

the state highway system, and I feel that a primary step in any program to assure the future of Indiana roads should include a more thorough study of highway financing from the viewpoint of giving the motorist the best system of roads for what he is willing to pay.

There are many other suggestions that I might make as to the future of Indiana's roads, and doubtless there are many of you who could make valuable additions to those I have outlined. Possibly this discussion will inspire in some way the attainment of the common purpose that we all have—the best possible system of roads, now and in the future as well.

I realize that I could have stood before you this afternoon and sketched for the future of Indiana roads a vision of multiple-lane highways with all the refinements that an unrestrained fancy could conceive. But road-building is practical first, and we who are engaged in the building and maintaining of roads can not overlook our present problems or those of the immediate future.

PAVEMENT DESIGN

C. N. Conner,
Senior Highway Design Engineer,
Public Roads Administration,
Washington, D. C.

For many years highway designers have endeavored to build more and better pavements at the lowest possible cost. Their efforts in that regard have been directed largely toward the structural design of the pavement, including such essentials as character and proportioning of aggregates, amount and distribution of wheel loads, pavement thickness, and the general economy of the structure. That properly is classed as structural design.

With increasing emphasis being placed on highway safety throughout the country, designers have undertaken, as their part, the development of basic data on which to modernize and develop design principles that will promote maximum safety of traffic, a greater utility of highways, that is, a better operating service. The fact has been established and is now generally accepted that there is no real economy in highway design until or unless roads can be traveled at reasonably fast speeds in comfort and safety. Designing for speed with safety is known by the new term "geometric design" because it has to do with the visible dimensions of the highway. Of particular interest in pavement design are width of pavement and number of lanes as related to traffic behavior.

The purpose of this paper is to summarize important facts and trends that have been developed in both the structural and geometric design of pavements and how these developments came about. To cover this rather wide field with rea-

sonable completeness, some subjects must be discussed briefly and others at considerable length. Specifically, then, this paper concerns the dimensional design of one-, two-, three-, and four-lane highways, and quite briefly the structural design of flexible- and rigid-type pavements.

HIGHWAY CLASSIFICATION BASED ON SERVICES RENDERED

A proper classification of highways should be based on the services to be expected of the particular roads under consideration. Such services include, among others, traffic density, character of traffic, its speed, weight of vehicles, and the general safety and facility of travel conditions. The traffic capacity of the highway is defined as the maximum traffic density that will permit vehicles to travel at the assumed design-speed without appreciable delay. Speed has an extremely important bearing on design and must be considered if safety is to be built into the highway. The assumed design-speed of a highway is considered to be the maximum approximately uniform speed that probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones. The assumed design-speeds should, therefore, indicate the speed at which traffic may travel under fair conditions with a reasonable margin of safety. Speed classifications of 30, 40, 50, 60, and 70 miles per hour have been approved by the American Association of State Highway Officials for design purposes. Each classification is indicated by two figures and a letter. For example, the classification 1000 M 50 indicates a highway on which a mixed vehicular traffic of 1,000 vehicles per hour can be accommodated at a speed of 50 miles per hour; 600 T 30 indicates a highway on which 600 vehicles per hour, of which a considerable percentage are trucks, can be accommodated at a speed of 30 miles per hour. Likewise, a 3000 P 50 classification indicates a highway capable of accommodating about 3,000 passenger cars per hour at a speed of 50 miles per hour.

TRAFFIC BEHAVIOR INDICATES PROPER WIDTH OF LANES

The Public Roads Administration, after making a study of passing vehicles on two-lane highways, concluded that pavements of 18-foot width are too narrow for modern passenger cars alone or for mixed traffic. Pavements of 20-foot width were found to be reasonably adequate for light-traffic roads used infrequently by light trucks, but inadequate for mixed traffic, and that further increases in speed tend to make necessary widths greater than 22 feet. A number of states already are using widths greater than 24 feet for two-lane traffic.

Highways at least two lanes wide should be provided where traffic density is greater than five vehicles per hour, and the

suggested minimum width of surfacing for such two-lane highways is indicated in the following table:

MINIMUM WIDTH OF SURFACING FOR TWO-LANE HIGHWAYS
TRAFFIC DENSITY CLASSIFICATION

Assumed design-speed m.p.h.	5 to 30 per hour			30 to 100 per hour			100 to 200 per hour			Greater than 200 per hour		
	Type of Traffic											
	P	M	T	P	M	T	P	M	T	P	M	T
30†	16*	18	20	18	18	20	20	20	20	22*	22*	22*
40	16	18	20	18	18	20	20	20	22*	22*	22*	22*
50	18	18	20	20	20	20	20	22	22	22	22	24*
60	20	20	20	20	20	22*	22	22	22	22	22	24*
70	20	20	20	20	22	22	22	22	24	24*	24*	24

A study of the table indicates the minimum width of 16 feet for very light traffic of not over 5 to 30 vehicles per hour and the relatively low travel-speed of 30 miles per hour, and ranges to a maximum of 24 feet where traffic is greater than 200 vehicles per hour, truck traffic seriously impedes the smooth operation, and the speed of travel is 50 miles or more per hour, and 24 feet also for passenger and mixed traffic traveling at 70 miles per hour.

