MULTIPLE SERVICE LEVEL BRIDGE RAILINGS--PERFORMANCE AND DESIGN CRITERIA

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The current AASHTO Specification provides designers with static design criteria and/or crash test criteria to qualify a bridge railing system. Accordingly, a bridge railing system meeting the AASHTO specifications is used on any bridge regardless of vehicle mix, traffic volume, and speed and bridge geometry. The Multiple Service Levels Approach (MSLA) procedure for selecting bridge railings is a new approach differing markedly from traditional practice. The objective of the MSLA is to provide a level of motorist protection consistent with the degree of traffic hazards present at a highway site. With the MSLA, the degree of risk is the combined measurement of the probability of an impact occurrence, the probability of collision severity and the consequences of that impact occurrence. Accordingly, the procedures described in this paper consider encroachment rates, traffic volume, vehicle mix, category speed, shoulder widths, and horizontal alignment as these factors relate to probability of an impact occurring and the severity probability of the impacts. Using a collision severity index as an indicator of bridge railing performance requirements, six service levels were established. By setting critical impacts corresponding to a uniform probability factor, service level requirements are determined for a site. Thus, using the MSLA procedures, a designer selects a higher service level device at locations where collisions are numerous and severe; and lower service level devices are indicated for the relatively safe or improbable accident locations. Since the higher service devices are generally more costly to construct, highway safety funds can be more wisely expended by selecting the service level appropriate for each location.

The current AASHTO(1,2) specification provides designers with static design criteria and/or crash test criteria to qualify a bridge railing system. Accordingly, a bridge railing system meeting the AASHTO specifications is used on any bridge regardless of vehicle mix, traffic volume, and speed and bridge geometry. Although not specifically stated, the AASHTO static/elastic design criteria are directed to the passenger-size vehicle with no specific containment goal for heavy vehicles (trucks and buses). Highway engineers are concerned that this single service level bridge railing design approach is not cost-effective for use on roads with low traffic volumes and may be inadequate for highways with high traffic volume or with significant truck traffic. For these reasons, a discriminating approach is needed in the selection of bridge railing installations to improve overall safety performance and cost-effectiveness of particular barrier systems.

Although this paper is concerned with describing the multiple service level selection process, the design and development of lower service level bridge railing hardware is underway at SwRI as part of this same NCHRP project. In addition, further refinement of the Multiple Service Level Approach (MSLA) is a possibility in the near future.

Research Approach

The Multiple Service Levels Approach (MSLA) procedure for selecting bridge railings is a new approach differing markedly from traditional practice. The objective of MSLA is to provide a level of motorist protection consistent with the degree of traffic hazards present at a highway site. Based on this approach, higher service level devices are indicated for the relatively safe or improbable accident locations. Since the higher service level devices are generally more costly to construct, highway safety funds can be more wisely expended by selecting the service level appropriate for each location.

Definition of Safety(3)

The keystone to the MSLA is a clear definition of the term "safety". A simplistic dictionary definition of "safe" is "free from harm or risk." Because nothing can be absolutely free of risk, nothing can be said to be absolutely safe. There are degrees of risk, and, consequently, there are degrees of safety. Safety, then, is a judgment of the acceptability of risk; and risk, in turn, is defined as a measure of the probability and severity of harm to human health. In other words, something is safe if its risks are judged to be acceptable.

In highway applications, the engineer designs hydraulic structures based on a 50-year mean

recurrence interval for rainfall or sign supports for a 25-year mean recurrence interval for wind velocity. He has balanced the probability of an overload condition and its consequences against costs to produce a more conservative design. Although the engineer can design for a 200- or 1000-year mean recurrence interval, the cost of the structure would be judged excessive for the derived benefits.

In the field of traffic barrier systems, the challenge is to select a bridge railing for a particular site based on acceptability of risk. Placing a low performance railing on a heavily used highway would be an unacceptable risk. On the other hand, placing high performance bridge railings on low traffic volume roads where chance for an impact is practically nil is a waste of public funds.

Degree of Risk

In the MSLA, the degree of risk is the combined measurement of the probability of a bridge railing impact occurrence, the probability of collision severity and consequences of that impact occurrence.

Probability of Occurrence. The number of vehicles that inadvertently leave the pavement and collide with a unit length of bridge railing within a specified period of time can be predicted.

Probability of Severity. The severity of collision is determined by vehicle dynamics at impact. Currently, the dynamic performance of bridge railings evaluated by full-scale crash tests is assessed according to three factors: (1) containment of the impacting vehicle, (2) redirection of the vehicle such that the occupants can survive, preferably uninjured, and (3) vehicle post-impact trajectory such that other traffic is not subjected to undue hazard.(4) Unfortunately, the present state of technology does not permit evaluation of a barrier design by the second and third factors with any degree of precision. Therefore for MSLA, the dynamic performance of a bridge railing is evaluated only by its ability to contain the impacting vehicle.

Graduated Containment Capability. Based on the containment standard, a bridge railing can be developed to contain and redirect an array of vehicles that impact the barrier at or below a specified level of dynamic conditions. Graduated levels of vehicle dynamic conditions can be established over the range of all possible impact conditions; these graduated levels are defined as multiple service levels.

