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16. Abstract

This report summarizes the findings of a detailed two-year study of freeway frontage road operations. The objectives of the study were to identify the safety and operational problems of ramp-frontage road intersection, terminals of one-way frontage roads; the probable effect of conversion from two-way to one-way service roads and finally, to suggest warrants for conversion from two-way to one-way frontage road operation.

Data were collected at nine frontage road conversion sites, forty-five ramps, including both entrance and exit ramps, and all types of ramps used on two-way and one-way frontage roads. Erratic maneuvers were recorded and accident experience examined statistically. From these data, it was determined that ramp type was not a significant influence on the accident rate. Degree of roadside development and frontage road ADT (total of both frontage roads) were the only statistically significant factors.

Two warranting conditions are suggested:

1) Volume Warrant
   - •Rural Area 7500 VPD (total of both frontage roads)
   - •Intermediate Area 6000 VPD (total of both frontage roads)
   - •Urban Area 5000 VPD (total of both frontage roads)
2) Accident Experience
   - •20 accidents/mile, average of three years
   - •30 accidents/mile in one year

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FREEWAY FRONTAGE ROAD OPERATIONS AND SAFETY STUDY

by

Donald L. Woods

Research Report 288-4F

Freeway Ramp and Frontage Road Operation
Research Study 2-8-80-288

Sponsored by

State Department of Highways and Public Transportation
In cooperation with the
U. S. Department of Transportation
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Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

March 1984

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The author wishes to thank the State Department of Highways and Public Transportation for providing the support necessary to conduct this study. Forward progress is only possible through a more complete understanding of the factors involved in highway transportation.

The author is particularly appreciative of assistance of the many District personnel from around the State who made a most difficult data collection process possible. The guidance of Mr. Jim Williams, D-18T, was instrumental in the project success. The assistance of Mr. Edwin Smith, Mr. John Nixon, Mr. Herman Haenel of the State Department of Highways and Public Transportation, and Mr. Ed Kristaponis of the Federal Highway Administration, Austin, Texas, is gratefully acknowledged.

ABSTRACT

This report summarizes the findings of a detailed two-year study of freeway frontage road operations. The objectives of the study were to identify: 1) the safety and operational problems of the ramp-frontage road intersection and terminals of one-way frontage roads, 2) the probable effect of conversion from two-way to one-way service road operation, and 3) to suggest warrants for conversion from two-way to one-way frontage road operation.

Data were collected at nine frontage road conversion sites, forty-five ramps, including both entrance and exit ramps, and all types of ramps used on two-way and one-way frontage roads. Erratic maneuvers were recorded and accident experience examined statistically. From these data, it was determined that ramp type was not a significant influence on the accident rate. Degree of roadside development and frontage road ADT (total of both frontage roads) were the only statistically significant factors.

Two warranting conditions are suggested:

1) Volume Warrant

- o Rural Area 7500 VPD (Total of Both Frontage Roads)
- o Intermediate Area 6000 VPD (Total of Both Frontage Roads)
- o Urban Area 5000 VPD (Total of Both Frontage Roads)

2) Accident Experience

- o 20 accidents/mile of freeway, average of three years data
- o 30 accidents/mile of freeway in one year

Vehicular delay dominates the benefits and costs analysis.

1. INTRODUCTION

This report is the last of a series of four reports dealing with the safety and efficiency of freeway frontage roads. The previous reports in this series are entitled:

Report 288-1 "An Evaluation of the 1979 Texas Law (V.C.S., Sec. 73.A.) Which Requires Frontage Road Traffic to Yield to Ramp Traffic," Texas Transportation Institute, March 1981

Report 288-2 "Operational and Safety Analysis For Two-Way and One-Way Frontage Roads," Texas Transportation Institute, July 1983

Report 288-3 "Accident Analysis of the Conversion From Two-Way to One-Way Frontage Road Operation," Texas Transportation Institute, July 1983

This report 288-4F summarizes the findings from these previous three reports and suggests warrants for two-way to one-way operation conversion.

2. EVALUATION OF THE LAW REQUIRING FRONTAGE ROAD TRAFFIC TO YIELD TO RAMP TRAFFIC

A detailed review of the 1979 Texas Law (V.C.S. Sec. 73.A.) which requires all traffic on the frontage road to yield to traffic entering the intersection from the ramp has generally been successful. A few isolated cases have been revealed for which the change was operationally inefficient and potentially unsafe. For this reason, a revision of the law may be needed.

The intent of the 1979 law, known as HB 1421, was to establish statewide uniformity in the control of frontage road/ramp intersections (i.e., ramp terminals). Prior to this legislation, the Department of Highways and Public Transportation determined the need for ramp terminal traffic control based on guidelines which had been in effect since January, 1974. These guidelines recognized that no single type of control was always applicable and gave considerable latitude to each Department District to use discretion in the selection of ramp terminal control consistent with driver expectations, operational efficiency, and safety at each site.

2.1 Ramp Type of Driver Expectancy

The literature review revealed a report from the National Cooperative Highway Research Program which recommends that frontage road traffic be required to yield to ramp traffic at braided ramps, while on buttonhook ramps the ramp traffic should yield to the frontage road traffic. Figure 1 illustrates the basic types of ramps used in Texas. Referring to the buttonhook design illustrated in Figure 1A, the natural driver reaction is to

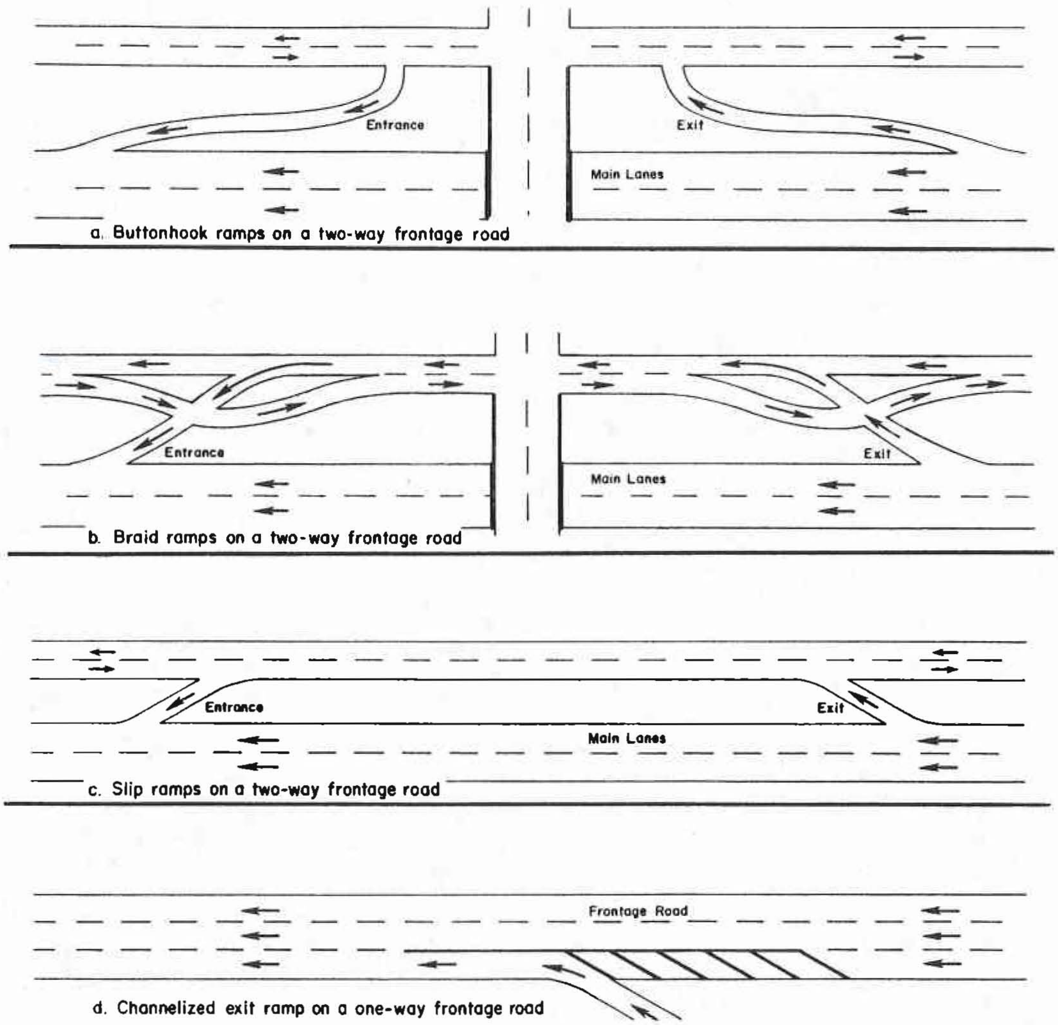


Figure 1. Four Types of Ramp Design in Texas

stop prior to entering or leaving the frontage road. This driver expectation is the result of the near right angle nature of the intersection and the required turn to exit or enter the ramp. The low speed combined with a required turn naturally assigns priority to the continuous movement on the frontage road. Therefore, the terminal control should favor the frontage road rather than the ramp.