Where three-lane pavements are used, all traffic lanes should be at least 11 feet in width. Where the highway is designed for speeds of 60 or 70 miles per hour or where truck traffic is a serious problem and design-speeds are 50 or more miles per hour, the total width should be 34 to 36 feet based on a design using one or more 12-foot lanes with the center lane of contrasting color.

For four-lane divided highways the importance of the road will justify a total width of pavement for each roadway of not less than 23 feet and preferably 24 feet.

TRAFFIC VOLUME INDICATES NUMBER OF LANES

One-lane pavements are generally considered a first step in the development of a two-lane highway. When used, it is generally advisable to construct the single lane with its inner edge along the center line of the graded roadway. Single-lane surfaces should be provided only on highways classified for a traffic density of not more than 5 vehicles per hour or

* Where shoulders flush with the pavement and capable of supporting vehicles at all times are provided, pavements 2 feet less in width may be used.

† Where topographic conditions force a design-speed of less than 30 miles per hour, a 14-foot minimum width of surfacing may be considered.



Fig. 1. A two-lane pavement carrying a procession of slow-moving vehicles on a long upgrade headed by a truck and trailer unable to climb the grade at normal driving speed.

approximately 50 vehicles per day, and the width of the pavement should be not less than 10 feet.

Two-lane pavements constitute at the present time about 97 per cent of the state highway systems and they are likely to comprise not less than 90 per cent of those systems for many years to come. In general, no highway should provide less than two traffic lanes for normal travel. Studies of the movement of many types of vehicles in many sections of the country have been made co-operatively by the Public Roads Administration and the state highway departments. As a result of these studies it is believed that a load of 400 vehicles per hour about evenly divided in each direction is a safe maximum for a two-lane road to carry without inconvenience some time during the year. Stated another way, pavements more than two lanes wide should be provided where traffic exceeds about 4,000 vehicles per maximum day. The average daily traffic for any month varies considerably from the average on a yearly basis, and traffic also varies from day to day during any one week. Average figures, therefore, do not truly indicate the necessary width of pavements, and such widths must be based on the maximum estimated traffic that will use the road at peak periods throughout the year.

A three-lane highway for safe usage should have very good sight distances at almost all sections to permit passing at high speed; otherwise a four-lane highway preferably should be constructed. The outside lanes preferably should contrast in texture and color with the inside lane, and both surfaces should be equally skid resistant. Usual practice calls for portland cement concrete in outer lanes and bituminous surface for the middle lane, sometimes of a lower-cost type.



Fig. 2. A three-lane highway should have good sight distances with traffic lanes of contrasting colors and should be considered as a temporary expedient in an ultimate four-lane development.

Opinion is sharply divided as to the wisdom of three-lane construction. The design capacity of a three-lane highway is approximately 75 to 100 per cent greater than the capacity of a two-lane highway, but this figure varies considerably. Some believe that the capacity of the three-lane highway is about 50 to 70 per cent of the capacity of a four-lane undivided highway for traffic traveling at the same speed on each. It is believed by some who have observed the operation of three-



Fig. 3. Sight distances are inadequate on this three-lane road; however, the lane markings serve to reduce hazards.

lane highways that, as traffic increases, the hazards increase in a greater ratio than in the case of two-lane or four-lane undivided highways. We conclude, therefore, that in general three-lane pavements, if used, should be considered only as a part of a program of progressive development from an initial two- or three-lane construction to an ultimate four-lane divided construction.

The increase of speed of motor vehicle traffic during recent years has called attention to the importance of lane marking, with the result that most states have developed some system of pavement striping or signing to warn traffic against encroachment upon the lane of opposing traffic within no-passing zones. This practice has resulted in safer driving in spite of

