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Strategy for Selection of Bridges for Safety Improvement

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In order to upgrade traffic safety of existing bridges in a systematic and cost-effective manner, we must have a clear understanding of how safety is measured and controlled. Safety is not an absolute but a relative condition that balances the risk of an event and society's acceptance of that risk. Something is considered safe if its risks are acceptable. Risk is measured by the probability of the occurrence of an adverse event (i.e., bridge accident) and the event's consequences (i.e., collision severity). Based on length alone, a bridge is 50 times more hazardous than the roadway in general. The large number of bridge accidents is attributed to narrow bridges and to obsolete approach guardrail and bridge rail installations. To improve bridge traffic safety, the ideal solution would be to widen all narrow bridges and upgrade barrier installations on all other bridges. Because of cost, this approach is not practical. As an alternative, bridge selection for safety improvement can be based on degree of risk and available funds concentrated on the high-risk bridges. This procedure, which is also applicable to other roadside safety problems, advocates uniform standards for degree of risk rather than uniform standards for design. In fact, design standards will be varied according to site requirements to achieve the acceptable level of risk. Two techniques are presented to identify bridges that have a high degree of risk: (a) adverse accident experience and (b) high traffic volume coupled with substandard highway features. The extent and type of safety improvements are presented.

The term safety is currently a very popular word, judging by its use as a topic in newspapers, books, magazines, and other media. The term safety carries a heavy emotional and political load. There is considerable public confusion about safety, and this confusion is not helping the highway community improve its system.

A simplistic and misleading definition of safe is "free from harm or risk." However, nothing can be absolutely free of 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 (Figure 1). 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 (1). In other words, something is safe if its risks are judged to be acceptable. Even with a specific measure of risk, the acceptability judgment, which is a value decision made by all or a segment of society, may vary with time and place.

Degree of risk is measured by the probability of an event multiplied by consequences or severity of the event:

$$\text{Degree of risk} = \text{probability of occurrence} \times \text{probability of consequences} \quad (1)$$

The degree of risk can be lowered by causing a decrease in the number of events or collisions or a reduction in the severity of the collisions when they occur. Unfortunately, it costs money to make these changes, so one should be sure the improvement in safety (reduction in risk) is worth the cost.

HIGHWAY SAFETY EFFORT

Traditionally, highways have been constructed or upgraded according to state or federal design standards. For example, highway features (such as typical cross sections, lane widths, maximum horizontal curvatures, maximum shoulder slopes, and minimum roadside clear zones) are consistently high on the Interstate system. Low fatality rates on the Interstate system have proved the effectiveness of the high-design standards. On the other hand, some believe that much of the Interstate system has been unnecessarily built to these high and costly design standards. Thus, safety funds have been spent on highway segments where the degree of risk and, therefore, the potential for reducing fatalities are low.

As the safety upgrading attention is directed away from the Interstate system to the remaining 6 200 000 km (3 838 000 miles) of highways, highway agencies are forced to be more prudent with expenditures.

An alternative to the upgrading of highways to one or more specified uniform design standards is the upgrading of highways to a uniform standard for degree of risk. Such a standard can be quantified in terms of kilometers of highway per run-off-the-road type of fatality. An initial goal can be set at, say, 800 km (500 miles) and then increased as additional safety funds become available. This approach implies a variable design standard that is determined by the degree of risk at a local site and is in contrast to the uniform standard design approach used on the Interstate system. This uniform risk approach is the only strategy that is both effective and affordable. To select a uniform design standard will be either grossly wasteful of public funds or ineffective in reducing fatalities.

The application of risk management to the assessment and implementation of safety is an emerging technique in highway technology. The number of spot safety improvement programs is increasing. The multiple-service-level bridge railing selection procedure, which is based on risk measurement and assessment (2), is another example of the emerging technology. Moreover, considerable research activity is under way in this area. Although it will be a few years before a comprehensive technology is developed, some things can be done now.

THE BRIDGE SAFETY PROBLEM

The table below is based on 1975 data (3,4) (1 km = 0.62 mile).