Critical Impacts. Thus, given the following factors--a bridge railing installation designed for a specified service level or containment capability, a bridge site with known or projected geometry, traffic characteristics and special environmental conditions--the probable number of impacting vehicles that will be contained and redirected can be estimated. More importantly, the probable number of impacting vehicles with dynamic conditions exceeding the containment capability of the barrier can be estimated. (It is assumed that a large percentage of critical impacts will result in penetration of the barrier by the vehicle.) These vehicle impacts exceeding a particular containment capability threshold are defined as critical impacts. Accordingly, the degree of risk for the MSLA is the estimate of the number of critical impacts that will occur along a unit length of barrier within a specified period of time.

Acceptability of Risk

Acceptability of risk is a subjective judgment that varies with time, region and circumstances. For the MSLA, the acceptability standard for risk is defined in terms of a containment goal. This containment goal is a national, state or regional policy that specifies the maximum number of critical impacts permitted for a unit length of bridge railing over a specified period of time.

Service Levels

Six service levels are presented and defined in terms of vehicle impact conditions that must be contained by each level. It is most likely that a highway agency will not require bridge railing designs that conform to all six service levels. Full-scale vehicle crash testing will be necessary to demonstrate the containment and redirection capabilities of bridge railing designs for the various service levels.

Content

The purpose of this paper is to provide an overview of the MSLA approach [described in detail in NCHRP Project 22-2(2) Phase I Report (5).] The MSLA approach procedures are briefly described in sections to follow. Even though the probabilistic model that predicts occurrence and severity of vehicle impacts is complex, the procedures to be used by design engineers in selecting appropriate service levels are simple and can be accomplished in a matter of minutes.

Bridge railing performance and design considerations are discussed, and the application of findings is presented, respectively, in sections to follow.

Development of Bridge Railing Service Level Selection Criteria

The Multiple Service Level Approach for selecting appropriate bridge railing designs for particular highway sites is presented in this section.

Vehicle Containment

Practical Limitations. It is neither technically nor economically feasible to construct bridge railing that will contain 100 percent of all possible impacts at every site. Unusually large vehicles with peculiar cargos or unpredictable collision conditions make the design of an all-containing barrier structure an impossible task. Furthermore, the cost of installing the "super barrier" structure at over 550,000 bridges in the United States would be over $8 billion [assuming a nominal $30 per linear meter for the 25,000 km (15,400 miles) of bridge railing]; not only is this amount prohibitive, but also the number of forestalled fatalities (about 1000 per year out of 50,000 total highway fatalities) can be achieved more readily by less expensive means, i.e., reduction of speed limits, mandatory use of active restraints for vehicle occupants, etc. Treatments such as pavement deslicking, signing, and delineation are other cost-effective ways of reducing the frequency of accidents.

Achievable Performance. As an alternative to the 100-percent containment ideal, the acceptance of a uniform containment policy would greatly reduce the structural requirements and cost of the barriers. The containment policy could be set on a national, regional or state-wide basis, and it would be adjusted depending on available funding.

Containment Percent or Critical Impacts. In the MSLA, the performance goal of a bridge railing is expressed in terms of a maximum probable vehicle critical impact rate. A convenient scale, based on current performance of bridge railing in the United States, is the number of critical impacts per 16-km (10-mile) length of bridge railing per 10-year period. The fact that a specific bridge railing installation is only 30 m (100 ft) and not 16 km (10 miles) in length is immaterial to application of the MSLA. Using the containment goal expressed in the rate of critical impacts, it can be reasoned that a bridge railing on a high traffic volume road with a great number of vehicle impacts will require a device that contains a high percentage of these vehicle impacts. In contrast, for low traffic volume roads with a small number of probable impacts, the bridge railing installation can contain a lower percentage of colliding vehicles and still satisfy the containment goal.

Although the designer prefers to think in terms of success rather than failure of bridge railing structures, it is necessary in the MSLA to deal with the probable number of critical impacts (i.e., possible penetrations) rather than the percent of vehicle impacts contained. A percent containment policy would provide essentially the same service level railing for a 100-ADT (average daily traffic) road as for a 100,000-ADT road assuming everything else is equal, even though the number of bridge railing impacts is a direct function of traffic volume. Thus, the same bridge railing would be used at locations where there is less likelihood of vehicle impacts and penetrations as is used at those locations where critical impacts are frequent. For this reason, the performance goal of a barrier expressed in terms of percent of impacting vehicle contained is not meaningful to the MSLA.

Containment Goal. In order to establish reasonable limits on the containment goal, the maximum number of critical impacts considered an acceptable risk can be inferred by safety performance of the existing bridge railing with this performance measured in terms of accident statistics.

Based on analyses of very limited data, it was determined that the current rate for the United States is approximately 2 penetrations per 10 years per 16 km (10 miles). This figure is considered a "ball park" number based on the best data available. Thus, a highway agency could select 2 critical impacts per 16 km (10 miles) per 10 years as its containment goal and maintain the level of containment reflected by the data analysis. By accepting a higher number, i.e., 3, as an acceptable critical impact rate, a highway agency can effect a savings in construction funds by lowering loading requirements on many low traffic volume bridges and increasing strength requirements on a few high traffic volume bridges. On the other hand, a highway agency may opt to use a lower critical impact rate, i.e., 1 or 0.5, and thereby reduce the total number of penetrations; of course, this decision will be more costly to implement. Regardless of the selected containment goal per critical impact rate, this approach will provide a rational and consistent technique for setting bridge railing service level requirements.

