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# Hydraulic Theory for Design of Storm-Water Inlets

WEN-HSIUNG LI, *Assistant Professor of Civil Engineering*
*Johns Hopkins University*

THE capacity of many storm-water inlets can be found by comparing the flow into the inlet with the flow into a wide opening. In this manner, formulas are derived for the design of curb-opening inlets without gutter depression, grate inlets, and combination inlets, with or without gutter depression. The formulas have been substantiated with numerous test data.

The characteristics of other types of inlet are also mentioned. It is found that the most-efficient types are the combination inlet and the grate inlet. In both cases, the grate should have only longitudinal bars. When the street grade is steep and gutter depression is considered undesirable, a curb opening with diagonal notches in the gutter may be used.

● A RESEARCH project in the Johns Hopkins University is being sponsored by Baltimore City, Baltimore County, and the Maryland State Roads Commission to investigate problems of storm drainage. The work is being done under the direction of the Department of Sanitary Engineering with the coöperation of the Department of Civil Engineering. Of the many problems in the program, one subject of study is the capacity of storm water inlets. Four papers on the subject have been published (*1*, *2*, *3*, *4*) and a booklet (*5*) is to be published shortly. In this paper, the comparative merits of different types of inlet are discussed, and formulas for the capacity of several types of inlet are derived. The derivation is released for publication for the first time and is believed to be helpful to highway engineers in understanding the hydraulic behavior of inlets.

The derived formulas for inlet capacity have been substantiated with numerous test data from models of 1-to-2 and 1-to-3 scales. The model results have also been checked with tests in the field. For the description of the model and the experimental data, the reader is referred to the references at the end of this paper.

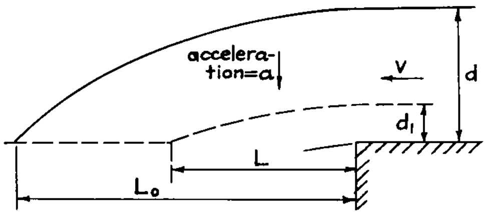


**Figure 1. Free drop at end of channel.**

### FLOW INTO A WIDE OPENING

Consider the flow at the end of an open channel with supercritical slope (Fig. 1). Assuming uniform velocity distribution in the channel, the length $L_0$ can be obtained as follows:

Since $L_0 = vt$ and $d = at^2/2$;

$$L_0 = v\sqrt{\frac{2d}{a}} \tag{1}$$

For an opening of length $L$ less than $L_0$, the depth of flow $d_1$ trapped into the opening is given by

$$L = v\sqrt{\frac{2d_1}{a}}$$

or

$$\frac{d_1}{d} = \left(\frac{L}{L_0}\right)^2 \tag{2}$$

Equations 1 and 2 are to be used for derivation of the formulas for inlet capacity. It should be mentioned that gutter flows are invariably supercritical when the street grade is one percent or more.

### LETTER SYMBOLS

In this paper, the symbols which follow are used. Other symbols used will be defined where they appear. Since only dimensionless coefficients are used in the formulas, any consistent system of units other than the foot-second system may be used.

