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16. Abstract

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THE USE OF FREEWAY SHOULDERS TO INCREASE CAPACITY

by

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Research Report Number 210-2

Evaluation of Urban Freeway Modifications

Research Study Number 2-18-77-210

Sponsored by
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ABSTRACT

Every sector of urban transportation faces the problems of rising costs, limited funds, and depleting resources with which to provide for increasing travel demands. Getting the greatest production out of the existing transportation facilities is the goal of every transportation agency. The Texas State Department of Highways and Public Transportation recently approved for testing the concept of increasing roadway capacity on urban freeways by restriping the mainline pavement with narrower lane widths and encroaching on the shoulder to create one additional lane for travel.

Two modified sections of U.S. 59 Southwest Freeway in Houston were selected for study. Before and after data were collected over a four-year period to determine the effectiveness of reconfiguring the surface geometrics of freeways.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. 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.

Key Words: Narrow lanes, travel on freeway shoulders, freeway accident analysis, freeway operation.

SUMMARY

This report is concerned with the operational efficiency and safety of freeways with surface geometrics that have been modified to provide additional capacity. Every urban area in the country experiences traffic congestion to some extent. When the congestion becomes so extensive and repetitive, measures to increase the capacity or to reduce the demand should be undertaken. However, sufficient funds to make major changes to urban freeways may not be available and in some instances, space may be so limited as to rule out normal expansions in roadway width. One approach that many transportation agencies are considering is the downscoping of design standards to achieve greater capacity at lower cost.

The usual method to accomplish this is to reduce lane widths and to reduce or eliminate the roadway shoulders and create an additional lane for travel. The modification is considered to be temporary until sufficient funding is available for major reconstruction or until alternative modes or routes of travel are available to reduce the traffic demand.

The application of reduced standards should be undertaken with care to achieve the expected operational improvements without undue hazard to the public. This study evaluated two typical freeway sections that were modified to determine the operational effectiveness and safety experience over a four-year period.

The operational improvements in increasing capacity were realized in one of the two sections. The other section required additional length of the modified roadway to achieve the expected usage. The resultant improvement in traffic congestion more than offset the cost of the modifications.

The additional lane formed by the partial shoulder and mainline pavement carried more than 2,000 vheicles during the peak period. The total traffic delay was significantly reduced as a result of the increased traffic flow. Immediately after the implementation, it was estimated that 1,000 vehicle-hours of delay per day were saved.

The principal concern of most transportation agencies was with the safety of the operation when lateral clearances were reduced and emergency parking areas were reduced or eliminated. The experience in the Houston study was that accident rates declined during the two years following the modification for each of the four time periods studied (24 hour, peak periods, daytime, nighttime). The severity of accidents was not significantly changed. The reduction is accident rates occurred while the ADT was increasing at a rate of 11.5 percent annually to reach a volume level of over 200,000 vehicles per day. The accident experience is similar to projects of this type implemented in other sections of the country.

The greatest difficulty experienced in Houston was maintaining the pavement surface and delineation. The shoulders were not designed for travel and required patching and structural maintenance. The lane lines were often moved to an area on the pavement that had oil accumulations. The narrow lanes also encouraged encroachment on the lane lines, requiring greater than normal maintenance.

Nevertheless, the cost to install and maintain the added capacity, $ 38,700, was very low in comparison to the benefits derived by the motoring public.

IMPLEMENTATION STATEMENT

The primary purpose of this research project was to determine if a freeway cross section with narrow lanes and limited shoulders can produce travel benefits with safety. This report concludes that modifications of surface geometrics is an effective and safe way to increase capacity.

Several conditions are offered to agencies considering implementation of this solution: the modified section should be as short as possible; the section should be maintained at a level that will provide good lane delineation and rideability; the modification should be considered as a temporary solution to be returned to normal design standards when funds and conditions warrant; finally, some form of emergency parking should be provided in the modified section, if possible.

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I. INTRODUCTION

Travel demands on urban freeways continue to increase, and state highway departments are unable to build new facilities at a rate to prevent the development and spread of traffic congestion. Techniques that reduce or control travel demands, such as ramp control, priority operations for high occupancy vehicles, and modal shifts, are being developed and implemented, but vehicular demands continue to increase. Low cost, temporary measures to increase the capacity of the urban freeway systems are needed. Texas, like most states, has programs to identify and eliminate bottlenecks on the urban freeways by widening bridges and pavements, relocating ramps, constructing continuous frontage roads, and eliminating capacity reducing geometric features. These betterment programs will be accelerated as time and money permit, but the type of improvement discussed in this report is designed to solve or alleviate capacity problems immediately and at low costs. California is conducting a similar betterment 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 will contribute to the knowledge of freeway operations and design.

STUDY SITE DESCRIPTION

The Southwest Freeway (U.S. 59) in Houston is a radial freeway that varies in design from six to ten lanes. At the interchange of the I.H. 610 Freeway, the growth in traffic has been at an annual rate of 8.5 percent and, the Average Daily Traffic (ADT) on both intersecting freeways in 1978 exceeded 200,000 vehicles. The traffic demand on sections adjacent to the interchange exceeded the capacity for several hours of the day. Major reconstruction to increase capacity will be necessary to relieve the congestion, but temporary relief to this sector of U.S. 59 was provided 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 right shoulder. The added lane was opened on May 1, 1976 and accommodated travel 24 hours per day. Emergency parking areas were provided on both sides of the roadway, except on bridge structures where the right shoulder was preempted totally for travel.

The study site was divided into four sections, two on either side of directional interchange with I.H. 610 (Figure 1).

Section 1: Shepherd to Weslayan

This section is 3.1 km (1.9 miles) long and is adjacent to the modified sections on the downtown end of the freeway. The surface geometrics were not modified, but traffic conditions were affected by the changes in Sections 2 and 3.

Section 2: Weslayan to I.H. 610

This section is 1.9 km (1.2 miles) long with a cross section before restriping of 3.1 m x 14.6 m x 3.1 m, with four 3.6 m (12 ft) concrete lanes, and two 3.1 m (10 ft) asphalt concrete shoulders in both directions. On the outbound (southbound) lanes, the cross section was restriped to 3.1 m x 16 m x 1.7 m (10 ft x 52.5 ft x 5.5 ft), with five 32 m (10.5 ft) lanes, 3.1 m (10 ft) half median and 1.7 m (5.5 ft) right shoulders (Figure 2). The right shoulder was eliminated at the two bridges over the railroad and Newcastle intersection.