Probability of Barrier Impact

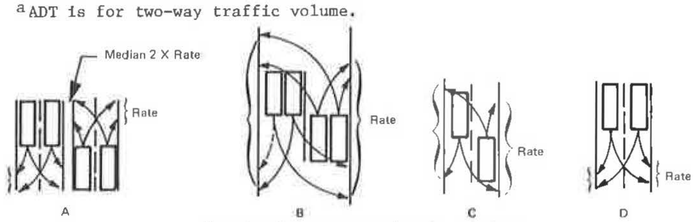
The probability of a bridge railing impact occurrence is based on encroachment rate and the lateral distance L_T between the traffic stream and the barrier face.

Encroachment Rate. Encroachment rate data as shown in Table 1 were obtained from Reference 6 and

Table 1. Encroachment rate table(6).

Type of Highway	Description of Collision Direction	Encroachment Rate events/km (mile)/year[a]	Sketch
Divided Urban Arterial Street	One direction each side, each direction separately for median	0.00021 (0.00033) ADT	A
Undivided Urban Arterial Street	Both directions	0.00042 (0.00067) ADT	B
	One direction only	0.00021 (0.00033) ADT	D
Narrow Two-lane Rural Highway (roadbed less than 11 m)	Both directions	0.00037 (0.00060) ADT	C
	One direction only	0.00019 (0.00030) ADT	C
Wide (roadbed of 11 m or greater) Two-lane or Undivided Four-lane Rural Highway	Both directions	0.00023 (0.00037) ADT	C
	One direction only	0.00011 (0.00019) ADT	D
Multi-lane Divided Rural Highway	One direction for each side, each direction separately for median	0.00009 (0.00015) ADT	A
Freeway	One direction for each side, each direction separately for median	0.00014 (0.00023) ADT	A

[a] ADT is for two-way traffic volume.



Boundary lines represent edge of traveled way

are considered state-of-the-art 1977. These rates are a function of highway type and direction of traffic. The encroachment probability is a linear relationship with traffic volume. MSLA is readily adjusted to other encroachment rate values.

Adverse Conditions. Factors not considered which may affect the encroachment rate at a specific site include the following: skid resistance, horizontal and vertical alignment, stopping sight distance, route discontinuity, narrow lanes, inadequate superelevation on curvature, shoulder surface type, length of grade, lane drops--shoulder drop or reduction, regional differences (climate, driver, etc.), pavement marking and delineation, and shoulder width. Some, if not all, of the above factors can be mutually exclusive (additive or subtractive) in their influence on encroachment rates. In other circumstances, the worst value of one factor alone can be overwhelming because of other associated inconsistencies violating driver expectancy.

Selection of adverse factors was not in the scope of this work; however, the reader is alerted to the existence of such data in the technical literature. It is conjectured that the adverse condition multiplier will generally range between 1 and 2. Since most of the data pertain to roadways, judicious selection procedures should be employed to apply these factors to bridges.

Figure 1. Distribution of lateral displacements.

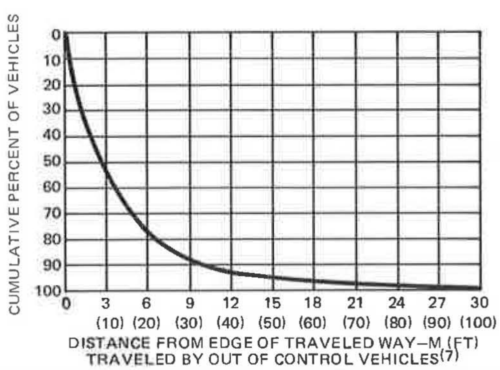
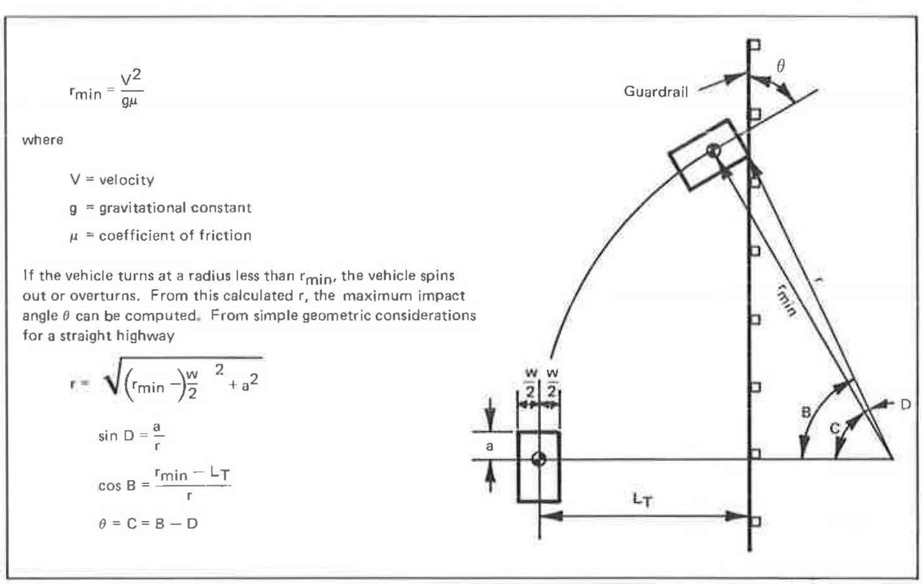


Figure 2. Point mass conditions for straight bridge.



