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16. Abstract

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
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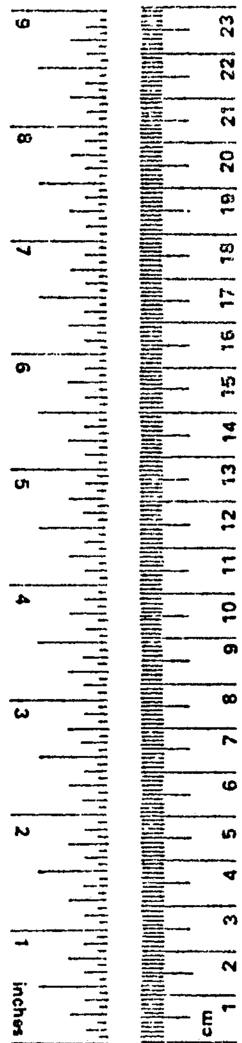
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

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		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
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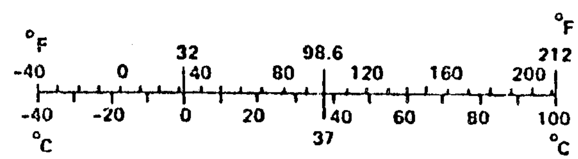

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

INCREASED CAPACITY OF HIGHWAYS AND ARTERIALS THROUGH THE USE OF GRADE SEPARATED RAMPS

by

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Research Report Number 376-2F
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College Station, Texas 77843

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ABSTRACT

This study analyzes grade separated ramps serving frontage roads to investigate operational and geometric requirements, to prepare guidelines on benefit and cost analysis and to propose warranting conditions. It has been observed that grade separated ramps can be a cost effective solution to weaving on freeways created by contiguous on- and off-ramps, and for access to and from some high demand points on the frontage road.

IMPLEMENTATION STATEMENT

This study has analyzed grade separated ramps to investigate operational and geometric requirements, to prepare an assessment method and to propose warranting conditions. It has been found that grade separated ramps can be a cost effective solution to weaving on the freeway created by contiguous on- and off-ramps, and for access to and from some high demand points on the frontage road.

Four examples were analyzed, two of which are based on partial data from past grade-separated ramp projects. The analysis procedure proposed here can be used to screen potential grade separated ramp sites. However, a detailed analysis using site geometrics, counts and other project specific data would be required to properly assess the viability of any one project.

ACKNOWLEDGEMENTS

The basis of this research report proceeds from those involved in the planning and design of several grade separated ramps in Texas. Benefit analyses of two grade separated ramps were prepared by William R. Stockton, Janet A. Nordstrom, Darrell W. Borchardt and Andrew J. Ballard. In the current study various persons from District 2 in Fort Worth, D-8, the Records Management Branch and other SDHPT offices provided willing support and advice. The guidance and assistance provided by Robert Stone and Rick Denney during the study is specially recognized.

SUMMARY

Grade separated ramps connecting with a frontage road have the potential to eliminate ramp weaving creating mainlane congestion and/or to improve access to or from some point on the frontage road, in a cost effective manner. However, a trade-off may exist because grade separated structures located between freeway mainlanes and frontage roads may delay or prevent the addition of exterior freeway lanes to increase the mainlane capacity.

When weaving or access problems can not be solved at-grade by ramp elimination or relocation, grade separated ramps merit consideration. If freeway expansion is contemplated and a grade separated ramp is being considered, four options should be analysed:

- reject the grade separated ramp in favor of eventual expansion,
- build a grade separated ramp and remove when mainlane expansion becomes necessary,
- build a lower design type grade separated ramp and/or modify the frontage road to leave enough space for eventual mainlane expansion, or
- build a grade separated ramp within the existing outer separation leaving enough space for the eventual addition of a freeway mainlane.

Frequently, grade separated ramps connecting with a frontage road are considered after a freeway has been operating for a number of years, and a weaving or access function of the freeway is recognized as a problem. If a freeway was built or modified with a narrow outer separation, the last option may not be feasible.

Current standards indicate a desirable outer separation width of 80 feet or more. A grade separated ramp can be built within a width at least 63 feet using SDHPT lateral safety standards. An outer separation 75 feet or wider allows construction of both, a grade separated ramp and an exterior mainlane. However, nearby ramps along the freeway topography and other geometrics affect the design of a grade separated ramp and determining physical

feasibility requires geometric and operational analysis. Construction cost of simple grade separated ramps appear to vary between $1.24 million and $1.79 million.

Benefits of grade separated ramps solving a weaving problem are accrued very different than those of a grade separated ramp improving access. A grade separated ramp replacing a weaving section can restore mainlane capacity, eliminate outer lane queues and on-ramp queues. Travel time savings can be very large because of the great number of vehicles affected.

Benefits of grade separated ramps improving access to a cross street or trip generator along the frontage road result from motorists using the freeway for a longer period of time while bypassing one or more signalized intersections. Secondary benefits are accrued by other motorists using the signalized intersection bypassed by those provided with improved access.

Two computer models are used to analyze operations and quantify benefits. FREQ8 has been used to simulate freeway operations. Six tables have been prepared to provide estimates of travel time of a freeway segment operating with a weaving section and operating with a grade separated ramp. These are intended for screening of potential grade separated ramps.

Another model, PASSER III-84, has been used to analyze delay incurred by motorists at diamond intersections. Benefits accrued by motorists bypassing such intersections and by those remaining once the grade separated ramp is built can be estimated using this model. Two tables have been prepared to provide estimates of delay to all motorists using the intersection. However, data required to use the tables is almost as simple to obtain as data to run the model and use of the model, rather than the tables, is encouraged.

The present worth of savings accrued through periods of 5, 10, 15 and 20 years indicate that it does not take fully saturated conditions to justify the cost of building a grade separated ramp and the methodology provided is emphasized rather than example results. It is concluded that grade separated ramps can be a cost effective solution to weaving on the freeway, and access to or from some point on the frontage road.

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INTRODUCTION

Freeway ramps connecting with a frontage road provide for the safe and smooth transition of traffic entering and exiting the freeway. As traffic grows with time, some on-ramps connected with an auxiliary lane to a closely following off-ramp become unable to discharge traffic into the freeway mainlanes. The combined effect of traffic on the freeway's outside lane, the on-ramp and the off-ramp is to create queues of vehicles on the outside lane and on the on-ramp. Such queues are the source of significant delay to motorists, increased fuel consumption and accidents. When at-grade options are not available or are undesirable, a possible solution is to grade separate the on- or the off-ramp to make the off-ramp traffic to exit first and the on-ramp traffic to enter the mainlanes further downstream. The grade-separated ramp pair effectively removes the short weaving section.

In other instances intensive development at locations adjoining the freeway may benefit from an additional ramp, allowing more direct access to or from the freeway. This is particularly desirable where such access traffic has to go through a signalized intersection while travelling along the frontage road. The signalized intersection is a source of delay to access traffic plus access traffic can significantly increase the delay of all other traffic using the signalized intersection. When other at-grade options are not possible or undesirable, an alternative is to build a new grade separated ramp over an existing one to provide more direct access.

A benefit cost analysis can help to justify this type of facility. Benefits are generally assessed over a 20 year or longer period of time. Through this method it can be demonstrated if a grade separated ramp is economically justifiable over the design life of the facility. However, other considerations may affect project feasibility. Of particular concern is the foreseen need to add mainlanes to increase capacity. When mainlane capacity is exhausted such ramp can become a barrier to add an exterior lane. If freeway expansion requires removal of the grade separated ramp within the design horizon, say a 20 year period, full benefits may never be achieved. Therefore, four options exist where grade-separated ramps are being considered:

- reject grade separated-ramps in favor of eventual mainlane expansion,
- build a grade separated-ramp and remove when mainlane expansion becomes necessary,
- construct a lower design type grade-separated ramp and/or modify frontage road to leave enough space for eventual mainlane expansion, or
- build a grade-separated ramp within the existing outer separation leaving enough space for the eventual addition of a freeway mainlane.

Available assessment procedures do not include guidelines for making these decisions, but does provide quantitive data to aid decision makers in selecting one of the four options.

Background

During the past few years some Districts of the Texas State Department of Highways and Public Transportation (SDHPT) have built grade separated ramps to improve access and mainlane operating conditions. Some of these have been built within a narrow outer separation that exists between mainlanes and a frontage road. The latter ramps virtually occupy all the width of the outer separation to maintain standard lateral clearances.

Examples are found in San Antonio at the southwest quadrant of the interchange between I-410 and I-10, and on I-410 between US-281 and the Airport Expressway. The first is an example of a weaving solution while the latter is a combination of two separate facilities, one providing access and the other egress, to a major shopping mall. Another is being built by District 15 in Houston at the northwest quadrant of I-45 and Airline Road. Other examples exist in Austin, Fort Worth, and El Paso although each one's characteristics are somewhat different.

A search using an "Automated Information Retrival System" did not contribute in a significant degree to document this type of treatment. This is not to imply that grade-separated ramp pairs have not been used but that they are considered a very special design with limited applications. The Green Book (AASHTO, 1984) gives general guidelines on freeways and ramps but does not directly address this issue. Yet, a photo of a viaduct freeway shows the use of a grade-separated ramp where the exit ramp is located in advance of the entrance ramps. It is explained that such configuration eliminates a weaving problem on the freeway and minimizes congestion on the local streets by isolating the entering and exiting traffic.

Reports by the Texas Transportation Institute (Nordstrom, 1982 and Borchardt, 1983) document the experience, benefits and costs of two grade separated ramps based on readily available information from each site. Overall, there is lack of guidelines for making decisions on this type of improvement.

The general study concept calls for documenting the freeway and/or frontage road operating characteristics throughout the range of conditions typical of existing cases. Computer models have been used to simulate operating conditions with and without the use of grade-separated ramps. FREQ8, a computer model developed at the University of California, has been used to analyze the weaving case and PASSER III-84, a computer model prepared by the SDHPT and TTI, has been used to analyze the access case.

Based on a range of loadings, present and future benefits of a grade separated ramp pair can be estimated. If construction costs can be estimated, and benefits are available on a yearly basis, the break even year when benefits will match or exceed costs can be calculated. This planning estimate provides decision makers with information to select one of the four options previously proposed. Procedures have been included to provide a simple method to analyze potential sites. Geometric characteristics are discussed to provide a visual perspective of this type of ramp pair and the approximate cost of "typical" grade separated ramps.

DESIGN CHARACTERISTICS

Grade-separated ramps are used to eliminate weaving in the mainlanes or to improve access to a cross street. In spite of the very different purposes served, geometric and other design characteristics are very similar. Figure 1 shows an aerial view of a grade separated ramp. The whole idea is to make use of the other separation of the freeway, that is, the area between the freeway mainlanes and the frontage road, to provide the ramp pair. This section explains geometric and other design characteristics of grade separated ramps.

Outer Separation and Ramp Width

The outer separation allows for ramp connections to and from the freeway. The outer separation must be fairly wide at interchanges to permit a high standard of ramp design. The desirable width of the outer separation, measured between lane lines, is 80 feet or more in urban areas but narrower widths may be used. The ability to provide a grade separated ramp and/or to add an exterior mainlane within an existing freeway (short of major reconstruction) is largely dependent on the outer separation width.

A grade-separated ramp pair using current SDHPT standards (SDHPT, 1981) requires about 63 feet minimum of outer separation. Ramps on structures should have a minimum width of 24 feet to include a passing lane and shoulders; a minimum at-grade ramp width of 22 feet is specified. Retaining walls and shoulders required by the freeway and frontage road to build a grade-separated ramp add to the minimum. Minor variations from these minimums may be used to match topography or other special conditions on a case by case basis. Table 1 presents some general geometric characteristics of five grade separated ramps in Texas.