Figure 1B illustrates the braided ramp. This design concept attempts to gain the high speed operational efficiency of a slip ramp with the right angle intersection of the buttonhook. The relatively short storage distance from the first intersection to the ramp intersection causes traffic to back up onto the freeway. This dictates control of the frontage road traffic rather than the ramp traffic.

The use of slip ramps from the main lanes to a two-way frontage road, as illustrated in Figure 1C, results in a high potential for the wrong way maneuver up the exit ramp with the corresponding head-on accident potential. This design, while discouraged, is sometimes used. Traffic control should be on the frontage road to permit the driver every opportunity to properly perceive the operational decisions which he or she faces. The slip ramp exit to a one-way frontage road should not require control for right-of-way assignment purposes if the concept illustrated in Figure 1D (slip ramp with a separate lane downstream) can be implemented. When the frontage road traffic volume does not permit removal of the left lane as illustrated in Figure 1D, the requirement to yield should be placed on the frontage road traffic.

It is apparent from the previous discussion that a uniform treatment of the traffic control at every ramp-frontage road intersection is undesirable since they tend to force the driver into unnatural and unexpected maneuvers.

2.2 The Concept of Uniformity

The general concept of uniformity is one of the more difficult concepts of traffic engineering. This concept, as explained in the Manual on Uniform Traffic Control Devices for Streets and Highways, states:

> "Uniformity is the use of similar traffic control devices for similar situations"

It is just as non-uniform to use uniform treatment of dissimilar situations as it is to use dissimilar devices for similar situations. Either way, the driver is misled by the traffic control system. The driver expectation at a Tee-Intersection is to yield to the intersecting street traffic. If this hypothesis is correct, then frontage road drivers would not be expected to fail to yield to ramp traffic on buttonhook ramps, while ramp traffic would tend to stop in spite of having the right-of-way.

2.3 Driver Perceptions of New Law

A survey of 471 ramp and frontage road drivers concerning the implementation of the 1979 Law (HB 1421) tends to confirm this hypothesis. A citation from Report 288-1 illustrates this point:

> "These drivers cited failure of frontage road drivers to yield right-of-way to ramp traffic as the most common problem. A number of the drivers reported apparent confusion over right-of-way assignments, which may give some indication of why the right-of-way violations are occurring. Examples of the confusion include: 1) ramp drivers stopping for frontage road traffic and 2) all traffic stopping due to uncertainty over which driver should yield."

Since HB 1421 resulted in a non-uniform system of control rather than the uniform one intended, causing inefficient and unsafe operation and violating driver's expectancy in some cases, Report 288-1 recommended Section 73.A of Vernon's Civil Statutes be changed to read:

Sec. 73.A. VEHICLE ON A CONTROLLED ACCESS HIGHWAY

Section 1. The driver of a vehicle proceeding on an access or frontage road of a controlled-access highway on which frontage road traffic is restricted to movement in only one direction shall yield the right-of-way to a vehicle entering or about to enter the frontage road from the highway, unless a separate lane is available to the entering vehicle, provided that at any location where a traffic and engineering study indicates traffic operations would be adversely affected by this requirement, the Department of Highways and Public Transportation may establish alternate traffic controls by the erection of appropriate traffic control devices.

Section 2. The Department of Highways and Public Transportation shall erect appropriate traffic control devices near the exits of controlled-access highways to advise motorists of the requirements of this act.

3. OPERATIONAL AND SAFETY EFFECTS OF TWO-WAY AND ONE-WAY FRONTAGE ROADS

3.1 Introduction

This phase of the study was undertaken in an attempt to identify conditions under which two-way operation of frontage roads results in such undesirable conditions that conversion to one-way operation is justified. The fundamental approach used was collecting accident data at selected ramp-frontage road terminals and observing erratic maneuvers at each location. The nature and frequency of such erratic maneuvers provide basic guidance on remedial treatments. Finally, from these data, unsafe conditions were identified and suggested as warranting conversion of two-way to one-way operation.

This chapter summarizes the findings of this phase of the study.

3.2 Concept of the Analysis Procedure

The concept of the analysis procedure is that erratic maneuvers and accidents would increase with increasing degrees of complexity in the frontage road operational mode and ramp type, as well as with increasing frontage road volume. Figure 2 illustrates this concept.

Since the ramp types for the two operational modes were not identical, it was not possible to statistically test the entire matrix. Rather, ramp type effects within each operational mode were tested and, if no significance was found, the operational modes could then be evaluated.

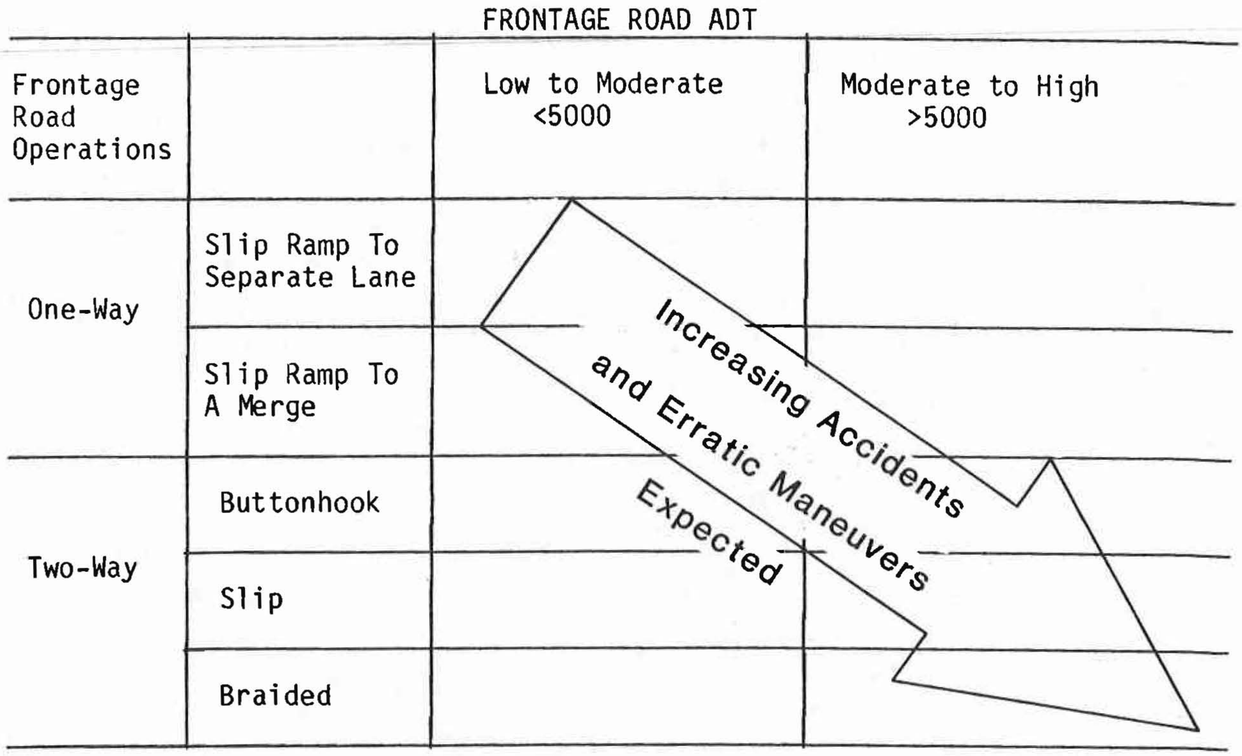


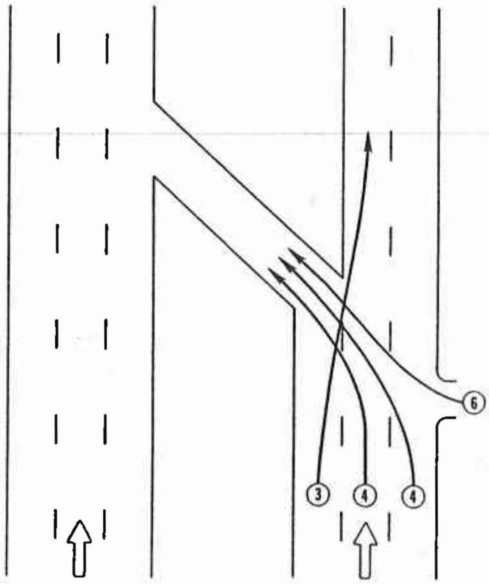
Figure 2
Conceptual Sketch of Analysis Procedure