Barrier Offset. The probability of an encroachment becoming an impact is affected by the distance from the pavement edge to the barrier. In general, the greater the offset distance, the greater the opportunity for the errant motorist to regain control of the vehicle and avoid collision. The percentage of encroachments resulting in barrier impacts is determined from the relationship (7) presented in Figure 1.

Probability of Vehicle Impact Conditions

As the vehicle mass, speed and approach angle increase, the collision generally becomes more severe and the containment requirements more difficult to satisfy. Bridge railing collisions consist of a full range of energy impacts. As the structural capability of a bridge railing is increased to contain a higher energy impact, the proportion of impacting vehicles that are contained by the bridge railing is also increased. Thus, a rational design approach is to select a bridge railing system that will contain a threshold vehicle impact energy corresponding to most possible impacts at that particular site in accordance with the containment goal.

To determine probability of vehicle impact conditions, the techniques described in the following sections were used:

Impact Angle (θ). It is widely accepted that maximum automobile impact conditions can be predicted by using a point mass model using a representative value for coefficient of pavement friction as illustrated in Figure 2. For passenger cars, a coefficient of pavement friction of 1.0 is used. Vehicles with high center of gravity have performance limits that increase the minimum possible turning radius, thus decreasing the maximum impact angle. These performance limits are applied to the heavy trucks and buses and can be accommodated in the point mass model by using an effective coefficient of friction of 0.47 determined from vehicle handling studies.

A distribution of impact angles based on the maximum possible angle was determined from field data by Ross. (8) Encroachment trajectory considerations are described in Figure 3.

Figure 3. Vehicle encroachment trajectories.

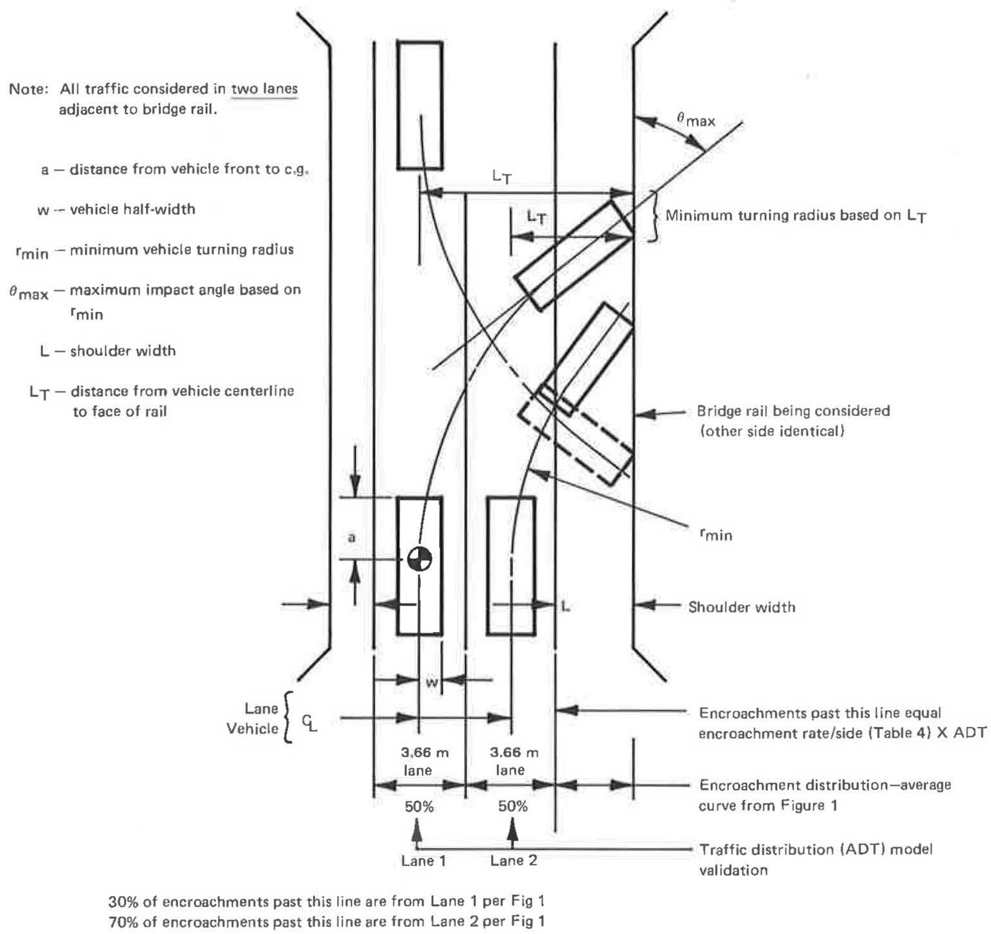


Table 2. Traffic mix description.

Vehicle Type	Traffic Mix Number 1[a]		4[a]		5[a]		6[b]		7[b]	
Passenger Cars										
1200 kg (2700 lb)	17.5		20.0		22.5		50.0		13.3	
1800 kg (4000 lb)	31.0		35.2		39.6		25.5		23.6	
2100 kg (4700 lb)	16.7		19.2		21.6		14.0		12.8	
2700 kg (6000 lb)	4.8		5.6		6.3		4.0		3.7	
Subtotal, %		70		80		90		93.5		53.4
Pickups and Panels										
2200 kg (5000 lb)	6.3		5.0		4.4		2.8		4.8	
3600 kg (8000 lb)	3.7		3.0		2.6		1.7		2.8	
Subtotal, %		10		8		7		4.5		7.6
Other Trucks and Buses										
10,500 kg (23,000 lb)	11.8		7.1		1.8		1.2		9.0	
18,000 kg (40,000 lb)	8.2		4.9		1.2		0.8		30.0	
Subtotal, %		20		12		3		2		39
Total Traffic, %		100		100		100		100		100

[a]Based on traffic count data.
[b]Hypothetical mix.

