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EVALUATION OF THE PERFORMANCE OF PORTABLE PRECAST CONCRETE TRAFFIC BARRIERS

by

Frank N. Lisle
Research Engineer

and

Bradley T. Hargroves
Faculty Research Engineer

Prepared by the Virginia Highway & Transportation Research Council Under the Sponsorship of the Virginia Department of Highways & Transportation and the Virginia Department of Transportation Safety

(The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

Charlottesville, Virginia

November 1978
VHTRC 79-R29

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ABSTRACT

The portable precast concrete traffic barrier is used to separate high speed vehicular traffic and construction activities. However, since there was a lack of information on the barrier's performance in a construction zone environment, officials of the Virginia Department of Highways and Transportation requested that the Virginia Highway and Transportation Research Council evaluate the performance of the barrier during the widening of the Virginia Beach-Norfolk Expressway (Rte. 44).

The scope of the evaluation included (1) a review of the literature on the performance of the concrete "safety shape" barriers, (2) an examination of the accident data before and during construction on Rte. 44 to determine the effects of construction on the frequency and characteristics of traffic accidents, (3) an analysis of tire marks and barrier-involved accidents to determine the effectiveness of the barriers in safely redirecting vehicles, and (4) an examination of the effects of construction on traffic characteristics.

The literature review revealed that in using the precast concrete traffic barrier the following factors should be considered: (1) the end of the barrier should never be exposed to oncoming traffic; (2) the barrier joints must be tight for the barriers to act as a system; (3) the longitudinal axis of the barriers should be placed parallel to the roadway, except when the barrier system is started with a flare; (4) the barrier system should have a minimum length of 100 feet (30 m); and (5) the barrier system must have lateral support in order to prevent vehicle penetration. For conditions on Rte. 44, it was found that (1) there was an average of 49 vehicle contacts with the barrier for every reported accident in which the barrier was involved; (2) there was a definite tendency for motorists to stay out of the barrier lane, but avoidance of the barrier lane was reduced as volume increased; and (3) with a 55 mph (88 km/h) posted speed limit, the vehicular speeds were reduced by only a few miles per hour when the barriers were in place.

Evaluation of the barrier's performance during the widening of I-95 is recommended, since that highway carries a much higher volume of tractor-trailers than does Rte. 44.

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ACKNOWLEDGEMENTS

The authors express sincere appreciation to G. J. Cherepon, M. D. Ball, R. Robins, and W. J. Simmith for efforts in collecting and reducing traffic operations data, and to E. Skibinski for computer processing traffic operations and accident data.

Special thanks go to M. E. Bronstad of the Southwest Research Institute for providing information and valuable insight into the performance of the barrier.

Appreciation is due all personnel of the Virginia Department of Highways and Transportation who participated in this study, especially, J. F. De Simone for maintaining barrier placement information on the study site; and L. W. Campbell for furnishing accident data.

Finally, the staff of the Virginia Highway and Transportation Research Council is acknowledged for their contribution. In particular, thanks go to Harry Craft for editing the report; to Ivy Carlton and Toni Thompson for typing the draft manuscript; and to Jean Vanderberry for typing the reproduction masters.

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SUMMARY OF FINDINGS AND CONCLUSIONS

Literature

1. Concrete median barriers with low batter curb heights can safely redirect cars impacting at high speeds in combination with impact angles less than 15°.

2. The minimum length of a temporary barrier system should be 100 ft. (30 m) to withstand vehicle impact forces.

3. Excessive movement of temporary barrier units can contribute to vehicle vaulting and hazardous vehicle trajectories.

4. The joints in a temporary barrier system must be tight for the individual units to perform as a system.

5. A temporary barrier system must have lateral support in order to prevent vehicle penetration.

6. The improper orientation of the barrier's axis of symmetry can contribute to vehicle rollover.

7. A temporary barrier system should not be placed more than 12 ft. to 15 ft. (3.7 m to 4.6 m) from the edge of the roadway because of the potential for high angle impacts.

8. The longitudinal axis of the barriers should be placed parallel to the roadway, except when the barrier system is introduced with a flare, and the flare rate should not exceed the rate given in Table 1 of the text of this report.

9. The end of the barrier system should never be exposed to oncoming traffic; it should be removed from the travelway by flaring or be made crashworthy by installing a crash cushion or some other appropriate device.

Route 44

1. A comparison of the frequency and characteristics of traffic accidents before and during the widening of Rte. 44 was not completed in this study, because 48% of the accidents in the before period were associated with other construction activities.

2. Vehicles contacted the concrete barriers in 15.4% of the accidents occurring during construction.

3. In the 10 reported accidents that involved barriers, 5 of the impacting vehicles remained in the lane adjacent to the barrier after contacting the barrier, 2 infringed on the adjacent lane, and 3 crossed into the adjacent lane with 1 hitting an adjacent vehicle.

4. Of the 10 vehicles which contacted the barriers in reported accidents, 2 rolled over; both struck the barrier at a high ($>15^\circ$) impact angle.

5. There was evidence of 49 vehicle contacts with the barrier for every reported accident in which the barrier was involved.

6. Based on observed tire marks, the end of the barrier flare adjacent to the travelway at the start of the work area was the most often hit "point location" in the barrier system.

7. There was an average of 9.7 vehicle involvements with the temporary barriers on Rte. 44 per million vehicle miles of exposure.

8. There was a definite tendency for motorists to stay out of the barrier lane during construction, but avoidance of the barrier lane was reduced as the traffic volume increased.

9. The traffic capacity of Rte. 44 during construction was reduced to 86% of its prior capacity.

10. Driver awareness of the construction zone was evidenced by a 2-mph (3.2-km/h) reduction in average s eed and a lower lateral placement variance in the barrier lane.

11. During daylight conditions the average lateral spacing between the lanes of traffic was 5.49 ft. (1.67 m) before construction and 3.35 ft. (1.02 m) with the barriers in place.

12. The vehicle placement trends exhibited before construction in different roadway alignment situations were similar to those found with the barrier in place.

RECOMMENDATIONS

1. The Department's current standards, policies, and practices on the use of concrete traffic barriers should be evaluated in light of the findings of this report.

2. The performance of the precast concrete traffic barriers should be evaluated during the widening of I-95, since that highway carries a much higher volume of tractor-trailer traffic than does Rte. 44.

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EVALUATION OF THE PERFORMANCE OF PORTABLE PRECAST CONCRETE TRAFFIC BARRIERS

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INTRODUCTION

The widening of an in-service freeway requires that construction activities take place adjacent to the traveled roadway. The interface between high speed vehicular traffic and construction activities necessitates that a device be employed to separate the motoring public and the workmen and provide a safe environment for both. To provide this safe environment, the device must satisfy two requirements — it must be constructed in a substantial manner to protect workmen for errant vehicles, while at the same time it must not cause severe damage to a vehicle striking it or injury to the vehicle's occupants.

The device most often employed in Virginia until a few years ago to separate high speed vehicular traffic and workmen was the timber barricade. In August 1975, a National Transportation Safety Board report raised questions as to the safety afforded motorists and workmen by the timber barricade during the widening of I-495 in Northern Virginia.(1) At the request of the Virginia Department of Highways and Transportation, the Virginia Highway and Transportation Research Council evaluated the performance of the timber barricades on I-495.(2) The evaluation revealed that 45.3% of the vehicles which contacted the timber barricades penetrated into the construction area and, consequently, generated a great deal of concern for the safety of workmen and the motoring public.

The literature available at the time indicated that a number of states (including Florida, Oregon, Idaho, Washington, North Carolina, and California) were using the portable precast concrete traffic barrier (PCTB) to separate workmen and vehicular traffic during construction. The profile of the PCTB was similar to that of the New Jersey type concrete "safety shape" median barrier shown in Figure 1. The literature indicated that a 10-ft. 2-ton section of the PCTB was reasonably portable and that it redirected

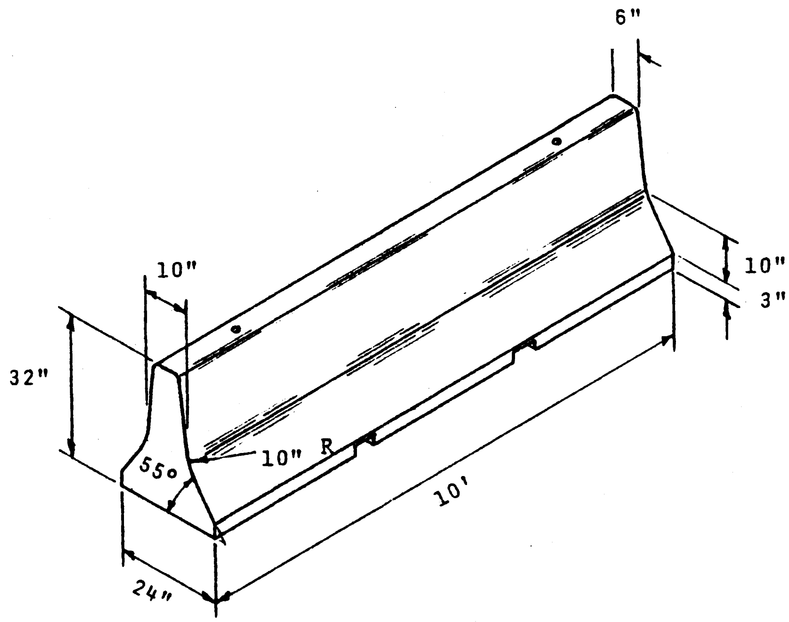

Figure 1. New Jersey type concrete "safety shape" median barrier. (1" = 25.4 mm)

impacting vehicles with minimal damage to the vehicle or injuries to the vehicle's occupants. There was, however, insufficient data to allow a complete assessment of the portable PCTB's performance in the construction zone environment. In addressing this lack of information, officials of the Department requested that the Research Council evaluate the performance of the PCTB during the widening of the Virginia Beach-Norfolk Expressway (Rte. 44). The results of that evaluation are contained in this report.

PURPOSE AND SCOPE

The overall purpose of this study was to evaluate the characteristics and performance of the PCTB when used as a device to separate high speed vehicular traffic and construction activities.

To achieve this purpose, the study had four specific objectives as listed below.

