Effect of Low-Cost Accident Countermeasures on Vehicle Speed and Lateral Placement at Narrow Bridges

BRIAN L. BOWMAN AND PHILIP BRINKMAN

The results of a research effort sponsored by FHWA are summarized, the primary purpose of which was to determine the effectiveness of low-cost countermeasures in reducing accident potential at narrow bridges. The operational-based evaluation was performed by conducting before-and-after analyses of vehicle speed and lateral placement at 18 narrow bridge approach sites. The low-cost countermeasures that were evaluated consisted of combinations of advance warning signs, pavement markings, raised pavement markers, roadside delineators, type 3 object markers, and adhesive delineators. Measurements of vehicle speed and lateral placement were obtained by using the FHWA Traffic Evaluation System. With one exception, the operational-based effectiveness evaluation did not reveal any statistically significant differences at the 10 percent level between the sites before and after the implementation of the countermeasures. The one exception was that these countermeasures significantly reduced speed variation when all vehicle types and time periods were analyzed together. For this analysis category, therefore, the low-cost countermeasures resulted in more uniform driving behavior.

Highway bridges are a necessary part of any roadway system and have always been the subject of specialized engineering efforts. Their construction requires a more sophisticated engineering design analysis and a higher construction cost than that for the roadways connecting them. In the past the primary purpose of the extra effort has been to ensure that the bridge structure would support dynamic design loads without failure. Until relatively recently, bridge width was not a major concern and would often be reduced for economic reasons. The results of this practice are narrow bridges, especially on the rural road system, which pose a threat to all motorists.

Because bridges are typically designed to provide longer service lives than are the connecting roadways, there are many instances in which the roadway is upgraded and, because of cost constraints, the bridge is not. Because of the relatively high cost of bridge widening and construction, some bridges date back to the early 1900s. Bridge abutments and parapets, many of which are unguarded, present dangerous physical obstructions to motorists. The changes in cross-section width between the approach roadway and the narrow bridge result in traffic flow restrictions and present unexpected hazards to motorists. The result is an increase in erratic driving behavior, fixed-object accidents, and vehicle-vehicle accidents.

The optimal solution would be to upgrade all narrow bridges on U.S. roadways. The extreme costs associated with rebuilding all the deficient bridges on our roadway system make the optimal solution, at least on a short-term basis, unrealistic. The result is that highway agencies are implementing countermeasures designed to reduce crash severity and improve motorist information by providing increased advance warning, delineation, and hazard conspicuity. The rationale behind the implementation of these countermeasures is that if it is not possible to physically protect the motorist from hazards, efforts must be made to provide them with sufficient information to protect themselves. However, it is difficult to ascertain from accident-based studies how effective these low-cost countermeasures are in actually increasing motorist safety.

The difficulty in determining the effectiveness of low-cost countermeasures at narrow bridges with accident-based analysis is the low number of accidents per bridge per year and inaccuracies in identifying the exact accident location from report forms and the exact date on which the countermeasures were installed. In this paper, results are presented of a study that was initiated in response to the recognized difficulties in conducting accident-based effectiveness evaluations of low-cost countermeasures at narrow bridge sites.

STUDY SCOPE AND OBJECTIVES

One of the primary purposes of this research study, sponsored by FHWA, was to determine the effectiveness of low-cost countermeasures at narrow bridges. The study concentrated on analyzing only operational data such as vehicle speed and lateral placement for countermeasures installed during the project tenure. Sites selected for project purposes consisted only of two-lane, single-structure, undivided bridges.

B. L. Bowman, Goodell-Grivas, Inc., 17320 W. Eight Mile Road, Southfield, Mich. 48075. P. Brinkman, FHWA, U.S. Department of Transportation, 6300 Georgetown Pike, HSR-30, McLean, Va. 22101.

BACKGROUND

Narrow bridges have been recognized as a highway safety problem for many years. In 1978, NHTSA reported that the severity of bridge-related accidents was roughly twice that of average accidents. Other studies have revealed that as many as 60,000 bridges are deficient in width (*1*).

Studies have shown that bridge accidents result in high severity rates, as emphasized by the accident experience for Virginia and Kentucky (Table 1). These findings indicate that bridge-related accidents are considerably more severe than other accident types and their frequency represents cause for concern.

Other researchers have also noted the safety problems with bridges. Kaiser determined that traffic accidents at bridges account for twice as many fatalities as do railroad crossing accidents and represent about 3 percent of all accidents in Ohio (*2*). Hilton estimated that narrow bridges account for 1.6 percent of all accidents and 3.4 percent of all fatalities on Interstate highways (*3*).

One of the major reasons that bridges may be hazardous is that many are functionally obsolete, having been built before the adoption of current design standards. Michie states that, on the basis of length alone, a bridge is "more hazardous than the roadway in general and a large number of bridge accidents can be attributed to narrow bridges, obsolete approach guardrails and inadequate bridge rail installations" (*4*). FHWA's national bridge inventory conducted in 1975 shows that 75 percent of the nation's 564,000 bridges were built before 1935 (*5*). In this inventory 20 percent, or 105,000 bridges, is structurally deficient or functionally obsolete, and this number is expected to increase by 2,000 per year. From this national inventory, Weaver and Woods estimated that the number of narrow bridges on two-lane rural roads was 37,000 (*6*).

Although bridge widening is thought to be the most desirable treatment for problems with narrow bridges, its high cost makes it infeasible in most instances (*7*). Mak and Calcote have pointed out that limited resources necessitate the selection of cost-effective treatments, such as signing, roadway delineation, and longitudinal markings (*8*). However, the effectiveness of these countermeasures is uncertain.