3.3 Data Collection

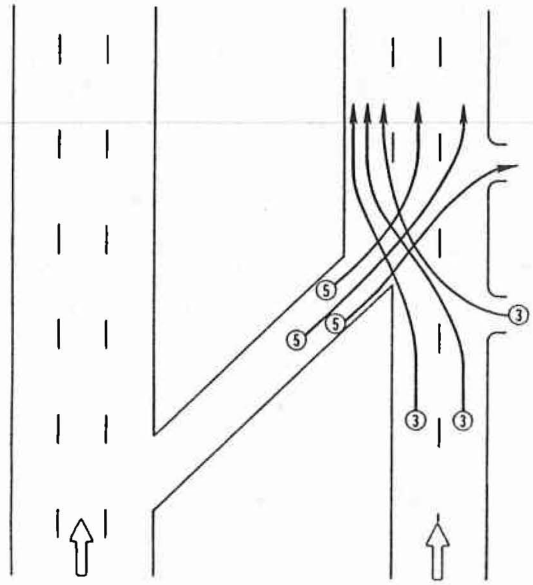
Operational data were collected at each type of ramp described in Figure 2 and illustrated in Figure 3. Data were recorded on color videotape for later reduction in the office. From the observations made during the data collection activities, knowledge of potential maneuvers and a list of erratic maneuvers were developed for each ramp type. These lists were then compared and similar maneuvers grouped together. The resulting list of potential erratic manuevers was developed and each assigned a unique number. The videotapes were then reviewed and each manuever which did not comply with the existing traffic law in Texas was coded into one of the erratic maneuver types. A description of the basic nine (9) erratic maneuver types is presented in Table 1:

Table 1. Definitions of Erratic Maneuvers on Freeway Frontage Roads

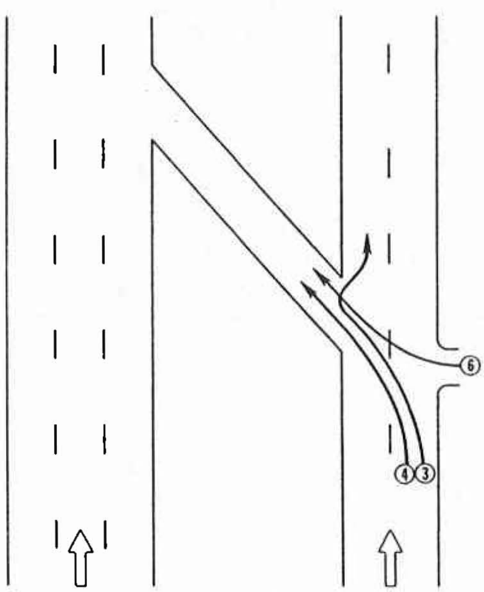
Maneuver Number	Definition
1	Vehicles on the ramp yield somewhere on the ramp. This can be due to the failure of frontage road traffic to yield the right-of-way, or due to driver hesitation.
2	Frontage road traffic fails to yield the right-of-way to ramp traffic. This manuever takes place on both one- and two-way frontage roads.
3	A vehicle on the frontage road that either approaches the gore area of the entrance ramp and then steers out at the last moment or exits the forced entrance lane at the last possible moment by crossing the gore area. This maneuver can occur on one-way or two-way frontage roads.
4	A vehicle on the frontage road crosses one or more travel lanes on the frontage road to enter a slip ramp. The maneuver can occur in two- or three-lane, one-way frontage roads.
5	A vehicle exiting from a ramp into a frontage road (1) crosses one or more travel lanes of a one-way frontage road, or (2) stays in the lane of opposing traffic for some time before moving into the proper lanes for a two-way frontage road, or (3) directly crosses all lanes in order to exit into a side street or driveway. This maneuver can occur for both one- and two-way frontage roads.
6	A vehicle entering a ramp from a frontage road (1) moves into the opposing traffic lanes before entering the ramp or (2) directly crosses all lanes of traffic (both one- and two-way) from a side street or driveway to the ramp.
7	A vehicle on an entrance or exit ramp strikes or clips the curb or shoulder of the ramp with either its left or right front tire. This maneuver takes place on both one- and two-way frontage roads.
8	A vehicle entering a frontage road from a side street adjacent to a braided ramp forces its way into the travel lane of opposing traffic until it is past the ramp channelization. This maneuver can take place only on braided ramp entrances or exits on two-way frontage road sections.
9	A vehicle making a U-turn around the channelization until it ends up going the direction it was originally headed. This maneuver occurs only on braided ramp entrances or exits of two-way frontage road sections.



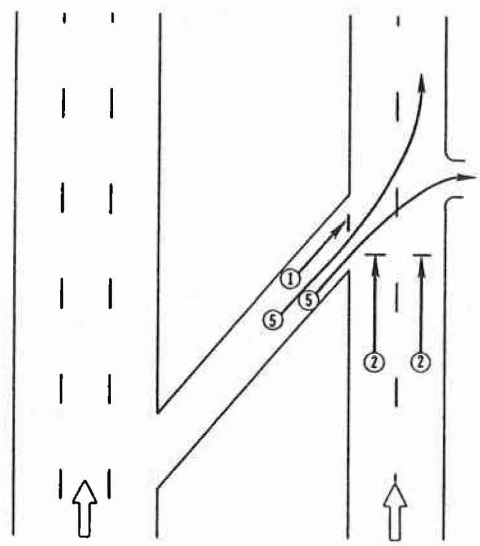
A. Erratic Maneuvers One-Way Operation Slip Ramp to a Freeway from a Separate Lane



B. Erratic Maneuvers One-Way Operation Slip Ramp Off of a Freeway into a Separate Frontage Road Lane

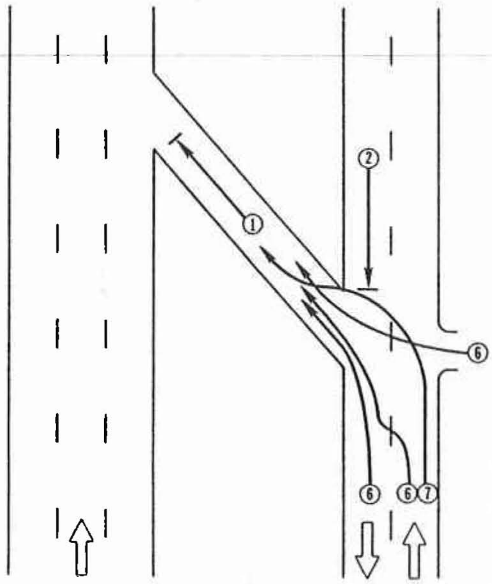


C. Erratic Maneuvers One-Way Operation -- Slip Ramp from a Combined Use Lane

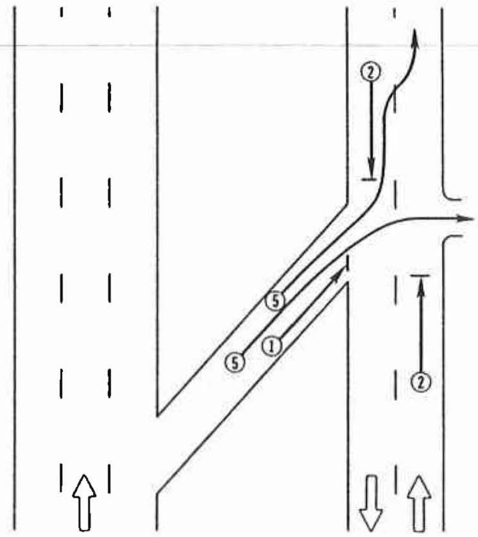


D. Erratic Maneuvers One-Way Operation to a Merge on the Frontage Road

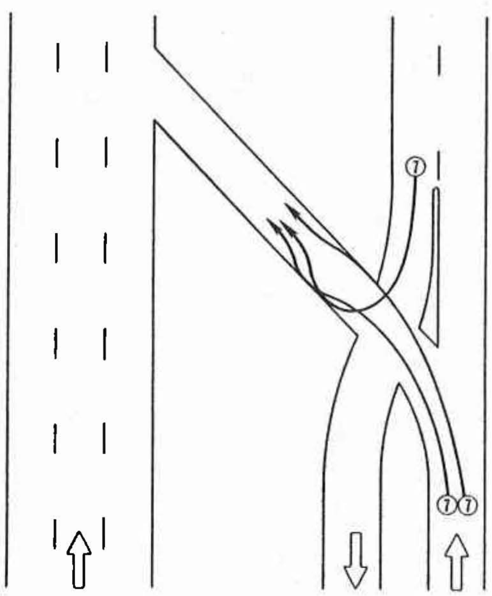
FIGURE 3. Illustration of Erratic Maneuvers