Category	Length (km)	Fatalities	Kilometers per Fatality
Roadway	6 175 000	11 300	546.5
Bridges	12 400	1 120	11.1

In 1975, 45 850 people were killed; 11 300 of them were involved in a single-vehicle, ran-off-the-road, hit-fixed-object type of collision (5). Moreover, we know that the fixed object involved with at least 1120 of these fatalities was a bridge or bridge barrier. By dividing lengths of roadways and bridges by these fatalities, one can see that a fatality occured for every 546.5 km (340 miles) of roadway and every 11.1 km (6.9 miles) of bridge length. The bridge-to-roadway hazard ratio is 546.5:11.1; that is, based on length alone, a bridge is about 50 times more hazardous than the roadway.

Causes of Bridge Fatal Accidents

The question arises as to why so many fatal accidents occur at bridges. Causation factors and remedial treatments must be identified before we can rationally reduce the degree of risk. Some of the causation factors influence both the number and the severity of the event.

One of the primary causes of the large number of fatal bridge accidents is the relative narrowness of the structure. Of the nation's 564 000 bridges, 75 percent were built prior to 1935, according to the Federal Highway Administration's (FHWA's) national bridge inventory. Many of these structures were designed to carry smaller cars and few trucks. In the intervening years, pavement width has been increased to carry larger vehicles in greater numbers; however, due to expense, bridge width has not been increased. Thus, as shown in Figure 2, we have been left with wide pavement and narrow bridges--an inconsistency for the motorist. Hutchinson states that such inconsistencies violate the driver's expectation and cause the accident (6). The importance of bridge width is seen in Figure 3, where the Arizona bridge accident rate expressed in million vehicle kilometers of travel varies from 0.733 to 0.447 million vehicle-km (1.18-0.72 million vehicle miles) (7). If bridge widths are increased from 9.1 to 12.89 m (30 to 42 ft), the accident rate decreases by 39 percent.

Solutions

If money were not a consideration, the ideal solution would be to replace all narrow bridges with wider structures and replace all obsolete bridge barriers with high-performance systems. If one assumes that bridge barrier safety could approach that of the highways in general [that is, 1 fatality/546 km (340 miles)], then the 1120 bridge-related fatalities would be reduced by more than 98 percent to about 23 per year. This approach would cost more than $100 billion (8). Even considering the benefit of 1000 fatalities forestalled per year for 25 years, the cost would be $4 million/fatality forestalled--an extremely high value with respect to other alternatives. Of course, if a bridge is being replaced for other reasons or if it has experienced numerous accidents, the widening of the bridge may be justified.

Under the Highway Bridge Replacement and Rehabilitation Program, enacted in November 1978, $4.2 billion in funds are available over a four-year period to replace or upgrade some existing bridges (9). Bridges are to be rated by the states according to structural adequacy and safety, essentially for public use and serviceability and functional obsolescence. A simplified decision path for this program is illustrated in Figure 4 and shows when traffic safety is considered in the process.

For cases where traffic safety conditions are inadequate (Figure 4), but the bridge has a low priority for replacement, there are alternatives to widening a narrow bridge that can be used to reduce the number of accidents (10). The effectiveness of these treatments, acting alone or in combination, is unknown:

1. Realign roadway;
2. Change approach grade;
3. Transition shoulder to bridge;
4. Add approach bridge delineation;
5. Place edge lines;
6. Place pavement transition markings;
7. Install narrow-bridge signs;
8. Install stop, yield, or signalization;
9. Place advisory speed signs; and
10. Reroute commercial vehicles.

SEVERITY OF BRIDGE BARRIER ACCIDENTS

Certain remedial actions may reduce the severity of a bridge barrier collision. More than one-half of bridge-related fatal accidents occur at the bridge end or terminal post (Figure 5) (11). The terminal post, or tombstone, was a typical feature of most bridge railing until recently. Its contribution to severity of collisions was recognized some 10 years ago, after which time approach guardrail was used to funnel traffic onto the bridge. In the initial effort, the importance of structurally attaching the approach guardrail to the bridge railing system was not recognized (Figure 6), and this resulted in systems that were completely inadequate. The pocketing of vehicles at the juncture of the approach guardrail and the bridge railing caused a large number of fatalities (Figure 7).

