TECHNOTE

Curb-Opening Inlet Interception On Grade

FHWA Publication No.: FHWA-HRT-22-061

FHWA Contact: Dr. Kornel Kerenyi, HRDI-40, Hydraulics Research Program Manager, Turner-Fairbank Highway Research Center, 202 493-3142, Kornel.Kerenyi@dot.gov

TABLE OF CONTENTS

INTRODUCTION AND NEED

Without adequate drainage, stormwater can accumulate on road surfaces creating safety hazards including vehicle hydroplaning, road spray, and obscured roadway markings. Therefore, it is essential for designers to have tools that accurately represent water accumulation, movement, and capture within the roadway environment so that criteria for allowable spread and depths on pavements for the applicable storm conditions can be met with confidence. This Technical Note (TechNote) addresses a subset of pavement drainage design on the performance of curb-opening inlets on grade.

Curb-opening inlet capacity depends on the inlet dimensions, longitudinal slope, gutter and roadway cross slope, local depression, and approach flow characteristics. Curb-opening inlets are effective at capturing flow from the roadway in many situations and designers commonly use them. The Federal Highway Administration's (FHWA) Hydraulic Engineering Circular 22 (HEC-22), *Urban Drainage Design Manual* (FHWA 2009) presents an equation (4-22) for estimating curb-opening inlet length to achieve 100 percent capture of the approaching gutter flow, which is adapted as follows:

$$L_t = K_u Q^{0.42} S_L^{0.3} \left(\frac{1}{nS_x} \right)^{0.6} \qquad (1)$$

Where:

L_t = Curb-opening inlet length required to intercept 100 percent of gutter flow.

K_u = Unit conversion constant: 0.6 in customary units (CU) (0.817 metric units (SI)).

Q = Gutter flow in ft^3/s (m^3/s).

S_L = Longitudinal slope in ft/ft (m/m).

S_x = Cross slope in ft/ft (m/m).

n = Manning's roughness coefficient.

Figure 1 illustrates pertinent variables in the equation and depicts the curved shape of the narrowing of the spread in the down-gradient direction as water is captured by the inlet. This equation, originally derived by Izzard (1950), uses a weir analogy for flow entering the curb opening, and assumes that the head driving the flow varies linearly from the up-gradient end of the curb opening to the down-gradient end. Schalla (2016) and Muhammad (2018) performed laboratory experiments on curb-opening inlet interception on grade and reviewed the development of the HEC-22 equation. They concluded that the HEC-22 equation underestimates the curb-opening length needed for 100 percent interception because

U.S. Department of Transportation
Federal Highway Administration

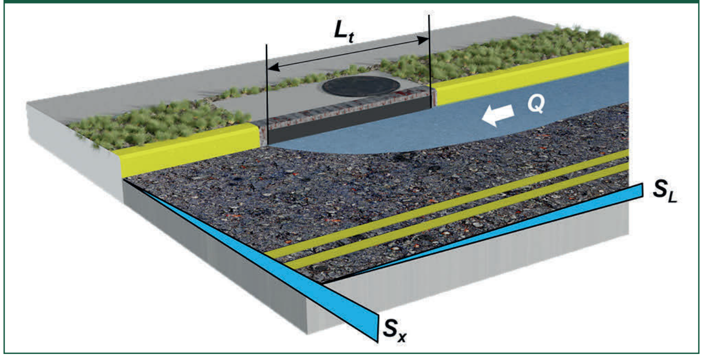
Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

https://highways.dot.gov/research

the head does not vary linearly as assumed but drops more quickly, thereby reducing interception. This finding is important for roadway safety because more water may be bypassing the inlet than intended by designers using the HEC-22 equation in some circumstances.

The objective of the research described in this TechNote was to develop an improved method for designing curb-opening inlets on grade. To accomplish this objective, FHWA researchers reviewed the HEC-22 curb-opening interception methodology and its development, reviewed subsequent research on the topic, and conducted a series of numerical experiments using computational fluid dynamics (CFD). This TechNote describes the research findings, outlines the semiempirical recommendations from the research, and provides the literature cited.

Figure 1. Illustration. 100 percent capture and pavement (gutter) slope definitions.



Source: FHWA.

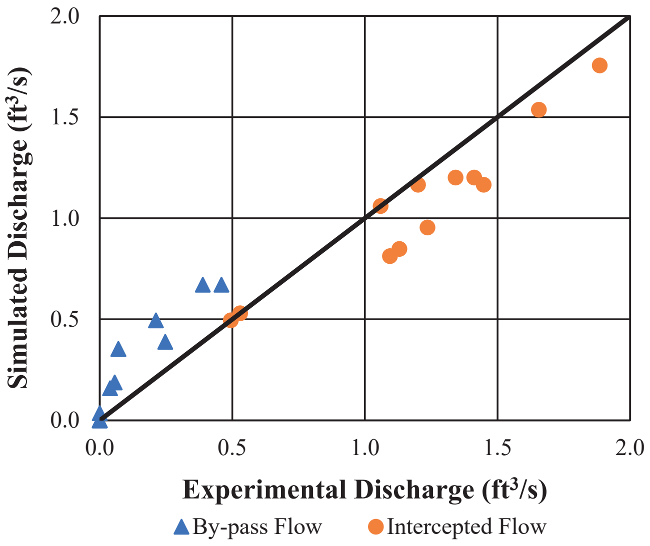
RESEARCH FINDINGS

FHWA researchers conducted a series of CFD simulations to complement and validate the laboratory experiments of Schalla (2016) and Muhammad (2018). The researchers performed the following CFD simulations:

- Curb-opening lengths (*L*) of 5, 10, and 15 ft.
- Cross slopes (S_x) of 0.02, 0.04, and 0.06 ft/ft.
- Longitudinal slopes (S_L) of 0.001, 0.005, 0.01, 0.02, 0.03, 0.04, and 0.05 ft/ft.

Figure 2 summarizes a validation of the FHWA CFD simulations against Schalla's experiments (2016). The figure indicates that the CFD results are mildly conservative (less interception and more bypass) compared with the laboratory results. FHWA researchers also compared results from this research to the laboratory experiments from Muhammad (2018), and the results from Hammons and Holley (1995). FHWA researchers discarded six of the simulations from further analysis because fully developed flow was not achieved in the CFD domain, or the results were considered outliers influenced by the prescribed upstream boundary conditions, or both. The six discarded simulations were for S_L equal to 0.04 ft/ft and 0.05 ft/ft for S_x equal to 0.02 ft/ft for all three curb-opening lengths (5, 10, and 15 ft).

Figure 2. Graph. Comparison of the experimental results of Schalla (2016) and the FHWA CFD simulations.



Source: FHWA.

Figure 3 illustrates a CFD representation of a curb-opening inlet capturing 100 percent of the approaching gutter flow. As shown in the figure, the origin of the *x* and *y* directions is defined at the invert of the up-gradient end of the curb opening. Consistent with the findings of Schalla (2016) and Muhammad (2018), Figure 3 does not show a linear water surface elevation from the up-gradient to down-gradient ends of the curb-opening inlet as assumed by Izzard (1950) and FHWA (2009). Instead, the profile approximates a parabolic curve that can be written as follows:

$$y_* = K\left(1 - x_*\right)^2 \qquad (2)$$

Where:

y_* = Dimensionless water depth along the curb-opening inlet ($y_* = y/E$).

x_* = Dimensionless distance along the curb-opening inlet ($x_* = x/L$).

x = Longitudinal distance from the up-gradient end of the curb-opening inlet.

y = Depth of flow at the curb at a distance x.

K = Profile constant.

L = Curb-opening inlet length.

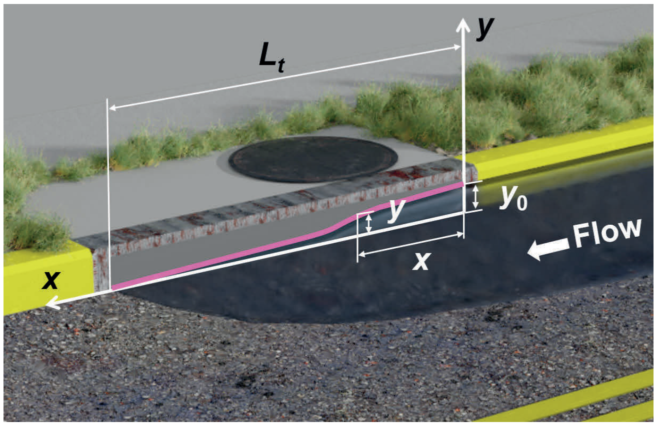
E = Specific energy at the curb-opening inlet.

Note that L represents any curb-opening length. L_t represents the length for 100 percent capture.

From equation 2, when $x_* = 0$, then:

$$K = y_* = y_0 / E \qquad (3)$$

Figure 3. Illustration. Steady, spatially varied flow at a curb-opening inlet with 100 percent capture.



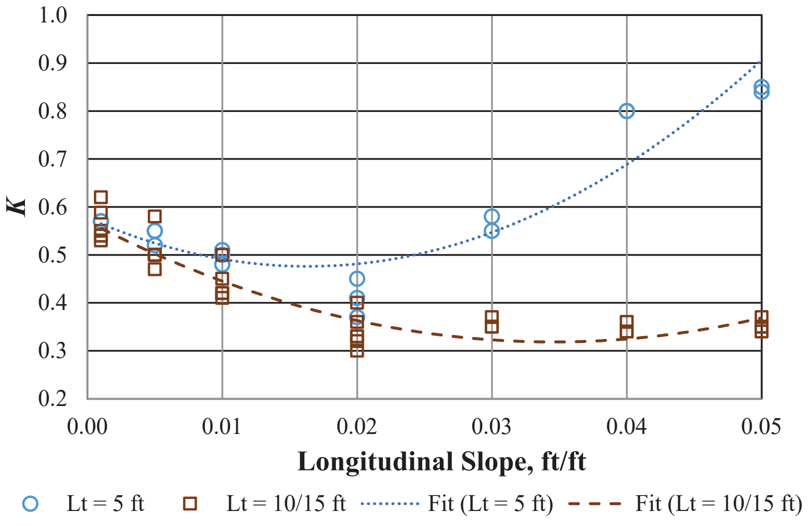
Source: FHWA.

Where y_0 is the water depth at the up-gradient end of the curb-opening inlet.

Therefore, K represents the ratio of water depth to specific energy (depth plus velocity head) at the up-gradient end of the curb opening at the curb edge of the gutter. The specific energy (E) is assumed to be constant over the length of the curb-opening inlet, i.e., energy loss is neglected.

