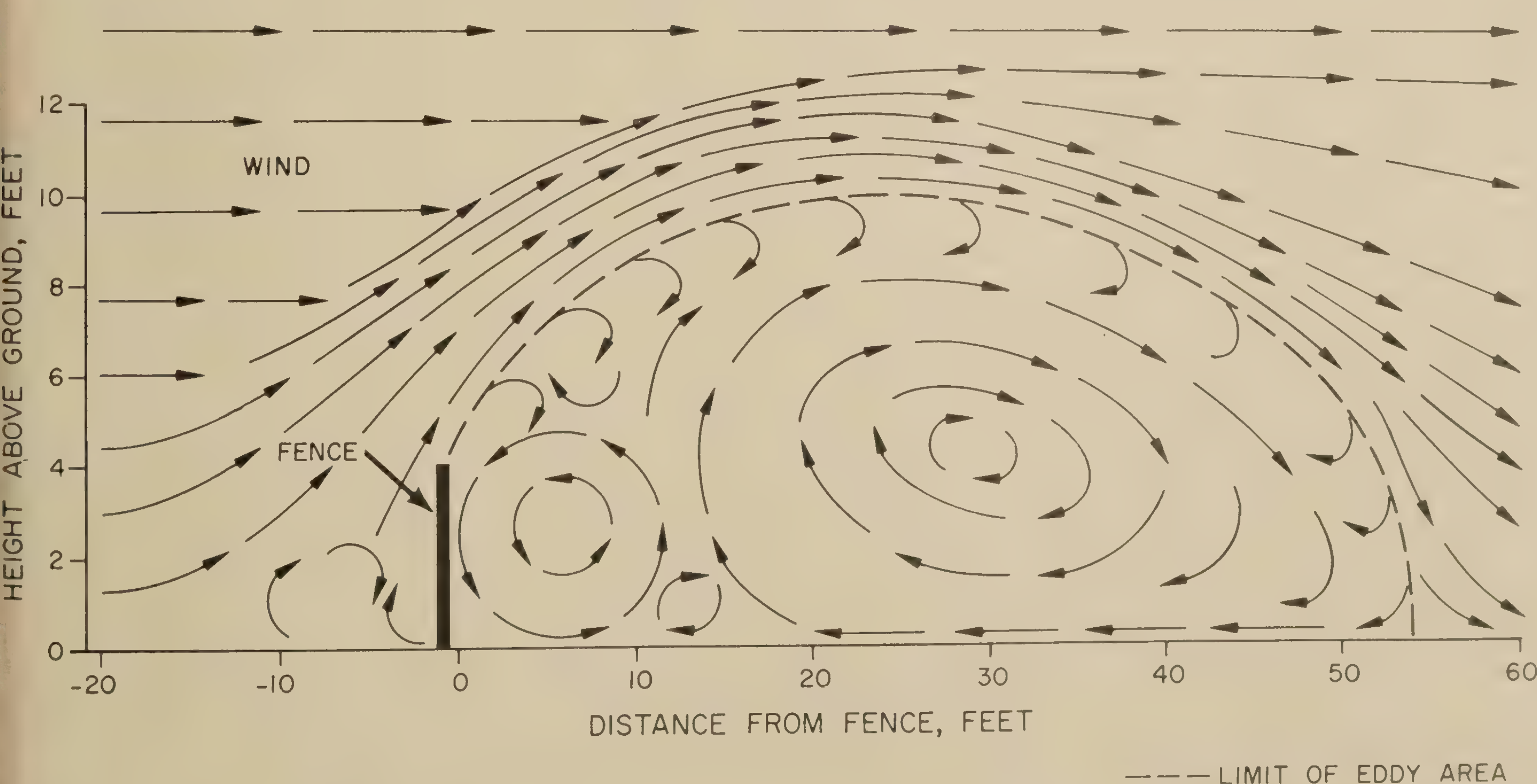

Figure 12.—Cross section of eddy area behind a solid fence (Finney, 1934).

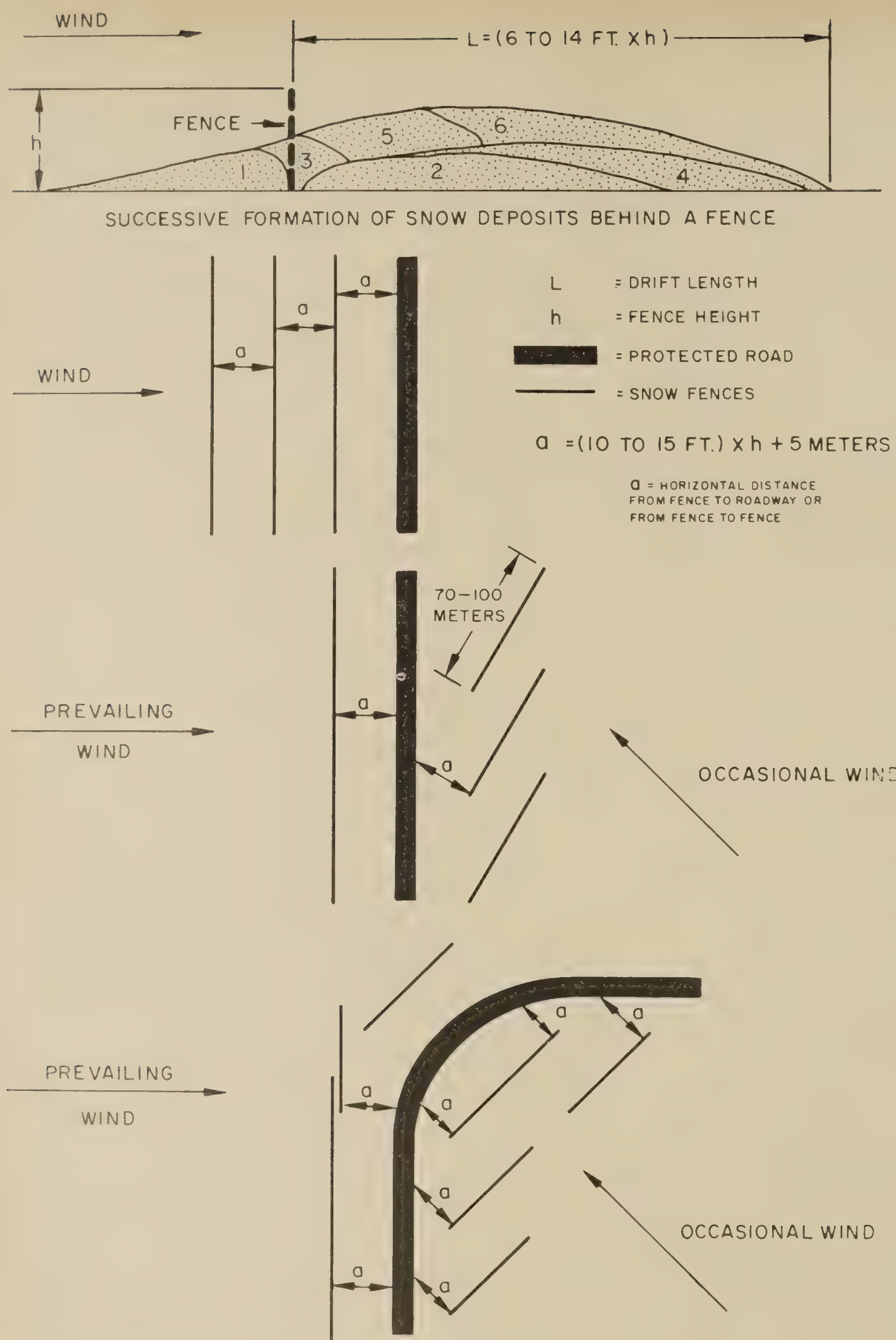

Figure 13.—Snow fence arrangements used in Germany (Bekker, 1951).

deciduous varieties are also useful (*1*). Snow accumulation is most effective when one or two dense shrub rows or branched small trees are used (*9*). Snow control hedges and shelterbelts also afford protection to birds and small game.

To be effective for snow control trees and shrubs do not need to be planted in long parallel rows. Discrete clumps, if properly planned, will work just as well, and with a more natural overall appearance (*1*). Stiffness and monotony of the plantings can also be relieved by varying the species, arrangement, and spacing (*14*).

Planting of hedges should be preceded by a number of years of operation with portable fences to establish by trial and error the best location and orientation for the permanent windbreak (*2*), and until planted hedges reach full effectiveness the drift spots must be protected by snow fences. Also, the snow hedges require annual care to maintain their effectiveness, but the cost is only about one-third as much as the annual re-erection of wooden snow fences. The effectiveness of the hedge or windbreak increases with age as the plants become higher provided that the density of the lower parts is maintained (*2*).

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Horizons in Highway Maintenance

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

Reported by [1] WILLIAM N. RECORDS
Highway Research Engineer,
Structures and Applied Mechanics Division

New horizons have opened up as a result of research and development studies. These studies provide the knowledge and techniques needed to make improvements in highway maintenance. The author describes the size of the maintenance function, explains the complexity and the problems that characterize highway maintenance, and emphasizes its challenge to the entire highway industry. He is convinced that, if all segments of the highway industry—management, research, design, construction, materials production, and equipment manufacture—rise to meet this challenge, substantial improvements can be made in maintenance during the next two decades.

MANY highway departments have attempted to reduce maintenance on highways built during recent years by improving design practices, construction procedures, and materials. These efforts are commendable, but total maintenance workloads of new highways have increased steadily. The reason for this increase is that the reductions in workloads as a result of better design, construction, and materials have been more than offset by increases arising from more safety features, beautification, higher standards, and expanded services for highway users. These same factors have caused substantial increases in the maintenance workloads for older highways. In addition, many older roads were not built to carry their present traffic load. Consequently, extensive work has been required to avert failure in structural components.

Maintenance is a major function of highway departments regardless of their size or area of responsibility. Indications are that it will continue to be a major function despite advances in design, construction, and materials. It is logical, therefore, that maintenance should receive considerable attention from all segments of the highway industry.

Highway maintenance is characterized primarily by (1) its size, (2) its complexity, (3) its many interrelated problems, and (4) its opportunities for improvement. Each of these aspects is examined in some detail in the following paragraphs.

Size of the Maintenance Function

There are more than 3.5 million miles of highway in the United States and, at the present time, about 30,000 separate organizations responsible for maintaining this vast network. These organizations employ over 300,000 men and use approximately 400,000 units of major equipment in carrying out the vital maintenance function. Expenditures are on a comparable scale. Figure 1 shows reported expenditures for highway maintenance by all governmental agencies during the period 1950 to 1965. In 1965, the cost of highway maintenance reached $3.23 billion, which was nearly 23 percent of total highway expenditures in that year. Figure 1 also illustrates that maintenance expenditures have been steadily increasing over a long period of time. The increase was $1.81 billion or 127 percent during the 16-year period from 1950 to 1965.

In figure 2, expenditures have been roughly adjusted to a standard dollar by applying the Bureau of Public Roads Maintenance Cost Index. The adjusted values still show a significant increase, $0.61 billion or 30 percent, from 1950 to 1965. Part of this increase is attributable to new highways added to systems; the remainder reflects additional work generated by more safety features, beautification, higher standards, and expanded services.

Complexity of Highway Maintenance

Highway maintenance is a function of great complexity. Obviously, this fact is not widely appreciated in the highway industry. Many individuals—even those directly connected with it—tend to think of maintenance in terms of a few operations such as patching, mowing, removing litter, and plowing snow. These particular activities do account for substantial portions of the total workload, but they do not begin to encompass the total maintenance function. Research studies conducted by the Bureau of Public Roads have identified more than 100 distinct maintenance operations. Some of these are illustrated in figure 3. In addition, there are at least 30 operations that arise out of secondary functions assigned to most of the organizations responsible for maintenance. A single management field unit, such as a gang, may perform more than 50 of these operations each year. Table 1 shows an actual case which is considered typical.

The complexities involved when a single maintenance gang tries to perform so many different activities with any degree of effectiveness and efficiency should be considered. The picture is further complicated by the fact that most operations are performed (1) by several different work crews, (2) on many different occasions, (3) at many widely scattered worksites, and (4) under varying worksite conditions. Each time a crew sets out to perform a particular operation, they are, in effect, faced with a new situation. Results are influenced by many factors including weather, traffic, quality of supervision, training of personnel, size of the job, and the availability of materials, equipment, and manpower.