Since 75 percent of bridges were built before 1935, it should not be surprising that the safety performance of bridge railings is obsolete with respect to today's safety standards (Figure 7).

Figure 1. Safety is a relative condition.

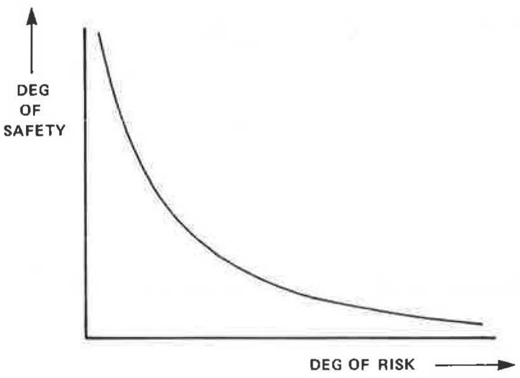


Figure 2. Abrupt constriction of roadway at narrow bridge causes accidents.

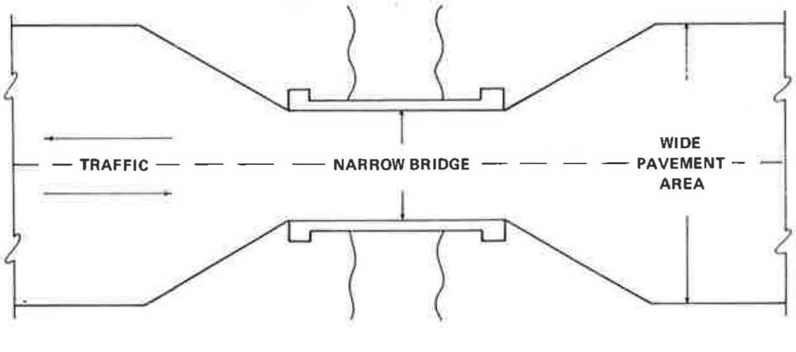


Figure 3. Accident rate as a function of bridge width.

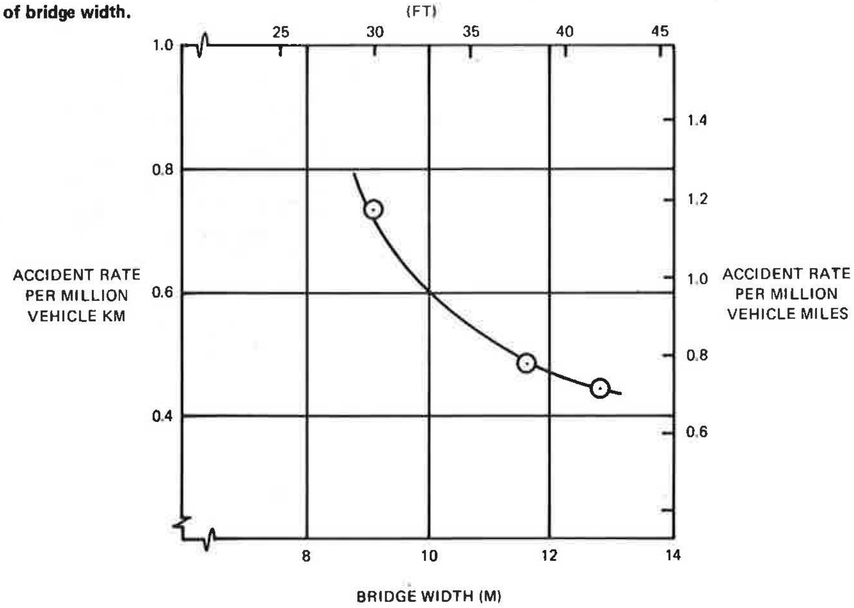
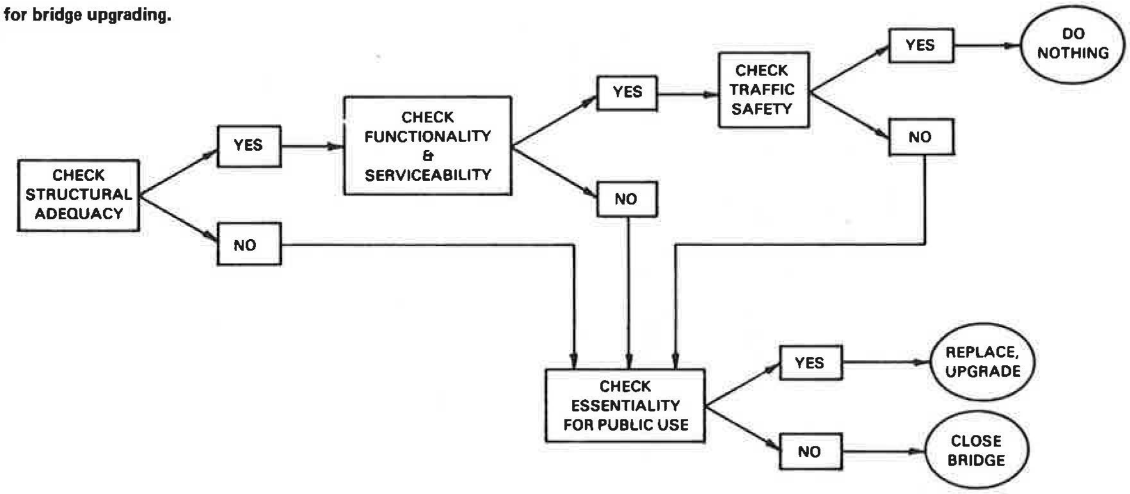


