Use of Freeway Shoulders to Increase Capacity

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The Texas State Department of Highways and Public Transportation approved for testing the concept of increasing roadway capacity on urban freeways by restriping the main-line pavement to create narrower lane widths and encroaching on the shoulder to create additional lanes for travel. Two sections of the US-59 Southwest Freeway in Houston were selected for study. The effectiveness of reconfiguring the main lanes was examined from the following aspects: operational characteristics of peak-period flow, driver acceptance of use of the shoulder lane, accident experience, benefit-cost analysis, and design and maintenance requirements. Expected improvements in operations during peak periods as a result of increased capacity were achieved. One section did not reach the anticipated level of improvement because of low driver use of the shoulder lane, and an analysis determined the need for a change in the length of that section. Accident experience was significantly reduced as a result of the modifications, and the benefit-cost analysis was extremely favorable to this type of low-cost improvement. The results of the study support the application of the use of shoulder and narrow freeway lanes for travel through bottleneck sections of urban freeways.

Travel demands on urban freeways continue to increase, and state highway departments are unable to build new facilities fast enough to prevent the development and spread of traffic congestion. Techniques that reduce or control travel demand—such as ramp control, priority operations for high-occupancy vehicles, and modal shifts—are being developed and implemented, but demand continues to increase. Low-cost, temporary measures to increase the capacity of urban freeway systems are needed.

Texas, like most states, has programs to identify and eliminate bottlenecks on urban freeways by widening bridges and pavements, relocating ramps, constructing continuous frontage roads, and eliminating geometric features that reduce capacity. These improvement programs will be accelerated as time and money permit, but the type of improvement discussed in this paper is designed to solve or alleviate capacity problems immediately and at low cost. California is conducting a similar program (1, 2, 3, 4), and a recent state-of-the-art report suggests using shoulders on freeways for travel (5). This project in Houston, one of the first to be undertaken by the Texas State Department of Highways and Public Transportation (SDHPT), has unique design and traffic requirements that contribute to knowledge about freeway operations and design.

STUDY SITE

The Southwest Freeway (US-59) in Houston is a radial freeway that varies in design from 6 to 10 lanes. At the interchange of the I-610 Freeway, average daily traffic (ADT) on both intersecting freeways exceeds 200 000 vehicles, and traffic demand immediately adjacent to the interchange exceeds the capacity for several hours of the day. Major reconstruction will be necessary to relieve the congestion, but temporary relief was provided to this section of US-59 in 1976 when the SDHPT designed and implemented a reconfigured cross section for the freeway to provide another lane for travel by narrowing the existing main lanes and encroaching on the emergency shoulder. The added lane was opened on May 1, 1976, and accommodated travel 24 h/d. Emergency parking areas are provided on both sides of the roadway except on bridge structures where the right shoulder has been totally preempted for travel.

The study site on the southbound lanes of US-59 is divided into the following two sections by the directional interchange with I-610 (Figure 1):

1. Section 1 (Weslayan to I-610)—The section is 1.9 km (1.2 miles) long with a cross section before restriping of 3.05 × 14.6 × 3.05 m (10 × 48 × 10 ft) made up of four 3.6-m (12-ft) concrete lanes and two 3.05-m (10-ft) asphalt concrete shoulders. The cross section was restriped to 3.05 × 16 × 1.7 m (10 × 52.5 × 5.5 ft) to make five 3.2-m (10.5-ft) lanes, a 3.05-m (10-ft) half median, and a 1.7-m (5.5-ft) right shoulder (Figure 2). The right shoulder was eliminated at the two bridges over the railroad and New Castle intersection.
2. Section 2 (I-610 to Westpark)—The section is 3.06 km (1.9 miles) long with a cross section before restriping of 3.05 × 14.6 × 3.05 m (10 × 48 × 10 ft) made up of four 3.6-m (12-ft) concrete lanes and two 3.05-m (10-ft) asphalt concrete lanes from I-610 to Chimney Rock. At Chimney Rock the cross section reduces to 3.05 × 10.97 × 3.05 m (10 × 36 × 10 ft) by dropping a lane and carrying three 3.6-m (12-ft) lanes from Chimney Rock to Westpark. The cross sections were restriped to 3.05 × 16 × 1.7 m (10 × 52.5 × 5.5 ft) and 3.05 × 12.8 × 1.2 m (10 × 42 × 4 ft) respectively (Figures 2 and 3) to create a 3.05-m (10-ft) half median, five 3.2-m (10.5-ft) lanes, and a 1.7-m (5.5-ft) right shoulder upstream of Chimney Rock and four 3.2-m (10.5-ft) lanes and a 1.2-m (4-ft) right shoulder downstream. The right shoulder was eliminated at the bridges over Rice Boulevard and Chimney Rock.