$A$, cross-sectional area of flow at the upstream end of grate (sq. ft.), see Figure 6;
$A_0$, cross-sectional area of gutter flow (sq. ft.);
$a$, depth of gutter depression (ft.), see Figure 6;
$g$, gravitational acceleration (ft. per sec. per sec.);
$L$, length of grate or curb opening (ft.);
$L_0$, length of curb opening to capture the entire gutter flow, see Figure 2; or length of grate required to capture all the flow over the grate, see Figure 3;
$L'$, length of grate required to capture the outer portion of flow, see Figure 3;
$L_1$, length of upstream transition of gutter depression (ft.), see Figure 6;
$L_2$, length of downstream transition of gutter depression (ft.), see Figure 6;
$Q$, discharge into inlet (cu. ft. per sec.);
$Q_0$, discharge of gutter flow (cu. ft. per sec.);
$q$, carry-over flow passing the inlet (cu. ft. per sec.), see Figure 6;
$q_2$, carry-over outside the grate (cu. ft. per sec.), see Figure 3;
$q_3$, carry-over across the grate (cu. ft. per sec.), see Figure 3;
$R$, ratio of total width of clear openings between bars to width of grate;
$s$, street grade (ft. per ft.);
$v$, mean velocity of flow at upstream end of grate (ft. per sec.), see Figure 6;
$v_0$, mean velocity of gutter flow (ft. per sec.);
$v'$, mean velocity of portion of flow outside the grate, see Figure 4;
$w$, width of grate (ft.);
$y$, depth of flow at curb at the upstream end of the grate (ft.), see Figure 6;
$y_0$, depth at curb of gutter flow (ft.);
$y'$, depth of flow at outer edge of grate (ft.), see Figures 3 and 6;
$\theta$, $\theta_0$ and $\theta'$, angle between cross-section of street and the vertical, see Figures 2, 3, 6.

### CURB OPENING IN A STRAIGHT GUTTER

*Length of Opening Required to Capture the Entire Gutter Flow*

Consider the case of a curb opening in a straight gutter without local depression (Fig. 2). The *plan* view of the flow at the inlet is similar to the *elevation* of a free drop (Fig. 1). The length of opening $L_0$ required to capture all of the gutter flow can therefore be obtained.

Neglect the frictional force offered by the gutter. The acceleration towards the curb opening is $g \cdot \cos\theta_0$. The width of flow (corresponding to $d$ in Fig. 1) is $y_0 \tan\theta_0$. From Equation 1,

$$L_0 = v_0\sqrt{\frac{2y_0 \tan\theta_0}{g \cdot \cos\theta_0}}$$

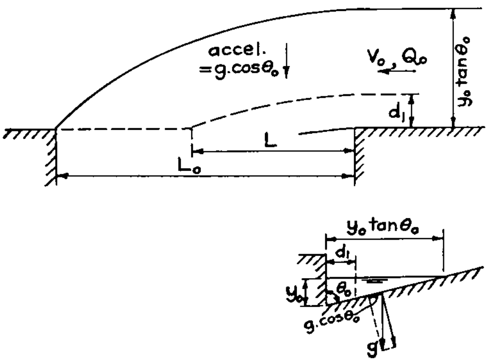


**Figure 2. Undepressed curb opening.**

Since the gutter discharge $Q_0 = v_0 y_0^2 \tan\theta_0/2$,

$$\frac{Q_0}{L_0 y_0 \sqrt{g y_0}} = \sqrt{\frac{\sin\theta_0}{8}}$$

For gutters used in practice, $\sin\theta_0$ is nearly equal to unity. Thus

$$\frac{Q_0}{L_0 y_0 \sqrt{g y_0}} = \frac{1}{\sqrt{8}} = 0.35$$

Since this expression has been obtained by neglecting the friction on the gutter, it is necessary to apply an empirical coefficient to the equation. From test data, it has been found that

$$\frac{Q_0}{L_0 y_0 \sqrt{g y_0}} = K \qquad (3)$$

where $K = 0.23$ for $\tan\theta_0 = 12$ (1 in. per ft. crown), and $K = 0.20$ for $\tan\theta_0 = 24$ and 48 (½ and ¼ inches per foot of crown respectively). The necessity of using an empirical coefficient may seem unfortunate. However, the significant fact is that the quantity on the left-hand side of Equation 3 is practically a constant. Furthermore, this empirical coefficient is one of the only three used in this paper.