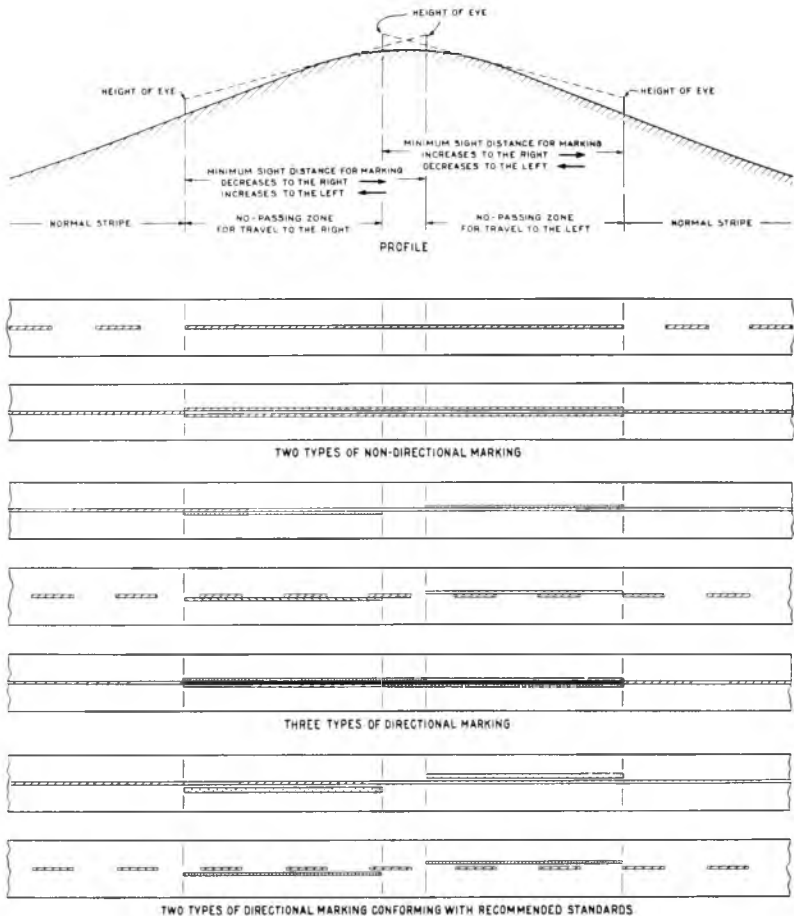


Fig. 4. Typical lane markings and recommended standards.

widely varying methods of marking used by the states. Very recently highway engineers have become convinced that the nation-wide adoption of rational uniform standards and marking of no-passing zones is desirable. As a result, the Public Roads Administration and other highway organizations have investigated and reported on this subject at recent meetings of the American Association of State Highway Officials and the Highway Research Board. A summary of their findings is published in the December, 1939, issue of *Public Roads*, the journal of highway research published by the Administration.

Undivided four-lane pavements carrying traffic in both directions have been considered safer than two- and three-lane highways despite statistics of the Michigan State Highway Department, which indicate that the number of accidents per million vehicle miles on four-lane undivided highways is greater than on three-lane highways. The traffic capacity of the undivided four-lane highway is probably greater than four times the capacity of a two-lane highway for vehicles of similar type and same rates of speed. They are universally conceded to be more hazardous than four-lane divided highways.

DIVIDED FOUR-LANE HIGHWAYS RECOMMENDED FOR HEAVY TRAFFIC

When traffic is sufficient in volume to require the use of four traffic lanes, the physical separation of traffic moving in opposite directions should be provided to reduce hazards and facilitate the free flow of traffic. Except in urban areas, the use of four-lane or six-lane undivided highways is undesirable, largely because of head-on and side-swiping collisions. Properly divided, they provide a sense of freedom and safety from opposing traffic that results in a faster and smoother operation than any other type of design. Figures show that the same freedom of movement possible on a two-lane pavement with a total hourly volume of 400 vehicles, 200 in each direction, will be found on a four-lane divided pavement with an hourly volume of 2600 vehicles, 1300 in each direction.

To determine the effectiveness of converting a four-lane undivided highway into a four-lane divided type, the New Jersey State Highway Department recently undertook before-and-after accident surveys on State Road 26 (U. S. 1). As reported in December, 1939, to the Highway Research Board by Traffic Engineer Vey, they found a decrease in accident severity after the conversion as follows: fatal accidents reduced 83.3 per cent; non-fatal injuries reduced 48.5 per cent; property damage reduced 17.6 per cent; and all accidents reduced 40.4 per cent.



Fig. 5. A four-lane divided highway with narrow, raised, and paved median strip four to six feet wide.

MEDIAN OR DIVIDING STRIPS

At the present time practically all highway designers agree on the basic principle that four-lane highways should be separated by a dividing strip of appreciable width. However, practice varies considerably as to profile, widths, lengths, and materials used in their construction. Points for consideration are design of strips at intersections, between intersections, over bridges, under bridges, in urban areas, and in rural areas, as well as the type and dimensions of vehicles



Fig. 6. A four-lane divided highway with planted median strip and sloping curbs, ten to twelve feet wide.

to be accommodated. These matters have all been given careful study in "A Policy on Highway Types," now under consideration by the American Association of State Highway Officials and the Public Roads Administration.