It is not surprising that research studies have uncovered substantial variations in the total quantity of work, quality of workmanship, productivity, and unit costs for the same operation, as performed by different maintenance crews or even the same crews on different occasions. Figures 4 and 5 are typical of the pattern observed in several maintenance organizations. It is surprising that maintenance organizations manage to do a reasonably acceptable job most of the time. This can be attributed largely to the devotion and ingenuity of individual engineers, managers, and employees.

Highway Maintenance Problems

Highway maintenance is a function characterized by many problems. These usually fall in two categories: (1) Management problems, and (2) technological problems. Management problems are those that arise from the process of planning, organizing, directing, and controlling the maintenance function. Technological problems arise out of the procurement and the use of facilities, equipment, tools, and materials.

A realistic appraisal of any maintenance organization will disclose that it faces many problems in both categories. Some of the problems uncovered by such appraisals are, as follows:

Management Problems

- Ineffective or nonexistent planning
- Budgeting based on inadequate factual data
- Reporting system that does not provide needed data

[1] Presented at the Louisiana State University Highway Engineering Conference at Baton Rouge, La., Mar. 1, 1967.

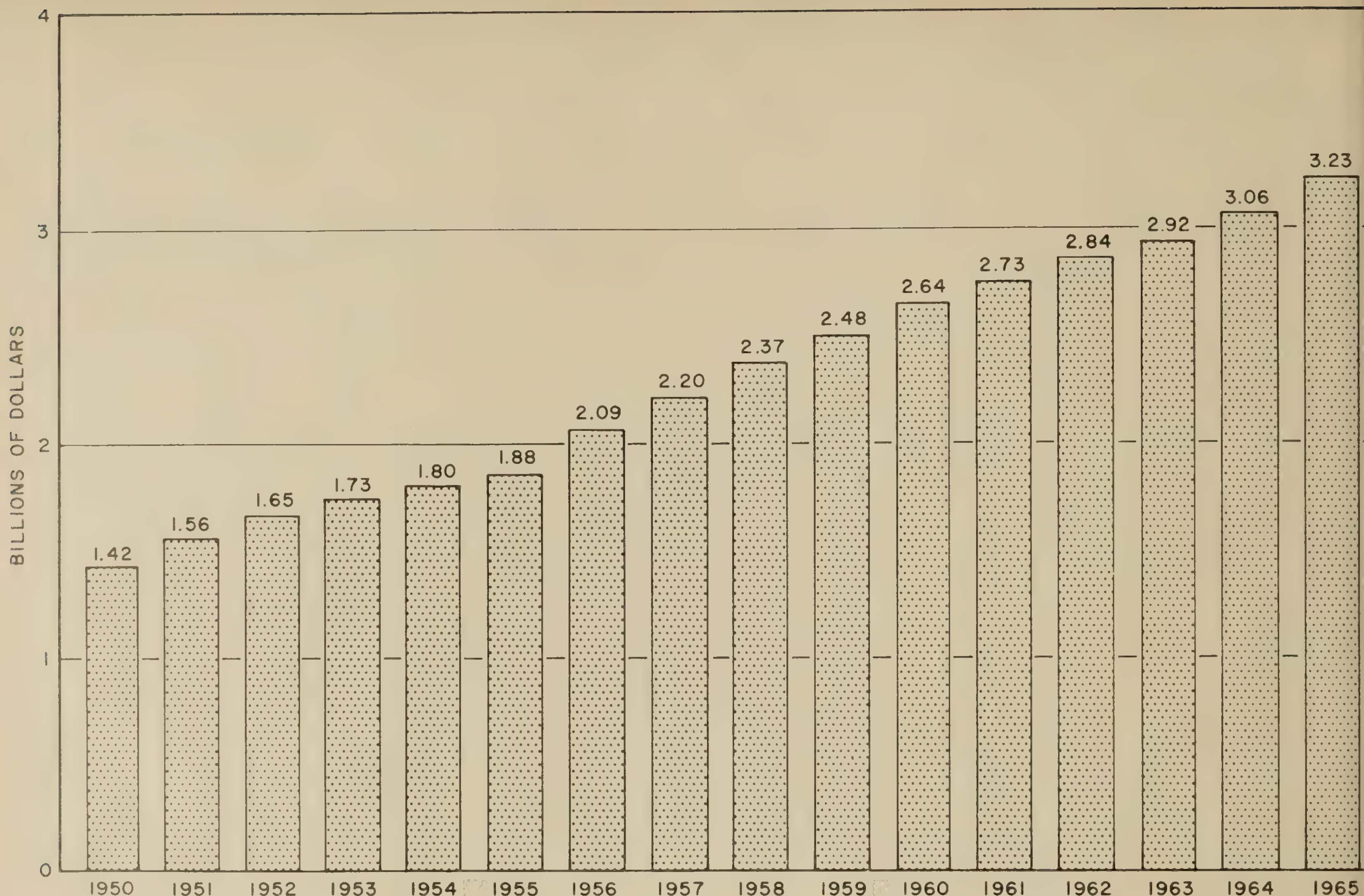


Figure 1.—Total expenditures for highway maintenance in the United States.[1]

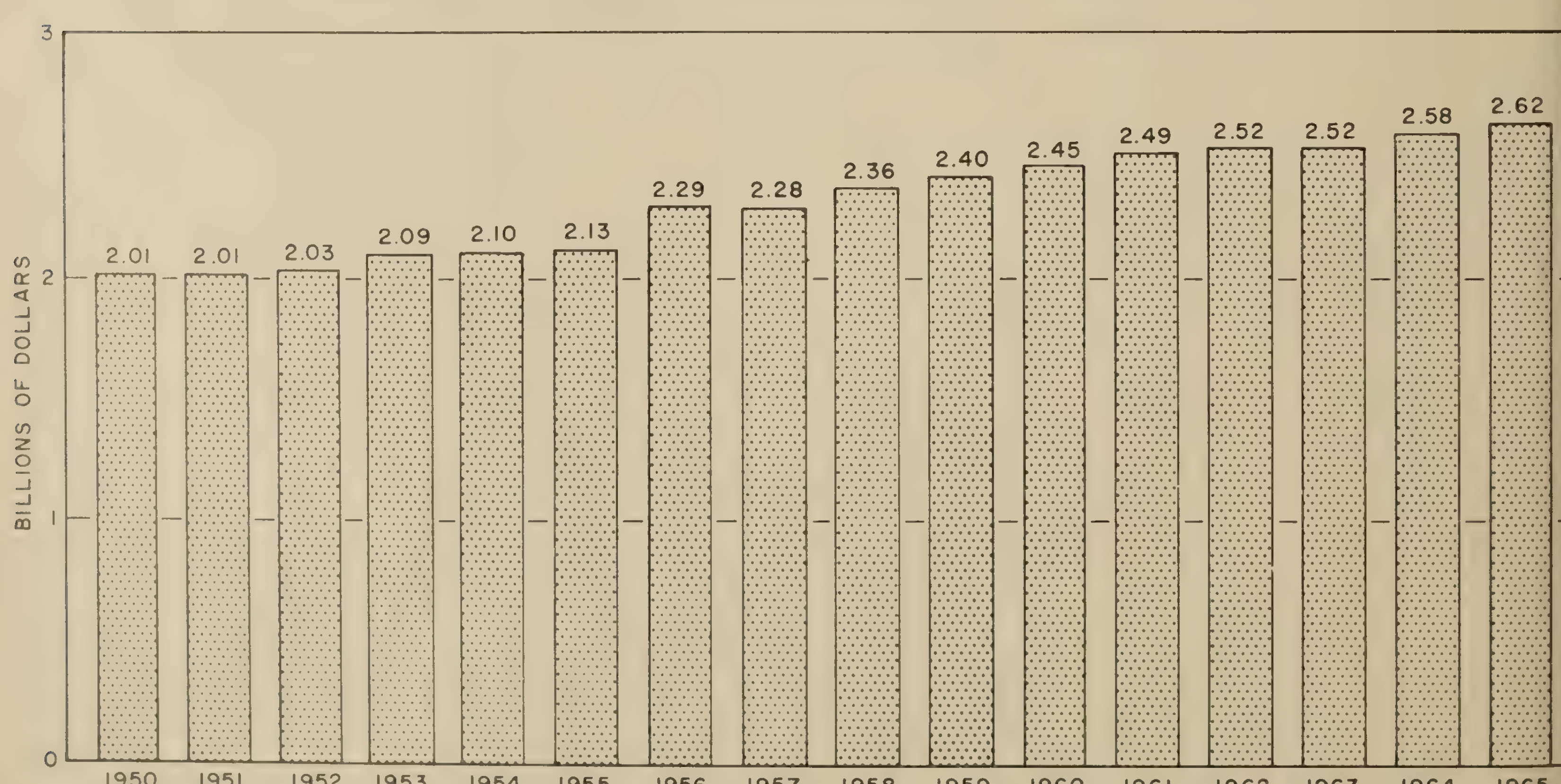


Figure 2.—Total expenditures for highway maintenance in the United States adjusted by Bureau of Public Roads Maintenance Cost Ind (1957–1959 base).[2]

[1] Data from Highway Statistics, Summary to 1965, U.S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads, March 1967.

[2] Basic data from Highway Statistics, Summary to 19 U.S. Department of Transportation, Federal Highw Administration, Bureau of Public Roads, March 1967.

- Poor communications
- Central office staff too small
- District staff too small
- Poorly trained field supervisors
- Widely varying productivity and unit costs
- No standardized work methods
- No definitive standards
- No formalized process for evaluating performance

Technological Problems

- Insufficient facilities
- Poorly designed or obsolete facilities
- Insufficient equipment
- Equipment not well suited for work to be done
- Inadequate equipment maintenance
- Materials not well suited for work to be done

Of course, no single organization will be faced with all these problems, nor will a particular problem be of equal severity for two organizations. But it is recognized that all maintenance organizations have problems and some of these are relatively severe.

Another aspect of the problems facing maintenance organizations should be recognized. They are often interrelated. For example, the problem of insufficient equipment is nearly always interrelated with problems in planning, budgeting, or work methods. Because of these interrelationships, effective solutions usually cannot be developed on a single-problem basis. Some attempts to solve a single problem have failed because the solutions were detrimental to the total maintenance function. This experience has led to the concept that maintenance problems can be solved best by an approach that deals with them both individually and totally.

Opportunities for Improvement of Highway Maintenance

Highway maintenance—large and complex—can be improved. New horizons have opened up as a result of research and development studies which are being conducted in Louisiana, North Carolina, Virginia, Utah, and a few other States. These studies are providing the knowledge and techniques needed to make improvements. They also serve to point out clearly the challenge that maintenance offers to the entire highway industry. If, after the next 20 years, the industry has risen to meet this challenge and has reached out for these new horizons, it is possible to visualize a topflight maintenance operation in 1987 that is capable of functioning as follows:

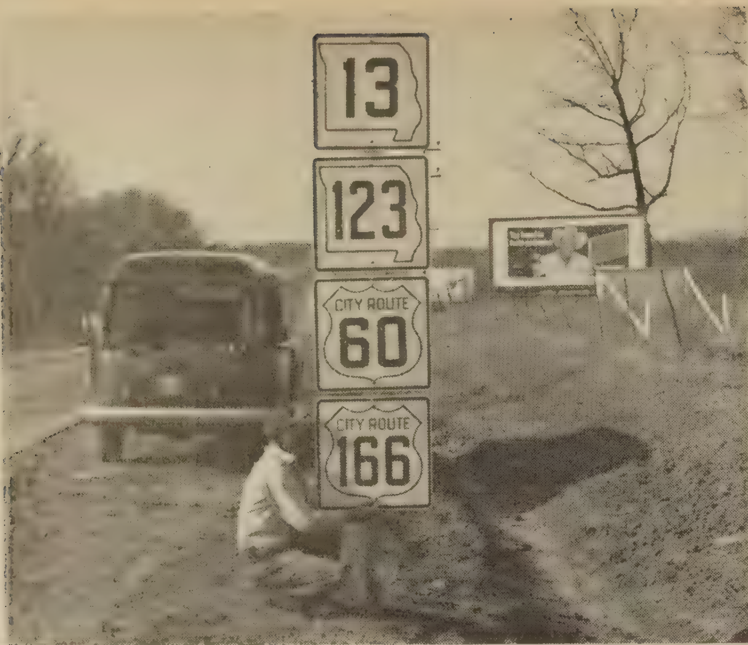
- It is manned by career engineers, managers, and technicians who are highly skilled in the use of scientific methods, automated equipment, and specialized materials.
- It is equipped with modern facilities and equipment designed expressly for maintenance.
- It has a communication system capable of providing instantaneous contact with practically every employee.