DEFINITION OF NARROW BRIDGE

There is no agreed-on single definition of what constitutes a narrow bridge. Most authors agree that width alone cannot be used. AASHTO considers narrow any bridge that has a width less than that of the approach traveled way (*9*). AASHTO also states that the term "narrow" is subjective and should be based on the following characteristics:

Geometrics	*Traffic Characteristics*
Approach roadway width	Approach speed
Approach sight distance	Traffic volume
Bridge width	Percent commercial vehicles
Bridge length	
Horizontal alignment	
Vertical alignment	

Other important factors requiring consideration may include area type and highway functional class. AASHTO provides a table that can be used to classify bridges as narrow on the basis of functional road type, average daily traffic, and percentage of commercial vehicles (*9*, pp. 84–85).

AREA OF BRIDGE INFLUENCE

Narrow bridges can cause accidents that do not occur at or on the physical structure of the bridge itself. Previous research has recognized that driver modifications of behavior on bridge approaches result in changes in vehicle lateral placement and speed, which can result in increased accidents. This requires an appropriate area of influence, which includes roadway segments approaching and leaving the bridge.

Turner and Rowan considered accidents occurring between 1972 and 1979 on 960 bridges on state routes in Alabama (*10*). Accidents on bridge approaches occurred at a rate more than twice as high as the rate as on the adjacent roadway. This increase was found to extend approximately 0.35 mi (573 m) from the bridge ends. Also, police officers were found to record bridge accidents to the nearest 0.1 mi (164 m) in more than half the cases, although some accident report forms required that they be recorded to the nearest 0.01 mi (*10*). This implies that accidents reported as occurring at the center of a short bridge may actually be occurring on the bridge approaches.

In a 1982 study of accidents on narrow bridges, Mak and Calcote collected bridge-related accidents that were coded as occurring on the bridge or within 500 ft (155 m) of either side of the bridge (*8*). This study established that the area of influence of a 200-ft (62-m) bridge totaled 1,200 ft (372 m).

TABLE 1 PERCENTAGE OF BRIDGE-RELATED ACCIDENTS (*1*)

	Interstate/Parkway Highways		Primary/Secondary Highways	
State	Percentage of All Accidents	Percentage of All Fatalities	Percentage of All Accidents	Percentage of All Fatalities
Virginia	3.2	7.1	1.6	3.4
Kentucky	7.6	17.2	2.9	3.8

SOURCE: NHTSA 1978 compilation of data.

The results of accident-based studies indicate a need to consider the approaches on both sides of the bridge when driver-related operational data are collected and when accident-based countermeasures are evaluated. The length should be a minimum of 0.1 mi (0.16 km) on each side of the bridge to account for inaccuracies in accident reporting and changes in vehicle encroachments and speeds on bridge approaches. For highway agencies whose locational reporting accuracy is low, a length of up to 0.3 mi (0.48 km) on each side of the bridge may be appropriate.

COLLECTION OF OPERATIONAL DATA

Measures of Effectiveness

The primary purpose of installing low-cost countermeasures at narrow bridge sites is to reduce accident frequency. Although the accident rate at a narrow bridge site may be twice as high as the rate on a roadway segment, the total number of accidents at a given bridge site is still small. Unlike an evaluation based on operational measures of effectiveness (MOEs), an accident-based evaluation at an individual location therefore requires an unacceptably long period to accumulate sufficient data for statistical validity. This study concentrated on obtaining operational MOEs for various narrow-bridge countermeasures.

Operational evaluations can be conducted shortly after countermeasure implementation (within 1 or 2 months) and require 2 or fewer days of data collection for both the before and the after time periods. Operational MOEs can be used as interim MOEs before an accident-based evaluation. The inherent assumption behind a non-accident-based evaluation is that a significant change in appropriate MOEs (i.e., lateral placement, encroachment, and speed change) indicates improved safety. It is assumed that if a countermeasure results in a significant reduction in vehicles crossing left of the centerline and other hazardous manuevers, this reduction is synonymous with a reduction in accident potential.

Appropriate operational MOEs were selected by establishing a causal chain of the predominant accident types, probable causes, countermeasures, and safety objectives (Figure 1). Low-cost countermeasures at narrow bridge sites are intended to reduce accidents by altering driving behavior. These intended changes in driver behavior are referred to as intermediate objectives in Figure 1. The MOEs selected to evaluate the low-cost countermeasures are primarily related to vehicle speed and lateral position. The logical relationships between these measures and the intermediate objectives are as follows:

1. Mean speed over all tapeswitch deployments. The low-cost countermeasures provide additional driver information and guidance. These driver inputs may result in changes in average speed through the bridge and bridge approach. The expected direction of this change between the before and after time periods is not, however, readily

