TENTATIVE RESULTS ON CAPACITY OF CURB OPENING INLETS

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SYNOPSIS

This paper presents a method of estimating the capacity of a curb opening inlet as a function of the depth of flow in the approach gutter, the depression of the inlet lip below the flow line of the gutter, and the length of the opening. The method not only indicates the flow which would be entirely intercepted by a given inlet but also the percentage of the total flow in the gutter which would be intercepted as the discharge is increased beyond that point. This method is based on a theoretical analysis which treats the curb opening as a weir with the head decreasing along the crest. Despite a number of simplifying assumptions in the analysis, experimental data from three independent investigations verify, within practical limits, the validity of the theory. The study substantiates the belief of practical engineers that depression of the gutter flow line is necessary to achieve reasonably efficient operation with the curb opening type of inlet. It also proves that the capacity of the inlet varies with the grade and also with the cross section of the street as it affects the depth of flow. The second part of the paper includes suggestions as to how the engineer might apply the results of this study to the design of curb opening inlets, especially for express highways. A brief discussion is included of the relative capacities of curb opening and grate inlets.

Recent examination of the plans for an express highway disclosed that the curb opening inlets, although well designed hydraulically, were so widely spaced that only 15 to 50 percent of the gutter flow would be intercepted. The result was that the stormwater would accumulate to a depth of about 1 ft. at the low points in the grade in three successive underpasses. The storm sewers collecting discharge from these inlets would flow at less than one quarter of their designed capacity while the gutters would be overloaded.

Recognizing the need for information on hydraulic capacity of curb opening inlets on grades, a study has been made of available experimental data as summarized in the first part of this paper. The results are expressed in equations developed by mathematical analysis. The second part of the paper utilizes graphs to enable direct and quick solution for the hydraulic capacity of any length of inlet depending on the depth of flow in, and cross section of, the approach gutter, and the depression of the gutter flow line at the inlet. A comparison is also made between the hydraulic characteristics of grate inlets and curb opening inlets. Suggestions are made on computation of inlet spacing.

There have been three investigations since 1945 which provide useful data on curb opening inlets adaptable to use on express highways. The work by Conner in 1945 has been abstracted in the *Proceedings* of the Highway Research Board (1)[2]. These tests were made on a roadway cross section with an 8-in. parabolic crown. Only the discharge which would be completely intercepted by the inlet was reported.

The Corps of Engineers have reported tests (2) on curb opening inlets installed on a cross section having a transverse slope of 1-1/2 percent where at least 50 percent of the flow in the gutter went past the inlet. These tests and those by Conner both included a depression of the gutter flow line at the location of the curb opening.

The only tests on curb opening inlets

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[2]Figures in parentheses refer to the list of references at the end of the paper.

having no depression of the gutter flow line have been made within the past year by the University of Illinois in cooperation with the Illinois Division of Highways and the Bureau of Public Roads. The final results of these tests will be published in the form of a bulletin of the University of Illinois Engineering Experiment Station.

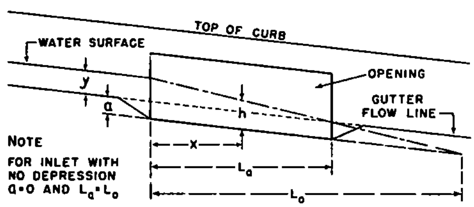

Figure 1. Diagrammatic Sketch of Typical Curb Opening Inlet

MATHEMATICAL DEVELOPMENT AND EXPERIMENTAL VERIFICATION

This analysis covers only the case where the curb opening inlet is located in a gutter on a continuous gradient. Under this condition the velocity of flow in the gutter is normal to the plane of the opening and is assumed to be wholly ineffective in inducing flow through the opening in the curb. It is also assumed that the energy due to the fall along the length of the inlet is dissipated in friction so that this fall has no effect on flow into the inlet. With these simplifying assumptions the basic theory is simply that water flows over the lip of the inlet in a manner similar to flow over a broad-crested weir with the head at the upstream end of the inlet being equal to the depth of the water in the approach gutter if there is no depression, or equal to the depth in the approach gutter plus the amount by which the inlet lip is depressed below the gutter flow line extended. The final simplifying assumption is that the head varies in direct proportion to the distance from the beginning of the inlet, becoming 0 at the downstream end of the inlet for the case where there is no depression and the inlet is just barely intercepting all the flow. If the inlet lip is depressed below the gutter flow line, then the head at the downstream end of the inlet when all the flow is just barely being intercepted is assumed to be equal to the amount of the depression.

We can therefore set up equations for the flow into the inlet as follows: Let h = head in feet on the inlet lip at a point x ft. from the beginning of the opening, y = depth of flow in feet in the approach gutter, a = depression in feet of the inlet lip below the gutter profile extended.

Taking the length of the inlet as L_a (see Fig. 1), then from the assumptions in the previous paragraph,

$$h = a + y - \frac{x}{L_a} y = y \left(\frac{a}{y} + 1 - \frac{x}{L_a}\right) \qquad (1)$$

If the opening is considered to be a weir then the depth of flow across the inlet lip is critical, and velocity of flow into inlet at point x is

$$v = \left[g\left(\frac{2}{3} h\right)\right]^{1/2}$$

(g being the acceleration of gravity). The flow through an elemental strip dx becomes

$$dQ = q\, dx = v \left(\frac{2}{3} h\right) dx.$$

Substituting values of v and h above, and integrating between limits x = 0 and x = L,

$$Q = \left(\frac{2}{3}\right)^{3/2} g^{1/2} y^{3/2} \int_0^L \left(\frac{a}{y} + 1 - \frac{x}{L_a}\right)^{3/2} dx$$

$$= 1.23\, L_a y^{3/2} \left[\left(\frac{a}{y} + 1\right)^{5/2} - \left(\frac{a}{y} + 1 - \frac{L}{L_a}\right)^{5/2}\right] \qquad (2)$$

Equation (2) is the discharge in cu. ft. per sec. which would be intercepted by an inlet of length L provided the theoretical assumptions are reasonably correct. It cannot be applied directly because the length L_a is unknown. The equation can be simplified if we first consider the case where the inlet has no depression, that is a = 0.

Inlet Without Depression - For the case where a = 0, equation (2) becomes

$$Q = 1.23\, L_o y^{3/2}\left[(1 - \frac{L}{L_o})^{5/2}\right] \qquad (3)$$

This equation still does not give a direct solution unless the value of L_o is known, L_o being the length at which the inlet with no depression would just barely inter-

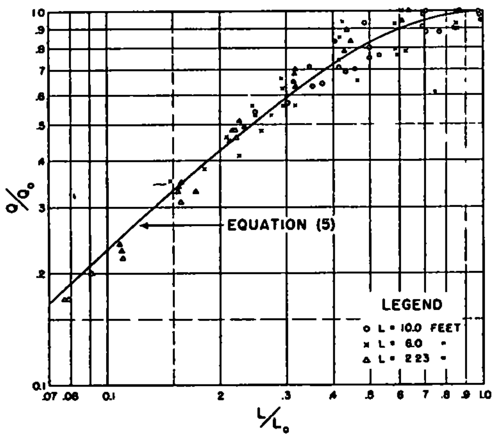

Figure 2. Illinois Data on Curb Opening Inlets Having No Depression

cept all of the flow in the gutter. If we make $L = L_o$, then equation (3) reduces to

$$Q_o = 1.23\, L_o y^{3/2} \qquad (4)$$

which is the theoretical capacity of an inlet of length L_o with no depression when it is just barely intercepting the total flow in the gutter. As will be shown later, accurate measurement of the discharge for this case is difficult. Therefore, in order to utilize more of the experimental data it was found desirable to set up an equation for Q/Q_o by dividing equation (3) by equation (4).

$$\frac{Q}{Q_o} = 1 - (1 - \frac{L}{L_o})^{5/2} \qquad (5)$$

The Illinois experimental data included tests on inlets with no depression 2.23 ft., 6 ft., and 10 ft. long on grades from 1/8 percent to 4 percent. The tests were made on a 1:3 scale model, all dimensions here being prototype values. The roadway cross section is shown in Figure 6.

