EXPERIMENTS ON FLOW THROUGH INLET GRATINGS FOR STREET GUTTERS

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In designing surface drainage facilities for streets and highways, the highway engineer has been handicapped by the general lack of data on the capacity of grate inlets. The limited data available indicates that for many of the grate inlets now in use, the capacities are quite low, particularly on moderate and steep grades. In addition, clogging of grate inlets with paper, leaves, and other debris continues to be a serious maintenance problem. For the purpose of alleviating these problems, an experimental investigation was undertaken at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota, under the sponsorship of the Minnesota Department of Highways.

A test gutter with a cross-slope of 20.6 to 1 and with a nearly vertical curb was constructed in the 36-in. tilting channel of the Laboratory. Near the end of the gutter, a test section was provided, in which full-scale inlets and curb openings of any shape could be installed. Tests of various grate inlets were conducted at several slopes, using a wide range of discharges at each slope. In all tests the entire flow was introduced at the upper end of the gutter. Measurements were taken of the depth and discharge in the gutter, and of the quantity of water passing over and around the inlet, which was termed "carryover." The portion of the flow intercepted by the inlet, referred to as "inlet capacity," was~~, of course,~~ the difference between the gutter flow and the carryover. Tests were also made with simulated debris added to the flow.

In tests conducted at the North Carolina Engineering Experiment Station (*1*)[1], N.W. Conner found that deflecting slots in a gutter are self-cleaning when set at an angle of 45 deg. with the direction of flow. In an attempt to improve the self-cleaning ability of grate inlets, an experimental inlet was constructed with its bars and openings set at this angle. Tests were made of this inlet both with and without a curb opening. This experimental inlet was then improved by rounding the surface of each of its bars. Standard inlets tested included a Minnesota Highway Department inlet, which has openings parallel to the flow, and a city street department inlet, which has openings normal to the direction of flow.

Since the test gutter was considerably smoother than the average gutter, differences in roughness must be considered in applying the test results to grate inlets in actual gutters. In addition, one may wish to apply the data to inlets in various gutters having different degrees of roughness. For these reasons, the test results are not presented on the basis of slope alone, but rather on the basis of the quantity $\sqrt{s}/n$, in which s is the highway slope and n is the Manning roughness coefficient. This factor is a constant for any given gutter. Since this index is pro-

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[1] Italicized figures in parentheses refer to the list of references at the end of paper.

portional to velocity for a given depth of flow, it will be referred to as the "velocity index." The four test slopes selected gave a range in velocity index from 6.6 to 17.2, resulting in super-critical flow within the entire range. This range includes gutters of ordinary roughness at slopes of 1 to 6 percent.

The data obtained in the capacity tests are presented in Figures 1 through 4, in the form of "rating" curves. In these curves. inlet capacities are plotted as ordinates, and carryovers as abscissas. For any point on these curves, the corresponding gutter discharge can also be determined directly by following the sloping lines to the carryover scale. The letter designations on the figures indicate the various inlets or inlet setups, as follows:

A. Experimental inlet, with curb opening
B. Experimental inlet, without curb opening
D. Improved experimental inlet
G. Highway Department inlet
H. City inlet