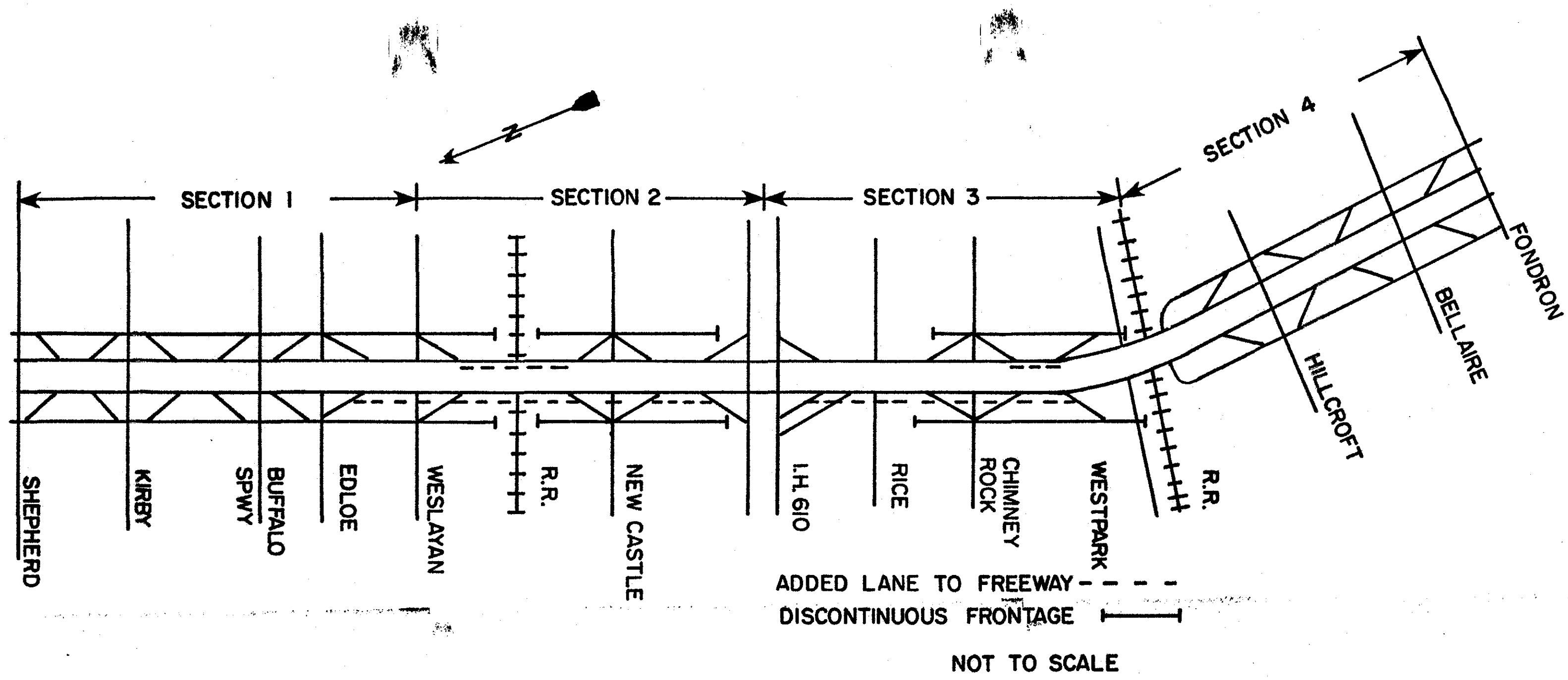
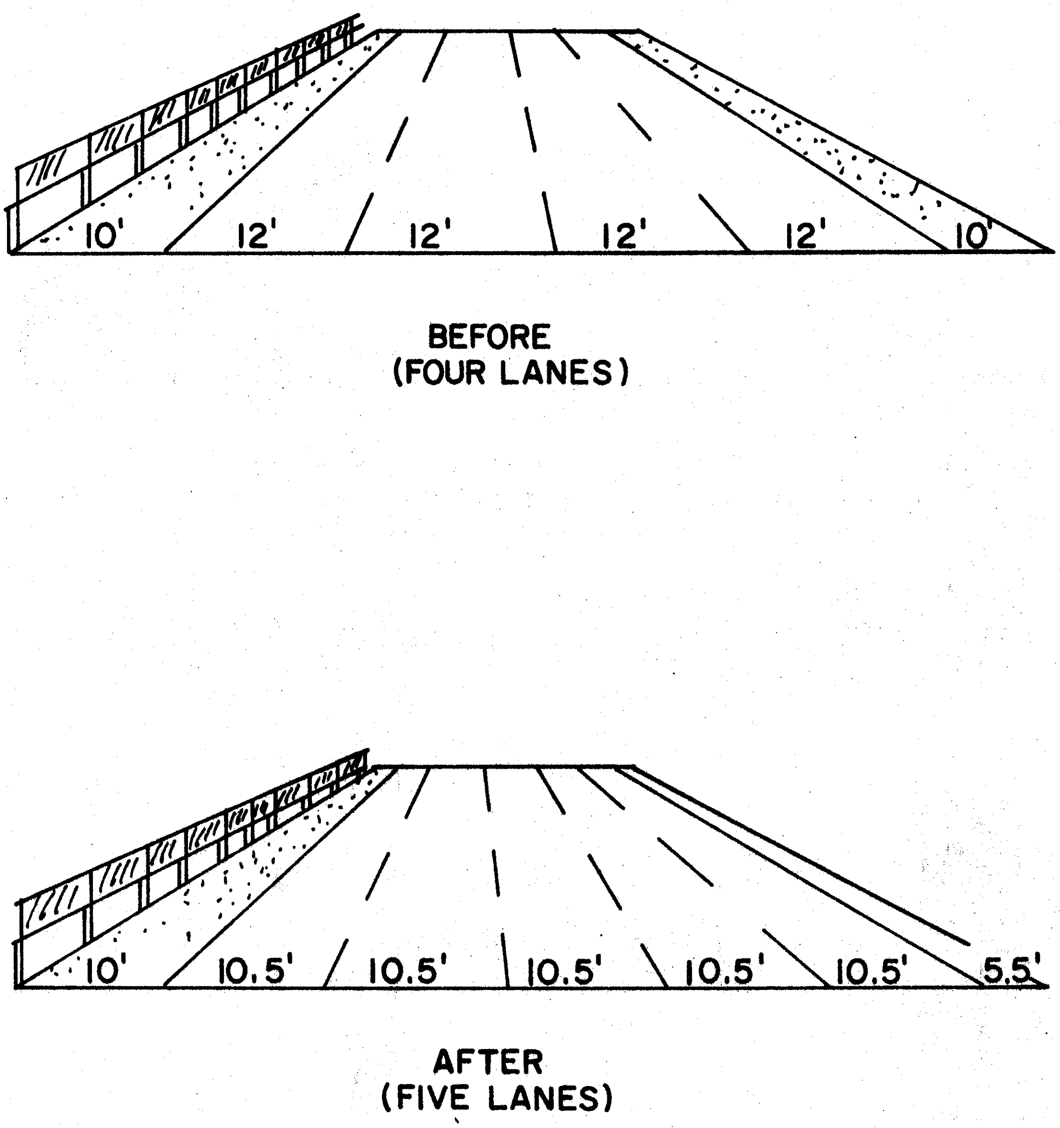


Figure 1. Study Sites
U.S. 59 Southwest Freeway in Houston



(1 foot = 0.3 metres)

Figure 2. Cross Section Reconfiguration
Four Lanes to Five Lanes

On the inbound (northbound) lanes, a minor change was made to the cross section between the Newcastle entrance ramp and the Weslayan exit ramp. The shoulder was converted to a travel lane, the width of the right lane was reduced, but the other lane widths were unchanged.

Section 3: I.H. 610 to Westpark

The section is 3.1 km (1.9 miles) long with a cross section before restriping of 3.1 m x 14.6 m x 3.1 m (10 ft x 48 ft x 10 ft), with four 3.6 m (12 ft) concrete lanes, and two 3.1 m (10 ft) asphalt concrete lanes from I.H. 610 to Chimney Rock in both directions. At Chimney Rock the cross section reduces to 3.1 m x 11.0 m x 3.1 m (10 ft x 36 ft x 10 ft) by dropping a lane and carrying three 3.6 m (12 ft) lanes from Chimney Rock to Westpark.

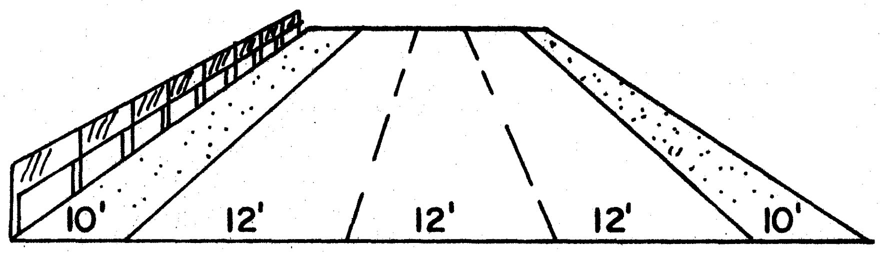
On the outbound (southbound) lanes, the cross sections were restriped to 3.1 m x 16 m x 1.7 m (10 ft x 52.5 ft x 5.5 ft) and 3.1 m x 12.8 m x 1.2 m (10 ft x 42 ft x 4 ft), respectively (Figure 2 and 3), with a 3.1 m (10 ft) half median, five 3.2 m (10.5 ft) lanes, and 1.7 m (5.5 ft) right shoulder, upstream of Chimney Rock and four 3.2 m (10.5 ft) lanes and 1.2 m (4 ft) right shoulder downstream. The right shoulder was eliminated at the bridges over Rice Boulevard and Chimney Rock.

On the inbound (northbound) lanes, a minor change was made to the cross section between the Westpark entrance ramp and the Chimney Rock exit ramp. The shoulder was converted to a travel lane, and the width of the right mainline lane was reduced. All other lane widths were unchanged.

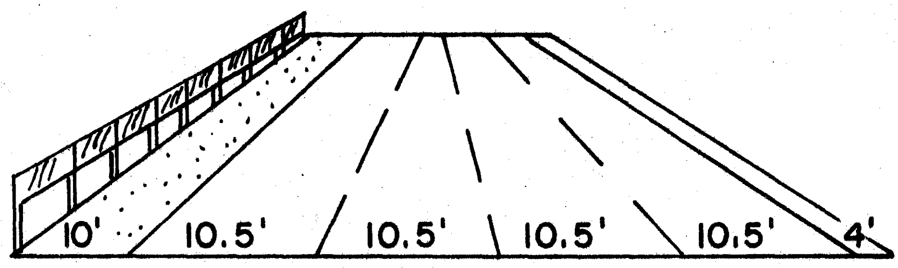
In Sections 2 and 3, emergency parking was accommodated on the narrow right shoulder by encroaching on the turf area of the outer separation.

Section 4: Westpark to Fondren

This section is 3.7 km (2.3 miles) long and is adjacent to the modified sections on the suburban end of the freeway. The surface geometrics were not changed in this section.



BEFORE
(THREE LANES)



AFTER
(FOUR LANES)

(1 foot = 0.3 metres)

Figure 3. Cross Section Reconfiguration
Three Lanes to Four Lanes

II. RESULTS

Although modifications were made in both directions of the freeway, the operational analysis was concentrated on the major modifications on the outbound (southbound) directions, but the safety analysis was conducted on both directions.

OPERATIONAL CHARACTERISTICS

Study Section 2: Weslayan to I.H. 610 - Southbound

This section is the last bottleneck upstream of the I.H. 610 interchange. Traffic demand for this section comes from the four main lanes and two high volume entrance ramps at Edloe and Weslayan interchanges. The freeway lanes normally queue upstream from the Newcastle exit ramp for a distance of 3.2 or more km (2 or more miles), and ramp queues at Edloe and Weslayan often exceed 100 vehicles.

The capacity of the bottleneck was approximately 7,600 VPH, but peak hour flow rates of 7,800 VPH were observed, as the traffic occasionally encroached on the shoulder upstream of the Newcastle exit ramp.

After the conversion from 4 to 5 lanes of travel, the peak hour volume through the bottleneck was unchanged, and the total 2-hour peak period volume increased only 3 percent (Table 1A). An analysis of the lane usage indicated that traffic did not use the added lane in a manner that would increase the flow rates through the bottleneck section.

The level of service was improved within the section, but the total delay was not reduced significantly. The bottleneck was shifted approximately 100 metres upstream of the merge point of the Weslayan entrance ramp.

TABLE 1A

PEAK PERIOD VOLUMES FOR
SECTION 2 SOUTHBOUND BOTTLENECK
AFTER RESTRIPING

	Before Restriping	After Restriping	Percent Change
Vehicles Per Peak Hour	7,870	7,830	0
Vehicles Per 2-Hour Peak	14,180	14,600	+3.0

TABLE 1B

PEAK PERIOD VOLUMES FOR
SECTION 2 SOUTHBOUND BOTTLENECK
AFTER EXTENSION OF ADDED LANE

	After Restriping	After Extension of Restriping	Percent Change
Vehicles Per Peak Hour	7,830	8,280	+5.7
Vehicles Per 2-Hour Peak	14,600	15,170	+3.9

To encourage a more effective use of the added lane, the SDHPT extended the new shoulder lane upstream to the Edloe entrance ramp. This resulted in significant increases of 5.7 percent in peak hour volume and 3.9 percent in the two hour volume (Table 1B). Greater increases would be possible if the capacity of the downstream interchange with I.H. 610 were increased.