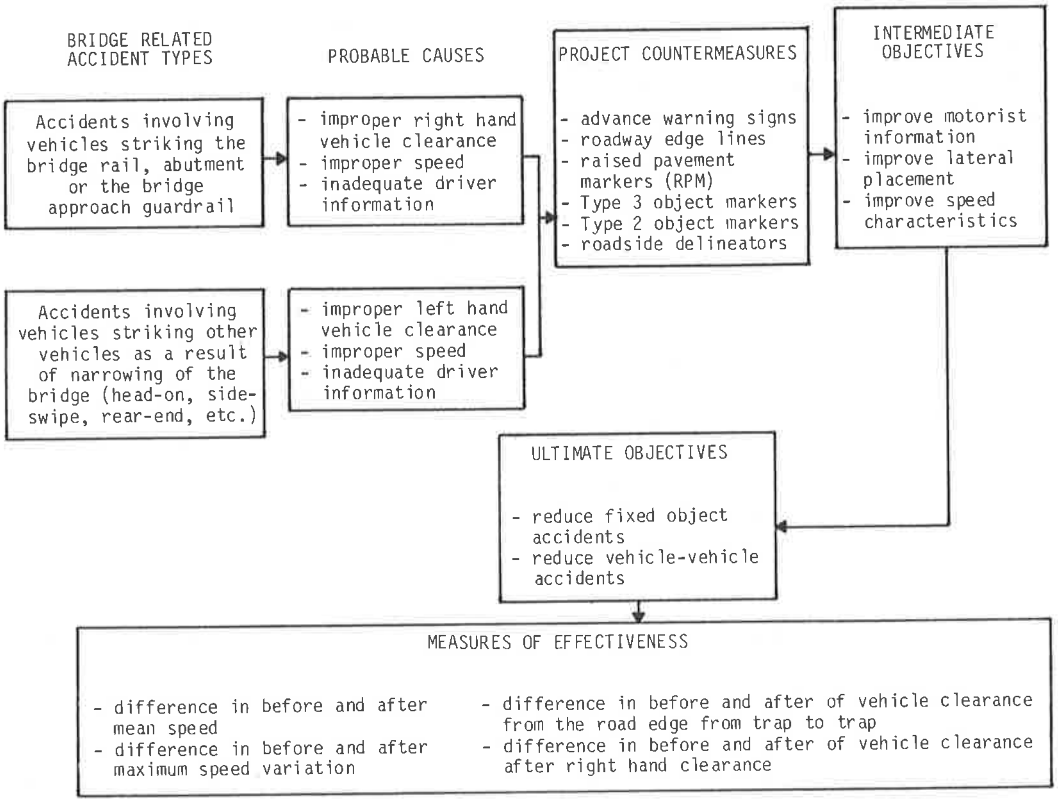

FIGURE 1 Causal chain and appropriate MOEs for low-cost countermeasures at narrow bridge sites.

evident. The installation of a countermeasure to improve driver awareness could result in either an increase or a decrease in average speed, depending on the physical conditions at the bridge site.

For example, some bridge approaches with limited sight distance may pose problems for vehicles approaching too fast and then decelerating rapidly to pass safely over the bridge. In this instance, countermeasures such as advance warning signs would be intended to reduce average speeds on the approach. Evaluation of this countermeasure, using mean speed as the MOE, could interpret a reduction in speed as an indication that the countermeasure is effective. However, consider the case of a narrow bridge where the visibility is so poor (i.e., no lighting or delineation) that motorists must slow down at night to safely traverse the bridge site. An effective delineation treatment (e.g., raised pavement markers, paddle markers, or striping) may improve visibility such that motorists can adequately recognize the bridge site and maintain their approach speed safely. In this instance, an effective countermeasure may result in vehicle speeds that remain unchanged or increase slightly.

2. Maximum speed variation across deployment. This MOE was obtained by measuring the maximum variation in speed exhibited by individual vehicles in the trap array. This maximum speed variation was averaged over all the observations to obtain the analysis value. The increased visual conspicuity and motorist information provided by the countermeasures can logically be expected to result in more uniform speeds through the bridge approach. Speed variability may be indicative of the potential for accidents. A sudden deceleration on the bridge approach could create unexpected hazards, resulting in rear-end (from a trailing vehicle), bridge-related, or head-on accidents (excessive speed causing the inability to maintain proper lateral position). Increased motorist information (adequate delineation or advance warning) could theoretically result in a more gradual deceleration by the motorist and enhanced safety through the bridge site.

3. Mean speed at tapeswitch deployments. This MOE was obtained by averaging the speeds at each trap of every valid vehicle that traversed the test site. The purpose of this MOE was to determine whether the countermeasures resulted in changes to the speed profile at the bridge sites. The most advantageous condition would be to have identical average speeds or a linear reduction in average speed at every tapeswitch deployment. This would be indicative of increased motorist information and confidence in the vehicle guidance tasks required of the narrow bridge site. This analysis differs from the analysis of speed variance in that it provides a measure of the average speed at each trap. The analysis of speed variance used the average speeds at each trap to develop a variance measure of the entire approach site. The analysis of mean speeds by tapeswitch deployment permits the further analysis of which traps had the highest or lowest mean speeds if significant differences are revealed by the statistical analysis of the before and after time periods.

4. Right-hand lateral position at tapeswitch deployments. This measure of lateral placement was selected to provide an indication of the effectiveness of the countermeasure in changing the lateral position of the vehicles. It provides an indication of the potential for accidents with fixed objects located to the right of the roadway and with opposing vehicular traffic. Analyzing lateral position from trap to trap allows determination of the change in right-hand distance from trap to trap and of the location on the approach at which these changes occurred. The lateral placement measures were obtained by measuring the distance from the right edge of the paved roadway surface to the outside edge of the right front tire.

5. Deviations in right-hand lateral placement between tapeswitch deployments. This MOE was obtained by determining the differences in the average right-hand lateral distance between adjacent tapeswitch deployments for both the before and the after time periods. The purpose of these analyses was to determine whether the countermeasures were effective in providing increased motorist guidance, resulting in a more uniform vehicle path.

Many of the low-cost countermeasures evaluated during the project consisted of treatments that would benefit the motorist primarily at night. To evaluate the effect of light conditions on MOE effectiveness, the data were collected separately for day and night conditions. The type of vehicle was also noted, to permit a determination of whether various classes of vehicles are affected differently by the implemented countermeasures.

Characteristics of Selected Test Sites

Nine narrow bridge sites were selected for analysis. Data were obtained from both approaches to the nine bridges, resulting in measurements on 18 approaches. A summary of the physical characteristics of each approach is presented in Table 2, inspection of which shows that all of the narrow bridges selected for analysis were less than 24 ft (7.3 m) in total width (curb to curb). Approach widths were measured as the total distance from roadway edge to roadway edge. The bridge directional width was obtained by measuring from the curb, when present, or from undisturbed debris near the bridge rail [approximately 6 in. (152 mm)] to the center of the centerline on the bridge deck. For all the test sites, total bridge width was less than the approach roadway width.