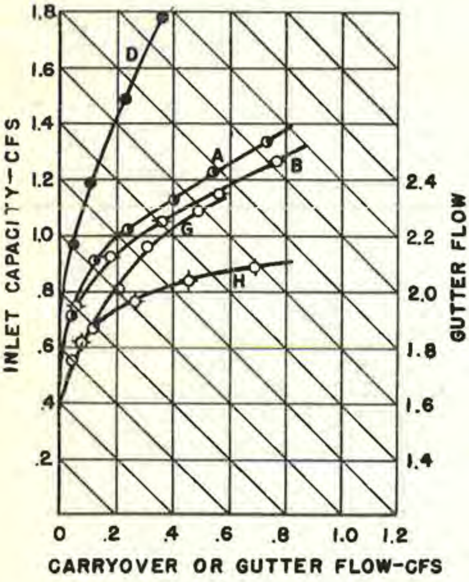

Figure 1. Rating Curves at Velocity Index of 17.2

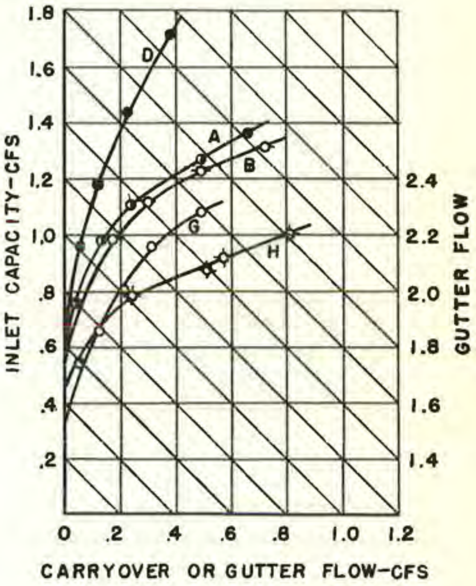

Figure 2. Rating Curves at Velocity Index of 14.0

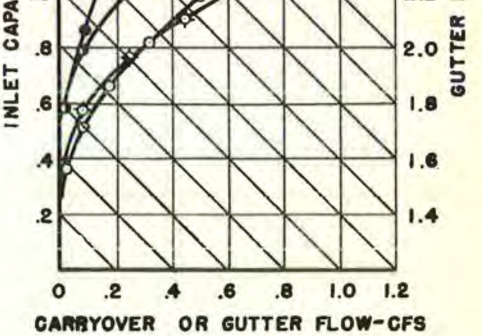

Figure 3. Rating Curves at Velocity Index of 9.8

Each of Figures 1-4 contains the data obtained at a certain test slope, and is therefore applicable only for a particular velocity index.

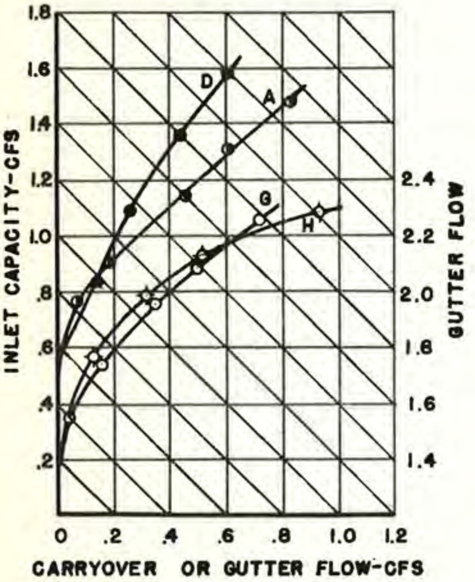

Figure 4. Rating Curves at Velocity Index of 6.6

Figures 5, 6, and 7 are plots of velocity indexes versus inlet capacities corresponding to several carryovers. For these carryovers then, one can determine the corresponding inlet capacity at any velocity index within the range of the tests. These curves also indicate the manner in which the capacity of any of the inlets varies with slope.