Vehicle Size. The distribution of vehicle by mass was determined from traffic count data compiled by FHWA and other data sources. Based on analyses of these data, five vehicle mixes (1, 4, 5, 6 and 7) were deemed adequate as described in Table 2.

As shown in this table, vehicles weighing more than 18,000 kg (40,000 lb) were not considered in this study. These heavier vehicles, which are generally tractor-trailer rigs, have performance limits that result in larger minimum radii of curvature and, hence, represent a less formidable impact possibility for a given weight, speed, and offset distance. The mechanics of articulated vehicle impacts are very complex and were not included in this study because of the lack of current information. Based on recent crash test results with the new collapsing ring bridge rail system,(9) the following comparisons can be made:

Vehicle	Vehicle Weight, kg (lb)	Impact Speed, km/h (mph)	Impact Angle, deg	Max Deflection, m (in.)
Intercity Bus	18,000 (40,000)	86.8 (53.9)	15	1.2 (48)
Tractor/Trailer	32,000 (70,000)	71.4 (44.4)	10	0.3 (12)

Thus, the inclusion of a 18,000-kg (40,000-lb) single unit vehicle [as well as the 10,000-kg (23,000-lb) vehicle] gives assurance that single unit vehicles in this weight range are adequately considered; and it can be inferred, as demonstrated above, that articulated vehicles weighing in excess of 18,000 kg (40,000 lb) are included also because of performance limits previously discussed. The inclusion of a 10,000-kg (23,000-lb) vehicle assures that the upper limit of school bus mass has been considered in the vehicle mix.

Impact Speed. Speed distributions for accidents are not available in any degree of precision. Accordingly, four speed categories, 56, 72, 88 and 105 km/h (35, 45, 55 and 65 mph) are used. The designer must select what he considers a representative speed for his site.

Collision Severity Index

To rank the relative severity of all predicted barrier impacts, a Collision Severity Index (CSI) was developed in the program. Essentially, the CSI was developed by curve-fitting results from BARRIER VII(13) computer simulations of 16 vehicle/barrier impact cases. The vehicle size was varied from a passenger vehicle to an intercity bus, the approach angle was varied from 7 to 25 deg and the speed was varied from 65 to 95 km/h (40 to 60 mph). Maximum lateral deflection was the selected measure of impact intensity using an extremely stiff, but deformable barrier.

$$CSI = 2.598 \times 10^{-7} m^{(0.50)} I_z^{(0.82)} V^{(2.50)} \sin \theta^{(3.00)} \quad (1)$$

where

CSI = collision severity index,

m = vehicle mass, kg (slugs)

V = impact speed, m/s (fps)

θ = approach angle, deg

I_z = vehicle mass moment of inertia about vertical axis (yaw) kg-m^2 (slug-ft^2)

Bridge Railing Service Levels

Six bridge service levels are defined in Table 3 on the basis of the Collision Severity Index. Also, impact conditions corresponding to CSI values are shown for each service level. These levels were arbitrarily selected with some preference given to current design performance range and the type of vehicles that may have to be contained. Service Level 2 coincides with the current AASHTO bridge rail crash test option specification; however, test experience has demonstrated that railings designed to the 44.5-kN (10-kip) static force are not significantly damaged when impacted by a 1640-kg (3620-lb) car at 99 km/h (61.4 mph) and a 25-deg angle.(10) Thus, the ultimate containment capacity of this railing design may be much greater than the level indicated by these test conditions. The service levels indicated are based on ultimate containment; large deflections are permissible if containment is achieved. It should be emphasized that these large deflections would occur infrequently if a goal such as 1 critical impact per 10 years per 16 km (10 miles) were adopted.

Bridge Railing Service Level Selection Procedures

All of the factors discussed previously are combined to provide a range of impact conditions based on: five vehicle mixes (Table 2) (eight vehicle weight categories); four category speeds (55, 70, 90, 105 km/h) km/h x 0.62 = mph; four shoulder widths (0.6, 1.8, 3.0 m) m x 0.33 = ft; five alignment variations (horizontal curves of -10, -5, 0, +5, +10 deg); one encroachment rate (0.00037 ADT events/km/year). Note: This encroachment rate value is for one side of the bridge and corresponds to a narrow two-lane rural highway with traffic in both directions. Collision Severity Index values are calculated based on all of these variables. By using a containment goal of 1 critical impact per 10 years per 16 km (10 miles), maximum equivalent ADT values can be obtained that correspond to this goal for each of the conditions. These values are illustrated in Table 4. For the purpose of increasing the encroachment rate due to unusual site conditions, an adverse conditions factor is included; however, no recommendations for these values are presented. For other encroachment frequencies and goals, the adjusted ADT values are linear and can be readily calculated as follows:

Actual (ADT) x (Ratio of Encroachment Rates) x

Environmental Factor/No. of Permissible

Critical Impacts

Typical Selection Procedure--An example problem and worksheet are illustrated in Table 5.