To be adequate, the design of median strips should accommodate all vehicles likely to use the highway. Dimensions and turning radii of vehicles have been analyzed to determine dimensions for vehicles which should be used in design. The characteristics of the design truck have been further checked against dimensions measured by the state-wide highway planning surveys. The design passenger vehicle has an over-all length of 19 feet, an over-all width of 6 feet, and a minimum turning radius of the outer front wheel of 28 feet. The design truck has an over-all length of 30 feet, an over-all width of 8 feet, and a minimum turning radius of the outer front wheel of 45 feet. Intersection lay-outs that accommodate these vehicles will accommodate substantially all vehicles except tractor-trailer combinations. Design vehicles, their paths and overhang, are shown in Fig. 8.

At intersections at grade, the median strip dividing opposing traffic should be opened up and designed to accommodate the expected traffic that turns and crosses at these points. The width of the median strip combined with the length of opening should safely accommodate vehicles making left turns to and from the inside lanes of the divided highway and should, if possible and feasible, accommodate U-turns. Unnecessarily long openings encourage promiscuous driving and should be avoided. The desirable width of median strip at highway grade crossings is at least 25 feet for P or passenger



Fig. 7. The Mount Vernon Boulevard with artistic grade separation structure is an excellent example of divided-lane construction.

type of traffic, 32 feet for the M or mixed type of traffic, and 43 feet for the T or truck type of traffic. These widths, when combined with proper lengths of opening, provide full protection for all crossings and all left-turning vehicles, and accommodate nearly all U-turning vehicles.

The proper lengths of opening in combination with these widths are 67 feet, 98 feet, and 87 feet, respectively. Compromise shorter lengths may be considered. Where the desirable width of median strip cannot be obtained, its width may be reduced to 19 feet for P traffic and 30 feet for M and T traffic without a material sacrifice in the protective features for crossing and left-turning traffic. In this case the proper lengths become 73 feet and 100 feet, respectively, with pos-

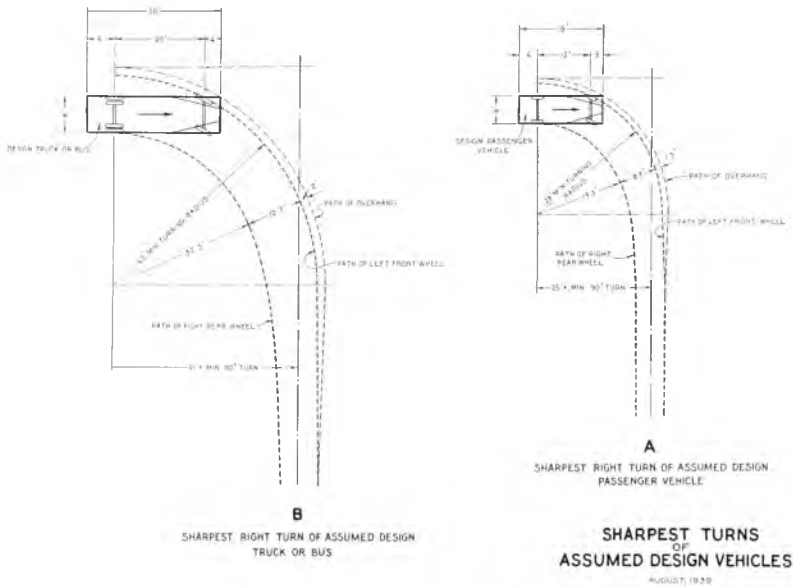


Fig. 8. Passenger vehicle and truck or bus assumed for design purposes by American Association of State Highway Officials.

sible compromise lengths of 56 feet and 80 feet. Although widths of median strips of less than 19 feet for passenger traffic and 30 feet for truck traffic will not afford full protection for cross traffic at grade in area between median strips, these narrow widths in combination with proper lengths of median openings may be utilized to afford full protection for left-turning movements. Median strips at intersections and openings generally are constructed with semicircular ends, and this shape is practical to construct, pleasing in appearance, and fairly satisfactory.

At points between intersections, the width of the median strip may be governed by topography, available right-of-way, construction costs, and maintenance costs. In general, the median strip should be as wide as can be used advantageously. When the median strip is restricted by right-of-way, every effort should be made to construct it at least 10 to 12 feet in width because of the difficulty of maintaining plant growth on narrow strips. Paved median strips encourage encroachment even where curbs are provided, particularly by vehicles left turning to and from adjoining property. They also encourage parking. It is desirable, therefore, to limit the width of median strips to not more than 6 feet if a 10 to 12 foot width for plant growth cannot be provided. Median strips less than four feet in width should not be considered as dividing highways. When flush with adjoining pavement surfaces, they are in effect a wide and effective center line marker. The color of the surfacing of narrow strips should contrast sharply with that of the traffic lanes and have a surface texture readily discernible to the eye and ear of the driver.