All the test sites were located in rural environments with one-way volumes that varied from a minimum of 800 to a maximum of 2,625 vehicles per day. The majority of approaches consisted of straight roadway sections with sight distances greater than 900 ft (279 m). Those locations that had reduced sight distances because of horizontal and vertical curves were posted at speeds below 55 mi/hr (88 km). In all cases, the available sight distance was greater than the minimum safe stopping sight distance recommendations of AASHTO for the posted speeds (*9*, p. 138).

TABLE 2 PHYSICAL FEATURES AT NARROW-BRIDGE TEST SITES

Site and Approach	Total Bridge Width (ft)	Length (ft)	Percent Reduction		Alignment and Sight Distance
			Roadway to Bridge	Roadway and Shoulder to Bridge	
11	24.0	24	13.6	35.4	Straight +900'
12			14.5	36.1	Vertical Curve 600'
21	18.4	50	8.0	34.3	Straight +900'
22			10.7	18.6	Straight +900'
31	20.5	56.6	5.1	28.3	Vertical Curve 600'
32			9.7	26.0	Straight +900'
41	19.9	39.5	16.0	40.9	Horizontal Curve 321'
42			17.1	23.5	Horizontal Curve 525'
51	18.0	44	18.6	35.9	Straight +900'
52			20.0	36.8	Straight +900'
61	20.2	46	11.0	29.6	Straight +900'
62			9.4	28.6	Straight +900'
71	20.3	82.2	9.0	21.0	Straight +900'
72			9.4	21.3	Straight +900'
81	19.4	44	20.5	40.1	Vertical and horizontal curve +900'
82			21.8	40.9	Vertical and Horizontal curve +900'
91	18.5	42	1.6	31.0	Straight +900'
92			2.6	31.5	Straight +900'

Descriptions of Implemented Countermeasures

The selection of countermeasures for project implementation was based on a consideration of what was already present and the standard practice of the respective highway agency. Standard practice for some agencies, for example, did not include the installation of raised pavement markers. In such instances, raised pavement markers were not considered for installation because they would have resulted in roadway conditions that were abnormal, especially at night, for the driver expectancy of area motorists.

A summary of the traffic control and delineation devices that were present before countermeasure installation is presented in Table 3. The countermeasures were always installed as additions to existing conditions, the only exception being mutually exclusive countermeasures such as different edgeline widths. One test bridge, for example, initially had two Type 3 object markers; an additional four were added as part of the project countermeasures. There were therefore a total of six Type 3 object markers, three on each side of the approach, present during the after time period.

Collection of Field Data

Field data were collected by using FHWA's fully automated Traffic Evaluation System (TES). The TES is a computerized data collection system that receives input through a series of tapeswitches. The tapeswitches consist of two copper strips separated by a thin plastic divider along each edge of the switch. As a vehicle passes over the switch, its weight causes the strips to come in contact, which closes the circuit. The electrical impulse generated by each closed circuit is transmitted to a rheostat, which identifies the switch location, and the resultant current triggers the recording of the time, the switch code, and the location code.

TABLE 3 TRAFFIC CONTROL FEATURES AT EACH APPROACH TO NARROW-BRIDGE TEST SITES

Traffic Control Feature	Number of Approaches	
	Before	After
Edgeline		
4 inches	16	12
6 inches	2	2
8 inches	0	4
Post Delineators (Type 2)		
Left Hand Side	0	12
Right Hand Side	0	12
Type 3 Object Markers		
2 on Each Approach	18	8
4 on Each Approach	0	10
Raised Pavement Markers		
Left and Right Hand Sides	4	6
Centerline	4	6
Adhesive Delineation Markers	2	6
Narrow Bridge Signs	10	14
Centerlines		
Approach Marking		
Solid	15	15
Skip	3	3
Bridge Marking		
Solid	9	9
Skip	5	5

Four tapeswitch stations, each configured as presented in Figure 2, were deployed on each narrow bridge approach to record the speed, vehicle type, vehicle width, and lateral placement of traffic. The lateral placement was determined by applying the vehicle speed, measured from Traps A and B, in conjunction with the known angle and distance of Tapeswitch C. The approximate positions at which the four tapeswitches were deployed are shown in Figure 3 and described as follows:

- At a free flow point on the narrow bridge approach—An additional diagonal switch was installed at this location to determine vehicle width, which was necessary for the determination of encroachments. The free flow point was determined to exist at a distance from the bridge that was equal to or beyond the safe stopping sight distance.
- At points that were two-thirds and one-third of the safe stopping sight distance.
- At the beginning of the bridge.

The above guidelines were used for the deployment of TES tapeswitches, but the actual deployment was dependent on the physical site characteristics. Roadway surface condition, the location of physical features (such as trees) for securing the TES unit, and other site characteristics resulted in variations of the actual tapeswitch locations.

ANALYSIS OF OPERATIONAL DATA

The analyses of the MOEs related to vehicle placement and speed were performed using a before-and-after experimental design. The before period consisted of TES deployment ahead of the installation of any countermeasures. The after-period data were obtained after the countermeasures had been in place for at least 2 months. The 2-month waiting period was used to allow any possible novelty effects to dissipate before data collection.

The before-and-after design was considered appropriate because (a) data were being collected at the same sites for each time period, (b) the amount of total elapsed time between finishing the before-and-after data collection tasks was less than 4 months, and (c) the total amount of data collection at each site generally exceeded 24 hr. The result was relatively large sample sizes obtained within a short time interval. The possible effects of biasing factors such as trends over time and regression to the mean were not, therefore, considered threats to statistical validity as they often are when accidents are used as MOEs.

The data obtained for both the before and the after time periods were divided into day and night conditions and into categories by vehicle type. The categories of vehicle type were determined by such criteria as the number of axles, wheelbase, and wheelpath width.