Table 1.—Distribution of labor time in Johnson County [1]

[Including distributed overhead]

Operation	Labor time		Proportion of total available working time	
	Per operation	Total	Per operation	Total
OVERHEAD OPERATIONS—UNDISTRIBUTED	*Hours*	*Hours*	*Percent*	*Percent*
Supervise maintenance activities	------	1,976	------	6.0
Service and repair equipment	------	6,019	------	18.3
Clean, repair, or improve garage facilities	------	1,211	------	3.7
DIRECT OPERATIONS—MAINTENANCE OF EXISTING SYSTEM				
Routine surface:				
Patch roadway surfaces with aggregate	1,481	------	4.5	------
Patch roadway surfaces with bituminous cold mix	2,095	------	6.4	------
Blade gravel surfaces	286	------	0.9	------
Fill joints and cracks in roadway surfaces	177	------	0.6	------
Apply dust palliatives to gravel surfaces	142	------	0.4	------
Clean or drain roadway surfaces	34	------	0.1	------
Total	------	4,215	------	12.9
Special surface:				
Mudjack concrete pavements	303	------	0.9	------
Seal bituminous and concrete pavements	1,662	------	5.1	------
Resurface with bituminous mixes	758	------	2.3	------
Plane or roll bituminous pavements	136	------	0.4	------
Total	------	2,859	------	8.7
Shoulder and approach:				
Patch shoulders and approaches with soil	589	------	1.8	------
Patch shoulders and approaches with aggregate	791	------	2.4	------
Patch shoulders and approaches with bituminous cold mix	917	------	2.8	------
Reseed or resod shoulders and approaches	102	------	0.3	------
Blade or reshape shoulders and approaches	226	------	0.7	------
Total	------	2,625	------	8.0
Roadside and drainage:				
Repair cut- and fill-slopes	177	------	0.5	------
Repair or replace pipes and tiles	87	------	0.3	------
Clean pipes, tiles, and box culverts	257	------	0.8	------
Clean or repair unpaved drainage ditches	430	------	1.3	------
Clean paved flumes, gutters, and drop inlets	4	------	------	------
Remove trees from roadsides	89	------	0.3	------
Mow roadsides with tractors (including shoulders)	1,596	------	4.8	------
Spray weeds on roadsides	157	------	0.5	------
Total	------	2,797	------	8.5
Snow and ice:				
Remove snow from roadway surfaces and shoulders	3,780	------	11.5	------
Erect snow fences	619	------	1.9	------
Remove snow fences	492	------	1.5	------
Sand roadway surfaces	469	------	1.4	------
Salt roadway surfaces	691	------	2.1	------
Remove ice from roadway surfaces and shoulders	485	------	1.5	------
Remove snow and ice from drainage ditches	89	------	0.3	------
Put out and remove cinder barrels	122	------	0.4	------
Total	------	6,747	------	20.6
Traffic service:				
Paint centerlines and edgelines	479	------	1.5	------
Paint bridge endwalls, medians, and miscellaneous markings	317	------	1.0	------
Erect, replace, repair, or paint signs and guideposts	606	------	1.8	------
Clean signs and reflectors	97	------	0.3	------
Remove or paint guardrails	77	------	0.2	------
Miscellaneous work at weigh stations and roadside parks	88	------	0.3	------
Total	------	1,664	------	5.1
Other:				
Clean or repair bridges	29	------	0.1	------
Remove litter from right-of-way	140	------	0.4	------
Miscellaneous work resulting from disasters	15	------	0.1	------
Miscellaneous work resulting from maintenance contracts	48	------	0.1	------
Total	------	232	------	0.7
DIRECT OPERATIONS—NEW CONSTRUCTION				
Detour:				
Patch roadway surfaces with bituminous cold mix	174	------	0.5	------
Rebuild aggregate base courses	168	------	0.5	------
Mow roadsides with tractor (including shoulders)	19	------	0.1	------
Erect, replace, repair, or paint signs and guideposts	244	------	0.8	------
Miscellaneous work	142	------	0.4	------
Total	------	747	------	2.3
Miscellaneous work resulting from construction contracts	------	111	------	0.3
Net available working time	------	31,203	------	95.1
NONOPERATIONAL				
Major nonoperational delays	------	1,597	------	4.9
Total available working time	------	32,800	------	100.0

[1] Source HRB Special Report 65, Supplement I.



Replacing sign

Regraveling surface

Tractor mowing

Hand mowing

Blading gravel surface

Replacing damaged guardrail

Figure 3.—Typical maintenance operations.

Picking up litter

Painting pavement marking

Filling shoulder edge rut

Patching pavement

Plowing snow

Cleaning ditch

Figure 3.—Typical maintenance operations (continued).

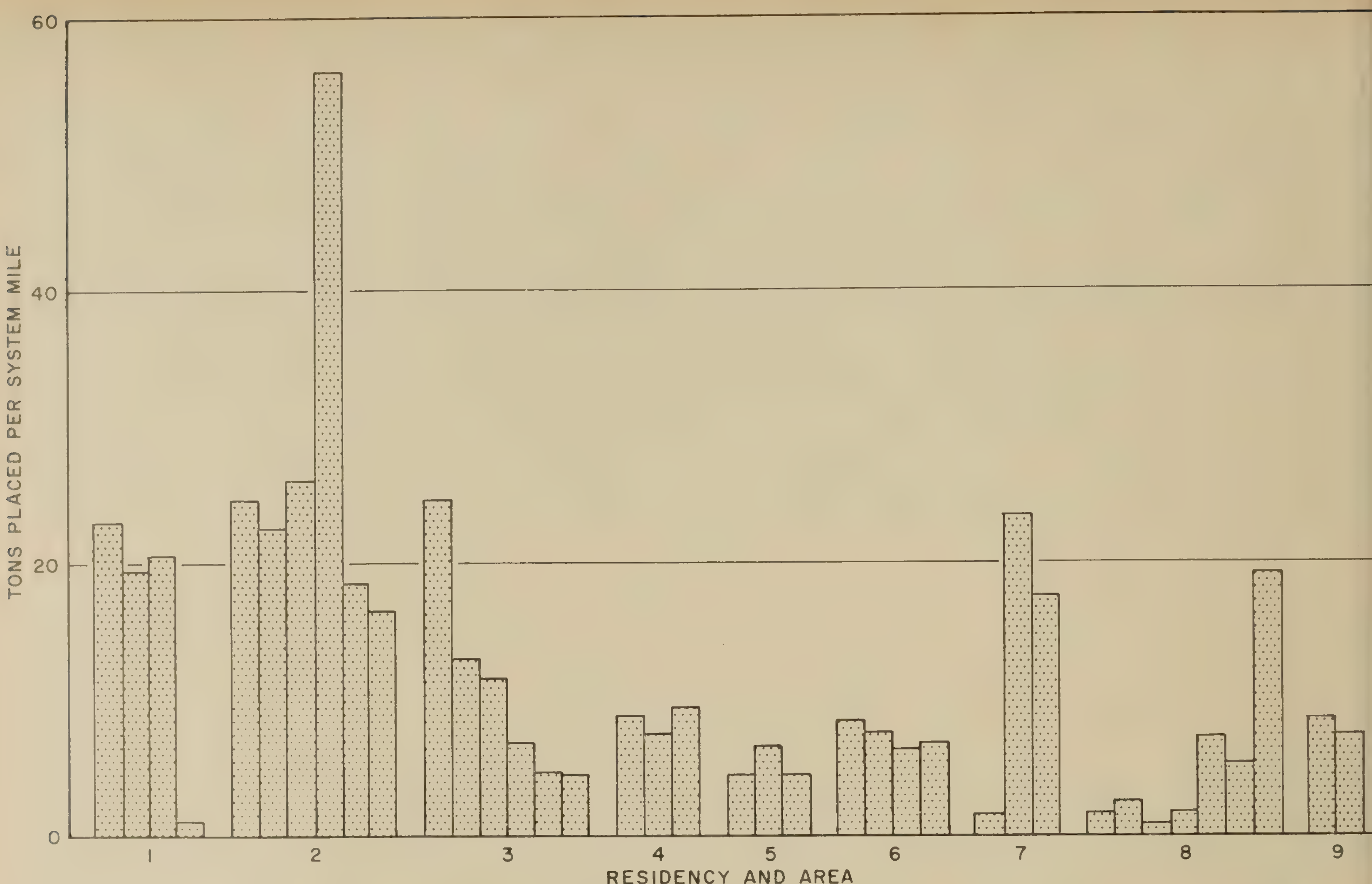


Figure 4.—Average amount of skin patching on surface treated secondary roads.[3]

- A wide spectrum of data is recorded automatically or semiautomatically and transmitted directly to computers for processing.
- There is a strong and continuing program to seek out and develop new methods, equipment, and materials.
- There is a strong and continuing program to train all personnel using sophisticated techniques and advanced equipment such as programed instruction and closed circuit television.
- New types of nondestructive testing equipment are used to detect incipient failures in structural components. (Many components of highways require practically no maintenance at all other than replacement or rehabilitation at long intervals.)
- Many failing or damaged structural components are replaced by standard, preassembled units.
- Failing pavements are patched with a liquid material that is self-leveling and hardens almost instantly.
- At regular intervals, ranging from 1 to 6 weeks, every highway is traversed by crews which simultaneously remedy all known defects and take care of all needed services.
- Highways are continuously patrolled by maintenance personnel who make inspections, take care of emergency situations and aid motorist in trouble.
- Expenditures for maintenance are, relatively speaking, no larger than those at the present time.

These horizons can be reached if the highway industry is willing to devote the necessary attention and effort toward improving maintenance during the next two decades. Highway construction operations offer ample proof that the industry is capable of making significant improvements. One good example is portland cement concrete paving. In 1947, a typical paving crew consisting of 40–50 men could produce and place about 50 cubic yards of concrete per hour, using a single dual-drum paver. Today, many crews of only 30–40 men use a central mix plant and a slip form paver to produce and place about 300 cubic yards per hour. This spectacular improvement has been the result of intensive effort by several segments of the highway industry.

The information available indicates that personnel of the highway industry already have the know-how to effect improvements which would reduce total maintenance expenditures 5–10 percent without sacrificing anything in quality or level of service. Nationally, this could mean savings of over $1[…] million per year. The savings could be us[…] to improve safety, raise standards, mainta[…] new highways, or construct more new hig[…]ways. This is not a one-time saving; it wou[…] be repeated each year. Ultimately, it shou[…] be possible to effect improvements that wou[…] result in much larger savings—large enoug[…] in fact, to more than cover the cost of tra[…]forming existing maintenance organizatio[…] and operations into something akin to what[…] imagined for the future.

To move forward toward these new horizo[…] there must be a change in attitude on t[…] part of all segments of the highway industr[…] Interest must be stimulated, complacen[…] converted into dissatisfaction with the stat[…] quo, and lethargy changed into a willingn[…] to take action. Once the right climate [...] created, it will not be difficult to move in[…] an action stage where problems can be iden[…]fied and defined, the needed technology c[…] be developed, and improvements can [...] instituted. If all segments of the highw[…] industry—management, research, design, co[…]struction, materials production, and equi[…]ment manufacture—participate fully, t[…] maintenance function will be improved a[…] these new horizons can be reached.

[3] Data from Virginia Maintenance Study Report—Part II, Performing Highway Maintenance Operations in Virginia, by Virginia Department of Highways, January 1966.