Emergency parking can be accommodated on the narrow right shoulder along sections 1 and 2 by encroaching on the turf area of the outer separation.

RESULTS

Operational Characteristics

Section 1

Section 1 is the last bottleneck upstream of the I-610 interchange. Traffic demand for this section comes from the four main lanes and two high-volume entrance ramps at the Edloe and Weslayan interchanges. The freeway lanes are congested upstream from the New Castle exit ramp for a distance of more than 3.2 km (2 miles), and ramp queues at Edloe and Weslayan often exceed 100 vehicles.

The capacity of the bottleneck is approximately 7600 vehicles/h, but peak-hour flow rates of 7800 vehicles/h were observed as the traffic occasionally encroached on the shoulder upstream of the New Castle exit ramp.

After the conversion from four to five lanes of travel, peak-hour volume through the bottleneck was unchanged, and the total number of vehicles in the 2-h peak increased by only 3 percent, as given below:

Condition	Peak Hour	2-h Peak
Before restriping	7870	14 180
After restriping	7830	14 600

Figure 1. Study sections 1 and 2 of southbound US-59, Southwest Freeway, in Houston.

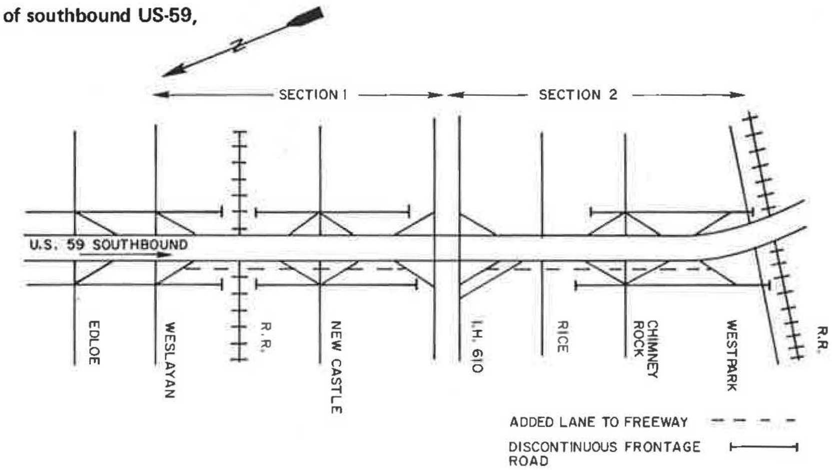
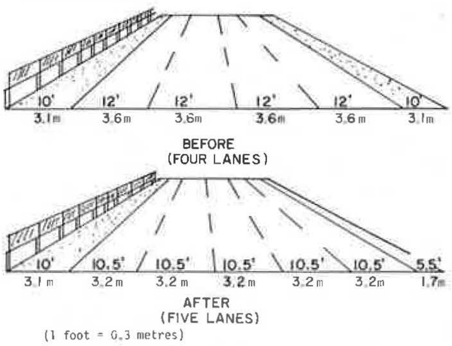
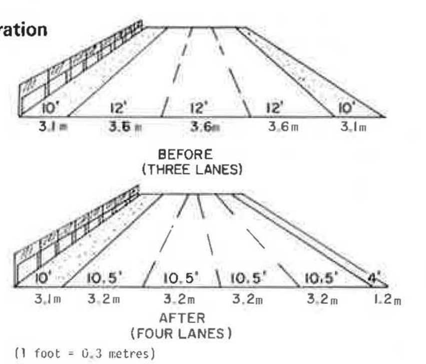


Figure 2. Reconfiguration of cross section from four to five lanes.



(1 foot = 0.3 metres)
(1 metre = 3.3 feet)

Figure 3. Reconfiguration of cross section from three to four lanes.