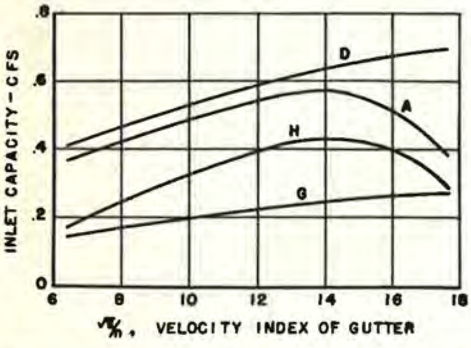

Figure 5. Inlet Capacities with No Carryover

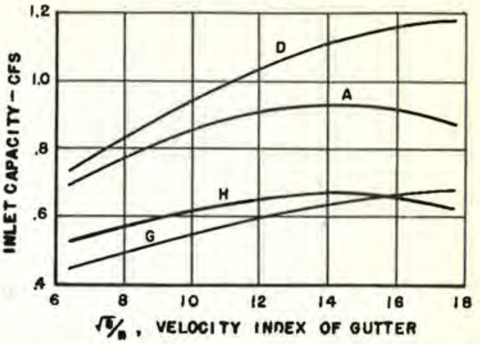

Figure 6. Inlet Capacities with Carryover of 0.10 cu ft per sec

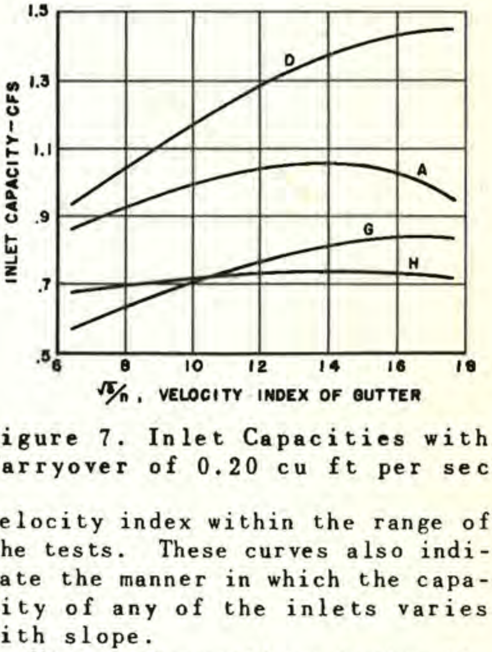

Figure 7. Inlet Capacities with Carryover of 0.20 cu ft per sec

Visual observations during the tests indicated that the data do not fully explain differences in behavior between the various inlets. To supplement the data, therefore, a number of photographs were taken of the inlets in operation. Figures 8 through 11 show Inlets A, D, G, and H operating with approximately the same gutter discharge.

RESULTS OF CAPACITY TESTS

Perhaps the most important fact developed by these tests is that the capacities of grate inlets can be greatly increased by permitting a small amount of carryover. This statement appears to apply to any grate inlet. The rating curves show that the capacities of most of the inlets tested are approximately doubled by allowing carryovers from 0.10 to 0.20 cu. ft. per sec. In the case of inlets in series, these small carryovers from inlet to inlet produce no ill effects other than a slight increase in the gutter flow, since carryover is not cumulative. Greater carryovers produce diminishing returns. Thus a carryover in the range of 0.10 to 0.20 cu. ft. per sec. appears to be the optimum for inlets in series in the ordinary case where the gutter discharge is a limiting factor.

The capacity test data show that the capacity of a grate inlet is affected both by the characteristics of the inlet and by the characteristics of the approach flow. Furthermore, variations in the nature of the approach flow produce varying and sometimes opposite effects upon inlet capacity, depending on the characteristics of the inlet. Of primary importance in determining inlet capacity are the following inlet characteristics: the width of the inlet, and the efficiency of the inlet openings.

The width of the inlet measured normal to the direction of flow, is an influential factor in that the carryover in almost every case is either partly or wholly composed of water which passes around the inlet. In other words, no inlet can be expected to intercept a large portion of the flow unless it extends well into the path of the flow. The importance of width can be seen from an inspection of the rating curves for Inlet D, the improved experimental inlet, and for Inlet G, the Highway Department inlet, both of which take water readily. Inlet D, being 24 in. in width, has a high rating curve, while Inlet G, which is 17 in. wide, has a low rating. Thus, it appears worthwhile to make grate inlets at least 24 in. wide for a gutter of this shape, and perhaps wider for highways with flatter crown slopes.

The efficiency of grate inlet openings was found to depend mainly on the effective length of the individual openings, which, in all cases, is measured in the direction of flow. The importance of this characteristic is well demonstrated in a general way by the test results. Since it has 1 3/16-in. transverse openings, the city inlet, Inlet H, permitted an appreciable portion of the flow to pass directly over the openings. The rating curve for this inlet therefore rises slowly. In the Highway Department inlet, Inlet G, 1 1/4-in. by 11-in. openings are placed parallel to the flow, making their effective length 11 in. The photographs show that these openings allowed no water to pass over the inlet, and a steeper rating curve was the result. The narrower width of Inlet G, however, caused its capacity to fall below that of Inlet H in the region of no carryover.

During tests of inlets with transverse bars, it was observed that only a thin sheet of water was di-

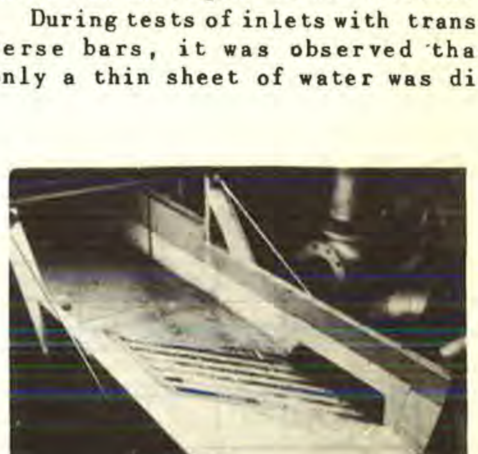

Figure 8. Experimental Inlet, $\sqrt{s}/n = 14.0$, $Q_G = 1.02$, $Q_I = 0.92$, $Q_C = 0.10$ cu ft per sec

Figure 9. Improved Experimental Inlet, Series D, $\sqrt{s}/n = 14.0$, $Q_G = 1.05$, $Q_I = 0.98$, $Q_C = 0.07$ cu ft per sec.