Figure 4. Decision path for bridge upgrading.



Thus, to decrease the potential severity of a bridge barrier collision, it is important to have a good approach rail that funnels the traffic onto the structure and is adequately attached to the bridge barrier (Figure 8). Crash cushions (such as sand drums) have been successfully used in cases where an approach guardrail is not feasible. Then the obsolete bridge barrier should be safety upgraded or replaced by current standard systems. Techniques for upgrading deficient barriers have been developed and are illustrated in Figure 9.

New barrier systems are contained in the American Association of State Highway and Transportation Officials (AASHTO) publications.

BRIDGE SELECTION

Up to this point, we have discussed what can be done to reduce the degree of risk. The problem is which bridges should be upgraded and to what extent, given a restricted amount of funds. An obvious means of identifying hazardous sites is by traffic accidents. Normally, we would filter out single-accident sites as a random event location; however, since bridges are known to have a high accident potential, a single accident at or on a bridge should trigger a design review of the facility.

In the absence of accident records, hazardous sites can be identified on the basis of traffic conditions and geometrics. Contrary to popular belief, single-vehicle ran-off-the-road encroachments and accidents are not completely random incidents but occur with a degree of predictability. Although we cannot predict the exact time and place that an accident will occur, the more hazardous locations can be identified (2). The most important highway feature related to encroachment is traffic volume. The number of encroachments is directly related to traffic volume; that is, the larger the traffic volume, the greater the number of encroachments (13). Other traffic and highway features have important influence on encroachments, but they have not been quantified. These include the following (10):

1. Severe highway curvature, downgrade, and inadequate superelevation;
2. High traffic speed;
3. Adverse prevailing environmental conditions;
4. Inadequate signing, lighting, delineation, and site distance;
5. Low skid resistance; and
6. Route discontinuity and lane drops.

Figure 5. Bridge barrier element involved in 350 fatal accidents.

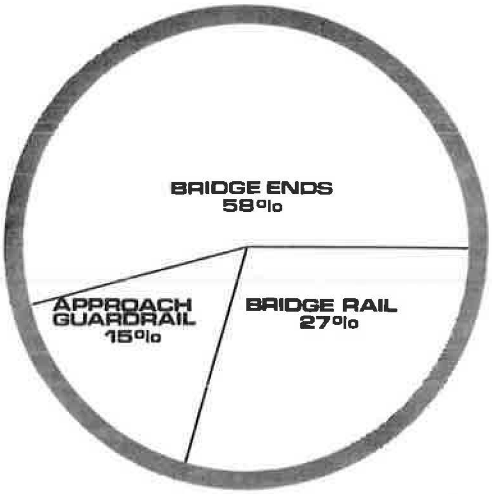


Figure 6. Example of approach guardrail not anchored to bridge railing.