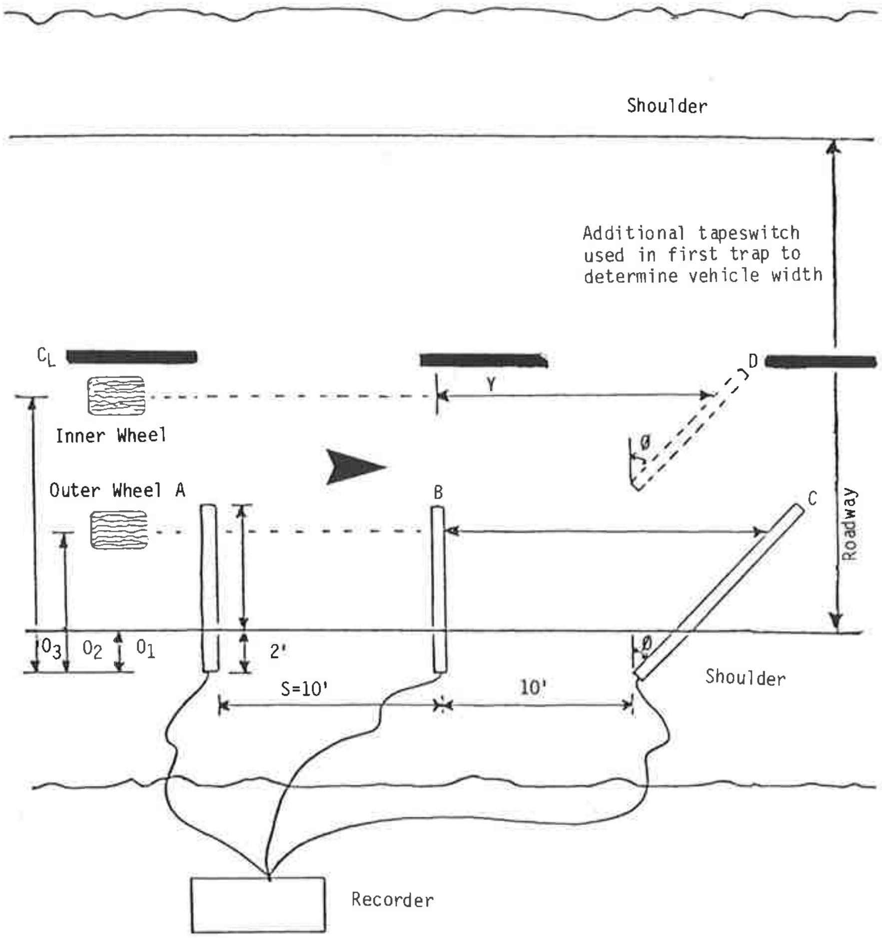

FIGURE 2 Typical tapeswitch deployment.

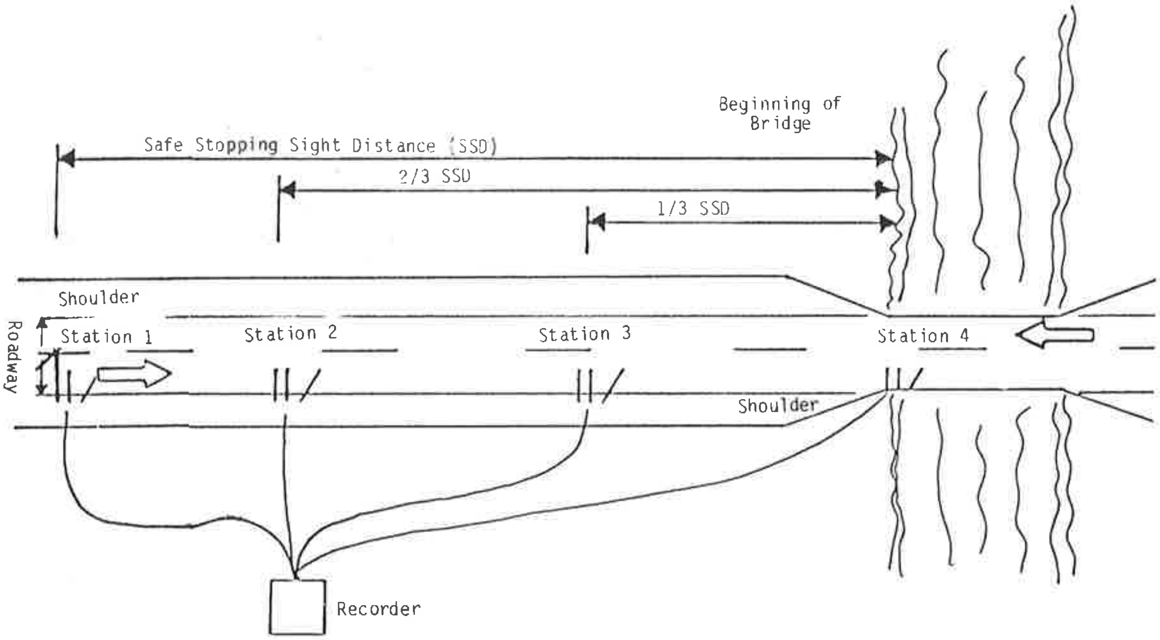

FIGURE 3 Typical approach layout of TES tapeswitches (same tapeswitch configuration set up on other bridge approach).

Type of Analysis

The type of analysis performed was dependent on the MOE and whether each MOE was obtained on a site or a trap-to-trap basis. All the data were divided into categories of bridge approach by time of day and vehicle type. A significance level of 10 percent (i.e., level of confidence of 90 percent) was used for all the statistical tests in this study.

Analyses Based on Individual Observations

The software logic of TES enabled the system to identify a vehicle at the first tapeswitch deployment and to follow that vehicle through the trap array. A unique identifier was assigned to each vehicle, and the speed and lateral position at every tapeswitch deployment were recorded as part of that vehicle's data. It was possible, therefore, to determine the speed and lateral position changes exhibited by each vehicle as it progressed through the trap array. The individual vehicle data were used as input for the first battery of statistical tests. The resulting group means and statistical tests were thus based on large sample sizes and degrees of freedom. Statistical analyses between before-and-after MOE values of individual vehicle measures were conducted by using computerized statistical analysis packages (*11*).