(1 foot = 0.3 metres)
(1 metre = 3.3 feet)

Lane use indicated that traffic did not use the added lane effectively enough to increase flow rates through the bottleneck section. The level of service was improved within the section, but total delay was not significantly reduced. The bottleneck was shifted approximately 100 m (330 ft) upstream of the merge point of the Weslayan entrance ramp.

Section 2

The Westpark overpass has a geometric design that would usually result in a bottleneck: horizontal and vertical curvature, no shoulders, and discontinuous frontage roads. But the volumes on upstream ramps have established the bottleneck section between the Chimney Rock entrance and the Westpark exit ramps. High traffic demand is maintained at this bottleneck by the high volumes that enter the section from the main lanes and the I-610 connection ramps upstream of the lane drop at Chimney Rock. Heavy congestion and queuing are maintained throughout the peak period.

The capacity of the bottleneck was 5800 vehicles/h, but peak-hour flows of 6000 vehicles/h were observed as the Westpark exiting traffic encroached on the shoulder.

In contrast to section 1, the addition of one lane for travel from the I-610 interchange had a significant impact on traffic volumes (Figure 4). The peak-hour volumes and throughput of the section increased, and the bottleneck shifted downstream to the Westpark overpass:

	Section 2 Bottleneck		
Item	Before Restriping	After Restriping	Increase (%)
Vehicles per peak hour	5 800	7 100	22.5
Vehicles per 2-h peak	11 600	13 800	19.0

	Section 2 Throughput		
Item	Before Restriping	After Restriping	Increase (%)
Vehicles per peak hour	7 250	8 400	15.9
Vehicles per 2-h peak	14 450	16 400	13.5
Vehicle kilometers per peak hour	16 130	19 430	20.4
Vehicle kilometers per 2-h peak	32 770	37 900	15.6

Some of the increase in vehicle kilometers is the result of the improvement in traffic flow through this section. Traffic that used the Chimney Rock exit and frontage road to bypass freeway congestion now remains on the freeway. This results in a reduction of traffic demand on the congested Chimney Rock-Frontage Road intersection.

The high flow rates and volumes through the Westpark overpass bottleneck (12 000 vehicles/h for 2 h) were not expected (Figure 5). However, several counts have confirmed these results, and the following factors are offered in explanation:

1. Truck volumes are very low (1.3 percent).
2. Volumes of small vehicles are high (20 percent).
3. Speeds of vehicles approaching and leaving the overpass are maintained at a high level throughout the peak period because of high-volume, high-speed exit ramps on both sides of the overpass.

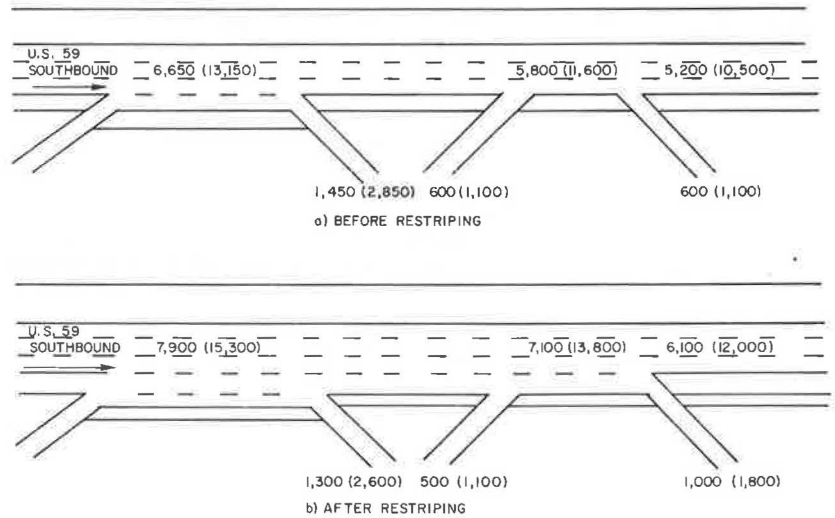


Figure 4. Result of adding one lane to section 2: 1- and 2-h traffic volumes in p.m. peak period.