*Capacity of Inlet with Length less than $L_0$*

When the actual length $L$ of curb opening is less than $L_0$, the width of flow captured is $d_1$ (Fig. 2). Comparing Figure 2 with Figure 1, we have from Equation 2

$$\frac{d_1}{y_0 \tan\theta_0} = \left(\frac{L}{L_0}\right)^2$$

Since the area of flow for a width $d_1$ in the gutter is $\left(y_0 d_1 - \frac{d_1^2}{2\tan\theta_0}\right)$, the flow $Q$ trapped into the opening is given by

$$\frac{Q}{Q_0} = \frac{y_0 d_1 - \dfrac{d_1^2}{2\tan\theta_0}}{\dfrac{y_0^2 \tan\theta_0}{2}} = 2\left(\frac{L}{L_0}\right)^2 - \left(\frac{L}{L_0}\right)^4$$

For $L/L_0$ equal to or greater than 0.6, this equation may be approximated, without introducing serious error, as

$$\frac{Q}{Q_0} = \frac{L}{L_0}$$

That is, as long as the carry-over flow past the inlet is less than about 40 percent of the gutter flow, the capacity of the inlet is practically proportional to the length of the inlet. Thus from Equation 3,

$$\frac{Q}{L y_0 \sqrt{g y_0}} = K \qquad (4)$$

where $K = 0.23$ for $\tan\theta_0 = 12$, and $K = 0.20$ for $\tan\theta_0 = 24$ and 48.

Equation 4 has been verified with numerous tests under a great variety of field conditions. In using this formula, $y_0$ can be computed from the gutter flow $Q_0$ by using any convenient formula for open channel flow. Graphs can be prepared to facilitate quick solution (*2*).

### GRATE INLET WITH LONGITUDINAL BARS IN A STRAIGHT GUTTER

In grate inlets with longitudinal bars in a straight gutter without local depression (Fig. 3), carry-over may occur in three ways: (1) flow past the inlet between the curb and the first slot (this quantity is always very small and can be neglected in practice); (2) flow outside the last slot, $q_2$; and (3) carry-over across the grate itself, $q_3$.

*Eliminating $q_2$*

To find the length of grate $L'$ required to reduce $q_2$ to zero, compare Figure 4 with Figure 2. It can be seen that the flow outside the grate is similar to the flow into a curb opening, with $L'$, $y'$, $\theta'$ and $v'$ in Figure 4 equivalent to $L_0$, $y_0$, $\theta_0$ and $v_0$ in Fig. 2. In the

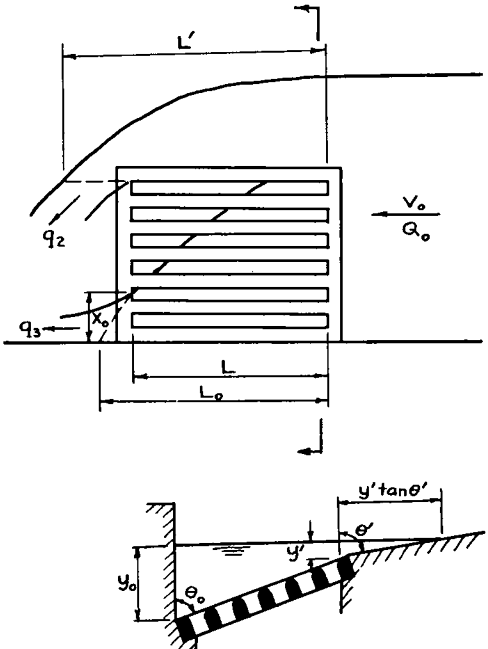


**Figure 3. Undepressed grate inlet.**

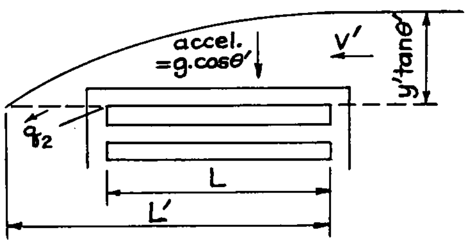


**Figure 4. Flow outside the grate.**

case of curb openings, from Equation 3,

$$\frac{Q_0}{L_0 y_0 \sqrt{g y_0}} = K$$

Since the gutter flow $Q_0 = v_0 y_0^2 \tan \theta_0 / 2$, the expression above can be reduced to