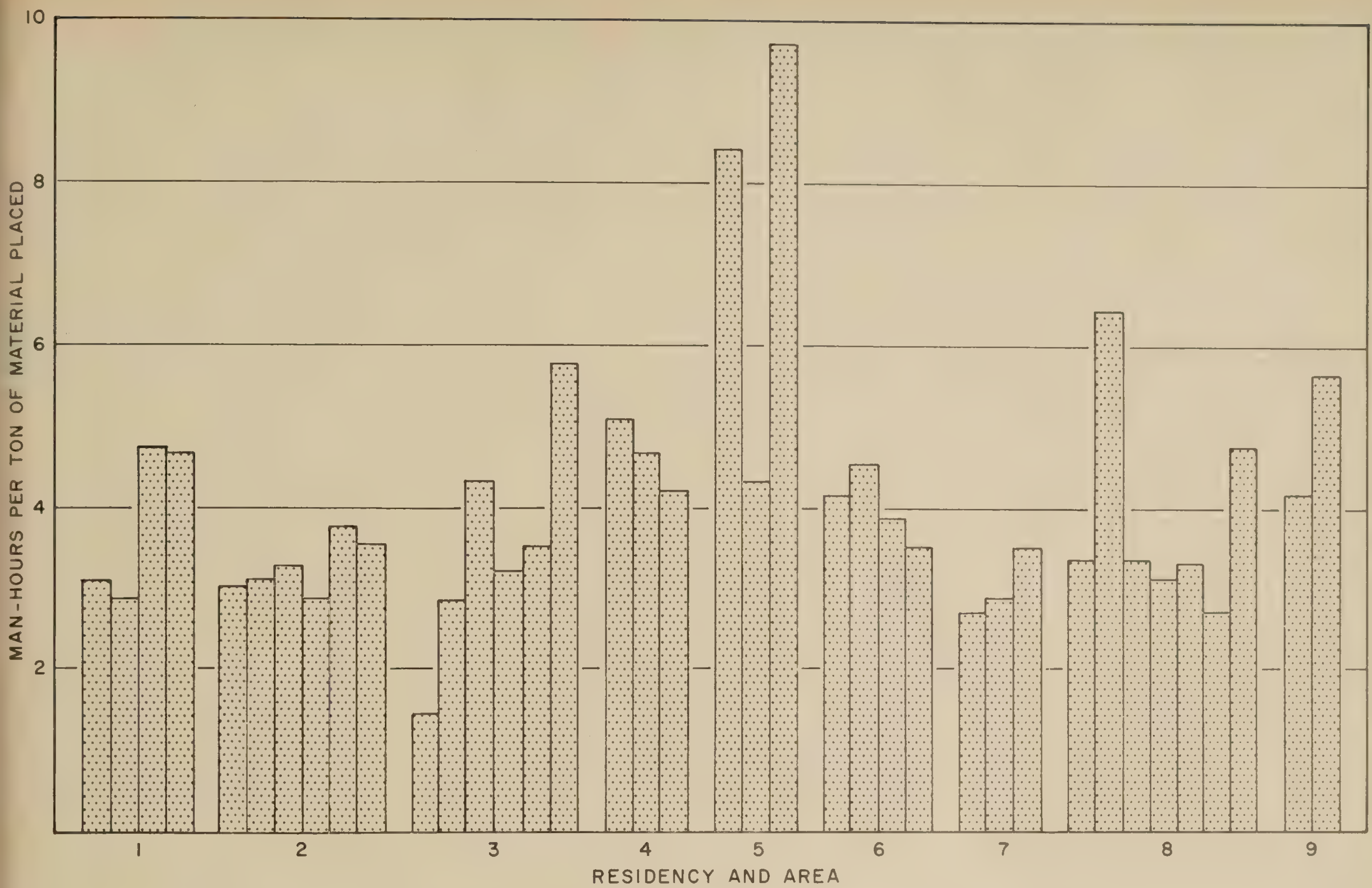


Figure 5.—Average productivity on skin patching.[3]

NEW PUBLICATIONS

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

Guidelines for Trip Generation Analysis

Guidelines for Trip Generation Analysis (65 cents a copy), published in June 1967, is one of a series of procedural manuals and guidelines produced by the Office of Planning in an effort to document the various elements of the transportation planning process.

Trip generation is commonly used to describe the number of trips starting or ending in a particular area in relation to the land use or socioeconomic characteristics of that area. These guidelines provide a framework for the conduct and evaluation of the trip generation element of the planning process. Existing techniques are documented and new approaches and emerging concepts in trip generation analysis are discussed.

Overtaking and Passing on Two-Lane Highways

Overtaking and Passing on Two-Lane Highways (20 cents a copy), a 44-page research and development report, contains a review of the published literature reporting observational and experimental studies of overtaking and passing maneuvers on highways having only 2 lanes. The literature review was conducted for the Bureau of Public Roads as part of a contract directed toward gaining a conceptualization of overtaking and passing maneuvers. The work performed by the contractor was in support of the Public Roads research and development program to reduce the number of rear-end and head-on accidents on rural highways and to increase the service volume on them.

As most of the work reviewed was performed in the 1930's or early 1940's, and the emphasis was on providing the highway engineer with design information for laying out passing zones, much of the data presented is concerned with the times and distances required to pass; relatively little information is presented on passing judgment—the conditions under which a driver will or will not pass.

To facilitate comparisons between the results of the different studies, the review is organized topically as follows: Distance required to pass, time required to pass, passing headway, passing performance, passing reaction time, traffic conditions and passing, and gap acceptance.

Typical Plans for Retaining Walls

Typical Plans for Retaining Walls, 1967 (45 cents a copy), are intended to serve as a useful guide to State, county, and local highway departments in the development of suitable and practical retaining wall designs and should be particularly valuable to the smaller highway departments with limited engineering staffs. An effort has been made to give sufficient information on all plans so that they may be readily adopted in the preparation of contract drawings.

(Continued on p. 250)

[3] Data from Virginia Maintenance Study Report—Part II, Performing Highway Maintenance Operations in Virginia, by Virginia Department of Highways, January 1966.

Residential Density Structure—An Analysis and Forecast With Evaluation

BY THE
OFFICE OF PLANNING
BUREAU OF PUBLIC ROADS

Reported by[1] CARL N. SWERDLOFF,
Highway Research Engineer,
Urban Planning Division

In this article Swerdloff reports on an analysis of the residential density structure of a small urban area. The procedures discussed for studying known density structures and forecasting future ones are simple, and can be readily used by planners with minimal data resources.

Such a study is valuable to the urban transportation planner concerned with bringing order and efficiency to urban space. Through the development of urban density structure models that forecast future population density distribution and the likely fluctuations in residential development caused by changes in planning standards or socioeconomic conditions, the transportation planner can favorably influence future residential density patterns. By providing and depriving transportation access the planner establishes heterogeneity in the distribution of land value and consequently in the pattern of population density. Because transportation accessibility is an effective control on residential population density distribution, the location of future transportation facilities influence the location and intensity of residential development.

Introduction

URBAN population density has been of interest to professionals in many different, but related disciplines. Since 1951 when Colin Clark (*1*)[2] published his exponential decay formulation of the spatial arrangement of urban population densities, economists ecologists, geographers, city planners, and others have been concerned with determining the universality of the Clark formulation. The factors contributing to interregional variability in the parameters and in the temporal stability or lack of stability of the formula are still questioned.

The onrush of urban transportation planning studies in the late 1950's focused attention on the fact that the future land-use distribution in urban areas must be estimated before transportation demands could be forecasted. Attention to the analysis and forecasting of urban land use necessarily involved an increased interest in the matter of population density. The measurement of population or residential density is a necessary part of the land-use distribution process used in traditional transportation planning programs. The population density estimates are used either to determine whether the forecasted population distribution shows realistic zonal residential densities, or to compute the consumption of previously vacant land by the increment of residential growth in each zone. The computation of consumption of previously vacant land is of particular importance when the urban simulation process is performed in a finite number of consecutive time periods that require the relevant data to be updated at the conclusion of each time period in preparation for the next time period. The residential population density is also used in the population distribution process as illustrated by the individual density submodels used in the forecasting model system developed at the Delaware Valley Regional Planning Commission (DVRPC) (*2*). In the DVRPC simulation system the land-use distribution reflects the existing residential density pattern of the study, just as the forecast residential density pattern reflects the existing land-use distribution. However, the land-use distribution processes usually rely on exogenously determined land-use density values as explanatory variables.

Land-use density is used in trip generation analysis in many transportation studies. Trip generation—the estimation of the total number of trips originating or terminating in each analysis zone—is frequently determined by use of multiple regression analysis equating trip production with measurable characteristics of the analysis zone, such as existing density. Trip generation analysis thus shows that the arrangement of households will affect the volume of daily trips. The external economies associated with more dense land-use arrangements apparently influence trip generation. Transportation planners are currently interested in mode split that is, the distribution of daily travel between private and public transportation facilities. The land-use density pattern is important to this area of analysis; and speculation on the future role, function, form, and viability of large urban regions is contingent on the assessment of the density levels that the future population will be willing to maintain.

The lack of operational procedures and normative guides for estimating the future distribution of urban residential densities has prompted the study presented in this article. The residential density pattern of a small urban region was investigated in two time periods 12 years apart. The author has attempted to establish the conformity of the observed density structure of the study area to the universal formulation of urban population density by Clark (*1*). Many multiple regression analyses were undertaken and the observed shifts in the parameters over the 12-year study period are presented. Also, the author has attempted to examine the relative accuracy of each of the forecasts of the residential density structure. The analysis and forecasting procedures examined were kept simple so that they would be practical for application in transportation planning studies for moderate sized urban areas.

Residential density refers to the ratio of some measure of the volume of residential activity to the total land or space used. But there are many ways in which land use and total land can be defined and measured (*3*). The numerator of the ratio is the volume of residential activity; that is, the number of persons, households, or dwelling units. For the purposes of the study reported in this article it was expressed in total dwelling units. The denominator of the ratio, the total land or space area, has been a source of definitional inconsistency, but for the purposes of this paper gross density land area refers to the total area of the analysis unit; that is, the area arrived at by planimetering the boundaries of the land. Gross census tract dwelling unit density is then calculated by dividing the total number of dwelling units in a census tract by the total land area contained within the boundaries of the tract. Net residential density land area is a sharper measure than is gross density primarily because it reflects the actual uses of land that make up the total

[1] Presented at the 46th annual meeting of the Highway Research Board, Washington, D.C., Jan. 1967.

[2] References identified by italic numbers in parentheses are listed on page 250.

land area of the different analysis units. For example, all land constituting a given census tract can be classified as used or vacant and the net census tract dwelling unit density per square foot of used land computed. Used land can be further classified as residential or nonresidential and a dwelling unit density per square foot of residential land computed. For the study reported here net residential density is defined as total number of dwelling units per unit of residentially used land, including street area. Because of personal bias, the bulk of the analysis was in terms of net density.

Conclusions

Results from the study reported in this article are not conclusive because they are based only on a single analysis of a single urban area over a single time period. It is the belief of the author, however, that the procedures for the analysis and forecasting of residential density in small and medium size urban areas can be advanced through the results of the study. Several conclusions have been drawn from the study results.

- The author believes that future analysis of urban residential structure should be concentrated on net as opposed to gross density measures. Net density is a more exact measure, is compatible with a substantial body of existing theory, and is possibly more conducive to meaningful analysis and projection.