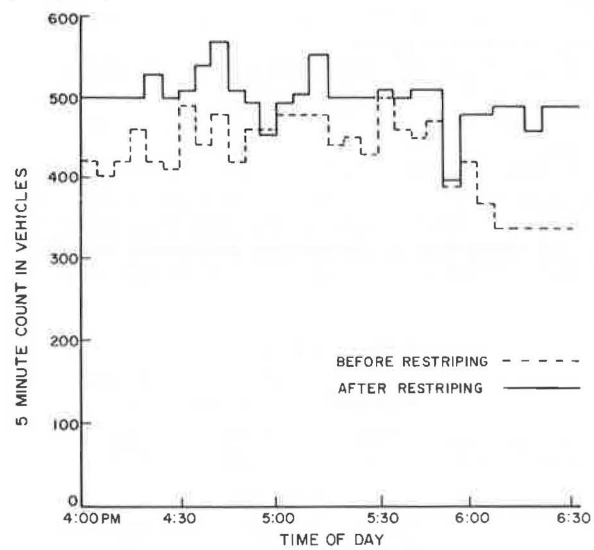


Figure 5. Traffic volume on US-59 southbound at Westpark in p.m. peak period.

4. The traffic volume that uses the added lane upstream of the Westpark exit is high.

5. Demand for the three through lanes at the Westpark exit ramp is high throughout the peak period. Some vehicles merge into the through lanes from the added lane at or near the termination of the lane at the Westpark exit ramp.

6. Although the overpass has a 5 percent grade and is on a 3° horizontal curve, sight distance, lateral clearances, and design features are adequate for high-volume, high-speed operation.

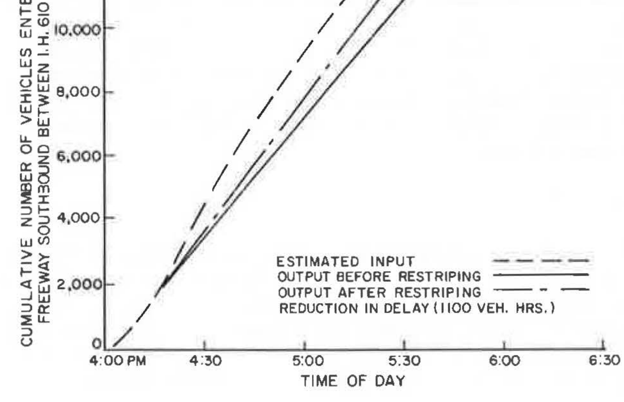
7. Driving performance may be more efficient when vehicles enter a section of freeway that has lanes of standard width after traveling several minutes in a section that has narrow lanes.

8. The population of motorists who use this freeway could be classified as aggressive drivers who tend to overdrive traffic conditions. This results in better operational efficiency but also an accident rate higher than that of other freeways used by less aggressive motorists.

To determine the effects of added capacity on traffic delays, traffic demand for these sections over the 2-h period was assumed to be constant before and after restriping. The demand curve is represented by the input curve shown in Figure 6. The output curve is the sum of the volumes at the Westpark overpass and the Westpark and Chimney Rock exit ramps. The output curve before restriping indicates traffic congestion between 4:20 and 6:10 p.m. Output after restriping causes the length of the congestion period to be reduced by 20 min to 5:50 p.m. and the total amount of delay to be reduced by 1100 vehicle-h/d.

Although the demand curve was assumed to be unchanged to measure the effects on traffic delays, traffic volumes after 1 year of operation have actually increased. Peak-period demand increased by 14 percent whereas ADT increased by 8.7 percent. The increase in peak-period traffic is especially significant when it is compared with the 2 percent increase experienced the year before restriping. As a result of this increase in traffic volumes, the length of the congestion period has

Figure 6. Input-output flow rates for US-59 southbound between I-610 and Westpark overpass in p.m. peak period.



stayed the same or increased slightly, but the section accommodates 1950 more vehicles during the 2-h peak period.

The level of service has been improved, particularly for exit ramp traffic. However, traffic demand for the section has increased and still exceeds the capacity of the bottleneck, and congestion develops throughout the peak period.

Driver Acceptance of Use of Shoulder Lane

The key to a successful freeway reconfiguration is the use of the added lane. In this project, the lane was composed partly of the right shoulder and partly of the main-line pavement. Several factors against its use are (a) the texture and contrast of the two pavement materials, (b) the restrictive lateral clearance on the approaches to bridges, and (c) the condition of the riding surface. Factors in favor of its use are (a) the high percentage of local traffic, particularly during the peak periods; and (b) the high volumes of traffic throughout the day. To test the effectiveness of low-cost design, no major construction or maintenance activities were conducted to minimize the adverse factors during the first year of the project. If the concept proved to be successful, a more permanent design was to be implemented.