$$\frac{L_0}{v_0} \sqrt{\frac{g}{y_0}} = \frac{\tan \theta_0}{2K}$$

By similarity, for the flow outside the grate,

$$\frac{L'}{v'} \sqrt{\frac{g}{y'}} = \frac{\tan \theta'}{2K}$$

Since it is more convenient to work with the mean velocity $v_0$ in the gutter than with the mean velocity $v'$ of the portion of flow outside the grate,

$$\frac{L'}{v_0} \sqrt{\frac{g}{y'}} = \frac{v'}{2K v_0} \tan \theta'$$

From tests covering cases with width of gutter flow 25 to 100 percent greater than the width of the grate, it has been found that

$$\frac{L'}{v_0} \sqrt{\frac{g}{y'}} = 1.2 \tan \theta' \qquad (5)$$

*Carry-Over* $q_2$

When the length of the grate $L$ is less than $L'$, $q_2$ can be computed as follows: It has been demonstrated for curb-openings (see Equations 3 and 4)

$$\frac{Q}{Q_0} = \frac{L}{L_0}$$

and

$$\frac{Q_0}{L_0} = K y_0 \sqrt{g y_0}$$

Thus the carry-over flow past the curb opening is given by

$$Q_0 - Q = (L_0 - L) \frac{Q_0}{L_0} = K(L_0 - L) y_0 \sqrt{g y_0}$$

By similarity, for the flow outside the grate,

$$q_2 = K(L' - L) y' \sqrt{g y'}$$

From numerous test data, it has been found that a value of ¼ for $K$ fits the data better than either 0.23 or 0.20. Thus

$$q_2 = \tfrac{1}{4}(L' - L) y' \sqrt{g y'} \qquad (6)$$

*Eliminating Carry-Over Across Grate*

In order to eliminate the flow across the grate itself, it is necessary to have the length of grate $L$ greater than the length $L_0$ (Fig. 3). Compare this case with Figure 1, it can be seen that, if the slot openings are large compared with the width of the bars, we have from Equation 1

$$\frac{L_0}{v_0} \sqrt{\frac{g}{y_0}} = \sqrt{2}$$

Since the actual width of opening is not much greater than the width of the bars, a larger value for $L_0$ is required. Let

$$\frac{L_0}{v_0}\sqrt{\frac{g}{y_0}} = m \tag{7}$$

where the value of $m$ is greater than $\sqrt{2}$, and depends on the ratio of the width of openings to the width of the bars. For grates with bars as wide as the clear openings, it has been found that $m = 4$. For grates with thin ribs, a smaller value of $m$, say 2, may be appropriate. The same value of $m$ may be used when a few recessed transverse bars are attached to the bottom of the longitudinal bars. However, if the transverse bars are not recessed, water striking them will jump the grate, and $L_0$ needs to be larger. For example, for cast-iron grates with three transverse bars put level with the longitudinal bars at quarter points, a value of $m = 8$ seems to be appropriate.

*Carry-Over $q_3$*

For shorter grates, the carry-over $q_3$ across the grate may be estimated as follows:

At a distance $x$ from the curb, the depth of flow in the gutter is

$$y_0 - \frac{x}{\tan\theta_0} = y_0\left(1 - \frac{x}{y_0 \tan\theta_0}\right)$$

To trap this depth of flow, the length of grate required is, according to Equation 7,

$$\frac{mv_0}{\sqrt{g}}\sqrt{y_0\left(1 - \frac{x}{y_0\tan\theta_0}\right)} = L_0\sqrt{1 - \frac{x}{y_0\tan\theta_0}}$$