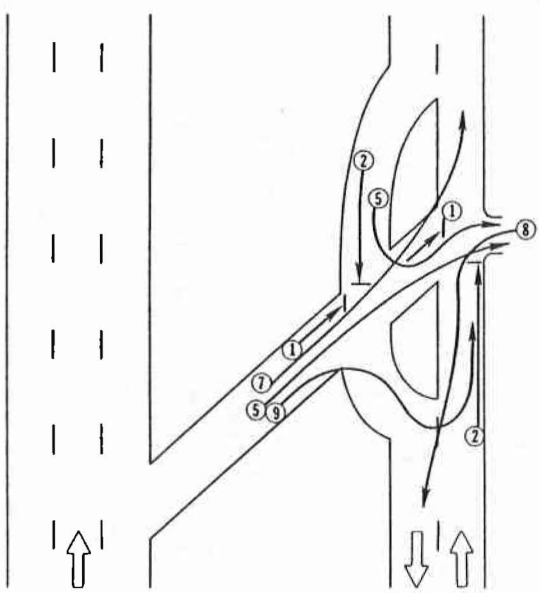
E. Erratic Maneuvers
Two-Way Operation
Slip Ramp Onto a
Freeway



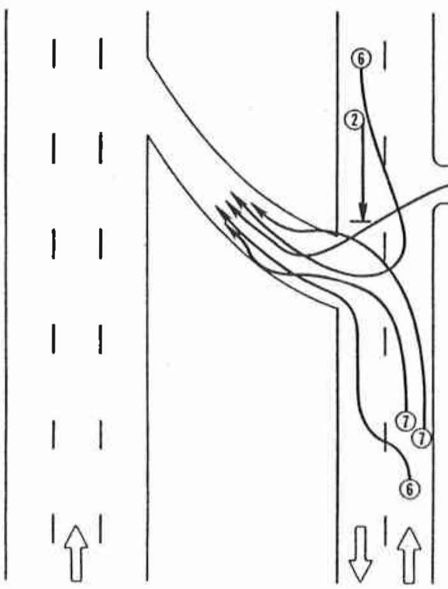
F. Erratic Maneuvers
Two-Way Operation
Slip Ramp to a
Frontage Road



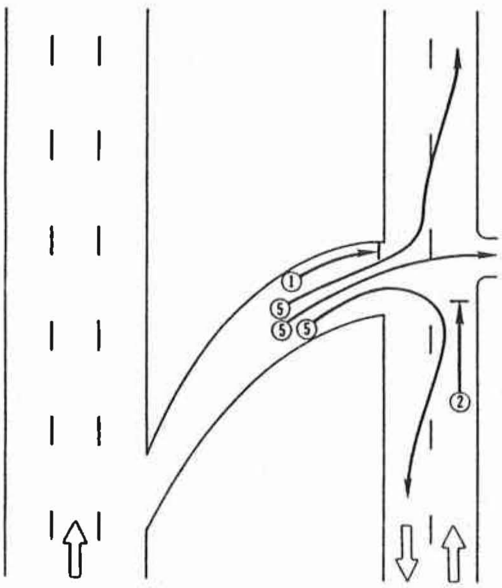
G. Erratic Maneuvers
Two-Way Operation
Braided Ramp Onto
a Freeway



H. Erratic Maneuvers
Braided Exit Ramp
from a Freeway to a
Frontage Road



I. Erratic Maneuvers
Two-Way Operation
Buttonhook Ramp
Onto a Freeway



J. Erratic Maneuvers
Two-Way Operation
Buttonhook Ramp to
a Frontage Road

In addition to the operational data, accident data were extracted from the master tape of the Texas Department of Public Safety. Statistical analysis was performed on these data to: 1) determine if a significant difference exists between ramp types and, if no significant effect was found, 2) determine if a significant difference exists between operational modes.

3.4 Results of the Operational and Safety Studies

3.4.1 Erratic Maneuver Data

A summary of the erratic maneuver data is presented in Table 2.

Table 2. Observed Percentage of Erratic Maneuvers by Ramp Type

Mode of Frontage Road Operation	Type of Ramp	Frontage Road Maneuver	
		Entrance From	Exit To
One-Way	Slip Ramp to or from a Separate Lane	19.0%	41.6%
	Slip Ramp to a Merge or Combined Use Lane	14.0%	33.5%
Two-Way	Buttonhook	12.0%	11.5%
	Slip	18.1%	17.0%
	Braided	10.6%	9.5%

The primary feature of these data is the unusually high percentage of erratic maneuvers associated with slip exit ramps on one-way frontage roads. This is probably due to the general "openness" of the slip ramp designs used in Texas, which in general, allows a much wider range of possible maneuvers.

Based on the erratic maneuvers observed, suggested changes in geometric design and traffic control are suggested in Figures 4 through 11.

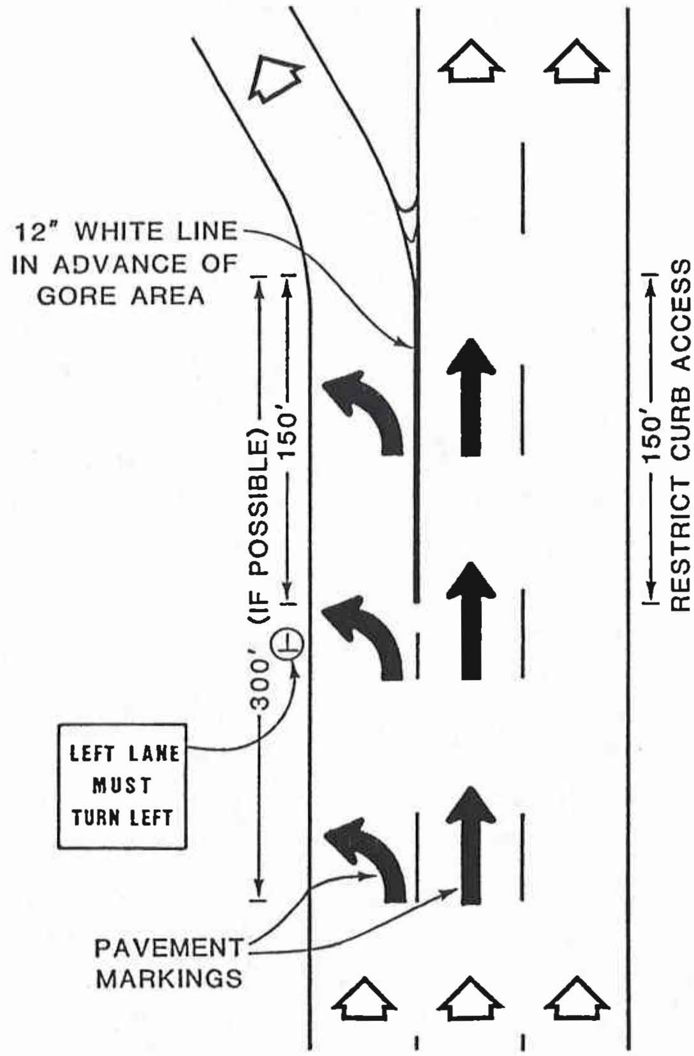


FIGURE 4

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

SLIP RAMP, ENTRANCE FROM A ONE-WAY OPERATION WITH A LANE DROP

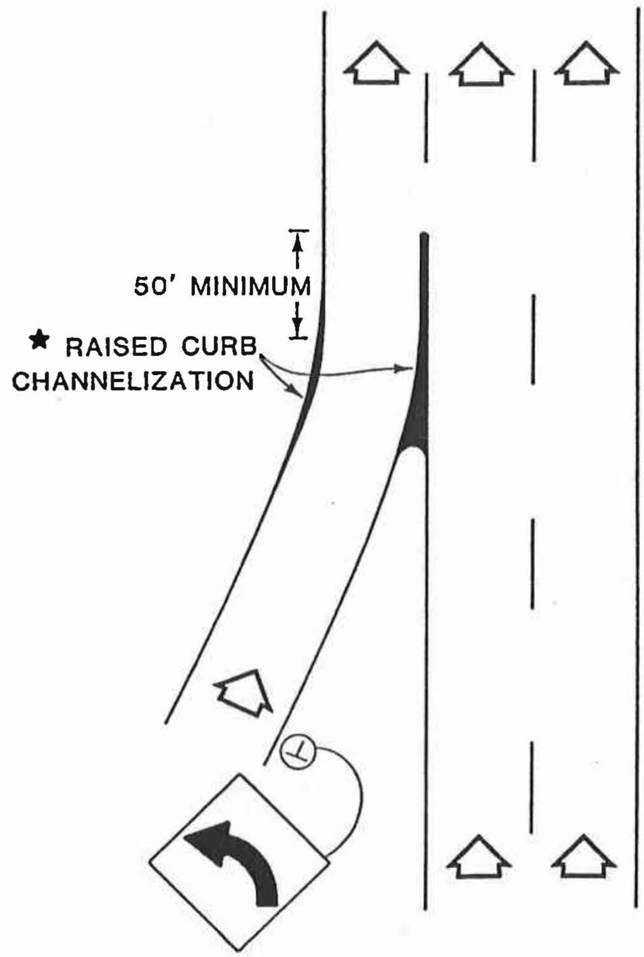


FIGURE 5

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

SLIP OFF RAMP ONE-WAY OPERATION WITH A SEPARATE LANE ON THE FRONTAGE ROAD

★Controlling access, however, provides a better solution than introducing curbs.