The Illinois experimental data were found to fit equation (5) reasonably well if

$$L_o = \frac{Q_o}{0.7y^{3/2}} \qquad (6)$$

This equation will be noted as identical to equation (4) except that the numerical coefficient has been changed from 1.23 to 0.7. The values of L/L_o plotted against the values of Q/Q_o shown in Figure 2, together with a curve drawn for equation (5), indicate that the equation is a reasonable approximation of the entire range of data. The scatter of these points for high values of the discharge ratio indicates why it is difficult to evaluate the numerical coefficient by the use of equation (4) alone.

Inlet with a Depression - When a curb inlet with the lip depressed a ft. below the flow line of the gutter is just barely intercepting the total flow in the gutter, the capacity, which we will call Q_a, can be approximated by the equation:

$$\frac{Q_a}{L_a} = 0.7(a + y)^{3/2}\left[1 - (1 - \frac{y}{a + y})^{5/2}\right] \qquad (7)$$

This equation will be observed as similar to equation (4) except that the numerical coefficient has the same value as in equation (6), (a + y) is substituted for y and the term in brackets is added. The latter term corrects for the fact that the head at the downstream end of the inlet reduces to a instead of reducing to zero as in equation (4).

From Figure 1 it will be found by similar triangles that

$$\frac{y}{a + y} = \frac{L_a}{L_o}$$

where L_o is the value of x when h = 0, having the same significance as in equation (4). If L_a/L_o is substituted in equation (7) for

$$\frac{y}{a + y}$$

the term in brackets will be observed as being identical with the right hand side of equation (5). Consequently this term is actually the ratio of Q_a/Q_o, Q_o being the capacity of an inlet of length L_o when the approach depth is (a + y). If we substitute Q_a/Q_o for the term in brackets, equation (7) becomes

$$\frac{Q_o}{L_a} = 0.7(a + y)^{3/2} \qquad (8)$$

Equation (8) is roughly in agreement

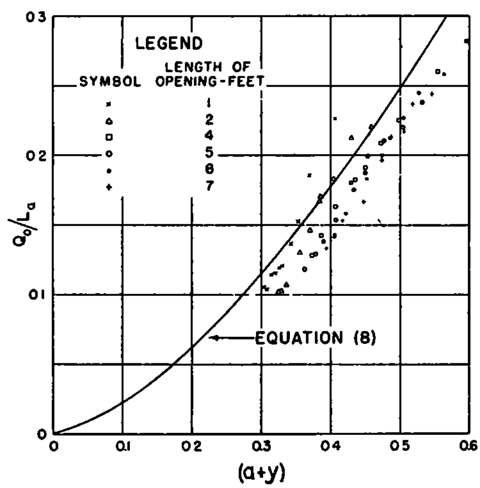

Figure 3. North Carolina Data on Curb Opening Inlets with 3-in. Depression

with the experimental data reported by Conner (3) as shown in Figure 3. In these tests, a = 0.25 ft., L varied from 1 ft. to 7 ft., and gutter grades from 0.5 percent to 10 percent. The gutter cross section is shown in Figure 6. As previously noted, Conner reported only a discharge Q_a at which the inlet barely intercepted the entire flow.

A limited number of tests (2) were made by the Corps of Engineers, St. Paul District, on inlets 3 ft. and 8.92 ft. long with a = 0.167 ft. on grades of 0.75 percent and 1.0 percent with some tests of the longer inlet on a 2 percent grade. These tests were made on a 1:2 scale model. Prototype dimensions are used in this paper. The flow intercepted was never greater than 50 percent of the total flow. The cross section is shown in Figure 6.

From this case it is necessary to set up an equation for the ratio Q/Q_a in which Q is the flow intercepted and Q_a is the flow in the gutter. If L in equation (2) is made equal to L_a, then Q/Q_a becomes

$$\frac{Q}{Q_a} = \frac{\left(\frac{a}{y} + 1\right)^{5/2} - \left(\frac{a}{y} + 1 - \frac{L}{L_a}\right)^{5/2}}{\left(\frac{a}{y} + 1\right)^{5/2} - \left(\frac{a}{y}\right)^{5/2}} \qquad (9)$$

This equation is plotted in Figure 8 for

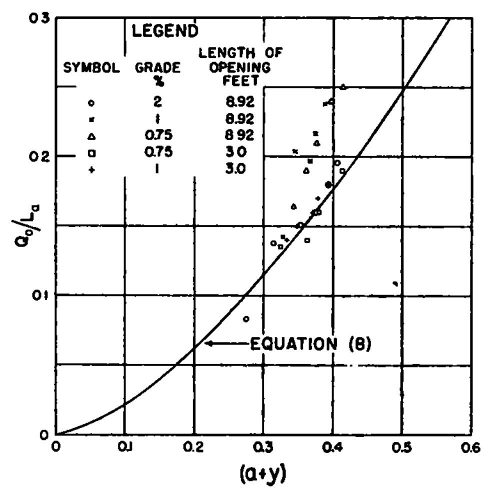

Figure 4. Corps of Engineers Data on Curb Opening Inlets with 2-in. Depression

different values of the parameter $\frac{a}{y}$ to facilitate solution.

From the experimental values of a, y, and Q/Q_a reported by the Corps of Engineers (including values of $\frac{a}{y}$ up to 1.6), L/L_a in equation (9) was determined directly from Figure 8. Then, dividing the length of inlet L by L/L_a, the theoretical length L_a was computed at which the entire gutter flow would be intercepted. This converted the data into the same variables appearing in equation (7). The final step was to compute Q_o which was done in the same manner as described for the North Carolina data. Dividing Q_o by L_a gave the experimental points plotted in Figure 4. Equation (8) is plotted for comparison.

Discussion of Experimental Data - In

order to compare the data from the three independent investigations, all of the points plotted in Figures 2, 3, and 4 are combined in Figure 5. The curve gives the values computed by equation (8) and also the values given by equation (6), which is simply the special case where a = 0. From the scientific viewpoint the deviation of the experimental points from the curve is too great to ignore and suggests that there are other variables which are affecting

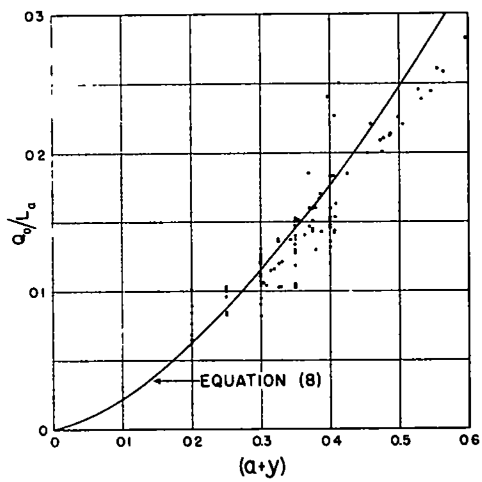

Figure 5. Composite Plot of Data from Figures 2, 3, and 4

the experimental results. The scatter is probably due in only a minor extent to experimental errors because in each investigation the data for the most part are consistent for each combination of length of inlet and roadway grade. It would probably be possible to derive a more complicated expression for the basic relationship than is given by equation (8), but it is not believed that there is a sufficient range of data in any of the investigations to justify that effort at the present.