1. Review of the literature dealing with the performance of the concrete "safety shape" barrier in full-scale crash tests, permanent roadway installations, and temporary construction zones.

2. Examination of the traffic accident data before and during construction on Rte. 44 to determine the effects of construction on the frequency and characteristics of traffic accidents.

3. Analysis of tire marks and accidents involving a barrier to determine the effectiveness of the barrier in safety redirecting vehicles.

4. Examination of the effects of construction on traffic characteristics such as traffic volume, vehicle speed, and lateral placement.

THE BARRIER

The PCTB is a portable barrier designed to restrain and redirect impacting vehicles with minimal damage to the vehicle or injury to its occupants. Its use as a temporary barrier followed from the successful use of the concrete median barrier (CMB) on permanent installations. The ability of the PCTB to safely restrain and redirect impacting vehicles lies in the design characteristics of its forerunner, the CMB.

Use of the CMB's in Louisiana (1942) and in California (1946) provided the initial insight into their performance capabilities. Based on these experiences, New Jersey highway officials developed a specially contoured profile to give vehicle redirection capabilities to the concrete barrier. The earliest New Jersey design barriers were only 18 in. (0.46 m) high, but when it was found that vehicles climbed these barriers the height was increased to the present 32 in. (0.81 m). The width and thickness were made sufficient to prevent the barrier from fracturing or overturning when impacted by a vehicle.[3]

Today's standard New Jersey barrier, often referred to as the "safety shape" barrier, is 32 in. (0.81 m) high and has a 24-in. (0.61-m) base with a 6-in. (0.15-m) top width as shown in Figure 2. It incorporates a 55° batter curb face with an upper portion (stem) at 84° from the horizontal.

The theory of the concrete barrier performance is relatively simple. With reference to Figure 2, when a vehicle strikes the barrier at angles less than 15° the initial contact is between the 3-in. (76-mm) vertical curb and the vehicle tire. This contact deforms the tire and tends to slow the vehicle. The front wheel then climbs up the 55° batter curb face and the vehicle is lifted

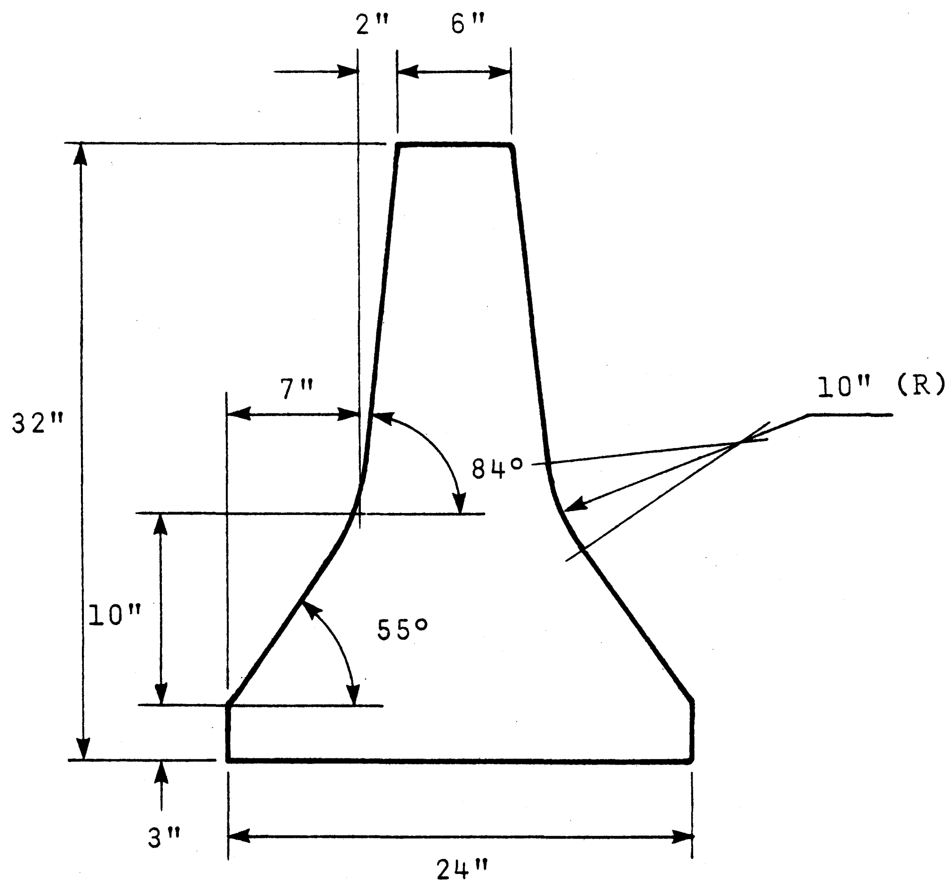

Figure 2. Profile of the New Jersey "safety shape" concrete median barrier. (1" = 25.4 mm)

from the roadway. The lifting of the vehicle dissipates some of its kinetic energy and places it in a position such that the redirecting forces perpendicular to the barrier can be applied to its suspension system. At a low-angle of impact there is usually no contact between the side of the car and the barrier. If the impact speed is high and the impact angle is more than a few degrees, the vehicle may climb up the 55° sloped face to its intersection with the upper portion of the barrier. As the front portion of the vehicle wheel contacts the upper (near vertical) portion of the barrier, the wheel is turned parallel to the barrier's longitudinal axis and the vehicle is redirected. Depending on the impact speed and angle, the vehicle may continue to climb up the near vertical portion of the barrier before returning to the roadway.

Crash Tests

Full-scale crash tests have been performed on CMB's in California by the Department of Transportation (Caltrans), in Texas by the Texas Transportation Institute (TTI) and the Southwest

Research Institute (SRI), and in England by the Transport and Road Research Laboratory (TRRL). The purpose of these tests was to determine the strength of various CMB designs and to evaluate their effectiveness in safely redirecting impacting vehicles. The principal results of these studies indicate that the permanent CMB designs tested were effective in restraining vehicles at all speeds and impact angles, and safely redirecting standard size vehicles at high speeds in combination with impacting angles of less than 15°. Those designs which incorporate a high batter curb height* were found to cause subcompact cars to roll over after impacting the barrier.

Crash tests have also been performed on some temporary PCTB designs by the Caltrans, TTI and SRI. The California study used 12.5-ft. (3.8-m) and 20-ft. (6.1-m) unanchored barrier sections with pinned-end connections. The study results indicated that barrier roll (about longitudinal axis) and excessive lateral movement contributed to vehicle vaulting and hazardous vehicle trajectories. The report on the tests recommended that precast barrier units similar to those tested should be used only at locations where impact conditions are expected to be in the moderate range of impact speed/angle of 40 mph (64 km/h)/20° to 60 mph (97 km/h)/13°. The report also recommended that temporary barrier installations should be a minimum of 100 ft. (30 m) long to withstand vehicle impact forces.(4) Two additional crash tests have been performed by the Caltrans and resulted in a recommendation that the temporary precast barriers used in construction and maintenance zones should be a minimum of 20 ft. (6.1 m) in length, unless they are restrained against lateral movement at the base.**

Crash tests were performed by the TTI using 30-ft. (9.1-m) temporary barrier units with male-female joints. A 4,540-lb. (2,060-kg) vehicle impacted the barriers at 60 mph (96 km/h)/24°. The vehicle was redirected and the maximum barrier displacement was 13.5 in. (343 mm). The barrier did not roll during impact. The study concluded that the 30-ft. (9.1-m) barrier units tested would be acceptable as a temporary barrier but considerable maintenance could be anticipated after high speed, high angle impacts if some lateral restraint was not provided to prevent sliding.(5)

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*Distance from the bottom of the barrier to the intersection of the 55° batter curb and the near vertical portion of the barrier.

**E. F. Nordlin: personal communication, June 20, 1978.

The crash tests by the SRI used 20-ft. (6.1-m) barriers with tongue and groove connections. The connections were modified by the addition of steel plates at the lower corners of the barriers to increase joint yaw moment capacity. Styrofoam pads were placed under the joints to prevent the ball bearing effect produced by gravel or sand between the barrier and pavement. The first crash test on the temporary barrier used a 4,500-lb. (2,000-kg) vehicle impacting at a speed/angle of 60 mph (95 km/h)/ 25°. The barrier failed in flexure due to insufficient reinforcement. The second crash test using four #4 longitudinal rebars in the barrier and a pipe insert to develop yaw capacity of the joints resulted in a redirection of the 4,500-lb. (2,000-kg) vehicle which impacted the barrier at a speed/angle of 56 mph (90 km/h)/24°. The maximum barrier displacement was 41 in. (1 m). The authors concluded that the portable barriers require either large permissible translations during standard strength test impacts or considerable joint resistance to rotation, unless the barriers are restrained by some foundation.[6]

In summary, full-scale concrete barrier crash tests identified the following points.

1. Those barrier profiles with a low batter curb height can safely redirect cars at high speeds in combination with impact angles of less than 15°.

2. The minimum length of a temporary barrier system should be 100 ft. (30 m).

3. Excessive movement of the units in temporary barrier systems should be prevented. Based on the crash tests cited, the movement of temporary barriers can be restricted by (a) increasing the length of the individual units, which reduces the number of joints and increases the weight of individual units; (b) providing lateral support at the base; or (c) increasing the joint strength to transmit impacting loads to adjacent barrier units.