Figure 7. Fatal accidents due to obsolete approach guardrail and bridge railing.

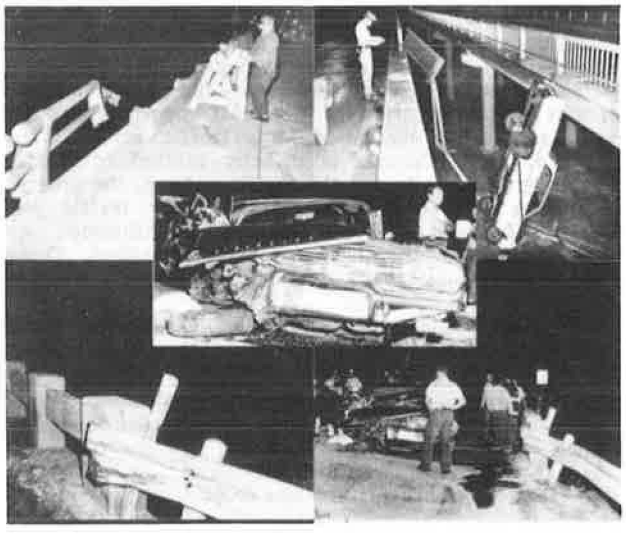
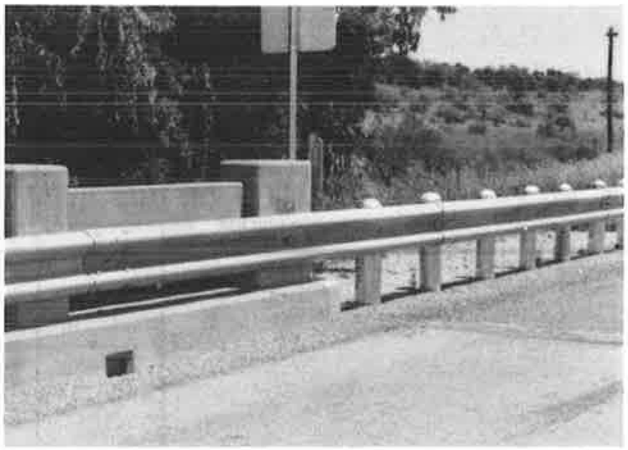


Figure 8. Example of good practice for the transition from approach guardrail to bridge barrier.



Even though it is unknown how each of these features, acting alone or in combination, specifically affect encroachments, general cause-effect relationships have been noted. At highway sites where one or more features are present, the rates of encroachments are atypically high.

EXTENT OF UPGRADING

The extent of safety upgrading can also be adapted to suit the degree and severity of hazard. A range of options that are available include the following:

1. Replace functionally obsolete bridge (most costly),
2. Replace obsolete bridge barrier,
3. Upgrade existing bridge barrier or approach railing,
4. Improve signing and delineation, and
5. Do nothing (least costly).

Based on traffic volume alone, the replacement of a heavily traveled obsolete bridge may be justified economically. On the other hand, it may be justified on a cost-effectiveness basis to do nothing to a functionally obsolete bridge that carries only a few vehicles per day.