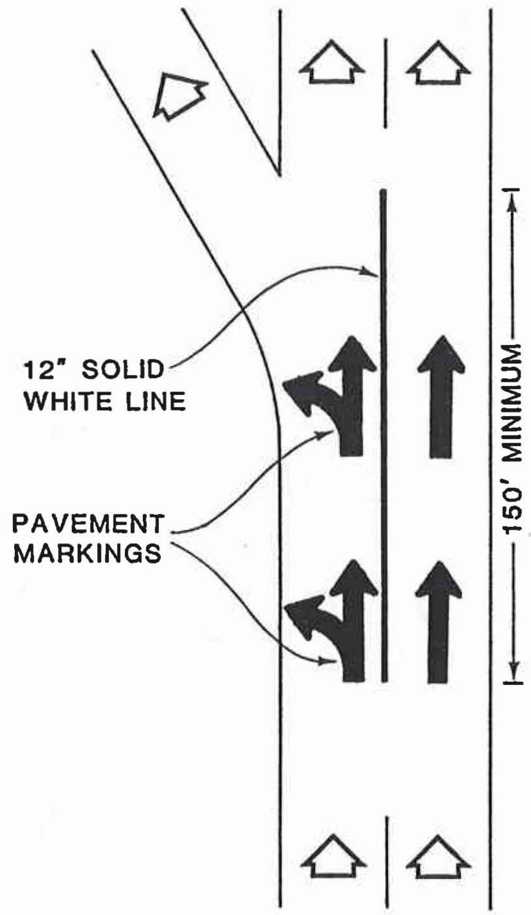


FIGURE 6

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

SLIP ON-RAMP TO A FREEWAY

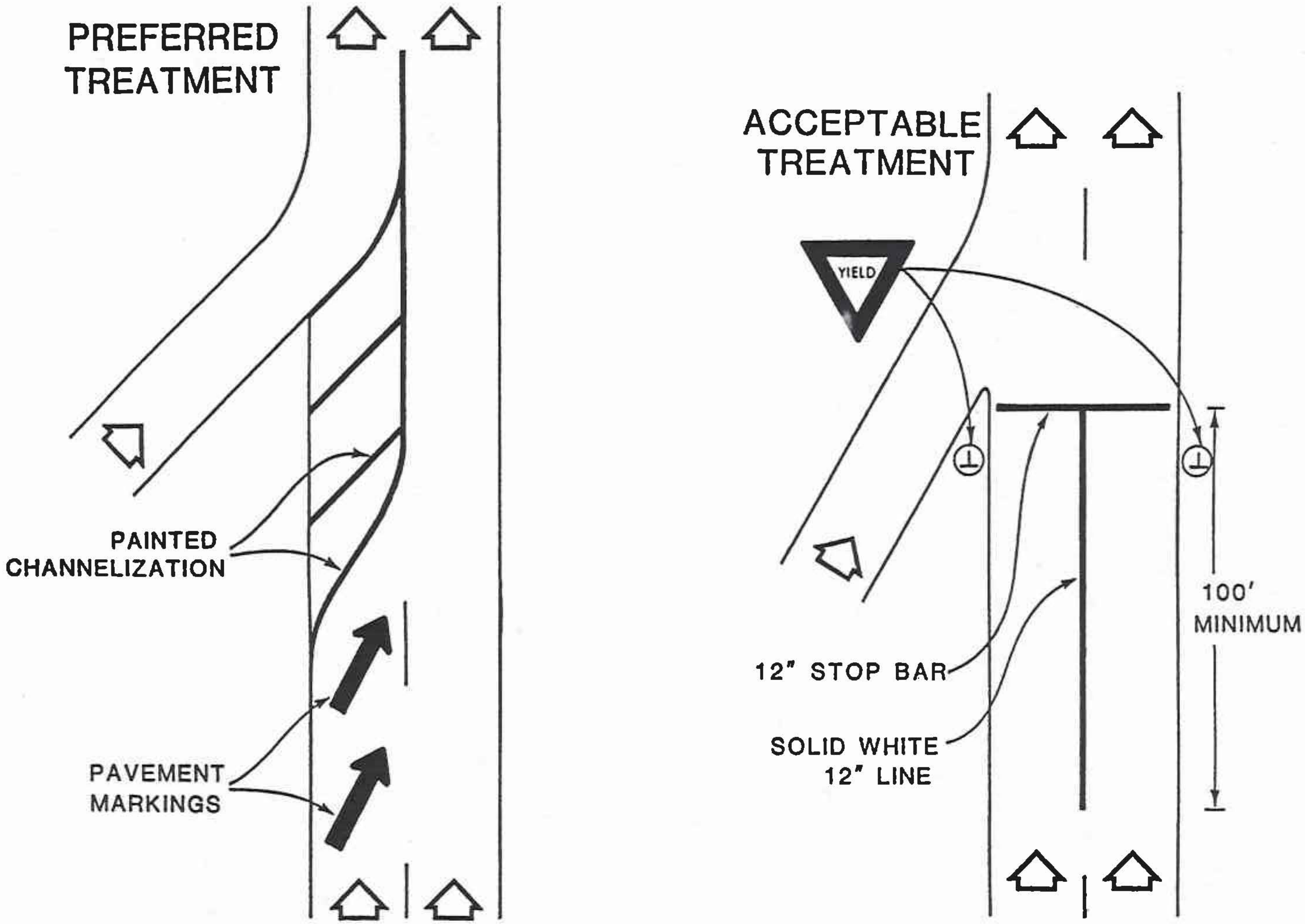


FIGURE 7

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

SLIP RAMP OFF RAMP TO A ONE-WAY FRONTAGE ROAD

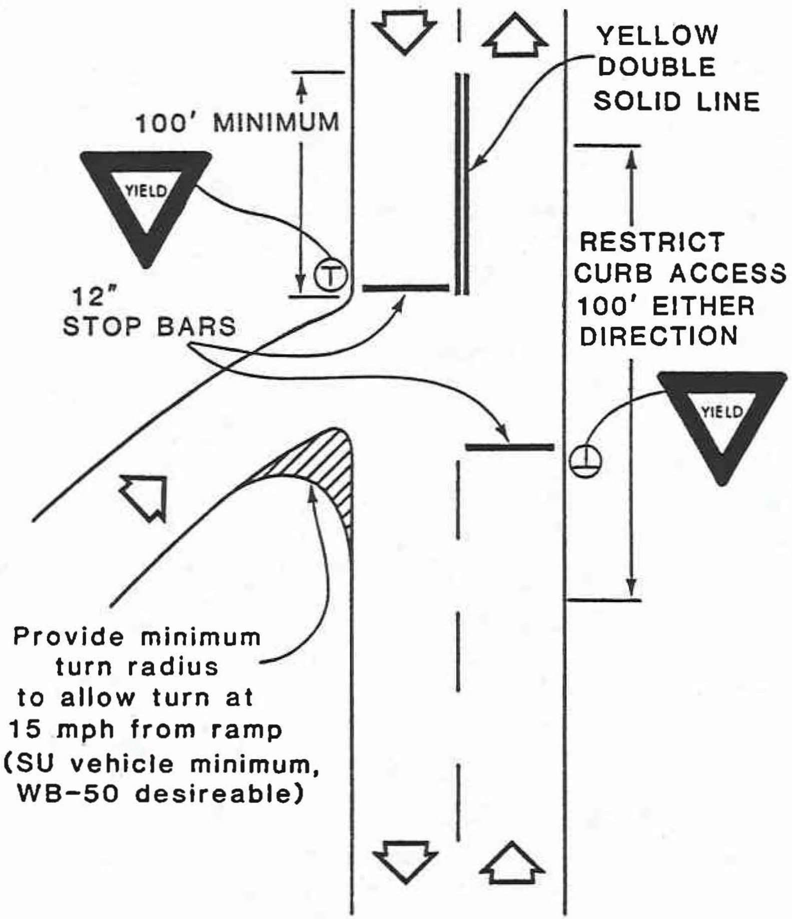


FIGURE 8

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

BUTTONHOOK OFF-RAMP TO A TWO-LANE FRONTAGE ROAD

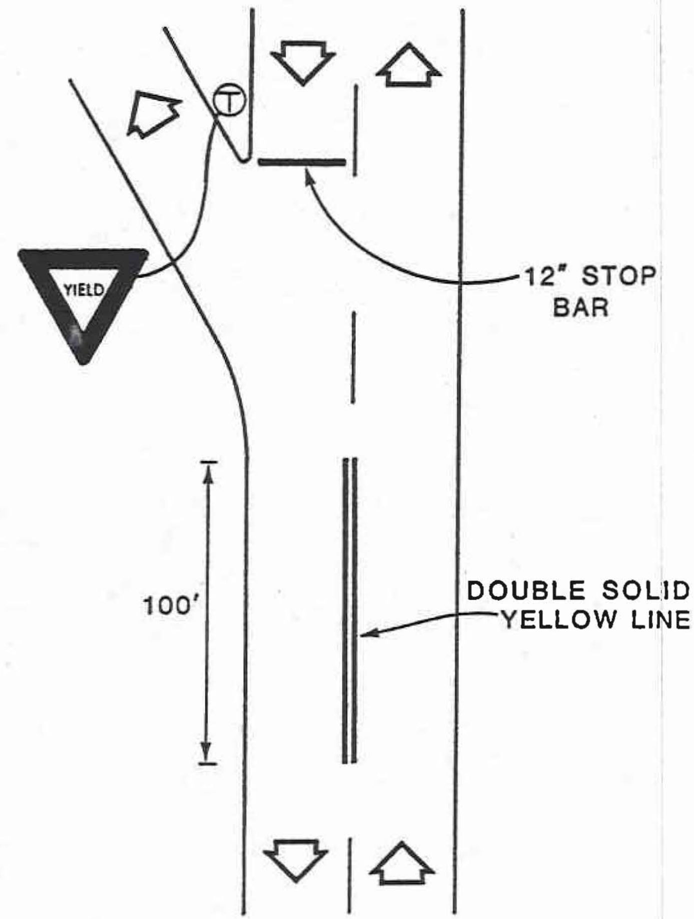


FIGURE 9

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

SLIP ON-RAMP FROM A TWO-WAY FRONTAGE ROAD

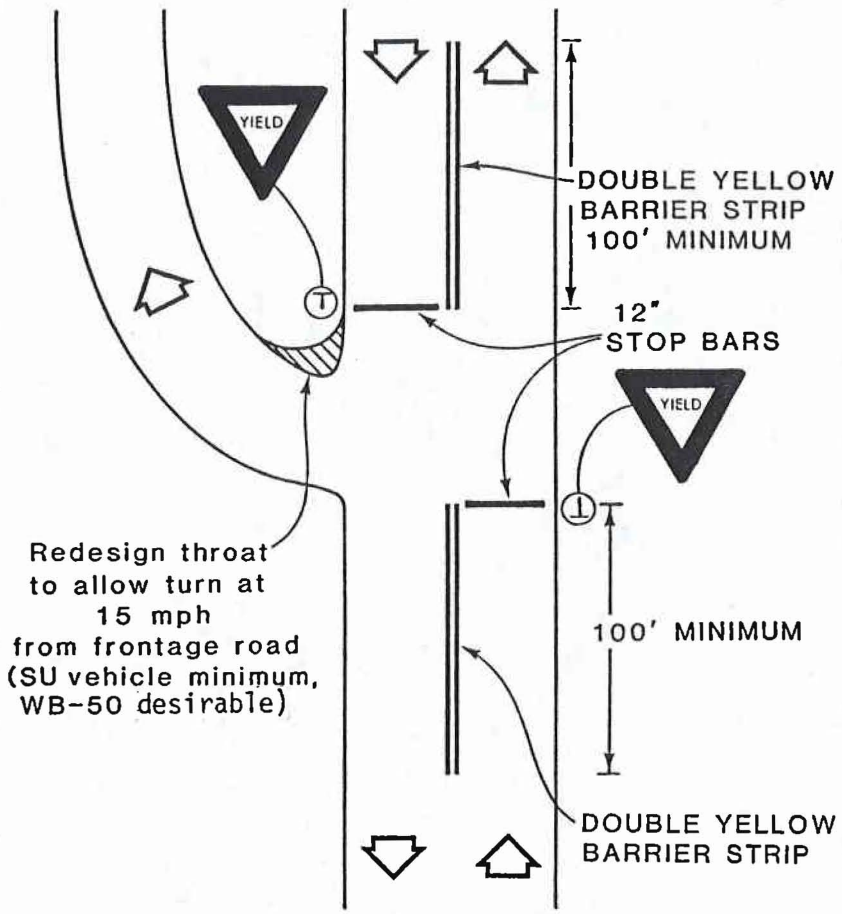
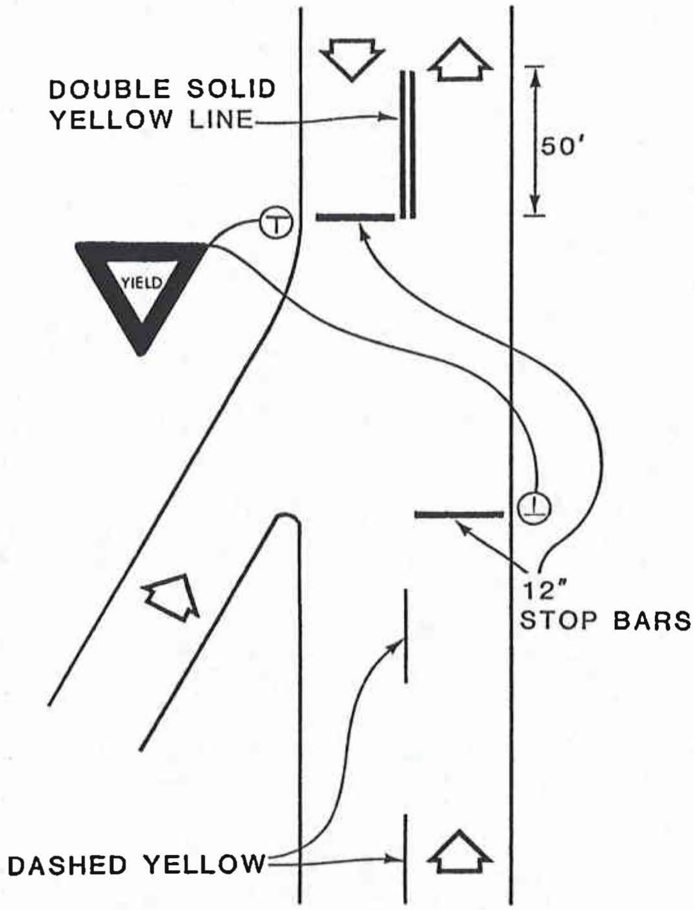


FIGURE 10

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

BUTTONHOOK ON-RAMP FROM A TWO-LANE FRONTAGE ROAD



NOTE: This is not a recommended design. Rather, it is a suggested improvement to reduce the magnitude of the erratic maneuvers observed.

FIGURE 11

SUGGESTED DESIGN AND OPERATIONAL IMPROVEMENTS

SLIP OFF-RAMP TO A TWO-LANE FRONTAGE ROAD

3.4.2 Accident Data

The ramp terminal accident data were generated by adding 0.1 miles to the mile-point of the projected ramp centerline--frontage road centerline intersection--then subtracting one-tenth mile and searching for all accidents occurring in that mile-point range. Accidents not associated with a driveway were termed "ramp related" accidents. Table 3 contains a summary of the accident frequency data (ACC/year).

Table 3. Table of Average Annual Accident Frequency at Various Ramp Types

Frontage Road Operation	Ramp Type	Frontage Road Volume: Low to Moderate Volume		Frontage Road Volume: Moderate to High Volume		