Section 1

The number of vehicles in 2-h and peak-hour traffic volumes for the various traffic movements shown in Figure 7 are given below:

Movement	Peak Hour	2-h Peak
$R_1 + R_2$	450	770
R_3	140	320
F_1	970	1700
L_1	470	710
L_2	640	1310

No special signing was used to designate the shoulder lane for travel. Lane arrows were used downstream of the Weslayan entrance ramp to encourage full use by entering traffic, but only 30 percent remained in the lane (see movement R_3 in Figure 7). The contrast between the concrete acceleration lane taper and the asphalt concrete shoulder appeared to guide the entering traffic out of the shoulder lane. Peak-period use by main-line traffic (F_1) was high, but the traffic entered the lane too late to improve upstream flow rates. This movement will be improved by extending the lane upstream to the next entrance ramp (Edloe), which will enable most of the 1700 vehicles that originate upstream of the Weslayan ramp and use the shoulder lane (movement F_1) to weave into that lane before they reach the bottleneck section.

The lane is available for 24 h, but it is used primarily during the peak period when all other lanes become congested. ADT in the lane is 8155 vehicles, approximately 25 percent of which uses the lane during the peak period (Figure 8).

Section 2

Use of the shoulder lane at the second study site was much greater. Although the lane was "black and white" pavement, the riding surface and the lateral clearances were better than those of section 1. The high exiting volumes at the Chimney Rock and Westpark exits account for much of the success of this lane. ADT is 13 445 vehicles, approximately 20 percent of which uses the lane during the peak period (Figure 8). The greater use in the off-peak period is a measure of the acceptability of the design in comparison to that of section 1.

Accident Experience

Total accident experience for sections 1 and 2 in the 2 years before restriping is compared below with accident experience for 1 year after restriping (1 km = 0.62 mile):

Figure 7. Peak-period use of shoulder lane: section 1 of Southwest Freeway.

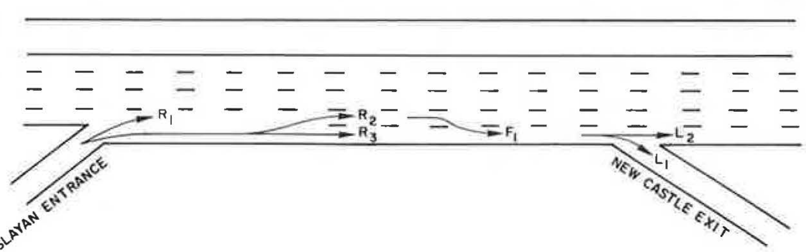
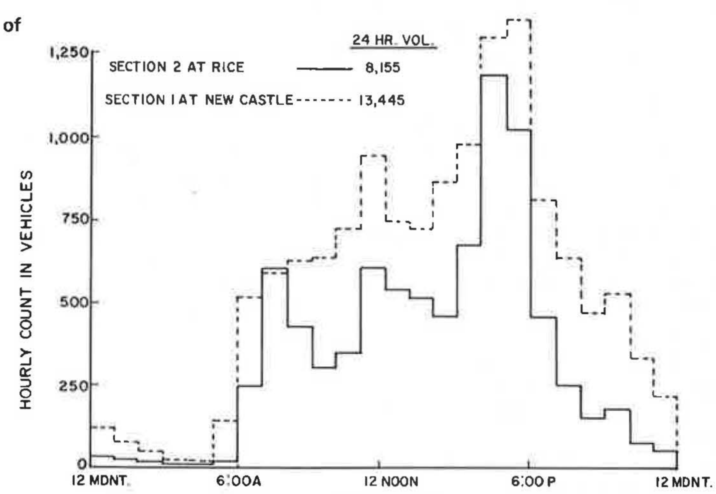


Figure 8. Use of shoulder lane over 24-h period: sections 1 and 2 of Southwest Freeway.