Study Section 3: I.H. 610 to Westpark - Southbound

The Westpark overpass has a geometric design that usually would result in a bottleneck; horizontal and vertical curvature; no shoulders; and, discontinuous frontage roads. However, the volumes on upstream ramps established the bottleneck at a location between the Chimney Rock entrance ramp and the Westpark exit ramp. High traffic demand was maintained at this bottleneck by the high volumes entering the section from the main lanes and the I.H. 610 connection ramps, upstream of the lane drop at Chimney Rock. Heavy congestion and queueing were maintained throughout the peak period.

The capacity of the bottleneck was 5,800 VPH, but peak hour flows of 6,000 VPH were observed as the Westpark exiting traffic encroached on the shoulder.

In contrast to Study Section 2, the addition of one lane for travel from the I.H. 610 connections had a significant impact on traffic volumes (Figure 4). The peak hour volumes and throughput of the section increased. The bottleneck was observed to shift downstream to the Westpark overpass (Tables 2 and 3).

The increase in travel was due in part to the improvement in flow through this section. Traffic that used the Chimney Rock exit and frontage road as a bypass of freeway congestion remained on the freeway, thus reducing the traffic demand on the congested intersection at Chimney Rock.

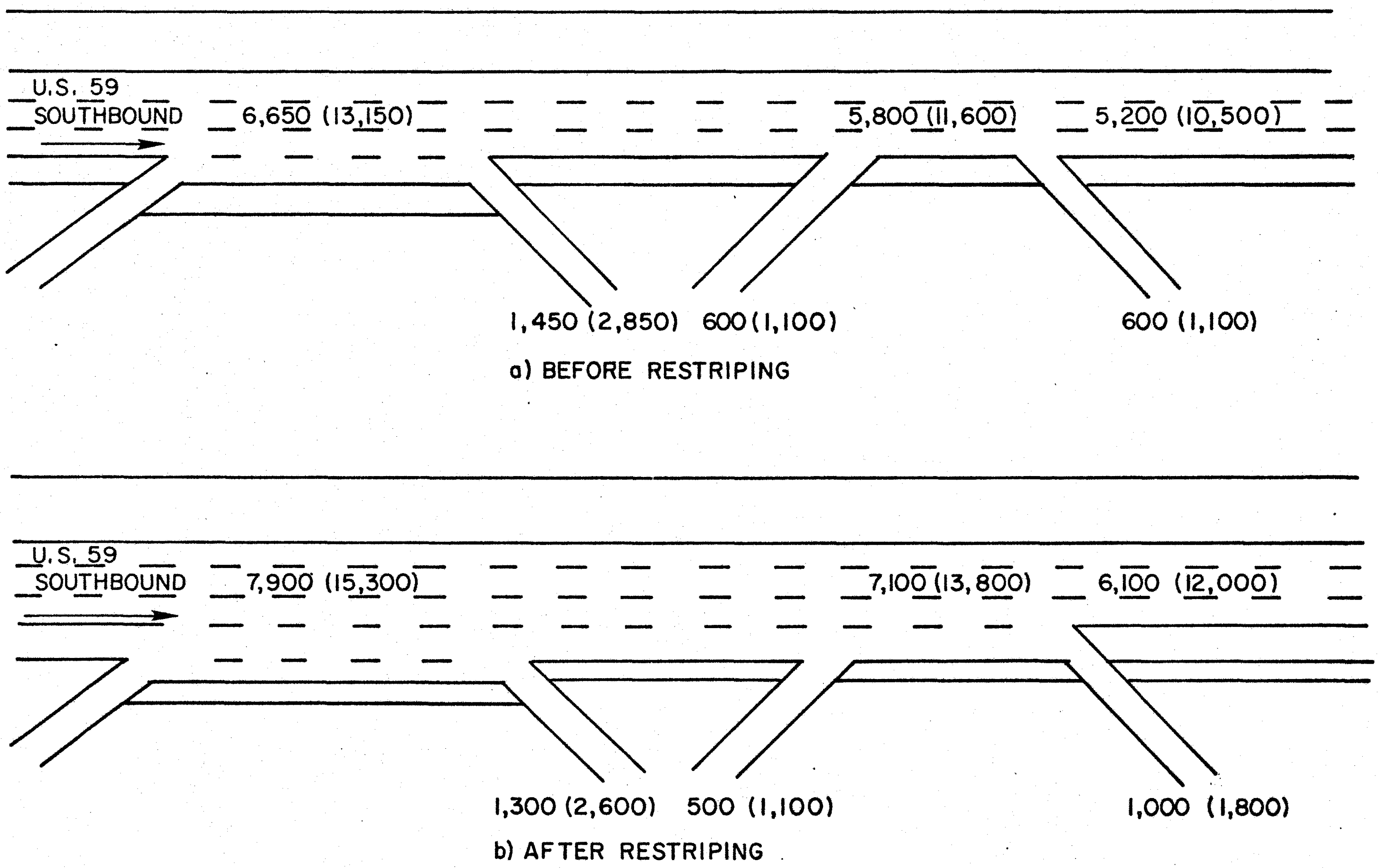


Figure 4. One and (Two) Hour Traffic Volumes - P.M. Peak Period
Section 3

TABLE 2

PEAK PERIOD VOLUMES FOR
SECTION 3 SOUTHBOUND BOTTLENECK

	Before Restriping	After Restriping	Percent Change
Vehicles Per Peak Hour	5,800	7,100	+22.5
Vehicles Per 2-Hour Peak	11,600	13,800	+19.0

TABLE 3

PEAK PERIOD THROUGHPUT FOR SECTION 3 SOUTHBOUND

	Before Restriping	After Restriping	Percent Change
Vehicles Per Peak Hour	7,250	8,400	+15.9
Vehicles Per 2-Hour Period	14,450	16,400	+13.5
Vehicles Kilometres Per Peak Hour	16,130	19,430	+20.4
Vehicle Kilometres Per 2-Hour Peak	32,770	37,900	+15.6

1 kilometre = 0.6 miles

Because of the grades and horizontal curvature, the high flow rates and volumes through the Westpark overpass bottleneck (12,000 VPH for two hours) were not expected (Figure 5). However, these data were confirmed, and the following factors are offered in explanation:

1. The percent of trucks was very low (1.3 percent).
2. The percent of small vehicles was high (20 percent).
3. The speeds approaching and leaving the overpass were maintained at a high level throughout the peak period, because of the high volume, high speed exit ramps on both sides of the overpass.
4. The volume using the added lane upstream of the Westpark exit was high.
5. Demand for the three through lanes at the Westpark exit ramp was high throughout the peak period. Some vehicles merged 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-degree horizontal curve, the sight distance, lateral clearances, and design features are adequate for high volume, high speed operation.
7. Driving performance may be more efficient when entering a section of freeway with standard width lanes after traveling several minutes in a section with narrow lanes. A lane is considered to be narrow if the width is less than 12 feet.
8. The population of motorists using this freeway could be classified as aggressive drivers who tend to over-drive traffic conditions. This results in better operational efficiency, but also a