Analyses Based on Individual Vehicle t*-Test Results*

The results of the statistical analysis of individual vehicle measurements consisted of determinations as to whether individual sites or individual traps exhibited a significant difference in their before-and-after MOE values. The sign test was then applied to the results of the site-specific analysis. The purpose of the sign test was to determine whether there were a sufficient number of instances in which a significant difference existed to conclude that the countermeasures resulted in a net effect.

Analysis of Mean MOE Values

The mean MOE values generated by the *t*-tests on the individual vehicle data were analyzed by site and by tapeswitch deployment. This was accomplished by using the appropriate mean from each test site and performing statistical tests to determine whether significant changes had occurred between the before and after time periods.

Mean Speed Over All Tapeswitch Deployments

The before and after mean speeds across all of the tapeswitch deployments were first analyzed by applying the *t*-test to determine whether the magnitude of any exhibited changes was sufficiently large to be considered statistically significant at the 10 percent level within each test site. The purpose of this test was to determine whether the countermeasures installed at a particular site had an impact on the mean speed at that site.

Inspection of the direction of significant changes in mean speed did not reveal discernible patterns. Only three sites had an increase with no accompanying decrease in mean speed across all analysis categories (i.e., categories of vehicle types and time of day). Each of these test approaches consisted of straight roadway sections with no sight restrictions. The test approaches with horizontal curves displayed a greater number of significant mean speed reductions across analysis categories than speed increases (eight reductions versus four increases).

The results of the *t*-test were also investigated to determine whether a sufficient number of increases or decreases in mean speed had occurred within the test sites to signify the presence of trends. This was accomplished by applying the sign test to determine whether, at a 90 percent level of confidence, an increase or decrease in mean speeds could be expected to occur from the installation of low-cost countermeasures. The results of these tests, shown in Table 4, indicate that the probability of observing an equal or greater number of changes due to chance alone exceeds the desired significance level of 0.10. It cannot be concluded, therefore, that the countermeasures being evaluated were the cause of the observed speed changes.

The mean speeds at each test site were also analyzed to determine whether there were any statistically significant differences between the before and after data among the test sites. These analyses were performed separately for day and night conditions in the category of all vehicle types. The results of these analyses are given in Table 5, which reveals that the probability for neither the day nor the night conditions indicated a statistically significant difference at the 0.10 significance level. The low-cost countermeasures did not, therefore, result in significant changes in the mean speeds when evaluated among all the test sites.

Speed Variation Across Deployment

Analysis of the maximum speed variation within sites was performed by applying the *t*-test. This analysis indicated that only three approach test sites experienced a significant increase in speed variability at the 10 percent level. All of the remaining approach sites experienced either a reduction in speed variability across all analysis categories or no significant change.

The speed variations were analyzed by the sign test to determine whether the frequencies with which increases and decreases in variability occurred between the sites were significantly different. Inspection of the summary of the sign test (Table 6) reveals that there is a significant reduction in speed variability for the category of all vehicle types when analyzed for all time periods. The low-cost countermeasures do, therefore, result in more uniform driving behavior. This uniformity was not evident, however, when the data were analyzed separately for day and night conditions.

TABLE 4 SIGN TEST ON CHANGE IN MEAN SPEED BETWEEN BEFORE AND AFTER TIME PERIODS

	All time periods and vehicle types	All vehicle types	
		Day	Night
significant increases (+)	8	6	5
significant decreases (-)	4	3	4
no significant difference	6	9	9
probability of a greater number of speed increases	0.19	0.25	0.50

Note: Data are in miles per hour (1 mph = 1.6 km/hr).

TABLE 5 STUDENT'S *t*-ANALYSIS OF MEAN SPEEDS AT EACH TEST SITE FOR ALL TYPES OF VEHICLES

	Day		Night	
	Before	After	Before	After
Mean	49.00	48.95	49.02	48.89
Standard Deviation	4.99	4.59	4.74	4.36
t value	0.03		0.08	
degrees of freedom	34		34	
probability	0.98		0.93	

Note: Data are in miles per hour (1 mph = 1.6 km/hr).

TABLE 6 SIGN TEST ON DIRECTION OF CHANGE FOR MAXIMUM SPEED VARIATION

	All Time Periods and Vehicle Types	All Vehicle Types	
		Day	Night
significant increase (+)	2	3	2
significant decrease (-)	9	7	6
no significant difference	7	8	10
probability of a greater number of speed increases	0.03[a]	0.17	0.15

Note: Data are in miles per hour (1 mph = 1.6 km/hr).
[a]Denotes significant difference at level of 10 percent.

Student's *t*-test was performed on the mean speed variation to determine whether there were statistically significant differences between the before and after data for day and night conditions. A summary of the analysis is given in Table 7. Note that the overall means for all of the time periods are relatively close to each other. Because the Student's *t*-test probabilities are greater than 0.10, it cannot be concluded that a significant difference exists between the before and after measurements for either day or night conditions.

Mean Speed at Tapeswitch Deployments

Vehicle speeds at each tapeswitch deployment were inspected to determine whether the speed profile of motorists changed because of the installation of the low-cost countermeasures. This analysis indicated that trends that were present during the before time period continued into the after period. For example, four site approaches exhibited higher speeds at the bridge during the before period than at any other tapeswitch locations on their respective roadway approaches. This trend continued into the after period.