Researchers derived K by fitting the results from the CFD simulations. Figure 4 summarizes the estimates of K for three curb-opening inlet lengths (5, 10, and 15 ft) for longitudinal slopes ranging from 0.001 to 0.04 ft/ft. FHWA researchers found that K varied insignificantly with cross slope, S_x, for the cross slopes tested.

Figure 4. Graph. CFD simulation results for *K* based on inlet length and longitudinal slope.



Source: FHWA.

Figure 4 also displays second order polynomial fits to the data for each inlet length. The observations for the 10- and 15-ft inlets were sufficiently close that they were grouped together; therefore, the equations for these two lengths are the same. The equations for each fitted line, along with the *R*-squared goodness of fit are as follows:

$$K_5 = 379 S_L^2 - 12.4 S_L + 0.577 \quad \left(R^2 = 0.849\right) \tag{4}$$

$$K_{10} = 211 S_L^2 - 14.6 S_L + 0.570 \quad \left(R^2 = 0.872\right) \tag{5}$$

$$K_{15} = 211 S_L^2 - 14.6 S_L + 0.570 \quad \left(R^2 = 0.872\right) \tag{6}$$

Where *K* is the profile constant for curb-opening lengths (*L*) = 5, 10, and 15 ft.

For curb-opening lengths (*L*) other than 5, 10, and 15, the profile constant (*K*) can be interpolated from these values and, within limits discussed later, extrapolated.

As a result of the theoretical development of flow over a zero-height (no flow obstruction) side weir combined with the results from the CFD simulations, FHWA researchers developed the following equation for 100 percent curb-opening inlet interception capacity:

$$Q = \left[0.67\, M\, L_t \sqrt{g}\, E^{1.5}\right]\left(\frac{\gamma_1}{\beta_{S1}}\right) \tag{7}$$

Where:

Q = Flow captured by the curb-opening inlet in ft^3/s (m^3/s).

M = Side weir flow coefficient.

L_t = Curb-opening inlet length for 100 percent capture in ft (m).

g = Gravitational acceleration in 32.2 ft/s^2 (9.81 m/s^2).

E = Specific energy at the up-gradient end of the curb-opening inlet in ft (m).

β_{S1} = Slope adjustment factor ($\beta_{S1} = 0.44 S_L^{-0.19}$).

γ_1 = Risk modification factor (equals 0.88).

Appendices A and B summarize the development of the slope adjustment factor and risk modification factor, respectively. For the 100 percent capture condition, flow captured by the inlet is the same as the flow in the gutter. Solving for inlet length as follows:

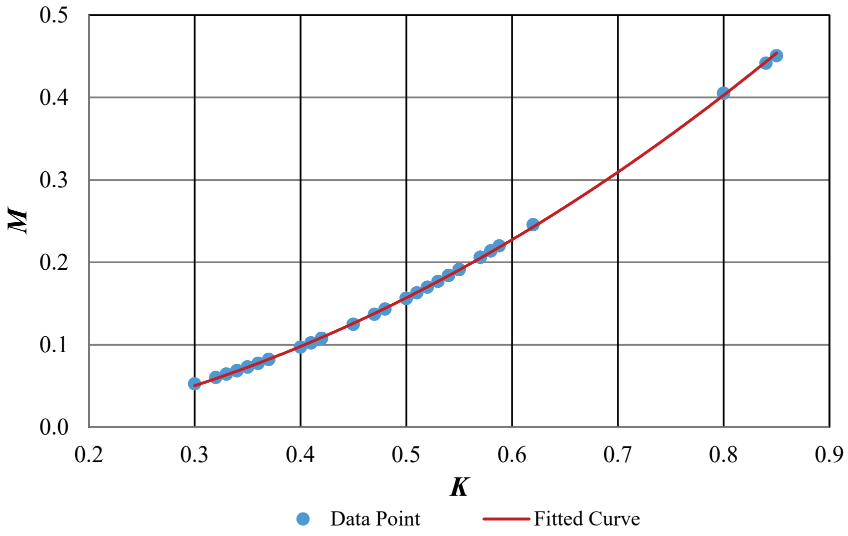
$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M \sqrt{g} E^{1.5}} \tag{8}$$

Figure 5 illustrates the relationship between the profile constant, *K*, and the side weir flow coefficient, *M*. The figure also shows the polynomial fit for the relationship, which is as follows:

$$M = 0.573\, K^2 + 0.0743\, K - 0.0235 \quad (R^2 = 0.999) \tag{9}$$

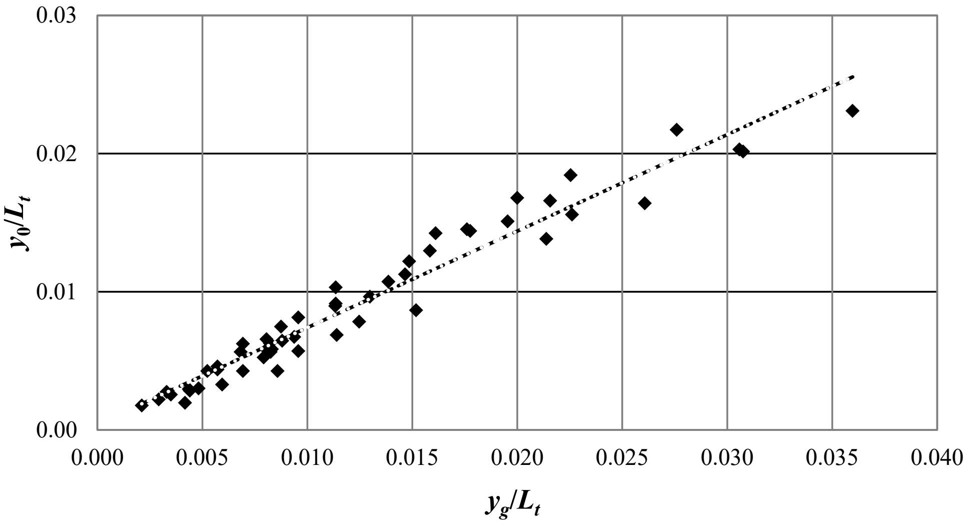
The relationship of the side weir flow coefficient (*M*) to *K* is consistent with the literature, e.g., Hagar (1987), that found relationships between Froude number and the side weir flow coefficient. The profile constant (*K*) represents the ratio of the flow depth to specific energy at the upstream end of the curb opening, which is related to the Froude number and other geometric and hydraulic conditions in the gutter.

Figure 5. Graph. Relationship between side weir flow coefficient, *M*, and profile constant, *K*.



Source: FHWA.

Figure 6. Graph. Comparison of normalized gutter (y_g) and curb-opening depths (y_0).



Source: FHWA.

To apply equation 7 or equation 8, a designer needs the water depth, y_0, at the up-gradient end of the curb-opening inlet to compute the specific energy (E). Typically, designers will have the depth in the gutter upstream where uniform flow prevails (y_g) but not at the up-gradient end of the curb-opening inlet. Uniform flow prevails until the presence of the curb opening begins to alter the flow field toward the inlet.

Based on the CFD simulations, FHWA researchers compared these depths, normalized by curb inlet opening length, and summarized the relationship in Figure 6. Figure 6 also shows the best-fit linear relationship forcing the line through the origin ($R^2 = 0.986$) and then multiplying both sides by L_t:

$$y_0 = \alpha y_g \qquad (10)$$

Where:

α = Constant equal to 0.72.

y_g = Water depth in the gutter (at the curb) where uniform flow prevails in ft (m).

Because all of the CFD simulations were for conditions where y_0 was less than or equal to the curb-opening height, this relation is only applicable to the same situations.

FHWA researchers also developed an alternative approach expressed in terms of gutter parameters. It is based on the modified Manning's equation from HEC-22 (equation 4-2) as follows (FHWA 2009):

$$Q = \left(\frac{K_u}{n}\right) S_x^{1.67} S_L^{0.5} \left(\frac{y_g}{S_x}\right)^{2.67} \qquad (11)$$

Where:

Q = Gutter flow in ft^3/s (m^3/s).

K_u = Unit conversion constant in 0.56 in CU (0.376 in SI).

Using equation 3 and equation 10, $E = (\alpha y_g/K)$. Substituting this relation into equation 7 and then replacing y_g with equation 11 reduces to curb-opening inlet length for 100 percent capture as follows:

$$L_t = \frac{K_u^{0.56} K^{1.5}}{\alpha^{1.5}\, 0.67 M \sqrt{g}} \left(\frac{Q \beta_{S2}}{\gamma_2}\right)^{0.44} S_L^{0.28} \left(\frac{1}{n S_x}\right)^{0.56} \qquad (12)$$

Where:

K_u = Unit conversion constant, 1.216 in CU (0.817 in SI).

β_{S2} = Slope adjustment factor ($\beta_{S2} = 0.043\, S_L^{-0.50}$).

γ_2 = Risk modification factor (equals 0.79).

Solving for flow given the inlet length as follows:

$$Q = \left[L_t \Big/ \left(\frac{K_u^{0.56} K^{1.5}}{\alpha^{1.5}\, 0.67 M \sqrt{g}} S_L^{0.28} \left(\frac{1}{n S_x}\right)^{0.56} \right) \right]^{2.3} \left(\frac{\gamma_2}{\beta_{S2}}\right) \qquad (13)$$

EVALUATION

For each of the CFD simulations, Figure 7 displays the computed versus simulated discharge for the recommended equation (equation 8), the alternate equation (equation 12), and the HEC-22 equation (equation 1). The figure also includes a line representing the 1:1 match between computed and simulated discharges. The computed values for the recommended and alternate equations are with a risk modification factor equal to one. Figure 8 provides a closer view of the same data displayed in Figure 7 for simulated flows less than 3 ft^3/s.

Table 1 summarizes the performance of the equations represented by the ratios of the computed to the simulated flows. The mean ratio of the recommended equation is 0.98 with a standard deviation of 0.09. Table 1 also contains the root mean square error (RMSE) metric for comparison.