The influence of changes in a and y upon the capacity of an inlet to intercept 100 percent of the gutter flow can be visualized from Figure 7 which is plotted from equation (7). The ordinate is the average capacity in cubic feet per second per foot of length and the abscissa is the depth (feet) in the approach gutter for the indicated values of the depression.

For an inlet of length L_a, the capacity Q_a in cubic feet per second may be read directly by multiplying the ordinate scale in Figure 7 by L_a. Thus the scale on the right hand margin, which is 10 times the scale for Q_a/L_a, will give the capacity of a 10-ft. inlet directly in cubic feet per second.

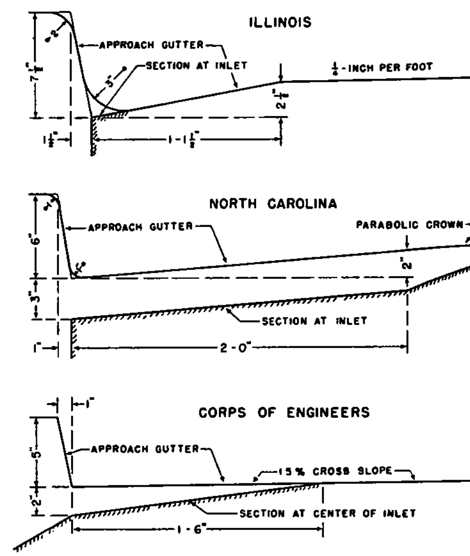

Figure 6. Sections Through Approach Gutter and Through Inlet for the Three Investigations

Balanced Capacity - The capacity of an inlet in relation to the gutter capacity can be directly compared by superimposing on Figure 7 a curve for gutter capacity. The dotted line in Figure 7 is such a curve of Q_a (right margin) plotted against y for a gutter having a longitudinal grade of 1 percent and a cross slope of 2 percent (z = 50), assuming a roughness coefficient n = 0.015. The intersection of this curve with the inlet capacity curve for a given value of a gives a value of Q_a which may be termed the "balanced capacity." If the discharge increases beyond the balanced capacity, part of the gutter flow will not be intercepted. The actual interception in that case cannot be read from the inlet capacity curve since it applies only to the condition where 100 percent of the flow is being intercepted, but can be determined from Figure 8 as will be shown. If the gutter flow is less than the balanced capacity, all the flow will be intercepted in a length less than the full length of the inlet. Thus the inlet might be considered inefficient unless it was desired to provide reserve capacity to handle greater storm intensities.

To obtain reasonable efficiency from a curb opening inlet, a depression of at least 0.1 ft is essential, as can be observed by studying Figure 7 or Table 1 based on that figure.

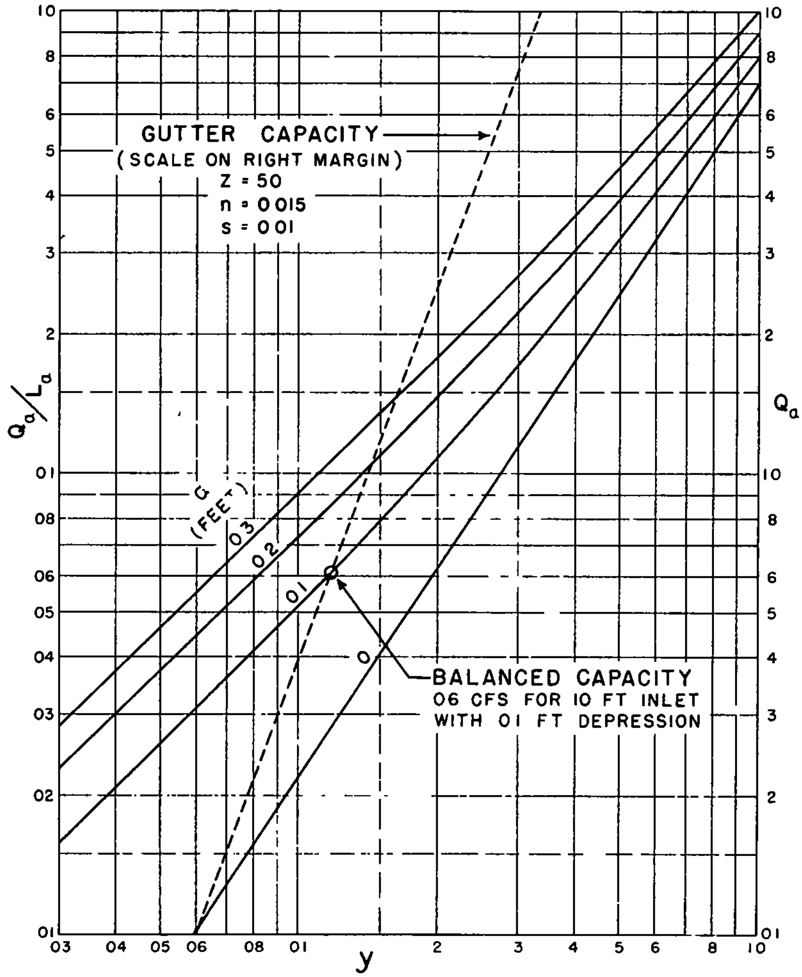

Figure 7. Average Interception per Foot of Curb Opening as Function of Depth Flow in Approaching Gutter and Depression of Flow Line when Entire Flow is Just Barely Intercepted

Where it is possible to increase the cross slope of the gutter (for example, on a parking lane) the efficiency of a given inlet is greatly increased. This is illustrated in the third column of the table which gives the balanced capacity of the same 10-ft. inlet when the cross slope is increased from 2 percent to 4 percent.

When the capacity of an inlet to intercept all the flow is exceeded, the actual interception may be determined from Figure 8 which provides a graphic solution for equation (9). depending on the ratios a/y and L/L_a The latter is the ratio of the actual length of the inlet to the theoretical length required to intercept the entire gutter flow as determined from Figure 7. The actual interception in cubic feet per second with water flowing past the inlet will always be greater than the balanced capacity because of the increased head.

From examination of Figure 8 it will be apparent that for low values of a/y an inlet may be considerably shorter than the theoretical length L_a and still intercept a high percentage of the gutter flow. When the depression is several times the depth of flow in the approach gutter, however, the partial interception ratio Q/Q_a is almost equal to the length ratio L/L_a.

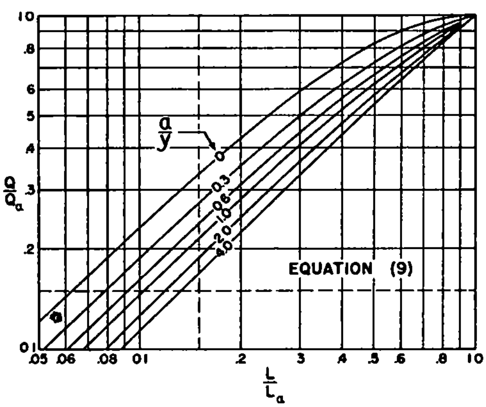

Figure 8. Partial Interception Ratio as Function of Length of Inlet Relative to Length Required to Intercept Entire Flow and Depression Relative to Depth of Flow in Approach Gutter

For convenience the symbols used in the foregoing analysis are tabulated below, followed by a summary of the characteristics of curb opening inlets.