		Rural	Int.	Rural	Int.	Urban
One-Way	Slip Ramp to Merge	0.17	1.00	1.0	0.0	3.0
	Slip Ramp to a Separate Lane	0.50	0.0	NA	1.5	5.0
Two-Way	Buttonhook	0.3	1.7	0.5	0.0	5.0
	Slip Ramp	2.0	1.7	0.0	0.7	NA
	Braided	NA	NA	NA	1.0	0.0

Reviewing Table 3, it is apparent that the intensity of the development and level-of-frontage-road traffic are very significant. Indeed, statistical analysis using the Statistical Analysis System package revealed that only traffic volume level on the frontage road and degree of development (i.e., rural, intermediate, or urban) were statistically significant. No statistically significant effect was identified between the various ramp types.

Traffic volume data were obtained for the study sites late in the project activity, and the breakdown between low to moderate and moderate to high frontage road traffic became apparent. In general, low to moderate classification frontage roads were under 5000 ADT, while those judged as moderate to high were typically over 5000 ADT. A summary of the statistical analysis factors indicating those variables for which statistical significance were found is presented in Table 4.

Table 4. Factors and Factor Significance
Ramp Accident Study

	Factors			
	Frontage Road Operational Mode	Ramp Type	Roadside Development*	Frontage Road Volume*
Levels	One-Way Two-Way	o Slip w/Merge o Slip w/Lane o Slip to 2-way o Braided o Buttonhook	o Rural o Intermediate o Urban	LM MH

*Significant Factors

3.4.3 Ramp Terminal Accidents Findings

From statistical tests of the hypothesis that no difference exists in any of the matrix cells, the following findings can be stated with a high degree of confidence.