Performance Characteristics

Many characteristics of the barrier significantly affect its performance. The following is a brief summary of some but not all of the characteristics which should be considered when using a PCTB barrier system. For characteristics not covered in this report, the reader is referred to the 1977 AASHTO publication for permanent barrier installations, Guide For Selecting, Locating, and Designing Traffic Barriers.[7]

Crash tests have shown that the shape of the concrete barrier can significantly affect the performance of an impacting vehicle. Eight barrier profiles, including the General Motors, New Jersey and Configuration F designs (see Figure 3), were evaluated by the SRI. The tests indicated that all designs performed well in restraining the vehicles from penetrating the barrier and most did not cause major damage to the impacting vehicle. However, the General Motors design did cause rollover of a subcompact vehicle with an impact speed/angle of 57 mph (92 km/h)/16°. Generally, those designs which incorporated a low batter curb height (Configuration F and New Jersey designs) were found to be least likely to cause rollover of subcompact cars.[8] Crash tests performed in England by the TRRL with mini cars confirmed the crash test results by the SRI. However, in a TRRL crash test, a mini car was rolled over when impacting a New Jersey barrier at an impact speed/angle of 70 mph (113 km/h)/20°. The TRRL study also found that with a 3-in. (75-mm) overlay placed in front of the New Jersey barrier, an impacting mini car at 70 mph (113 km/h)/20° was not rolled over. The overlay results in a batter curb height of 10 in. (254 mm), which is equal to that of the Configuration F design.[9]

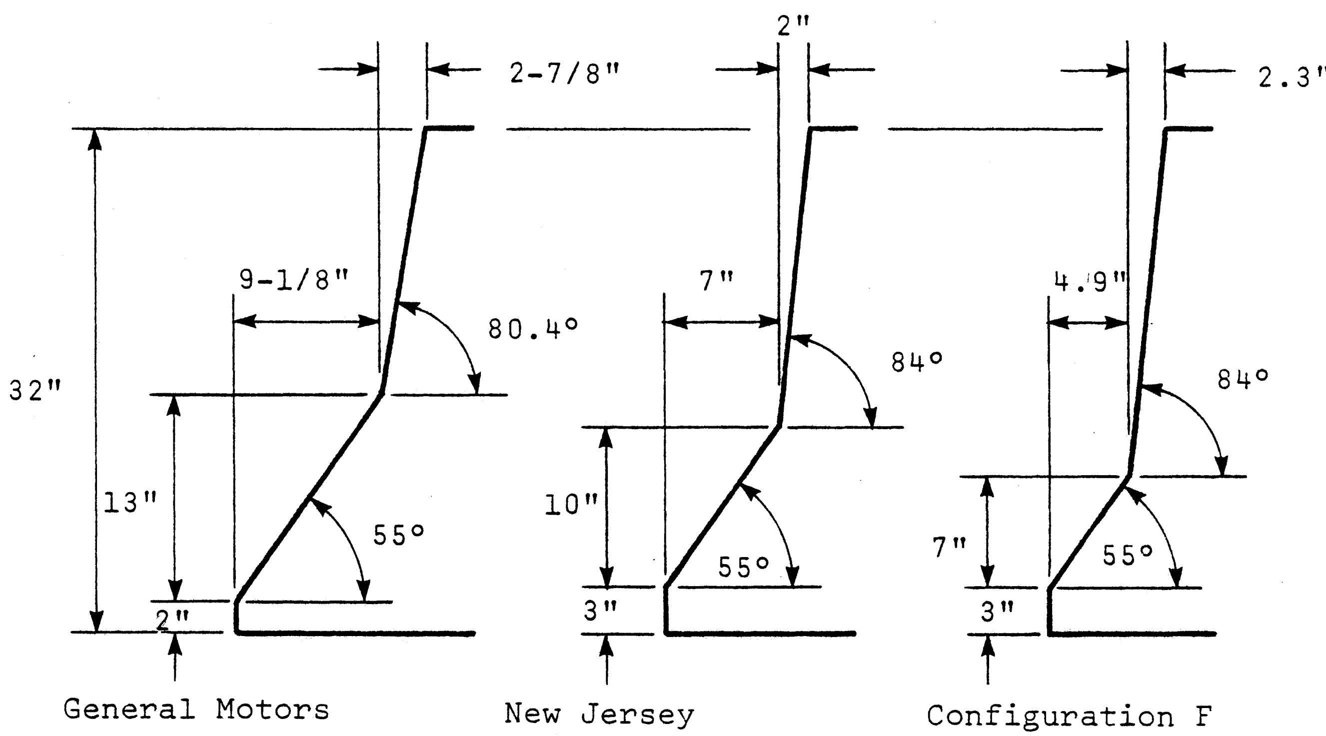

Figure 3. The General Motors, New Jersey and Configuration F barrier profiles. (1" = 25.4 mm)

The potential for high angle impacts increases as the distance between the travelway and a concrete median barrier increases. The TTI, based on vehicle accelerations at impact, recommended that concrete barriers should not be installed more than 12 ft. (3.7 m) from the edge of the roadway because of the potential of a high angle impact if the barrier were further away.(10) The AASHTO publication, cited above also suggests that rigid barriers should not be used more than 15 ft. (4.6 m) from the edge of the roadway.(11) These references emphasize that the barriers are designed to safely redirect a vehicle impacting at an angle of 15° or less.

The movement of the temporary barrier when impacted can also significantly affect the performance of the vehicle. The Caltrans crash strength tests cited previously showed that barrier roll and excessive lateral movement contributed to vehicle vaulting and hazardous vehicle trajectories. The report stressed the need for tighter barrier joints to reduce the potential hazards produced by barrier movement.(12) Crash strength test by the SRI demonstrated that temporary barriers offer substantially less resistance to impact than do barriers which are restrained by a continuous foundation. The report on the study recommended that temporary barriers should have some continuous support. If this is not possible, the barrier mass and base friction must provide lateral restraint and the joints must be capable of transmitting yaw movement to adjacent barriers. The authors also noted that in considering barrier movements of roll, yaw and lateral displacement, the restriction of barrier roll is the most important because it induces vehicle ramping.(13)

Computer-simulated vehicle crashes by the SRI identified the orientation of the barrier axis of symmetry as a factor contributing to vehicle rollover. In the analysis only plus and minus 10% superelevations were used (see Figure 4). Rollover of a subcompact vehicle occurred when impacting a New Jersey barrier with the axis of symmetry orientated perpendicular to the roadway surface with a -10% superelevation. After completing their analysis the researchers concluded that the preferred orientation of the barrier's axis of symmetry is "perpendicular to the roadway when the traffic is going up the super and vertical when the traffic is going down the super."(14) The orientation of the barrier's axis of symmetry should be considered when the PCTB's are to be placed on a surface which slopes away from the roadway. If it is determined that the surface must be graded prior to installation of the barrier, it is important to ensure that (1) vertical support is provided across the full width of the barrier to reduce barrier roll, and (2) the toe of the barrier is not placed below the approach surface level.

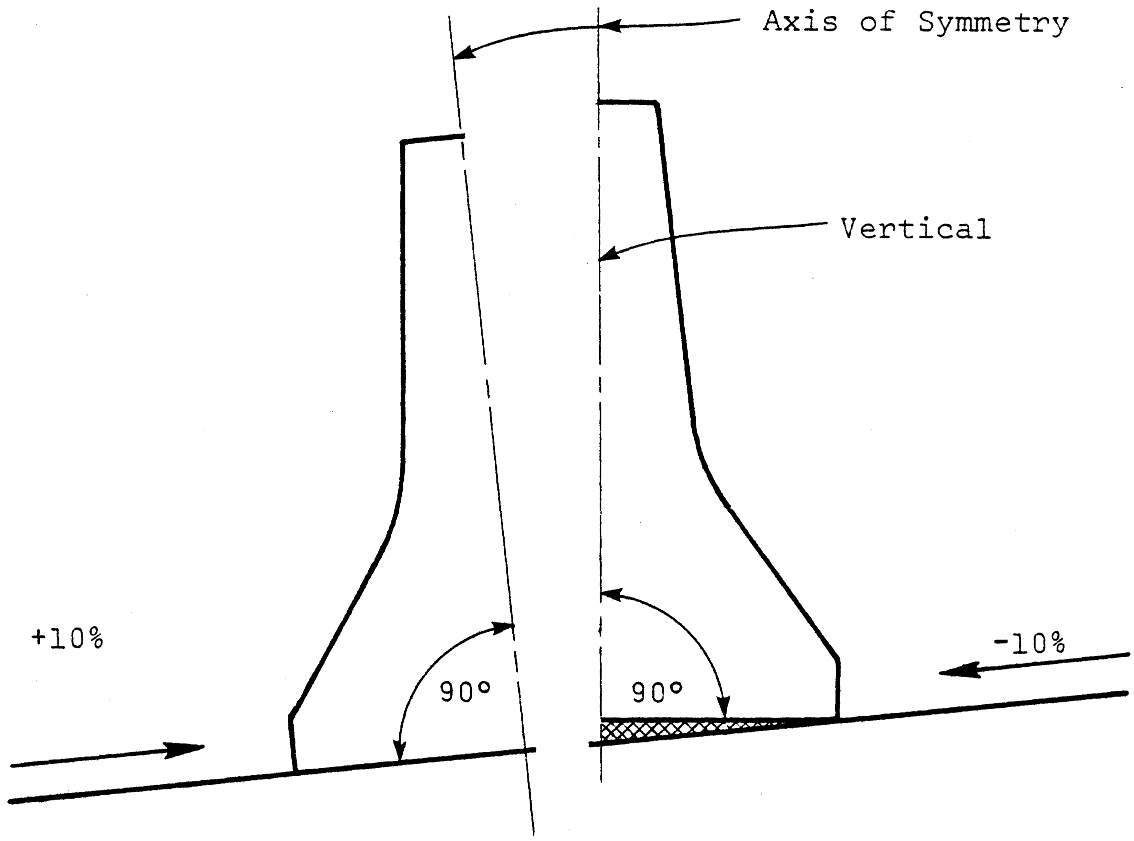

Figure 4. Preferred barrier orientation on superelevated surfaces.

The manner in which a barrier system is introduced can significantly affect the severity of the impact if it is struck by a vehicle. The end of a barrier system should never be exposed to oncoming traffic; it should be removed or shielded from errant vehicles. The end can be removed from a roadway by flaring the system. The AASHTO publication, Guide for Selecting, Locating, and Designing Traffic Barriers, provides information on the rate at which a barrier system should be flared from the roadway. The flare rates, which are a function of the operating speeds, are shown in Table 1. According to the AASHTO guide, the purpose of the flare is "(1) to locate the barrier and its terminal as far from the traveled way as is feasible, (2) to redirect an errant vehicle without serious injuries to its occupants, and (3) to minimize a driver's reaction to a hazard near the traveled way."[15] The end of a barrier flare should be located beyond the clear zone line discussed in Chapter III of the AASHTO guide. However, if this is impracticable, the end should be shielded from errant vehicles, which can be accomplished by flaring the barrier system behind a guardrail system in such a manner as to avoid the possibility of a vehicle hitting the end or of pocketing if it hits the guardrail. Another method of making the end of a barrier system crashworthy would be the installation of a crash cushion or some other appropriate impact-attenuating device.

