significantly high. However, if material is available from nearby freeway construction improvement work and the cost of material removal from the right-of-way is anticipated to be high, construction of sound berms appears to be a desirable highway policy.

5. Sound barriers should be designed and constructed with major consideration for the topography of the freeway and adjacent land, for the existing or planned development of the neighboring land, and for the effects of height and length of the barriers on anticipated results.

6. From the negative comments concerning berm construction it was concluded that sufficient public relations should be performed in the development stage of sound barriers to obtain sufficient information to properly locate the barriers and inform the public of anticipated results of the barriers.

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Abridgment

Hydraulic and Safety Characteristics of Selected Grate Inlets

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With the recent increase in the number of bicycles on our nation's highways and streets, there has been a corresponding increase in the number of bicycle accidents. Some of these accidents are related to highway grate inlets. The purpose of the comprehensive study summarized in this paper was to identify, develop, and analyze selected grate inlets that maximize hydraulic efficiency and bicycle safety.

Fifteen grate inlet designs were initially selected for consideration. They included seven steel-fabricated grates and eight cast grates.

The test program was conducted using two test facilities. The bicycle safety tests were conducted on an outdoor test site consisting of a 6.7-m (22-ft) wide, 152-m (500-ft) long abandoned roadway. A 2.44-m (8-ft) wide, 18.3-m (60-ft) long hydraulic test flume was constructed in the U.S. Bureau of Reclamation, Hydraulic Research Laboratory, and used as a test facility for the hydraulic efficiency tests.

ANALYSIS OF STRUCTURAL INTEGRITY

Figure 1 illustrates the basic grate inlet designs that were structurally analyzed and the reticuline grate that was not structurally analyzed because it is commercially available and the manufacturer's publications provide vehicle load tables based on AASHTO specifications.

The general-purpose computer program STR5 was used to perform the structural analysis of the selected grates. In some cases it was determined by a preliminary analysis that the bearing bars of the grate acted independently as simple supported beams. In those cases, a simple beam analysis was performed.

The grates tested have been code-named to standardize the names. The first symbol refers to the grate design (parallel bar grate P, curved vane grate CV, 45° or 30° tilt bar grate 45 or 30, and reticuline R). The second number is the nominal center-to-center longitudinal bar spacing. The last number is the nominal center-to-center transverse bar spacing. Therefore, the P-48-102 (P-1$\frac{7}{8}$-4) grate refers to a parallel bar grate with center-to-center spacing of the longitudinal bars of 48 mm (1$\frac{7}{8}$ in) and center-to-center spacing of the transverse bars of 102 mm (4 in).

ANALYSIS OF BICYCLE AND PEDESTRIAN SAFETY

Bicycle and pedestrian safety tests were performed on 11 grate inlets to preselect safe grate inlets for the hydraulic testing phase of the study. The grate size of 0.61 × 1.22 m (2 × 4 ft) was selected for use in the bicycle safety tests. Table 1 presents principal features of the grates evaluated in the test program and gives their bicycle safety rankings.

Two grates were tested in the hydraulic efficiency tests that were not tested in the bicycle safety tests. The curved vane grate CV-83-108 (CV-3$\frac{1}{4}$-4$\frac{1}{4}$) design was very similar to the 45-83-102 (45-3$\frac{1}{4}$-4) grate, which satisfactorily passed the bicycle safety tests. The parallel bar grate with transverse spacers P-29 (P-1$\frac{1}{8}$) was tested independently for bicycle safety (1).

The transverse spacing of grate bars is a critical factor in bicycle safety performance. It is a more critical factor than whether the grate is of the reticuline, 45° tilt bar, curved vane, or parallel bar with

Figure 1. Basic grate designs.