The median strip need not be of constant width and the two pavements separated by it need not be at the same level. It may be necessary to change the distance between paved roadways at definite locations, such as on long bridges where for economical reasons it may be necessary to reduce widths to 4 or 6 feet. Four-lane, undivided highways and those flush with median strips paved to the general level of the adjoining traffic lanes are treated like two- and three-lane highways with respect to crown and superelevation. The highest point of crown is at the center, and the road drains to both sides.



Fig. 9. The median strip need not be of constant width, and the separated pavements need not be at the same elevation or have the same curvature.

Four-lane divided highways with wide median strips covered with vegetation should be treated like two independent two-lane roads, each two-lane roadway draining to both edges and each being independently superelevated. Where construction, as at grade separations, makes it desirable to narrow the median strip on tangents, then it should be effected by reverse curves of one degree or less.

Curbs intended to prevent vehicles from leaving the pavement should be nearly vertical and at least 2 feet from the pavement edge. At all other places curbs, when used, should be low with flat slopes readily mounted in emergencies. All curbs should be highly visible at all times.



Fig. 10. Illustrating construction of high-visibility fluted curbs with flat slopes on narrow median strips.

ULTIMATE WIDENING OF INITIAL IMPROVEMENT IS FEASIBLE

Most of the foregoing statements refer directly to designs for new construction. However, the possible conversion by reconstruction of existing unsafe highways into relatively safe highways is frequently feasible and desirable. Moreover, an initial improvement may be so laid out as to make later widening by stage construction desirable. Following are some of the possibilities to be considered:

1. Where the ultimate development is a three-lane highway, the initial two-lane width should occupy two adjacent lanes of the ultimate development.
2. Where the ultimate development is a four-lane divided highway, the initial two-lane width should form one of the ultimate one-way-width pavements.

3. In urban areas where the ultimate development is a four-lane highway divided by a median strip flush with the pavement, about four feet wide, the initial construction may consist of the two inside traffic lanes and the median strip.

4. Where the ultimate development is a four-lane divided highway with a median strip of width greater than one lane, the initial three-lane construction should consist of one one-way pavement and one additional lane of the same surface texture, which may or may not be removed at the time of the ultimate development.

5. Where the ultimate development is a four-lane divided highway with a dividing strip one lane in width, the initial three-lane construction should consist of inside lanes of both future one-way pavements and the future median strip. The middle lane preferably should be paved with a material of contrasting color and texture but of equal rideability with that of the outside lanes. If possible, the materials should be such that they can be removed readily in order to be replaced with topsoil upon the progressing to four lanes.

6. Where the ultimate development is a four-lane divided highway with a median strip 4 to 6 feet in width, the initial construction should consist of two lanes of one of the ultimate one-way pavements and a third lane adjacent thereto.

Trend in Crown of Pavement Shows Little Change in Recent Years. High-type pavements have a lower rate of crown than low-type pavements. There has been little change in either since 1936 when most high-type pavements under state control were constructed with a crown of 1/8-inch per foot and low types with a crown of 1/4-inch per foot.

Amount of Superelevation Is Limited by Low Speeds. Superelevation must be limited for practical reasons. When traveling around a curve at low speed, large superelevation results in a tendency for the vehicle to slide down the slope because centrifugal force is negligible. The amount of friction developed will resist sliding, but field tests indicate that when ice is encountered the maximum frictional resistance that may be developed before sliding occurs is 1/10 the weight of the vehicle. A superelevation of 1/10 of a foot per foot of pavement or approximately 1 1/4 inches is the maximum desirable rate. In some cases as much as 1 1/2 inches may be used for surfaces high in skid-resistance where frost and ice do not occur.

Because of practical limits to the amount of superelevation, it is not possible to compensate fully for centrifugal force on sharp curves, and it becomes necessary to rely upon friction in addition to superelevation in order to prevent a

vehicle from sliding outward on a curve. Using a maximum superelevation slope of 1/10 and a maximum safe factor for friction resistance of .16, designating the rate of superelevation as S, the friction factor as F, and the radius of curvature as R, the formula becomes

$$S + F = .26 + \frac{.067V^2}{R}$$

where V = miles per hour. The maximum safe radius, therefore, equals $0.258V^2$. For speeds of 30, 40, 50, and 60 miles per hour curves with radii less than 232 feet, 412 feet, 644 feet, and 928 feet, respectively, should not be used. These correspond roughly to curves of 25, 14, 9, and 6 degrees, respectively. For speeds higher than 60 miles per hour, friction factors less than 0.16 should be used.

It is suggested that superelevation be designed for 3/4 of the assumed design used for other pavement features. By so doing, slow-moving vehicles would be aided and the faster-moving vehicles would not be inconvenienced.