Figure 11. City Inlet, Series H, $\sqrt{s}/n = 14.0$, $Q_G = 1.00$, $Q_I = 0.77$, $Q_C = 0.23$ cu ft per sec

Figure 10. Highway Department Inlet, Series G, $\sqrt{s}/n = 14.0$, $Q_G = 1.00$, $Q_I = 0.81$, $Q_C = 0.19$ cu ft per sec

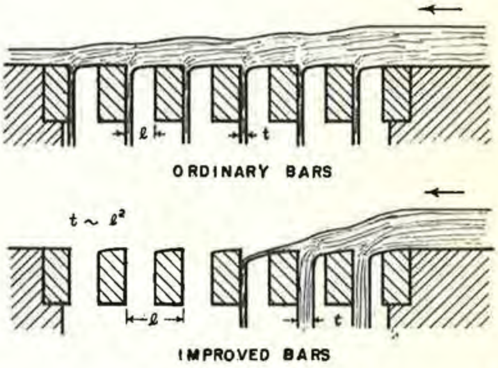

Figure 12. Flow Over Ordinary and Improved Grate Bars

verted downward at the face of each bar. Theoretically, the thickness of this sheet of water varies as the square of the overfall distance (effective length of opening) for flow of a given velocity, if the path of the water crossing the opening is assumed to be that of a freely falling body. For this reason, it would appear highly desirable to increase the effective length of opening in any way possible.

In Series D, the length of the openings of the experimental inlet was increased by rounding the grate bar surfaces. The surface of each bar was rounded to conform approximately to the shape of a free overfall from its leading edge, as shown in Figure 12. In effect, this change moved the beginning point of each overfall from the trailing edge to the leading edge of the bar. Since the bar thickness was equal to the bar spacing, the overfall distance or effective length of opening was approximately doubled. Thus, the thickness *t* of the sheet of water diverted by each bar, as well as the capacity of each opening, was theoretically quadrupled. Although no measurements were made of the capacity of individual openings, the photographs demonstrate that this improvement actually is very effective. Figure 8 shows that six of the openings failed to intercept all of the water flowing over the original experimental inlet, while with the improved grate bars, Figure 9, almost the entire flow was intercepted by the first two openings. This simple improvement appears to be applicable to any inlet with transverse bars, and would result in little, if any, increase in the cost of casting this type of inlet.

The use of curb openings with grate inlets was found to produce little or no increase in capacity, depending on the efficiency of the inlet. The B series of tests was conducted with the experimental inlet as it was used in the A series, except that the curb opening was replaced by a section of curb. Comparison of the rating curves, Figures 1 and 2, shows that only a small percentage of the inlet capacity, less than 5 percent, can be credited to the curb openings. In this case, the curb opening intercepts some water which would otherwise flow over the inlet. In the case of inlets with more efficient openings, which permit no water to flow over the inlet, it is evident that a curb opening provides practically no increase in capacity, unless the inlets are affected by backwater.

The characteristics of the approach flow were also found to have a pronounced effect on the capacity of grate inlets. The tests showed that high velocities tend to decrease the capacity of an inlet by increasing the tendency for water to flow or spray over the openings. On the other hand, high velocities tend to increase the capacity of an inlet by concentrating a greater flow in a given width of gutter. Figures 5, 6, and 7 show that either of these opposing tendencies may be predominant, depending on the width of the inlet and the efficiency of the inlet openings. Within the range of the tests, these curves also show that the improved experimental inlet and the Highway Department inlet, which have efficient openings, operate with increasing capacity as the slope and velocity are increased. The original experimental inlet and the city inlet, which have less efficient openings, increase in capacity with increased velocity indexes up to approximately 14, but decrease in capacity for velocity indexes higher than 14.

DEBRIS TESTS

In order to have a quantitative basis for comparing the self-cleaning abilities of the various inlets, an arbitrary procedure for debris tests was adopted, using as debris pieces of paper 1 by 2 inches in size. Since no attempt was made to duplicate actual gutter debris, the results of these tests were not intended to indicate the percentage of actual debris which a given inlet will handle. However, the results are believed to serve as a basis for comparing the various inlets tested.