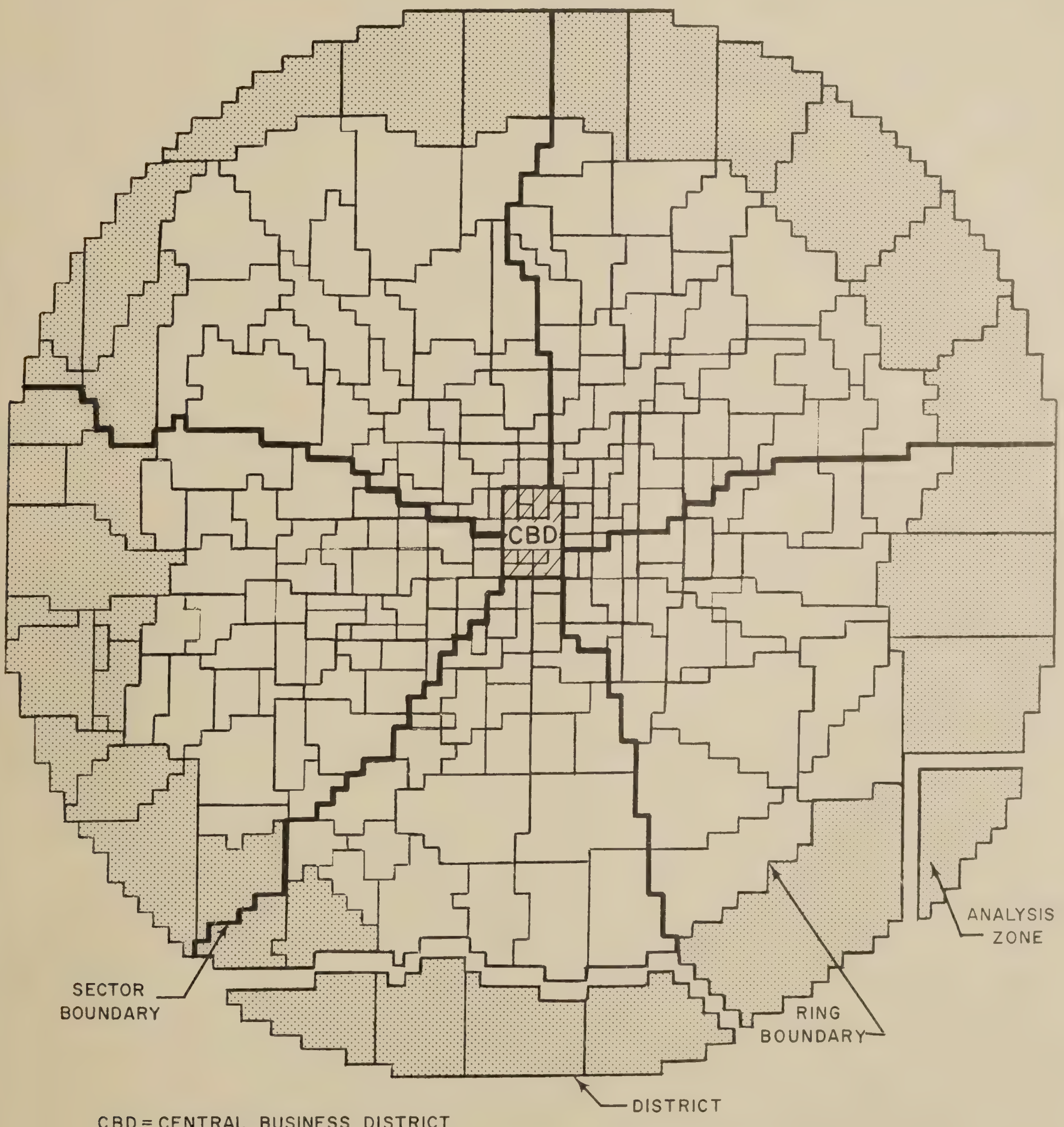


Figure 1.—Greensboro, North Carolina Study Region.

- The district unit of analysis used in the study reported here has an average internal population of 2,000 persons and is comparable in size to the urban transportation travel analysis zone. It is a useful level of aggregation for the study of urban residential density structure.
- Density distance gradients are useful in analyzing the density structure of the urban area and can also serve as forecasting devices. However, because density gradients are not static, the author suggests that additional research be devoted to the development of rational explanations and procedures for estimating the parametric shifts so that the forecasting potential of density distance gradients can be improved.
- Accurate net residential density models that are structured in terms of existing theories of economic equilibrium and land-use distribution should be developed.
- Central core areas should be separated from the rest of the urban region in the development of residential density models. Also, the inclusion of substantially rural areas, in which significant urbanization is not expected, distorts residential density analysis.
- Future residential density configurations should not be used merely as exogenously determined input constraints for residential location simulation models. Future residential densities should and can be functionally related to a number of socioeconomic variables, including the existing and forecasted urban activity location pattern.

Study Conditions

The Greensboro, N.C., metropolitan region was the locale for the study reported here. A complete data supply for Greensboro was available at a detailed geographic level for the years 1948 and 1960 (*4*, *5*). The primary data contained measures of total dwelling units, land area for usable and unusable land, and assessed land value, which were coded to 3,980 square foot grid cells covering the circular study area, approximately 8 miles in radius, centered around the Greensboro central business district (CBD). The data also contained measures of the proximity to urban activities and CBD. Additional data on total employment and an index of accessibility to the employment was also available at the travel analysis zone level. Figure 1 shows the entire study area structured into 249 analysis zones and five sectors, and illustrates the form of the analysis rings and districts. Average family income was not present in the original data, but was available for 1950 and 1960 from the U.S. Bureau of the Census publications (*6*, *7*). Each zone was assumed to have an average family income equal to the mean for the census tract into which it fell.

The study area was divided further into five sectors radiating out from the center of Greensboro and into circular rings 1-mile wide. The sector boundaries of the study area were forced to analyses zone boundaries. The first ring was one-half mile in radius and circumscribed the central core of Greensboro City.

Table 1.—Analysis of variance results for interdistrict net residential density

Source of variation	Sum of squares	Degrees of freedom	Estimate variance	F
Between districts	6,860.1	39	175.9	[1] 2.92
Within districts	11,494.4	191	60.2	

[1] $F=\frac{175.9}{60.2}=2.92$—significant at 0.001 level.

Table 2.—Analysis of variance results for intersector and interring net density

Source of variation	Sum of squares	Degrees of freedom	Estimated variance	F
Between rings	703.1	7	100.4	[1] 29.5
Between sectors	14.8	4	3.7	[2] 1.1
Residual	98.8	29	3.4	

[1] $F=\frac{100.4}{3.4}=29.5$—significant at the 0.001 level.

[2] $F=\frac{3.7}{3.4}=1.1$—not significant.

The primary analysis unit utilized in this study was the district defined as that area contained within the intersection of successive sector and ring boundaries. The study area could have been structured into *driving time to the CBD* time increment rings as opposed to distance increment rings, but previous work (*4*) with the same data showed little advantage to either method of structuring. Therefore, distance units were selected primarily to correspond with the bulk of existing structural density analyses data. Excluding the central core ring, the remaining 8-mile rings and five sectors totaled 40 districts. The district was used as the basic analysis unit because it most nearly approximated, in average resident population, the typical traffic analysis zone used in traffic simulation analyses. The average district in Greensboro had a total of 660 dwelling units in 1948. The traffic analysis zone was previously shown to be too fine in residential location model tests (*4*) and was therefore judged inappropriate for net density analysis.

To justify the use of the district as the analysis unit, a one-way analysis of variance was performed on the 1948 net residential density. Results of the analysis are shown in table 1. Statistically significant between-district variance indicated that the district aggregation of zones did not destroy the prevailing zonal net density variability; therefore, the district was shown to be an appropriate analysis unit. The central core district and its composite analysis zones were removed from analysis in the study reported here because density quantities computed for the central core district consistently deviated substantially and illogically from what would be expected, based on the findings for the remainder of the study area. The central core area is traditionally distinct in residential terms and is often treated as such in transportation simulation analysis; also the quality of the residential land use and dwelling unit data is often less reliable than that for the remainder of the urban area and could cause further difficulty in analysis.

The sectors and rings were investigated as additional levels of geographic analysis of residential density structure. A two-way analysis of variance was performed on the 1948 zonal net density values stratified by ring and sector. Results of this analysis, shown in table 2, reveal that between-ring variability was significant but between-sector variability was not and the sector analysis unit was eliminated. Apparently distance away from the region's center is a more appropriate indicator of prevailing residential density than is distance in an angular direction from some reference axis. Having investigated several possibilities, the district and ring were determined to be the most appropriate geographic units for the analysis of the distribution of gross and net residential density. The central Greensboro core area was not considered in the analysis.

Methodology

The study reported here was an investigation of the residential density structure of a typical small-sized urban region. During the 12-year period from 1948 to 1960 the study area increased 52 percent in number of dwelling units, a rate of growth above the average for the Nation. Density-distance gradients were developed for both the 1948 and 1960 condition using the least squares criterion. Multiple regressions of net density were calibrated for 1948 and 1960; expected error in forecasting density was determined. The primary objectives of the study were (1) to investigate the appropriateness of several simple techniques that could be used by a small planning study with a minimal data supply; (2) to provide comparative quantitative measures of forecasting accuracy in procedures and methods investigated, and (3) to present any apparent advantage or disadvantage for selecting either gross or net residential density as the unit of measurement. Because only a small amount of material on the forecasting of trends in residential density exists and because the data were available for only two time periods, the selection of even simple forecasting techniques was severely limited.

Two district multiple regression analyses were formulated for the 1948 condition and were tested as valid forecasting devices. The initial regression formulation was modeled after the general form of the SPACEC I submodel of the Delaware Valley Regional Planning Commission Activities Model system. The second regression formulation was modeled in the usual multiple linear form. All calibration and forecasting errors are reported as coefficients of determination (R^2) and therefore maintain comparability for cross-comparisons:

$$R^2=\frac{\text{Original variance}-\text{explained variance}}{\text{Original variance}}$$

Where estimates by particular techniques are transformations of density, that is logarithmic, they have been converted to density prior to the computation of residual error.

Gross residential density has been defined as the number of dwelling units per unit of land. By using total land area and not land divided into units according to use, simplified gross density measures are achieved that give a superficial measure of the use of land by individual households. Gross density provides little improvement over a simple accounting of the fluctuations in dwelling units in a time series analysis and provides little information on the living compactness of the population. Gross residential density (D_G) is defined as:

$$D_G=\frac{\text{D.U.'s}}{A} \qquad (1)$$

Where

D.U.'s = Number of dwelling units in the analysis unit.

A = Land area of the analysis unit.

That is, a general expression of gross density for any geographic unit, i, may be expressed as:

$$D_{G_{it}}=(c)\ \text{D.U.'s}_{it} \qquad (2)$$

Where,

$D_{G_{it}}$ = Gross density in analysis unit i for time t.

D.U.'s$_{it}$ = Number of dwelling units in analysis unit i for time t.

c = Constant equal to $\frac{1}{A}$.

The gross residential density of each 8-mile-wide ring in the study area was computed for 1948 and 1960. Land-use data from a 1,000-foot square grid file of the total analysis land area was coded in ninths of land units according to the particular use of the land; therefore all residential density values are in terms of dwelling units per ninth of the total land area of the 1,000-foot square grid.

This rather awkward dimension does not affect the structural analyses or the measures of calibration and forecasting accuracy. Any of the density values reported in this paper can be converted either to dwelling units (D.U.) per acre by multiplying by the constant 0.392 or to D.U. per square mile by multiplying by the constant 250.9. The 1948 gross residential density results were plotted as a function of the distance of the ring from the CBD, in miles. A nonlinear relation exists between gross density and distance from CBD. A logarithmic plotting of the gross density data is shown in figure 2. A straight line fit in figure 2 would give evidence of a negative exponential relation of gross density to distance from CBD, but a definite straight line tendency was observed. A simple linear regression line fit to the gross density points resulted in the following equation:

$$\ln D_{G.48}=2.43-0.648X \qquad (3)$$

Where,

X = Miles from the CBD.

$D_{G.48}$ = Gross residential density 1948.

When this regression equation is transformed to exponential form, the result is:

$$D_{G.48}=11.36e^{-0.648X} \qquad (4)$$

The least squares fit obtained for the dependent variable in logarithmic form will not necessarily result in the best equation in terms of minimum residual variance when the equation is solved for the dependent variable in nonlogarithmic terms.

The coefficient of determination (R^2) for equation 4 was computed to be 0.886. The same equation, calibrated on the ring gross density values, was examined when it was applied to the gross density measures at the district level. Solutions to equation 4 for the districts yielded an R^2 of 0.834. A reduced R^2 is to be expected because of the disaggregation and the resultant introduction of greater variability.