Table 1

Flare Rates for Rigid Barrier Systems
(1 mph = 1.6 km/h)

Operating Speed, mph	Flare Rate*, ft./ft.
70	20
60	17
50	14
40	11

*The number of feet parallel to the roadway per foot perpendicular to the roadway.

In summary, the performance of an impacting vehicle can be significantly affected by (1) the profile of the barrier, (2) the distance between the travelway and the barrier as it relates to angle of impact, (3) excessive barrier movement, (4) the orientation of the barrier axes of symmetry, (5) the barrier system flare rate, and (6) the exposed end of the barrier system.

THE WIDENING OF THE VIRGINIA BEACH-NORFOLK EXPRESSWAY

The Virginia Beach-Norfolk Expressway (Rte. 44) is a limited access toll roadway extending from Interstate 64 on the west end to the city of Virginia Beach on the east end. Rte. 44 is 12.10 mi. (19.47 km) in length, and the westerly 6.16 mi. (9.91 km) were being widened from two to three lanes in each direction. The traffic volume in the section being widened ranged from 40,000 to 95,000 vehicles per day. The distribution of traffic by vehicle type during construction was 84% passenger cars, 15% single-unit trucks, and 1% trailer trucks.[16]

The widening was performed in one contract with a bid price of $4,355,249 and, primarily, consisted of adding a median lane in each direction to the existing four-lane limited access roadway. Figure 5 shows the existing 24-ft. (7.3-m) roadway for one direction of travel and the 12-ft. (3.7-m) widening in the median area. The PCTB's were placed 6 in. (150 mm) from the edge of the existing roadway to allow room for construction reference points. The passing lane during construction was 9.5 ft. (2.9 m) wide and the traffic lane remained at 12 ft. (3.7 m).

The widening project was divided into three sections of approximately 2 mi. (3 km) each. Work on section "A" as shown in Figure 6 was initiated in September 1976. As each section was completed, the PCTB units were moved to the next section. The new lanes were opened for traffic when possible and all portions were in service by June 1978.

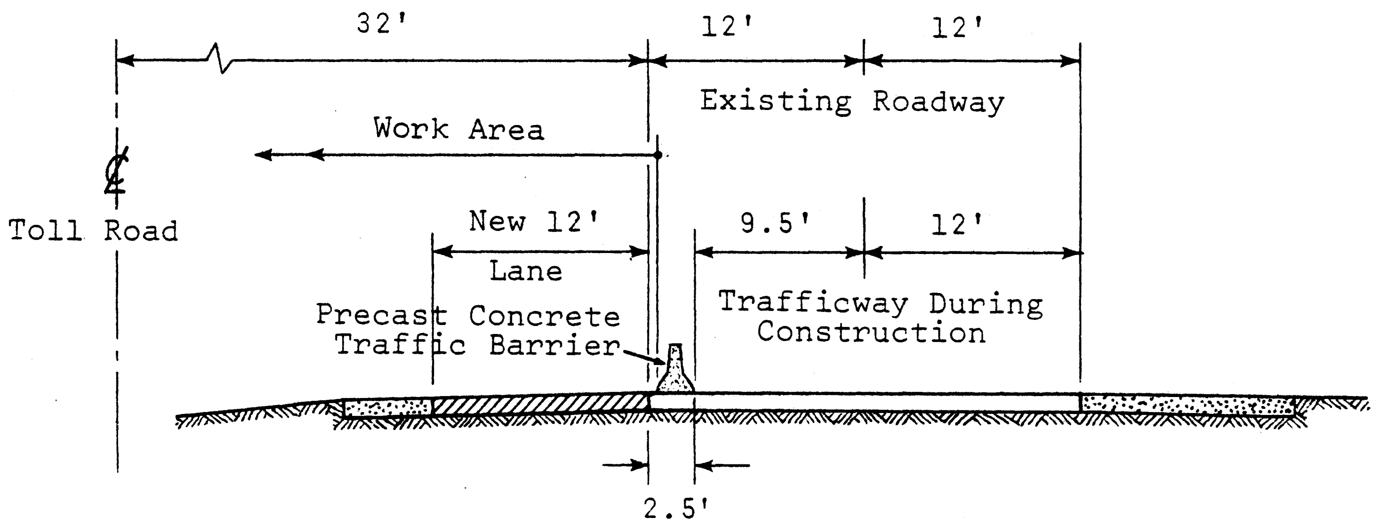

Figure 5. Cross section of Rte. 44 for one direction of travel during construction. (1' = 0.305 m)

1964

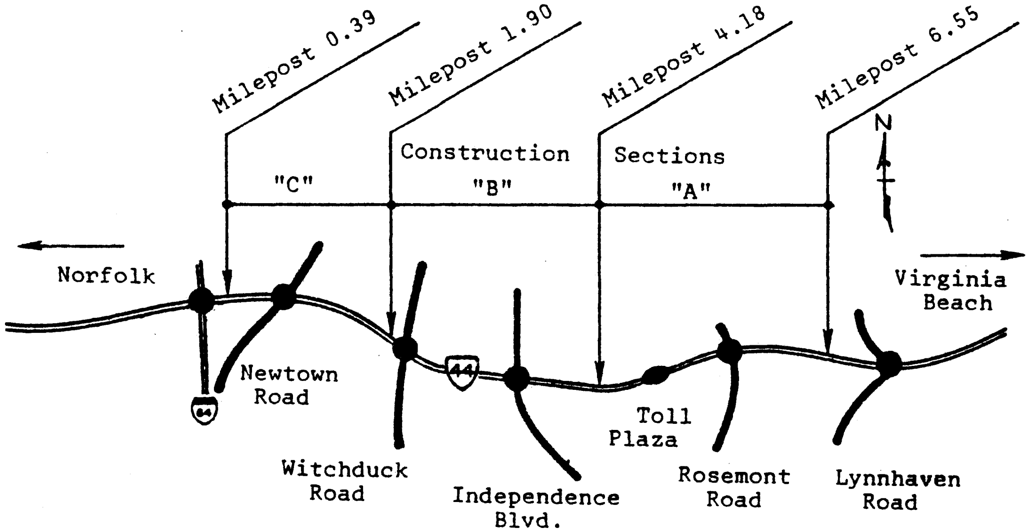

Figure 6. Rte. 44 widening project.

The PCTB units employed on Rte. 44 had the New Jersey "safety shape" profile. The units were 24 in. wide, 32 in. high and 12 ft. long (0.61 m x 0.81 m x 3.66 m) with an approximate weight of 4,800 lb. (2,200 kg). The joints were of the tongue and groove design. Individual sections were either a tenon member (male-male) or a mortise member (female-female), which facilitated the removal of a member at the midsection (see Figure 7). Lateral support was provided only on bridge decks, where the units were placed on channels bolted to the bridge deck as shown in Figure 8. Two channels were used for each barrier unit. The barrier system was introduced at the start of the work area by either a 300-ft. (91-m) barrier taper as shown in Figure 9 or by a sand-filled plastic barrel crash cushion as shown in Figure 10.

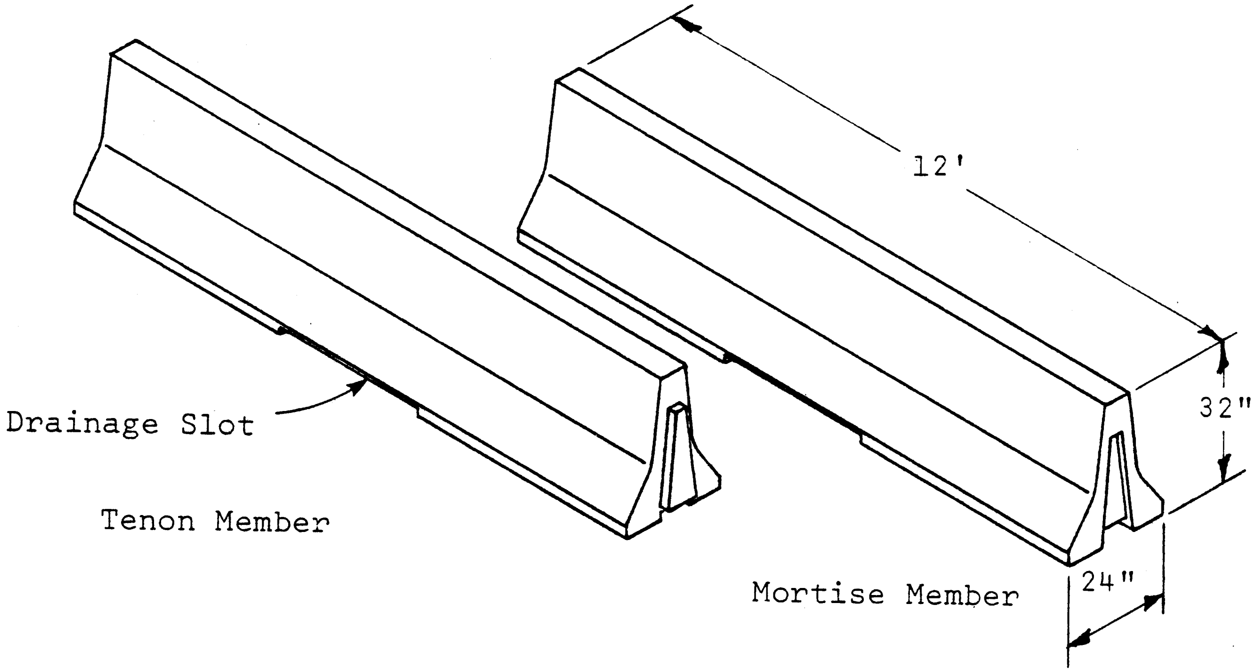

Figure 7. Precast concrete traffic barriers. (1" = 25.4 mm)