A practical application of these standards can be observed in Figure 2. Here a westbound entrance ramp to I-410 in San Antonio has been built over an off-ramp to form a grade separated ramp. Prior to improvements the existing on-ramp allowed southbound traffic on the Airport Expressway to enter I-410

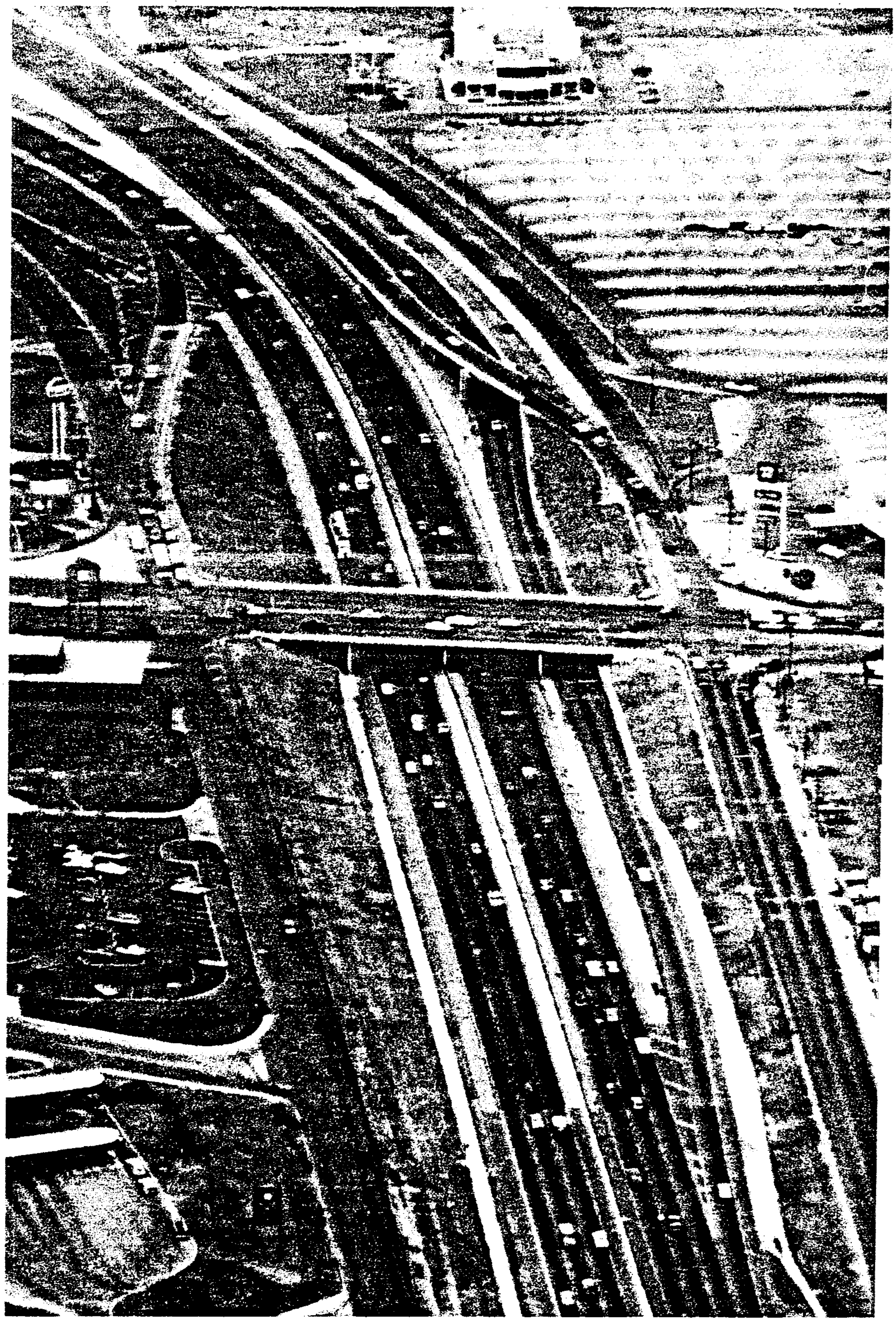


Figure 1. Aerial View of Grade Separated Ramp Connecting Freeway Mainlanes with A Frontage Road

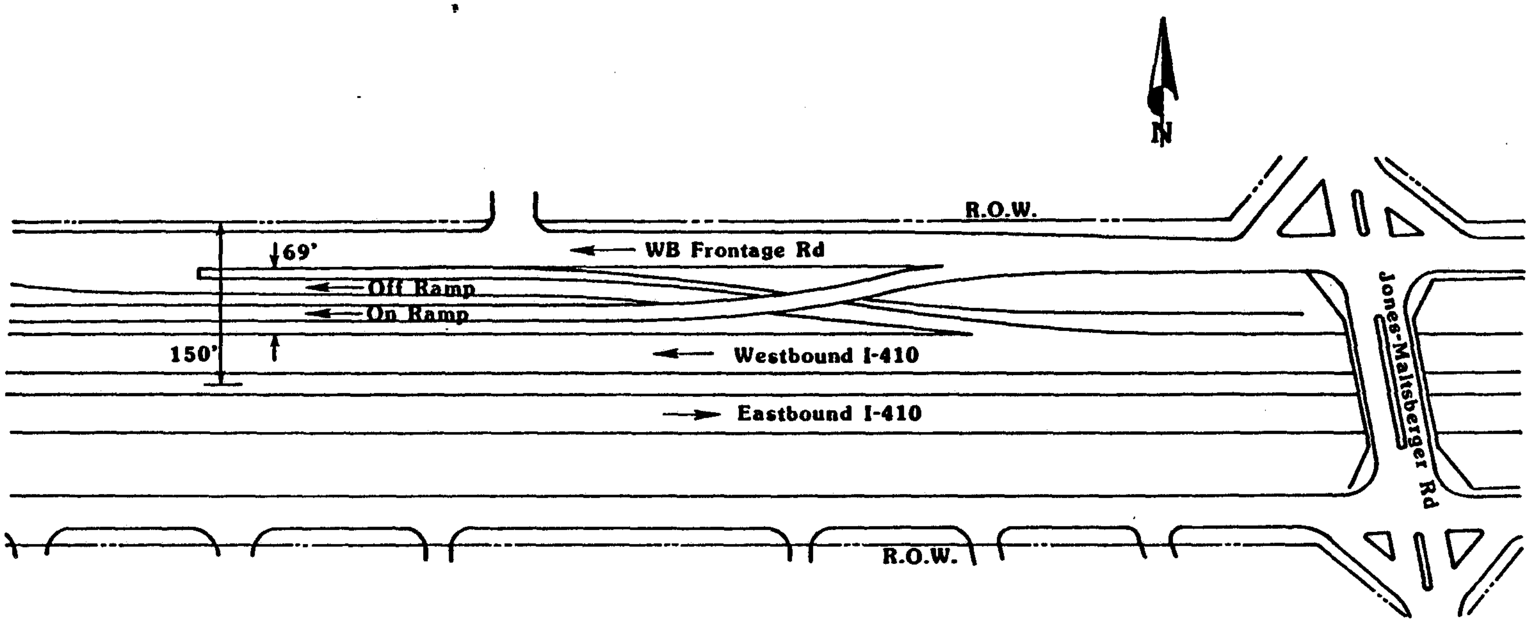


Figure 2. Grade Separated Ramp to Improve Access

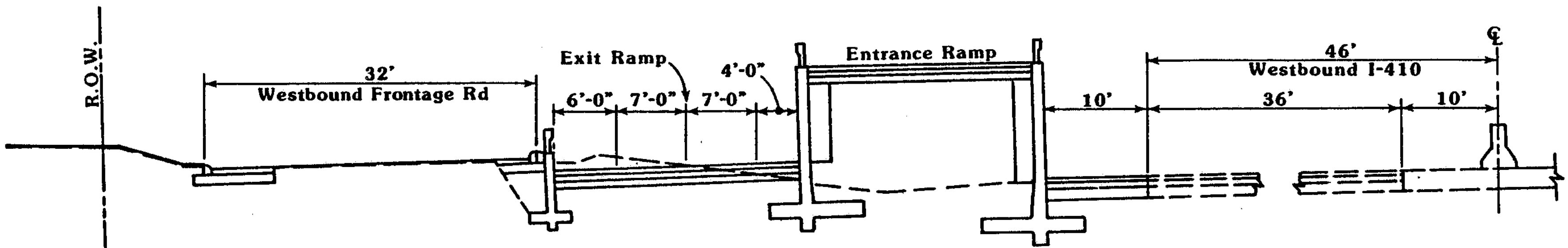
westbound. The grade-separated ramp also allows westbound I-410 traffic to exit the freeway and access the North Star Mall. The frontage road operates with two westbound lanes and the freeway with three westbound mainlanes.

Table 1. Geometric Characteristics of Grade-Separated Ramps

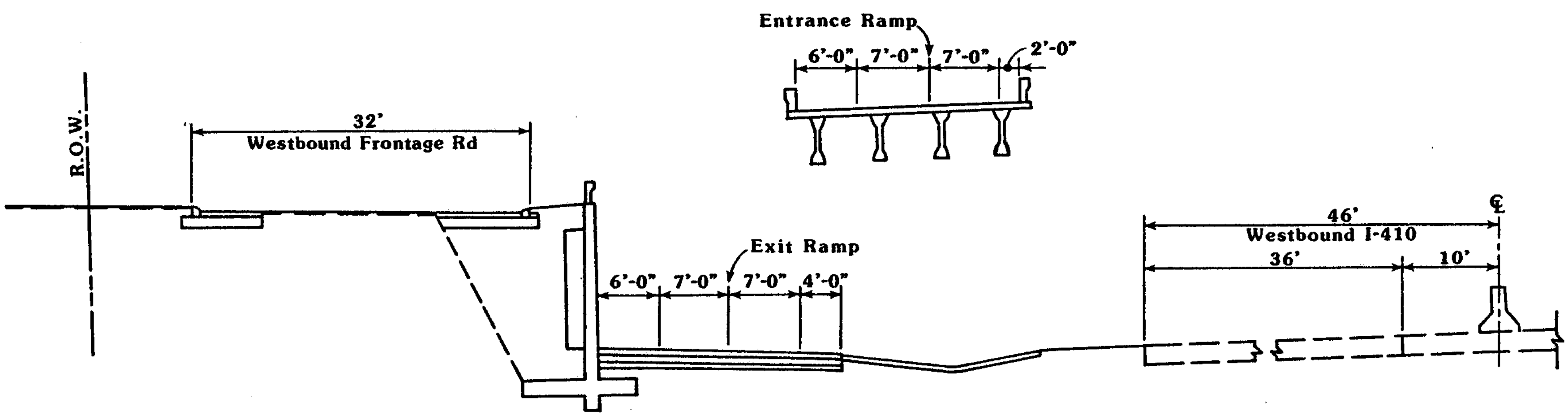
Location	Outer Sep. Width (feet)	Bridge Length (feet)	Bridge Width (feet)	Max. Hor. Curve (Degrees)	Max. Vert. Grade (percent)
1. WB I-410, San Antonio West of Jones-Maltsberger Rd.	69	570	24	3.5	7.9
2. EB I-410, San Antonio East of McCollough Ave.	70	680	26	4	6.6
3. EB I-410, San Antonio West of I-10	90	301	24	5	6.3
4. SB Loop-1604, San Antonio, South of Lookout Rd.	135	240	26	5	7.3
5. SB I-35, Austin, North of US-290	220	699	27	5	6.1

Source: SDHPT design drawings

All the space between the outside shoulder of the mainlanes and the inside shoulder of the frontage road has been taken by the grade separated ramp. The outer separation is about 69 feet as may be abserved in Figures 2 and 3. The use of reversed curves by both the on- and off-ramps reduces the structure length but does not affect the outer separation width. The on-ramp bridge is 570 feet long and 24 feet wide, including guard rails which add 1 foot on each side. The at-grade off-ramp is 24 feet wide. On-ramp horizontal curves are 3 to 3 1/2 degrees while off-ramp horizontal curves are only 2 degrees. The on-ramp begins with vehicles climbing a 7.9 percent grade until passing over the off-ramp, to go down a long 1.3 percent grade to merge with westbound mainlane traffic.



LOOP 410 STA. 796+30



LOOP 410 STA. 800+00

Figure 3. Cross Sections of Grade Separated Ramp

The available outer separation is wide enough to provide a grade-separated ramp but in the way built, not wide enough to add an extra mainlane to I-410. The ramps are located at the minimum distance possible from the mainlanes and an additional 12 feet separation would be required to provide the extra lane.

An outer separation of 75-feet wide seems to be about the minimum lateral space required to provide a grade separated ramp and an extra main-lane. Thus, a typical outer separation 80-foot wide should provide enough space to satisfy both needs without sacrificing SDHPT's lateral safety standards.

Slightly narrower outer separations may be used with narrower ramps. Twenty foot wide ramps together with large radius horizontal curves can be built within outer separations as narrow as 57 feet and still provide adequate space for passing a stalled vehicle. This criteria is valid for traffic conditions with sufficient single unit trucks (SU) to govern design, and consideration for an occassional semitrailer (AASHTO, 1984). Another lane would add 12 feet and thus, it is possible to accommodate a grade separated ramp and an extra mainlane within a 70 feet outer separation.

On the other hand, instead of reducing ramp widths and associated safety clearances, the outer separation may be made wider. Narrower frontage road lanes, paving gutters or moving lanes closer to the right-of-way boundary are possible options. Each case should be analyzed based on local conditions that may indicate the most economic or otherwise desirable option. Figure 4 shows a plan view of a proposed grade separated ramp within a wide outer separation. The outer separation is approximately 135 feet wide at the crossover point of the ramp pair. The bridge length is just 240 feet and requires only one bent to straddle the on-ramp. The bridge structure including guardrails is 26 feet wide. Maximum horizontal curve of each ramp is four degrees at the crossover.