When the ring gross densities for 1960 were plotted, the nonlinear relation was similar to that found for the 1948 data. Semilogarithmic plotting of the 1960 points, presented in figure 3, resulted in the following least squares equation:

$$\ln D_{G.60}=2.75-0.585X \qquad (5)$$

which transforms to:

$$D_{G.60}=15.58e^{-0.585X} \qquad (6)$$

The R^2's for equation 6 for 1960 ring analysis and district analysis are 0.989 and 0.923, respectively. The marginal shifting of parameters between the 1948 and 1960 gradients suggested that the 1948 equation be tested as a predictor of 1960 density. Solutions of the 1948 equation were then used as estimates for 1960 at both a ring and district level, resulting in R^2's of 0.784 and 0.743 respectively.

Negative exponential formulations of the general form,

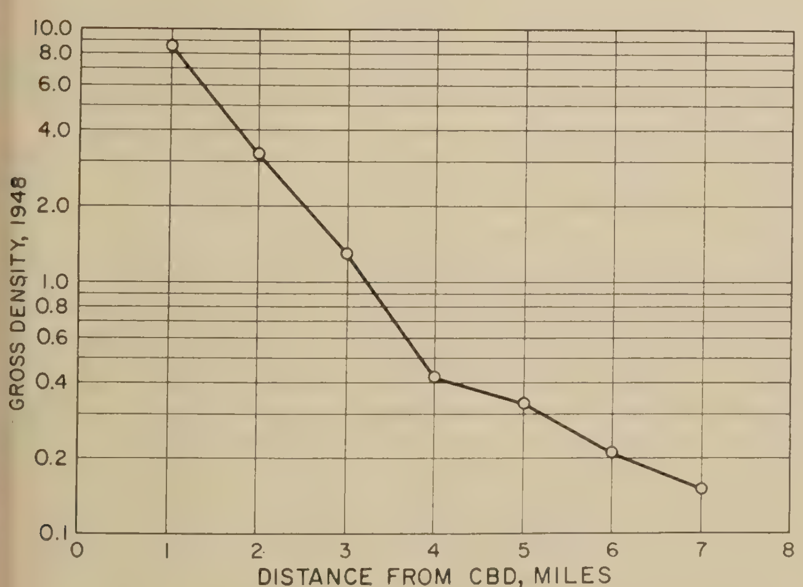


Figure 2.—Semilogarithmic plotting of 1948 gross density by distance bands.

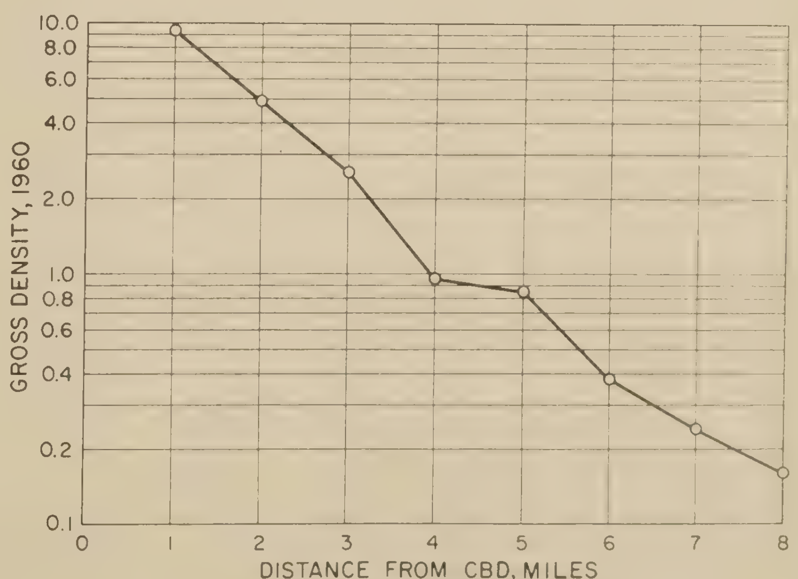


Figure 3.—Semilogarithmic plotting of 1960 gross density by distance bands.

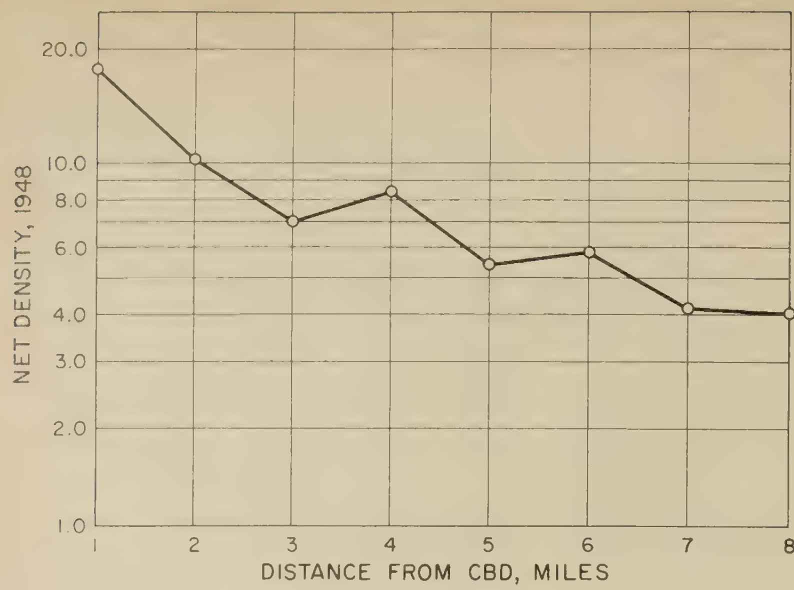


Figure 4.—Semilogarithmic plotting of 1948 net density by distance bands.

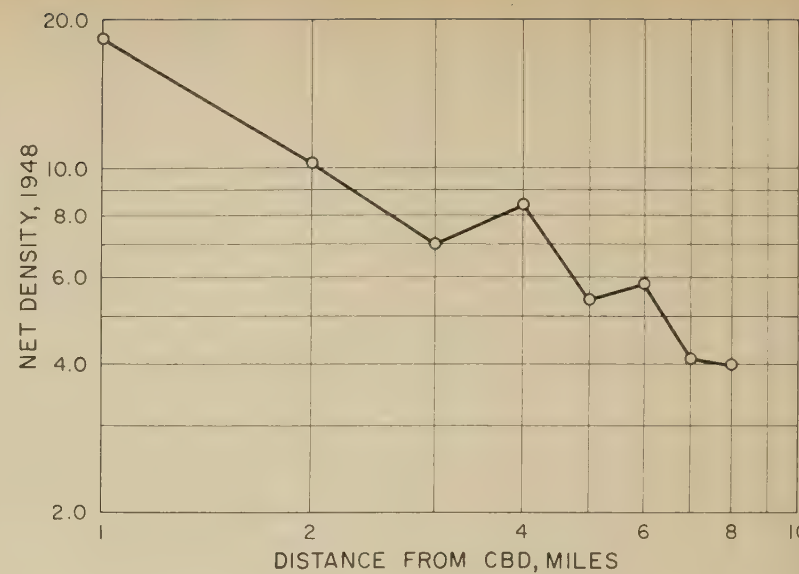


Figure 5.—Logarithmic plotting of 1948 net density by distance bands.

$$D_G = a(X)^b$$

were also investigated as potential gross density gradients, but the calibration and forecast R^2's were consistently below those previously discussed.

Net Residential Density Analysis

Residential land consumption results from an economic equilibrium between supply and demand; selection of a residential location is influenced by the economic condition of the household, its preference pattern for different commodities, the state of the housing market, and the transportation needs of the household (*8, 9, 10, 11*). Household income must be allocated to the purchase of goods and services in an effort to achieve the most satisfaction for the money available. For simplicity assume that household expenditures are divided into three groups: Transportation, housing, and other. If it is assumed that other purchases use a fixed part of the total income, then remaining funds are allocated to housing and transportation in such a way that the household derives maximum satisfaction. To get the best value for his money the head of the household might buy a house where land is least expensive; that is, in an area remote from the urban center. But, although he gets more value for his housing money, he has excessive transportation expenses. The head of another household might locate in an area convenient to transportation, but where housing costs are high thereby forcing him to purchase little housing space. These examples illustrate the causal relation existing between housing costs and transportation accessibility; the most accessible areas are the most desirable and consequently the most costly. The linkage between the decisions of the urban transportation planner and the course of residential development is thus partially illustrated (*12*).

Net density analysis can best reflect the different land-use situations and the relation of land use to transportation; gross density analysis is not so sensitive. The author believes that analytical procedures will be forthcoming which incorporate the relations and provide the transportation planner with practical methods for determining the composition and location of marginal residential development resulting from proposed transportation routes and improvements.

The net density was computed for each district and ring in the study area by dividing the number of dwelling units by the total area of residential land. A more precise measure of average net density can be computed from averaging the density of each individual dwelling unit, but this requires individual household density data. Average net density, as computed for the study presented here, is sensitive to the density variability within each district or ring. Unlike the gross density measure, net density can rise or fall with increases or decreases in the total dwelling units within the total analysis land area.

The plot of the computed ring net densities for 1948 according to the distance of the ring from the CBD generally conformed to the equivalent gross density plot. Figure 4 presents a semilogarithmic plot of these data. However, as suggested partially by the evidence of nonlinearity in the plot in figure 4 and from the study by Kramer (*13*), the net residential density data were plotted logarithmicly as shown in figure 5. Least squares fits were computed for both figures 4 and 5 and R^2's computed. The doubly logarithmic relation proved to be a better linear fit. The linear equation fit to the 1948 net ring densities was:

$$ln\ D_{N.48} = 2.850 - 0.688\ lnX \qquad (7)$$

which transposes to the following form:

$$D_{N.48} = 17.29(X)^{-0.688} \qquad (8)$$

and the R^2 for equation 8 was 0.957. Equation 8 was then examined as a predictor of the 1948 district net densities and yielded an R^2 of 0.835.

Assuming that the net density structure of the study area was stable over the 12-year period, equation 8 was tested as a valid predictor of the 1960 net densities at both the ring and district levels and the resulting values of R^2 were 0.927 at the ring level and 0.844 at the district level. The 1960 net ring densities were then plotted linearly and logarithmically. A linear equation was fit to the logarithmic plot of 1960 net ring densities as shown in figure 6. The resulting equation was:

$$ln\ D_{N.60} = 2.855 - 0.876X \qquad (9)$$

or

$$D_{N.60} = 17.4(X)^{-0.876} \qquad (10)$$

The R^2 for equation 10 was 0.986 and 0.934 at the ring and district levels respectively.

The success in applying equation 8 as predictor of 1960 densities suggested the testing of the following less involved procedure; ring densities in 1960 were estimated to remain exactly as they were computed to be in 1948. This simplifying assumption implies that the added dwelling units over the test period consumed, on the average, the same amount of land as the average dwelling unit existing in the ring in 1948. The computed R^2 for the 1960 net ring densities was 0.849. Carrying this procedure down to the districts, incremental dwelling growth in each district was assumed to locate at the same average 1948 net density as for the particular ring to which it fell. Implicit in this trial is that the intraring net density variability is diminishing over time with each district's net density approaching its ring average. The percent of 1960 net district variance explained utilizing this technique was 0.533. Finally, each district was assumed to maintain constant average net density from 1948 to 1960, the 1948 values then serving as 1960 estimates. An R^2 of 0.640 was computed for this case.

The analysis of the net residential density included the development of multiple regression equations that used selected data as independent explanatory variables. The net density multiple regressions were calibrated at the analysis zone level and were used as predictors for districts and rings. Although strict regression procedure was violated, the resulting errors were estimated to be minor based on results of the interdistrict analysis of variance in relation to intradistrict variance. This procedure required that the dependent variables for each of the regressions be an intensive quantity and thereby independent of the size of the analysis observation unit.