Transition Curves Promote Speed with Safety. Drivers cut corners on curves without transitions because of a natural desire to soften the shock of changing direction from tangent to curve and curve to tangent. It is also difficult to maintain a maximum uniform speed and hold to the proper traffic lane where transition curves are not used. Consequently, transitions should be used for all except extremely flat curves to aid the driver and to provide a smoother-riding pavement.

The use of transition curves is growing, and it is reasonable to believe that all curves on the most important highways planned for construction or reconstruction will be so designed. Simple and usable calculations for transition curves for highways have been prepared in great detail and accuracy by the Public Roads Administration. The book containing them, entitled *Transition Curves for Highways*, may be obtained from the Superintendent of Documents for the nominal price of 60 cents.

High Speeds Call for Widening of Pavements on Curves. Pavements on sharp curves are widened to allow for the extra width occupied by a single vehicle or tractor with trailer and because of the difficulty of driving in the center of an unwidened traveled lane. Present practice regarding the degree of curve below which no widening is required varies between 5 and 8 degrees. A formula for widening originally developed and recommended by the American Association of State Highway Officials has been modified for modern speeds and conditions. With this formula as a basis, it has been suggested that no pavement requiring less than two feet of

widening be widened. This results in no widening on two-lane pavements on curves flatter than

- 4 degrees for speeds of 70 miles per hour,
- 5 degrees for speeds of 60 miles per hour,
- 6 degrees for speeds of 50 miles per hour,
- 7 degrees for speeds of 40 miles per hour, and
- 8 degrees for speeds of 30 miles per hour.

Under existing practice widening is on the inside of the curve. However, where curves have been properly transitioned, widening may be divided equally on both sides of the normal center line of the pavement.

Pavements Should Be as Glare-proof as Possible. The glare of approaching headlights on wet pavements constitutes a hazard that may be considerably reduced by using a proper type of pavement texture. Investigations have shown that smooth-textured pavements reflect more light and consequently are more glaring than rough-textured surfaces. Moreover, both smooth- and rough-textured surfaces have a film of water on them during rains, which greatly increases glare. Very recent observations on pavements in Oregon showed that smooth-textured pavement surfaces reflected 20 times as much light when wet as when dry. Apparently, the remedy is to construct rough-textured surfaces, such as the transversely-broomed or ribbed-concrete pavements, open-type bituminous-concrete, and bituminous-macadam surfaces, provided, of course, that the bituminous surfaces are well sealed and non-porous.

Proper Pavement Texture Reduces Skidding. Investigations by Moyer and his associates indicate that skid-resistance can be provided in road surfaces of any type, and that the greater hazard caused by snow, ice, and mud can be materially reduced by proper maintenance methods. Many surfaces in wet condition were found in Moyer's tests to be almost as safe as the same surfaces in dry condition, but the tests indicated that there is a large mileage of surfaces in the United States still dangerously slippery when wet. While many skidding accidents are probably caused by driving at excessive speed, it is quite probable that many occur at slow speeds and normal speeds on surfaces having low friction between tire and pavement. No road surface should be so slippery that skidding of the vehicle can occur when it is operated in a reasonable and proper manner. Investigations have shown that the margin of safety for high-speed driving is small even on dry surfaces having high coefficients of friction.

Friction between vehicle tires and the road surface, if high enough, will prevent skidding, and practically all surfaces when dry will develop sufficient friction to prevent

dangerous skidding. It appears that pavements with a coarse sandpaper or slightly rough texture are more skid-resistant than those having a rough knotty texture.

For several years the Committee on Antiskid Properties of Pavements of the Highway Research Board, George Martin, Chairman, has advocated the routine use of a machine similar to the one used by Moyer for testing the skid-resistance of pavements by state highway departments, municipalities, and other organizations in charge of highways. Comparative data such as can be obtained by research of that character are badly needed.

STRUCTURAL DESIGN

Since about 1915, designers and researchers have been developing facts on which to base the shape and thickness of the pavement cross-section. Progress has been slow, and rational analyses have been involved, complicated, and full of inherent intangibles not readily understood by the practicing highway engineer. Instead of involved theory, he asks for a simple solution to his problem and is inclined to pay scant attention to theoretical analyses.

LOADS AND THEIR DISTRIBUTION

Numerous formulas have been developed to determine pavement thickness. For flexible-type surfaces such formulas are largely empirical and are based on experimentation. They show a bell-shaped distribution of a wheel load passing through the pavement to the subgrade in such a manner that the pavement will not be broken or the bearing power of the subgrade exceeded.

Formulas for rigid-type surfaces are based on three positions of a wheel load and an assumed bearing power of subgrade. Because of their greater rigidity and stiffness, rigid pavements develop greater beam action than the flexible pavements and spread wheel loads over a greater area of subgrade. Consequently, unit pressures on subgrades under rigid types are smaller than under flexible-type surfaces.