NOMENCLATURE

Gutter

Symbol	Unit	
Q_a	cfs.	flow in gutter; also inlet capacity when entire gutter flow is just barely intercepted
y	ft.	depth of flow in approach gutter for normal cross section
z		ratio of width to depth of flow in gutter for uniform cross slope
s	ft. /ft.	longitudinal slope of gutter
a	ft.	depression of inlet lip below normal gutter flow line at face of curb

Inlet

L	ft.	clear length of curb opening inlet
L_a	ft.	clear length of curb opening inlet required to intercept entire gutter flow for inlet with lip depressed a feet
L_o	ft.	same as L_a for special case when gutter flow line is not depressed
x	ft.	distance from upstream end of inlet (see Fig. 1)
h	ft.	head on inlet lip at distance x from upstream end of inlet
v	ft. per sec.	velocity of flow into inlet through elemental strip under head h
q	cfs.	discharge through elemental strip into inlet
Q	cfs.	discharge intercepted by an inlet of length L
Q_o	cfs.	discharge just barely intercepted by an inlet of length L_o having no depression
g	ft. per sec.^{2}	acceleration of gravity = 32.2

TABLE 1

Depression a ft	Balanced Capacity of 10-ft Inlet on 1% Grade Cross Slope 2% cfs	Cross Slope 4% cfs	Increase Due to Change in Cross Slope %
0	0 1	0 3	200
0 1	0 6	1 1	80
0 2	1 0	1 8	80
0.3	1 5	2 4	60

SUMMARY OF HYDRAULIC CHARACTERISTICS OF CURB OPENING INLETS

The flow intercepted by a curb opening inlet on a continuous grade depends primarily on: (1) the length of opening; (2) the depression of the gutter flow line; (3) the cross section of the approach gutter; and (4) the depth of flow in the approach gutter, y. Other factors may have some effect but are not covered in this paper.

1. To estimate the flow which a given inlet will intercept, the depth of flow in the approach gutter must first be known. This may be determined from Figure 9 or otherwise computed. For a standardized cross sections stage-discharge curves for various grades are convenient, or a single curve of depth as a function of $Q/s^{1/2}$ may be used.

2. The gutter flow will be completely intercepted if that flow divided by the length of the inlet does not exceed the value of Q_a/L_a read from Figure 7 for the known depth of flow in the approach gutter and the known depression of the gutter flow line at the inlet.

3. If the actual gutter flow divided by the length of inlet is less than the amount read from Figure 7 then the entire gutter flow will be intercepted in a length less than the full length of the inlet.

4. If the actual gutter flow divided by the length of inlet is greater than the amount read from Figure 7, only part of the flow will be intercepted.

5. The length of inlet necessary to completely intercept a given gutter flow may be determined from Figure 7 by dividing the known gutter flow by the value of Q_a/L_a for the known values of y and a. This length is designated L_a and the flow so intercepted is called the balanced capacity.

6. When the balanced capacity is exceeded, the ratio of the flow intercepted to the total flow in the approach gutter may be read from Figure 8 using the two ratios L/L_a and a/y. L is the actual length of the inlet and L_a the theoretical length found under 5.

7. The balanced capacity of a given inlet decreases as the grade of the gutter increases in a manner similar to that indicated by any one of the curves for inlet capacity in Figure 10.

8. The balanced capacity of a given inlet on a given grade increases with the cross-slope of the gutter.

9. A curb opening inlet with no depression of the gutter flow line is inefficient; the flow intercepted may be markedly increased without changing the length of opening if the gutter flow line is depressed by an amount exceeding the anticipated depth of flow in the approach gutter.

10. After the balanced capacity is exceeded the actual flow intercepted will increase and the rate of flow past the inlet will also increase, these rates being determinable from Figure 8 by the method described under 6 above.

ESTIMATING CAPACITY OF A CURB OPENING INLET

(This portion of the paper is intended to indicate to the design engineer how the research data may be applied to practical problems.)

Gutter Capacity - From the foregoing analysis it will be evident that the capacity of a curb opening inlet cannot be estimated without knowing the depth of flow in the approach gutter. Accordingly, the first step is to compute the stage-discharge relationship for the given gutter section. A simplified equation based on the Manning formula has been presented in a discussion of

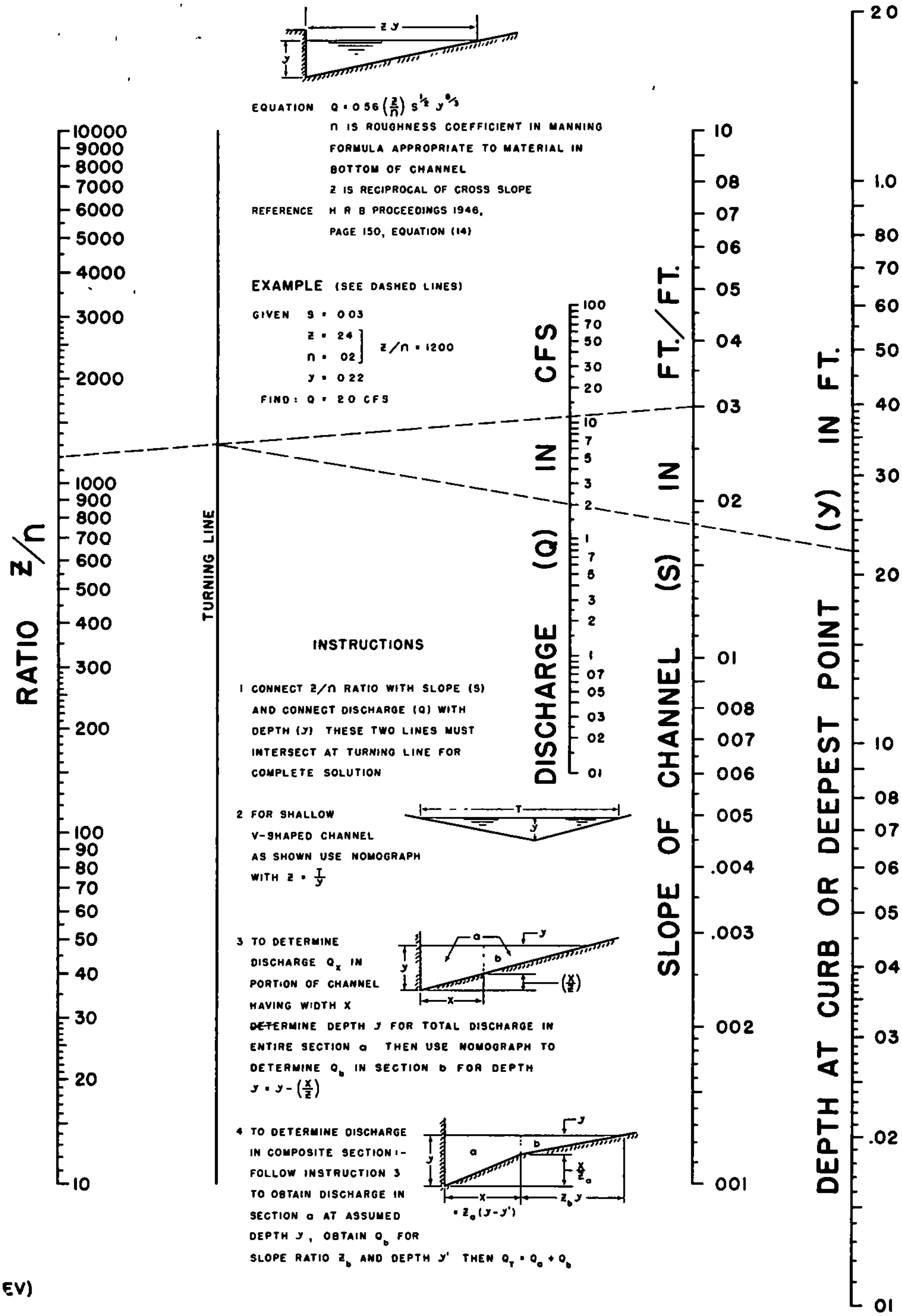

Figure 9. Nomograph for Flow in Triangular Gutters

Larson's paper (4) and is shown in the nomograph, Figure 9. The validity of this equation has been verified, with certain limitation, in a master's thesis by Larson (6). For curved cross sections the gutter capacity for each depth over the required range can be computed by dividing the flow prism into subsections about 1 ft. wide and computing the velocity in each by the Manning formula, using the average depth as the hydraulic radius. For cross sections of gradually varying depth it is not permissable to compute the hydraulic radius for the entire cross section.