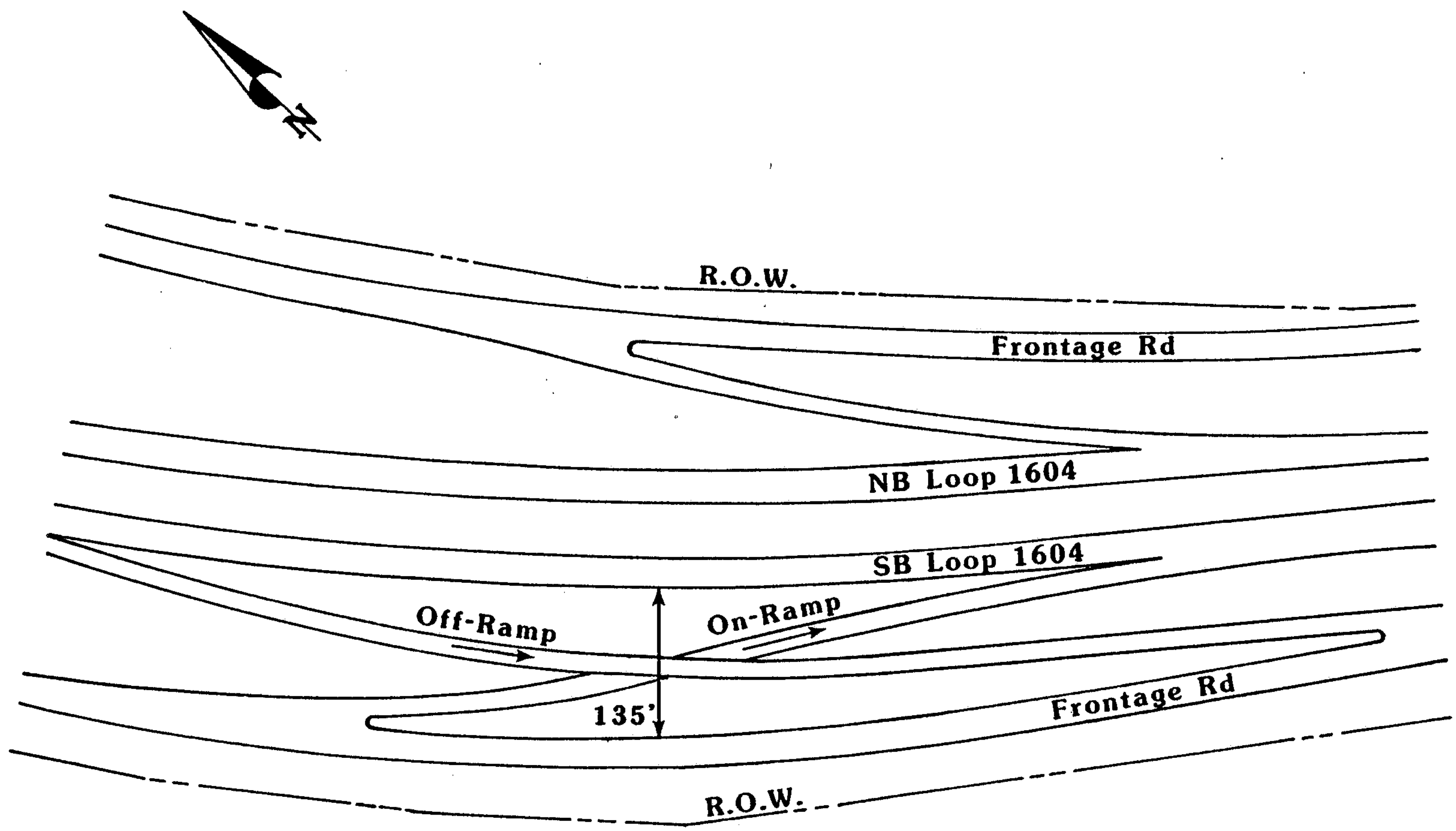


Figure 4. Loop 1604, South of Lookout Road, San Antonio

Other Geometric Considerations

Another factor affecting the ability to provide a grade separated ramp is the distance between adjacent ramps serving the mainlanes. One of the objectives of providing a grade separated ramp is to eliminate weaving. This option moves the diverge point of exiting traffic upstream, or the merge point of entering traffic downstream, to remove the weaving section on the freeway. Quite often this lateral displacement may affect an upstream or downstream ramp.

Schemes that require a long deceleration ramp prior to bridging over or under another ramp may require the diverge point to be 1000 to 2000 feet upstream from the existing merge. The Green Book (AASHTO, 1984) recommends a minimum ramp terminal spacing of 1600 feet between an on-ramp and an off-ramp. Also, moving upstream the diverge point of an off-ramp may affect another off-ramp. The Green Book recommends a minimum ramp terminal spacing of 800 feet between off-ramps. Further, the traffic volumes generated by the upstream on- or off-ramp should be carefully examined to ascertain that the bottleneck removed by the grade separated ramp will not be recreated elsewhere.

The on-ramp of a grade separated ramp pair will require a similar analysis. The addition of an acceleration lane may impact a downstream ramp. Fortunately, the typical spacing of properly designed ramps should allow enough flexibility to locate a grade separated ramp in such way that impacts to nearby ramps are minimized.

Grade-separated ramps designed for access also may find spacing problems but generally at the upstream or downstream end only. The existing ramp would most likely have a deceleration or acceleration lane (or taper) already in place. Therefore, only one of the two speed adjustment lanes needs to be constructed.

An access off-ramp built to form a grade separated ramp pair may affect the frontage road traffic. Separation from the nearby intersection should be analyzed to insure that ramp traffic may weave, stop and queue prior to the nearest signalized intersection. Adequate storing length should prevent a possible "spillback" of ramp vehicles into the freeway (Messer, 1976). The absolute minimum separation for this operation to be performed safely varies between 260 to 580 feet, depending on the frontage road and on the exit ramp volumes.

Several other factors such as topography affect ramp design. However, these are typical of all freeway ramps and design characteristics are addressed elsewhere.

Construction Cost

Construction costs vary by geographic location, materials of construction, etc. For planning purposes two types of structures may be considered: those with a very narrow outer separation requiring a long bridge as shown in Figure 2, and those with a wider outer separation where a shorter structure is possible as shown in Figure 4.

Direct construction costs can be broken down as follows:

- the bridge structure,
- the at-grade ramp and approaches to the bridge,
- signs, markings, and utility relocations.

Multiplying the sum of their cost by a factor of 1.2 accounts for mobilization, engineering and contingencies.

Table 2 shows a breakdown for the two types of grade separated ramps considered. The short bridge example is $1.24 million while the long bridge is $1.79 million. Note that the bridge as well as the at-grade ramp is more expensive with the long bridge example. However, ramp length is a function of grade, acceleration and even sight distance, and the cost may vary depending on site specific characteristics.

Table 2. Construction Cost of Grade-Separated Ramps

(1985 million dollars)

Major Item	Short Bridge (240 feet)	Long Bridge (570 feet)
1. Bridge structure	0.17	0.41
2. At-grade ramp	0.81	1.02
3. Signs & utility	0.05	0.06
4. Engineering & Contingencies	0.21	0.30
Total	1.24	1.79

Sources: Cost estimate for project control 2452-03-051 in Bexar County by District 15, SDHPT dated 3/25/86; cost estimate for project control 720-03-051 in Harris County by District 12, SDHPT, dated 1/07/86; SDHPT Bridge Division Statistical Report for 1984; 1984 Dodge Guide to Public Works for Heavy Construction (McMahon, 1983).

In the absence of more specific design information, the above costs may be used for planning purposes.

BENEFIT ANALYSIS

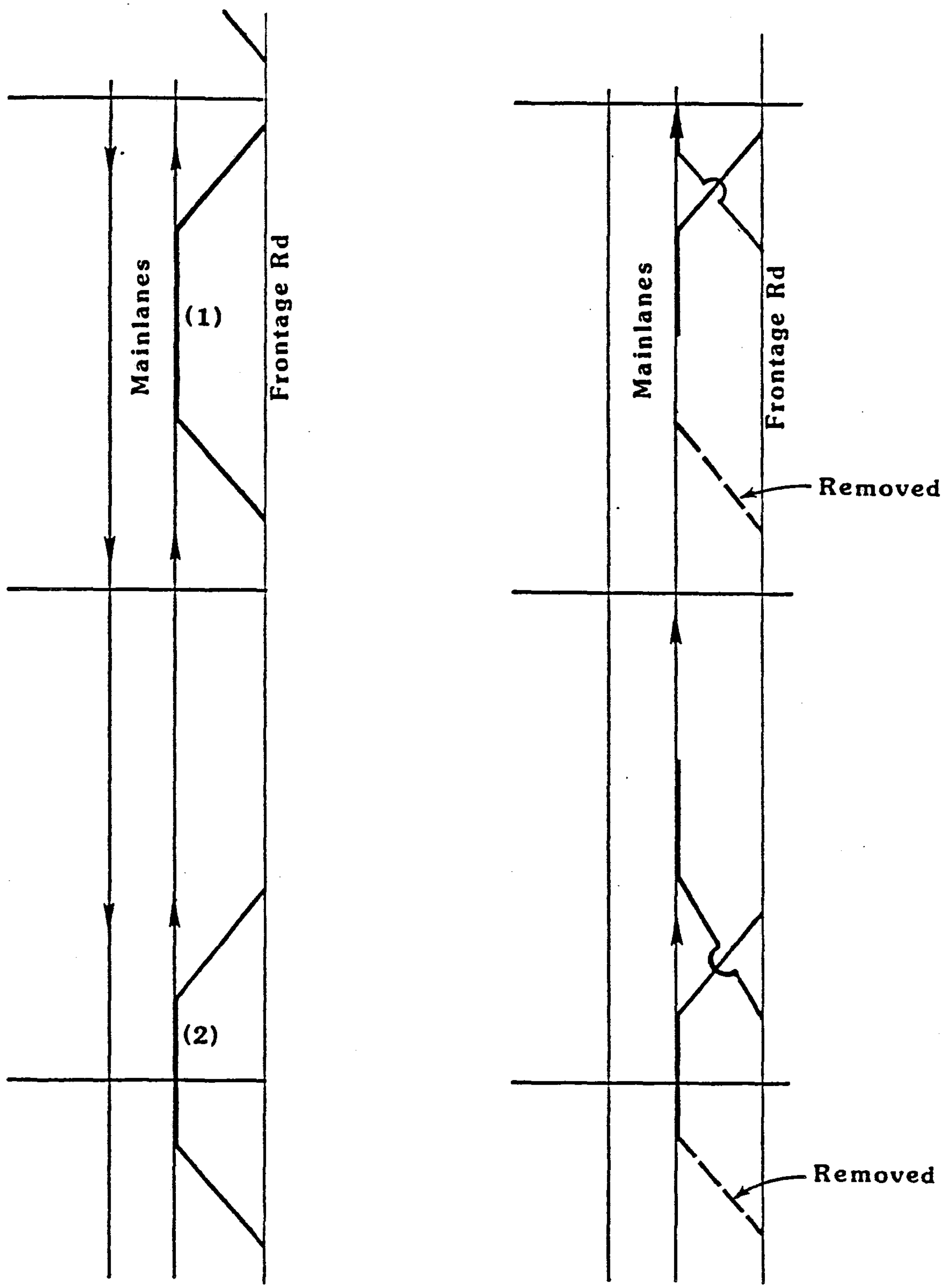
Geometric characteristics are very similar between the two type of uses proposed here for grade separated ramp pairs, but benefits are accrued very differently. The freeway function to be improved and the location where the grade separated ramp pair is to be built influences benefits.

Ramp Function

A grade separated ramp used instead of a weaving section can restore the capacity of the mainlanes bringing it close to the section capacity without ramps. At low mainlane and weaving volumes the improvements do not make much difference in motorists travel time. As weaving increases the effect is to reduce mainlane capacity, creating a bottleneck that results in long queues of vehicles. Queues may also form along the frontage road and may interfere with adjacent signalized intersections.

Freeway weaving by traffic using on- and off-ramps may occur (1) between cross streets and, (2) at cross streets, as shown in Figure 5a. Grade separated ramps can eliminate the weaving, as shown in Figure 5b. The ramp not related to the grade separation may need to be removed but such action depends on site specific conditions such as the location of nearby ramps, topography, etc. The ramp to remain may be modified as required. The grade separated ramp should have a minimum distance of 500 feet between the exit and entrance gores (AASHTO, 1984) but a capacity check should be made.