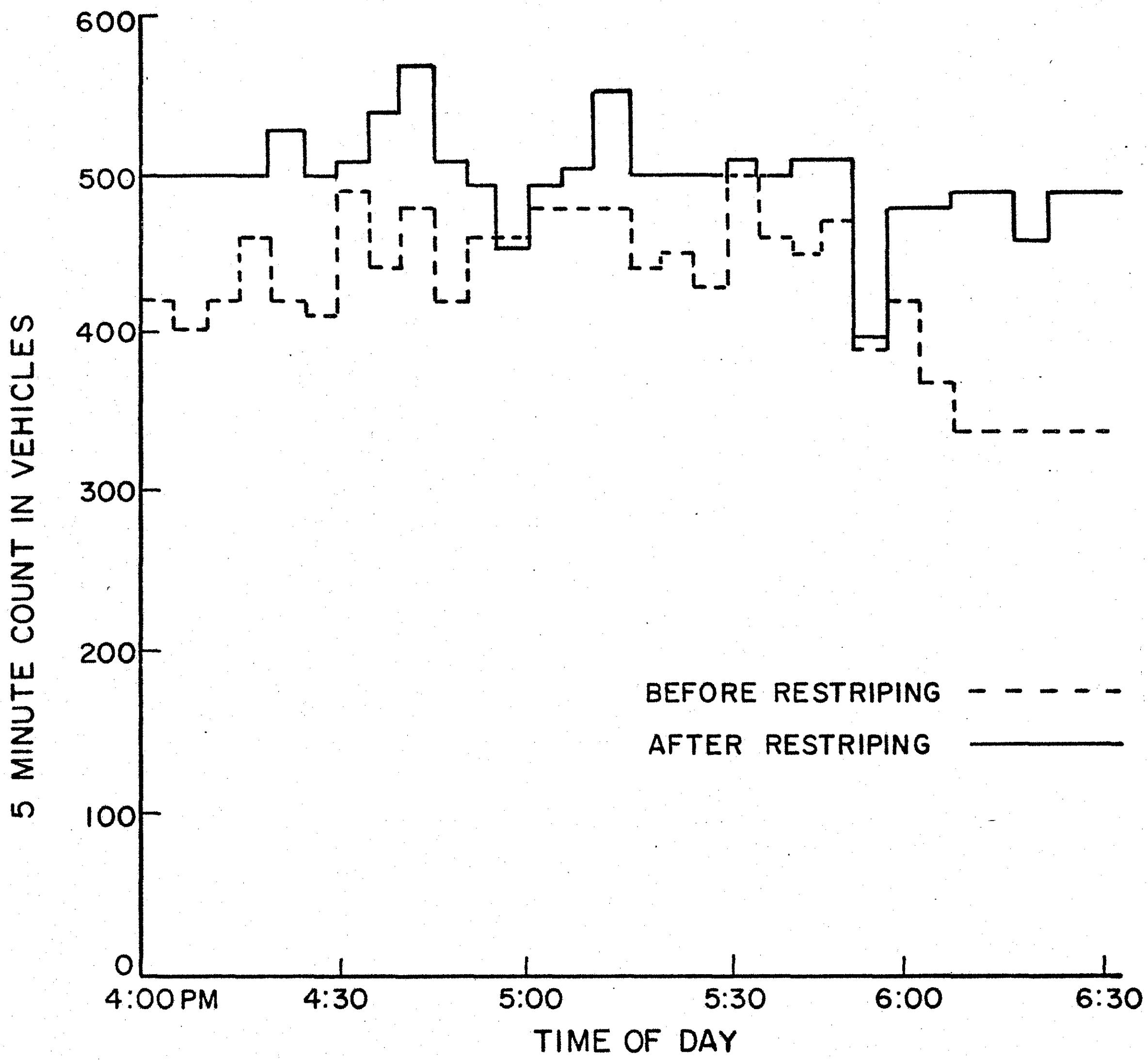


Figure 5. Volume Count on U. S. 59 Southbound at Westpark

higher accident rate than other freeways with less aggressive motorists.

To determine the effects of the added capacity on traffic delays, traffic demand for the sections over the two-hour period was assumed to be constant before and after the restriping.

The demand curve is represented by the input curve in Figure 6. The output curve is the sum of the volumes at the Westpark overpass, Westpark exit ramp and Chimney Rock exit ramp. The output curve before restriping indicates traffic congestion between 4:20 and 6:10 PM.

The output after restriping causes the length of congestion to be reduced by 20 minutes to 5:50 PM and the total amount of delay to be reduced by 1,100-vehicle hours per day.

Although the demand curve was assumed to be unchanged in order to measure the effects on traffic delays, in fact, the traffic volumes after two years of operation have increased. The peak period demand increased by 14 percent, whereas the ADDT increased by 8.7 percent. The increase in peak period traffic is especially significant in comparison to the 2 percent increase the year before restriping.

Therefore, the length of congestion has remained the same or increased slightly, but the section now accommodates 1,950 more vehicles during the two-hour peak period.

The level of service has been improved particularly for the ramp exit volumes. But since the demand for the section has increased and still exceeds the capacity of the bottleneck, congestion persists throughout the peak period.

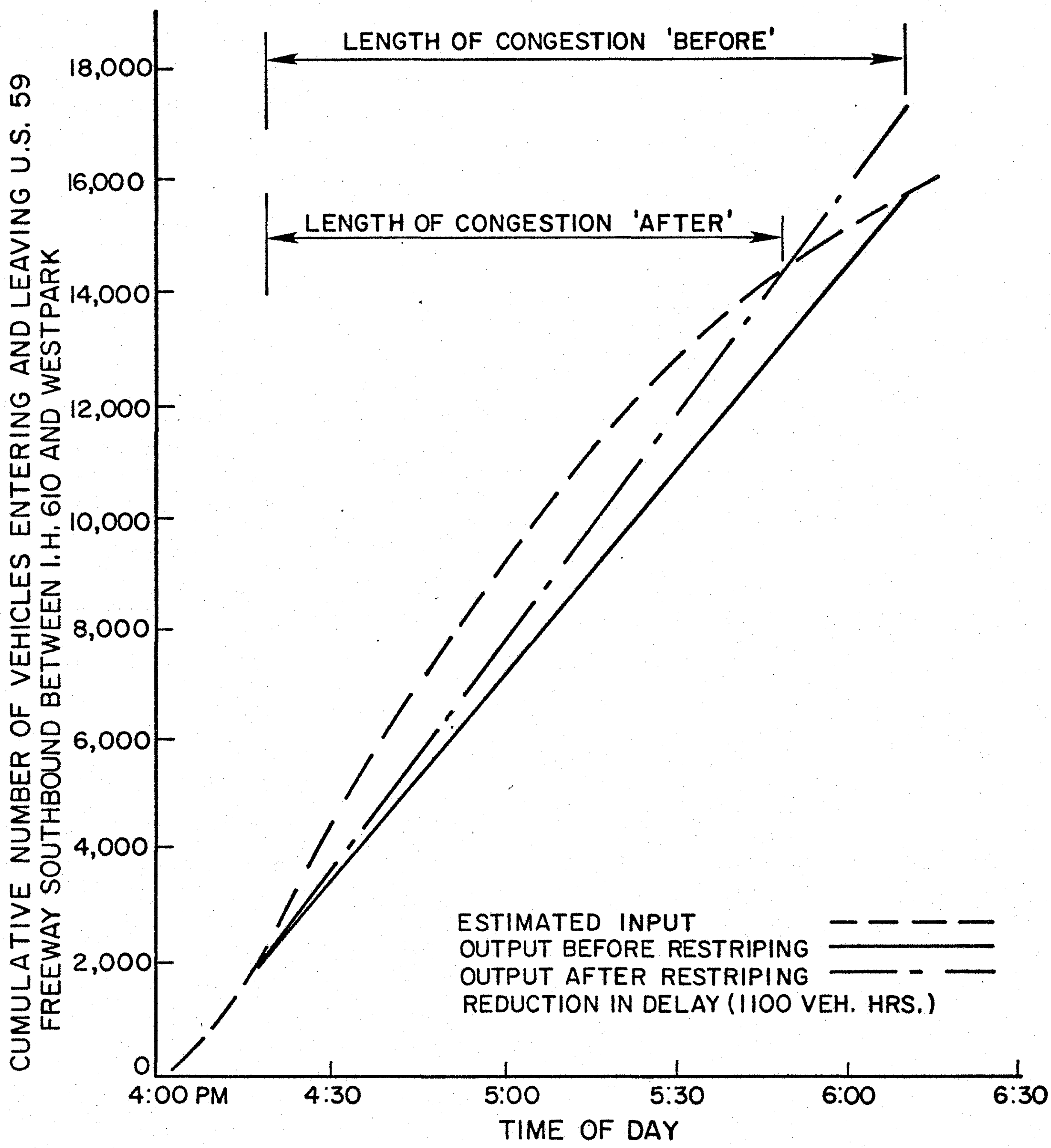


Figure 6. Input-Output Flow Rates for U. S. 59 Southbound Between I. H. 610 and Westpark Overpass

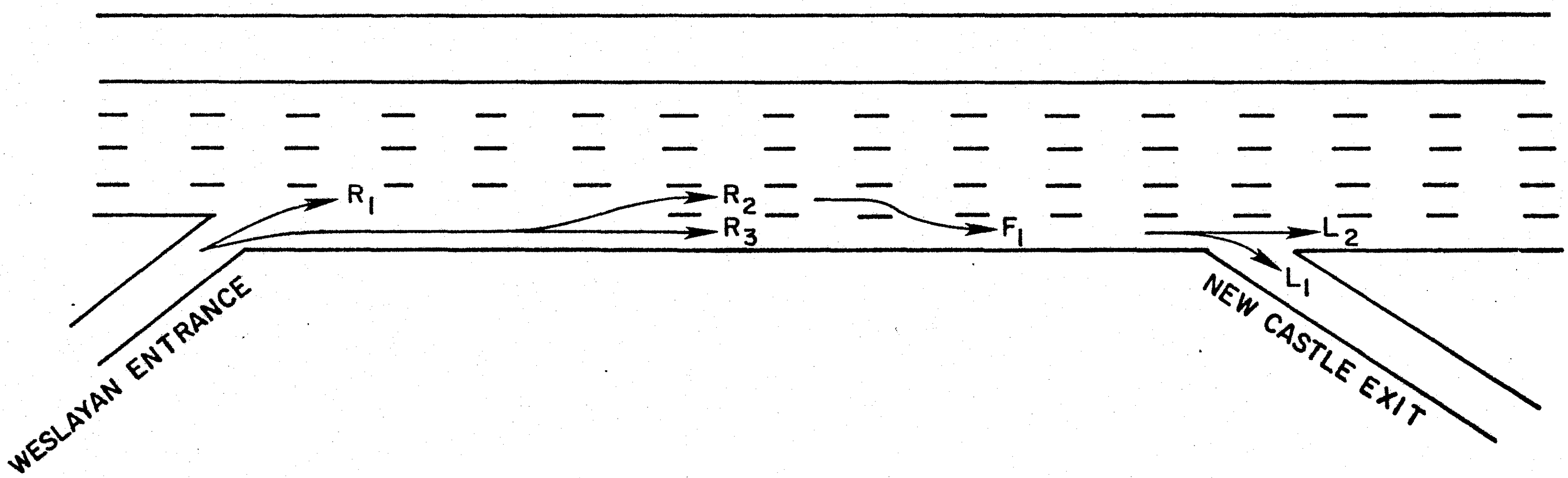
Driver Acceptance - Shoulder Lane Usage

The key to a successful freeway reconfiguration is the usage of the added lane. In this project the lane was composed partly of the right shoulder and partly of the mainline pavement. Several factors against its usage were: the texture and contrast of the two pavement materials; the restrictive lateral clearance on the approaches to bridges; and the condition of the riding surface. Factors in favor of its use were: the high percent of local traffic, particularly during the peak periods; and the high volumes of traffic throughout the day. In order to test the effectiveness of the 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, then a more permanent design was to be implemented.