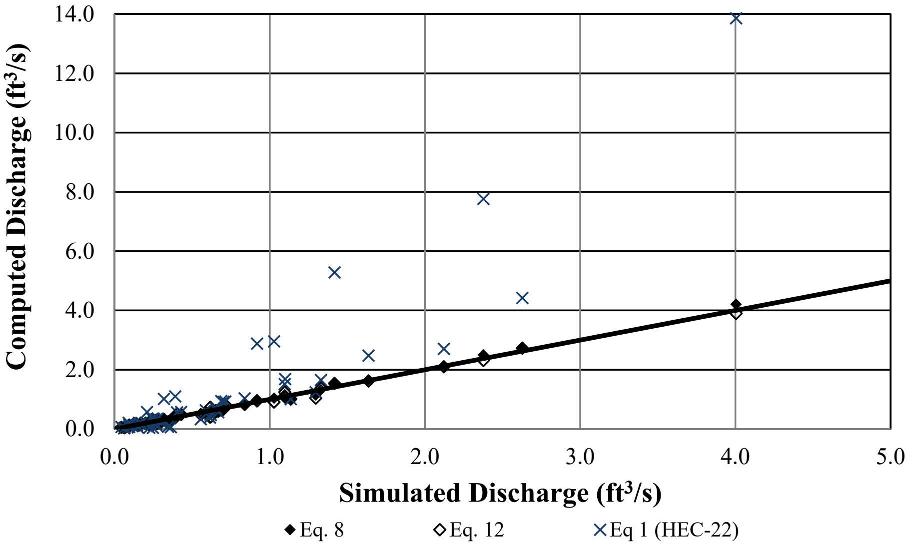
The HEC-22 equation (equation 1) generally overestimates the flow accepted by the curb opening inlet (FHWA 2009). The recommended equation (equation 8) and the alternate equation (equation 12) exhibit much lower RMSE errors than the HEC-22 equation. The recommended and alternate equations show a ratio close to one with the risk modification factor (γ) equal to one (no risk adjustment) with conditions where they overestimate and conditions where they underestimate. With the recommended risk modification factors appropriate for design, the equations become more conservative, with the mean ratio decreasing and the RMSE increasing.

Table 1. Summary of equation performance based on the CFD simulations.

Equation	Ratio Mean	Ratio Standard Deviation	RMSE (ft^3/s)
Equation 8 (recommended) with γ_1 = 1	0.98	0.09	0.06
Equation 12 (alternate) with γ_2 = 1	0.96	0.19	0.09
Equation 8 (recommended) with γ_1 = 0.87	0.87	0.08	0.11
Equation 12 (alternate) with γ_2 = 0.73	0.76	0.15	0.24
Equation 1 (HEC-22)	1.33	0.89	1.73

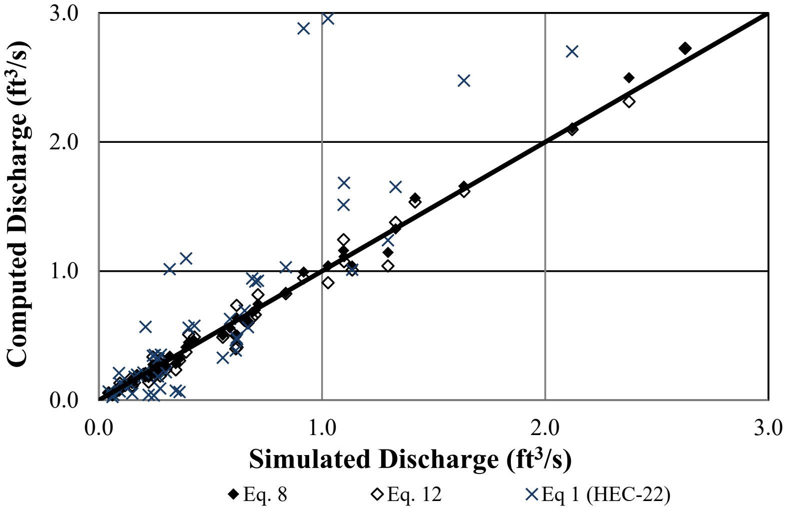
This comparison was based on computing a flow based on a curb-opening length. Designers generally compute a curb-opening length based on a flow rate. For all three equations, overestimating flow given a curb-opening length also means underestimating the needed curb opening length to capture 100 percent of flow.

Figure 7. Graph. Comparison of computed and simulated discharge.



Source: FHWA.

Figure 8. Graph. Comparison of computed and simulated discharge less than 3ft^3/s.



Source: FHWA.

APPLICATIONS AND RECOMMENDATIONS

This FHWA research provides a recommended equation intended to replace the existing equation in HEC-22 (equation 4-22) for estimating curb-opening inlet length on grade for 100 percent capture (FHWA 2009). Related procedures for interception for inlets shorter than required for 100 percent interception and for composite gutters remain the same. HEC-22 equation 4-23 is used for the former situation based on the estimated 100 percent curb-opening inlet length (L_t) estimated from the recommended equation (FHWA 2009). HEC-22 equation 4-24 is used to compute an equivalent cross slope for composite gutters that is used in place of the cross slope (S_x) in the recommended equation from this research (FHWA 2009).

Example applications of the recommended equation are provided in this section and are compared with results from the alternate equation and the existing HEC-22 equation. The recommended equation is applied in the following steps:

1. Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).
2. Assume a curb-opening inlet length for 100 percent interception (L_t).
3. Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.
4. Determine the specific energy (E) at the upstream end of the curb opening.
5. Estimate L_t from the recommended equation.

If the result of step 5 is close to the assumption in step 2, the process is complete. If not, a new curb-opening inlet length is selected and the designer repeats steps 2 through 5. The iteration continues until the designer is satisfied that further iterations will not affect the design length. The following examples demonstrate the iteration process.

Step 1 establishes the hydraulic conditions approaching the curb-opening inlet on grade whether the approaching gutter is uniform, composite, or locally depressed at the inlet. HEC-22 describes the use of an equivalent cross slope that is used to iteratively compute the spread and depth at the curb for composite or locally depressed inlets (FHWA 2009). The recommended approach does not alter this procedure.

The alternate equation is applied in the following steps:

1. Assume a curb-opening inlet length for 100 percent interception (L_t).
2. Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.
3. Estimate L_t from the alternate equation.

Steps 1 and 4 from the recommended equation are not needed for the alternative approach because the gutter equation has been incorporated into the alternate equation. The alternate equation also requires an iterative process for estimating L_t.

Example One

Given a uniform gutter section, find the required curb-opening length to intercept 100 percent of a 0.252 ft^3/s design flow. This example illustrates each of the three methods. Given:

$S_L = 0.005$ ft/ft.
$S_x = 0.02$ ft/ft.
$n = 0.016$.

Application of the HEC-22 Approach (Equation 1)

Step 1. **Estimate L_t.**

$$L_t = K_u Q^{0.42} S_L^{0.3} \left(\frac{1}{nS_x}\right)^{0.6} = (0.6)(0.252)^{0.42}(0.005)^{0.3}\left(\frac{1}{(0.016)(0.02)}\right)^{0.6} = 8.6 \text{ ft}$$

Application of the Recommended Approach (Equation 8)

Step 1. **Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).**

Start with calculating depth in the gutter using the HEC-22 gutter equation.

$$T = \left[(Qn)/\left(K_u S_x^{1.67} S_L^{0.5}\right)\right]^{0.375} = \left[((0.252)(0.016))/\left((0.56)(0.02)^{1.67}(0.005)^{0.5}\right)\right]^{0.375} = 4.9 \text{ ft}$$

$$y_g = T\,S_x = (4.9)\,(0.02) = 0.098 \text{ ft}$$

Step 2. **Assume a curb-opening inlet length for 100 percent interception (L_t).**

Assume a 10 ft inlet.

Step 3. **Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.**

Find K using equation 5.

$$K_{10} = 211\,S_L^2 - 14.6\,S_L + 0.570 = 211\,(0.005)^2 - 14.6\,(0.005) + 0.570 = 0.502$$

Find M using equation 9.

$$M = 0.573\,K^2 + 0.0743\,K - 0.0235 = 0.573\,(0.502)^2 + 0.0743\,(0.502) - 0.0235 = 0.158$$

Step 4. **Determine the specific energy (E) at the upstream end of the curb opening.**

Use equation 10 to estimate depth at the up-gradient end of the inlet:

$$y_0 = 0.72\,y_g = 0.72\,(0.098) = 0.070 \text{ ft}$$

$$E = y_0 / K = 0.070 / 0.502 = 0.140 \text{ ft}$$

Step 5. **Estimate L_t from the recommended equation.**

$$\beta_{S1} = 0.44 S_L^{-0.19} = 0.44(0.005)^{-0.19} = 1.210$$

$$\gamma_1 = 0.88$$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M \sqrt{g} E^{1.5}} = \frac{0.252(1.210)}{(0.88)(0.67)(0.158)\sqrt{32.2}\,(0.140)^{1.5}} = 10.9 \text{ ft}$$

A length of 10.9 ft is greater than the 10-ft length assumed in step 2. Repeat the computations assuming a longer L_t in step 2.

Step 2. (second iteration). Assume a curb-opening inlet length for 100 percent interception (L_t).

Assume a 10.9 ft inlet. (Note that K does not change in this range, so the length produced in the first iteration is a good choice.)

Step 3. (second iteration). Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.

Find K using equation 5 or equation 6. Interpolation is not necessary as they are the same.

$$K_{10} = 211\left(0.005\right)^2 - 14.6\left(0.005\right) + 0.570 = 0.502$$

Find M using equation 9.

$$M = 0.573\ (0.502)^2 + 0.0743\ (0.502) - 0.0235 = 0.158$$

Step 4. (second iteration). Determine the specific energy (E) at the upstream end of the curb opening.

$y_0 = 0.070$ ft (does not change from the previous iteration)

$E = y_0 / K = 0.070 / 0.502 = 0.140$ ft

Step 5. (second iteration). Estimate L_t from the recommended equation.

$\beta_{S1} = 1.210$

$\gamma_1 = 0.88$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M\sqrt{g}E^{1.5}} = \frac{0.252\left(1.210\right)}{\left(0.88\right)\left(0.67\right)\left(0.158\right)\sqrt{32.2}\left(0.140\right)^{1.5}} = 10.9 \text{ ft}$$

As expected, the calculated result matches the assumed length in step 2. Therefore, $L_t = 10.9$ ft. No further iterations are needed. If L had been estimated between 5 and 10 ft, an interpolation of K would be needed.

Application of the Alternative Approach (Equation 12)

Step 1. Assume a curb-opening inlet length for 100 percent interception (L_t).

Assume a 10 ft inlet.

Step 2. Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.