The grade separated ramp used to provide access to or from a cross street or major trip generator reduces delay to motorists that have to use frontage road instead of the freeway to get to their destination. Figure 6 shows this concept. When many motorists need to get off the freeway in advance of their destination, to travel through a frontage road and go through one or more signalized intersections, the delay incurred may be significant. Usually this condition exists because geometrics preclude adding one more at-grade ramp. However, a grade separated ramp may be accommodated with little effect on nearby ramps. The primary benefit is



a) Weaving

b) Weaving Eliminated

Figure 5. Grade Separated Ramp Options to Reduce Weaving

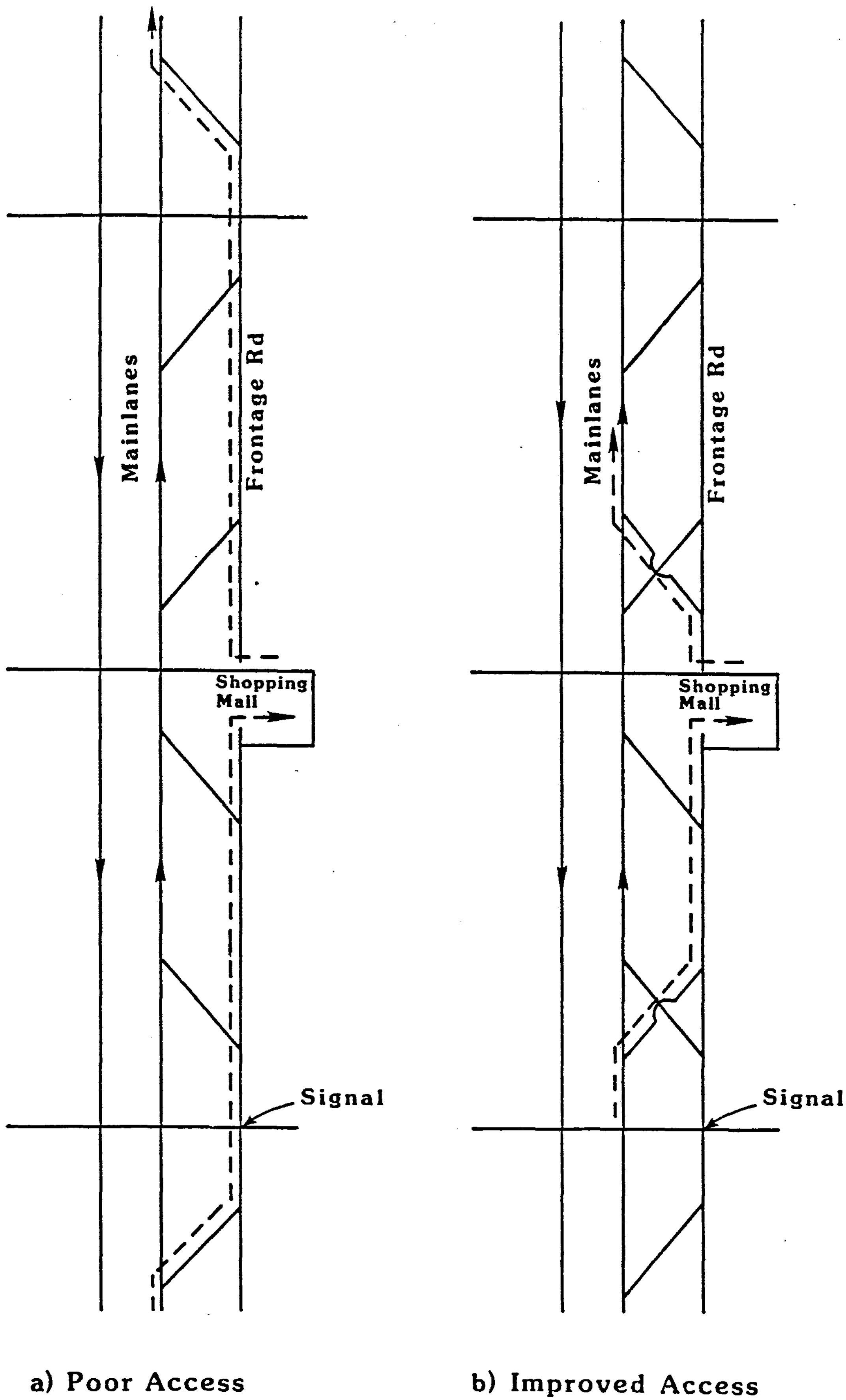


Figure 6. Grade Separated Ramp Options to Improve Access

accrued by motorists using the faster freeway lanes. Secondary benefits are received by motorists still using the signalized intersection but that operates with a lower volume of traffic. Similar benefits will be received by motorists provided with a grade separated ramp to enter the freeway, instead of having to travel the frontage road further downstream to access.

Simulation

Benefit analysis provides a quantifiable measure of savings achieved through the use of a grade separated ramp. The principal benefit comes from the reduced motorists travel time. Savings in travel time can be assigned a dollar value using current evaluation procedures (AASHTO, 1977; SDHPT, 1981).

Benefit analysis of grade separated ramps has been based on the function served (weaving or access) by each ramp. Computer models (FREQ8 and PASSER III) have been employed to simplify the calculation of time savings under expected field conditions. Several variables affecting travel time have been selected for each ramp function to measure travel time. Each variable has been broken down into a minimum number of categories that define selected or expected field conditions, i.e., single lane ramp volumes of 400, 800, 1200 and 1500 vehicles per hour.

Other benefits include fuel savings and accident reduction. These should be considered in the assessment of grade separated ramps, as will be explained later.

Freeway Weaving

A computer model, FREQ8, developed by the University of California at Berkeley, has been used to simulate freeway operations. This model is particularly useful because the effect of ramp merge and diverge on queuing and travel time can be analyzed. Also the weaving effects of entering and exiting traffic can be simulated.

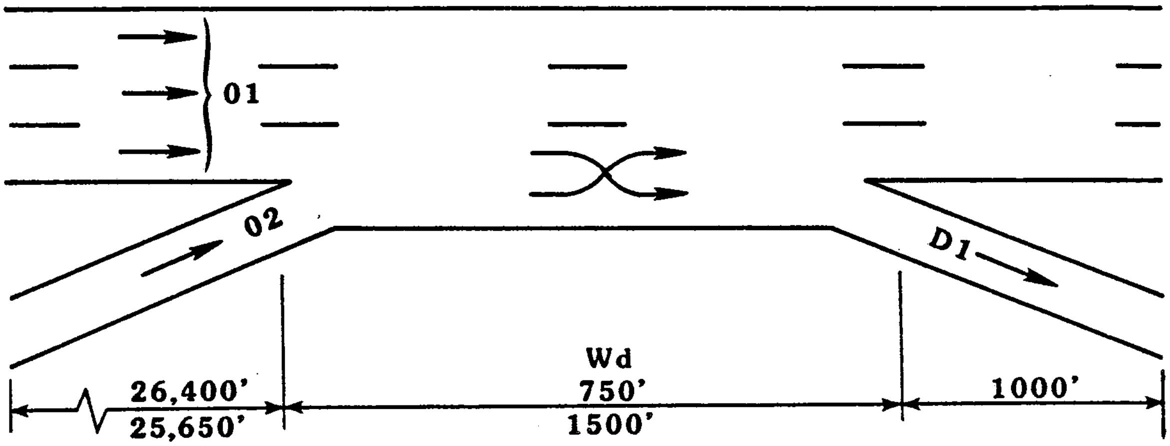
Several assumptions have been made to input the model. Figure 7 shows the geometric inputs to FREQ8. The freeway segment is approximately 5.2 miles long. The weaving subsegment is either 750 feet or 1500 feet long. The 750 feet distance is a very short weave similar to that which was in existence on I-410 in San Antonio prior to improvements. The 1500 feet distance is close to the minimum recommended by AASHTO. With the grade separated ramp, distance between the exit and entrance is assumed to be 1050 feet. A downstream subsegment is 1000 feet long and an upstream subsegment is about 5.0 miles in length. The downstream subsegment allows the model to properly consider ramp effects while the upstream is available for queuing as congestion increases.

Other assumptions include:

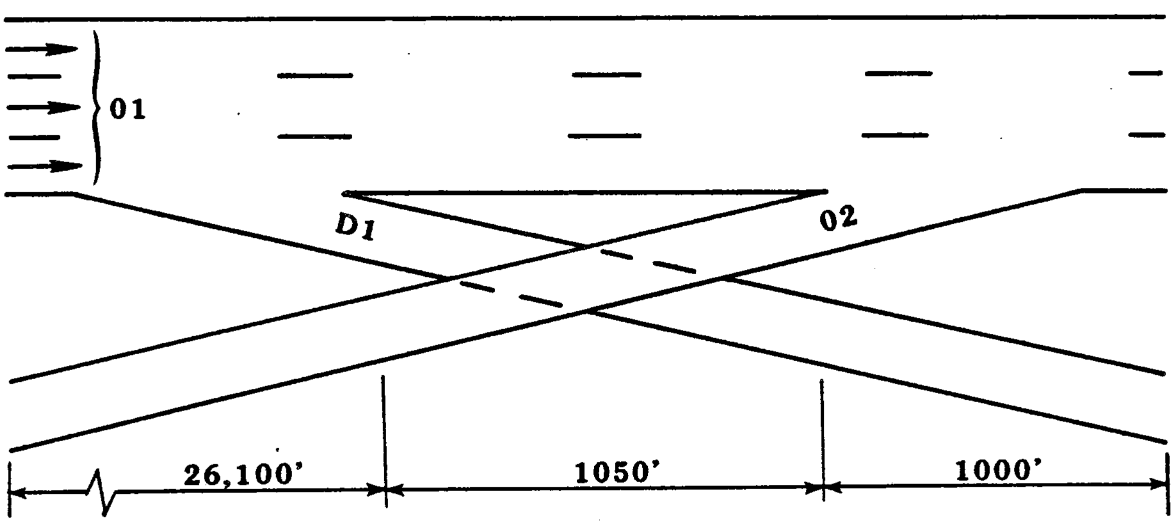
- Trucks are 5 percent of traffic, and 95 percent of these are diesel;
- Capacity per lane is 2000 vehicles per hour including the auxiliary lane;
- Ramp capacity per lane is 1600 vehicles per hour;
- A special speed capacity curve developed by TTI for Texas freeways is used;
- A period of three hours including the peak a.m. hour, is used for simulation;
- The 3-hour period was divided into 12 time slices of 15 minutes each to simulate the dynamic flow of the freeway;
- Mainlane, on-ramp and off-ramp peaking patterns found in I-410 in San Antonio were used to input vehicle volumes by time slice (See Appendix A).

All the above were part of the input to the FREQ8 model to simulate the desired conditions.

Variables considered were broken down into categories. Categories were selected to provide a range of likely transition points while keeping them to a minimum. A six dimensional matrix of the variables involved defined the



a) Freeway Weaving



b) Grade Separation

Figure 7. Geometric Inputs to FREQ8

options considered. Limiting the categories reduced the number of computer runs to a manageable level. The effect of independently loading on- and off-ramps was analyzed in four categories ranging between 400 vehicles per hour (vph) to 1500 vph. However, the total number of vehicles weaving was limited to 2000 vph. Mainlane traffic volumes were divided into four categories ranging between 1,000 to 2,000 vph per lane. The effect of distance between ramps was investigated for intervals of 750 feet and 1500 feet. Only freeways operating with three and four lanes were considered.

Output from the FREQ8 model are extensive. The sample summary table, shown in Figure 8 includes freeway travel time and ramp delay expressed in vehicle hours. Both combined give the total freeway travel time that can be used to calculate travel time benefits. The travel time of the freeway with weaving minus the travel time of the freeway with the grade separated ramp gives the travel time benefit derived from the grade separated ramp improvement. Appendix B contains the travel time values obtained from the FREQ8 runs.

Output Findings

The tabulated output were plotted to identify any relationship or pattern between traffic volume and vehicle hours. Figure 9 is an example of the weaving plots. This figure corresponds to the modeling of a freeway segment with three one-way mainlanes and an off-ramp traffic of 400 vph. Other assumptions previously discussed apply. On-ramp volumes vary between 200 to 1500 vph. Distance between on- and off-ramp gores is either 750 or 1500 feet, as labeled.

Figure 10 is an example of the grade separated ramp plots, where other conditions are the same as those of the previous figure. Only one distance between ramp gores has been used, 1050 feet, which is an adequate design at most constrained locations.