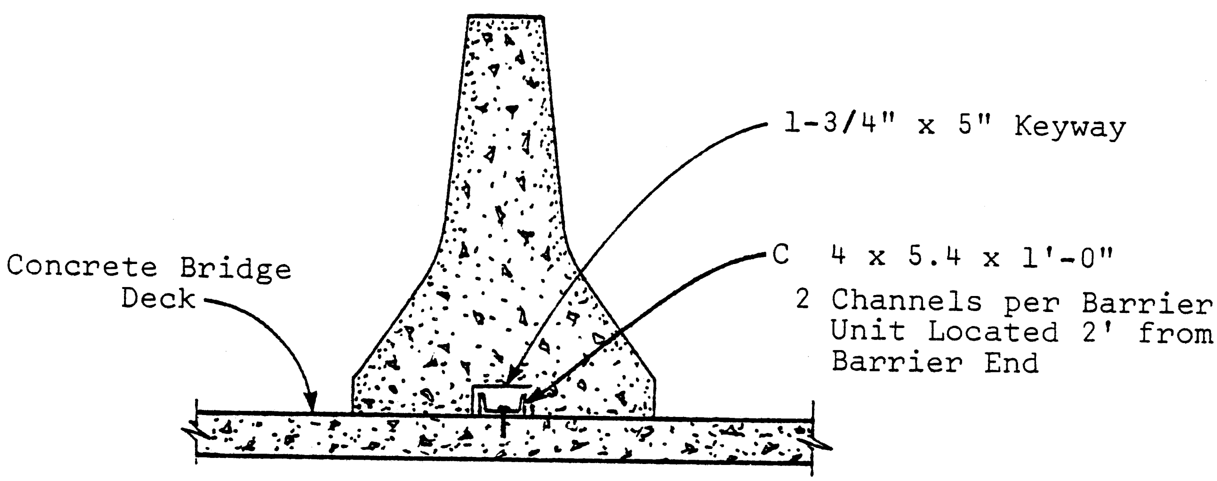

Figure 8. PCTB installation on bridge deck. (1" = 25.4 mm)

1966

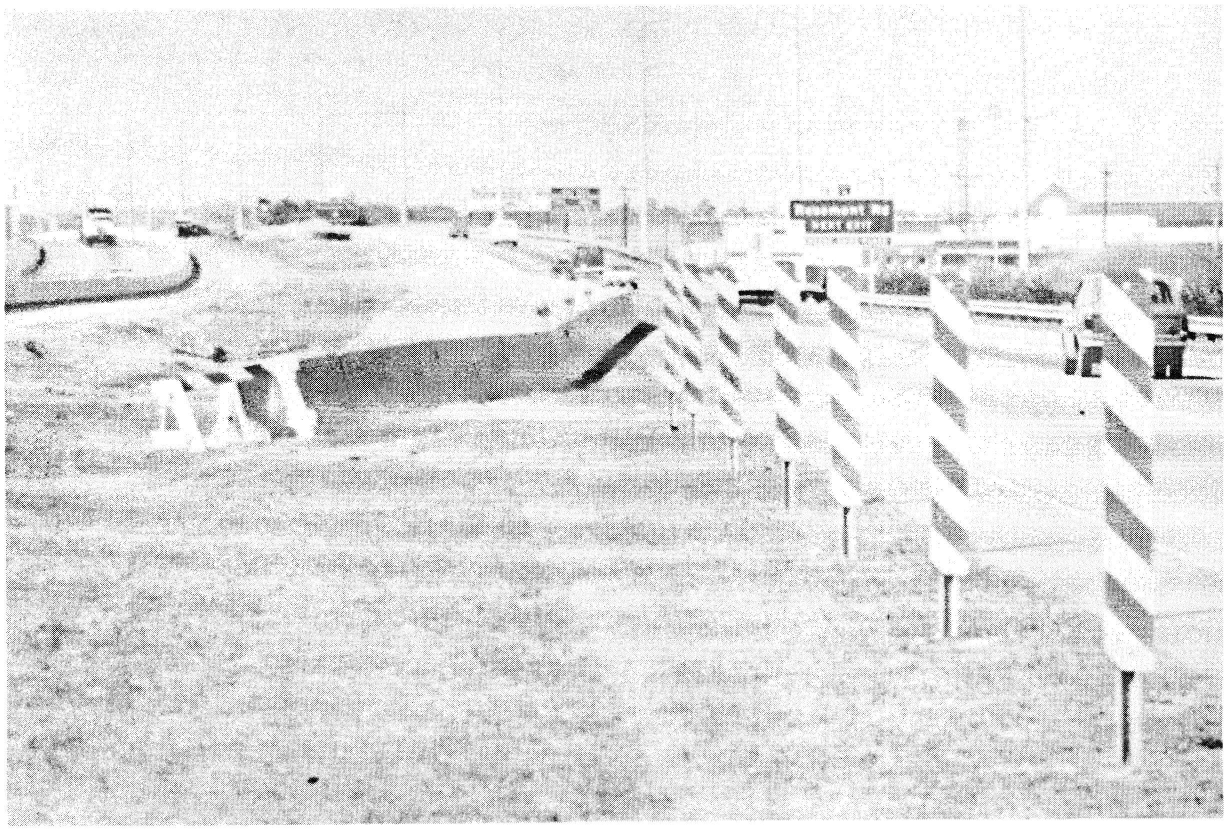

Figure 9. Three hundred-foot barrier taper.

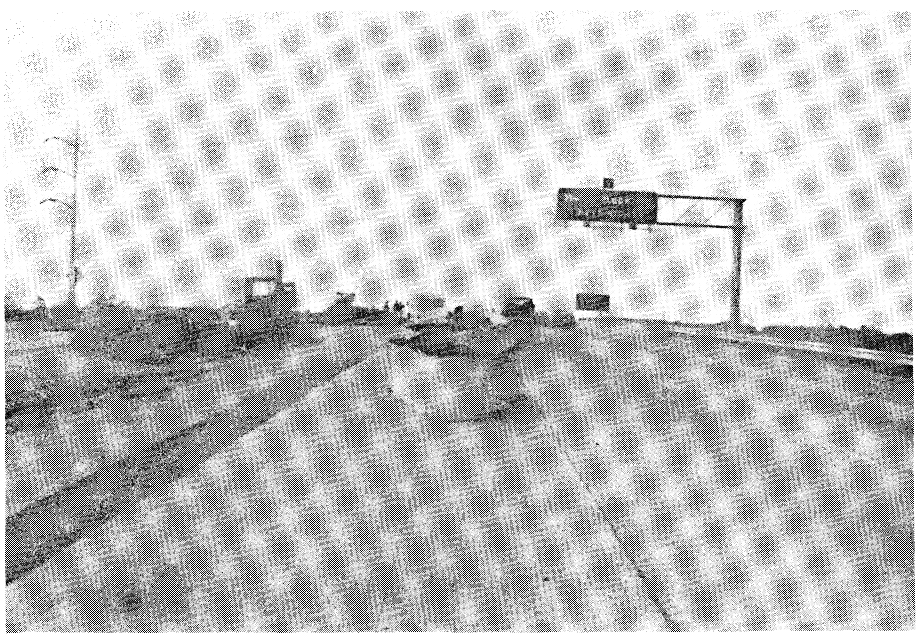

Figure 10. Sand-filled plastic barrel crash cushion.

TRAFFIC SAFETY

The purpose of the traffic safety analysis was to determine the effect of the Rte. 44 construction work on the traffic safety environment with specific emphasis on the performance of the PCTB. There were three phases: (1) An examination of the traffic accident data on Rte. 44 before and during construction in an attempt to determine the effects of construction on the frequency and characteristics of traffic accidents; (2) a study of the reported accidents on Rte. 44 in which vehicles came into contact with the PCTB's; and (3) an analysis of the tire marks on the barrier and barrier-involved accidents to obtain an indication of the effectiveness of the PCTB in safely redirecting vehicles.

Traffic Accidents

In this phase, FR-300 accident reports were compiled by accident date and location to provide a comparison of crash data for periods before and during construction. Since the widening project was divided into three work segments, different time periods were used for each road segment as shown in Table 2. Section "C" was excluded from the analysis since the widening in this section extended beyond December 31, 1977, and accident reports after that date were not available at the time the data were being collected for this analysis. The time periods during construction were not started until the entire length of a section was under construction.

After the study time periods were determined, an effort was made to identify any work activity on Rte. 44, other than ordinary maintenance and the widening project itself, which might influence the number or characteristics of accidents. This search revealed the following activities:

1. The improvement of the interchange ramps at Rosemont Road from August 1974 to July 1976;
2. the improvement of the interchange ramps at Independence Blvd. from July 1975 to June 1977;*
3. the repair of pavement from June 1976 to December 1976.

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*Barricades used on ramp work were removed during widening of the main line.

4. the application of slurry seal on shoulders from August 1977 to September 1977; and

5. the addition of toll plaza lanes from December 1976 to March 1978.

Table 2

Description of Study Periods and Construction Sections on Rte. 44

Construction Section	Before Construction	During Construction
A Milepost 4.18 - 6.55	December 1, 1975 - June 26, 1976	December 1, 1976 - June 26, 1977
B Milepost 1.90 - 4.18	July 22, 1976 - September 14, 1976	July 22, 1977 - September 14, 1977

The first three activities may have affected the before construction data but did not affect the during construction data. The fourth activity could have affected the accident data during the widening of section "B". The toll facility area was excluded from the analysis since the fifth activity was going on during the entire widening project.

In performing the accident analysis, it was determined that 48% (21 of 44) of the accidents before construction involved vehicle contact with the timber barricades which were used in the two ramp improvement projects.* Since 48% of the before construction accidents were associated with ramp improvement projects which were not in progress during the widening, the effects of the widening project on traffic accidents could not be isolated in a before-during comparison. Therefore, an attempt was made to identify a control roadway for comparative purposes. However, because of the unique nature of Rte. 44, a limited access, toll roadway with 1% tractor trailer traffic, there was no available roadway in Virginia with similar characteristics. Thus the magnitude of the traffic safety problem associated with the construction could not be determined with reliable results, and the analysis was limited to the following summary of during construction accident data.

*The ramp improvement projects were initiated prior to the ban on the use of timber barricades imposed by FHWA Notice N 5160.27, issued on February 2, 1977.