as the balanced capacity. It can be found by simultaneous solution of equation (7) and the equation for gutter capacity. This is most easily done by finding the intersection of the two curves on logarithmic graph paper. The best technique to use will depend on whether the solution is desired for many values of a and L_a or for a specific inlet. For the latter case the inlet capacity curve and the gutter capacity curve can be plotted as for the example in Figure 7.

For the general case it is convenient to plot the inlet capacity curves with the ordinate Q_a/L_a and the gutter capacity

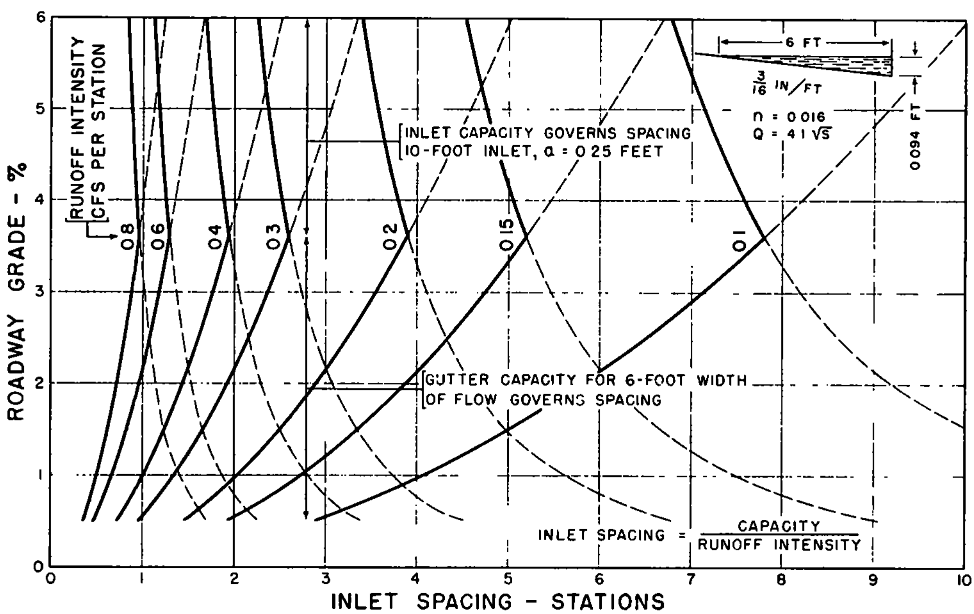

Figure 10. Typical Working Chart for Determining Inlet Spacing on Various Grades, Applicable only to 10-ft. Curb Opening with 3-in. Depression and Gutter with 3/16-in. per ft. Cross-Slope

The stage-discharge, or gutter-capacity, curve need be computed for only one longitudinal grade since the discharge for a given depth at any other grade will be in proportion to the square roots of the respective grades. The curve may be plotted as a conveyance curve with $Q/s^{1/2}$ as a function of depth.

Complete Interception - The capacity of a curb opening inlet just barely intercepting the entire gutter flow is defined

as a conveyance curve with ordinate $Q/s^{1/2}$ on the same sheet of logarithmic cross-section paper. The position of the latter curve is immaterial as it will be shifted anyway. Take the given value of roadway grade s and for any assumed depth y_1 find the corresponding discharge Q_1 in the gutter, using the conveyance curve. Divide this by L_a (which is equal to the actual length of inlet at balanced capacity) and plot the point (Q_1/L_a, y_1) on the inlet capacity graph. Shift the conveyance curve to pass through this point.

If the cross slope of the gutter is a straight line, the conveyance curve will be a straight line (as in Fig. 7) and the shifted position is simply a line through the plotted point parallel to the original conveyance curve. Otherwise the curve can be shifted easily by tracing it on an overlay. A whole series of conveyance curves can be drawn on the overlay to cover the expected range in superelevation of the roadway.

Once the conveyance curve is correctly positioned, Q_a/L_a may be read at the intersection with a given inlet capacity curve and multiplied by L_a to determine the balanced capacity. This result should be regarded as an approximate estimate which may differ from the true value by as much as 20 percent plus or minus. Considering the uncertainties in estimation of peak rates of runoff, this possible error is not serious.

If the balanced capacity is exceeded, the head builds up and actual interception will be greater than the balanced capacity. It can be estimated by the method given under "Partial Interception."

When the depth of flow and discharge in a given gutter are known, the length of inlet required to completely intercept this flow may be estimated from Figure 7 (or a similar plot) by dividing Q_a by the value of Q_a/L_a for this depth and any desired depression. This method may also be used to estimate the length of opening in a curb needed to discharge the entire flow through an open spillway across a roadway shoulder. In that case the curb line should turn out gradually, utilizing the full length of the opening to complete a 90-degree change in direction. It is also applicable to estimating the length of opening in a curb necessary to divert flow to a grate placed in a sump offset back of the curb line, the depression of the gutter flow line in that case usually being zero, unless the pavement surface is warped.

Partial Interception - The dimensionless graph Figure 8 may be used to estimate the partial interception ratio Q/Q_a. The first step is to find by the method described above the theoretical length of inlet L_a which would intercept the entire gutter flow Q_a. The ratio of the actual length of inlet L to the length L_a, and the ratio a/y, locate a unique point in Figure 8 from which Q/Q_a is read. The actual interception is then obtained by multiplying Q_a by this ratio (see Table 3 for examples). The accuracy of this estimate is subject to the same comments as given above for complete interception.

The length of inlet required to obtain a given partial interception ratio when a and y are known may be estimated by finding the ratio L/L_a from Figure 8 and the length L_a for complete interception from Figure 7. Then the length required to intercept the given portion of the total flow is the product $L_a(L/L_a)$.

Inlet Spacing - The techniques described above may be used to analyze probable operating characteristics of existing curb opening installations or to design new installations. A complete discussion of design procedures and criteria is beyond the scope of this paper, but a few suggestions may be useful in illustrating applications as they have been developed.

On express highways where the contributing drainage area is clearly defined the rate of runoff may be estimated by the usual "rational" formula $Q = CiA$. The runoff coefficient may be taken as $C = 0.9$ so long as surfaces are impermeable, or, if in grass, are steeply sloping. If relatively flat areas of turf are involved the coefficient for such areas may be reduced to perhaps 0.5 more or less, depending on the drainage characteristics of the soil. Then a weighted coefficient would be used to compute the runoff for the entire area contributing to a given inlet. Usually the time of concentration for an inlet may be taken as 5 min. if the maximum instantaneous peak runoff is desired, or may be arbitrarily increased to some duration such as 20 min. during which the width of water on the pavement would cause marked interference with traffic flow.