Item	1	2	Total
Accidents per year			
Number before restriping (2-year average)	128	205	333
Number after restriping (1-year average)	120	196	316
Percentage decrease	6	4	5
Accidents/100 million vehicle-km			
Number before restriping	207	229	220
Number after restriping	173	197	187
Percentage decrease	16	14	15

These accident frequencies and rates indicate that section 1 had the better accident experience for the 24-h period. After the shoulder lane was added, accident rates for both sections decreased significantly when they were tested at the 95 percent level of confidence for the Poisson comparison of means test (6) (figures for percentage decrease in accidents/100 million vehicle-km are significant at the 95 percent confidence level for the Poisson test).

Analysis of accident experience during the peak 2-h period when there is the greatest use of the added lane indicates much greater reductions in frequency and rate of accidents for the two sections (1 km = 0.62 mile):

Item	1	2	Total
Accidents per year			
Number before restriping (2-year average)	43	38	81
Number after restriping (1-year average)	22	33	55
Percentage decrease	49	13	32
Accidents/100 million vehicle-km			
Number before restriping	602	370	465
Number after restriping	279	292	287
Percentage decrease	54	21	38

The rate for section 1 and the combined rate for sections 1 and 2 are reduced significantly when they are tested at the 95 percent level of confidence for the Poisson comparison of means test (6) (figures for percentage decrease in accidents/100 million vehicle-km are significant at the 95 percent confidence level for the Poisson test). Although the accident rate for section 2 is reduced by 21 percent, it does not satisfy the test because of the low number of accidents before restriping (38).

The accident rate for section 2 was much lower than that for section 1 before restriping because section 2 had less congestion during the peak period 2 years ago. Travel demands and congestion have greatly increased in section 2 but have remained somewhat constant in section 1. In addition, the small number of accidents varies greatly from year to year.

Benefit-Cost Analysis

The benefits of restriping had not been realized in section 1 at the time this paper was written. It was estimated, however, that the extension of the lane to the Edloe entrance would result in a significant reduction in vehicle delay.

As a result of the added lane, section 2 achieved a 13.5 percent increase in the number of vehicles that exit the section in a 2-h period. The estimated savings in total travel time were calculated to be 1100 vehicle-h/d for 14 600 vehicles with an occupancy rate of 1.3 persons/vehicle. A cost of \$5.51/vehicle-h for private vehicles was used to calculate a savings of \$6061/weekday or \$1 515 250/year [1975 prices taken from Buffington and McFarland (7)].

Fuel savings resulted from a reduction in travel time. Each vehicle saved an average of 4.52 min. This represents a time difference of 9 min at a speed of 32 km/h (20 mph) and 4.48 min at 64 km/h (40 mph) over a distance of 4.83 km (3 miles). Running cost at 32 km/h (20 mph) is \$0.0613/vehicle-km (\$0.0987/vehicle-mile); at 64 km/h (40 mph), it is \$0.04/vehicle-km (\$0.0644/vehicle-mile) or

$$(\$0.0613 - \$0.04)/\text{vehicle-km} (\$0.0987 - \$0.0644) \div \text{vehicle} \times 14\,600 \text{ vehicles} \times 4.83 \text{ km} = \$1502.34 \text{ operating cost savings/d or } \$375\,585/\text{year} \quad (1)$$

Approximately 75 percent of the operating costs are attributed to fuel. Therefore, the number of liters of gasoline conserved each year by the improvement can be estimated as follows (1 L = 0.26 gal):

$$(\$375\,585)(0.75)(\text{L}/\$0.125) = 2\,253\,510 \text{ L} \quad (2)$$

Similar calculations of benefits can be made for noise and air pollution and traffic accidents, but those categories were not included in this analysis. Therefore, total annual benefits are \$1 890 835.

The cost of restriping the lanes was \$38 700. The project required relocating two lighting standards and three roadside warning signs; modifying a metal guard beam section and two curb inlets; removing sections of curb, traffic buttons, and paint; applying asphalt overlay strip to smooth pavement-shoulder transition; stabilizing shoulders; and applying paint stripes. Lane lines were restriped after three months at a cost of \$471, and additional lane markings and lane arrows were added at the Weslayan ramp at a cost of \$157.

Some maintenance was required in the outer separation that had been used as emergency parking areas. Inadequate shoulder strength during wet weather caused the material to rut badly. Costs for this work were absorbed in normal maintenance activities, but the extra expense should be included as an annual cost of maintaining the installation.