The analysis of the during construction accident data revealed that there were 39 accidents during the periods shown in Table 2. There were no fatal accidents and 10 injury accidents. The total accident rate was 136.8 and the injury accident rate was 35.1 per 100 million vehicle miles of travel. Driver inattention was identified as the major cause in 25 of the 39 accidents (64.1%) and driving under the influence was listed for 7 (17.9%) of the accidents. Six of the 39 accidents (15.4%) involved vehicle contact with the concrete barrier. Twenty-four of the 39 accidents (61.5%) were of the rear-end type. Twenty-two of the 72 vehicles (30.6%) involved in the construction accidents were traveling at a speed of less than 20 mph (32 km/h) prior to impact. The high percentage of rear-end accidents and slow moving vehicles is indicative of stop-and-go traffic. Of the 72 vehicles involved in these accidents 60 (83.3%) were cars and 10 (13.9%) were single-unit trucks. These figures approximate the traffic mix of 84% cars and 15% single-unit trucks. A review of the accidents by location found no clustering of accidents at any specific location.

Barrier-Involved Accidents

This phase in the traffic safety analysis included a summary of data for the 10 reported accidents in which a vehicle came in contact with the PCTB units between September 22, 1976, when the first concrete barriers were placed on Rte. 44 and December 31, 1977. Note that this time period is longer than those shown in Table 2 and includes all three construction sections. The small sample size precludes any in-depth statistical analysis of the data; therefore, a summary of general facts concerning the accidents is given.

Of the 10 reported accidents involving vehicle contact with the barrier, 3 were injury accidents and 7 property damage only accidents. Five of the impacting vehicles remained in the lane adjacent to the barrier after contacting the barrier, 2 infringed on the adjacent lane and 3 crossed into the adjacent lane, with 1 hitting an adjacent vehicle. Two vehicles which struck the barrier at a high impact angle (>15°) rolled over. The barrier was struck first in 6 of the 10 accidents, 3 of the remaining accidents were rear-end accidents, and 1 vehicle hit a guardrail prior to hitting the barrier. In 6 of the 10 accidents only 1 vehicle was involved, and in the remaining 4 only 1 vehicle in each accident contacted the barrier. While the typical barrier displacement due to vehicle contact was less than 1 ft. (0.3 m), 1 incident involving a van which impacted the barrier at an estimated speed/angle of 55 mph (88 km/h)/45° resulted in a displacement of 8 ft. (2.4 m). Concerning this accident, note that (1) the impact conditions were severe when compared to those under which the strength tests on the permanent barriers are made,[17] (2) the van rolled over after impact, and (3) the van did not enter the construction area.

Tire Mark Surveillance

The purpose of this section of the traffic safety analysis was to determine the effectiveness of the PCTB used on Rte. 44 in safely redirecting vehicles. The principle upon which this determination was based is that the profile of the PCTB is designed to safely redirect vehicles which impact it at a shallow angle of incidence. If the PCTB performed as anticipated, a traffic accident analysis would not identify those vehicles which impacted it and were safely redirected. However, evidence of the vehicle's involvements would remain on the face of the PCTB in the form of tire marks. Thus, a correlation between vehicle involvements with the barrier and traffic accidents in which a vehicle contacted the barrier should give an indication of the effectiveness of the PCTB in safely redirecting vehicles. It should be noted that the correlation between vehicle involvements and barrier-involved accidents can be affected by any factor which can affect barrier performance. These factors include the profile of the barrier, the orientation of the axis of symmetry, the tightness of the joints, the distance from the travelway to the barrier, and the flare rate. Thus, the correlation is a measure of not only the particular design of the barrier used but also the conditions under which it was used.

Tire Mark and Accident Data

In section "A" of the widening project, the PCTB units were installed during the period from September 22, 1976, through November 23, 1976. The tire marks on the barrier were identified, photographed, and catalogued as to roadway location on February 28, 1977, and then updated on June 14, 1977. There was evidence of 154 vehicle involvements above the 3 in. (76 mm) vertical curb. Scuff marks on the 3-in. (76 mm) vertical curb were identified during the logging operation, but were not included in the number of vehicle involvements, since they could have been made by the side of the tire and thus might not be an indication of vehicle climb on the barrier. During this same time period there were 3 reported accidents in which a vehicle came in contact with the barrier. In section "B" of the widening project, the PCTB units were installed during the period June 27, 1977, through July 21, 1977. The tire marks were identified, photographed, and catalogued as to location on August 11, 1977. There was evidence of 89 vehicle involvements with the barrier above the 3-in. (76-mm) vertical curb. During this same period there were 2 reported accidents in which a vehicle came in contact with the barrier. The information cited above indicates that there was an average of 49 vehicle involvements with the barrier for every reported accident in which the barrier was involved. The rate of 49 to 1 is defined for this report as the barrier effectiveness rate.

In an attempt to determine the significance of the barrier effectiveness rate found on Rte. 44, a literature search was initiated to identify any similar data. This search found a 1976 SRI study(18) which reported that on two Indiana roadway sections, there were 99 vehicle involvements which resulted in 32 reported accidents or a barrier effectiveness rate of 3 to 1. However, the barriers in Indiana were not temporary barriers but New Jersey shaped CMB's located in a median which varied in width from 4 to 11 ft. (1.2-3.4 m). Since the New Jersey profile was used on Rte. 44 and on the Indiana roadways, this suggests that the distance between the travelway and the barrier can significantly affect the barrier's effectiveness rate.

Roadway Location

The tire mark data can also be utilized in evaluating the performance of an installed barrier system. A review of the Rte. 44 tire mark data by roadway location revealed that the end of the barrier flare adjacent to the travelway at the start of the work area was the most often hit "point location" on the barrier system. There were 20 (13% of total) vehicle involvements at these locations in section "A" and 7 (8% of total) in section "B". It appears that the drivers of the vehicles did not expect the barriers to encroach into their lane to the extent that they did. This information identifies a need to adequately warn and physically move traffic prior to the introduction of the barrier system which encroaches or in some way reduces the lane width.

Roadway alignment also appears to be associated with the frequency of vehicle involvements with the barrier. With reference to Table 3, barriers located in the left-hand curves had an average of 12.4 vehicle involvements per million vehicle miles of exposure. Tangent sections had an average rate of 8.7 and right-hand curves (barrier on left) had an average rate of 7.1. A notable deviation from the average involvement rates was the rate of 32.3 in the right-hand curves in section "B". This high rate was the result of a large number of involvements in a particular curve which was preceded by a 1.7-mi. (2.7-km) tangent section. Seventy-one percent of the involvements in this curve were located in the first 500 ft. (150 m) of the curve. Time-lapse film taken at this location showed a tendency of drivers to start turning after the vehicles were already in the curve, thus moving closer to the barrier than when in the tangent section. This observation may indicate that additional lane width or the shifting of the lane away from the barrier is required under these circumstances to compensate for the delayed driver maneuvers.

The average involvement rate varied considerably from 7.2 in section "A" to 17.3 in section "B". One possible reason for this difference may be that section "A" was widened during the winter months when the average daily traffic (ADT) volume was 43,000 and section "B" was widened during the summer months when the ADT was 94,000. Thus, the involvement rate increased slightly faster than did the ADT volume. This apparent relationship between the involvement rate and the ADT is similar to that found between accident rates and ADT's. However, there was insufficient data to allow verification of this observation.

Table 3

Vehicle Involvement Rate With the PCTB

Alignment	Section A Rate	Section B Rate	Average Rate
Tangent	5.6	15.7	8.7
Left-hand curve	12.3	14.2	12.4
Right-hand curve	4.9	32.3	7.1
Average	7.2	17.3	9.7

Note: Rate taken as involvements above the 3-in. (76-mm) vertical curb per million vehicle miles of exposure.

TRAFFIC OPERATIONS

One of the concerns in using the barrier was its potential adverse effects on traffic operations, in particular the effect of physically reducing the median lane width from 12 ft. to 9.5 ft. (3.66 m to 2.90 m) by the placement of the barrier on the left-hand edge of the normal travelway. To evaluate the effects of this condition, a set of experiments were designed to examine a variety of traffic characteristics with and without the barrier under an array of traffic volume, roadway alignment, and lighting conditions. Specifically, the analysis consisted of an identification and examination of the effects of the barriers on trends in average vehicular speeds, lane distribution, capacity, and lateral placement. The sections below describe the procedures used for data collection and reduction and the results of these experiments.

Data Collection

The basic hardware used for data collection consisted of pavement tape switches connected to a pen type chart recorder. For each vehicle, information was recorded and coded from the chart recorder output to determine speed, vehicle type, lateral placement, and arrival time. Data were recorded for both the median (barrier) lane and the shoulder lane.

To evaluate the effect of the barrier under different roadway alignments, data were collected at three sites. Site #1 was an eastbound tangent section just east of Independence Boulevard. Data were collected on June 7, 1977, for the before construction situation and on August 2, 1977, for the during condition. Site #2 was located in the westbound lanes of a 1° 30' right-hand curve section just east of Witchduck Road. Data were taken on June 14 and August 9, 1977. Site #3 was also just east of Witchduck Road, but in the eastbound lanes. Before and during data were collected for this 1° 30' left-hand curve on June 21 and August 11, 1977.

To evaluate the effects of the barrier under a variety of volume and lighting conditions it was planned that data be taken during four periods throughout the day (i.e., during the morning peak hours, at noon, during the afternoon peak hours, and late at night). However, because of switch failures and the time and cost of data reduction, only three time periods were used for each of the three sites.

Vehicular Speeds

The analysis of vehicular speeds was undertaken to partially identify driver reaction to the barrier as well as to assist in the capacity analysis. In regard to the driver reaction, it was assumed that any serious traffic flow problems would show up in the speed analysis.