The original experimental inlet was found to pass only 20 to 30 percent of the test debris, and would therefore probably clog quite easily. It was hoped that this inlet would be self-cleaning as a result of the component of flow along the axis of each bar, but this component was not strong enough to remove the test debris. Rounding the bars of this inlet, however, permitted approximately 70 percent of the test debris to pass through the inlet openings.

Because its openings are parallel to the flow, the Highway Department inlet handled the test debris as easily as it did water, having a debris efficiency of about 95 percent. However, it should be noted that for larger debris, this inlet might clog as easily as any other. The city inlet, which is a rough casting with the bars normal to the flow, passed only 17 percent of the test debris.

Of the inlets tested then, only the Highway Department inlet, which has openings parallel to the flow, can be considered highly efficient in passing this type of debris. The debris tests also indicate that improving the hydraulic efficiency of inlet openings increases the ability of the inlet to pass debris.

APPLICATION OF RESULTS

For a given set of design conditions, the results of this investigation can be used to determine the required spacing for inlets of any of the types tested. Moreover, the data can be used to predict the operating capacity of any individual inlet, either under the design conditions or under other circumstances, such as rainfall intensities higher or lower than the design intensity, or clogging of one or more inlets in a series.

If one of these inlets is to be used in a location where no carryover is permissible, it is necessary merely to select the inlet capacity which will give no carryover at the appropriate velocity index. In such a location, however, the inlet may be affected by backwater from intersecting streets or from changes in grade, in which case the capacity of the inlet will probably be greater than the capacity found in the tests.

In a series of inlets where some carryover is permissible, a considerably greater inlet capacity, and correspondingly, a greater inlet spacing can be used. In designing such a series of inlets, the "design" or "normal" inlet capacity, corresponding to a suitable carryover, can be selected from Figures 5 through 7, or from rating curves. For a series of uniformly spaced inlets, it can be shown readily that, if succeeding inlets operate with equal carryover, the flow intercepted by each inlet will be equal to the runoff per inlet. Thus, the required inlet spacing can be found by equating the design capacity to the runoff per inlet, if the rate of runoff can be expressed in terms of the dimensions of the drainage area and the rainfall intensity. For the idealized case of a rainfall of uniform intensity for a period longer than the time of concentration, assuming no infiltration, the expression thus obtained for the inlet spacing L in feet is:

$$L = \frac{43{,}200\ Q_I}{bI} \qquad (1)$$

in which Q_I is the design inlet capacity in cu. ft. per sec, b the width of street drained in feet, and I the rainfall intensity in inches per hour. The depth and width of flow in the gutter upstream of each inlet can then be computed if desired. The gutter flow Q_G, is given by:

$$Q_G = Q_I + Q_C \qquad (2)$$

where Q_C is the design carryover. For the gutter under consideration, Manning's formula may be applied to obtain the following depth discharge relation:

$$Q_G = 9.5 \frac{\sqrt{s}}{n} y^{8/3} \qquad (3)$$

in which y is the depth of flow in feet at the curb. If it is to be used repeatedly, this relation can be plotted as a family of curves for various values of $\sqrt{s}/n$, the velocity index. Since the cross-slope of the experimental gutter is 20.6 to 1, the maximum width of flow, w, is given by:

$$w = 20.6\,y \qquad (4)$$

An example best illustrates the use of these data or similar data in a design problem. In a gutter of the same shape as the test gutter on a 3.5 percent grade, the roughness coefficient n is estimated to be 0.015. The velocity index is then 12.5. A rainfall having a uniform intensity of 5 in. per hr. is to be drained from a 24-ft. width of paved street or highway by inlets of Type A. Assuming that a carryover of 0.20 cu. ft. per sec. is permissible, it is seen from Figure 7 that, at a velocity index of 12.5, the corresponding inlet capacity is 1.05 cu. ft. per sec. The required inlet spacing can then be obtained by use of Equation (1):

$$L = \frac{43{,}200 \times 1.05}{24 \times 5} = 378 \text{ ft.}$$

The gutter flow just above each inlet is given by:

$$Q_G = 1.05 + 0.20 = 1.25 \text{ cu. ft. per sec.}$$

The depth of flow can be found by substitution in Equation (3):

$$y = \left[\frac{1.25}{9.5 \times 12.5}\right]^{3/8} = 0.18 \text{ ft.}$$

and the maximum width of flow is found to be:

$$w = 20.6 \times 0.18 = 3.7 \text{ ft.}$$

If it appears advisable to consider the effects of gutter storage and storms shorter than the time of concentration, the inlet spacing cannot be determined directly by an equation such as Equation (1). The actual gutter hydrograph can be determined, however, by a method originated by Horner and Jens(2). This method was verified experimentally and developed further by Izzard(3). Further development of this procedure is necessary to determine the effect of carryover on the gutter hydrograph.