Once the peak rate of runoff for a given inlet has been estimated the size of the inlet could be adjusted to intercept that flow but as a practical matter the designer will wish to standardize on a limited number of inlet lengths. Consequently, the procedure should be to limit the size of the drainage area so that the peak flow will not exceed the balanced capacity of the inlet which will vary with the cross-section and the roadway grade. The simplest way to do this is to express the peak runoff for the typical section of the roadway under consideration in terms of cubic feet per second per station. From the "rational" formula

$$q = \frac{Ci\ \overset{\text{width}}{(\text{of d. a.})}\ \overset{\text{length}}{(\text{of d. a. in station})}}{432}$$

Then from a graph of balanced capacity for a given inlet on various roadway grades, the spacing may be computed as

$$L_g = \frac{Q_a}{q} = \frac{\text{balanced capacity in cfs.}}{\text{runoff in cfs. per station}}$$

the answer being in stations. To speed up computations where gutter section and inlet design are fixed, a graph such as Figure 10 may be plotted which gives inlet spacing directly for various roadway grades and various runoff intensities.

Inlets may be spaced for full interception at runoff intensities of frequent occurrence, thus operating at partial interception for less frequent storms. The designer may quickly prepare alternate designs for various frequencies to arrive at a decision as to the premium measured in increased cost which is justified by the higher degree of protection against flooded roadways.

Inlet Spacing Controlled by Gutter Capacity - On high-speed expressways carrying large volumes of traffic it is advisable to limit the extent to which the water flowing in the gutter encroaches upon the travel lane, especially for the frequent storms (reference 4, page 27). In that case it will be found where the gutter is immediately adjacent to the travel lane, rather than on the outside edge of the shoulder, that inlet spacing will be governed by the width of flow on the roadway except on the steep grades. The solution of this problem is easy as the capacity of the gutter for a fixed width of flow from the equation in Figure 9 becomes

$$Q = 0.56\ (\tfrac{z}{n})\ y^{8/3}\ s^{1/2} = \text{constant}\ (s^{1/2})$$

the constant being 4.1 for the example in Figure 10. For other types of sections the conveyance curve for the fixed depth determines the constant. Then the spacing of inlets in stations becomes

$$L_g = \frac{\text{limiting gutter flow}}{\text{runoff in cfs. per station}}$$

The curves in Figure 10 which converge on the origin give inlet spacing for various runoff intensities when the limiting width is 6 ft. as indicated by the inset diagram. It will be noted that up to a 3.6 percent grade the gutter capacity controls inlet capacity with allowable spacing increasing to a maximum at that grade. For steeper grades the balanced capacity of the given inlet controls, this capacity decreasing slowly as the grade becomes steeper than 3.6 percent.

Charts such as Figure 10 can be drawn up quickly as the computations are simple, and will save time for the designer when the same gutter and inlet standards are used repeatedly. Attention is called to the fact that this chart may be used for drainage areas which vary in width, provided only that an average width for each area is used in estimating the runoff intensity in cubic feet per second, per station.

On superelevated curves the balanced capacity of the inlets, and the gutter capacity for a given width, will increase, thus increasing allowable spacing over that on tangent sections. If enough superelevated sections are involved, a chart may be prepared for each rate of superelevation. Charts showing balanced capacity as a function of roadway grade for each rate of superelevation may suffice.

Other Considerations for Inlet Spacing - Care should be taken to locate inlets of adequate capacity at points where the crown begins to reverse so as to minimize the quantity of water flowing across the pavement from one side to the other.

Since it is important to avoid excessive ponding at low points in the grade line, any inlet near the beginning of the vertical curve ought to be designed to intercept all of the flow reaching that point, at least for frequent storms. This inlet would then also take off the coarser sediments being transported which otherwise would begin to deposit in the gutter as the velocity diminished with the decreasing grade. (Under some circumstances the engineer might prefer to clean up the sediment in the gutter rather than to permit it to accumulate underground.) The criterion for limiting depth will roughly indicate the need for additional inlets on the vertical curve, but it should be pointed out that the conveyance curve and Figure 9 are not strictly applicable when the slope is changing, and probably should not be used for grades less than about 0.5 percent approaching the low point on the vertical curve. Experimental data are needed to define flow criteria in such cases. Except for the drawdown of the water surface as flow approaches an inlet, depths on flat grades are likely to be greater than that computed for the roughness coefficient applicable on steeper grades.

Form of Computations - A form of tabulation which has been found convenient in analyzing the interception by inlets on a given project is shown in Table 2. Constants used in this table were z = 64, n = 0.016, L = 6 ft., and a = 0.25 ft.

TABLE 2

COMPUTATIONS OF FLOW INTERCEPTION BY EXPRESSWAY INLETS

Station	Grade s ft per ft	Discharge Q_a cfs	$\frac{Q}{s^{1/2}}$	Depth y ft	Width zy ft	$\frac{Q_a}{L_a}$	$L_a = \frac{Q_a}{Q_2/L_a}$	$\frac{L}{L_a}$	$\frac{a}{y}$	$\frac{Q}{Q_a}$	Interception $Q = \frac{Q}{Q_a} \times Q_a$	$Q_c = (Q_a - Q)$
800+22	3 7	4	21	18	12	14	29	21	1 4	28	1 1	2 9
805+50	5 0	4	18	17	11	13	31	19	1 5	25	1 0	
	with Q_c	6 9	31	20	13	16	43	14	1 2	19	1 3	5 6
809+50	1 5	3	24	18	12	15	17	35	1 4	44	1 3	
	with Q_c	8 6	70	27	17	22	39	15	0 9	22	1 9	6 7
813+20	0 4	3	47	23	15	19	13	46	1 1	58	1 7	
	with Q_c	9 7	154	36[a]	23	30	32	19	0 7	29	2 8	6 9

[a]Over curb

The computations were made from two curves plotted on logarithmic graph paper, (1) average discharge per ft. of inlet for a = 0.25 as in Figure 7, and (2) a conveyance curve for the gutter. The latter is faster to use than the nomograph Figure 9 when many computations are needed. The computations may be checked using Figures 7, 8, and 9.

There are two lines of computations for the last three inlets. The first line gives the flow interception for the runoff from the individual drainage area and the second line the flow intercepted when the "carryover" Q_c from the inlets above is added.

Comparing Grate and Curb Opening Inlets - An inlet grate with efficient openings will intercept substantially all the water flowing within the width of the grate. The water flowing on the roadway outside this width can be assumed to flow past the inlet, although if the grate has an appreciable length a small quantity may flow in along the edge. A grate may be assumed to have efficient openings if the bars are parallel to the direction of flow in the gutter and the unobstructed openings are long enough so that the water has a chance to fall through the openings before hitting the downstream end. The required length can be estimated by the formula

$$X = \frac{V}{4}(y)^{1/2}$$

where V is the mean velocity in the approach gutter for the width of the grate and the depth y. Other arrangements of bars can be reasonably efficient as has been demonstrated by Larson (5), but experimental tests are necessary to determine the characteristics of such inlets. On the other hand, the flow intercepted by a grate with parallel bars can be estimated directly, following the procedure prescribed under instruction 3 of Figure 9.

The partial interception ratio for a grate inlet may be approximated by using the curve for a = 0 in Figure 8, substituting for L/L_a the ratio of width of grate to total width of flow (zy) in the approach gutter. (This is due to the fact that the function for flow in a fixed width relative to total width of flow gives numerical values almost identical to the function expressed by equation (9).) Thus, if the grating is half as wide as the water surface, it will intercept about 0.83 percent of the gutter flow.