Study Section 2: Weslayan to I.H. 610 Southbound

There was no special signing used to designate the shoulder lane for travel, although a sign indicating the absence of a paved shoulder was added later. Lane arrows were used downstream of the Weslayan entrance ramp to encourage the full use by entering traffic, but only 30 percent (Movement R_3) remained in the lane (Figure 7). The contrast between the concrete acceleration lane taper and the asphalt concrete shoulder appeared to guide the entrance ramp traffic out of the shoulder lane. Peak period usage by mainline traffic (F_1) was high, but the traffic entered the lane too late to improve upstream flow rates. As noted in the previous section, this section was improved by extending the lane upstream to the next entrance ramp at Edloe.

The extension of this lane was implemented by the SDHPT in August 1978. This enabled many of the vehicles that originate upstream of the Weslayan



MOVEMENT	2 HOUR VOLUME	PEAK HOUR VOLUME
$R_1 + R_2$	770	450
R_3	320	140
F_1	1,700	970
L_1	710	470
L_2	1,310	640

Figure 7. Peak Period Usage of the Shoulder Lane on U. S. 59 Southwest Freeway - Section 2

ramp to merge and weave into the shoulder lane prior to the bottleneck section. The usage of the shoulder lane for the peak two-hour period increased significantly from 1150 vehicles per hour to 1550 vehicles per hour.

The lane is available for 24 hours, but it is used primarily during the peak period when all other lanes become congested. The average daily traffic in the lane was 8,155 vehicles, with approximately 25 percent usage during the peak period (Figure 8). Since the opening of the lane extension to Edloe, the usage has increased by 40 percent to 11,750 vehicles per day.

Study Section 3: I.H. 610 to Westpark - Southbound

Usage of the shoulder lane in Study Section 3 was much greater. Although the lane was "black and white" pavement, the riding surface and lateral clearances were better than Section 2. The high exiting volumes at the Chimney Rock and Westpark exits account for much the success of the lane. The average daily traffic in the lane was 13,445 vehicles, and the peak period usage was approximately 20 percent (Figure 8). The greater use in the off peak period was also a measure of the acceptability of the design in comparison to Section 2.

ACCIDENT ANALYSIS

Both inbound and outbound directions of the four sections were studied in the accident analysis. Since the first and last sections of the four were not modified, their accident experience was used as control sections to measure the impact of the geometric changes in the two interior sections. Also, a two-year before and after comparison of the modified sections was made. Because of the growth in traffic volumes on the freeway, accident rates were used to evaluate the changes in accident experience.

There were several factors other than the geometric modifications that influenced the accident experience: a new section of freeway connecting

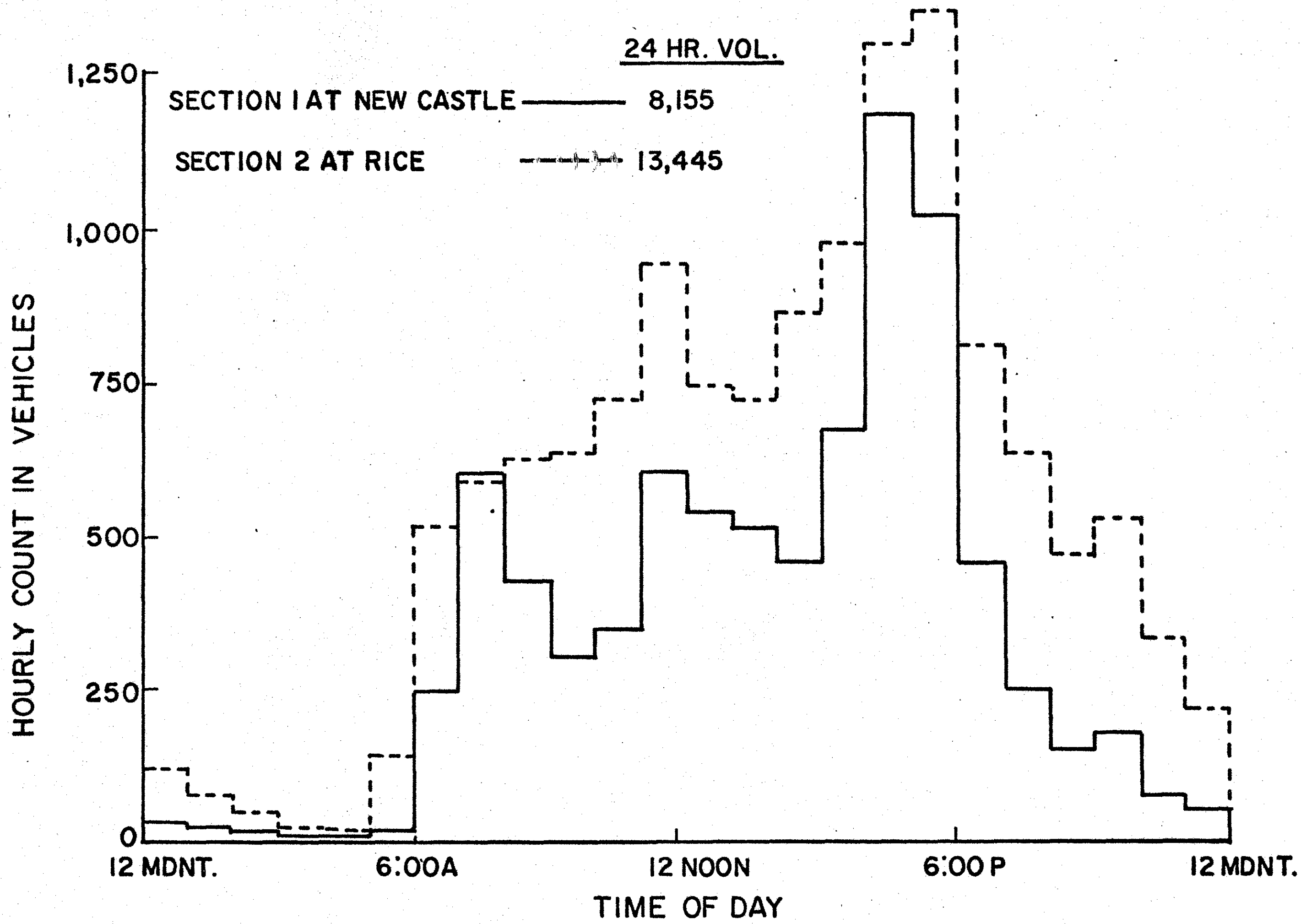


Figure 8. 24 Hour Usage of the Shoulder Lane
on U. S. 59 Southwest Freeway - Sections 2 and 3

I-45 was opened in October 1974; a ramp control system was installed in August 1975; and, the length of Daylight Savings Time was changed in 1975. No attempt was made in this report to relate the accident experience to these and other events.

Total and Peak Period Accident Summary

The average annual number of accidents has increased for both directions of travel for the entire 7.3 mile length of the study area. However, the outbound direction which received the greatest benefit from the capacity improvements increased only 3.4 percent, while the inbound direction increased by 21.3 percent (Table 4a). When the accidents are expressed in rates, the outbound accident experience actually decreased by 12.8 percent and the inbound increased by 3.7 percent (Table 4b). The reduction in the outbound accident rate was significant when tested by the Poisson Comparison of Means Test at the 95 percent level. All tests of significance will use this conservative comparison, unless specified in the analysis. Because of the large changes in volumes, only the accident rates were tested for significant change.

Outbound Direction

The accident experience in both of the outbound modified sections decreased in the two years following the geometric changes (Table 5). The reduction in accident rates were significant, with Section 2 having the lower rates and greater percent reductions than Section 3. This was probably due to two things: first, Section 3 has more merging and lane changing, resulting in more vehicle conflicts; second, the added capacity in Section 2 was not fully utilized because of the location of the start of the lane. Thus, there was a reduction in lane density in this section, compared to Section 3.

TABLE 4

Accident Experience - Total Reported Accidents
(Both Directions of Travel)

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Outbound	702	726	+3.4
Inbound	620	752	+21.3
Total	1322	1478	+11.8

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Outbound	235	205	-12.8*
Inbound	216	224	+3.7
Total	226	214	-5.3

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometer = 0.6

TABLE 5

Accident Experience - Total Reported Accidents

Outbound

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Section 1	259	250	-3.5
Section 2	129	108	-16.3
Section 3	205	202	-1.5
Section 4	109	166	+52.3
Total	702	726	+3.4

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Section 1	356	275	-22.8*
Section 2	208	147	-29.3*
Section 3	229	192	-16.2*
Section 4	143	184	+28.7*
Total	235	205	-12.8*

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometre = 0.6

Section 1 had a reduction in accident rates which could be attributed in part to better operations in downstream Sections 2 and 3. The increase in accident rate for Section 4 may also be attributable to a worsened quality of flow (increased demand but no increase in capacity) in Section 4 after improvement of Sections 2 and 3.

The major operational benefits of the added lane were realized in the peak periods. Therefore, the larger reductions in accident frequencies and rates during this period of heavy usage were significant (Tables 6a and 6b).

For the two years prior to the striping changes, the peak period accident rates for the four outbound sections decreased in order from the upstream section to the downstream section (Figure 9). The probable reason for this trend was the congestion in the two interior sections which backed up into the first upstream section. The downstream section number 4 is free flow. In the second year, the same pattern holds, but some rates particularly in the downstream sections increased as travel and congestion increased.

After the restriping in 1976-77, the upstream rates decrease significantly, but the downstream section continued to increase as travel increased. Further reductions are evident in the second year after restriping as the usage of the added lane increased.