A series of inlets possesses a valuable attribute in its ability to adjust its capacity to any rate of runoff within a considerable range. To demonstrate that each inlet in a series tends to operate at a capacity equal to the runoff per inlet, another example will be given. In a gutter having a velocity index of 14.0, ten of the improved experimental inlets, Type D, are spaced to receive 1.00 cu. ft. per sec. of runoff per inlet, which results in a normal carryover of 0.07 cu. ft. per sec. By some unusual circumstance, Inlet No. 5 becomes completely clogged. The gutter discharge is therefore considerably more than normal at Inlet No. 6, and is less than normal at the beginning of the series. The discharge intercepted by each inlet of the series can be determined, however, by use of the appropriate rating curve, as shown in Table 1.

Beginning at Inlet No. 1 of this series, the gutter discharge is 1.00 cu. ft. per sec., since there is no carryover from a preceding inlet. The rating curve for $\sqrt{s}/n = 14.0$, Figure 2, shows that with this gutter flow, 0.94 cu. ft. per sec. is intercepted and 0.06 passes by the inlet as carryover. This carryover results in a gutter flow of 1.06 cu. ft. per sec. at Inlet No. 2 and the rating curve is referred to again to determine the flow intercepted and the carryover. This procedure may be followed on through the series. In this example, the normal inlet capacity, equal to the runoff per inlet, is reached at Inlet No. 3, and all succeeding inlets will normally operate at this capacity. Clogging of Inlet No. 5 upsets this equilibrium, since none of the flow is intercepted by this inlet. The result is a carryover of 1.07 and a gutter flow of 2.07 cu. ft. per sec. to Inlet No. 6. This gutter flow, however, is quickly reduced at succeeding inlets, and normal inlet capacity is again reached at Inlet No. 10. This example shows that if the gutter flow at any inlet happens to be more or less than the normal amount for the series, the flow intercepted by succeeding inlets will increase or decrease, as the case may be, until the normal inlet capacity, equal to the runoff per inlet, is reached at some inlet downstream.

TABLE I

COMPUTATION OF INDIVIDUAL CAPACITIES OF TYPE D INLETS IN SERIES AT A VELOCITY INDEX OF 14.0

Inlet Number	Runoff	Condition	Q_G	Q_I	Q_C
1	1.00	Clean	1.00	0.94	0.06
2	"	"	1.06	0.99	0.07
3	"	"	1.07	1.00	0.07
4	"	"	1.07	1.00	0.07
5	"	Clogged	1.07	0	1.07
6	"	Clean	2.07	1.71	0.36
7	"	"	1.36	1.23	0.13
8	"	"	1.13	1.05	0.08
9	"	"	1.08	1.01	0.07
10	"	"	1.07	1.00	0.07

This investigation is limited chiefly by the fact that the data obtained are applicable only to inlets in gutters having cross sections identical to that of the test gutter, that is, with a uniform cross-slope of 20.6 to 1. However, it seems likely that many of the general findings of these experiments will apply, in greater or lesser degree, to grate inlets in gutters having other cross-slopes.

In planning the tests and preparing the data, the effects of lateral inflow on the flow conditions in an actual gutter were neglected, since the side inflow per foot of gutter will normally be only a fraction of a percent of the gutter flow near an inlet. Any resulting discrepancies would therefore be small, and would be reflected mainly in the velocity index scale, which in practice is subject to an error of several percent in the estimation of the roughness coefficient.

Of the standard and experimental inlets investigated, none is believed to represent the best solution to the requirements of capacity, self-cleaning ability, and economy in grate inlets. Nevertheless, the tests have developed considerable evidence of the relative importance of various inlet characteristics. It is possible that the best features of the test inlets can be combined to best satisfy these requirements, for a gutter of the shape used. Further tests are being planned for this purpose.

SUMMARY OF RESULTS

The results of this investigation are summarized briefly in the following conclusions, which are applicable to a continuous gutter having a cross-slope of approximately 20 to 1, and a velocity index within the range of these tests.

1. The capacity of a grate inlet can be greatly increased by allowing a small amount of carryover.

2. The capacity of a grate inlet is determined mainly by its width normal to the flow and by the efficiency of its openings.

3. The efficiency of grate inlet openings depends largely on the effective length of the openings in the direction of flow.