Find K using equation 5.

$$K_{10} = 211\ S_L^2 - 14.6\ S_L + 0.570 = 211\left(0.005\right)^2 - 14.6\left(0.005\right) + 0.570 = 0.502$$

Find M using equation 9.

$$M = 0.573\ K^2 + 0.0743\ K - 0.0235 = 0.573\ (0.502)^2 + 0.0743\ (0.502) - 0.0235 = 0.158$$

Example One (continued)

Step 3. Estimate L_t from the alternate equation.

$\alpha = 0.72$

$$\beta_{S2} = 0.043 S_L^{-0.50} = 0.043\left(0.005\right)^{-0.50} = 0.608$$

$\gamma_2 = 0.79$

$$L_t = \frac{K_u^{0.56} K^{1.5}}{\alpha^{1.5} 0.67 M \sqrt{g}} \left(\frac{Q\beta_{S2}}{\gamma_2}\right)^{0.44} S_L^{0.28} \left(\frac{1}{nS_x}\right)^{0.56}$$

$$= \frac{\left(1.216\right)^{0.56}\left(0.502\right)^{1.5}}{0.72^{1.5}\left(0.67\right)\left(0.158\right)\sqrt{32.2}} \left(\frac{0.252(0.608)}{0.79}\right)^{0.44} \left(0.005\right)^{0.28} \left(\frac{1}{\left(0.016\right)\left(0.02\right)}\right)^{0.56} = 10.8 \text{ ft}$$

A length of 10.8 ft is greater than 10 ft, which was initially assumed. Repeat the computations assuming a longer L. The iteration yields a final curb length of 10.8 ft. (See Example One, Application of the Recommended Approach, for an illustration of the iteration process.)

Example Two

Given a uniform gutter section, find the required curb-opening length to intercept 100 percent of a 0.654 ft³/s design flow. The following example illustrates each of the three methods.

Given:

$S_L = 0.03$ ft/ft.
$S_x = 0.04$ ft/ft.
$n = 0.016$.

Application of the HEC-22 Approach (Equation 1)

Step 1. Estimate L_t.

$$L_t = K_u Q^{0.42} S_L^{0.3} \left(\frac{1}{nS_x}\right)^{0.6} = \left(0.6\right)\left(0.654\right)^{0.42}\left(0.03\right)^{0.3}\left(\frac{1}{\left(0.016\right)\left(0.04\right)}\right)^{0.6} = 14.5 \text{ ft}$$

Application of the Recommended Approach (Equation 8)

Step 1. Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).

Start with calculating depth in the gutter using the HEC-22 gutter equation.

$$T = \left[\left(Qn\right)/\left(K_u S_x^{1.67} S_L^{0.5}\right)\right]^{0.375} = \left[\left(\left(0.654\right)\left(0.016\right)\right)/\left(\left(0.56\right)\left(0.04\right)^{1.67}\left(0.03\right)^{0.5}\right)\right]^{0.375} = 3.24 \text{ ft}$$

$y_g = T\,S_x = (3.24)\,(0.04) = 0.130$ ft

Example Two (continued)

Step 2. **Assume a curb-opening inlet length for 100 percent interception (L_t).**

Assume a 15 ft inlet.

Step 3. **Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.**

Find K using equation 6.

$$K_{15} = 211\, S_L^2 - 14.6\, S_L + 0.570 = 211\left(0.03\right)^2 - 14.6\left(0.03\right) + 0.570 = 0.322$$

Find M using equation 9.

$$M = 0.573\, K^2 + 0.0743\, K - 0.0235 = 0.573\, (0.322)^2 + 0.0743\, (0.322) - 0.0235 = 0.060$$

Step 4. **Determine the specific energy (E) at the upstream end of the curb opening.**

Use equation 10 to estimate depth at the up-gradient end of the inlet:

$$y_0 = 0.72\, y_g = 0.72\, (0.130) = 0.093 \text{ ft}$$

$$E = y_0 / K = 0.093 / 0.322 = 0.290 \text{ ft}$$

Step 5. **Estimate L_t from the recommended equation.**

$$\beta_{S1} = 0.44 S_L^{-0.19} = 0.44\left(0.03\right)^{-0.19} = 0.861$$

$$\gamma_1 = 0.88$$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M \sqrt{g} E^{1.5}} = \frac{0.654\left(0.861\right)}{\left(0.88\right)\left(0.67\right)\left(0.060\right)\sqrt{32.2}\left(0.290\right)^{1.5}} = 18.0 \text{ ft}$$

A length of 18.0 ft is greater than the 15-ft length assumed in step 2. Repeat the computations assuming a longer L_t in step 2. Since the 10- and 15-ft lengths have the same K value, the extrapolated K value is also the same. Therefore, iterations yield a final curb inlet length of 18.0 ft. (See Example One, Application of the Recommended Approach, for an illustration of the iteration process.)

Application of the Alternative Approach (Equation 12)

Step 1. **Assume a curb-opening inlet length for 100 percent interception (L_t).**

Assume a 15 ft inlet.

Step 2. **Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.**

Find K using equation 6.

$$K_{15} = 211\, S_L^2 - 14.6\, S_L + 0.570 = 211\left(0.03\right)^2 - 14.6\left(0.03\right) + 0.570 = 0.322$$

Find M using equation 9.

$$M = 0.573\, K^2 + 0.0743\, K - 0.0235 = 0.573\, (0.322)^2 + 0.0743\, (0.322) - 0.0235 = 0.060$$

Example Two (continued)

Step 3. Estimate L_t from the alternate equation.

$$\alpha = 0.72$$

$$\beta_{S2} = 0.043 S_L^{-0.50} = 0.043(0.030)^{-0.50} = 0.248$$

$$\gamma 2 = 0.79$$

$$L_t = \frac{K_u^{0.56} K^{1.5}}{\alpha^{1.5} 0.67 M \sqrt{g}} \left(\frac{Q\beta_{S2}}{\gamma_2}\right)^{0.44} S_L^{0.28} \left(\frac{1}{nS_x}\right)^{0.56}$$

$$= \frac{(1.216)^{0.56}(0.322)^{1.5}}{0.72^{1.5}(0.67)(0.060)\sqrt{32.2}} \left(\frac{0.654(0.248)}{0.79}\right)^{0.44} (0.030)^{0.28} \left(\frac{1}{(0.016)(0.04)}\right)^{0.56} = 16.8 \text{ ft}$$

A length of 16.8 ft is greater than 15 ft, which was initially assumed. Repeat the computations assuming a longer *L*. Since the 10- and 15-ft lengths have the same *K* value, the extrapolated *K* value is also the same. Therefore, iterations yield a final curb inlet length of 16.8 ft. (See Example One, Application of the Recommended Approach, for an illustration of the iteration process.)

Discussion of Examples

The initial concern driving this research was that the HEC-22 equation overestimates interception capacity under some conditions. Table 2 compares the results from the two examples. The CFD simulation values for Example One and Example Two were 10 ft and 15 ft, respectively. Design estimates greater than these values are "conservative" because a longer opening is estimated than is needed according to the CFD simulation. Conversely, design estimates less than the CFD values are not conservative and may not perform as expected during the design event.

The HEC-22 equation produces estimates that are not conservative for both examples although the Example Two estimate is close to the simulated value. With the risk modification factor, the recommended approach shows a conservative design for both examples. The alternate equation, with the risk modification factor, is also conservative for both examples. Other examples will have different relationships between the estimates depending on the site conditions and flow rate. However, FHWA researchers selected risk modification factors so that the recommended and alternate equations are conservative in most situations (see Appendix B).

Table 2. Summary of example problem results.

Source	Curb-Opening Length (ft)	
	Example One	Example Two
CFD simulation	10	15
Equation 8 (recommended)	10.9	18.0
Equation 12 (alternate)	10.8	16.8
Equation 1 (HEC-22)	8.6	14.5

Application

The recommended approach is limited to situations evaluated in this research with limited extrapolations beyond the simulated experiments. Recommended applicable limits are as follows:

- Longitudinal slopes greater than or equal to 0.1 percent and less than or equal to 5 percent.
- Cross slope less than or equal to 6 percent.
- Curb-opening lengths between 4 and 30 ft, inclusive, capturing 100 percent of the flow.

Although the CFD simulations were limited to 15 ft, the differences between the 10- and 15-ft *K* values are small and they were grouped together. This *K* value applies for lengths greater than 15 ft up to 30 ft.

Similarly, the smallest curb-opening length tested for 100 percent capture with CFD simulations was 5 ft. This can be modestly extended to 4 ft for 100 percent capture by using the *K* values for the 5-ft length for lengths between 4 and 5 ft. Smaller openings can also be evaluated for less than 100 percent capture if they are based on a 100 percent capture length no less than 4 ft.

Although the recommended approach applies to most common applications of curb-opening inlets on grade, there are circumstances beyond the stated limits of the method. In such cases, the designer computes the estimated design length using the current HEC-22 method and the recommended or alternative method at their bounds (FHWA 2009). The longest inlet of the two is selected for the application. For example, if a project application is for a site with a longitudinal slope of 6 percent and a cross slope (or equivalent cross slope) of 8 percent, the designer selects the longer length computed from the following:

- The recommended approach in this TechNote with longitudinal slope of 5 percent and a cross slope of 6 percent.
- The existing approach in HEC-22 with actual design slopes (FHWA 2009).

If the longer inlet length is from the recommended approach and the estimated length is greater than 30 ft, the recommended approach may not have produced a valid length. At the same time, the existing HEC-22 method may produce an underestimate. In this case, the designer might consider locating one or more inlets up-gradient to reduce the gutter flow to the design location.

The recommended approach requires an iterative solution in some situations where a trial curb opening inlet length is selected to begin the design process. Although more complex than direct solutions, pavement drainage design includes other iterative solutions, e.g., computing gutter depth and spread in a composite gutter. The recommended approach is amenable to spreadsheet programing and vendors of urban drainage software can update their computations. The examples in this TechNote provide a model for computations and a benchmark.

Related design situations, such as interception efficiency for curb-opening inlet lengths that do not capture 100 percent of the gutter flow, composite gutters, and local depression are unchanged by this research and its recommendations. The flow capture for the curb opening of "sweeper" inlets is also computed in the same way as described in HEC-22 with the recommended methodology used to compute L_t as the starting point (FHWA 2009). All other aspects of the design process are unchanged by this TechNote.