Experimentation and theoretical analysis show that a single wheel load causes critical stress in all types of pavement, and that neither the axle load, axle spacing, or gross weight of vehicles produces critical stress.

SUBGRADE DATA ESSENTIAL

Regardless of the type of pavement under consideration, a knowledge of the bearing power of the subgrade is of first importance. If the natural subgrade soil cannot be maintained under varying climatic and moisture conditions so as

to have a uniform and known bearing power to support the pavement, it should be removed and replaced with granular soil selected for its uniformity and stability. Where the subgrade is found by investigation to be poor and no local materials in a natural state are available at a reasonably low cost, the subgrade should be stabilized by well-known artificial means, such as the addition of properly proportioned granular material and soil binder or one of several types of commercial binder like portland cement, asphalt, tar, calcium chloride, or other salt, or the base course should be thickened.

The Rational Design of Flexible-Type Surfaces Is Complicated. The general problem of flexible-pavement design is one of wide scope and great complexity. It also is of great importance. An early solution is not anticipated, but appreciable progress can be expected. A number of formulas have been devised for determining thickness of flexible-type surfaces. The principal ones were developed by the Massachusetts State Highway Department, Harger and Bonney, Downs, Gray, and more recently, by Housel, Hawthorne, Nevitt, and Pope. Gray's formula is probably as well known as any and is given here to indicate the type of formula being developed by researchers on this subject.

$$\text{Minimum thickness } t = 0.564 \sqrt{\frac{W}{S}} - e$$

Where W = wheel load in pounds
 S = subgrade resistance in pounds
 per square inch
 e = radius of tire area contact.

In an excellent report published in *Public Roads* for January, 1938, A. C. Benkleman, Associate Research Specialist of the Public Roads Administration, has digested and discussed substantially all published material pertinent to the analytical design of flexible pavements. The report is written in simple and straightforward language and is particularly recommended to those desiring to study flexible designs from a technical viewpoint.

Flexible-Pavement Designs Are Based on Judgment and Experience. As indicated, pavement thickness should be designed to be consistent with the expected wheel loads and the bearing power of the subgrade. Economy in design can be obtained either by varying the pavement thickness according to natural subgrade support or by increasing the subgrade resistance. Macadam and stone bases are used

under all types of bituminous surfaces, but particularly under penetration macadam and the cold-laid type of mixtures. The lower-cost bases, such as sand clay, gravel, and limerock, are usually covered with heavy surface treatments or one of the mixed-in-place types. Bituminous base courses are commonly constructed three or four inches in thickness and gravel or stone base courses five or six inches in thickness. Wherever traffic indicates, bases are constructed to a greater thickness in two or more courses.

Having then constructed a subgrade of uniform bearing and a base course of sufficient thickness and regularity, the base course is next primed with from 3/10 to 4/10 of a gallon per square yard of suitable tar or asphalt. Following the application of this primer, the surface may be covered with one of three well-known types of bituminous surfacing called the surface-treatment type, the road-mixed type, and the plant-mixed type. The surface-treatment type consists of successive applications of tar or asphalt, each covered with crushed stone and stone chips, gravel, or slag, which, when spread and rolled, form a surface from 1/2 to 1 inch in thickness. The road-mix type consists of similar aggregates spread on the base course, covered with tar or asphalt, and mixed in place on the road by commercially-available equipment and finally rolled. It has a compacted thickness generally of from 1 1/2 to 3 inches. The plant-mixed type consists of stone or gravel and tar or asphalt, sometimes with the addition of sand and filler, thoroughly mixed in a plant in the vicinity of a road or at some distance from the road. This mixture is hauled to the road, spread on the primed base course, and then rolled to a compacted thickness of about two inches. It commonly is laid in two courses when thicker than two inches. The surface-treatment type costs from 15 cents to about 30 cents per square yard; the road-mix type from 30 cents to about 45 cents per square yard; and the plant-mixed type from 40 cents to about 60 cents per square yard. Bituminous-penetration macadam, using either tar or asphalt and crushed stone, is a very satisfactory type of surfacing when laid on substantial gravel or stone base courses. It is generally laid to a compacted thickness of 2 1/2 inches and costs about 50 to 70 cents per square yard.

Design Standards for Rigid Pavements Are Reasonably Adequate. The shape of cross-section and thickness of rigid-type pavements are based on observations of pavements in service under fairly well-known conditions of soil, climate, and traffic and, to a lesser extent, on controlled field tests and formulas. Only concrete pavements are considered in the following discussion.

The corner formula originally suggested by Goldbeck in 1919 has been found to give stresses under wheel loads con-

siderably higher than actual stresses in pavement slabs under service conditions. The stress analyses of Westergaard, with the modification suggested by Public Roads Administration tests, are suitable for use in the design of concrete pavement slabs and form the only adequate basis for such design. Because the physical characteristics of natural subgrades and of the concrete can never be foretold to a certainty, it is desirable to be conservative in the selection of values to be used in these formulas. However, if the subgrade is improved to have a known and constant bearing value, the reliability of results will be increased. Although the Westergaard formulas are based on a slab of uniform thickness with load applied at three specified points, present practice in most states calls for slabs with thickened edges, largely because of the results of the Bates Road Tests and service records.