FREEWAY SUMMARY TABLE
SIMULATION BEFORE CONTROL

TIME SLICE	FREEWAY TRAVEL TIME		RAMP DELAY		TOTAL FREEWAY TRAVEL TIME		TOTAL TRAVEL DISTANCE		AVERAGE SPEED	GASOLINE CONSUMED	HYDROCARB EMISSIONS	CARBON MONOXIDE	NITROUS OXIDES	BEGIN TIME
	VEH-HR	PAS-HR	VEH-HR	PAS-HR	VEH-HR	PAS-HR	VEH-MI	PAS-MI	MPH	GALLONS	KILOGRAMS	KILOGRAMS	KILOGRAMS	
1	79.	102.	0.	0.	79.	102.	4530.	5879.	57.7	274.	11.	61.	22.	6:30
2	97.	126.	0.	0.	97.	126.	5487.	7119.	56.5	327.	14.	79.	25.	6:45
3	118.	153.	0.	0.	118.	153.	6525.	8467.	55.2	383.	17.	101.	29.	7:00
4	135.	175.	0.	0.	135.	176.	7327.	9508.	54.2	426.	19.	116.	32.	7:15
5	209.	271.	27.	35.	235.	305.	7933.	10293.	38.0	404.	25.	188.	29.	7:30
6	209.	271.	62.	81.	271.	352.	7942.	10306.	38.0	424.	28.	228.	29.	7:45
7	209.	271.	69.	90.	278.	361.	7960.	10329.	38.1	429.	29.	237.	30.	8:00
8	209.	271.	50.	65.	259.	336.	7962.	10332.	38.1	419.	27.	215.	29.	8:15
9	136.	176.	25.	33.	161.	209.	7361.	9552.	54.2	442.	21.	146.	32.	8:30
10	121.	157.	9.	11.	130.	169.	6675.	8662.	55.1	396.	18.	114.	30.	8:45
11	104.	135.	3.	4.	107.	139.	5855.	7598.	56.1	349.	15.	90.	27.	9:00
12	93.	120.	0.	0.	93.	120.	5273.	6842.	56.8	315.	13.	75.	25.	9:15
TOTAL	1719.	2231.	245.	318.	1964.	2549.	80831.	104886.	47.0	4588.	237.	1650.	338.	

Figure 8. Sample Output From FREQ8

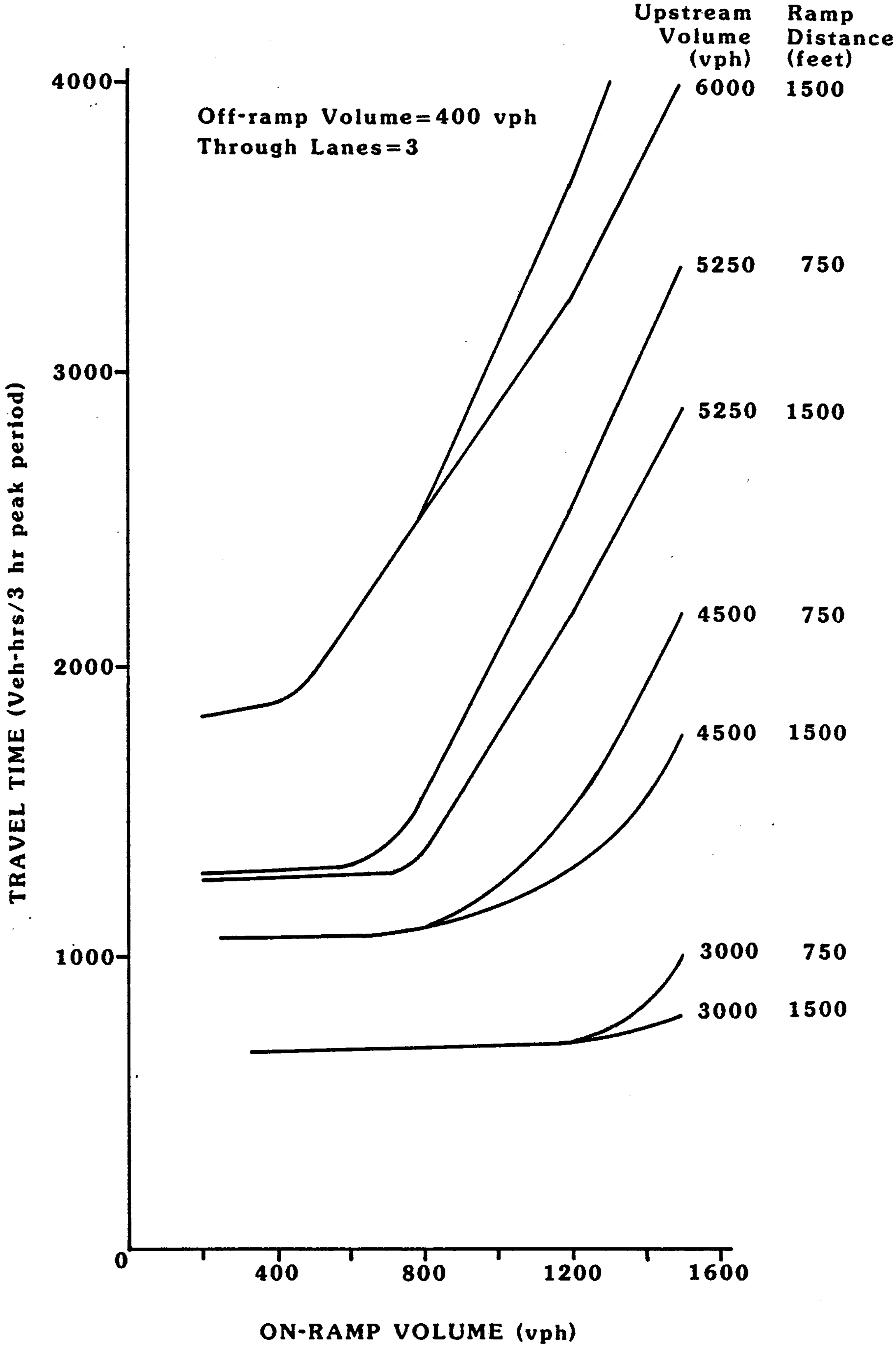


Figure 9. Travel Time With Weaving

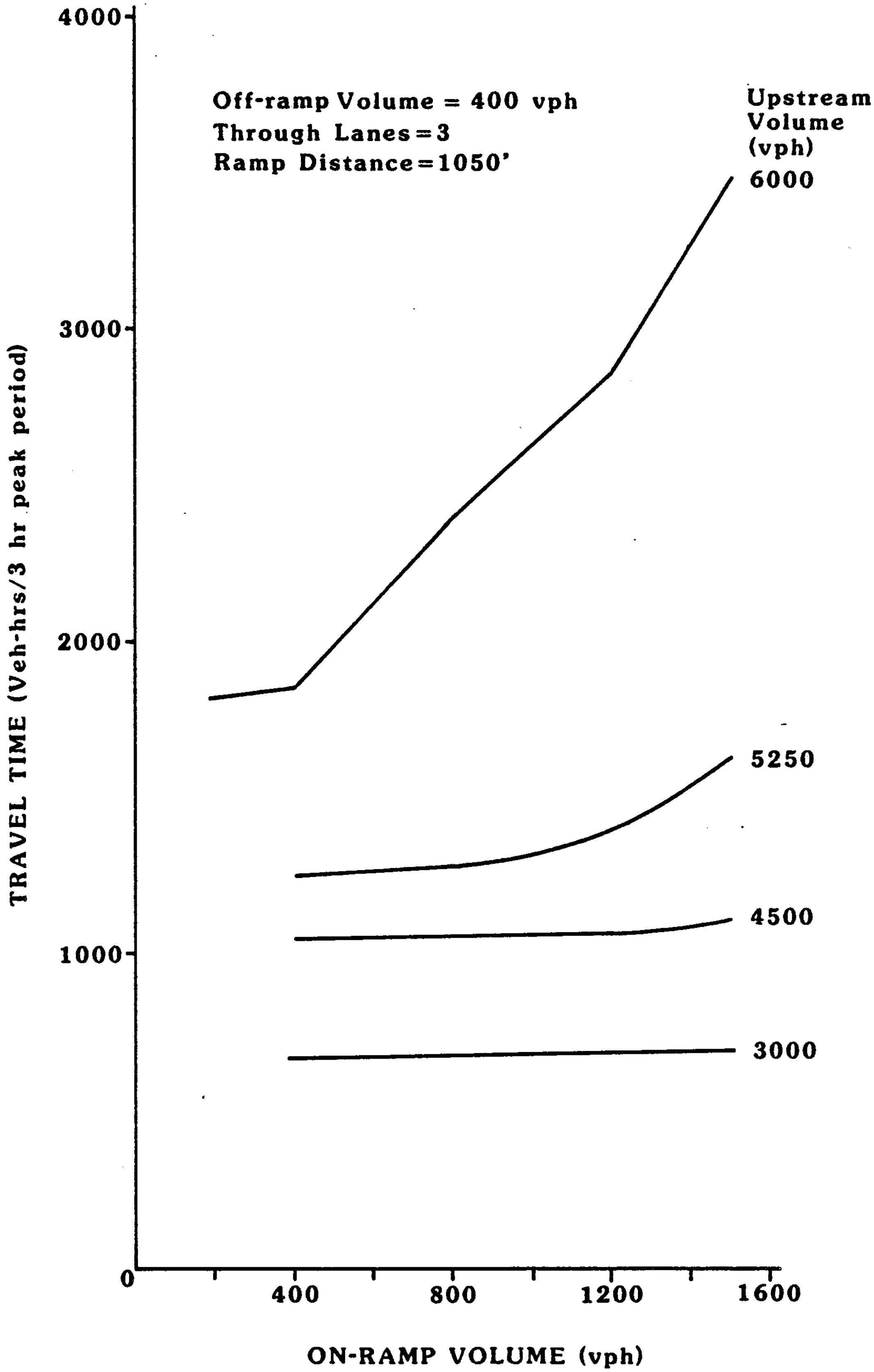


Figure 10. Travel Time With Grade Separated Ramp

The following observations have been made from the tabulated travel time plotted values.

- There is a limited combination of on-ramp, off-ramp and through traffic that can be served by the outside lane while maintaining close to a constant travel time. As that volume approaches the capacity of a single lane, travel time of the whole segment increases very fast. Heavy weaving further reduces the total volume required at the outside lane to reach capacity. As off-ramp volumes approach the off-ramp capacity, on-ramp volumes above 400 vph increase travel time geometrically.
- Grade-separated ramps can maintain travel time close to constant for a much higher combination of on-ramp, off-ramp and through traffic on the outside lane. The larger the off-ramp volume, the closer that total travel time remains close to constant.
- Grade-separated ramps have the potential to simultaneously improve the flow of mainlane and on-ramp traffic. However, low off-ramp volumes combined with high on-ramp volumes and high through traffic, bring about mainlane congestion downstream from the grade separated ramp. Volume to capacity ratios may exceed 0.9 although no queues form at that location. Yet, downstream congestion increases mainlane travel time and reduces ramp savings attributable to the grade separation. Such effect is incorporated in Appendix B tables where, with stated traffic conditions, ramp contributions to travel time savings (shown within parentheses) are higher than the total travel time savings.
- At lower levels of exit ramp volumes a short weaving distance induces more delay than a longer (typically recommended) weaving distance. Yet, as exit ramp volumes increase such difference is not as evident.

The tables prepared with the model's output can be used to estimate the travel time savings incurred by motorists going through a freeway segment provided with a grade separated ramp instead of a weaving section. The values represent a three hour peak period. The examples below explain the use of the travel time tables.

Example No. 1

Problem: Determine the current peak period travel time savings of a 6-lane freeway where a grade separated ramp is being considered to substitute a northbound weaving section. Off-ramp volume is 400 vph, the upstream directional peak hour volume is approximately 4500 vph and the on-ramp volume is 1200 vph. The gore to gore distance of the existing ramps is approximately 750 feet. Use Table B.1 to solve for savings in vehicle hours.

Solution: Enter Table B.1 at the through traffic volume of 4,500 vph, then look for the on-ramp volume of 1,200 vph, move right to the weaving line and the off-ramp volume of 400 vph. Travel time savings are about 449 vehicle-hours. Note that all 449 vehicle-hours are due to ramp delay (shown in parentheses).

Estimates of savings with other volumes can be obtained by interpolation to determine the travel time with and without the grade separated ramp in place.

Example No. 2

Problem: Determine the peak period travel time savings of the existing grade separated ramp on I-410 in San Antonio, located at the southwest quadrant of the interchange with I-10. Assume 1979 conditions when the off-ramp peak hour volume was 1,095 vph, on-ramp volume was 870 vph and peak hour through traffic upstream from the weaving section was 4,415 vph. Three mainlanes are available for through traffic. The weaving section gore to gore distance is approximately 800 feet. Figure 11 shows a sketch of the geometric configuration and of traffic volumes. Use Appendix B tables to approximate the travel time savings.