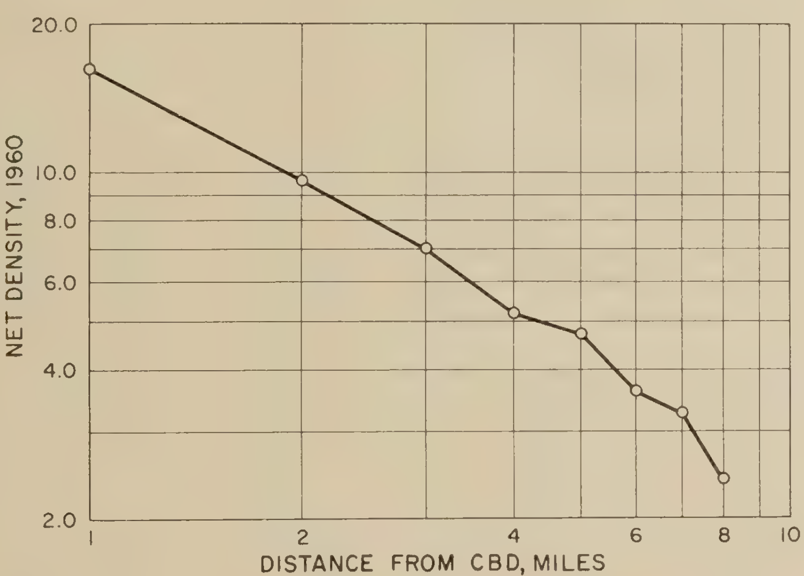


Figure 6.—Logarithmic plotting of 1960 net density by distance bands.

The functional form of the DVRPC density submodel, SPACEC I, was investigated as representative of the density pattern of the region:

$$D_N = a\, e^{\sum_i b_i X_i} \qquad (11)$$

Where,

X_i = Independent variable i.

b_i = Coefficient of variable i.

a = Constant.

D_N = Net residential density.

Equation 11 transforms by logarithmic conversion to the standard linear multiple regression equation:

$$ln\ D_N = ln\ a + \sum_i b_i\ X_i \qquad (12)$$

By stepwise regression, least squares equations were developed for 1948 and 1960 net densities. Two final equations were accepted that were logically sound and contained only statistically significant explanatory variables. The 1948 equation computed was:

$$ln\ D_{N.48} = 1.534 + 0.005X_1 + 0.017X_2 + 0.109X_3 \qquad (13)$$
$$\qquad\qquad (1.92) \qquad (2.12) \qquad (6.62)$$

or,

$$D_{N.48} = (4.64)e^{(0.005X_1+0.017X_2+0.109X_3)}$$

Where,

X_1 = Land value per square foot for 1948.

X_2 = Percentage of developed land in industrial use for 1948.

X_3 = Gross residential density for $1948 = D_{G.48}$

The numbers in parenthesis below each coefficient are the regression t values. Equation 13 was used to estimate the 1948 ring and district net densities by substitution of the appropriate independent variables. The R^2 computed for the rings was 0.802 and for the districts, 0.714.

To test its stability, equation 13 was used as a predictor for 1960, substituting 1960 variables for the 1948 variables. The land value for 1948 (variable X_1) was not replaced because 1960 land value was not available. The R^2's resultant from this prediction were 0.902 and 0.802 for the rings and districts respectively. Solutions to equation 13 were transformed to nonlogarithmic form prior to the calculation of residual errors.

A least squares regression of the general form of equation 12 was then made for the 1960 net ring density distribution. The 1960 least squares equation was:

$$ln\ D_{N.60} = 0.086 + 0.123X_1 + 0.542X_2 \qquad (14)$$
$$\qquad\qquad (6.83) \qquad (8.21)$$

or,

$$D_{N.60} = (1.9)e^{0.123X_1+0.542X_2}$$

Where,

$D_{N.60}$ = Net residential density in 1960.

X_1 = Gross residential density for 1960.

X_2 = Logarithm of net residential density for $1948 = ln\ D_{N.48}$.

The R^2's for the ring and district were 0.805 and 0.832 respectively.

Multiple regression estimates were developed for a nontransformed dependent variable. A stepwise procedure was used to test independent variable combinations and the following equations for 1948 and 1960 were accepted:

$$D_{N.48} = 6.25 + 0.085X_1 + 0.206X_2 + 0.922X_3 \qquad (15)$$
$$\qquad\qquad (4.04) \qquad (2.96) \qquad (6.49)$$

Where,

X_1 = Cost of land per square foot, 1948.

X_2 = Percentage of developed land in industrial use, 1948.

X_3 = Gross residential density, $1948 = D_{G.48}$.

and,

$$D_{N.60} = 1.960 + 0.012X_1 + 0.053X_2 + \qquad (16)$$
$$\qquad\qquad (2.00) \qquad (3.12)$$
$$1.082X_3 + 0.119X_4$$
$$(28.47) \qquad (7.00)$$

X_1 = Cost of land per square foot, 1948.

X_2 = Percentage of developed land in industrial use, 1960.

X_3 = Gross residential density, $1960 = D_{G.60}$.

X_4 = Net residential density, $1948 = D_{N.48}$.

The R^2's for the ring and district were 0.755 and 0.561, respectively, for equation 15. Equation 15 was then used to predict 1960 ring and district densities. The 1960 independent variables were substituted for 1948 independent variables in equation 15 and R^2's of 0.264 and 0.151 were determined. The R^2's for the ring and district were then computed as 0.963 and 0.938, respectively, for equation 16.

The independent variables and the coefficients in equation 15 seem causally related to the 1948 densities being estimated. The positive coefficient of assessed land cost reflects economic supply and demand: as land cost rises, the individual family must buy less land and, consequently, the net density increases (*8*). The positive coefficient of percentage of industrial land probably reflects the tendency for low income families to settle in marginal residential areas often characterized by industrial development. Preliminary calibration of the SPACEC I model by DVRPC resulted in a positive relation between residential density and industrial activity, (*16*), similar to that found in equations 15 and 16. In contrast, Muth (*9*) states that a negative relation exists between net population density and proximity to local industrial centers; he states that a net decline in housing cost occurs because the neighborhood proximating the industrial area is generally undesirable. However, the findings by Muth suggest two explanations for the positive relation shown in equations 15 and 16. First, the advantage of accessibility to transportation in areas of industrial activity causes an increase in housing cost which is high enough to offset the blighting effect of the industrial environment. Second, areas of industrial activity usually remain in the old sections of the city where housing has a higher density than in new and developing residential areas.

Both explanations are partially supported by data in the analysis zone simple correlation matrix. The variables, accessibility to employment and percentage of land in industrial use, exhibit a moderate positive correlation of 0.37 and substantiate the first explanation given in the previous paragraph. The employment accessibility index is a regional measure in which the built-in colinearity in the two variables is not severe. However, recent findings by Lansing (14) show that the urban worker gives only secondary consideration to employment accessibility when selecting a residence. Therefore as the mobility of the urban worker is increased and the work week is shortened, it is unlikely that the advantage of accessibility to employment would be substantial enough to overcome the nuisance of proximate industrial activity. Further, in small sized urban regions accessibility as a factor in residential location is less influential than in large urban areas.

Although no data were available for the age of industrial development in an area, data for the percentage of land not in use were considered a comparable measure. A negative correlation of 0.38 was found for percentage of land not in use and percentage of land in industrial use. This correlation supports the second explanation for a positive correlatioa between net residential density and degree of industrial development. The coefficient of gross residential density in equation 15 shows the strong positive correlation between gross density and net density. As more families locate in an area, increased demand for available land will cause increased land cost and density. The gross residential density equation 16 is the same as equation 15, but a fourth independent variable, net 1948 residential density, is used in equation 16. A large amount of the dwelling unit land stock in 1960 existed in 1948, even though development was significant during this 12-year period. The serial correlation between net density variables for 1948 and 1960 is 0.53, which may be a reflection of general inertia in new residential development. That is, the density pattern in an area influences the density of new residential development so that great contrasts in densities within small geographic areas are not common. The correlation of net density variables for 1948 and 1960 is probably dependent on the amount and rate of development. Further investigation of the correlation would require density data for the dwelling units developed during the study period. Such data were not available for the study reported in this article.

Change in Density Structure

Two density distance gradients for equations 3 and 5, given in figure 7, were fit to the ring gross density data for 1948 and 1960. Two changes in the gross density configuration are shown by the deviation of the two linear gradients. First, gross density consistently increased in each ring. The increase was expected as a result of the 52 percent growth in dwelling units in the study area over the

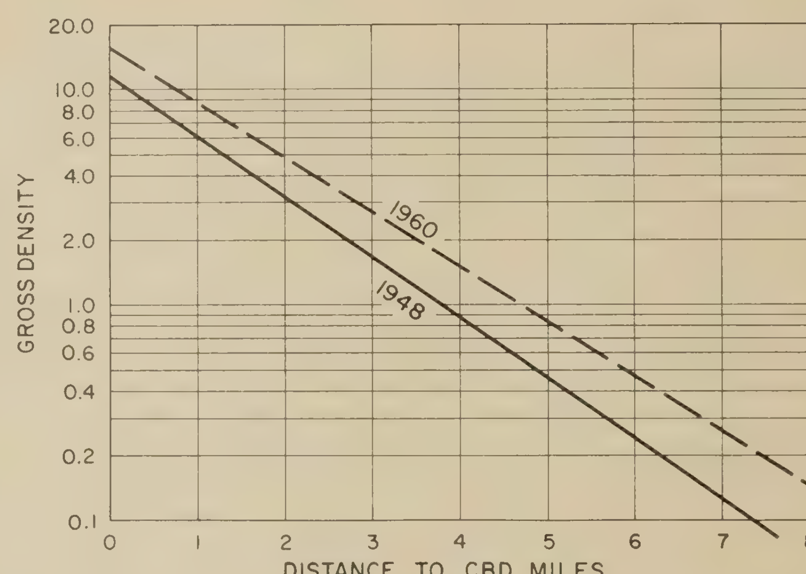


Figure 7.—Calibrated gross density gradients by distance bands for 1948 and 1960.

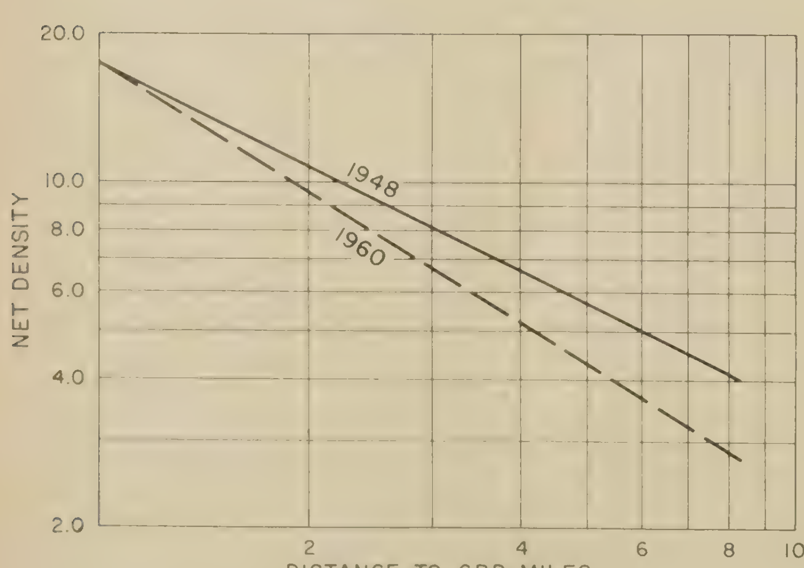


Figure 8.—Calibrated net density gradients by distance bands for 1948 and 1960.

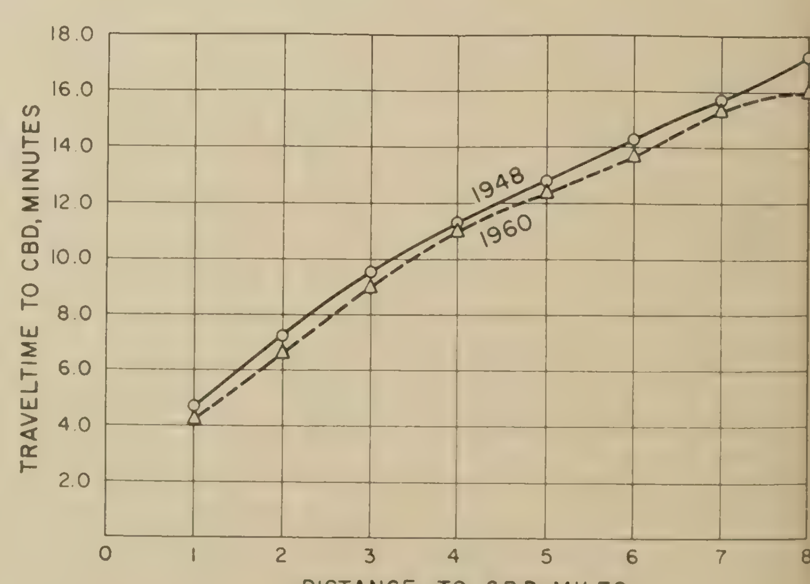


Figure 9.—Traveltimes to the CBD by distance bands for 1948 and 1960.