Table 3 gives the flow intercepted by an inlet grate 2 ft. wide in comparison with the capacity of curb opening inlets 4 ft., 7 ft., and 10 ft. long having a 2-in. depression of the gutter flow line. The approach gutter is assumed to be on a 1 percent grade with a cross slope of 1/4 in. per ft. and a roughness coefficient n = 0.015.

The second column of the table gives the width of flow in the gutter at the discharge indicated in the first column.

TABLE 3

COMPARISON OF COMPUTED FLOW INTERCEPTION BY GRATE AND CURB OPENING INLETS

Roadway grade 1 percent, cross-slope ¼ in per ft (z = 48), n = 0 015

Grate 2 ft by 2 ft with bars parallel to curb

Curb openings of indicated lengths, depression of gutter flow line a = 2 in

Flow in Gutter: Discharge Q_a	Flow in Gutter: Width zy	L_a Length of Curb Opening Required for 100 Percent Interception[a]	Partial Interception Ratio Q/Q_a: Curb Opening Inlet[b] L = 4	L = 7	L = 10	Grate Inlet[c]
ft	ft	ft				
0 038	2.0	1 3	1 00	1 00	1.00	1.00
0 50	5 3	6.9	67	1 00	1.00	72
1 0	6.9	10 5	49	77	97	60
1.5	8.0	13 5	41	.64	83	54
2 0	8 9	16 0	.36	58	.74	50

[a]Computed from Figure 7

[b]Computed from Figure 8

[c]Computed from Figure 9

In order to intercept the entire flow, the inlet grate would have to be as wide as the flow in the gutter. The comparable length of curb opening necessary to intercept 100 percent of the flow is given in the third column. Note that the 2-ft. grate will completely intercept a discharge of only 0.038 cu. ft. per sec. A 7-ft. curb opening inlet, on the other hand, will completely intercept approximately 0.5 cu. ft. per sec. and will intercept more water than the 2-ft. grate at all of the indicated rates of flow in the gutter.

Larson (4) found that the use of curb openings in combination with efficient grate inlets provides practically no increase in capacity, unless inlets are affected by backwater. However, a curb opening placed upstream from a grate inlet has been found useful (7) in taking off the trash brought down at the beginning of runoff which otherwise would lodge on the grate. A curb opening back of a grate located at the low point in the roadway grade will provide an outlet if the grate becomes clogged.

Attention is called to the fact that the relative capacity of grate and curb opening inlets of the sizes used in Table 3 will change as the grade changes. In general, as the grade becomes steeper, grate inlets, if of sufficient length, will increase in interception capacity while curb openings decrease in capacity. Conversely, on grades less than that used in Table 3 the grate becomes less efficient and the curb openings more efficient.

The principal objective of this paper has been to provide the designer with some tools he may use in making more intelligent designs for storm drain inlet systems. He will bear in mind, however, that the construction and maintenance problems and costs may overshadow purely hydraulic considerations. Simplicity in structural design is important if low unit costs are to be obtained. For this reason, and because curb openings are less susceptible to clogging by debris than are grate inlets, some cities are using curb opening inlets almost exclusively. Another point to remember is that the efficiency of a given inlet on an old street with a steep crown may be greatly reduced if the same inlet is used on a flat crown typical of express highway sections. This paper provides a means of roughly evaluating the relative capacities under such conditions.

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DISCUSSION

STIFEL W. JENS[1] - Preliminary studies and designs of drainage facilities for the depressed portion of an expressway through an old part of St. Louis have had the great advantage of the recent research on inlet design as reported by Conner (1)[2] (3), the Corps of Engineers (2), Larson (4) (5), and by Mr. Izzard in this paper, "Tentative Results on Capacity of Curb Opening Inlets." The portion of the proposed St. Louis Expressway to be built in cut (some with turfed 3:1 slopes, and part with vertical retaining walls) involves about 1,700 ft. of 6-lane pavement with a 4-ft. dividing land strip and 3-ft.-wide concrete gutters (see Fig. A for cross sections) immediately adjacent to the outer edges of the pavement; ramps (about 4,800 lin. ft.) will be 24 ft. wide with gutters along both edges. Turf shoulders are 10 ft. wide (including the concrete gutter). On tangents, crown slopes are 1/8 in. to the foot. Curved portions of the ramps have superelevations up to a maximum of 7 percent transverse slope. Longitudinal slopes range from 1.3 percent to 6 percent, the latter on the ramps.

The Missouri State Highway Department is designing the expressway and had selected the gutter section with the following as criteria: (a) depth of flow at the pavement edge is to be limited to a maximum of 1 in., which with the 1/8 in. per ft. cross-slope results in a maximum sheet of water 8 ft. wide from edge of running slab towards the center of the pavement; (b) no grating is to extend into the running slab; (c) except in emergency, wheels are not expected to run in the concrete gutter; (d) any depression below the gutter flow line is undesirable.

With the probable final design rainfall frequency of 20 years, criterion (a) would involve infrequent short-duration flooding of the slab. This criterion, along with design runoff, determines the spacing of inlets, assuming that an inlet grating will intercept all the flow coming to it. Criterion (b) means a "carryover" of any flow along the pavement edge, with ultimate interception at some downstream inlet where the "carryover" has re-entered the gutter proper upstream, or interception at the low-point inlet. While these studies have been for preliminary designs, it is anticipated that the gutter may be painted or otherwise colored to indicate that it is not a part of the running slab. A foot-wide corrugated strip of white concrete along the edge of the lane next to the gutter might be desirable to discourage careless use of the gutter as part of the outer traffic lane.

Criterion (d) recognizes that on all high-speed urban expressways there will be occasional crowding or other careless driving which may force a car to run its right-hand wheels in the gutter for a short distance. It is realized that normally the driver of an automobile will run with his right wheels 1-1/2 to 2 ft. from the edge of the pavement, and under such usual conditions a warping of the outer 1-1/2 ft. along the edge of the pavement to create a depression of

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[2]See list of references in Mr. Izzard's paper.

2 or 3 in. below the gutter flow line in front of a side opening curb inlet is tolerable. This writer asks if experience has suggested that such a relatively sudden drop of a speeding car's right-hand wheels does not cause any loss of control with attendant serious consequences. Analytically, it would seem to have inherent potentialities for grave troubles, if not tragedies.