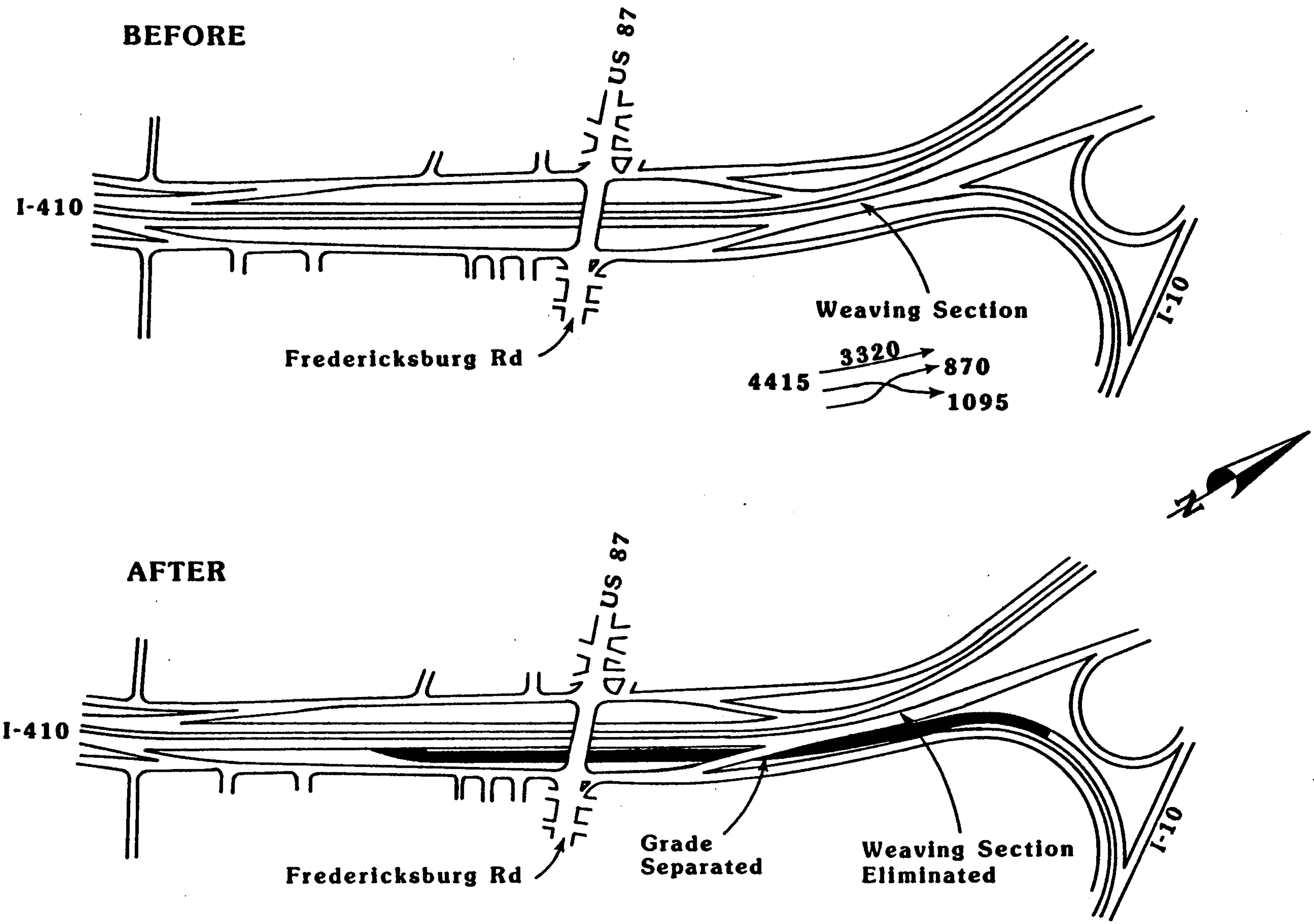


Figure 11. Geometric Configuration and Peak Hour Traffic Volumes, I-410 San Antonio

Solution: Table B.1 shows travel times for a range of traffic volumes based on the use of 3-mainlanes and a 750 foot ramp weaving distance between ramps. Since travel time for the on-ramp volume (870 vph) and the off-ramp volume (1,095 vph) lie somewhere between the travel times corresponding to 800 vhp and 1,200 vph, interpolation is necessary. Also, through traffic of 4,415 vph is between 3,000 and 4,500 vph. Assume values for a weaving distance of 750 feet are the same as for 800 feet.

Only three values on travel time are available in this case for the corresponding ramp volumes since cells shown blank are considered beyond the realm of weaving (weaving exceeds 2,000 vph). Interpolation may be done using only those three values in the following sequence:

- on-ramp
- off-ramp
- through traffic

The peak period travel time savings are:

$$PPS_{1095,\ 870,\ 4415} = 2{,}506 \text{ veh-hrs/peak period}$$

Reasonableness of Results:

The above calculations indicate very high savings. A closer examination of Table B.1 reveals that ramp delay contributes most of the travel time. This is the combined result of the ramp merge and weaving, as performed by FREQ8. Once merging volumes approach capacity (2,000 vph), queuing on the right most lane increases very rapidly. Since actual traffic volumes loaded on the mainlanes and ramps is a function of time, as shown in Appendix A, weaving volumes above 2000 vph occur over several time slices. As traffic volumes go down, weaving recedes below 2,000 vph and queues begin to dissipate. However, queues may not totally clear during the simulated period. Ramp delay with the grade separated ramp was observed to be very limited at through traffic volumes below capacity and considerably lower than ramp delay with weaving at through traffic volumes of 2000 vphpl.

Mainlane travel time is also affected by weaving traffic. Weaving lowers the effective capacity of the mainlanes and at high volumes of through traffic, speed is reduced.

The interaction with upstream ramps has not been considered in the analysis. The long 5-mile segment allows for queuing under very congested conditions but the merge queue sometimes exceeds the segment length. This may be realistic for long distance trips but local motorists using the freeway are likely to deviate. In practice, delay may be lower than estimated due to diversion. The results are nevertheless reasonable for project planning purposes.

A previous study (Borchardt, 1983) estimated delay savings at about $136.00 per day, using the abbreviated procedure of economic analysis explained in Appendix E of the "Operations and Procedures Manual" (SDHPT, 1981). At an assumed rate of $3.00 per vehicle hour delay would only be about 45 hours per day. Many assumptions inherent in that procedure are very different from those in the above example and it is not possible to make direct comparisons.

Ramp Access

Grade-separated ramps can improve access by reducing the travel time spent by motorists that travel along a frontage road and through one or more signalized intersections. PASSER III-84, a diamond interchange operations model developed by the SDHPT and TTI, has been used to analyze travel time through the intersection. Average free flow speed on both facilities is assumed to be known or obtainable. Motorists savings are accrued from the improved travel time of motorists provided with a more direct access, from reduced delay of remaining users of a signalized intersection, from reduced fuel costs and from reduced accidents.

The general simulation also required several assumptions for input to the PASSER III-84 model. Figure 12 shows a replicated input to the model. A three phase cycle was selected because it produces the most conservative delay estimate. The intersections were considered to operate isolated. A single inside lane was considered to be available for left turns in both directions. Capacity of the through lanes was assumed at 1,750 vph per lane while that of inside left turns was considered to be 1,500 vph. External movements were assumed to have no separate left or right turn lanes, thus, all turning movements were occurring from the through lanes. Saturation flow of each external turning and through movement was allocated on a proportional basis of the total approach capacity. A minimum green (actually green plus yellow) of 15 seconds per through movement and 10 seconds per left turn movement was provided to allow sufficient time for walk and walk clearance. The program was coded to select the overlap that would give the minimum delay.

Variables selected for intersection travel time analysis were broken down into categories. Peak and off-peak periods were considered. The off peak period was assumed to have balanced approach volumes of 25 percent per approach. Of this, 60 percent would be through traffic, 20 percent left turns and 20 percent right turns. Peak period traffic was assumed to have an unbalanced external approach of 40 percent traffic from the left side (using the PASSER III-84 designation), and 20 percent from each of the three other approaches. Through traffic was still assumed as 60 percent while left and right turns were 20 percent each.

Figure 13 shows a sample output. Tables 3 and 4 contain the results obtained from the PASSER III-84 model runs. These are for peak hour delay and off-peak hour delay respectively. Total vehicles approaching the intersection were 800, 1,600, 2,400 and 3,200 vehicles per hour (vph) or 100, 200, 300 and 400 vehicles per hour per lane (vphpl). It was assumed that eight lanes approached the intersection from four different directions or 2 lanes per approach. Access vehicles vary between zero and 800 vph; these are the vehicles that would use the extra ramp provided by the grade separated ramp.

DIAMOND INTERCHANGE SIGNALIZATION - 145105
PASSER III-84
INTERCHANGE INPUT DATA (CONTINUED)

INTERCHANGE 8 EIGT LN 400
****

DIRECTION	DISTANCE	PROGRESSION SPEED	DIRECTION - QUEUE CLEARANCE
FROM 8 TO 9	0 FT.	0 MPH.	'A' - 0 SEC.
FROM 9 TO 8	0 FT.	0 MPH.	'B' - 0 SEC.

PERMISSIVE LEFT TURNS ALLOWED?
****

AT LEFT SIDE INTERSECTION ---- NO
AT RIGHT SIDE INTERSECTION --- NO

INTERIOR TRAVEL TIME ACROSS THE INTERCHANGE
****

FROM LEFT TO RIGHT --- 12 SEC.
FROM RIGHT TO LEFT --- 12 SEC.

INTERIOR QUEUE STORAGE
****

THROUGH MOVEMENT AT LEFT SIDE INTERSECTION ----- 20 VEH.
LEFT TURN MOVEMENT AT LEFT SIDE INTERSECTION --- 6 VEH.

THROUGH MOVEMENT AT RIGHT SIDE INTERSECTION ----- 20 VEH.
LEFT TURN MOVEMENT AT RIGHT SIDE INTERSECTION --- 6 VEH.

INTERNAL OFFSET
****

(@ REPRESENTS OPTIMIZATION BEING REQUESTED)

CODE 1 OR LEAD-LEAD ---------- @ SEC. OFFSET
CODE 2 OR LAG-LEAD ---------- SEC. OFFSET
CODE 3 OR LEAD-LAG ---------- L SEC. OFFSET
CODE 4 OR LAG-LAG -----------}y SEC. OFFSET
CODE 1A OR TTI 4-PHASE -------}u SEC. OFFSET

EXTERNAL OFFSET
****

(@ REPRESENTS NO FORCED OFFSET REQUESTED)

CODE 1 OR LEAD-LEAD ---------- @ SEC. OFFSET
CODE 2 OR LAG-LEAD ---------- SEC. OFFSET
CODE 3 OR LEAD-LAG ---------- SEC. OFFSET
CODE 4 OR LAG-LAG ---------- SEC. OFFSET
CODE 1A OR TTI 4-PHASE ------- SEC. OFFSET

MOVEMENTS	1R	1T	1L	2R	2T	2L	2U	3R	3T	3L	4R	4T	4L	4U	5	6	7	8
VOLUMES	256	768	256	128	784	128	0	128	384	128	128	384	128	0	128	512	256	896
SATURATION FLOW	699	2099	699	429	2638	429	0	699	2099	699	699	2099	699	0	1499	3299	1499	3299
MINIMUM GREEN		15			15				15			15			10	25	10	25

Figure 12. Sample Input for PASSER III-84

PASSER3

TEXAS DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION
DIAMOND INTERCHANGE SIGNALIZATION - 145105
PASSER III-84

VER 1.0 MAR 85

GENERAL SIGNALIZATION INFORMATION

400VPHPL;40 20 20 20 AT EIGT LN 400 RUN NO. 2 07/16/86

MEASURES OF EFFECTIVENESS	LEFT SIDE				RIGHT SIDE			
	A	B	C	A+C	A	B	C	A+C
GREEN TIME (SEC.)	23.9	21.1	10.0	33.9	18.7	18.6	17.7	36.4
VOLUME/CAPACITY RATIO, X	1.01	0.96	0.78	0.29	0.68	0.69	0.69	0.46
LEVEL OF SERVICE	F	E	C	A	B	B	B	A
DELAY (SEC./VEH.)	46.23	35.54	42.34	6.81	19.97	20.13	23.30	6.54
LEVEL OF SERVICE	D	C	D	A	B	B	B	A
PROBABILITY OF CLEARING QUEUE	0.00	0.00			0.86	0.85		
LEVEL OF SERVICE	-	-			C	C		
STORAGE RATIO			0.33	0.05			0.36	0.08

PHASE ORDER - ABC/ABC
INTERNAL OFFSET - 14 SECONDS
TOTAL INTERCHANGE DELAY - 73.17 VEHICLE-HOURS PER HOUR

Figure 13. Sample Output for PASSER III-84

Table 3. Unbalanced Intersection Hourly Delay (Veh-hrs/hr)[1]

Approach Vol[2] (vph)	Access Vehicles[3] 0	200	400	600	800
800	3.48	4.43	5.23	6.02	7.07
1600	7.81	9.26	11.05	13.86	21.16
2400	14.32	16.98	21.30	31.85	71.06
3200	28.56	39.48	73.17	170.21	217[4]

[1]Split (%) for movements 1, 2, 3 and 4 is 40, 20, 20 and 20, respectively. Split (%) for left, thru and right lane distribution is 20, 60 and 20, respectively.