12-year period. A decline in gross density could only result if the number of dwelling units decreased, and such a decrease is unlikely in a rapidly expanding region. Second, the gross density gradient for 1960 has leveled slightly. The leveling indicates a decrease in population distribution density from 1948 to 1960; the decrease is characteristic of suburban development. Berry, Simmons, and Tennant (15) have observed this leveling situation for Western cities; density gradients tend to decline over time for a given city, and the decline is larger for larger cities.

Net residential density gradients, shown in figure 8, have declined consistently from 1948 to 1960 regardless of distance from the CBD. The decline cannot be explained by absolute population growth; existing market conditions and consumer preferences were influential. Furthermore, a major cause for density decline could be the improvement in transportation service. Figure 9 shows a plot of traveltime to the CBD for each ring for 1948 and 1960. Highway service to the CBD has consistently improved during the 12-year period and, consequently, transportation costs have been reduced. The effects of substantial transportation cost reductions could produce profound shifts in residential patterns owing to possible lower location rents and income effects. Reduced transportation costs would probably result in the use of more living space per household and a decline in net density, as shown in figure 8. However, in spite of continued transportation improvements the decline in net densities is not irreversible; the purchase of additional household space may be halted as the individual households determine that it is no longer to their benefit to acquire more land (*8*). Based on findings by Lansing (*14*) the decline in net residential density can be expected to level. Lansing reports that most households that expressed dissatisfaction with their small lots would prefer to live on lots as large as three-tenths of an acre and that most households that expressed dissatisfaction with lots larger than one-half acre would prefer to live on smaller lots.

Findings

The R^2 entries in table 3 show that the negative exponential formulation, which equates gross density with distance away from the center of the urban area, is an effective measure of the existing gross residential density. Considering that the reported district residual errors are the result of the application of the equation calibrated for the ring, it seems that the intraring variance is relatively minor in comparison with the intraring gross density variability. The negative exponential formulation fitted to the 1948 density distribution was moderately successful as a forecasting device for 1960. The decrease in variance from 1948 to 1960 was 11 percent at the ring and district levels. The distance gradient fit to the 1960 gross density distribution was flatter than that for 1948 and, as shown by the R^2 values, accounted for approximately 11 percent more variance at the ring and district levels. The 1948 gross density distance exponent of 0.648 is probably small for the size of the study area as compared to findings by Muth (*8*).

Results of the net density analysis are contained in table 4. Four procedures were used in the net densities analyses: Distance gradients, multiple regressions with transformed dependent variables, multiple regressions with untransformed dependent variables, and assumed stability of densities. The distance gradients fit to the 1948 net and gross density distributions show significant R^2 at both the ring and district levels. However, accuracy at the district level is substantially less for net density than for gross density analysis. But the stability of the 1948 net density gradient is considerably better than that of the gross density gradient, as shown by the R^2 results when the 1948 density gradient was used to forecast the 1960 density. Explained 1960 ring variance had only a minor decrease and explained district variance increased 10 percent. The increase in district variance undoubtedly reflects the peculiarities possible when linear estimations are forced through nonlinear data by the expedient of logarithmic transformation. The R^2's for the 1960 density gradient were high and almost exactly matched the equivalent gross density gradient. The slope of the net density gradient increased from 1948 to 1960. Overall, the density distance gradient formulations provided comparable accuracy at the district and ring levels for net and gross residential densities, and the 1948 net density gradient was shown to be an accurate predictor of 1960 conditions.

The multiple regression R^2's for the net density distribution are also presented in table 4. Moderate success was achieved in calibration for the 1948 nonlinear formulation of net density. The residual variance was larger for the net density distributions than for the distance gradient at both the ring and district levels, and the explained variance for the ring analysis decreased. But, unexpectedly, the analysis resulted in higher R^2 for forecasts than it did in calibration. Solutions to the 1948 equation with the 1960 independent variables, with the exception of land cost, had less residual error after transformation to linear form than the equation calibrated to the 1960 data. The results in table 4 for the linear regression estimating equation show that the accuracy of the 1948 calibration and forecast is inferior at the district and ring levels to the nonlinear regression and distance gradient formulations although the same independent variables are used in the linear and nonlinear 1948 regressions. However, the calibration R^2's for the 1960 linear regressions are comparable to those for the distance gradient and better than those for the nonlinear regression formulation. The strong serial correlation between 1948 and 1960 net densities probably accounts for the sharp increase in accuracy of the 1960 equation as compared to that for 1948 inasmuch as both equations use the same independent variables, except that the 1948 net density is included in the 1960 equation.

The stability of the net density pattern over the 12-year period explains to a large extent the results obtained when the 1948

Table 3.—Calibration and forecast R^2's for gross density distance gradients

Equation	R^2, 1948		R^2, 1960	
	Ring	District	Ring	District
$D_{G\cdot 48}=11.36e^{-0.648X}$	0.886	0.834	[1] 0.784	[1] 0.743
$D_{G\cdot 60}=15.58e^{-0.585X}$	-----	-----	0.989	0.923

[1] Forecast results.

Table 4.—Calibration and forecast R^2's for net density analysis

Analysis procedure	Model form	1948		1960	
		Ring	District	Ring	District
Distance gradients	$D_{N.48}=(17.3)X^{-.688}$	0.957	0.761	[1] 0.927	[1] 0.844
	$D_{N.60}=(17.4)X^{-.876}$	-----	-----	0.986	0.934
Log linear multiple regression.	$\ln D_{N.48}=1.534+0.005$ Land value $+0.017\%$ Industrial land $+0.109$ Gross density$_{48}$	0.802	0.714	[1] 0.902	[1] 0.820
	$\ln D_{N.60}=0.086+0.123$ Gross density$_{48}$ $+0.542 \ln D_{N.48}$	-----	-----	0.805	0.832
Linear multiple regression.	$D_{N.48}=6.257+0.085$ Land value $+0.206\%$ Industrial land $+0.922$ Gross density$_{48}$	0.755	0.561	[1] 0.264	[1] 0.151
	$D_{N.60}=1.960+0.012$ Land value $+0.053\%$ Industrial land $+1.082$ Gross density$_{60}$ $+0.119\ D_{N.48}$	-----	-----	0.963	0.938
Assumed no change in net densities.	Assume 1960 ring densities same as 1948 ring densities.	-----	-----	[1] 0.849	[1] 0.533
	Assume 1960 district densities same as 1948 district densities.	-----	-----	-----	[1] 0.640

[1] Forecast results.

ring and district densities were assumed to hold for 1960. Considerable net density variability can be explained as a carryover from the base time period. However, only 64 percent of the variance is accounted for when 1960 district densities are assumed to be the same as 1948. The assumption of stability in the density gradient equation was a more accurate forecasting procedure than that of projecting no change in the density distribution. However, by simulating the effects of temporal changes in the urban region, through the use of properly structured regression equations, density variability can be expected to be more accurately explained.

The results given in tables 3 and 4 indicate that the analysis and projection of net residential densities can be made as accurately as for gross density. Success can be expected in forecasting urban net densities by simple distance gradients. Results obtained from the multiple regression equations were somewhat inconsistent; the nonlinear regression equation was superior to the linear equation in calibration to 1948 conditions and in forecasting to 1960, but the linear equation was superior in calibration for 1960. Significant regression equations containing rational explanatory variables can be developed. The addition of a household income measure as a variable in regression equations might contribute to the investigation of urban residential density. However, the income data available for the study reported in this article were census tract medians that were too aggregated to be consistent with the analysis zone level of the other data used in the study.

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(*15*) *Urban Population Densities: Structure and Change*, by Brian J. L. Berry, James W. Simmons, and Robert J. Tennant, Geographical Review, July 1963, pp. 389–405.

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New Publications

(*Continued from p. 241*)

The volume contains information on two types of reinforced concrete retaining walls subject to various loading conditions. The first type is cantilever retaining walls on spread footings designed for four different loading conditions. The walls range from 6 feet to 30 feet in height. Pile foundation alternates were prepared for the first two cases of loading and are suggested for use where materials of adequate strength are too deep for economic use of spread footing design, but where the upper strata around the piles have sufficient strength to provide the required lateral support for the piles. The second type is counterforted retaining walls founded on spread footings designed for two different loading conditions. The walls range from 18 feet to 36 feet in height.

Use of Riprap for Bank Protection

Use of Riprap for Bank Protection, published in June 1967 (40 cents a copy), is No. 11 in the Bureau of Public Roads series of hydraulic engineering circulars. It discusses the design and construction of riprap for bank protection and contains sample specifications for different types of riprap. Information on the design and construction of filter blankets is included.

The principal source of material for this circular is the summary of slope protection methods in Proceedings of the American Society of Civil Engineers, vol. 74, 1948. This source is complemented by more recent research on protecting earth dams particularly the effect of gradation of stone on riprap performance.

Also available from the U.S. Government Printing Office are Hydraulic Engineering Circular No. 5 (1965), *Hydraulic Charts for the Selection of Highway Culverts* (45 cents), and Hydraulic Engineering Circular No. 10 (1965), *Capacity Charts for the Hydraulic Design of Highway Culverts* (65 cents).

ERRATA

In the second installment of the article, *Capacity Analysis Techniques for Design of Signalized Intersections*, which appeared in the October issue of PUBLIC ROADS, *A Journal of Highway Research*, vol. 34, No. 10, three of the illustrations contained errors as noted below.

Figure 17:

- In APPROACH N table, for movement NW under heading CHART REFERENCE—*18-B, -C* should read *17-D, Fig. 9*.
- In APPROACH N table, for movement NE under heading G/C REQ'D—*0.21* should read *0.17*
- In APPROACH W table, for movement WN under heading CHART REFERENCE—*18-B, -C* should read *17-B, -E*.
- In APPROACH E table, under heading REMARKS—$D_a=225$ should read $D_a=275$.

Figure 19:

- On Ramp D—*520* should read *540*.

Figure 22:

- Table titles *DE-FG* should read *EF-GH* (2 places).
- In table INTERSECTION *EF-GH*, AM PEAK, under heading APPROACH OR MOVEMENT—*EE* should read *EF*.

Figure 26:

- In table INTERSECTION *EF-GH*, PM PEAK, under heading POSSIBLE CAPACITY—*870* should read *1400*.

U.S. GOVERNMENT PRINTING OFFICE: 1967

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A list of the more important articles in PUBLIC ROADS *and title sheets for volumes 24–33 are available upon request addressed to Bureau of Public Roads, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. 20591.*

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REPORTS TO CONGRESS

Federal Role in Highway Safety, House Document No. 93 (1959). 60 cents.
Highway Beautification Program. Senate Document No. 6, 90th Cong., 1st sess. (1967). 25 cents.
Highway Cost Allocation Study:
Supplementary Report, House Document No. 124 (1965). $1.00.
Maximum Desirable Dimensions and Weights of Vehicles Operated on the Federal-Aid Systems, House Document No. 354 (1964). 45 cents.
The 1965 Interstate System Cost Estimate, House Document No. 42 (1965). 20 cents.

PUBLICATIONS

A Quarter Century of Financing Municipal Highways, 1937–61. $1.00.
Accidents on Main Rural Highways—Related to Speed, Driver, and Vehicle (1964). 35 cents.
Aggregate Gradation for Highways: Simplification, Standardization, and Uniform Application, and A New Graphical Evaluation Chart (1962). 25 cents.
America's Lifelines—Federal Aid for Highways (1966). 20 cents.
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Highway Transportation Criteria in Zoning Law *and* Police Power and Planning Controls for Arterial Streets (1960). 35 cents.
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Standard Traffic Control Signs Chart (as defined in the Manual on Uniform Traffic Control Devices for Streets and Highways) 22 x 34, 20 cents—100 for $15.00. 11 x 17, 10 cents—100 for $5.00.
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