4. The capacity of inlets with transverse bars and openings can be increased substantially by rounding

the top surface of each bar.

(5) In the normal range of application, inlets with efficient openings operate with increasing capacity as the slope of the gutter is increased.

(6) Except where capacity is provided by ponding, curb openings are of little or no value in increasing the capacity of a grate inlet.

ACKNOWLEDGEMENTS

The writer wishes to acknowledge his indebtedness to Mr. A.W. Verharen, Hydraulic Engineer of the Minnesota Department of Highways, who suggested this investigation and who has followed its progress closely, and to Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory, under whose direction the experiments were conducted. For authority to publish these test results, the writer is indebted to the Minnesota Department of Highways, Mr. O.L. Kipp, Chief Engineer, and to the Director of the Laboratory.

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DISCUSSION

CARL F. IZZARD, *Highway Research Engineer, Public Roads Administration* - The paper by Mr. Larson is a valuable contribution to an understanding of the hydraulics of inlet gratings for street gutters. The reader will be glad to know that Mr. Larson has conducted tests on modifications of the inlets described and that a complete report will be published by the University.

In interpreting the data in this paper the effect of the cross-section of the approach gutter must not be overlooked. For example, the capacity of Inlet G, as reported, will be reduced nearly 30 percent if the transverse slope of the gutter is flattened to a 50 to 1 slope.

The capacity of Inlet G, or of any other grating having efficient openings, can be closely approximated by assuming that all the water flowing within the width of the grating will be intercepted, while the water flowing on the pavement beyond the outside edge of the grating is the "carryover" discharge. Hicks[1] made this assumption in 1944 and the data in Larson's paper may be used as verification.

The rating curve for Inlet G may be computed with a maximum difference of 3 percent in a range of gutter flow from 0.5 to 2.0 cubic feet per second using equations (3) and (4) to estimate depth and width of gutter flow and Hicks' flow distribution curve to estimate flow within the width of the grating. However, it is not necessary to use the latter curve as will be shown.

For gutters having a triangular cross-section, equation (3) can be generalized by making the numerical coefficient equal to 0.468 z, where z is the ratio of width of flow to depth of flow (20.6 in Larson's experiments). The factor 0.468 is taken directly from equation (11) in Reference 3. The general equation is then

$$C_G = 0.468\ z\ \frac{\sqrt{s}}{n}\ y^{8/3} \qquad (5)$$

Substituting 20.6 for z gives a numerical coefficient of 9.64 instead

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[1] Hicks, W.I. "Runoff Computations and Drainage Inlets for Parkways in Los Angeles," *Proceedings*, Highway Research Board, Vol. 24 pp 138-147 (1944).

of 9.5 as in equation (3) because Reference 3 ignores friction on the curb face in order to simplify the derivation, the error having no practical significance in working with shallow depths. Also, because of this fact, the same equation may be used to estimate the carryover discharge by taking y as the depth at the outside edge of the grating. Assume $Q_G = 1.0$ cubic feet per second and take $\sqrt{s}/n \doteq 14$ as in Figure 2. Then equation (5) reduces to $Q_G = (9.64 \times 14)y^{8/3} = 135\ y^{8/3}$ from which $y = 0.159$ feet for the assumed gutter flow. The depth will be $1.42/20.6 = 0.069$ feet less at the outer edge of the grating or 0.090 feet. Substituting this depth in the same equation $Q_C = 135\ (1/11.1)^{8/3} = 0.22$ cubic feet per second. (Note: reciprocals are easier to work with than small decimals; use tables of fractional powers in hydraulic handbook to facilitate computation.). Then from equation (2), $Q_I = 1.0 - 0.22 = 0.78$ cubic feet per second which agrees closely with the observed value of 0.80 cubic feet per second read from Fig. 2.

From equation (5) it follows that the width of flow for a given discharge in a triangular gutter on a given grade will vary as $(z)^{5/8}$ while the depth varies inversely as $(z)^{3/8}$. Thus when the transverse slope is flattened to 50 to 1 making $z = 50$, the width of flow in the gutter is $(50/20.6)^{5/8} = 1.74$ times that in Larson's tests. The depth for $z = 50$ would be $(20.6/50)^{3/8} = 0.717$ times that in Larson's tests.