1. Both area development and frontage road traffic volume have a significant effect on ramp terminal accidents at the 99% confidence level. Specifically, ramp terminal accidents increase with increasing roadside development and frontage road ADT.

2. The type of ramp does not significantly affect the ramp terminal accident rate regardless of the type of frontage road operation. This finding is not intuitively correct, however; the data available does not support a hypothesis that a real difference exists.

3.4.4 Limitations of the Study

It is cautioned that the findings regarding the insignificance of ramp type and ramp terminal accidents are limited in the sense that the study sites result in an unbalanced statistical design. Certain cells had data missing and some had an unequal number of observations. Also much of the data are qualitative rather than quantitive in nature.

3.5 Erratic Maneuver Data For Terminals

Erratic maneuver data were collected at each of six sites where the operation transitioned from one-way to two-way. Table 5 summarizes the findings.

Table 5. Summary of One-Way to Two-Way Terminal Sites

Type of Traffic Control	Number of Sites	Observed Number of Erratic Maneuver	Total Number of Vehicles Observed
Signs Only	2	1	177
Signs with Channelization	2	0	139
Signal and Signs	2	1	120
TOTALS	6	2	436

The values in Table 5 indicate little, if any, problem with the terminal designs or operational elements of one-way to two-way conversions.

4. TWO-WAY TO ONE-WAY CONVERSION

4.1 Introduction

In recent years, there have been several sections of freeway frontage roads converted to one-way operation. These sites provide an opportunity to test, using the before and after methodology, the accident reduction potential of conversion from two-way to one-way operation. Nine sites were identified for which the roadside development was essentially the same on both sides of the freeway and for which the conversion was accomplished for both frontage roads at the same point in time. The resulting data set is presented in Table 6.

Table 6. Two-Way to One-Way Conversion Accident Data

Site Highway No. District	196-2 IH-35E 18	15-13 US 81 14	168-2 US 87 4	9-11 IH-30 18	271-6 US 90 12	6-6 IH-20 4	34-1 US 83 8	33-6a US 83 8	33-6b US 83 8	TOTAL
Before	91	90	220	16	37	4	47	5	44	554
After	72	74	157	7	39	4	54	5	24	436
Percent Change	-21	-18	-29	-56	+5	0	+15	0	-45	-21
Statistically Significant $\alpha = 0.05$	Yes	Yes	Yes	Yes	NO	NO	NO	NO	Yes	Yes
Frontage Road Volume	11,000	3,400	NA	NA	3,250	4,800	700	3,000	10,000	--
Accidents/Mile	27.6	24.3	47.3	4.8	3.9	4.4	15.7	4.2	36.7	--

The before and after methodology has an inherent weakness in that it must be assumed that no time trend changes occur. In reality, this rarely, if ever, occurs. The alternate comparison is the paired study sites approach which is equally difficult, since two identical locations, both from a geometric and traffic point of view, are virtually impossible.

From Table 6, it should be noted that those sites with 20 or more accidents per mile had a significant reduction in accidents in every case. Those sites with less than 20 accidents per mile had significant reductions only once in five cases. Since accidents are a relative poor basis for decision making, the warranting condition should be rather conservative (i.e., one should be certain that a significant reduction could result). Therefore 20 or more accidents per mile of frontage road (total of both frontage roads) seems an appropriate warranting condition.

Accident data are, however, highly variable. Accidents are random, discrete events which follow a Poisson distribution. The Poisson distribution is unique in that the mean and variance are equal. For mean values greater than 10, the Poisson distribution curve is essentially normal, and normal statistics can be used to estimate the probability of an event occurring. Given a mean of 20 accidents per mile, the number in one year required to be 95 percent certain that the observed value is not just random chance is 20 + 1.96 x 20 or 29.

4.2 Analysis of Potential Accident Reduction Through Conversion From Two-Way to One-Way Operation

Reviewing Table 6, it is apparent that high volume sites tended to have statistically significant accident reductions, while the lower volume situations tended to have no change or a small increased accident rate after conversion. A least squares regression of the available data yielded a best fit linear relationship of:

$$Y_E = -0.0043\ X_0 + 13.2 \qquad r^2 = 0.68$$

where:

Y_E = expected percentage accident reduction

X_0 = ADT on the Frontage Roads (Total of Both)

For large before accident frequencies (60 or more), a 20 percent reduction in accident experience is necessary to be reasonably certain that real change exists, based on the Poisson assumption. The frontage road volume (-ADT) corresponding to a 20 percent reduction can be estimated as:

$$-20 = -0.0043\ (ADT) + 13.2$$

$$ADT = \frac{-20 - 13.2}{-0.0043} = 7720 \text{ vehicles per day}$$

This finding suggests that a total frontage road flow of 7500 (sum of both frontage roads) is needed in order to be reasonably certain that a real reduction in accident experience can be expected. At 5,000 ADT, the expected reduction would be 8 percent.

A Kolmogorov-Smivnov test was performed to test the hypothesis that the accident severity remained essentially the same before and after conversion. No statistically significant difference in accident severity was found.

COST-EFFECTIVENESS OF TWO-WAY TO ONE-WAY CONVERSION

The decision to convert two-way frontage road operation to one-way operation must be made with due consideration of the total impacts of the conversion. These include:

a) The expected reduction of accidents.

b) The added delay to the motoring public.

c) The added fuel cost due to the increased trip length and idle time.

These three factors are, in turn, dependent upon the level of traffic using the frontage road, that using the intersecting roadways, and the average trip length in the area of concern. For this reason, an exact evaluation of the costs is not possible. The guidelines below provide a basis for the evaluation and the example illustrates the use of the procedure.

Basic Values

The following basic assumptions can be used, in the absence of more definitive data, to provide some insight as to the relative benefit that can be associated with a conversion from two-way to one-way operations. Table 7 contains the additional average travel time expected, due to the added travel distance after conversion.

Table 7
Average Added Travel Distance
One-Way Operation vs. Two-Way Operation

Interchange Spacing in Miles	Difference in Travel Time in Minutes One-Way vs. Two-Way
0.5	0.3
0.75	0.5
1.0	0.7
1.25	0.8
1.5	1.0
1.75	1.2
2.00	1.3

Furthermore, the driver will be forced to make one additional stop and one additional left turn, on the average, with one-way as opposed to two-way operation. The type of traffic control in place as well as the traffic volume will influence the delay on each of these maneuvers. The following guidelines are suggested in lieu of more definitive site specific field data on delay.

Table 8
Estimated Delay During Stop and Left Turns Maneuvers

Volume Level	Stop Required	Left Turn Across Traffic Required
Low	0.3 mins.	0.1 mins.
Moderate	0.6 mins.	0.3 mins.
High	1.2 mins.	0.6 mins.

The ASSHTO "Manual on User Benefit Analysis of Highway and Bus Transit Improvements," 1977, suggests $0.48 per passenger car hour for small time increments. Since very small time savings are involved in this computation, this value, updated to reflect inflation since 1975, is appropriate. A car value of $0.90 per hour is used in the example problem computations. Truck value of time is assumed to be $6 per hour.

Using these or more site specific data, the added time costs of one-way operation can be estimated.

The increased complexity of signalization with two-way frontage road operations must also be included in any cost estimate of the conversion from two-way to one-way operation. While no definitive data are generally available on delay associated with two-way signal operation as compared to one-way operation, a reasonable estimate, based on the experience of research personnel, is provided in Table 9.

Table 9
Estimated Added Signalization Delay
Estimate with Two-Way Frontage Road Operation
as Compared to One-Way Frontage Road Operations

Traffic Condition	Added Delay Per Intersection Vehicle
Light	0.2 mins.
Heavy	0.5 mins.

Accident reduction benefits can be estimated from Figure 12 which is extracted from Report 288-3.