[2]Approach volumes correspond to 100, 200, 300 and 400 vph per lane, with 2 lanes per approach and no external turn lanes. Access vehicles not included.

[3]Access vehicles are the number of vehicles per hour that would divert to a grade-separated ramp, if available, but currently go through the intersection together with other users (approach volume).

[4]Manually adjusted to account for one movement which the PASSER III-84 model considers saturated (X-ratio above 1.2) and assigns zero delay per vehicle. Manual adjustment uses 105 seconds, recommended by the model's documentation.

Table 4. Balanced Intersection Delay (Veh-hrs/hr)[1]

Approach Vol[2] (vph)	Access Vehicles[3]				
	0	200	400	600	800
800	3.61	4.25	4.91	5.75	6.93
1600	8.11	9.14	10.19	11.34	13.06
2400	14.34	16.01	18.19	21.71	26.68
3200	23.11	26.78	32.01	41.77	57.94

[1]Split (%) for movements 1, 2, 3 and 4 is 25, 25, 25 and 25, respectively. Split (%) for left, thru and right lane distribution is 20, 60 and 20, respectively.

[2]Approach volumes correspond to 100, 200, 300 and 400 vph per lane, with 2 lanes per approach and no external turn lanes. Access vehicles not included.

[3]Access vehicles are the number of vehicles per hour that would divert to a grade-separated ramp, if available, but currently go through the intersection together with other users (approach volume).

A lead-lead three phase, 55-second cycle was assumed in all cases. A check using other phasing schemes revealed minor increases in delay, although negligible for planning purposes. A low-delay solution is secured by restricting the cycle length to 55 seconds, near the minimum possible (SDHPT, 1985). Further refinements may be possible with other assumptions, yet the selected variables and categories do allow generalized statements as to the economic feasibility of grade separated ramps.

The travel (running) time using the frontage road and the freeway mainlanes were based on average traffic speed for the segment involved. These may be taken as the posted speed but if significantly different conditions prevail, actual speed should be obtained. If the lack of an access ramp creates queues on the freeway mainlanes this should be separately accounted for, using FREQ8 to measure the difference in travel time. For study purposes, no queues were assumed to occur on the freeway. Freeway and frontage road distance were assumed to be the same, measured from gore to gore.

Travel time on the frontage road is a function of distance, traffic speed and the number of vehicles to be provided improved access by the grade-separated ramp. Vehicle hours of travel time is calculated as:

$$TT = \frac{D}{S} * V \qquad \text{eq (1)}$$

where: D is distance from ramp to ramp (miles);
S is speed in miles per hour (mph), and
V is the traffic volume to be diverted during the period studied (generally one hour).

Figure 14 provides a perspective on the magnitude of travel time for distances between 0.2 to 2.0 miles and speeds between 20 to 60 mph. Note that travel time is expressed in vehicle hours per 1000 vehicles. Vehicle hours for a different number of vehicles to be provided with access by a grade separated ramp equals the figure value times the number of vehicles divided by 1000.

Intersection delay plus frontage road travel time, minus freeway travel time gives the vehicle-hours per hour saved by a grade separated ramp. The benefit plus fuel savings and reduced accidents constitute the quantifiable benefit of grade-separated ramps designed to improve access.

Output Findings

Unlike the weaving problem, several major variables affect access travel time. The number of possible outcomes is greater and the significance of the tables developed is very site specific. However, at-grade intersection geometrics and traffic counts are commonly available or readily obtainable for the analysis of a major project. And unlike FREQ8, PASSER III-84 requires minimum input data and provides easy to understand outputs. Therefore, it is recommended that PASSER III-84 be used to determine total intersection delay with and without access vehicles, instead of using the general values given in Tables 3 and 4.

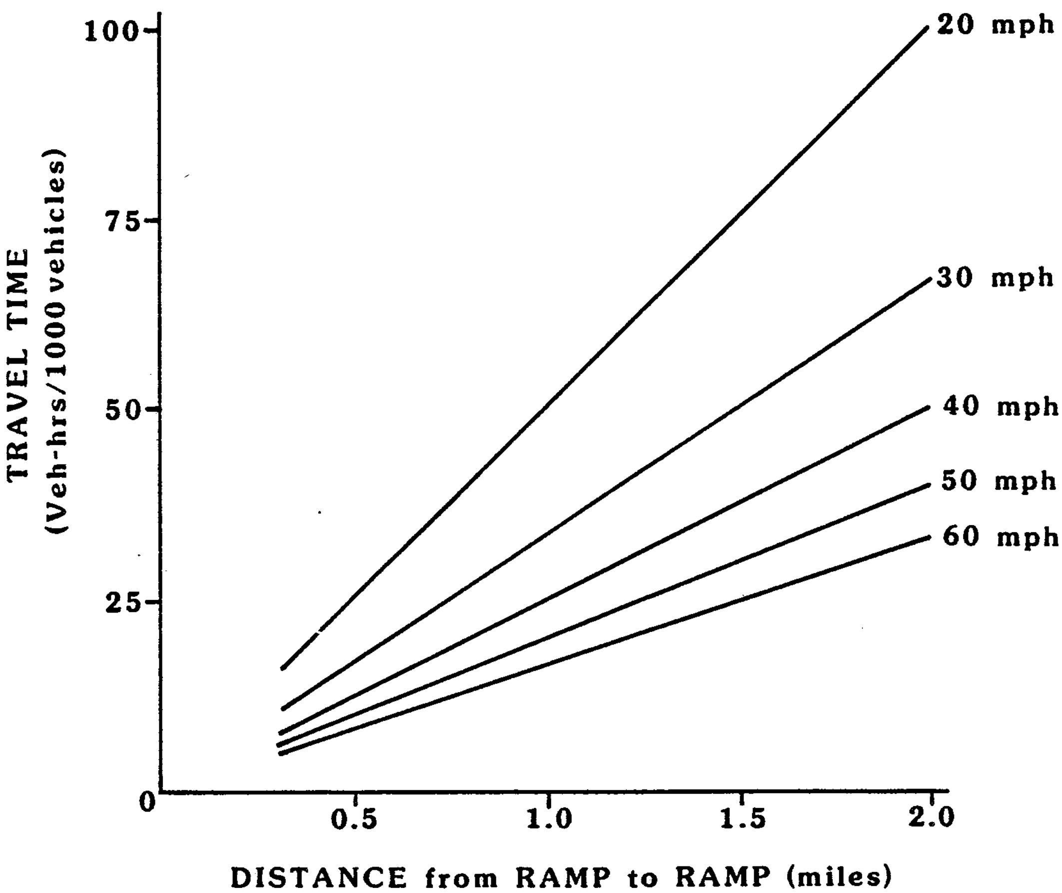


Figure 14. Travel Time Freeway or Frontage Road

Nevertheless, some generalizations can be made with the values given in the above tables. Figures 15 and 16 depict intersection delay for unbalanced and balanced conditions. With a total of 800 vph approaching the intersection from all directions, an average of 100 vph per lane, total intersection delay is fairly insensitive to the effect of up to 800 access vehicles (extra load). There is little difference between the balanced and unbalanced intersection delay. Also, with no access vehicles intersection delay is about the same at the various approach volumes.

As the approach volume to an intersection goes up delay becomes non-linear. This effect is more pronounced with unbalanced approach volumes and becomes critical as the intersection approaches capacity. For example, with 3,200 vph approaching the intersection an extra 600 access vehicles increase delay from 29 to 170 vehicles-hours per hour. Operations break down with 800 access vph. With approach volumes of 1,600 and 2,400 vph operations are stable but increase as access vehicles increase and congestion sets in at the left side of the intersection.

The balanced intersection maintains a fairly stable level of delay through the range of assigned loadings, as shown in Figure 16. This applies in specific to approach volumes between 800 and 2,400 vph. With an approach volume of 3,200 vph delay remains stable through 400 access vph. Beyond 400 vph the intersection becomes "supersaturated", that is, the composite X-ratio for the left side of the intersection is at or above 0.95. Ratios above 0.95 create unduly long queues. Oversaturated queues do not dissipate during the study period (SDHPT, 1985) and motorists diversion is very likely.

The examples following demonstrate the use of travel time and intersection delay to determine benefits of a grade separated ramp considered to improve access.