The variation in the relationship between Q and L_t in the three approaches may explain the differential performance between the three approaches. Increases in Q result in slower increases in L for HEC-22 and the alternate approach because of the exponent on Q. However, M and K affect L_t and are functions of L_t. The relationships are as follows:

- HEC-22: L_t is proportional to $Q^{0.42}$.
- Recommended approach: L is proportional to Q, $1/M$, and $1/E^{1.5}$. M is a function of L_t and E is independent of L_t.
- Alternate approach: L_t is proportional to $Q^{0.44}$, $1/M$, and $K^{1.5}$. M and K are functions of L_t.

Observations and Future Research

Both the recommended and alternate approaches require the use of the gutter equation to estimate a depth at the curb in the uniform flow section of the gutter upstream of the curb opening inlet. This equation tends to overestimate depth at the curb (and spread) for a given flow rate. This depth is used to estimate the water surface depth at the upstream end of the curb opening, y_0, which was used by FHWA researchers to develop the methodology but is not directly available to the designer.

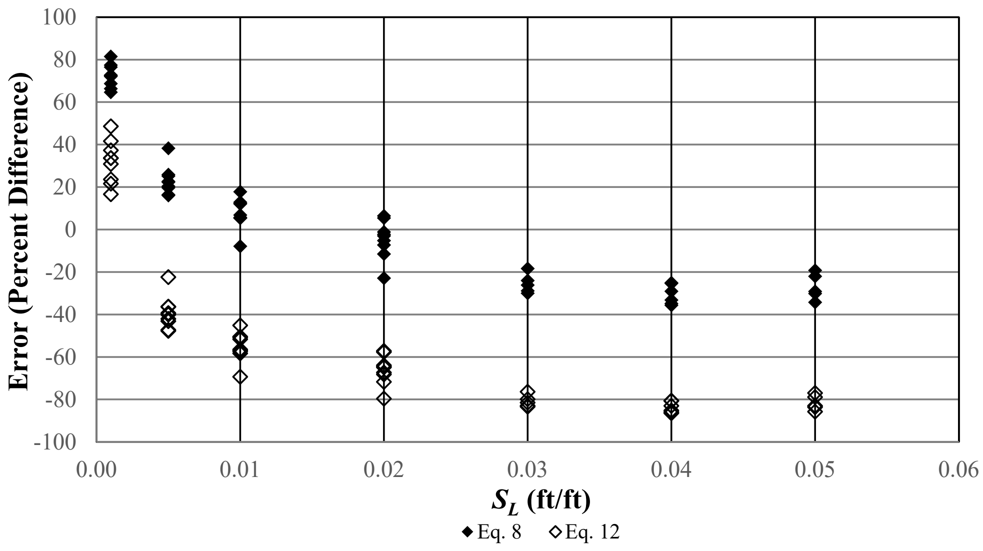
The potential for further research includes the following areas:

- Developing a more accurate gutter equation.
- Distinguishing between situations where HEC-22 and the recommended procedure differ. Schalla (2016) observed that HEC-22 overpredicted capture for longer, e.g., 15-ft, depressed inlets. What defines a "long" inlet and does this apply to undepressed inlets?
- Examining larger flows and flow depths. Wang et al. (2021) documented large errors in curb-opening inlet efficiency for small flows and this research focused only on these small flows and depths.
- Evaluating the need for the slope adjustment factor and alternative ways of incorporating the slope adjustment factor in the equation.
- Evaluating slot inlets and their similarity in performance to curb-opening inlets.

APPENDIX A. SLOPE ADJUSTMENT FACTOR

Prior to the introduction of a slope adjustment factor, the recommended (equation 8) and alternate (equation 12) design equations exhibited prediction errors that varied with longitudinal gutter slope. Figure 9 summarizes the error represented as a dimensionless percent difference ((computed-simulated)/simulated) versus the longitudinal slope.

Figure 9. Graph. Recommended and alternate equation errors without adjustment.



Source: FHWA.

Figure 10 summarizes the ratios of computed to simulated values averaged by longitudinal slope. To improve the effectiveness of the equations for design, FHWA researchers developed slope adjustment factors to reduce the errors associated with unadjusted equations based on these ratios. For the recommended equation (equation 8), the slope adjustment factor is as follows:

$$\beta_{S1} = 0.44 S_L^{-0.19} \tag{14}$$

Where β_{S1} is the slope adjustment factor for equation 8.

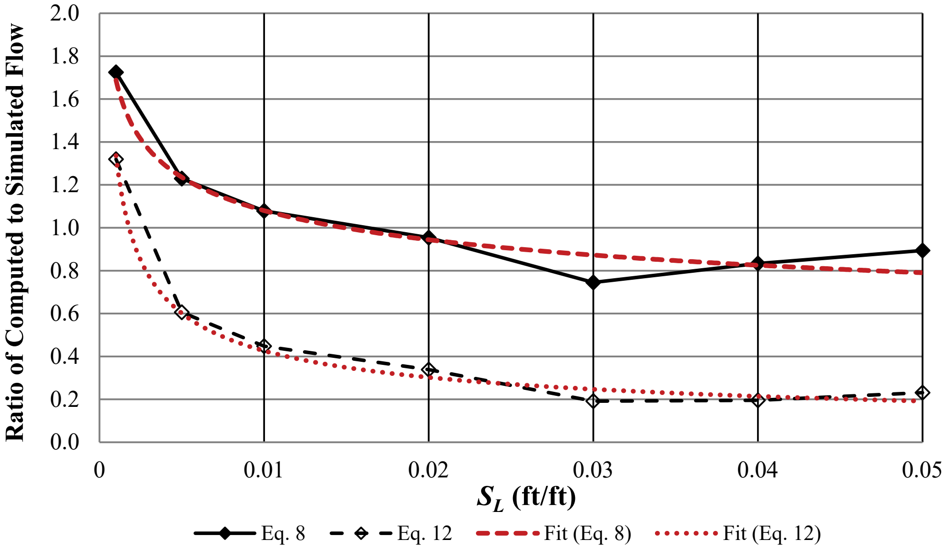
Similarly, for the alternate equation (equation 12), the slope adjustment factor is as follows:

$$\beta_{S2} = 0.043\, S_L^{-0.50} \tag{15}$$

Where β_{S2} is the slope adjustment factor for equation 12.

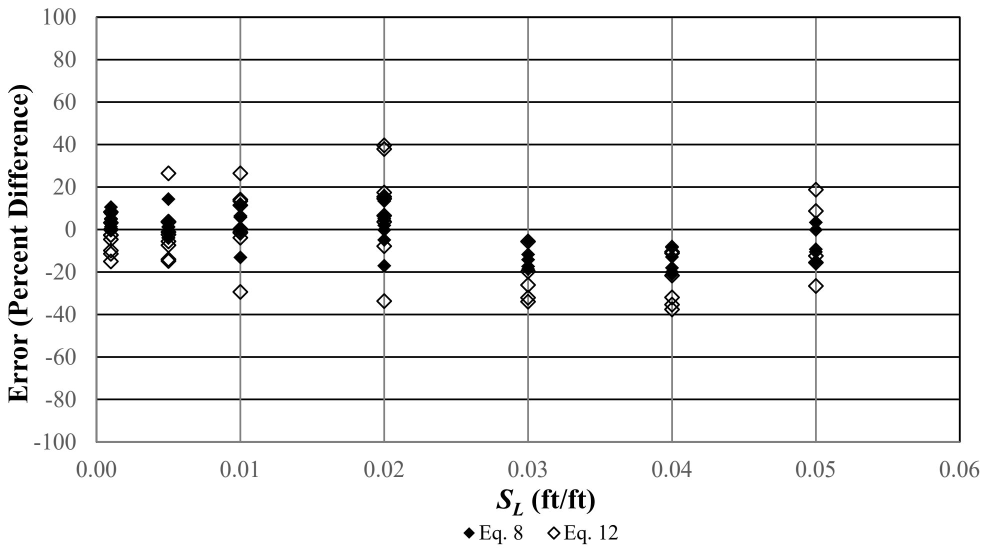
Figure 11 summarizes the errors for both design equations with the slope adjustment factor.

Figure 10. Graph. Ratio of computed to simulated flow averaged by longitudinal slope.



Source: FHWA.

Figure 11. Graph. Recommended and alternate equation errors with slope adjustment.



Source: FHWA.

APPENDIX B. RISK MODIFICATION FACTOR

FHWA researchers performed a reliability study of the recommended and alternative approaches to determine a modification factor appropriate for design. Referring to Figure 7, the x-axis is the simulated discharge (Q_{CFD}) from the CFD at a given L_t, and the y-axis is the computed discharge (Q_{design}) calculated from three design equations at the same L_t. In this figure, any markers below the solid line indicate Q_{design} is smaller than Q_{CFD}. For a given Q in these cases, an equivalent or larger L_t will be calculated from the design equation compared with the CFD. This result is considered conservative from a design perspective. Conversely, markers above the solid line indicate that Q_{design} is larger than Q_{CFD}. In this case, a smaller L_t will be calculated by using the design equations than the CFD for a given Q. This results in a design length that is not conservative.

To calculate the failure probability, a relative error is defined as follows:

$$err_{relative} = \frac{Q_{design} - Q_{CFD}}{Q_{CFD}} \quad (16)$$

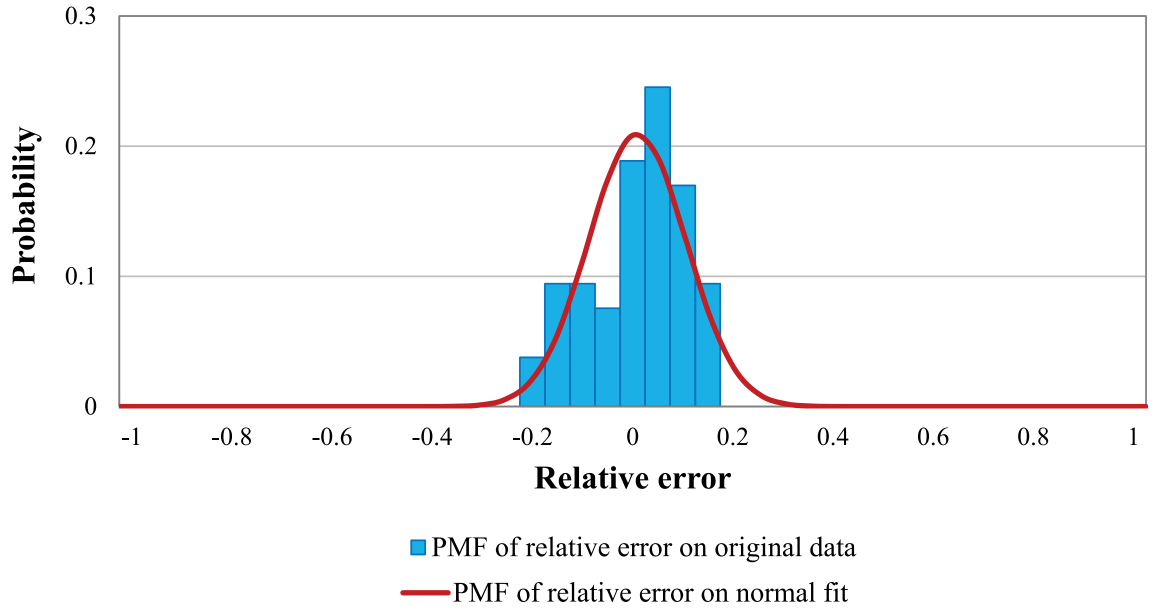
For cases where $err_{relative}$ is less than or equal to zero, the design equation is considered conservative. For the cases where $err_{relative}$ is greater than zero, the design equation is not conservative. For this study, FHWA researchers selected 5 percent as the target probability of failure (the relative error greater than zero) for the design equations. The failure probability is defined as follows:

$$P_f = P(err_{\text{relative}} > 0) \quad (17)$$

To analyze the distribution of errors, FHWA researchers assumed the errors from the 53 simulations in the study were distributed normally. The probability mass function (PMF) of $err_{relative}$ and the PMF of its normal fitted distribution without risk adjustment are shown in Figure 12 and Figure 13 for equation 8 and equation 12, respectively. The failure probabilities calculated from the fitted distributions are 43 percent and 52 percent for equation 8 and equation 12, respectively.

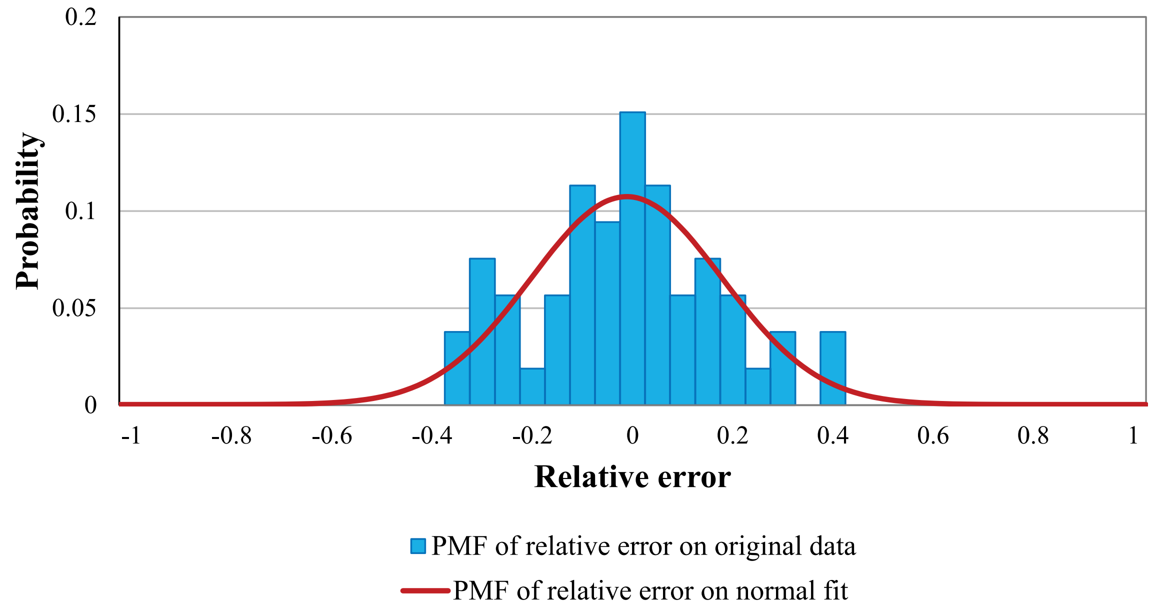
To reduce these probabilities, FHWA researchers introduced a risk modification factor (γ) that adjusts all values such that the probability of failure—the probability of a nonconservative design result—is 5 percent. Figure 14 shows the relation between the failure probability and the risk modification factor. To reduce the failure probability of equation 8 to 5 percent requires a risk modification factor of 0.88. Similarly, to reduce the failure probability of equation 12 to 5 percent requires a risk modification factor of 0.79.

Figure 12. Graph. PMF of relative error based on equation 8 and a normal distribution.



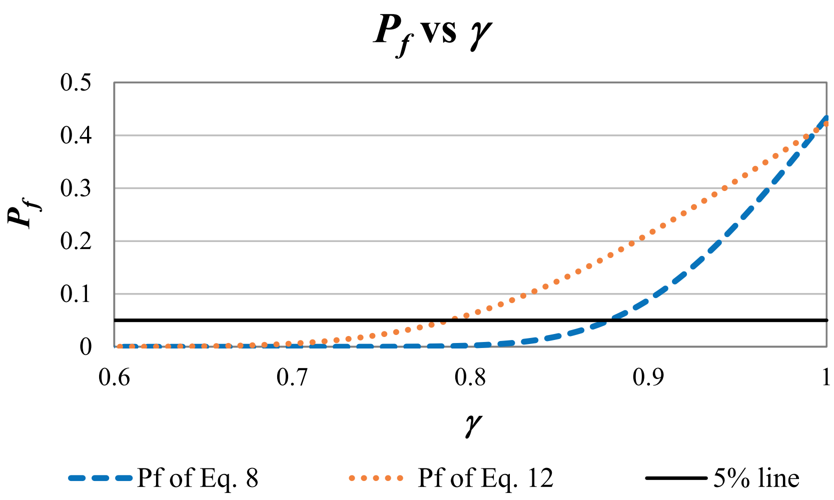
Source: FHWA.

Figure 13. Graph. PMF of relative error based on equation 12 and a normal distribution.



Source: FHWA.

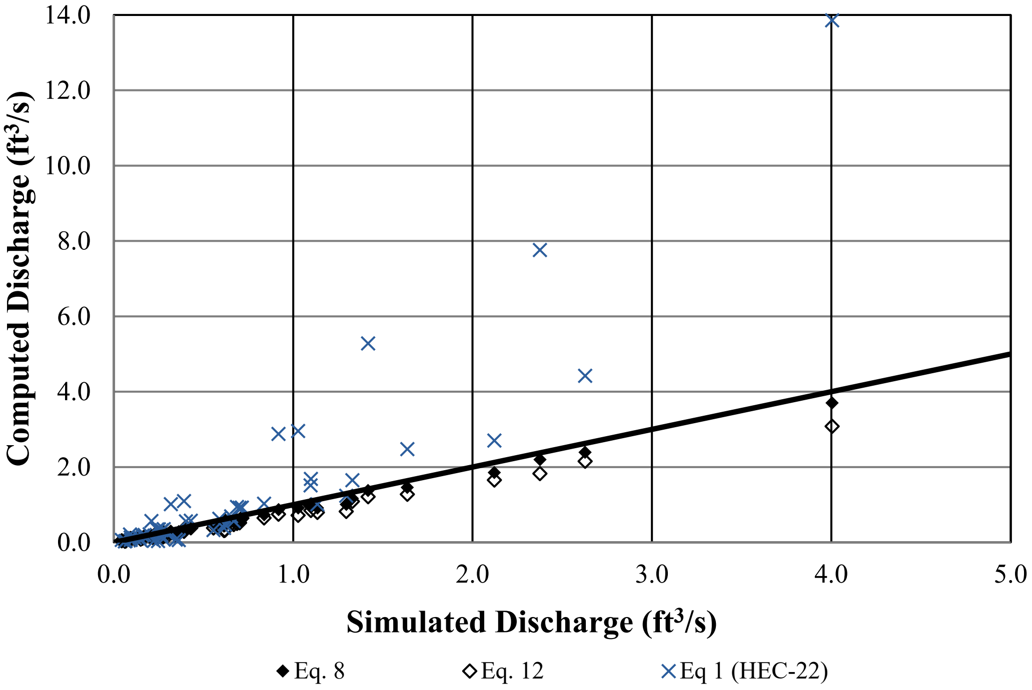
Figure 14. Graph. Failure probability versus modification factor (γ).



Source: FHWA.

Figure 15 shows the comparison of computed and simulated discharge with the modification factors applied. Most points (95 percent) from equation 8 and equation 12 are below the solid line (1:1 match line), which indicates that the modified design equations are more conservative than they would be without the modification factor.

Figure 15. Graph. Comparison of computed and simulated discharge with the modification factor.



Source: FHWA.

APPENDIX C. ADDITIONAL EXAMPLES

Additional examples are provided in this appendix that demonstrate the use of the recommended equations in situations where the curb opening captures less than 100 percent of the gutter flow, composite (depressed) gutters, locally depressed inlets, and combination inlets. The following examples are taken from HEC-22 and compared with the HEC-22 results (FHWA 2009).

HEC-22 Example 4-9a

This example compares the interception capacity of a curb-opening inlet on grade with a uniform gutter versus and with a composite (depressed gutter). Given:

$Q = 1.77$ ft^3/s.
$S_L = 0.01$ ft/ft.
$S_x = 0.02$ ft/ft.
$n = 0.016$.
$L = 9.84$ ft.

For the composite gutter:

$a = 1$ inch.
$W = 2$ ft.

Solution 1: Find the intercepted flow for a uniform gutter section.

Step 1. **Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).**

$$T = \left[(Qn)/\left(K_u S_x^{1.67} S_L^{0.5}\right)\right]^{0.375} = \left[\left((1.77)(0.016)\right)/\left((0.56)(0.02)^{1.67}(0.01)^{0.5}\right)\right]^{0.375} = 8.93 \text{ ft}$$

$y_g = T\,S_x = (8.93)\,(0.02) = 0.179$ ft

Step 2. **Assume a curb-opening inlet length for 100 percent interception (L_t).**

Assume a 10 ft inlet.