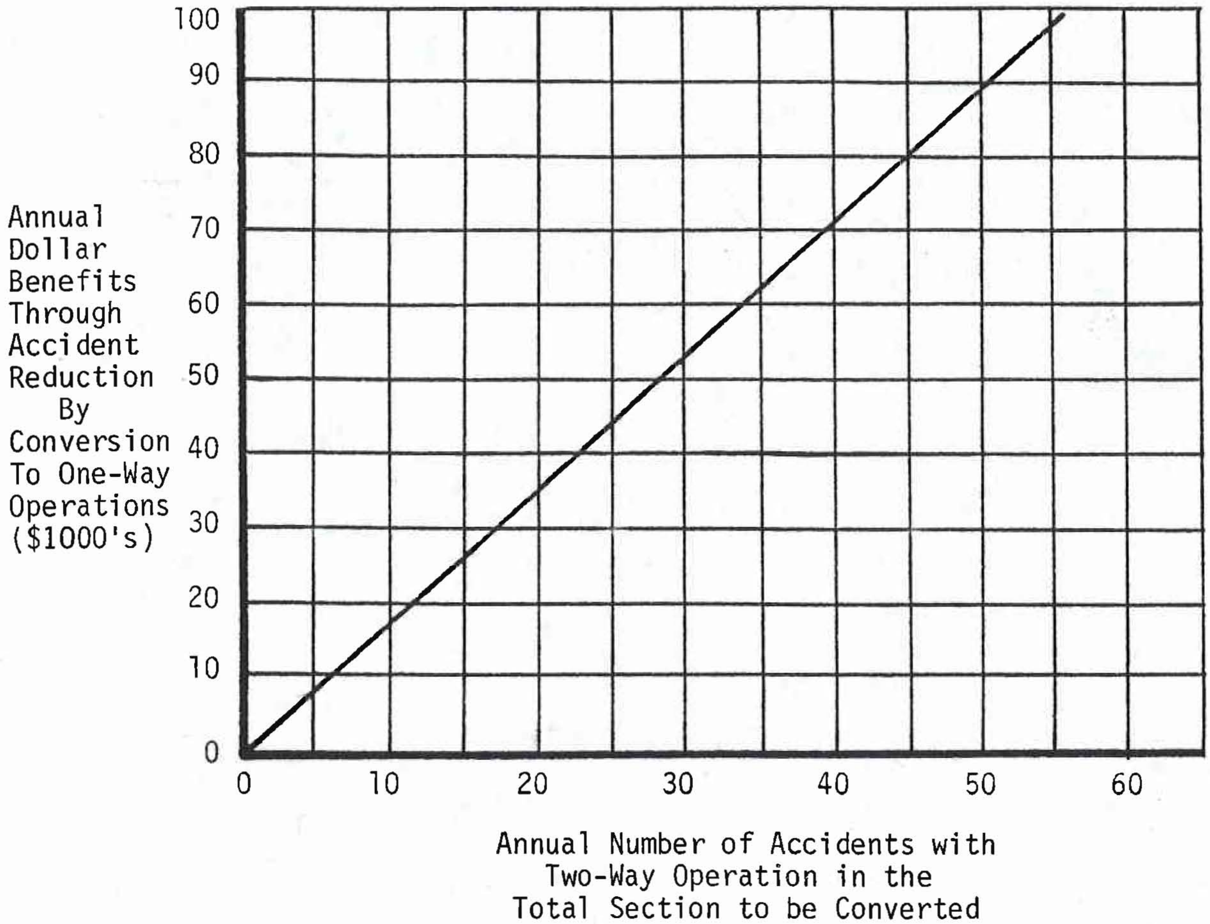


Figure 12. Annual Dollar Benefits Through Accident Reduction After Conversion to One-Way Operation vs. Annual Number of Accidents Before Conversion

Added Fuel Cost

The additional automobile fuel consumed in the added travel distance due to one-way operation can be estimated based on the following values:

Automobiles (1, 2)

Stopped Time Fuel Consumption	0.01 gallons per hour of Delay
Running Speed Fuel Consumption	0.05 gallons per mile

These values are typical passenger car fuel consumption rates, and different values from those above should be used when they seem more appropriate. Truck fuel mileage, based on 8 miles per gallon of fuel, can be estimated as:

Trucks

Stopped Time Fuel Consumption	0.02 gallons per hour of Delay
Running Speed Fuel Consumption	0.13 gallons per mile

Where truck characteristics differ substantially from those referred to above, another value should be used.

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1 Robert Herman and Leonard Evans, "A Simplified Approach to Calculations in Fuel Consumption in Urban Traffic Systems," General Motors Laboratory, Traffic Engineering and Control, Vol. 17, Nos. 8 and 9, August and September, 1976.

2 R. Akcelik, "A Mathematical Analysis of Route Choice," J.Y.K. Luk (Editor), ARRB Workshop on Traffic Control, Bisbane, Australian Road Research Board, Research Report No. 92, pp. 33-60, August, 1978.

EXAMPLE PROBLEM
SOLUTION

GIVEN	FIND
ADT = 5000 VPD (Total of both frontage roads) Percentage Trucks = 6% Interchange Spacing = 1.5 miles Sum of Cross Street Volumes = 20,000 vpd Ramp Modification Costs = $40,000/mile Average Accidents Per Mile = 20.0	o Added Annual Travel Time Costs o Added Annual Fuel Costs o Annual Accident Reduction Benefits o Benefit/Cost Ratio of Conversion

SOLUTION

Cars = 0.94(5000) = 4700 vpd
Trucks = 0.06(5000) = 300 vpd
Added Travel Time: Moving 3 Minutes/Vehicle; Stopped 0.3 Minutes/Vehicle

Annual Delay Estimate

Cars

Moving Delay: $4700\ (1.0)\ \frac{1}{60}\ (365) = 28{,}592$ vehicle-hours/year

Stopped Delay: $4700\ (0.3)\ \frac{1}{60}\ (365) = 8{,}578$ vehicle-hours/year

Trucks

Moving Delay: $300\ (1.0)\ \frac{1}{60}\ (365) = 1{,}825$ vehicle-hours/year

Stopped Delay: $300\ (0.3)\ \frac{1}{60}\ (365) = 548$ vehicle-hours/year

Annual Delay Cost

Cars: (28,592 + 8,578) $0.90/hr = $33,453
Trucks: (1,825 + 548) $6/hr = 7,119

Added Annual Fuel Costs (Fuel @ $1.10/gallon)

Cars: Moving - 28,592(0.05)1.10 = $1,573
Stopped - 8,578(0.01)1.10 = 94
Trucks: Moving - 1,825(0.10)1.10 = 201
Stopped - 548(0.02)1.10 = 12

Annualized Cost of Ramp Conversion

0.1(40,000) = $4,000

Total Delay And Fuel Cost = $38,732/year

Accident Cost Reduction Benefits (From Figure 12)

Benefits = $36,000

Signalized Intersection Benefits of One-Way Operation (Table 9)

$$\text{Cars:} \quad (18{,}800)(0.2)\left(\frac{1}{60}\right)(365)\$0.90 = \$25{,}733$$

$$\text{Trucks:} \quad (1{,}200)(0.2)\left(\frac{1}{60}\right)(365)\$6.00 = \underline{10{,}950}$$

Total Intersection Vehicle Delay Reduction Benefit = $36,683

Benefit/Cost Ratio of Conversion

$$B/C = \frac{72{,}683}{38{,}732} = 1.88$$

5. WARRANTING CONDITIONS

5.1 Definition of a Warrant

A warrant is defined as "the situation or conditions under which the proposed improvement would, in all probability, result in an improvement in the operational efficiency and, therefore, the safety of the site." A warrant does not necessarily mean that the improvement will be made. Rather, it is the first of two evaluations:

1) Is the warrant satisified? and if "yes"

2) Is the improvement economically justified?

For this reason, the warranting conditions are for practical purposes set as low as is reasonable, given the available facts. The accident analysis indicates that only total frontage road volume and degree of roadside development were statistically significant. Thus, these two factors are the logical ones to be used in a warranting condition statement.

Given that the best fit relationship suggests that for daily traffic volumes below 3000 ADT, no reduction in accident experience should be expected; and given that a 7500 ADT value would be required to be reasonably certain a significant reduction in accidents would result, some volume between these two limits would be the logical warranting condition. In rural areas, due to the added trip length and lower typical traffic volumes, the warranting condition should be near the upper end of the range. In urban areas, the interaction with roadside development and greater frequency of conflict suggest a somewhat lower value, but not as low as 3000 where no accident reduction would be expected.

Thus, for rural areas an ADT of 7500, while unlikely, should be required. In urban areas, a value of 5000 ADT seems to be an appropriate compromise between the extreme limits of the range and might be appropriate if delay is not considered. Delay costs so dominate the cost structure that no economic warranting condition exists using the HEEM values for time.

5.2 Suggested Warrants for Two-Way to One-Way Conversion

Based on the accident analysis and the erratic maneuver data, the following warranting conditions are suggested.

WARRANT 1 - FRONTAGE ROAD VOLUME WARRANT

Rural Area* (0% to 30% roadside development)

A total frontage road ADT (sum of both frontage roads) exceeding 7500 vehicles per day warrants conversion to one-way operation.

* Undeveloped rural areas within the extraterritorial jurisdiction area of a city are to be considered as Intermediate Areas for purposes of this analysis.

Intermediate Area (30% to 60% roadside development)

A total frontage road ADT (sum of both frontage roads) exceeding 6000 vehicles per day warrants conversion of the frontage roads to one-way operation.

Urban Area (60% to 100% roadside development)

A total frontage road ADT (sum of both frontage roads) exceeding 5000 vehicles per day warrants conversion to one-way operation.

WARRANT 2 - ACCIDENT EXPERIENCE WARRANT

Two-way frontage roads with an average accident experience over the last three years of 20 accidents or more per mile or a one-year history of 30 accidents per mile or more warrants conversion to one-way operation.