Table 3. Bridge rail service levels.

Service Level	CSI	Performance-Related Impact Conditions — Vehicle Weight, kg (lb): 1000 (2250)	2000 (4500)	10,500 (23,000)	18,000 (40,000)
1	4	95 km/h (60 mph) @ 25 deg	95 km/h (60 mph) @ 15 deg	65 km/h (40 mph) @ 7 deg	
2	16		95 km/h (60 mph) @ 25 deg	50 km/h (30 mph) @ 15 deg	80 km/h (50 mph) @ 7 deg
3[a]	60			80 km/h (50 mph) @ 15 deg	55 km/h (35 mph) @ 15 deg
4[a]	100			95 km/h (60 mph) @ 15 deg	70 km/h (45 mph) @ 15 deg
5[a]	400			95 km/h (60 mph) @ 25 deg	65 km/h (40 mph) @ 25 deg
6[a]	1000				95 km/h (60 mph) @ 25 deg

[a]Staging of these systems may be required to provide desirable safety performance for impacting automobiles. Staging is provided by a softer barrier placed in front of a more rigid barrier.

Table 4. Typical MSLA selection guide 1.8-m (6-ft) shoulder.

Shoulder Width, m (ft)	Designated Speed km/h (mph)	Degree of Curve	Vehicle Mix	Maximum Equivalent ADT Barrier Service Level 1	2	3	4	5	6
1.8 (6)	90 (55)	-10							
			1	835	27911	No Limit	No Limit	No Limit	No Limit
			4	901	33691	No Limit	No Limit	No Limit	No Limit
			5	975	41792	No Limit	No Limit	No Limit	No Limit
			6	1407	64585	No Limit	No Limit	No Limit	No Limit
			7	678	17303	No Limit	No Limit	No Limit	No Limit
1.8 (6)	90 (55)	-5							
			1	255	1348	12580	53169	No Limit	No Limit
			4	123	2098	20997	88911	No Limit	No Limit
			5	457	5510	84223	361599	No Limit	No Limit
			6	637	8386	126377	542407	No Limit	No Limit
			7	157	600	4130	15778	No Limit	No Limit
1.8 (6)	90 (55)	0							
			1	159	559	2695	6274	499024	No Limit
			4	203	870	4492	10479	835012	No Limit
			5	294	2296	17885	42368	No Limit	No Limit
			6	399	3486	26840	63553	No Limit	No Limit
			7	100	257	1023	2158	138103	No Limit
1.8 (6)	90 (55)	5							
			1	125	353	1334	2597	57025	No Limit
			4	157	543	2221	4334	95388	No Limit
			5	219	1365	8761	17456	388637	No Limit
			6	290	2067	13152	26185	582955	No Limit
			7	81	169	532	973	16400	No Limit
1.8 (6)	90 (55)	10							
			1	106	268	854	1533	18484	581856
			4	130	407	1420	2557	30905	973672
			5	175	960	5539	10269	125638	No Limit
			6	228	1446	8319	15405	188457	No Limit
			7	72	131	349	597	5609	159899

Table 5. Service level selection example.

Example Problem. A bridge railing system is needed on a divided rural highway with an ADT of 20,000. The traffic mix contains 20 percent trucks corresponding to Mix 1. The traffic on this section moves about the posted speed of 88 km/h (55 mph) and there is a 2-m (6-ft) shoulder. The engineer has been instructed to use a goal of 1 critical impact/10 miles/10 years.

Input

1. Bridge Example 1
2. Total ADT 20,000
3. Vehicle mix (see Table 2) 1
4. Category speed, km/h (55, 70, 90, 105) 90
5. Shoulder width, m (0, 0.6, 1.8, 3.0) 1.8
6. Horizontal curvature, deg (-10, -5, 0, +5, +10) 0
7. Encroachment rate from Table 3 0.00015
8. Adverse conditions factor 1
9. Containment goal (critical impacts/16 km (10 mile)/10 years) 1

Step 1: Calculate maximum equivalent ADT, ADT

$$ADT = \textcircled{2} \times \frac{\textcircled{7}}{0.0006} \times \textcircled{8} \div \textcircled{9}$$

$$ADT = (20,000) \; \frac{0.00015}{0.00060} \; \frac{(1)}{(1)} = 5000$$

Step 2: Enter Table 4 and select lowest service level bridge rail by comparing adjusted ADT with applicable Table 4 value.

$6274 > 5000 < 2695$

USE SERVICE LEVEL 4

Bridge Railing Performance and Design Considerations

There is apparently no relationship between the AASHTO load criteria and the crash test requirement. While not stated as a design objective, the static force criterion generally is believed to guarantee little or no damage to the railing system during the severe strength crash test [2040-kg (4500-lb) car, 95 km/h (60 mph), 25 deg].(4) The ultimate containment capacity of these railing systems is not known. Furthermore, the margin of safety to which the system has been designed according to this static criterion will influence its ultimate capacity. In other words, the AASHTO static force is a lower limit, and overdesigned bridge railings are not prohibited. The current AASHTO specification does not specify behavior of the barrier past the elastic range. The failure of a post, for example, could occur either above the deck or within the deck itself. Designs where deck failure controls are considered to be unsatisfactory for a number of reasons:

1. The failure mechanism in the concrete deck is complex and, therefore, cannot be reasonably predicted.
2. Bridge deck repair is a costly item compared to simple replacement of posts and beam.
3. Deck damage may go unnoticed until a more severe impact causes noticeable failure. The weakened structure will not perform as designed.