The trend in drainage design on urban highways is to space inlets so that the width of flow in the gutter for a design rainfall intensity will not exceed an arbitrary amount for frequent storms. The design rainfall intensity, for example, may be the average intensity for a duration of 20 minutes and a frequency of one or two years. The intense rainfall of shorter duration obscures vision so that traffic is forced to move slowly or even stop, but with adequate inlets the roadway will clear rapidly within a few minutes after the intense rainfall ceases. Thus the traffic delay will probably not be serious, particularly since these occurrences will be infrequent. The storm sewer sizes should be based on, for example, a 10-year storm for durations corresponding to the respective times of concentration so that water will not be ponded on the roadway because of inadequate outlet capacity except for the extreme storms for which it is not considered economical to design.

Rating curves similar to those in Figure 2 may be computed for any given width of inlet with any value of z in equation (5), assuming the inlet to have efficient openings. From such curves computed for various grades inlet capacity curves for different rates of carryover, similar to Figures 5, 6 and 7, can be drawn. These will show, as Larson ably demonstrates, that a small amount of carryover greatly increases the inlet capacity. Since the spacing of inlets by equation (1) is directly proportional to the inlet capacity, the spacing also increases with the amount of carryover, thereby reducing the initial cost. Charts may also be drawn for gutter capacity in relation to grade of roadway for various widths of flow. These can be used to check inlet spacing by the criterion established for width of flow in the design storm, which may be found on the flatter grades.

A common practice on express highways is to provide a 2-foot gutter on a one-inch per foot slope outside the edge of the 12-foot traffic lane. Equation (5) can be used to compute capacity of this type of cross-section as follows. Assume steeper slope to be extended, compute discharge for a given depth on one percent grade and subtract discharge computed for depth at point where slope changes. Then, for the latter depth, compute discharge on the flatter slope. Add this discharge to that computed for gutter to obtain total discharge. Repeat computations for other depths. Then plot discharge against depth or width with grade as parameter (discharge on other grades will vary with square root of grade), or plot discharge against slope with depth or width as parameter. Since the inlet grating is usually the same width as the steep portion of the gutter, the discharge computed for the latter will also be inlet capacity if inlet can be assumed as having efficient openings. This type of cross-section enables carrying a given discharge with much less encroachment on the traffic lane in comparison to a section with the curb at the edge of the traffic lane.

In applying equation (5) to estimating inlet capacities for gutter sections differing from that used by Larson, study must be given to his experimental data in judging whether or not a proposed grating has efficient openings which can be depended on to intercept all the flow over the grating. In general it appears that a grating with bars parallel to the approaching flow and a clear length of opening sufficient to permit the falling jet of water to clear the far end of the grating will have satisfactory characteristics. A length of opening in the direction of approach flow of about 18 inches is sufficient for maximum velocities likely to be encountered on express highways, based on a free-fall drop of 0.5 feet in the time required for the water to move the length of the opening. A length of 24 inches would provide some factor of safety to allow for debris accumulating on the downstream end of the bars. A greater length gives no increased capacity except when ponding occurs as at sag vertical curves.

In the past widely-spaced bars parallel to the curb have been frowned on because of the hazard of wheels on narrow-tired vehicles, such as buggies and bicycles, dropping through the openings. On limited access highways where there is little possibility of such traffic this objection doesn't apply, nor is it necessary to give consideration to high heels on women's shoes in determining the maximum width of opening. Where bicycle traffic may be encountered diagonal bars with rounded tops as in Inlet D may be used.

Attention is called to the fact that the increased capacity of Inlet D over Inlet G, which has bars parallel to the curb, is due almost entirely to the width of 24 inches within the range of velocity index tested. This can be proved by computing flow in a width of 24 inches as compared to 17 inches by the method previously illustrated. The length of opening, 11 inches, for Inlet G would begin to restrict capacity at greater depths and velocities of flow, but Inlet D may also fail to intercept all the flow in its width under similar conditions.

Gutter storage probably has no significant effect on required inlet capacity as used in equation (1) if the rainfall intensity used is the average for a duration of about 20 minutes which is the present trend of design practice as previously noted. This time is in excess of the time of concentration for most cases so that the outflow hydrograph at each inlet would have reached equilibrium with the inflow hydrograph for the drainage area.

Larson deserves great credit for developing his theory of the manner in which grating-type inlets in series on a continuous grade will adjust to the rate of runoff because of the characteristic of increased inlet capacity with increased carryover. By applying Larson's method for determining inlet spacing, satisfactory results can be obtained with fewer inlets than would be required for the assumption that each inlet on a continuous grade should intercept all the flow in the gutter.