If the length of the grate $L$ is less than this length, the depth of flow not trapped by the grate (corresponding to the depth $d - d_1$ in Fig. 1) is given by Equation 2 as

$$y_0\left(1 - \frac{x}{y_0\tan\theta_0}\right)\left(1 - \frac{L^2}{L_0^2\left(1 - \frac{x}{y_0\tan\theta_0}\right)}\right)$$

that is,

$$y_0\left(1 - \frac{L^2}{L_0^2}\right) - \frac{x}{\tan\theta_0}$$

The width $x_0$ (Fig. 3) in which carry-over flow $q_3$ occurs is determined by setting this depth equal to zero, that is

$$x_0 = y_0 \tan\theta_0\left(1 - \frac{L^2}{L_0^2}\right)$$

To have an efficient grate, this width $x_0$ must be small compared with the width of the grate. For such cases, the carry-over flow $q_3$ may be obtained as follows:

$$q_3 = \int_0^{x_0}\left[y_0\left(1 - \frac{L^2}{L_0^2}\right) - \frac{x}{\tan\theta_0}\right] v_0\, dx$$

$$= \tfrac{1}{2} v_0 y_0^2 \tan\theta_0\left(1 - \frac{L^2}{L_0^2}\right)^2$$

or

$$q_3 = Q_0\left(1 - \frac{L^2}{L_0^2}\right)^2 \tag{8}$$

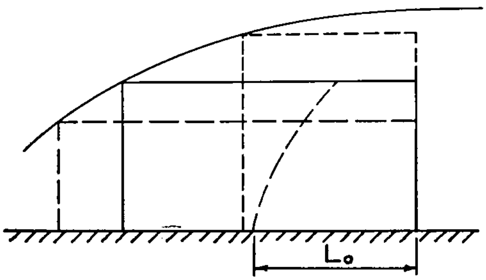


**Figure 5. Different proportions of grate.**

*Proportion of Grate*

To have a grate with no carry-over flow, it is required that the length of grate $L$ is greater than both $L'$ and $L_0$ as determined from Equations 5 and 7 respectively. From Figure 5, it can be seen that, for a given gutter flow, different values of $L'$ will be obtained from Equation 5 by using different values of grate width $w$. Structurally, a shorter and wider grate is more desirable. However, a longer and narrower grate is more efficient than a shorter and wider grate when they become clogged with debris. It should be mentioned that a grate with bars of 4-foot clear span has been found economically and structurally satisfactory in Baltimore. The grate is made of cast-steel and the bars are 1-inch by 2-inch in cross-section (*5*).

*Grate Combined with Curb Opening*

If a curb opening, with a length equal to that of the grate, is put beside the grate, the only effect on the flow is to reduce the length $L_0$. From tests with cast-iron grates, it has been found that the value of $m$ in Equation 7 is 3.3 instead of 4.

### GRATE WITH LONGITUDINAL BARS IN A GUTTER DEPRESSION

It has been demonstrated above that, for a grate with longitudinal bars in a straight gutter, Equations 5 to 8 are applicable. For the case of such a grate in a gutter depression (Fig. 6), Equations 5 and 7 will read as

$$\frac{L'}{v}\sqrt{\frac{g}{y'}} = 1.2 \tan \theta' \tag{5a}$$

$$\frac{L_0}{v}\sqrt{\frac{g}{y}} = m \tag{7a}$$

In these two equations and Equation 6, the quantities $v$, $y$, $y'$ and $\theta'$ refer to the values at the upstream end of the grate.