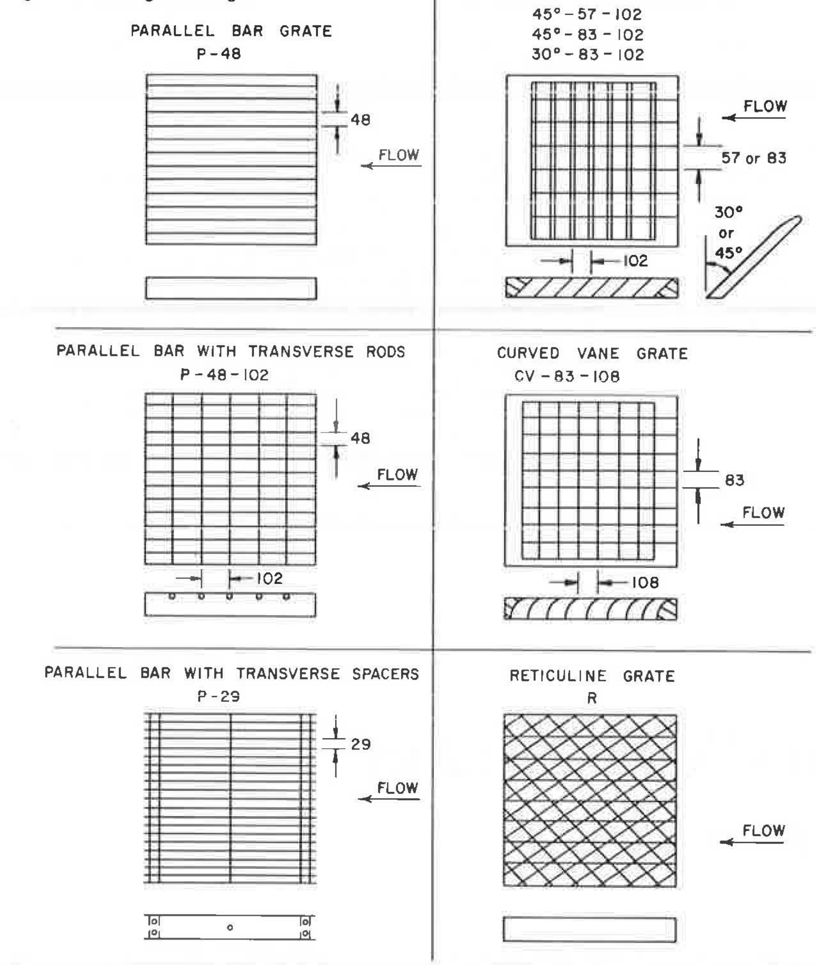

Table 1. Principal grate dimensions and bicycle safety ranking.

Type	Longitudinal Spacing[a] (mm)	Longitudinal Bar Width (mm)	Transverse Spacing[b] (mm)	Transverse Bar Width (mm)	Bicycle Safety Ranking
Reticuline	67[d]	6.4	127[c]	4.8	3
Parallel bar	48[d]	6.4	102	9.5 rod	2
	48[d]	6.4	152	9.5 rod	8
	48[d]	6.4	203	9.5 rod	11
	60[d]	6.4	102	9.5 rod	6
45° tilt-bar	57[e]	13	76	19	7
	57[e]	13	102	19	4-5
	57[e]	13	159	19	9
	83[e]	13	76	19	1
	83[e]	13	102	19	4-5
	83[e]	13	159	19	10

Note: 1 mm = 0.39 in.

[a]Center-to-center spacing of bars parallel to direction of flow.
[b]Center-to-center spacing of bars transverse to direction of flow.
[c]Center-to-center spacing of rivets, reticuline grate only.
[d]Fabricated steel grate.
[e]Grates made of white oak to simulate cast grates.

transverse rod type. The analysis suggests that deterioration in bicycle safety performance begins as transverse spacings are increased somewhat above 102 mm (4 in). Keeping the grates wet increased the chances of skidding.

TEST FACILITY AND EXPERIMENTAL APPROACH

To accurately investigate the hydraulic characteristics of grate inlets, the decision was made to use a full-scale test facility. The width of the roadbed selected for the test facility was 2.4 m (8 ft) including a 0.61-m (2-ft) gutter section and one-half of a 3.7-m (12-ft) traffic lane, generally considered the allowable width of flow spread. The test roadbed was 18.3 m (60 ft) long with the grate inlet test section located 12.2 m (40 ft) from the headbox. The facility was designed and constructed to accommodate the following test conditions: (a) longitudinal slopes, S_o = 0.5-13 percent; (b) cross slopes, 1/Z = 1:48-1:16; (c) maximum gutter flow, Q_T = 0.16 m^3/s (5.6 ft^3/s); and (d) Manning roughness factor, n = 0.016-0.017.

For each grate design, size, longitudinal slope, and cross slope, five different gutter flows were tested. The maximum gutter flow was limited by either the pump capacity of 0.16 m^3/s (5.6 ft^3/s) or width of spread limited to T′ = 2.3 m (7.5 ft). The minimum gutter flow was the flow that was completely captured by the grate inlet or provided a flow spread of T′ = 0.61 m (2 ft). The five data points obtained were sufficient to develop curves relating hydraulic efficiency (E = intercepted gutter flow/total gutter flow, $E = Q_I/Q_T$) to gutter flow (Q_T) and width of spread (T′) for each combination of longitudinal and cross slopes.

DISCUSSION OF TEST RESULTS

The preliminary structural analysis and bicycle-pedestrian analysis led to the selection of eight grate designs for the hydraulic tests. They included a steel-fabricated parallel bar grate that was not bicycle safe but provided an excellent standard for hydraulic efficiency with which to compare other grate inlet designs. Three

Table 2. Grate inlet classification.