Inbound Direction

The accident experience in the two inbound modified sections is mixed. For the total accidents, Section 2 increases and Section 3 decreases, both in frequency and rate. The modifications on the inbound sections do not affect off-peak travel, and thus it is difficult to explain the total accident data in Tables 7a and 7b. However, in Tables 8a and 8b, the peak

TABLE 6

Accident Experience - Peak Two Hours
Outbound

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Section 1	80	46	-42.5
Section 2	43	13.5	-68.6
Section 3	38	30	-21.1
Section 4	12.5	22	+76.0
Total	173.5	111.5	-35.7

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Section 1	812	432	-46.8*
Section 2	601	171	-71.5*
Section 3	369	265	-28.2
Section 4	141	225	+59.6
Total	484	284	-41.3*

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometre = 0.6 miles

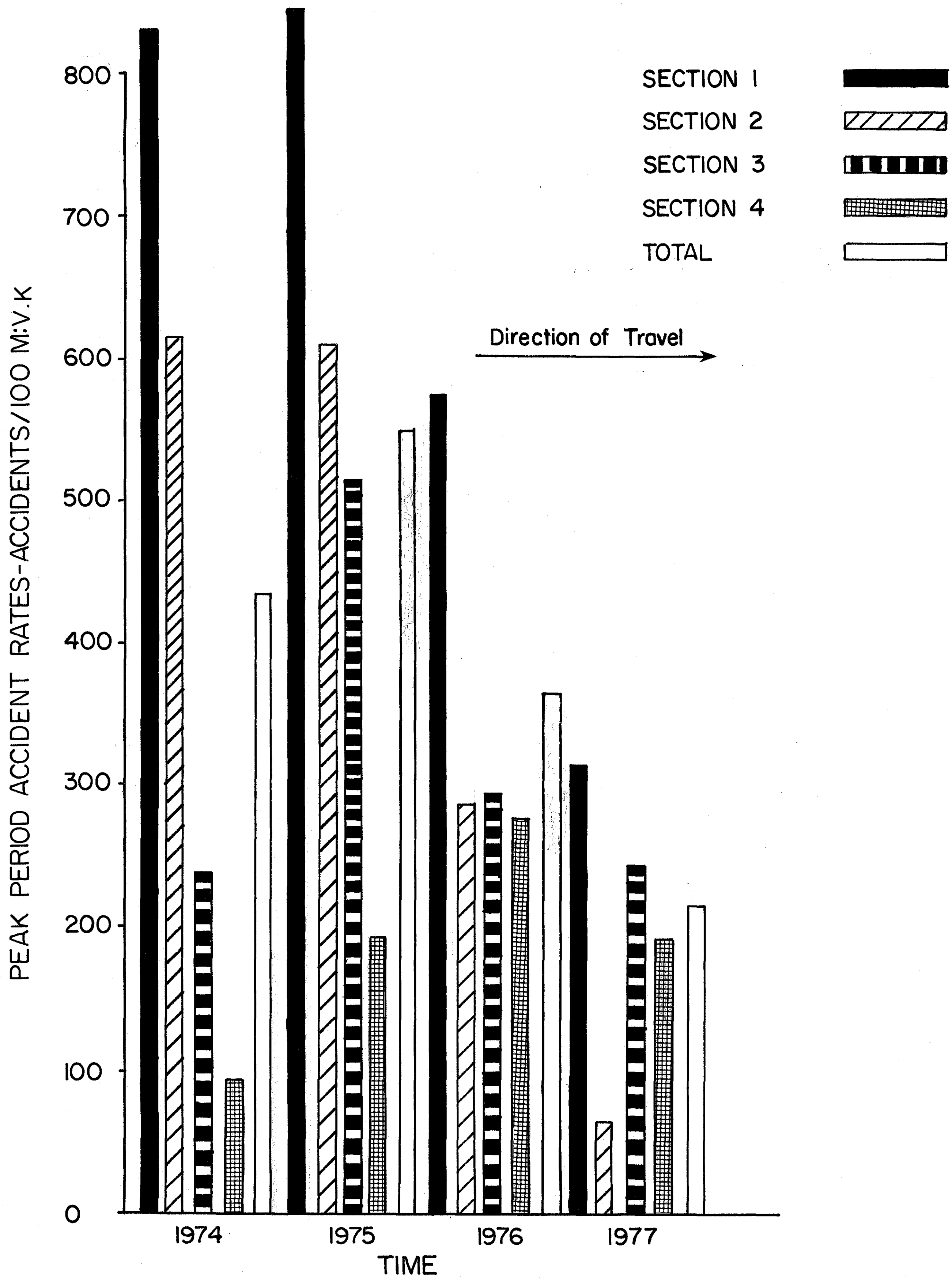


FIGURE 9 — PEAK PERIOD ACCIDENT RATES BY SECTION OUTBOUND U.S. 59

TABLE 7

Accident Experience - Total Reported Accidents
Inbound

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Section 1	198.5	245.5	+23.7
Section 2	92.5	136.5	+47.6
Section 3	217.5	189	-13.1
Section 4	111.5	181	+62.3
Total	620	752	+21.3

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Section 1	277	280	+1.1
Section 2	151	185	+22.5*
Section 3	260	195	-25.0*
Section 4	155	217	+40.0*
Total	216	224	+3.7

[1]Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometre = 0.6 miles

TABLE 8

Accident Experience - Peak Two Hours
Inbound

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Section 1	29.5	25.0	-15.2
Section 2	32.0	16.5	-48.4
Section 3	52.5	17.0	-67.6
Section 4	19.5	10.5	-46.1
Total	133.5	69.0	-48.3

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Section 1	271	205	-24.4
Section 2	445	230	-48.3*
Section 3	530	173	-67.3*
Section 4	229	130	-43.2
Total	364	178	-51.1*

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometre = 0.6 miles

period analyses indicate consistent improvement in frequency and rates when the added lane was most beneficial.

In Figure 10, the pattern of accident rates in 1974 follows the same trend of the outbound direction, with the exception of the upstream Section 4. This was probably due to the fact that traffic congestion inbound had not encroached on this section.

In 1975, increases in accident rates correspond to large increases in travel caused by the opening of a new section of freeway.

After the minor restriping in Sections 2 and 3, the accident rates during the peak periods were reduced significantly.

Comparisons of Modified and Unmodified Sections

Outbound Direction

Tables 9a and 9b indicate the changes in the outbound section that were not modified in comparison with the two sections that were modified. The overall reduction and the reductions in the accident rates for the modified sections were significant, but the unmodified sections were not significantly changed.

During the two-hour peak periods, the reductions in both the modified and unmodified sections were significant (Tables 10a and 10b). Part of the reason for the reduction in accidents in the unmodified sections is due to the improvement in traffic operations upstream of the sections with added capacity. For example, the upstream unmodified section had a 20 percent reduction in total accident rate, while the downstream section had a 28 percent increase in total accident rates. These figures are -44 percent and +60 percent for the peak period.

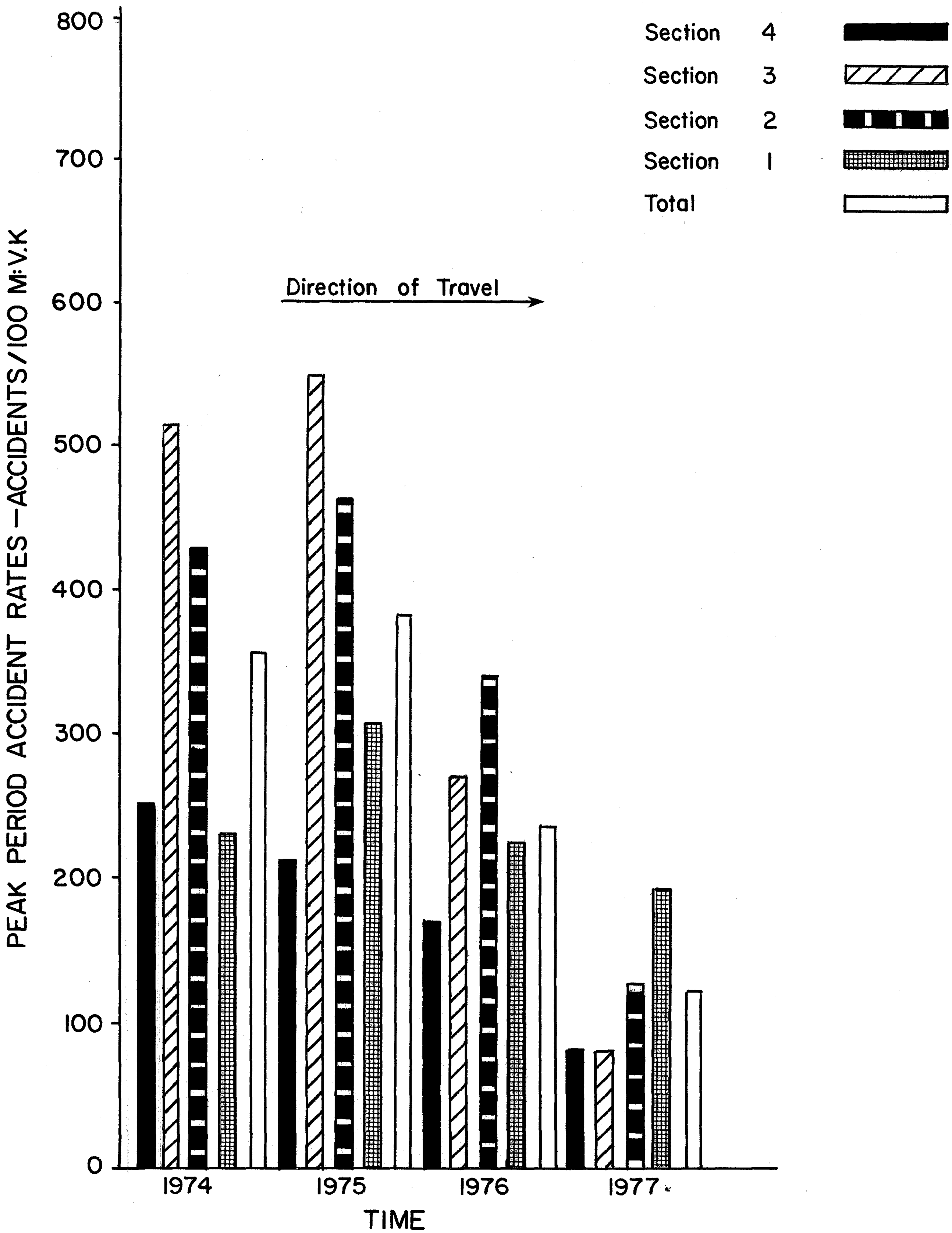


FIGURE 10 — PEAK PERIOD ACCIDENT RATES BY SECTION INBOUND U.S. 59

TABLE 9

Accident Experience - Total Reported Accidents
Outbound Modified vs. Unmodified

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Modified	334	310	-7.2
Unmodified	368	416	+12.8
Total	702	726	+3.4