*The Values of v, y and y'*

The value of $y$ can be computed from the elements of the gutter flow as follows: By the principle of conservation of energy, the total head at the beginning of the upstream transition is related to that at the end of the same transition by

$$\frac{v_0^2}{2g} + y_0 + z$$
$$= \frac{v^2}{2g} + y + \text{loss of head in transition } L_1$$

Assuming that the energy gradient in the transition is practically the same as the street grade $s$ (as for the uniform gutter flow), the loss of head in the transition $L_1$ is then equal to $sL_1$. Since $z = sL_1 + a$, $v_0 = Q_0/A_0$ and $v = Q_0/A$, the expression above can be transformed into the following form:

$$\frac{Q_0^2}{2gA^2} + y = \frac{Q_0^2}{2gA_0^2} + y_0 + a \tag{9}$$

Assuming that the water surface at the upstream end of the grate is horizontal laterally, the cross-sectional area of flow $A$ is determined by the depth $y$. The depth $y$ can, therefore,

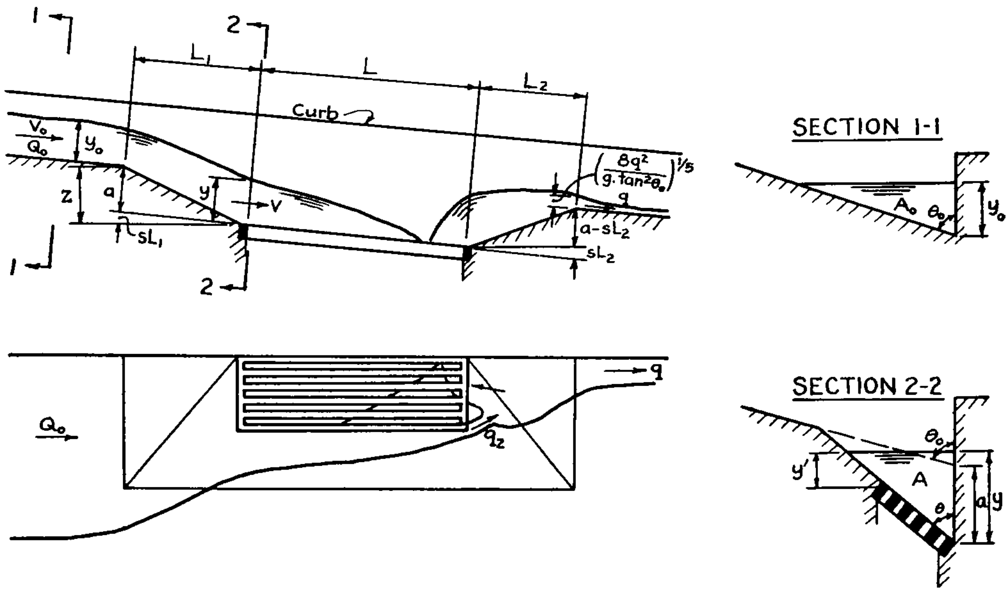


**Figure 6. Depressed grate inlet.**

be obtained from Equation 9 for a given depression under a given condition of gutter flow.

With the value of $y$ known, the values of $v$ and $y'$ can easily be computed. With these computed values, the quantities $L'$, $q_2$, $L_0$ and $q_3$ can be computed from Equations 5a, 6, 7a and 8, respectively. For the value of $m$ in Equation 7a, see the discussion following Equation 7.

*Carry-Over Flow q*

Due to the ponding at the downstream end of the depression, part of $q_2$ and $q_3$ will flow into the lower end of the grate. Since in designing an inlet, only small values of $q$ are of practical interest, the following method is suggested for finding $q$:

As gutter flow is invariably supercritical for street grades equal to or greater than 1 percent, it can safely be assumed that, for cases where $(a - sL_2)$ is greater than zero, the depth at the downstream end of the depression is equal to the critical depth, as shown in Figure 6. Since the velocity head at critical flow in a triangular channel is equal to ¼ of the critical depth, the total depth of the pond over the grate for cases with comparatively large $(a - sL_2)$ may be assumed to be

$$(a - sL_2) + \frac{5}{4}\left(\frac{8q^2}{g \cdot \tan^2 \theta_0}\right)^{1/5}$$

Using this depth, the discharge into the lower end of the grate may be approximated by the discharge formula for a triangular weir with the conventional value of 0.6 as the coefficient of discharge. Thus

$$q_2 + q_3 - q = 0.226\, R\sqrt{g}\tan\theta \cdot \left[(a - sL_2) + \frac{5}{4}\left(\frac{8q^2}{g \cdot \tan^2 \theta_0}\right)^{1/5}\right]^{5/2} \qquad (10)$$

where $R$ = ratio of the total width of clear openings to the width of grate, usually about 0.5 to 0.6 for cast-iron or cast-steel grates. The solution of Equation 10 is shown graphically in Figure 7.