As can be seen in Table 4, the average vehicular speeds decreased during construction in both lanes. In both lanes the average decrease was slightly over 2 mph (3.2 km/h) and the average

Table 4

Average Vehicular Speeds

Site	Time (Hr.)	Average Vehicular Speed in mph (Variance in mph^2)							
		Median Lane				Shoulder Lane			
		Without Barrier		With Barrier		Without Barrier		With Barrier	
#1 Tangent	0800	60.9	(20.3)	60.5	(19.7)	56.8	(37.8)	56.3	(29.6)
	1200	61.1	(16.5)	57.2	(16.4)	57.1	(28.2)	53.1	(20.5)
	2200	59.4	(16.7)	59.0	(17.4)	55.7	(21.5)	54.0	(22.8)
#2 Right-Hand Curve	0800[a]	57.2	(9.8)	50.2	(8.5)	54.9	(17.3)	48.8	(11.9)
	1600[a]	59.4	(12.9)	56.6	(15.1)	55.6	(21.4)	53.0	(18.3)
	2200	59.0	(19.3)	57.1	(17.3)	55.8	(21.2)	53.9	(22.3)
#3 Left-Hand Curve	0800	60.0	(12.6)	59.1	(20.5)	55.9	(17.1)	54.2	(26.6)
	1200[a]	58.6	(15.1)	57.4	(18.1)	54.5	(19.2)	53.6	(22.0)
	2200	58.3	(18.2)	56.8	(16.4)	54.8	(20.2)	53.1	(17.7)

[a]Average flow rate in both lanes in excess of 2,000 vph.

1 mph = 1.61 km/h; 1 mph^2 = 2.60 km/h^2

speed decreased significantly in all of the data collection periods (t-test, $p > 0.99$). Examination of the data in Table 4 also shows that the barrier had a similar effect on vehicular speeds in all three alignment conditions and under all traffic volume conditions. (The one exception to this, the speed reduction in the right-hand curve at 8:00 a.m. is discussed in the next section.) Finally Table 4 shows no discernible trends in the change in speed variance as a result of the barrier. This information taken together indicates that while drivers are no doubt aware of the construction activity as evidenced by the average speed reductions, both lanes were affected equally and the influence was small under the conditions examined.

Lane Distribution and Capacity

It was assumed that the presence of the barrier and the consequent reduction in the median lane width would present somewhat of an uncomfortable feeling to motorists using that lane. It was reasonable, therefore, to hypothesize that there would be some observable tendency for motorist to avoid using the median lane during construction. This hypothesis was examined by analyzing the distribution of traffic between the two lanes before and after the barrier was in place.

As expected, the distribution of traffic between the lanes changed with traffic volume. Figure 11 shows that at low traffic volumes, drivers exhibited a definite tendency to stay out of the median lane with the barrier present. As the volume increased, however, a larger percentage of motorists elected the left lane, no doubt due to its higher speed even with the barrier present. (See Table 5 for average flow rates.) Figure 11 also shows that there was a larger percentage of vehicles in the median lane at site #1 than at sites #2 and 3. This finding suggest that motorist feel relatively more comfortable when traveling immediately adjacent to the barrier in tangent sections than in curved sections. All of the above effects were also noted for larger vehicles (i.e., all vehicles except passenger cars and small, single-unit trucks); however the small sample size (i.e., 2% to 3%) makes any conclusions highly tentative.

Roughly 2% to 4% of the vehicles were identified as straddling the centerline or changing lanes. While the sample size was too small to allow any conclusive statements, these vehicles typically were traveling 0.5 mph (0.8 km/h) faster and had a slightly lower speed variance than all other vehicles. The presence of the barrier had no effect on the number or speed characteristics of these vehicles.

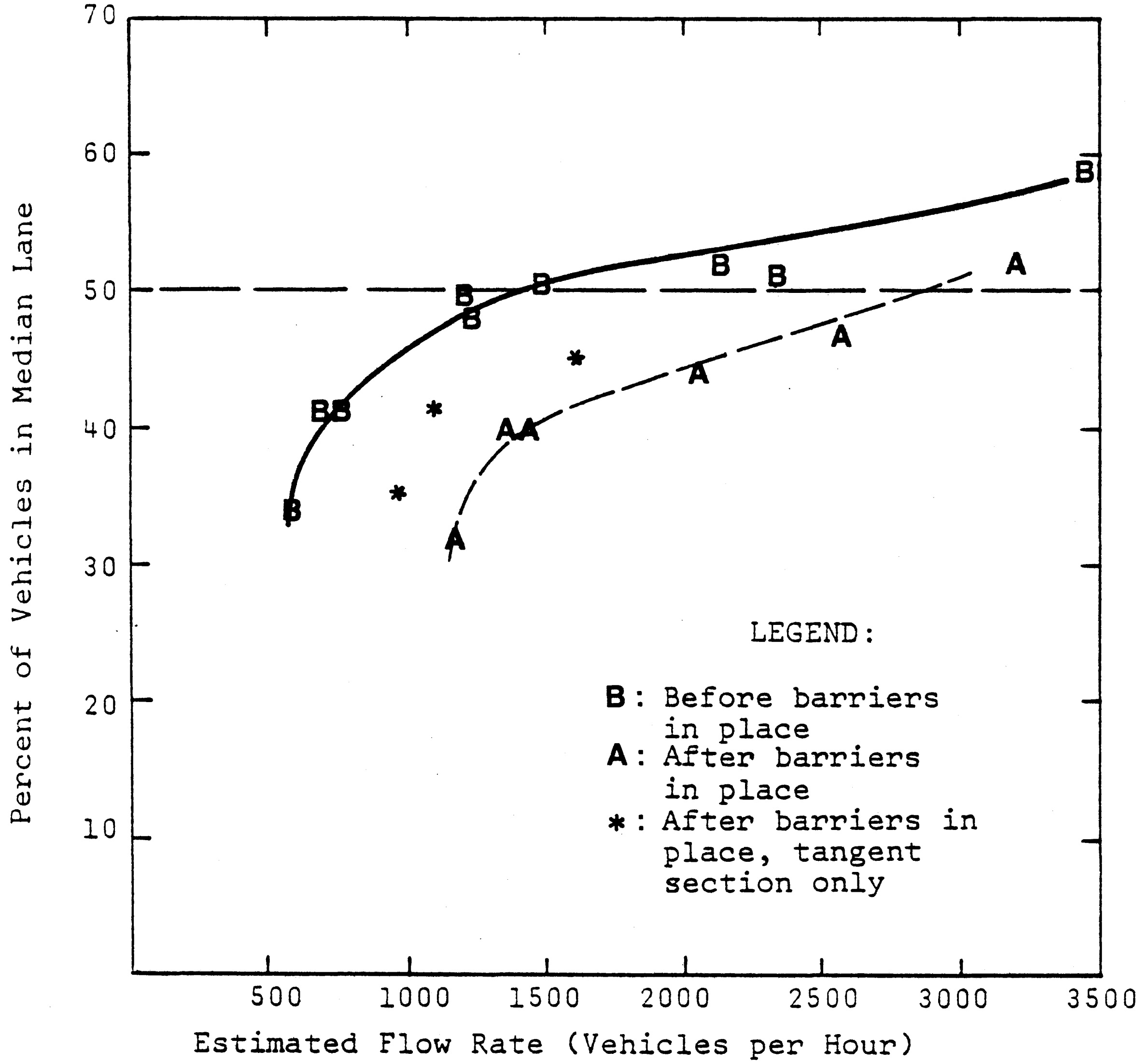


Figure 11. Lane Distribution.

Table 5

Average Flow Rates

Site	Time (Hr.)	Average Flow Rate (vph.)	
		Without Barriers	With Barriers
#1 Tangent	0800	1,212	1,062
	1100	1,223	1,609
	2200	659	924
#2 Right-Hand Curve	0800	3,396	3,173
	1600	2,291	2,560
	2200	543	1,171
#3 Left-Hand Curve	0800	1,475	1,416
	1200	2,125	2,036
	2200	731	1,381

Data were not available to allow a complete assessment of the impact of the barrier presence on the capacity of the roadway. Nevertheless the following is noteworthy. Without the barrier present an average flow rate of roughly 3,400 vehicles per hour (vph) could be maintained without a reduction of speed in either lane. (Average speeds of 57 and 55 mph [92 and 86 km/h] were maintained in the median and shoulder lanes, respectively; see Tables 4 and 5, site #2, right-hand curve, 8:00 a.m.) While speeds were typically 2 mph (3.2 km/h) lower in both lanes with the barrier in place, the speeds were 6-7 mph (10 km/h) lower in both lanes when the average flow rate reached roughly 3,200 vph (again see Tables 4 and 5, site #2, 8:00 a.m.). This finding suggests that the capacity of the roadway with the barrier in place was being approached at 3,200 vph. This observation is supported by data from the Highway Capacity Manual,[19] which suggest that the capacity under these conditions would be reduced to roughly 3,450 vph (86% of an assumed previous capacity of 4,000 vph).

Lateral Placement

This examination was concerned with the analysis of the lateral position of the vehicles with and without the barriers as a function of roadway alignment, traffic volume, and lighting conditions. The physical characteristics of the roadway which have a bearing on the analysis are as follows. In all of the sites examined, the existing centerline was left in place in anticipation of the tracking problems vehicles would have with the concrete centerline joint if the centerline was shifted. In addition, before construction, standard center- and edgelines were in use. No edgeline was placed next to the barrier after it was installed, however, standard barrier delineators (reflectors and barricade warning lights) were utilized throughout the project.

The lateral placement measurements for all three sites are summarized in Table 6. In all cases lateral placements were measured from the outside wheel of the vehicle to the edge of pavement or to the bottom of the barrier as shown in Figure 12.

Before construction the lateral placement in the shoulder lane averaged 3.3 ft. (1.0 m) with a relatively large average variance of 1.40 ft.^{2} (0.13 m^2). Before construction the larger shoulder lane lateral placements were observed at night and at site #3;the smaller lateral placements were observed at site #2 and during periods of high volume (i.e., flow rates greater than 2,000 vph). During construction, the average lateral placement in the shoulder lane decreased an average 0.6 ft. (0.2 m) to an average of 2.7 ft. (0.82 m). However, as in the before construction situation, the larger lateral placements were observed at night and at site #3 and the smaller lateral placements at site #2 and during periods of high volume. These findings suggest that while the barrier did result in a shift of traffic to the right (i.e., away from the median lane) it did not mask the natural tendency of the shoulder lane vehicles to (1) "cut the corners" in both the curved sections, (2) travel closer to the centerline at night, and (3) stay further to their side of the roadway during peak volume periods. While all of the lateral placement reductions were significant (t-test, $p > 0.99$) they were greatest at night (0.75 ft. [0.23 m])and least in the tangent section (0.48 ft. [0.15 m]). Table 6 also shows that the lateral placement variance changed very little after the placement of the barriers. This finding suggests that while motorists in the shoulder lane were no doubt keenly aware of the shift in the median lane vehicles, they did not feel unduly cramped.