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Modified	221	174	-21.3*
Unmodified	250	236	-5.6
Total	235	205	-12.8*

[1]Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometre = 0.6 miles

TABLE 10

Accident Experience - Two-Hour Peak Outbound Modified vs. Unmodified

a. Accident Frequency - Number of Accidents Per Year[1]

	Before Restriping	After Restriping	Percent Change
Modified	81	43.5	-46.3
Unmodified	92.5	68.0	-26.5
Total	173.5	111.5	-35.7

b. Annual Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

	Before Restriping	After Restriping	Percent Change
Modified	464	227	-51.1*
Unmodified	502	339	-32.4*
Total	484	284	-41.3*

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

1 kilometre = 0.6 miles

Summary of Tests for Significance

In addition to the conservative Poisson Comparison of Means Test, the liberal Poisson Distribution Test was applied to all sections in before and after analyses for the following time periods; 24-Hour (24); Two-Hour Peak Period (P); Daytime (D); Nighttime (N) (Figure 11).[7] If the conservative test is satisfied, it can be stated that it is 95 percent certain that the change in accident experience is significant. If only the liberal test is satisfied, more data should be collected before a statement of significance is made. If neither test is satisfied, then it is 95 percent certain that no change is attributed to the change in conditions. Table 11 summarized the direction of change in accident rates, and the tests that are satisfied by the data.

In the preparation of this paper it was noted by two reviewers that the use of the Poisson Comparison of Means Test was suspect. It was suggested that since the number of samples are large, a test using a normal approximation to the binomial distribution would be appropriate. These tests were conducted with the following results.

- all tests that were determined to have significance with the Comparison of the Means Tests were confirmed.

- One time period (Section 1, Inbound, Daytime) was found to be significant (Table 11).

- Two sections tested significant for changes in angular accidents (Table 13).

24-Hour Time Period - (24)

In the outbound direction, the reductions in accident rates in the two modified Sections 2 and 3 and the upstream Section 1 were significant. Only the downstream Section 4 had an increase which was also significant. The travel in this section was increased greatly. The total rate for the sum of the four sections was significantly reduced.

In the inbound direction, only the modified Section 3 was reduced significantly. This decrease was somewhat surprising, since the increase in capacity was only useful during the peak period, and for a short section. However, the total rate for the sum of the four sections increased, but not significantly.

The results of the 24-hour analysis supports the statement that the narrow lanes and reduction in shoulder widths did not increase the accident experience of the freeway.

Two-Hour Peak Hour Period - (P)

The outbound direction experienced the same changes in accident rates during the peak periods as the total 24-hour period, but because of the low number of accidents for Sections 3 and 4, the results only satisfied the liberal tests and were, therefore, inconclusive. However, the total rates for the peak period did satisfy the conservative test, indicating that the improved capacity resulted in a reduction in overall accident experience.

The inbound direction also had a reduction in accident rates throughout the four sections. The only unusual result was the reduction in rate in the

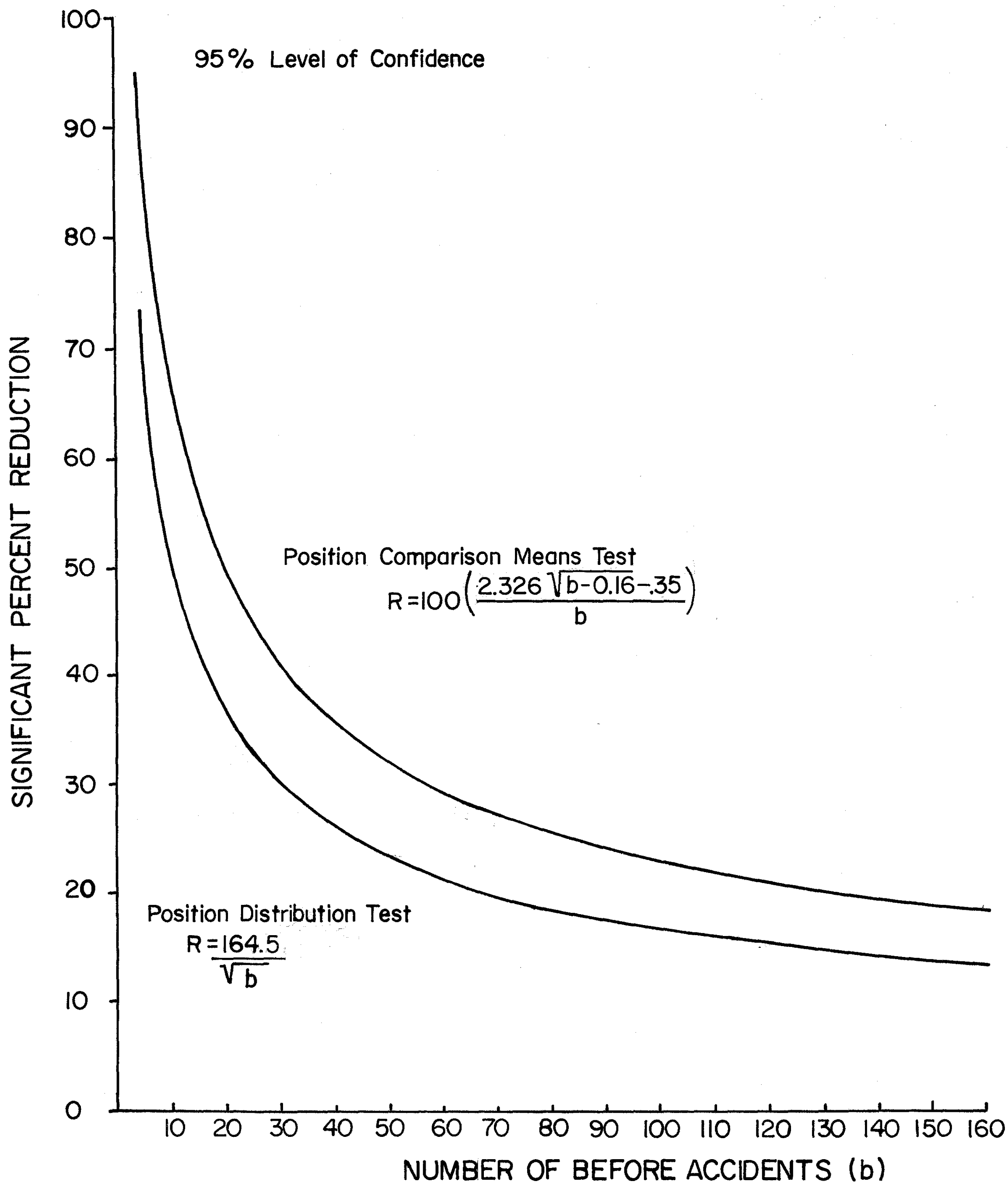


Figure 11. Poisson Tests for Significance

TABLE 11

DIRECTION OF CHANGE IN ACCIDENT RATES
AND TESTS FOR SIGNIFICANCE

	OUTBOUND				INBOUND			
Section Number	Time Period 24	P	D	N	Time Period 24	P	D	N
1	- *	- *	- *	- *	+	-	-(N)	+ (L)
2	- *	- *	- *	- *	+ *	- *	+	+ *
3	- *	- (L)	-	- *	- *	- *	- *	+
4	+ *	+ (L)	+ *	-	+ *	- (L)	+ (L)	+ *
Total	- *	- *	- (L)	- *	+	- *	- *	+ *

- Accident Rate Reduced

+ Accident Rate Increased

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test (Conservative)

(L) Significant at the 95 percent Confidence Level for the Poisson Distribution Test (Liberal)

(N) Significant at the 95 percent confidence level for the Normal Approximation Test downstream Section 1, but the change was not significant.

Daytime Period - (D)

Two-thirds of the travel occurred during the 12 hours defined as the Daytime Period. Therefore, the accident experience will generally follow the 24-hour results, as it did with the outbound direction. However, the total rate change was significant for the daytime period only for the liberal tests. On the inbound direction, there was a significant decrease in the overall accident rate for the daytime period.

Nighttime Period - (N)

There was much concern that the narrow lanes, offset from the pavement joints, would be difficult to follow at night. Also, the reduced shoulder widths might be more hazardous at night. The results in Table 11 indicate that the modified sections in the outbound direction at night had significant reductions in rates, and that the overall rate was also reduced.

In the inbound direction, the nighttime rates were all increased. Since there was a narrowing of the main lanes and limited reduction in shoulder widths, the increases must be attributable to other causes, such as increased travel.

In summary, the tests generally support the hypothesis that narrow lanes and reduced shoulder widths are not more hazardous, when they are accompanied by an effective increase in capacity. This increase in capacity may also reduce the accident experience of adjacent upstream sections whose designs were not modified, by reducing the time and severity of congestion that originates downstream.

An Analysis of the Type of Accidents

One of the concerns for the safety of operations in sections with narrow lanes was that the reduction in lateral clearance would result in higher accident rates, and in an increase in accidents involving vehicles in adjacent lanes. The accident records were coded by the following types of accidents:

1. Rear End
2. Fixed Object
3. Other (Pedestrian, Bicycle, Overturn, etc.)
4. Sideswipe
5. Left Turn
6. Right Turn
7. At an angle

The last four types represented accidents that more than likely involved vehicles in adjacent lanes or at ramp terminals. An analysis of the sum of these four types grouped under a general category of angular accidents was made with data from one year before the restriping and two years after restriping.