Other railing components such as beams and hardware also should be considered for ultimate performance. A bridge railing system that performs well in the elastic/small deflection range, but breaks down far below its ultimate capacity because of some undesirable failure mechanism (e.g., lowered system

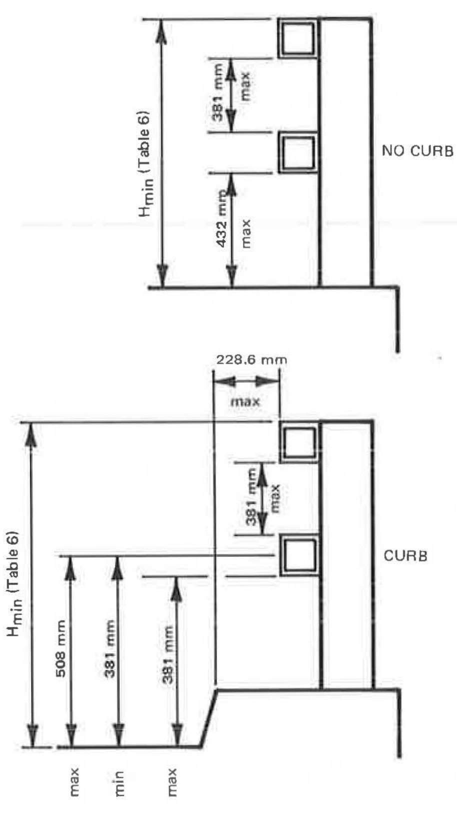
height allowing vaulting, beam splice failure due to fastener inadequacy, etc.) represents inefficient use of materials.

After 10 years of intensive barrier development and testing using all available tools, design methods, computer simulations, laboratory experiments and full-scale vehicle crash tests, the authors are convinced the prescriptive design approach is inadequate to effect barriers with predictable containment and safety performance. On the other hand, the performance standard approach would encourage the generation of a limited number of carefully developed standard barrier designs, hence, decreasing the time spent by every agency designing their own unique systems, decreasing material costs due to standardization and the smaller number of inventory items, and improving safety performance because of the more comprehensively developed barrier designs.

Performance Predictions

Use of a single force to design a service level traffic barrier is not recommended in this paper. Bridge railing performance beyond the elastic range requires analysis methods that go far beyond the current static method. However, complicated methods of analysis are considered unnecessary when available computer simulations can be employed that actually relate to a vehicle impact and are no more involved to use than a dynamic structural analysis program. Computer simulation programs currently available(11,12,13) provide reasonable assurance that the simulated impact forces are being applied to the barrier during the redirection process. In

Figure 4. Barrier beam geometry.



Note: Definitive dimensions shown are based on current AASHTO specification.(2)

addition, the use of a rollover vaulting algorithm (RVA),(14) coupled with 2-dimensional barrier models, predicts rollover or vaulting due to insufficient rail height. Wedging under a beam and so-called "pocketing" are difficult phenomena to ascertain from the current programs.

Performance and Design Criteria

Vehicle Containment. The proposed bridge railing service levels are related to vehicle impact conditions (presented in Table 3), and containment of the impacting vehicle for these respective impact conditions is recommended as the strength test for each railing category. Ultimate containment is considered to be the most efficient use of bridge railing structure. The ultimate containment approach requires an understanding of the failure mechanisms of the structural system as the ultimate loading threshold is reached. From the knowledge of the ultimate containment capacity, the full range of barrier performance is understood. Although full-scale crash tests at each performance level are necessary, preliminary designs can be formulated using computer simulation models.

Good Design Practice. Recent crash test experiments with both heavy vehicles and automobiles have revealed certain deficiencies in barrier behavior which can be averted by good design practice. These include:

1. Undesirable lowering of barrier height because of ductile post behavior reduces effectiveness of barrier in preventing vaulting/rollover.
2. Beams considered flexural members fail in tension during large inelastic deflections because of inadequate splice or tensile anchorage.
3. Unpredictable failure mechanisms of post/parapets make ultimate loads indeterminate and unrepeatable.
4. Barrier height is too low for heavy vehicle impacts.
5. Beam/vehicle interface is inadequate for full range of automobiles.
6. Beam/post geometry permits wheel snagging at even moderate impact angles.

Bridge railing performance criteria for each service level are suggested in Table 6. The performance test criteria of NCHRP Report 153 recognize the need for providing forgiving redirection to the small passenger cars. This class of vehicle currently constitutes approximately 25 percent of all passenger cars sold. Passenger cars are still the predominate vehicle representing up to 90 percent of the traffic on highways. Crash tests are recommended for performance and strength evaluation. Barrier heights based on rigid barrier RVA simulations are shown. Strength of barrier elements is suggested that encourage efficient ultimate performance. The evaluation criteria of NCHRP Report 153 are also recommended. There has been no systematic study of vertical bridge rail spacing; the current AASHTO recommendations are shown in Figure 4.

Discussion and Application of Findings

Discussion

Bridge Railing Service Levels. The multiple service bridge railing approach is a major change from current recognized practice, both from a

Table 6. Bridge railing performane criteria.