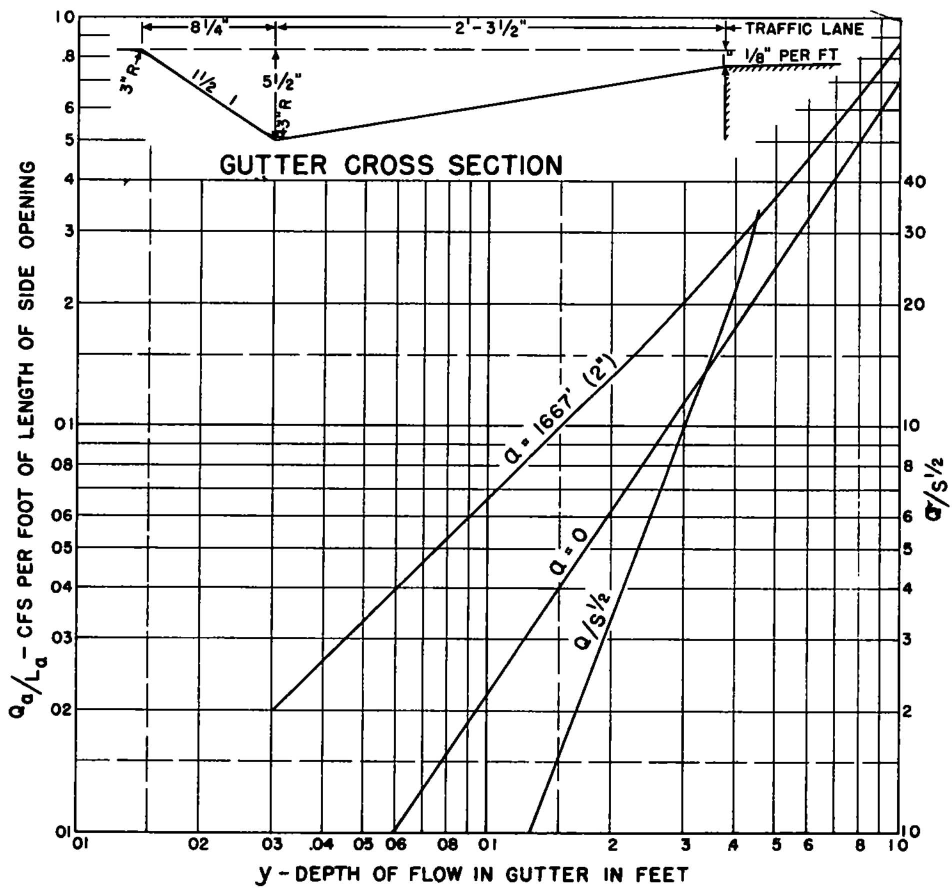

Figure A. Gutter Cross-Section and Inlet Capacity Curbs

Table A lists 10 of the 46 inlets required under preliminary design and gives the depth (column 3) and width (column 6) of flow in the assumed gutter for the design runoffs (column 5). With but two exceptions, the design flow has been confined to the gutter proper. Columns 8 and 10 give the curb opening lengths required for complete interception of the design flow for conditions of a continuous gutter with no depression in front of the inlet opening (column 10), and for a 2-in. deep depression (column 8). Figure A gives for this table the same information as Mr. Izzard's Figure 7 and all computations are based upon the formulas in his paper, assuming n to be 0.017. Inlet spacing ranged from 70 ft. to 330 ft. varying with width and character of area drained, and with longitudinal grade; the primary consideration in spacing was the gutter capacity. Attention is directed to the fact that side openings of 13 ft. minimum are required to give 100 percent interception without any depression in the gutter opposite the curb opening. If a 2-in. depression was permissible, a great many of the inlets could be satisfactory with only 8-ft.-long openings.

The grated inlet under preliminary designs has longitudinal slots with a clear opening of 2 ft. 3-1/2 in. by 1 ft. 9/16 in.; the concrete or brick-supporting structure has a 2-ft. inside dimension. The maximum gutter velocity of 9.5 ft. per sec. indicates a slot length of about 16.5 in. for a free-

TABLE A

URBAN EXPRESSWAY INLETS

LENGTHS OF CURB OPENING INLETS REQUIRED FOR COMPLETE INTERCEPTION OF GUTTER FLOW

Inlet No	Gutter Slope	Flow in Gutter				Curb Opening for 100 Percent Interception			
		y	z	Q_a	zy	Q_a/L_a	L_a	Q_a/L_a	L_a
						$a = 2$ in.		$a = 0$	
(1)	(2)	(3) ft	(4)	(5) cfs	(6) ft	(7)	(8)	(9)	(10)
1	4 1	.352	7 61	3.15	2.68	246	13 ft	148	21 ft
2	6 0	.348	7.61	3 80	2.72	242	16	.144	26
3	2 8	.360	7 61	2.75	2 74	252	11	152	18
4	2.2	.351	7 61	2 31	2 67	245	9	147	16
5	2 2	.440	10 83	4.40	4.77	317	14	206	21
6	2 2	358	7 61	2 32	2 72	250	9	151	15
7	1 7	363	7.61	2 19	2 76	.253	9	.155	14
8	2.2	355	7 61	2 36	2 70	247	10	150	16
9	FUTURE			2 00		INTER-RAMP AREA			
10	2 2	.350	7 61	2 26	2 66	243	9	.146	15

Note. Col (3) obtained by entering $Q_a/s^{1/2}$ curve of Figure 11. Cols (7) and (9) read from $a = 2$ and $a = 0$ curves for the depths y in Col (3)
Cols (8) and (10) result from dividing Col. (5) by Cols (7) and (9) respectively Lengths given to nearest full foot

fall drop of 6 in. A minimum slot length of 2 ft. above the clear opening of the supporting structure was adopted to allow for some clogging due to debris. Preliminary designs included provision of combination grated and side opening inlets at the low points in the expressway cut, in recognition of the fact that side opening inlets have a distinct advantage with respect to debris such as leaves, paper, and other street litter. Discussions with Mr. Izzard have resulted in the decision to incorporate in final design combination curb opening grated inlets not only at the low points, but also either side of such low points, placed such that they will be near the beginning of the vertical curve ahead of where the velocity slows down and loses its debris-transporting power. It is expected that this will result in the dropping of any transported debris in the approach inlets, and the delivery of relatively clean runoff to the low point inlet.

Because the St. Louis Expressway drainage will involve combined sewers, each inlet requires a water-sealed trap on the outlet connection to the sewer. This trap would be required for either grated or side opening inlets.

To achieve complete interception of design runoffs, the inlets for the depressed portion of the Third Street Inter-regional Highway in St. Louis have been designed as grated inlets, which it is believed will render efficient drainage service at a lesser cost than side-opening curb inlets for the particular conditions of this project.

The practicing engineer concerned with highway, expressway, and street drainage owes much to Mr. Izzard and the Bureau of Public Roads for the major part they have played in stimulating and participating in the recent research in the principles and practices of overland flow and the rational design of inlets. Mr. Izzard's paper is another noteworthy contribution to the clarification of the application of recent research to actual design.

CARL F. IZZARD, *Closure* - It is gratifying to know that the principles of inlet design described in this paper have already been used in developing the design for a major project. The customary lag between the release and the application of research data appears to have been notably shortened. However, some of the experiments from which the conclusions were developed were conducted nearly five years ago, but did not receive as much recognition by design engineers as they deserved, partly because the reported results applied to specific inlets, leaving the designer in some doubt as to how other inlets of different dimensions might operate.

Mr. Jens asks if experience has suggested that a relatively sudden drop of two or three inches created by warping the edge of the pavement in front of a side opening curb inlet might result in loss of control of the vehicle. Definite observations to answer this question are lacking. Even without a depression of the edge of the pavement, the writer is inclined to question the advisability of the steep pitch of the gutter cross section (Fig. A) from the viewpoint of traffic safety. This gutter drops 4-1/2 in. below the edge of the pavement in a distance of slightly more than 2 ft. Such a gutter is excellent for carrying water but may possibly prove unduly hazardous to vehicle operation. Both of these questions can be answered only by systematic observation of vehicle operation under such conditions. This is a research problem for the traffic engineer. The problem does bring out the necessity for compromise between ideal drainage designs and requirements of traffic safety.

Since the original paper was written, new experimental data have become available from the Storm Drain Research Project being conducted at the Johns Hopkins University and jointly sponsored by the City of Baltimore, Baltimore County, and the Maryland State Roads Commission. Preliminary examination of the initial report dealing with inlets in a gutter having no depression bears out the validity of the conclusions presented in this paper and sheds more light on certain refinements in design which may prove significant. It is hoped that a report from the Johns Hopkins University project may be presented at the next annual meeting of the Highway Research Board.