Step 3. **Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.**

Find K using equation 5.

$$K_{10} = 211\,S_L^2 - 14.6\,S_L + 0.570 = 211(0.01)^2 - 14.6(0.01) + 0.570 = 0.445$$

Find M using equation 9.

$$M = 0.573\,K^2 + 0.0743\,K - 0.0235 = 0.573\,(0.445)^2 + 0.0743\,(0.445) - 0.0235 = 0.123$$

Step 4. **Determine the specific energy (E) at the upstream end of the curb opening.**

Use equation 10 to estimate depth at the up-gradient end of the inlet:

$y_0 = 0.72\,y_g = 0.72\,(0.179) = 0.129$ ft

$E = y_0 / K = 0.129 / 0.445 = 0.289$ ft

Step 5. **Estimate L_t from the recommended equation.**

$$\beta_{S1} = 0.44 S_L^{-0.19} = 0.44(0.01)^{-0.19} = 1.060$$

$$\gamma_1 = 0.88$$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M\sqrt{g}E^{1.5}} = \frac{1.77(1.060)}{(0.88)(0.67)(0.123)\sqrt{32.2}(0.289)^{1.5}} = 29.3 \text{ ft}$$

A length of 29.3 ft is greater than the 10-ft length assumed in step 2. Repeat the computations assuming a longer L_t in step 2. Since the 10- and 15-ft lengths have the same *K* value, the extrapolated *K* value is also the same. Therefore, iterations yield a final curb inlet length for 100 percent interception of 29.3 ft. (The HEC-22 solution is 23.9 ft.)

Step 6. **Compute the interception of the specified inlet length.**

Use HEC-22 equation 4-23 to compute the interception efficiency for an opening length less than required for 100 percent interception for *L* = 9.84 ft. (A subscript *L* is added here to distinguish *E* from its use in this TechNote as the energy at the upstream end of the inlet.)

$$E_L = 1 - \left[1 - \left(\frac{L}{L_T}\right)\right]^{1.8} = 1 - \left[1 - \left(\frac{9.84}{29.3}\right)\right]^{1.8} = 0.52$$

$Q_i = E_L Q = 0.52(1.77) = 0.92$ ft^3/s

With the uniform gutter section, the curb-opening inlet captures 0.92 ft^3/s.
(The HEC-22 solution is 1.08 ft^3/s.)

Solution 2: Find the intercepted flow for a composite gutter section.

Step 1. **Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).**

Since this is a composite gutter section, compute:

$S_W = S_X + a / W = 0.02 + (1/12) / 2 = 0.0617$

As described in HEC-22, computing the spread in a composite gutter is an iterative procedure starting with assuming the flow on the non-depressed portion of the gutter and then iterating until the assumed flow is validated. (See HEC-22 for details.)

Assume $Q_s = 0.64$ ft^3/s

$Q_W = Q - Q_s = 1.77 - 0.64 = 1.13$ ft^3/s

$E_0 = Q_W/Q = 1.13/1.77 = 0.638$

HEC-22 equation 4-4 is solved for *T/W* as follows:

$$T/W = \frac{S_W/S_X}{\left\{\left[\dfrac{S_W/S_X}{\dfrac{1}{E_0}-1}+1\right]^{0.375}-1\right\}} + 1 = \frac{0.0617/0.02}{\left\{\left[\dfrac{0.0617/0.02}{\dfrac{1}{0.638}-1}+1\right]^{0.375}-1\right\}} + 1 = 4.061$$

$T = (T/W)W = (4.061)2 = 8.12$ ft

$T_S = T - W = 8.12 - 2 = 6.12$ ft

HEC-22 Example 4-9a (continued)

Verify the assumed Q_S using HEC-22 equation 4-2:

$$Q_s = \left(K_u / n\right) S_X^{1.67} S_L^{0.5} T_S^{2.67} = \left(0.56 / 0.16\right) 0.02^{1.67} 0.01^{0.5} 6.12^{2.67} = 0.64 \text{ ft}^3/\text{s}$$

This matches the assumed value. Therefore, iteration is not needed.

$y_g = T\,S_x + a = (8.12)\,(0.02) + (1/12) = 0.246$ ft

Step 2. **Assume a curb-opening inlet length for 100 percent interception (L_t).**

Assume a 15 ft inlet.

Step 3. **Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.**

Find K using equation 6.

$$K_{15} = 211\,S_L^2 - 14.6\,S_L + 0.570 = 211\left(0.01\right)^2 - 14.6\left(0.01\right) + 0.570 = 0.445$$

Find M using equation 9.

$$M = 0.573\,K^2 + 0.0743\,K - 0.0235 = 0.573\,(0.445)^2 + 0.0743\,(0.445) - 0.0235 = 0.123$$

Step 4. **Determine the specific energy (E) at the upstream end of the curb opening.**

Use equation 10 to estimate depth at the up-gradient end of the inlet:

$y_0 = 0.72\text{ yg} = 0.72\ (0.246) = 0.177$ ft

$E = y_0 / K = 0.177 / 0.445 = 0.398$ ft

Step 5. **Estimate L_t from the recommended equation.**

$$\beta_{S1} = 0.44 S_L^{-0.19} = 0.44\left(0.01\right)^{-0.19} = 1.060$$

$\gamma_1 = 0.88$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M \sqrt{g} E^{1.5}} = \frac{1.77\left(1.060\right)}{\left(0.88\right)\left(0.67\right)\left(0.123\right)\sqrt{32.2}\left(0.398\right)^{1.5}} = 18.2 \text{ ft}$$

A length of 18.2 ft is greater than the 15-ft length assumed in step 2. Repeat the computations assuming a longer L_t in step 2. Since the 10- and 15-ft lengths have the same K value, the extrapolated K value is also the same. Therefore, iterations yield a final curb-inlet length for 100 percent interception of 18.2 ft. (The HEC-22 solution is 14.3 ft.)

Step 6. **Compute the interception of the specified inlet length.**

Use HEC-22 equation 4-23 to compute the interception efficiency for an opening length less than required for 100 percent interception for $L = 9.84$ ft.

$$E_L = 1 - \left[1 - \left(\frac{L}{L_T}\right)\right]^{1.8} = 1 - \left[1 - \left(\frac{9.84}{18.2}\right)\right]^{1.8} = 0.75$$

$Q_i = E_L Q = 0.75(1.77) = 0.92$ ft^3/s

With the composite gutter section, the curb-opening inlet captures 1.33 ft^3/s. The composite gutter enables the inlet to capture 23 percent more than the uniform gutter. (The HEC-22 solution is 1.55 ft^3/s, which is a 44 percent increase in capture.)

HEC-22 Example 4-9b

This example estimates the curb-opening length needed to accept 100 percent of the gutter flow with a locally depressed inlet. Given:

$Q = 2.26$ ft^3/s.
$S_L = 0.01$ ft/ft.
$S_x = 0.02$ ft/ft.
$n = 0.016$.
$L = 9.84$ ft.

For the local depression:

$a = 2$ inches.
$W = 2$ ft.

Note that HEC-22 treats local inlet depression the same as a composite gutter.

Step 1. **Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).**

Since this is a locally depressed inlet, compute:

$S_W = S_X + a / W = 0.02 + (2 / 12) / 2 = 0.103$

As described in HEC-22, computing the spread in a composite gutter is an iterative procedure starting with assuming the flow on the nondepressed portion of the gutter and then iterating until the assumed flow is validated. (See HEC-22 for details.)

Assume $Q_s = 0.64$ ft^3/s

$Q_W = Q - Q_s = 2.26 - 0.64 = 1.62$ ft^3/s

$E_0 = Q_W/Q = 1.62/2.26 = 0.72$

(This value for E_0 is slightly higher than given in HEC-22 because of a change in flow value from the examples from which it was carried over.)

HEC-22 equation 4-4 is solved for T/W

$$T / W = \frac{S_W / S_X}{\left\{\left[\dfrac{S_W / S_X}{\dfrac{1}{E_0} - 1} + 1\right]^{0.375} - 1\right\}} + 1 = \frac{0.103 / 0.02}{\left\{\left[\dfrac{0.103 / 0.02}{\dfrac{1}{0.72} - 1} + 1\right]^{0.375} - 1\right\}} + 1 = 4.07$$

$T = (T/W)W = (4.07)2 = 8.14$ ft

$T_S = T - W = 8.14 - 2 = 6.14$ ft

Verify the assumed Q_s using HEC-22 equation 4-2:

$$Q_s = \left(K_u / n\right) S_X^{1.67} S_L^{0.5} T_S^{2.67} = \left(0.56 / 0.16\right) 0.02^{1.67} 0.01^{0.5} 6.14^{2.67} = 0.64 \text{ ft}^3/\text{s}$$

This matches the assumed value. Therefore, iteration is not needed.

$y_g = T\, S_x + a = (8.14)\ (0.02) + (2/12) = 0.329$ ft

Step 2. **Assume a curb-opening inlet length for 100 percent interception (L_t).**

Assume a 15 ft inlet.

HEC-22 Example 4-9b (continued)

Step 3. Find the profile constant (*K*) and the side weir flow coefficient (*M*) for the assumed L_t.

Find *K* using equation 6.

$$K_{15} = 211\,S_L^2 - 14.6\,S_L + 0.570 = 211\left(0.01\right)^2 - 14.6\left(0.01\right) + 0.570 = 0.445$$

Find *M* using equation 9.

$$M = 0.573\,K^2 + 0.0743\,K - 0.0235 = 0.573\,(0.445)^2 + 0.0743\,(0.445) - 0.0235 = 0.123$$

Step 4. Determine the specific energy (*E*) at the upstream end of the curb opening.

Use equation 10 to estimate depth at the up-gradient end of the inlet:

$y_0 = 0.72\,y_g = 0.72\,(0.329) = 0.237$ ft

$E = y_0 / \mathrm{K} = 0.237 / 0.445 = 0.533$ ft

Step 5. Estimate L_t from the recommended equation.

$$\beta_{S1} = 0.44 S_L^{-0.19} = 0.44\left(0.01\right)^{-0.19} = 1.060$$

$$\gamma_1 = 0.88$$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M\sqrt{g}E^{1.5}} = \frac{2.26\left(1.060\right)}{\left(0.88\right)\left(0.67\right)\left(0.123\right)\sqrt{32.2}\left(0.533\right)^{1.5}} = 15.0 \text{ ft}$$

This length matches the 15-ft length assumed in step 2. Therefore, no further iterations are needed. (The HEC-22 solution is 12.5 ft.)

HEC-22 Example 4-10

This example estimates the interception capacity of a combination (sweeper) inlet on grade with a composite (depressed gutter). Given:

$Q = 1.77$ ft^3/s.
$S_L = 0.01$ ft/ft.
$S_x = 0.02$ ft/ft.
$n = 0.016$.

For the composite gutter:

$a = 1$ inch.
$W = 2$ ft.