*Design Procedure*

In summary, the design of an inlet for a given gutter flow can be performed by first computing the values of $v$ and $y$ according to Equation 9, using the maximum allowable depression depth. Compute the minimum length $L_0$ for avoiding carry-over across the grate from Equation 7a. Use a length of grate $L$ equal to or greater than $L_0$, thus making $q_3 = 0$. Assume a width of grate, and compute $q_2$ according to Equations 5a and 6. Compute $q$ from Equation 10 or Figure 7. If this computed $q$ is too large, try a longer or wider grate. This method of computing inlet capacity has been found to give good results with carry-over flow up to 10 percent of the gutter flow.

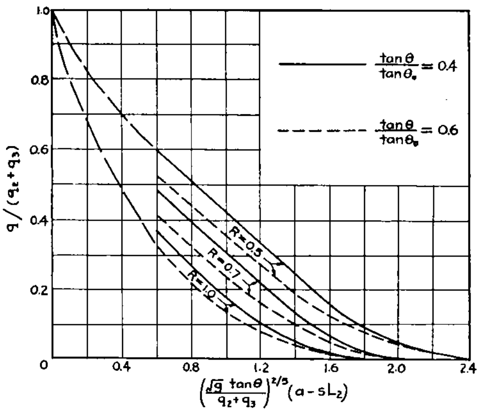

**Figure 7. Carry-over $q$ from depressed grate inlets.**

*Grate Combined with Curb Opening*

When a curb opening is built beside the grate, the minimum required length of grate $L_0$ is decreased and the carry-over flow $q$ is less because of a larger discharge into the lower end of the inlet. The curb opening also serves as a relief outlet when the grate is clogged.

The capacity of inlet can be found in the same way as for the case of a grate without the curb opening, with a smaller value of $m$ in Equation 7a. For grates with bars as wide as the clear openings between bars, a value of 3.3 may be used for $m$.

OTHER TYPES OF INLET

Besides the inlets described above, other types have also been investigated. Their characteristics are briefly discussed below.

### *Curb Opening in a Gutter Depression*

The capacity of a curb opening in a gutter depression is generally less than that of a depressed grate inlet with longitudinal bars of about the same cost. For the method of computing the capacity of depressed curb openings, the reader is referred to Reference 2.

### *Grates with Transverse Bars or Combination of Transverse and Longitudinal Bars*

Grates with transverse bars or with combination of transverse and longitudinal bars are found to be less efficient than grates of the same size with longitudinal bars only (*4*, *5*). Generally speaking, the most-efficient inlet for general use is the grate with longitudinal bars, together with a curb opening in a gutter depression if possible. The curb opening serves as a relief outlet when the grate gets clogged.

### *Grate Combined with Curb Opening Upstream or Downstream*

Some increase of capacity is obtained by putting a curb opening upstream or downstream instead of by the side of the grate, but this increase is insignificant when grates with longitudinal bars are used (*4*, *5*).

### *Undepressed Curb Opening with Diagonal Notches in Gutter*

Unlike other types of inlet, curb openings with diagonal notches in the gutter (Fig. 8) have higher capacity with steeper street grade. When the street grade is 5 percent or more, their capacity even exceeds that of undepressed combination inlets of the same length. Field tests show that the notches are self-cleaning and that they offer no disturbance to driving. For the method of computing the capacity of these curb openings, see Reference 3.