A paired *t*-analysis was performed on the trap data to ascertain whether there were significant differences in the before and after time periods. This analysis was performed by considering the data from the different time periods for each trap as paired observations. The paired *t*-analysis, for example, resulted in pairing the before data from Trap 1, approach 12, with the after data from Trap 1, approach 12. The paired *t*-analysis compensated for the differences in trap distance from the bridges. The results of the paired *t*-analysis, performed separately for day and night conditions on the category of all vehicle types, are summarized in Table 8. At a significance level of 10 percent, no statistically significant differences were indicated by either the day or night data sets. It cannot be concluded at a 90 percent level of confidence that the low-cost countermeasures resulted in significant changes in speed between tapeswitch locations.

Lateral Position at Tapeswitch Deployments

The analyses of lateral position at tapeswitch deployments were conducted to determine whether the countermeasures caused lateral position variations within each site and where on the approach these variations occurred. Lateral placement was determined by measuring the distance from the right edge of the paved roadway surface to the outside edge of the right front tire.

This inspection revealed that 10 and 6 approach sites experienced average movements to the right and left, respectively, at the traps closest to the bridge after countermeasure installation. Because of the way in which the directional movements are distributed among the approach sites, it is difficult to associate the direction of movement with the type of countermeasure installed. At four approach sites, 8-in. (203-mm) edgelines were installed as part of the countermeasure. At two of these approach sites, average movements to the left were experienced; at one site, there were movements to the right; and at the remaining site there was no change in any direction. There is therefore no evident direction of movement that can be associated with a countermeasure type.

Paired *t*-analyses were performed on the tapeswitch deployments to ascertain whether the differences experienced at each tapeswitch deployment were sufficiently large to be significant. These analyses were performed by considering the data from different time periods for each trap as paired observations. The paired *t*-analyses compensated for the differences in trap distance from the bridges. The results of the paired *t*-analysis, performed separately for day and night conditions on the category of vehicle type, are summarized in Table 9. No significant sign differences were indicated at the 10 percent level for either the day or the night data. It cannot be concluded, therefore, at a 90 percent level of confidence that the countermeasures resulted in significant changes in lateral placement between tapeswitch deployments.

Deviations in Lateral Placement Between Tapeswitch Deployments

Analyses were performed on the average variation that occurred between adjacent tapeswitch deployments and

TABLE 7 ANALYSIS OF MEAN VARIATION IN SPEED FOR ALL VEHICLE TYPES

	Day		Night	
	Before	After	Before	After
Mean	4.29	4.09	4.15	3.90
Standard Deviation	1.30	1.29	1.27	1.29
t value	0.48		0.58	
degrees of freedom	34		34	
probability	0.64		0.56	

NOTE: Data are in miles per hour (1 mph = 1.6 km/hr).

TABLE 8 PAIRED *t*-ANALYSIS OF MEAN SPEEDS AT TAPESWITCH DEPLOYMENTS

	Day		Night	
	Before	After	Before	After
Mean standard deviation	48.50 5.13	48.61 4.61	48.48 4.64	48.59 4.56
t Value degrees of freedom probability	-0.80 71 0.43		-0.59 71 0.56	

NOTE: Data are in miles per hour (1 mph = 1.6 km/hr).

between deployments that were the farthest apart. The purpose of these analyses was to determine whether the countermeasures were effective in providing increased motorist guidance resulting in a more uniform vehicle path. The data for these analyses were obtained by determining the difference in the lateral placement for the appropriate trap pairs.

Inspection of the resultant differences revealed that the type of movements between adjacent trap pairs remained relatively constant in both the before and after time periods. Those pairs that exhibited average movements to the right between the traps in the before period usually exhibited movements to the right in the after period. This observation was supported by the results of the paired *t*-analyses that are summarized in Table 10. There were no significant differences at the 10 percent level between the lateral movements exhibited by adjacent pairs in the before or after time periods.

Paired *t*-analyses performed on the differences in lateral movement between the farthest trap pairs (i.e., tapeswitch deployments 1 and 4) are summarized in Table 11. This analysis did not display any significant differences at the 10 percent level between the lateral movements of the farthest trap pairs in the before and after time periods.

CONCLUSIONS

The conclusions presented below are based on the results of the analysis of field data and the literature review.

1. Analysis of individual vehicle speeds indicated that the effects of the low-cost countermeasures were essentially the same for day and night conditions. Three sites during the day and four during the night experienced a significant decrease in speed. When both day and night conditions

TABLE 9 PAIRED *t*-ANALYSIS OF LATERAL POSITION OF TAPESWITCH DEPLOYMENT

	Day		Night	
	Before	After	Before	After
mean standard deviation	3.71 0.60	3.69 0.67	3.95 0.60	3.97 0.67
t value degrees of freedom probability	0.38 70 0.71		-0.58 71 0.56	

NOTE: Data are in feet (1 ft = 0.31 m).

TABLE 10 PAIRED *t*-ANALYSIS OF LATERAL POSITION CHANGE BETWEEN ADJACENT TAPESWITCH DEPLOYMENTS

	Day		Night	
	Before	After	Before	After
mean standard deviation	-0.06 0.68	-0.07 0.77	-0.13 -0.13	0.69 0.78
t value degrees of freedom probability	0.16 51 0.87		-0.01 53 0.99	

NOTE: Data are in feet (1 ft = 0.31 m).

TABLE 11 PAIRED *t*-ANALYSIS OF OVERALL DIFFERENCE IN LATERAL PLACEMENT

	Day		Night	
	Before	After	Before	After
Mean	-0.20	-0.25	-0.40	-0.40
Standard Deviation	0.92	0.72	0.89	0.72
t value	0.32		-0.02	
degrees of freedom	17		17	
probability	0.76		0.983	

NOTE: Data are in feet (1 ft = 0.31 m).

were analyzed together, eight sites experienced a significant increase, four a significant decrease, and six no significant difference in mean speeds between the before and after time periods. These results did not establish a sufficient difference in the mean speed increases or decreases to attribute the effects to the low-cost countermeasures. The low-cost countermeasures cannot therefore be assumed to result in significant changes in mean speeds.