For the combination inlet:

$L = 9.84$ ft (curb opening length).
$L_g = 2$ ft (grate length, curved vane grate).
$W = 2$ ft (grate width matches depressed gutter section width).

In HEC-22, the interception of a combination inlet is estimated by computing the interception of the curb opening upstream of the grate and the interception of the grate based on the remaining gutter flow.

HEC-22 Example 4-10 (continued)

Step 1. Estimate the water depth in the gutter (at the curb) where uniform flow prevails (y_g).

Since this is a composite gutter section, compute:

$S_W = S_X + a / W = 0.02 + (1 / 12) / 2 = 0.0617$

As described in HEC-22, computing the spread in a composite gutter is an iterative procedure starting with assuming the flow on the nondepressed portion of the gutter and then iterating until the assumed flow is validated. (See HEC-22 for details.)

Assume $Q_s = 0.64$ ft³/s

$Q_w = Q - Q_s = 1.77 - 0.64 = 1.13$ ft³/s

$E_0 = Q_w/Q = 1.13/1.77 = 0.638$

HEC-22 equation 4-4 is solved for T/W:

$$T / W = \frac{S_W / S_X}{\left\{\left[\dfrac{S_W / S_X}{\dfrac{1}{E_0} - 1} + 1\right]^{0.375} - 1\right\}} + 1 = \frac{0.0617 / 0.02}{\left\{\left[\dfrac{0.0617 / 0.02}{\dfrac{1}{0.638} - 1} + 1\right]^{0.375} - 1\right\}} + 1 = 4.061$$

$T = (T/W)W = (4.061)2 = 8.12$ ft

$T_S = T - W = 8.12 - 2 = 6.12$ ft

$$Q_s = \left(K_u / n\right) S_X^{1.67} S_L^{0.5} T_S^{2.67} = \left(0.56 / 0.16\right) 0.02^{1.67} 0.01^{0.5} 6.12^{2.67} = 0.64 \text{ ft}^3/\text{s}$$

Verify the assumed Q_s using HEC-22 equation 4-2:

This matches the assumed value. Therefore, iteration is not needed.

$y_g = T\, S_x + a = (8.12)\,(0.02) + (1/12) = 0.246$ ft

Step 2. Assume a curb-opening inlet length for 100 percent interception (L_t).

Assume a 15 ft inlet.

Step 3. Find the profile constant (K) and the side weir flow coefficient (M) for the assumed L_t.

Find K using equation 6.

$$K_{15} = 211\, S_L^2 - 14.6\, S_L + 0.570 = 211\left(0.01\right)^2 - 14.6\left(0.01\right) + 0.570 = 0.445$$

Find M using equation 9.

$M = 0.573\, K^2 + 0.0743\, K - 0.0235 = 0.573\,(0.445)^2 + 0.0743\,(0.445) - 0.0235 = 0.123$

Step 4. Determine the specific energy (E) at the upstream end of the curb opening.

Use equation 10 to estimate depth at the up-gradient end of the inlet:

$y_0 = 0.72\, y_g = 0.72\,(0.246) = 0.177$ ft

$E = y_0 / K = 0.177 / 0.445 = 0.398$ ft

Step 5. Estimate L_t from the recommended equation.

$$\beta_{S1} = 0.44 S_L^{-0.19} = 0.44(0.01)^{-0.19} = 1.060$$

$$\gamma_1 = 0.88$$

$$L_t = \frac{Q\beta_{S1}}{\gamma_1 0.67 M \sqrt{g} E^{1.5}} = \frac{1.77(1.060)}{(0.88)(0.67)(0.123)\sqrt{32.2}(0.398)^{1.5}} = 18.2 \text{ ft}$$

A length of 18.2 ft is greater than the 15-ft length assumed in step 2. Repeat the computations assuming a longer L_t in step 2. Since the 10- and 15-ft lengths have the same K value, the extrapolated K value is also the same. Therefore, iterations yield a final curb inlet length for 100 percent interception of 18.2 ft. (The HEC-22 solution is 14.3 ft.)

Step 6. Compute the interception of the specified inlet length.

Use HEC-22 equation 4-23 to compute the interception efficiency for an opening length less than required for 100 percent interception. For this combination inlet, only the length upstream of the grate is considered. Therefore, the effective $L = 9.84 - 2.0 = 7.84$ ft.

$$E_L = 1 - \left[1 - \left(\frac{L}{L_T}\right)\right]^{1.8} = 1 - \left[1 - \left(\frac{7.84}{18.2}\right)\right]^{1.8} = 0.64$$

$Q_i = E_L Q = 0.64(1.77) = 1.13 \text{ ft}^3/\text{s}$

The curb-opening upstream of the grate captures 1.13 ft^3/s. (The HEC-22 solution is 1.35 ft^3/s.)

Step 7. Compute the spread of the flow reaching the grate.

The gutter flow at the upstream end of the grate is the total flow minus that captured by the inlet estimated in step 6.

$Q = 1.77 - 1.13 = 0.64 \text{ ft}^3/\text{s}$

Because this is a composite gutter, an iterative procedure, as described in HEC-22, is used to compute spread in a composite gutter starting with assuming the flow on the nondepressed portion of the gutter and then iterating until the assumed flow is validated. (See HEC-22 for details.)

Assume $Q_S = 0.08 \text{ ft}^3/\text{s}$

$Q_W = Q - Q_S = 0.64 - 0.08 = 0.56 \text{ ft}^3/\text{s}$

$E_0 = Q_W/Q = 0.56/0.64 = 0.875$

$$T/W = \frac{S_W/S_X}{\left\{\left[\dfrac{S_W/S_X}{\dfrac{1}{E_0}-1}+1\right]^{0.375} - 1\right\}} + 1 = \frac{0.0617/0.02}{\left\{\left[\dfrac{0.0617/0.02}{\dfrac{1}{0.875}-1}+1\right]^{0.375} - 1\right\}} + 1 = 2.43$$

HEC-22 equation 4-4 is solved for T/W:

$T = (T/W)W = (2.43)2 = 4.86$ ft

$T_S = T - W = 4.86 - 2 = 2.86$ ft

Verify the assumed Q_S using HEC-22 equation 4-2:

$$Q_s = \left(K_u / n\right) S_X^{1.67} S_L^{0.5} T_S^{2.67} = \left(0.56 / 0.16\right) 0.02^{1.67} 0.01^{0.5} 2.86^{2.67} = 0.08 \text{ ft}^3/\text{s}$$

The computed flow matches the assumed flow, so no further iterations are needed. The spread of the flow reaching the grate is 4.86 ft. (The HEC-22 solution is 3.2 ft.)

Step 8. Compute the interception of the grate inlet.

Grate interception on grade is computed for the frontal and side flows separately and then added together. The frontal flow interception is based on the splash-over velocity. From Chart 5 (HEC-22) the splash-over velocity for a curved vane grate (L = 2 ft) is 6 ft/s. The velocity is computed for the frontal flow based on:

$y_g = T S_x + a = (4.86)\ (0.02) + (1/12) = 0.180$ ft

$A = 0.5\ (0.180 + 0.02(2.86))*2.0 = 0.237$ ft^2

$V = Q/A = 0.56/0.237 = 2.36$ ft/s

The estimated velocity is less than the splash-over velocity. Therefore, 100 percent of the frontal flow is captured by the grate inlet.

The side flow capture is based on HEC-22 equation 4-19 as follows:

$$R_S = 1/\left[1 + \frac{K_u V^{1.8}}{S_x L^{2.3}}\right] = 1/\left[1 + \frac{0.15\left(2.36\right)^{1.8}}{0.02\left(2\right)^{2.3}}\right] = 0.12$$

Grate inlet interception:

$Q_{ig} = 0.56\ (1.0) + 0.08\ (0.12) = 0.57$ ft^3/s

Step 9. Compute the interception of the combination inlet.

Total interception is:

$Q = Q_{ic} + Q_{ig} = 1.13 + 0.57 = 1.70$ ft^3/s

The combination inlet captures 1.70 ft^3/s or 96 percent of the gutter flow. (The HEC-22 solution is 1.76 ft^3/s or 99 percent of the gutter flow. The difference is small because the grate is able to capture most of the flow bypassed from the curb-opening inlet.)

REFERENCES

FHWA. 2009. *Urban Drainage Design Manual, Hydraulic Engineering Circular No. 22, Third Ed.* Report No. FHWA-NHI-10-009. Washington, DC: Federal Highway Administration.

Hagar, W. H. 1987. "Lateral Outflow Over Side Weirs." *Journal of Hydraulic Engineering* 113, no. 4.

Hammons, M. A. and E. Holley. 1995. *Hydraulic Characteristics of Flush Depressed Curb Inlets and Bridge Deck Drains*, Report No. FHWA/TX-96/1409-1. Austin, TX: Texas Department of Transportation.

Izzard, C. F. 1950. "Tentative Results on Capacity of Curb Opening Inlets." *Highway Research Board:* 11-13.

Muhammad, M. A. 2018. "Interception Capacity of Curb Opening Inlets." Phd dissertation. University of Texas at Austin.

Schalla, F. E. 2016. "Effects of Flush Slab Supports on the Hydraulic Performance of Curb Inlets and an Analysis of Design Equations." Masters thesis. University of Texas at Austin.

Wang, J., M. Zhao, N. Tu, X. Li, X. Fang, J. Li, J Jin, and D. Su. 2021. "Curb Inlet Efficiency Evaluation Under Unsteady Rainfall Situations Based on Full-Scale Rainfall-Runoff Experiments." *Journal of Hydrologic Engineering* 26, issue no. 2.

Researchers—This study was conducted by Zhaoding Xie, Ph.D. of Genex Systems under contract 693JJ320F000313. The main author of this TechNote was Roger Kilgore of Kilgore Consulting, with additional support from Nasi Zhang, Ph.D. (ORCID: 0000-0002-1175-6909) of Genex Systems. This research was developed under the technical direction of Kornel Kerenyi of FHWA and the FHWA Hydraulics Research Program.

Distribution—This TechNote is being distributed according to a standard distribution. Direct distribution is being made to the FHWA divisions and Resource Center.

Availability—This TechNote may be obtained at https://highways.dot.gov/research.

Key Words—Curb opening, inlet interception, pavement drainage.

MAY 2022

Recommended citation: Federal Highway Administration, Curb-Opening Inlet Interception on Grade (Washington, DC: 2022) https://doi.org/10.21949/1521863.

FHWA-HRT-22-061
HRDI-40/05-22(WEB)E