Some concrete pavements already built may be stronger than necessary for the traffic they are carrying and the subgrade on which they rest. It is probable, also, that most modern pavements have sufficient strength for a balanced design or are stronger than necessary. For normally heavily traveled rural highways common practice in concrete pavement design calls for a section 9 inches thick at the edges and 6 inches thick at the center; or a 9-7-9 section may be used depending on joint construction; for heavy duty pavements 10 inches at edges and 7 inches at the center; on subgrades of high supporting value and uniformity carrying reasonably heavy traffic, 8-inch thickened edges and 5 1/2 inches at center may be used; but in no case do designing engineers approve sections less than 7 inches at edges and 5 inches at center.

EXPANSION AND CONTRACTION CAUSE GREATEST STRESSES

Probably the greatest and most important stresses in concrete pavements are those resulting from expansion and contraction due to changes in temperature and moisture in the atmosphere, the subgrade, and the pavement itself. Concrete surfaces, therefore, should be divided longitudinally and transversely into sections by joints of approved design that will transfer loads between adjacent slabs and hold the surfaces in line. Joints in concrete surfaces should be so designed and so spaced as to permit the entire surface to expand, contract, and warp with a minimum of restraint. The essential requirements of an expansion joint are that it shall provide sufficient expansion space, prevent the infiltration of inert materials that make the openings ineffective, prevent the passage of water when the surface is constructed on certain soils, provide the load transfer across the joint, be easy to install, be reasonable in cost, and have a reasonably long life expectancy.

STEEL REINFORCEMENT DESIRABLE

In recent years steel reinforcement composed of members having a relatively small cross-section and closely spaced has been used in concrete pavements by highway designers to reduce and prevent extensive cracking of pavements during the setting-up period and later to hold together cracks that may develop, as well as to keep surfaces already cracked in an even plane. Steel reinforcement in pavements is not designed with respect to tension and flexure as we commonly consider reinforced concrete structures to be. Substantially all designs utilize a single layer of well-distributed reinforcement consisting of comparatively small wires or bars, closely spaced to prevent opening or widening of cracks. Experience has shown that large members widely spaced are not as effective.

Warping stresses due to changes in temperature and moisture within a slab may set up stresses as great as those caused by wheel loads. These stresses, when acting together, may become serious and result in cracking, spalling, and blow-ups. Heavy wheel loads will search out these weak sections and batter them to pieces unless the pavement is properly designed. A complete discussion of the application of results of research to the structural design of concrete pavements by E. F. Kelley, Chief, Division of Tests, Public Roads Administration, is published in *Public Roads* for July and August, 1939.

Most designers know that longitudinal joints satisfactorily control longitudinal cracking and that adequate steel reinforcement reduces the width of cracks to a harmless minimum. However, there is a relatively wide divergence of opinion as to the proper spacing of transverse joints, their design, and the type and number of load transfer devices to use in contraction and in expansion joints.

We are still in the transitory stage of joint development, and a recent survey by the Portland Cement Association indicates that there is more interest at the present time in research projects relating to jointing pavements than in any other phase of concrete-pavement design. Let us hope that the next five years will furnish definite conclusions on the life expectancy and proper functioning of the different joint devices now being used, and that spacing, design, and installation of joints will become simplified and standardized for the various conditions of soil, climate, and traffic. We have succeeded in simplifying and standardizing other features of concrete-pavement design, such as mixtures and cross-sections; and it is reasonable to expect with confidence that we can do the same with the joint problem.



Fig. 11. There is great need for express highways cut directly into and through cities. This sketch shows how it may be done.

CONCLUSIONS

As a result of 25 years of research and experience, highway engineers have mastered the details of the structural design of pavements. They can point with pride to the endurance and smoothness of highways designed and built to their plans and specifications. Radical changes in structural design, therefore, are not to be expected. On the other hand, geometric design is quite another matter. A determined and united attack on that problem has been in progress for three years only. However, remarkable results have been attained, and special credit is due the state-wide highway planning surveys and the Special Committee on Design Policies of the American Association of State Highway Officials. Their findings, which have been used extensively in this paper, are likely to become the basis for the superior design standards needed to modernize old roads and insure maximum safety, utility, and comfort in the use of new ones.

PAVEMENT DESIGN

M. R. Keefe

Chief Engineer, State Highway Commission of Indiana,
Indianapolis

I wish to compliment Mr. Connor on his excellent paper on pavement design. He has given us a very comprehensive