SUMMARY

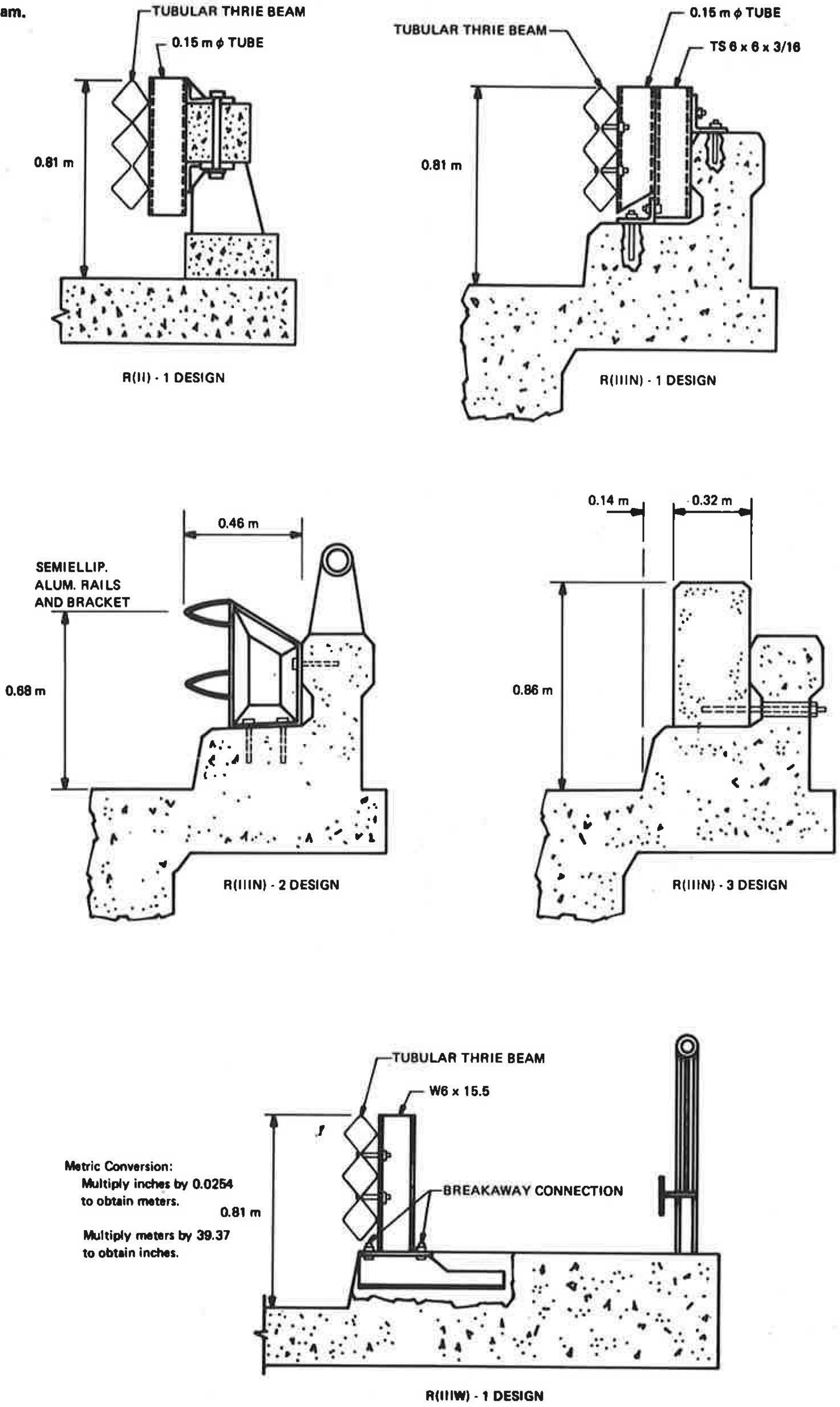
Safety is a societal judgment of the acceptability of risk. Safety is an ever-changing value judgment that balances the degree of risk against costs to reduce these risks. Risk is measured by the probability of an event and its severity. Uniform safety and risk can be achieved by varying the level-of-design standard to suit local site conditions.

Based on length alone, a bridge is 50 times more hazardous than the roadway. The disproportionately large number of bridge fatal accidents is attributed to the narrowness factor. Widening the bridge will reduce this accident rate. Other traffic control techniques may also reduce this rate. Severity of bridge barrier accidents is attributed to the following obsolete design features:

1. Tombstone terminals,
2. Inadequate or no approach guardrail, and
3. Inadequate bridge railing.

Because of funding limitations, a highway agency must be selective in identifying bridges for upgrading. A bridge should be selected based on accident records. Also, bridges selected should have high traffic volume and encroachment-causing features. Selectivity in the extent of upgrading is important.