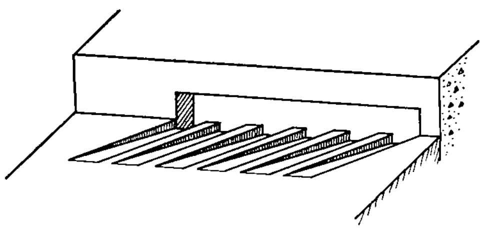

**Figure 8. Curb opening with diagonal notches in gutter.**

## CONCLUSION

In this paper, formulas for several types of storm-water inlets have been derived. These formulas have been substantiated with numerous test data. Graphs can be prepared according to these formulas to facilitate quick solution as demonstrated in References 1 to 5.

It can be seen from these formulas that the capacity of an inlet depends not only on its size, but also on the street crown, street grade, and the gutter flow. Generally speaking, the greater the crown, the higher the capacity. The greater the street grade, the less the amount of water flowing into the inlet (except for the case of curb openings with diagonal notches in the gutter). The larger the gutter flow, the greater the discharge into the inlet and the carry-over flow. In the case of inlets with grates, the capacity is greatly increased by allowing a small amount of carry-over flow.

When gutter depression is not permissible, grate inlets or combination inlets are preferable when the street grade is less than 5 percent. At steeper grades, curb openings with notches in the gutter are more economical. When gutter depression is permissible, grate inlets or combination inlets should be used. The grate should have longitudinal bars only with, if desired, a few small laterals attached to the bottom of the bars.

The purpose of this paper is to present a simple derivation of formulas useful in the design of inlets, and to outline the findings of a research project. For examples of design, see References 1 to 4. For further discussion on the subject and for calibration curves for different types of inlets, the reader is referred to Reference 5.

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# Relation between Automobile and Highway

K. A. Stonex, *Head, Technical Data Department*
*General Motors Proving Ground*

The purpose of this paper is to review briefly the more-important characteristics of automotive vehicles with respect to the requirements they impose upon highway design and particularly upon the design of highway systems.

The motivating force behind the development of the automotive transportation system is a compelling urge within the individual for a high degree of flexible private mobility. As a result of this urge we now have approximately 45 million privately owned cars on the road, and the American public travels somewhat more than 500 billion miles each year. The significance of the automobile in modifying the American way of life during the past generation has not yet been generally appreciated, nor is the probable future effect generally understood.

A review of accident fatalities shows that there has been a consistent reduction in the mileage rate of fatal accidents; what is seldom emphasized is the more-important fact that the total number of fatalities has leveled off and remained nearly constant during the past 20 years in spite of the tremendous increase in total miles traveled. Much has been accomplished and much remains in highway layout and highway system design to further improve the fatal-accident picture. A major cause of accidents is inattention, and highway design should continue to eliminate obstacles, provide more maneuver room, separate traffic, segregate traffic types, and provide alternate and bypass routes to distribute rather than concentrate traffic flow.

It is shown that fuel consumption of automotive vehicles increases very sharply with curvature and gradient, and that the ideal design of highway systems from the standpoint of cost of fuel would be to build roads level and straight. This is consistent also with the best mobility of traffic and the greatest safety.

We accept the fact that the inadequacy of our present highway system has resulted from lack of funds and not lack of engineering competence on the part of highway designers. A significant increase in expenditure is required to bring the highway system capacity into balance with the demands of the public. For this reason highway policy must be to select the best uses for available funds to accomplish long range construction programs, rather than to move from one expedient to another, and to look with suspicion upon proposals which may divert funds from maintenance and construction.

● THE automobile industry and the highway designers and builders are partners in our great transportation system; highway transportation is more than a major industry, it is a sociological factor of such magnitude as to be a major component of the American way of life. The function of the automobile industry and the highway designers and builders is to provide the best possible tools to aid in the continued development of highway trans-