2. An inspection of the mean individual vehicle speed at each tapeswitch deployment was performed to determine whether the speed profile of motorists changed because of the installation of the low-cost countermeasures. Inspection of the mean speeds at each trap deployment revealed that trends that were present in the before time period continued into the after period. Those sites that exhibited peak speeds at the trap located closest to the bridge during the before period also exhibited peak speeds at the bridge during the after period. It cannot be concluded at a 10 percent significance level that the low-cost countermeasures resulted in significant changes in mean speed between tapeswitch deployments.

3. Estimates of vehicle lateral placement were obtained by measuring the distance from the right road edge to the outside of the right front tire. Inspecting the manner in which the directional movements were distributed among the approach sites resulted in difficulty associating the direction of movement with the types of countermeasures installed. For example, four approach sites received 8-in. (203-mm) edgelines as part of their physical upgrade. At two of these sites average movements to the right, at one site movements to the left, and at one site no change in any direction were experienced. It could not be concluded that the low-cost countermeasures resulted in statistically significant changes in right-hand lateral placement between tapeswitch deployments.

4. Analyses were performed on the average variation that occurred between adjacent tapeswitch deployments and between deployments that were the farthest apart. The purpose of these analyses was to determine whether the low-cost countermeasures resulted in a more uniform vehicle path. Inspection of the differences indicated that the type of movement between adjacent trap pairs remained relatively constant between the before and after time periods. Those pairs that exhibited average movements to the right between the traps in the before period usually exhibited movements to the right in the after period. There were no significant differences at the 10 percent level between the lateral movements exhibited by either adjacent pairs or the farthest trap pairs in the before and after time periods.

5. Estimates of the maximum speed variation were obtained by measuring the greatest difference in speed exhibited by individual vehicles as they progressed through the trap array. This maximum speed variation was averaged over all the observations to obtain the analysis value. The intuitive logic in the selection of this MOE was that a reduction in speed variation denotes increased safety because of the more uniform speeds. This effect was expected to be more pronounced during the nighttime and periods of low visibility when the delineators, edgelines, and hazard markers provide maximum conspicuity. Analyzing data obtained by combining the day and night observations into one group revealed that a significant number of analysis sites experienced a reduction in speed variability after countermeasure implementation at the 10 percent level of significance. When the average speed variation was analyzed separately for day and night conditions, however, there were no significant differences between the before and after time periods.

6. The inability of the MOEs to exhibit statistically significant differences between the before and after time periods can be interpreted in two ways. The first interpretation is that the operational MOEs related to vehicle speed and position are not appropriate measures for narrow bridge sites. The literature review indicated that these measures had been used successfully in prior studies at narrow bridge sites. The use of TES in this study, however, resulted in much larger data bases and greater accuracy than in those studies that relied primarily on manual data collection techniques. In addition, because the narrow bridges studied existed on low-volume rural roadways, the majority of the roadway users were expected to be local motorists who were familiar with the roadway geometrics. These motorists know the presence of narrow bridges and developed driving patterns to safely negotiate the hazardous roadway feature before the installation of the low-cost countermeasures. Their driving characteristics may not, therefore, have been altered by the installation of low-cost countermeasures.

The second possible interpretation is that the countermeasures are not effective in influencing driver behavior. However, the inability of the operational MOEs to identify changes in driving behavior does not necessarily imply that the low-cost countermeasures are ineffective. Accidents are relatively rare events that result from circumstances related to the driver, vehicle, roadway, or environment, or to more than one of these variables. The low-cost countermeasures provide increased delineation and driver information. The impact of these enhancements on potential accidents involving unfamiliar drivers, impaired drivers, and unfavorable environmental conditions (such as restricted visibility and wet and slippery road conditions) cannot be ascertained by analyzing average operational measures. A determination of the actual effectiveness of low-cost countermeasures, therefore, requires a proper accident-based evaluation.

REFERENCES

1. D. L. Ivey, R. M. Olson, N. E. Walton, and G. D. Weaver. Safety at Narrow Bridge Sites. Presented at the 62nd Annual Meeting, AASHTO, Birmingham, Ala., Nov. 1976.
2. H. Kaiser. Traffic Accidents on Highway Bridges on Rural State Highways in Ohio. In *Proceedings of 10th Annual Ohio*

Engineering Conference, Ohio State University, Columbus, 1956.

3. M. H. Hilton. Some Case Studies of Highway Bridges Involved in Accidents. Presented at the 52nd Annual Meeting of the Transportation Research Board, Washington, D.C., 1973.
4. J. D. Michie. Strategy for Selection of Bridges for Safety Improvement. In *Transportation Research Record 757*, TRB, National Research Council, Washington, D.C., 1980, pp. 17–22.
5. *The National Highway Safety Needs Report*. U.S. Department of Transportation, March 1976.
6. G. D. Weaver and D. L. Woods. *No-Passing Zone Treatments for Special Geometric and Traffic Operational Situations.* Texas Transportation Institute, Texas A&M University System, Austin, Sept. 1981.
7. U.S. Congress. House. Committee on Public Works. Subcommittee on Investigations and Review. *Hearings: Highway Safety Design and Operations: Narrow Bridges—Driver Dilemmas.* 93rd Congress, June 1973.
8. K. K. Mak and L. R. Calcote. *Accident Analysis of Highway Narrow Bridge Sites*, Vol. 2: *Technical Documentation.* FHWA, U.S. Department of Transportation, Feb. 1983.
9. *Highway Design and Operational Practices Related to Highway Safety*, 2nd ed. AASHTO, Washington, D.C., 1974.
10. D. S. Turner and N. J. Rowan. Investigation of Accidents on Alabama Bridge Approaches. In *Transportation Research Record 847*, TRB, National Research Council, Washington, D.C., 1982, pp. 1–6.
11. *SPSS-X*. McGraw-Hill Book Company, New York, N.Y., 1983.