Figure 9. Retrofit designs evaluated in program.



Metric Conversion:
Multiply inches by 0.0254 to obtain meters.
Multiply meters by 39.37 to obtain inches.

In conclusion, bridges represent an important safety problem. Although the solution approach is indicated, it will not be cheap or easily accomplished. It will require a considerable amount of patience, persistence, and good sound engineering work.

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Highway Alignment and Superelevation: Some Design-Speed Misconceptions

JOHN C. HAYWARD

Horizontal alignment and superelevation of curves have an impact on the traffic safety performance of highway sections. Research that relates traffic safety to roadway horizontal alignment has consistently shown that traffic accidents increase with increasingly sharper curves. Sharp curves in segments that otherwise have good alignment tend to surprise drivers and create even more hazardous situations. Consistency in design speeds along significant sections of highways has been advocated by some as a means of controlling the incidence of surprise curves in otherwise gentle alignments. However, design speeds for horizontal curves are a function of the maximum superelevation policies adopted by a design agency. Therefore, a single curve design may be regarded as having different design speeds by agencies that have different maximum superelevation policies. For this reason, the use of design-speed criteria for identifying potentially hazardous horizontal alignments would not appear to be appropriate. This finding is discussed in relation to the resurfacing, restoration, and rehabilitation projects proposed by the American Association of State Highway and Transportation Officials.

In recent years the highway design community has focused its attention on the development of geometric standards for the rehabilitation of existing highways. One important element in the improvement of roadways is the elimination of horizontal curves that, because of their geometric design, have created hazardous situations for the motorist. This paper outlines some of the research that has related safety to horizontal alignment of roadways and examines differences in current design policies of the states. Emphasis is placed on nonfreeway locations so that the resultant material would be relevant to resurfacing, restoration, and rehabilitation (3R) improvements of two-lane rural roadways.

The literature relative to alignment and superelevation shows that the highway research community is in basic agreement that roadway alignment is a key factor in unsafe vehicular operation. Increasing degrees of curvature cause more accidents. Single sharp curves in a highway system, generally characterized by long tangents and flat curves, create hazardous situations. Horizontal curvature may have the highest correlation with accident rates of major geometric characteristics for two-lane rural roads.

An examination of design practices in various states indicated a substantial difference in the manner in which horizontal alignment and superelevation is provided for the driver. Some states employ transition or spiral curves normally in design, others do not. Treatment of superelevation runout or transition also varies from state to state.

Perhaps the most significant variation in state design practices, however, is the assumption employed by various states regarding the maximum allowable superelevation on curves. This assumption has a direct bearing on the meaning of the term design speed for a curve and hence could have significant impact on any national 3R program for highways.

The following pages support the contention that highway alignment is related to safety performance. The issue of design speeds and 3R improvements will be touched on and some problems pointed out with respect to current definitions of design speed for specific curves. A review of basic highway curve formulas will be given and an analysis of how design speed changes with respect to maximum superelevation will be presented. Finally, some conclusions will be offered that relate 3R improvements to some general misconceptions about what design speeds really mean and how they relate to the dynamics of vehicles on curves.

SAFETY RESEARCH AND HIGHWAY ALIGNMENT

Research into the relationship between accident rates and highway curvature has been consistent in the finding that increasing curvature causes increased accident rates. Several studies have been summarized by Leisch (1) in the chart reproduced as Figure 1. A recent National Cooperative Highway Research Program (NCHRP) report by Jorgensen (2), which used information developed by Coburn (3), arrives at identical conclusions for rural roads. An extensive study by Taragin (4) on driver performance on horizontal curves noted that the sharper the curve, the closer drivers will operate their vehicles at speeds that approach the safe speed. Therefore, the margin for error for sharper curves is less than for flat curves. These findings led to the adoption of American Association of State Highway Officials (AASHO) policies as early as 1954 that specify that (5, p. 79) "Every effort should be made to use as high a design speed as practicable to attain a desired degree of safety, mobility, and efficiency."

The research literature offers some evidence that the frequency of curves within a roadway section also affects