Service Level:	1	2	3	4	5	6
1. Crash Test Requirements Impact Conditions A. Strength Test Vehicle Weight, kg (lb)	1000 (2250)	2000 (4500)	10,500 (23,000)	10,500 (23,000)	10,500 (23,000)	18,000 (40,000)
Impact Speed, km/h (mph)	95 (60)	95 (60)	80 (50)	95 (60)	95 (60)	95 (60)
Impact Angle, deg	25	25	15	15	25	25
B. Redirection Severity Test	1000-kg (2250-lb) auto, 95 km/h (60 mph), 15 deg					
2. Dynamic Performance						
A. Posts/Parapets	Controlled, repeatable failure mechanisms outside bridge deck are required. Ductile failures of posts are discouraged unless separation of beam from post prior to rail lowering is controlled and repeatable. The post anchorage is designed to AASHTO working stresses using ultimate post failure load.					
B. Beam	Full tension of net section should be developed at splice. The AASHTO Standard Specifications for Highway Bridges,(1) Article 1.7.19, provide a good splice specification. Beam should be anchored (expansion joints require special treatment).					
C. Vehicle performance	The preferred vehicle acceleration criteria are found in recommendations of NCHRP Report 153. Values shown in this document are subject to change as technology becomes available. Other requirements specified for automobiles in Report 153 regarding snagging, pocketing, etc. are considered applicable also.					
3. Guidelines						
A. Geometry [a]1. Barrier height, m (in.) (min) 2. Beam (see Figure 4)	0.7 (27)	0.7 (27)	0.7 (27)	0.7 (27)	0.9 (34)	1.0 (40)
B. Maximum dynamic deflection	As a guide for design, the maximum dynamic deflection should not exceed the vehicle half-width. This value may be exceeded during crash test if redirection/containment is achieved.					

[a]Barrier height is a minimum; this height must be increased if beam/post interaction allows beam to drop below this height.

technical and administrative view. Rather than the synthesis design of a bridge railing system, MSLA implies the selection from a group of systems crash tested to specific impact conditions. The creation of unique bridge railing designs from prescriptive specifications using static loading/elastic design results in a proliferation of barrier systems that are not fully analyzed in terms of vehicle containment.

The national trend is toward the adoption of a limited number of carefully developed and demonstrated traffic barrier systems. The movement is prompted by the requirement for increased safety performance of traffic barriers and the realization of cost savings in design, fabrication and maintenance of widely accepted standard systems. These limited number of bridge railing designs can be developed on cooperative programs such as NCHRP where the development costs are shared.

Thus, the multiple service level bridge rail approach takes into account the trend toward standardization of bridge rail systems and presents a technique for selecting the most appropriate system for particular site conditions.

Service Level Selection Parameters. The service level parameters were selected based on what was considered state-of-the-art 1977. Certain parameters in this model are linear in the final product and may be varied or changed by simple multiplication. These linear factors include: ADT, encroachment rate, adverse conditions as related to encroachment rate, and containment goal. Other factors influencing the final results are more complex, and reformulation of probability equations is required if their values are changed. These nonlinear factors include: shoulder width as it relates to encroachment distribution, encroachment distribution (lateral distance traversed), vehicle mix characteristics (mass, geometry, etc.), speed (or speed distribution if available), impact angle distribution, and traffic distribution (e.g., unequal lane distribution, more than two lanes, etc.). It is recognized that parameter values such as encroachment frequencies, vehicle mix characteristics and impact speed and angle distributions are based on tenuous and sometimes scant research data. Undoubtedly refined values for these parameters will be forthcoming from future research efforts. Nevertheless, the authors strongly believe that the lack of precision in the values will not change the systematic method of selection nor should it be a reason to deter or delay the implementation of the MSLA.

Results. Bridges on roadways with high ADT, high speed traffic, horizontal curvature, and large truck percentages will require bridge railing structures with greater containment capacity than that specified by the current AASHTO specification. Conversely, bridges on roadways with low ADT, low traffic speeds and mostly automobile/pickup traffic will require a bridge railing less demanding than the current AASHTO specification. The degree of this variance will depend largely on the containment goal selected. Since this containment goal is new and no specific goal has been used previously, this goal will require study by highway agencies to ascertain influence on implementation funding.

Application of Findings

Service Level Selection. A rational basis has been derived which provides maximum protection where impacts are likely to occur and further accounts

for degrees of collision severity based on a number of factors. The use of this model to evaluate a barrier system on a regional or national basis requires a knowledge of barrier containment capacities both existing and proposed. Containment goals and encroachment frequencies can be varied as policy or better findings permit.

Barrier Design. The shortcomings of simplified barrier design were previously discussed. Currently available barrier simulation computer programs are available to provide insight for existing barrier systems as well as new designs. It is considered necessary to evaluate new and upgraded designs by crash test to prove the containment capacity. Suggested criteria and guidelines are presented for the six service levels of this paper.

The new concept of ultimate containment barriers which deviates from statically designed barriers is considered superior for these dynamically loaded structures. The range of costs among the six service levels cannot readily be determined until some definitive designs are formulated; however, using analyses such as presented in this report will justify high performance bridge railing costs when compared to current expenditures on lower traffic volume roadway bridge railings. The illustration of six service levels should not be construed as a recommendation; the number of levels actually needed will be the product of future investigations.

Acknowledgment

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program which is administered by the Transportation Research Board of the National Research Council.

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