Debris	Safety	Hydraulics: Favorable Gutter Flow Conditions	Hydraulics: Unfavorable Gutter Flow Conditions	Composite Selection: Favorable Gutter Flow Conditions	Composite Selection: Unfavorable Gutter Flow Conditions
Class I (high performance)					
CV - 83 - 108	P - 48 - 102	P - 48 - 102	CV - 83 - 108	P - 48 - 102	CV - 83 - 108
30 - 83 - 102	Reticuline	P - 29	P - 29	P - 29	P - 29
				Reticuline	
45 - 83 - 102	P - 29	Reticuline		45 - 83 - 102	
Class II (low performance)					
P - 48 - 102	45 - 83 - 102	CV - 83 - 108	45 - 83 - 102	CV - 83 - 108	45 - 83 - 102
45 - 57 - 102	45 - 57 - 102	45 - 83 - 102	P - 48 - 102	45 - 57 - 102	P - 48 - 102
Reticuline	CV - 83 - 108	45 - 57 - 102	45 - 57 - 102	30 - 83 - 102	45 - 57 - 102
P - 29	30 - 83 - 102	30 - 83 - 102	30 - 83 - 102		Reticuline
			Reticuline		30 - 83 - 102

other steel-fabricated grates were also tested: parallel bar grate with transverse rods at the surface, P-48-102 (P-1⅞-4); parallel bar grate with spacers, P-29 (P-1⅛); and a reticuline grate (R). Four cast grates were tested. They included two 45° tilt bar grates, 45-83-102 (45-3¼-4) and 45-57-102 (45-2¼-4); a 30° tilt bar grate, 30-83-102 (30-3¼-4); and a curved vane grate, CV-83-108 (CV-3¼-4¼) design. The test results are covered in detail elsewhere (2).

For a constant gutter flow, all the grates show some increase in hydraulic efficiency if the cross slope is held constant and the longitudinal slope is increased. At steeper longitudinal slopes, the same gutter flow occupies a smaller cross-sectional area; therefore, a greater percentage of the flow passes over the grate inlet. If no flow splashes completely across the grate, intercepted flow is greater and, hence, hydraulic efficiency is higher. All of the grate inlets, except the parallel bar and the curved vane grate, had splashing occurring under some flow conditions. The other six grates showed a decrease in hydraulic efficiency above a limiting longitudinal slope, related to grate design, size, and cross slope.

The seven bicycle-safe grate designs (discounting the parallel bar grate) can be classified in three hydraulic efficiency performance groups at the steeper longitudinal and cross slopes. The CV-83-108 (CV-3¼-4¼) and P-29 (P-1⅛) grates are consistently superior to the other bicycle-safe grates tested. The 0.61 × 1.22-m (2 × 4-ft) sizes of these two grates are within 3-4 percent of the parallel bar grate for the same test conditions.

At the other extreme, the reticuline grates generally rank last. At higher gutter flows with steep longitudinal and cross slopes, the reticuline grates usually had the lowest efficiency of the grates tested (for longitudinal slopes less than 3 percent, the reticuline grate is as efficient as the other grates). The remaining grates, the 45-57-102 (45 -2¼-4), the 45-83-102 (45 -3¼-4), P-48-102 (P-1⅞-4), and the 30-83-102 (30 -3¼-4), tend to have hydraulic efficiencies very close to each other. They rank somewhat better than the reticuline grates, but far below the CV-83-108 (CV-3¼-4¼) and the P-29 (P-1⅛) grates.

Tests to determine debris-handling capability showed a definite debris-handling advantage for grates with the 83-mm (3¼-in) longitudinal bar spacing over those with smaller longitudinal bar spacing.

SUMMARY AND CONCLUSIONS

In applying the three major test criteria for grate inlets, hydraulic efficiency, safety, and debris-handling ability, it is clear that the safety and debris-handling characteristics of a grate inlet are not as dependent on longitudinal slope, S_o, as the hydraulic characteristics. The hydraulic test results indicate that above certain longitudinal slopes, S_o, the hydraulic efficiency, E, of several grate inlets is adversely affected by the high-velocity flow striking the transverse bar members and splashing over the inlet. The specific longitudinal slopes depend on such variables as cross slope, 1/Z, gutter flow, Q_T, and grate length, L, but can be identified in two generalized categories as favorable and unfavorable gutter flow conditions.

Results of the debris tests indicate that the wider the longitudinal bar spacing, the better the debris-handling ability of a grate inlet.

The bicycle safety tests suggest that the deterioration in bicycle safety performance begins as transverse bar spacing is increased above 102 mm (4 in). In addition, grates having large, nearly square openings of 83 × 102 mm (3¼ × 4 in) are also judged to pose some potential danger to pedestrians.

Table 2 is a summary of the test results for debris, safety, and hydraulic efficiency considerations. An attempt has been made to classify the selected grates into high- and low-performance groups for the three major areas of consideration. The high-performance (class I) grates for bicycle safety are low performers (class II) with respect to debris-handling capabilities. For favorable gutter flow conditions (no splashing), the class I grates are slightly more efficient (less than 6 percent) than the class II grates. For the unfavorable gutter flow conditions, hydraulic efficiencies vary as much as 34 percent between class I and class II grates for a 0.61-m (2-ft) grate length and 15 percent for a 1.22-m (4-ft) grate length. The composite selection in the table is our overall classification of the selected grates tested.

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