Both before and during construction the average lateral placement in the median lane was 2.9 ft. (0.88 m). As in the shoulder lane, there was still a tendency for motorists to "cut the corner" at site #3; however, this phenomenon was less pronounced with the barrier in place. There was no consistent corner-cutting at site #2 with or without the barrier. At site #1 the motorist actually drove slightly closer to the barrier than to the edge of pavement without the barrier in place.

The most dramatic evidence of driver reaction to the presence of the barrier was the large and consistent reduction in the lateral placement variance in the median lane from an average of 1.30 ft.^{2} to 0.73 ft.^{2} (0.12 m^2 to 0.07 m^2). This reduction in the variance indicated that during construction motorists were paying much more attention to their lane position and, therefore, their steering tasks.

Table 6

Lateral Placement Summary

Site	Time (Hr.)	Mean Lateral Placement in Feet (Variance in Ft.^{2})			
		Median Lane		Shoulder Lane	
		Without Barrier[a]	With Barrier[b]	Without Barrier[a]	With Barrier[a]
#1 Tangent	0800	3.04 (1.18)	2.97 (0.59)	3.10 (1.51)	2.91 (1.43)
	1200	3.20 (1.52)	2.95 (0.60)	3.21 (1.34)	2.81 (1.31)
	2200	3.03 (1.50)	2.90 (0.64)	4.15 (1.52)	3.29 (1.34)
#2 Right-Hand Curve	0800[c]	2.87 (0.81)	2.90 (0.56)	2.89 (1.14)	2.27 (1.16)
	1600[c]	2.95 (1.16)	3.22 (0.88)	2.85 (1.32)	2.23 (1.39)
	2200	3.35 (1.44)	1.08 (1.06)	3.81 (1.54)	3.10 (1.29)
#3 Left-Hand Curve	0800	2.56 (1.21)	2.90 (0.94)	3.46 (1.25)	2.91 (1.65)
	1200	2.40 (1.15)	2.97 (0.71)	3.53 (1.31)	2.84 (1.50)
	2200	2.51 (1.42)	2.52 (0.70)	4.34 (1.50)	3.65 (1.63)

[a]Measured to edge of pavement

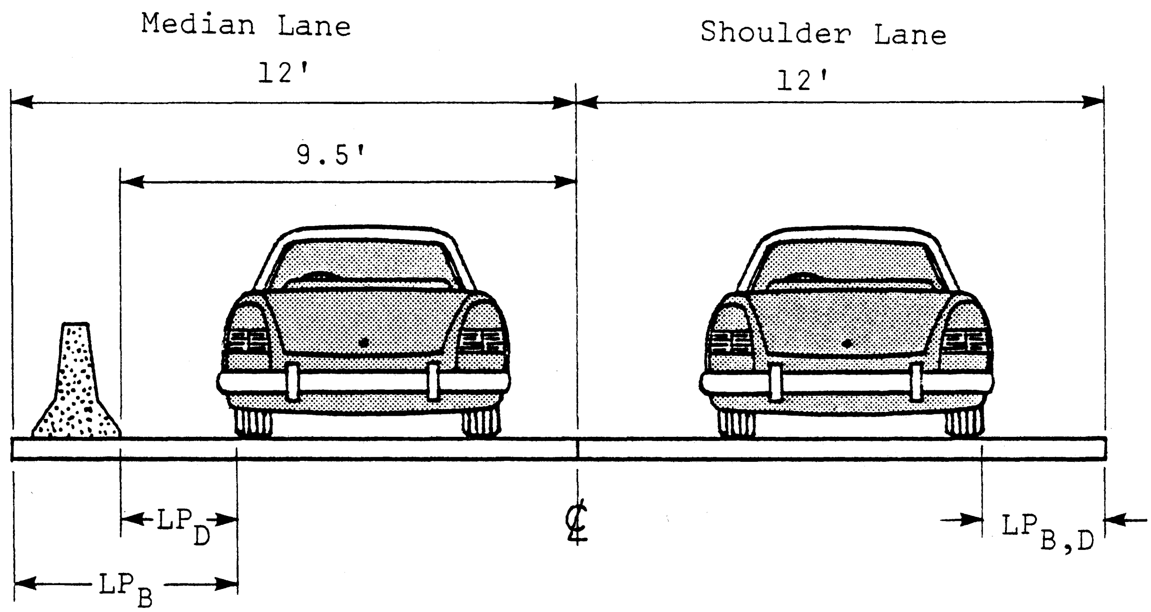
[b]Measured to bottom of barrier

[c]Average flow rate in both lanes in excess of 2,000 vph.

1' = 0.305 m

1979

1980



LP_B = Lateral Placement Before Construction

LP_D = Lateral Placement During Construction

Figure 12. Lateral placement measurements.
(1' = 0.305 m)

In the analyses discussed thus far, the lanes were examined separately without regard to the specific interactions that might exist between them at particular locations or times. In the initial attempt to examine this interaction, the lateral placements of individual vehicles were examined as a function of the position of vehicles in the adjacent lane. This approach revealed no significant relationships, except that in general individual vehicles were relatively unaffected by the presence of an adjacent vehicle. This finding may be partially explained by the typical speed difference between the two lanes.

In an alternate approach, the average lateral spacing between the vehicles was examined (see Figure 13). However, rather than considering the lateral spacing between individual vehicles, the average lateral spacing was defined in terms of the average lateral placements of the adjacent traffic streams. For this analysis a typical vehicle was assumed to be 6.5 ft. (2.0 m) wide, including a 3-in. (76-mm) overhang at each wheel. While the sizes of individual vehicles varied substantially, this assumption was convenient for comparative purposes.

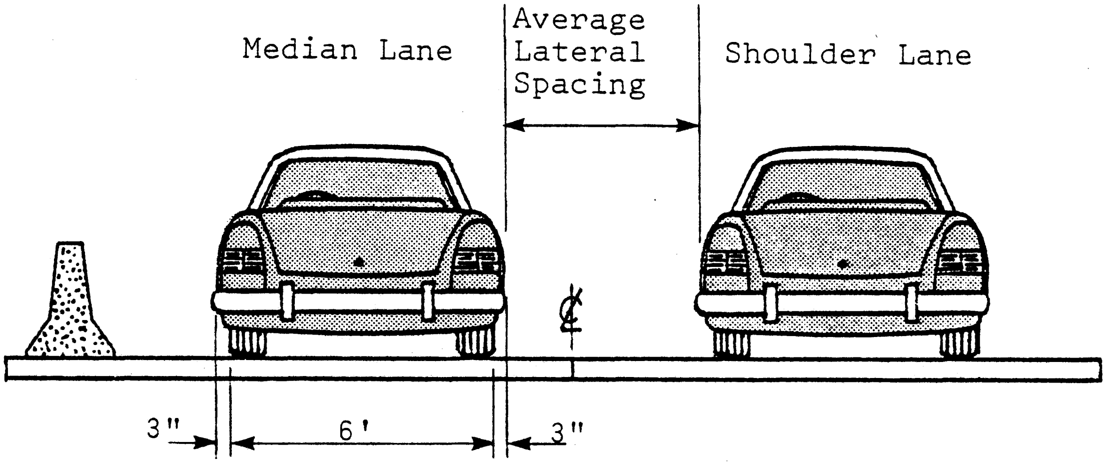


Figure 13. Average lateral spacing.
(1' = 0.305 m)

As shown in Table 7, the average lateral spacing between the traffic streams varied from a high of 5.74 ft. (1.75 m) without the barrier to a low of 2.81 ft. (0.86 m) with the barrier. The unusually low spacings at night (both with and without the barrier), however, were deleted from further analysis due to the characteristically low volume during these periods. With the night data deleted, the overall average lateral spacing was 5.49 ft. (1.67 m) before construction and 3.35 ft. (1.02 m) with the barriers in place. Thus before construction, median lane vehicles were on the average of 2.84 ft. (0.87 m) from the edge of the pavement and 5.49 ft. (1.67 m) from the shoulder lane traffic. During construction, however, the median lane vehicles were positioned an average of 2.98 ft. (0.91 m) from the barrier and 3.35 ft. (1.02 m) from the shoulder lane traffic. Clearly, then, motorists in the barrier lane were willing to travel substantially closer to the shoulder lane traffic in order to maintain an acceptable distance from the barrier. It is noteworthy that the average decrease in lateral spacing when the barriers were installed was 2.14 ft. (0.65 m),

1982

roughly 86% of the 2.5 ft. (0.76 m) of width removed from the median lane.

Also shown in Table 7, the largest lateral spacings were at site #2, the right-hand curve section. From the data presented earlier this is seen to be the result of the corner cutting in the shoulder lane. The most pronounced decrease in lateral spacing was at site #3, the left-hand curve section. This was due primarily to the tendency for the median lane vehicles to cut the corner less in this situation when the barrier was in place. The shoulder lane vehicles cut the corner the same amount with and without the barrier. Table 7 also shows the tendency for larger lateral spacings during periods of high volume.

Table 7

Lateral Spacing Between Traffic Streams

Site	Time (Hr.)	Average Lateral Spacing Between Traffic Streams, Ft.[a]		
		Without Barrier	With Barrier	Change
#1 Tangent	0800	5.36	3.12	-2.24
	1200	5.09	3.24	-1.85
	2200	4.32	2.81	-1.15
#2 Right-Hand Curve	0800[b]	5.74	3.83	-1.91
	1600[b]	5.70	3.55	-2.15
	2200	4.34	2.82	-1.52
#3 Left-Hand Curve	0800	5.48	3.19	-2.29
	1200[b]	5.57	3.19	-2.38
	2200	4.65	2.83	-1.82

[a]Assumes a typical vehicle to be 6.5 ft. wide with a 3 in. overhang at each wheel.

[b]Average flow rate in both lanes in excess of 2,000 vph.

1 ft. = 0.305 m.

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