The benefit/cost ratio for this project was \$1 890 835/\$39 328 or 48.1. Annual costs to maintain the system have not been calculated but should be considerably less than \$40 000. At some time in the future, however, the shoulders will deteriorate and have to be replaced. If only the shoulders were to be replaced, the estimated cost would be \$275 600 or \$39 245/year. This is calculated for an interest rate of 7 percent and a time period of 10 years by using the uniform series capital recovery calculation.

Design and Maintenance Requirements

Cross sections with uniform lane widths of 3.2 m (10.5 ft) were designed because of the following considerations:

1. The median shoulder width was maintained at 3.05 m (10 ft) because of the small, mountable curb and drainage inlets in the median.
2. A paved right shoulder was desired where it was practical.
3. The volume of large vehicles that used this freeway during peak periods was very low.
4. The minimum desirable width for travel on freeways was considered to be 3.2 m.

The cross sections were changed in a 250-m (820-ft) transition zone. The old stripes and delineator buttons were removed by maintainer blades and sandblasting, and new paint stripes were placed. The paint tended to wear quickly because of vehicle encroachment and accumulation of oil and dirt. New stripes placed after 3 months of operation have worn well, but better delineation by means of new stripes and buttons will be provided after 15 months of operation.

The shoulder lanes have held up well under the increasing volume of traffic. The turf area in the outer separation that has been used for emergency parking has become rutted and requires considerable maintenance. New stabilized shoulders will be provided in those areas. The longitudinal joint between the main-line pavement and the old shoulder pavement has widened and requires maintenance. However, the quality and the safety of the ride over the joint has not been substantially reduced.

CONCLUSIONS

1. Adding a traffic lane in a bottleneck section of a freeway produces benefits in travel time, safety and quality of operation, and the volume of traffic that can be accommodated.
2. Such solutions are generally accepted by the public.
3. The additional capacity in a converted roadway section reduces accident rates and thus offsets any increase in accident potential attributable to narrow lanes and fewer emergency parking areas.
4. Additional capacity can be achieved at low cost by reconfiguring existing roadway and parking pavements. Benefit/cost ratios for these projects are very favorable.
5. Reconfigured roadways require additional maintenance to provide adequate lane delineation, structural integrity of the shoulder lane, and emergency parking areas.

ACKNOWLEDGMENTS

I wish to express my appreciation to Musa J. Misleh of the Houston district of SDHPT for his assistance in collecting the accident data for this study and to Jocille Johnson for her contributions to the manuscript.

This paper discusses one phase of a research project conducted by the Texas Transportation Institute and SDHPT in cooperation with the Federal Highway Administration. The contents reflect my views, and I am responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Publication of this paper sponsored by Committee on Shoulder Design.

Structural Evaluation of PCC Shoulders

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A structural evaluation of portland cement concrete (PCC) shoulders has been conducted. The influence of the major design variables on the behavior of shoulders under load was determined by using a finite element analysis program and data from field surveys of several PCC shoulders. The major design variables studied include slab thickness and tapering, foundation support and loss of support, joint spacing, lane-shoulder tie, shoulder width, and design and condition of the adjacent lane. Results of analytical and field studies show that each of these variables can have a significant effect on the performance of PCC shoulders and also on the performance of the adjacent traffic lane. A minimum slab thickness of 15 cm (6 in) is recommended, but certain design situations—i.e., poor foundation support, need for significant load transfer support at the lane edge, heavy traffic, or a narrow shoulder—require greater thickness. The required thickness should be determined from structural analysis. To achieve the greatest structural benefits for the traffic lane and the shoulder, load transfer efficiency at the longitudinal joint should be greater than about 50 percent. Field studies indicate that this efficiency can be attained by providing tie bars across the longitudinal joint. Shoulder width should be at least 91 to 152 cm (3 to 5 ft) to contribute a significant structural benefit. A shoulder joint spacing of 4.6 m (15 ft) is recommended to minimize joint spalling and blowups and slab cracking. If the shoulder is designed properly, significant improvement in the performance of the traffic lane for both new construction and rehabilitation as well as long-term, low-maintenance performance of the PCC shoulder can be achieved.

Portland cement concrete (PCC) shoulders have been constructed for many years on some urban expressways but for only about the past 12 years on rural highways. They were first constructed on an experimental basis but have more recently become a part of regular construction. Because no structural design procedure is available, design has been based on engineering judgment and on the performance of a few experimental sec-