TABLE 12

ANGULAR ACCIDENT ANALYSIS

FREQUENCY

Number of Angular Accidents[1]

Outbound

	Before Restriping	After Restriping	Percent Change
Section 1	104	110.5	+6
Section 2	30	29	-3
Section 3	61	53	-13
Section 4	69	56	-19
Total	264	248.5	-6

Inbound

	Before Restriping	After Restriping	Percent Change
Section 1	148	105	-29
Section 2	18	31.5	+75
Section 3	60	66	+10
Section 4	62	75.5	+22
Total	288	278	-3

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

TABLE 13

ANGULAR ACCIDENT ANALYSIS

RATES

Angular Accident Rate - Accidents Per 100 Million Vehicle Kilometres[1]

Outbound

	Before Restriping	After Restriping	Percent Change
Section 1	130	128	-2
Section 2	46	40	-13
Section 3	65	50	-2
Section 4	87	34	-61*
Total	83	70	-16*

Inbound

	Before Restriping	After Restriping	Percent Change
Section 1	188	121	-36*
Section 2	28	45	+61*
Section 3	68	68	0
Section 4	83	92	+11
Total	94	83	-12 (N)

[1] Two-Year Average

* Significant at the 95 percent Confidence Level for the Poisson Comparison of Means Test

(N) Significant at the 95 percent confidence level for the Normal Approximation Test

TABLE 14

ANGULAR ACCIDENT ANALYSIS

PERCENT OF TOTAL ACCIDENTS[1]

Outbound

	Before Restriping	After Restriping	Percent Change
Section 1	36	44	+22*
Section 2	22	27	+23
Section 3	23	26	+13
Section 4	48	34	-29*
Total	32	34	+6

Inbound

	Before Restriping	After Restriping	Percent Change
Section 1	57	43	-25*
Section 2	19	23	+21
Section 3	27	35	+30*
Section 4	43	42	-2
Total	40	37	-8

[1] Two-Year Average

* A level of significance of 0.05 was accepted in the Binomial Test of Proportions.

On the outbound lanes, the critical sections which had narrow lanes were Sections 2 and 3. The frequency and rate of angular accidents decreased, but the percent of total accidents increased. None of the changes, were large enough to satisfy the statistical tests (Tables 12, 13 and 14). However, Section 4, which had no geometric modifications, had a significant reduction in angular accident rate and percent of total accidents.

The inbound lanes, which were not narrowed to increase capacity, were subjected to greater accident potential by increased traffic demand which results in more angular accidents (Tables 12 and 13). Section 1 is the exception in that it had sufficient capacity to accommodate the increased demand. The percent of total accidents that were classified as angular accidents declined, but the number of accidents were too small to satisfy the test of significance (Table 14).

The conclusion of the analysis of type of accident was that no definite statement can be made as to the effect of the narrower lanes on angular accidents.

An Analysis of Accident Severity

The impact that the change in the pavement surface geometrics may have on the severity of accidents was investigated. The number of accidents reporting an injury or fatality was analyzed by rates and percent of total by section (Tables 15, 16, and 17).

The critical outbound Sections 2 and 3 had reductions in the severe accident rates, but did not satisfy the statistical test of significance. However, the fact that the accident experience decreased was important.

TABLE 15

ACCIDENT SEVERITY ANALYSIS

FREQUENCY

Accident Frequency - Number of Injury - Fatal Accidents Per Year

Outbound

	Before[1] Restriping	After[1] Restriping	Percent Change
Section 1	38.5	33.0	-14
Section 2	18.5	14.0	-24
Section 3	31.5	32.5	+3
Section 4	19.0	24.5	+29
Total	107.5	104.0	-3

Inbound

	Before[1] Restriping	After[1] Restriping	Percent Change
Section 1	26.0	36.0	+38
Section 2	14.5	20.5	+41
Section 3	26.5	25.0	-6
Section 4	17.5	33.5	+91
Total	84.5	115.0	+36

[1]Two-Year Annual Average

TABLE 16

ACCIDENT SEVERITY ANALYSIS

RATES

Accident Rate - Injury - Fatal Accidents
100 Million Vehicle Kilometres

Outbound

	Before[1] Restriping	After[1] Restriping	Percent Change
Section 1	54	38	-30
Section 2	30	19	-37
Section 3	35	31	-11
Section 4	25	27	+8
Total	36	29	-19

Inbound

	Before[1] Restriping	After[1] Restriping	Percent Change
Section 1	36	41	+14
Section 2	24	29	+21
Section 3	32	26	-19
Section 4	25	41	+64
Total	30	34	+13

[1]Two-Year Annual Average

TABLE 17

ACCIDENT SEVERITY ANALYSIS
PERCENT OF TOTAL ACCIDENTS
Percent of Total Accidents Having An Injury or Fatality

Outbound Direction

	Before[1] Restriping	After[1] Restriping	Percent Change
Section 1	14.8	13.2	-11
Section 2	14.3	13.0	-9
Section 3	15.4	16.1	+5
Section 4	17.4	14.8	-15
Total	15.3	14.3	-7

Inbound Direction

	Before[1] Restriping	After[1] Restriping	Percent Change
Section 1	13.1	14.7	+12
Section 2	15.8	15.0	-5
Section 3	12.2	13.2	+8
Section 4	15.7	18.5	+18
Total	13.6	15.3	+13

[1] Two-Year Annual Average

Only Section 4, inbound, experienced a significant change in the rates of injury and fatal accidents. This section had no changes in the lane configuration but did have a large increase in volumes and congestion.

The total inbound section had an increase in severe accidents, while the outbound had a decrease in severe accidents.

The conclusion drawn from this analysis is that the reconfigured sections of the freeway did not produce a significant change in the number and rate of severe accidents for the study period of two years after modifications.

BENEFIT-COST ANALYSIS

Benefits of the restriping in Section 2 have not been realized at this time. It is estimated, however, that with the extension of the lane to the Edloe entrance, a significant reduction in vehicle delay will be achieved.

Section 3 achieved a significant increase in capacity as a result of the added lane, and resulted in a 13.5 percent increase in the number of vehicles exiting this section in the peak two-hour period. The estimated savings in total travel time were calculated to be 1,100-vehicle hours per day for 14,600 vehicles. With 1.3 persons per vehicle occupancy rate, a cost of $6.59* per vehicle hour for private vehicles resulted in a savings of $7,249 per weekday or $906,125 annually, assuming 50 percent incident-free days.

Fuel savings were realized with the reduction in travel time. Each vehicle saved an average of 4.52 minutes. This represents the time difference of 9 minutes at 32 km/h (20 mph) and 4.48 minutes at 64 km/h (40 mph) over 4.83 kilometres (3 miles). Running cost at 32 km/h (20 mph) is 7.12* cents per vehicle kilometre (11.46* cents per vehicle mile); at

*Prices used in this calculation taken from Reference (6) and updated to 1977

64 km/h (40 mph), it is 4.74* cents per vehicle kilometre (7.62* cents per vehicle mile). Therefore, a savings of $\frac{(\$0.00712 - \$0.0474)}{\text{vehicle-kilometre}}$ for 14,600 vehicles traveling 4.83 kilometres is equal to $1,678.33 in operating costs per day or $209,791 per year, for 125 incident-free days.

Approximately 75 percent of the operating costs can be attributed to fuel. Therefore, the number of litres (gallons) of gasoline conserved by the improvement was estimated to be:

$$(\$209{,}791)\ (.75)\ \left(\frac{\text{litre}}{\$.140}{}^{*}\right) = 1{,}126{,}755 \text{ litres } (256{,}080 \text{ gallons})$$

Similar calculations of benefits can be made for noise and air pollution and traffic accidents, but they were not included in this analysis. Therefore, total annual benefits were calculated to be $1,115,916.

The cost of restriping the lanes was $38,700. The project required the following work items: relocation of two lighting standards and three roadside warning signs; modification of a metal guard beam section and two curb inlets; removal of sections of curb, traffic buttons, and paint; application of asphalt overlay strip to smooth pavement--shoulder transition; stabilization of shoulders; and application of paint strips. Lane lines were restriped after three months at a cost of $471, and additional lane markings and lane arrows were added at Weslayan ramp at a cost of $157.

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

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* Prices used in this calculation taken from Reference (6) and updated to 1977

The benefit to cost ratio for this project was $1,115,916 to $39,328 or 28:1. Annual costs to maintain the system have not been calculated at this time but should be considerably less than $40,000. At some time in the future, the shoulders will deteriorate and will be replaced at an estimated cost of $275,600 or $39,245 annually.* However, it is anticipated that when this construction is programmed, the new design will provide for an added lane with shoulder, in order to return the section to standard cross section.

DESIGN AND MAINTENANCE REQUIREMENTS

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

1. The median shoulder width was maintained at 3.05 metres (10 ft) because of the small mountable curb and drainage inlets in the median.
2. A paved right shoulder was desired where practical.
3. The volume of large vehicles using this freeway during peak periods was very low (2-3 percent).
4. The minimum desirable width for travel on freeways was considered to be 3.2 metres (10.5 ft).

The cross sections were changed in a transition zone of 250 metres (820 ft). 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, as well as oil and dirt accumulations. New stripes, placed after three months of

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* Uniform series capital recovery factor of 0.1424 for i=7%, n=10 years

operation have worn very well, but new stripes and buttons will be placed after 15 months of operation.

The shoulder lanes have held up well under the increasing volumes of traffic. The turf area in the outer separation that has been used for emergency parking has become very rutted and requires considerable maintenance. New stabilized shoulders will be provided in these areas.

The longitudinal joint between the mainline pavement and the old shoulder pavement has widened, requiring maintenance. However, the quality and safety of the ride over the joint has not been reduced substantially.

III. CONCLUSIONS

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

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