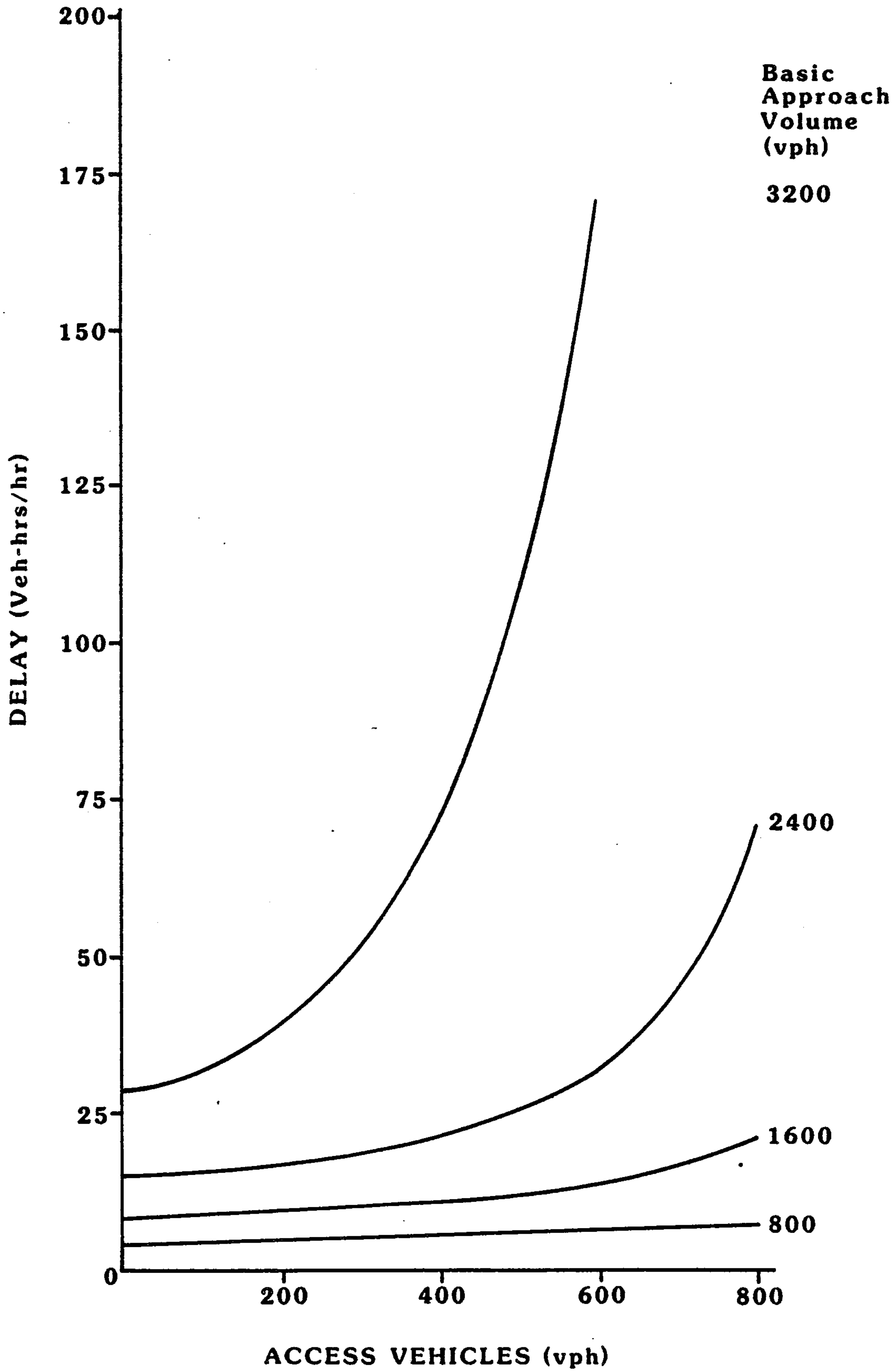


Figure 15. Unbalanced Intersection Delay

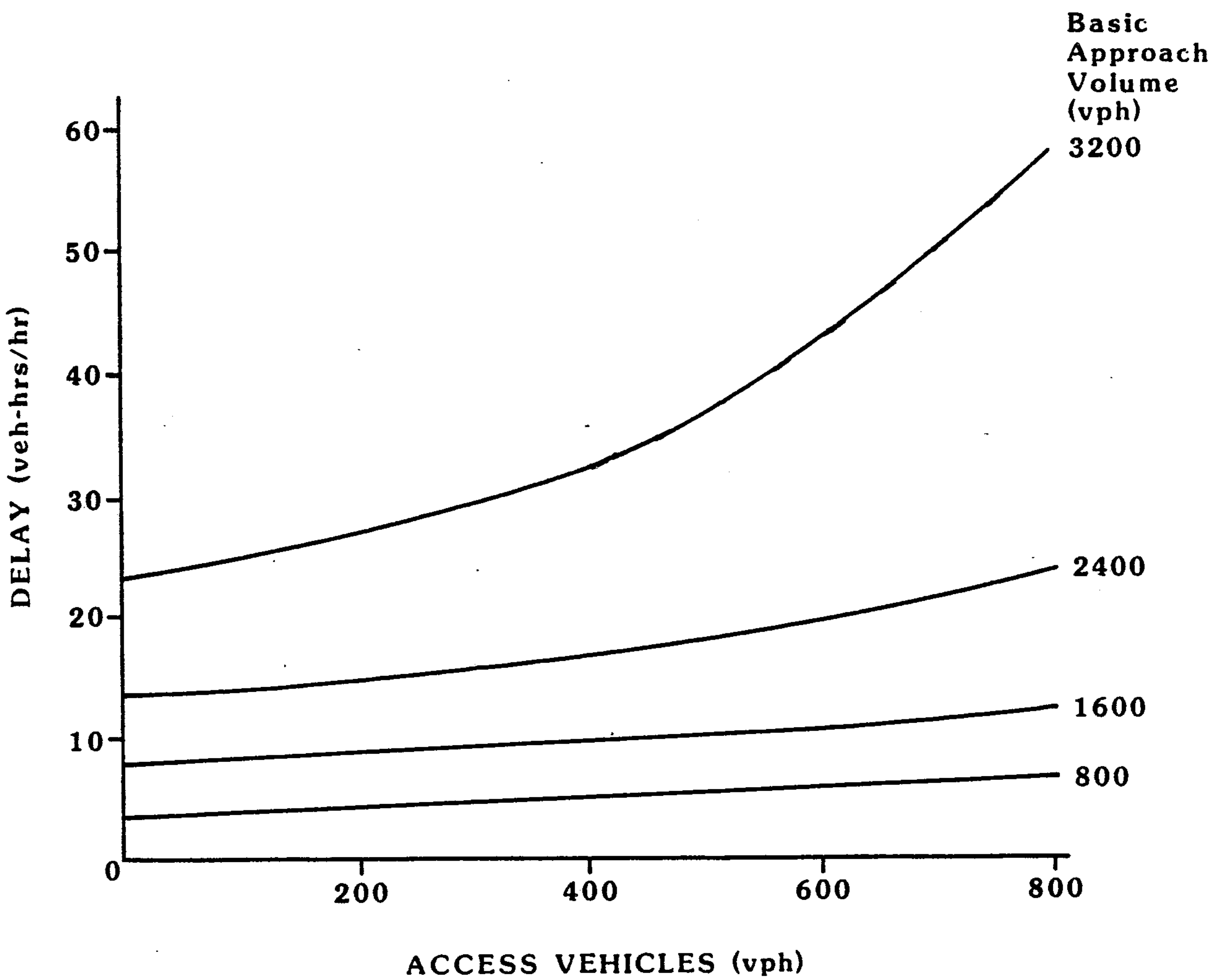


Figure 16. Balanced Intersection Delay

Example No. 3

Problem: Determine the current peak hour savings of 600 vehicles travelling on the frontage road. This traffic has to go through one signalized intersection that operates with 2,400 vehicles per hour, in an unbalanced mode. Traffic will be diverted to a grade separated ramp. Assume that there is no significant traffic during off-peak hours. Also, access traffic will remain on the freeway for one more mile traveling at a speed of 55 mph. The frontage road free flow speed is 35 mph. Use Table 3 to find the answer.

Solution: Use equation 1 to estimate travel time for a distance of 1 mile.

$TT_{35\ mph} = 17.1$ veh-hrs
$TT_{55\ mph} = 10.9$ veh-hrs

Travel time savings using the freeway are:

$TT_{35mph} - TT_{55mph} = 6.2$ veh-hrs per hour.

Enter Table 3 to estimate intersection delay savings with 600 vehicles per hour. Read the cell corresponding to an intersection approach volume (all directions) of 2400 vehicles per hour. A signal delay value of 31.85 is shown, or approximately 31.9 vehicle-hours per hour. Read the cell value for no access vehicles and this shows 14.32 or approximately 14.3 vehicle-hours per hour. Intersection delay savings amount to:

$$\begin{aligned} SD_{acc} - SD_{noacc} &= 31.9 - 14.3 \\ &= 17.6 \text{ veh-hrs/hr} \end{aligned}$$

Combined savings of the grade separated ramp are:

$$\begin{aligned} TTS &= 6.2 + 17.6 \\ &= 23.8 \text{ veh-hrs/hr.} \end{aligned}$$

Example No. 4

This example uses data from a real case on a grade separated ramp built to improve access. Part of the traffic data was reconstructed from various sources and represent conservative estimates of traffic flows previously reported (Nordstrom, 1983). Approach traffic to the intersection was not known.

Problem: A grade separated ramp is to be provided west of Jones-Maltsberger Road to improve access to McCullough Avenue and the North Star Shopping Mall, in San Antonio. Such access traffic travelling westbound on I-410 has to exit at the Airport Blvd. to go through that intersection, continue on the frontage road, go through the Jones-Maltsberger intersection and continue on the frontage road to reach McCullough Ave. Figure 17 shows the configuration prior to construction and the traffic pattern with the grade separated ramp. Peak and off-peak hourly volumes shown have been estimated from known ADT.

Distance between the Airport Blvd. on-ramp and the McCullough Ave. on-ramp is approximately 3800 feet. Assume that both the Airport and the Jones-Maltsberger intersections work unbalanced during the peak hour and balanced during off-peak hours. Further assume that both intersections operate with a total approach volume of 2400 vph during peak hours and 1200 vph during off-peak (both conservative numbers). Both intersections will have 560 access vph during peak and 225 access vph during off-peak (these are based on a 10 percent and a 4 percent of the 1982 ADT counts from the McCullough off-ramp operating with grade separation). Assume peak period volumes to last four hours per day and 14 off-peak hours per day. Peak period speed is estimated at 50 mph on the freeway and 35 mph on the frontage road. Off-peak speed is estimated at 55 mph on the freeway and 40 mph on the frontage road. Determine daily travel time savings.

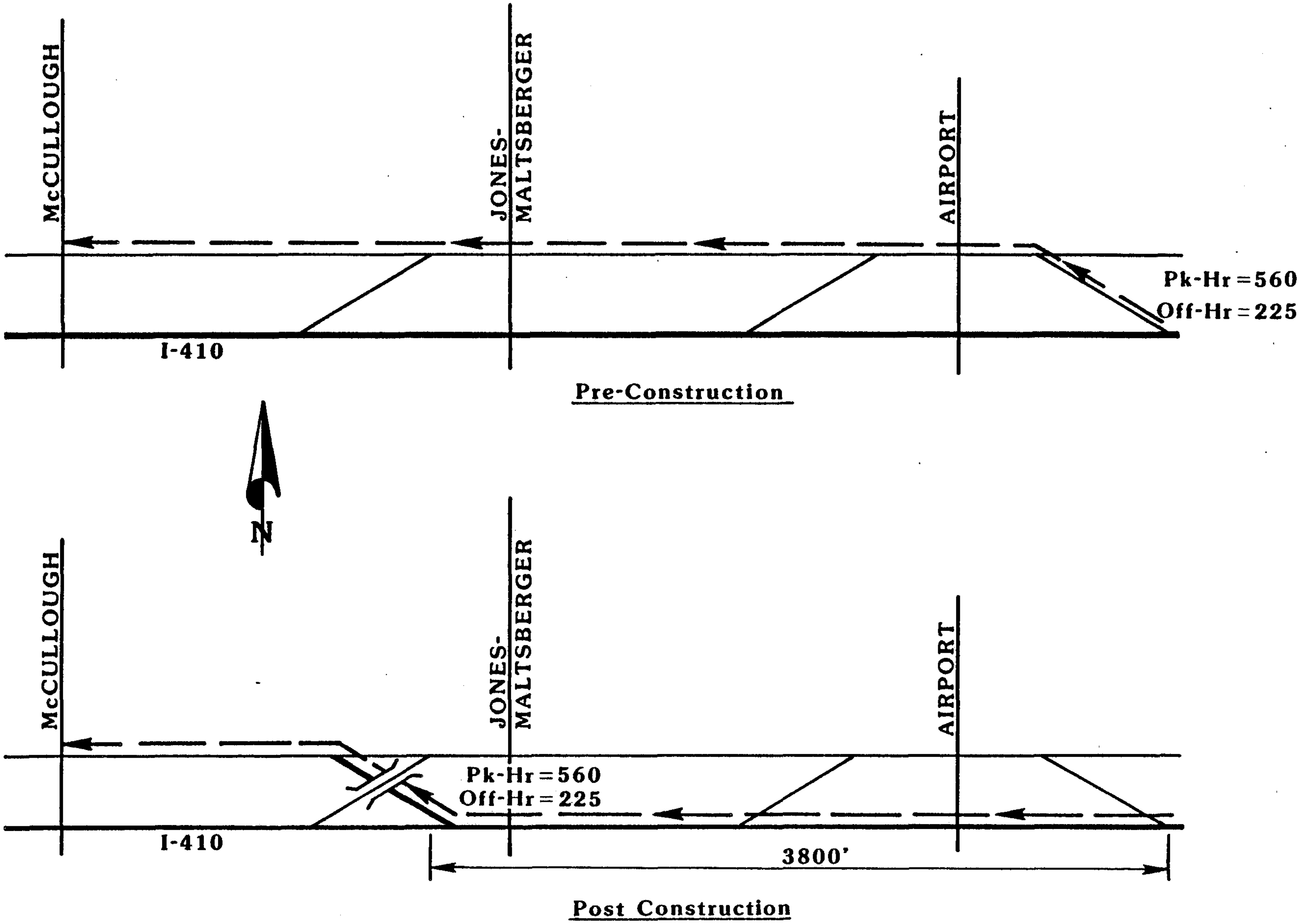


Figure 17. Traffic Patterns and Diverted Access Traffic Volume I-410, San Antonio, 1982.

Solution: With equation 1, peak travel time can be estimated for at-grade and grade separated, but adjusting distance to miles,

$$TT_{ag,p} = \frac{D * V}{5280 * S}$$

$$= 11.5 \text{ veh-hrs}$$

$$TTgs,p = 8.1 \text{ veh-hrs}$$

Off-peak travel time is similarly estimated:

$TT_{ag,\ of} = 4.0$ veh-hrs

$TT_{gs,\ of} = 2.9$ veh-hrs

Intersection delay can be estimated using Tables 3 and 4, as follows:

For peak period delay enter Table 3 with an approach volume of 2400 vph and move to the right to find time for 400 and 600 access vph and interpolate for 560 access vehicles.

$$ID_{p,\ 560,\ 2400} = 29.7 \text{ veh-hrs}$$

Delay with no access is,

$$ID_{p,\ o,\ 2400} = 14.3 \text{ veh-hrs}$$

and intersection delay savings is,

$$IDS_p = 29.7 - 14.3$$
$$= 15.4 \text{ veh-hrs.}$$

In a similar manner, intersection delay is obtained using Table 4 and double interpolation to properly account for the 1200 approach vehicles and the 225 access vehicles.

$$ID_{of,\ 225,\ 1200} = 6.8 \text{ veh-hrs}$$

Delay with no access is,

$$ID_{of,\ o,\ 1200} = 5.06 \text{ veh-hrs}$$

and intersection delay savings during off-peak is,

$$\begin{aligned} IDS_{of} &= 6.80-5.06 \\ &= 0.94 \text{ veh-hrs} \end{aligned}$$

Peak period time using the frontage road is the sum of travel time plus the signal time at the two intersections multiplied by the number of peak hours, or:

$$\begin{aligned} T_{ag,\ pp} &= (TT_{ag,\ p} + (2 * IDS_p)) * 4 \\ &= 169.4 \text{ veh-hrs} \end{aligned}$$

In the same manner, off-peak hour time is multiplied by 14 to obtain the peak period time,

$$\begin{aligned} T_{ag,\ ofp}\ & (TT_{ag,\ of} + (2 * IDS_{of})) * 14 \\ &= 83.0 \text{ veh-hrs} \end{aligned}$$

and peak and off-peak period travel time on the freeway is calculated,

$$\begin{aligned} T_{gs,\ pp} &= TT_{ag,\ p} * 4 \\ &= 32.2 \text{ veh-hrs} \end{aligned}$$

$$\begin{aligned} T_{gs,\ ofp} &= TT_{gs,\ of} * 14 \\ &= 41.2 \text{ veh-hrs} \end{aligned}$$

Then, weekday travel time savings are the time on the frontage road including intersection delay savings, minus time on the freeway,

$$TTS = (T_{ag,\ pp} + T_{ag,\ ofp}) - (T_{gs,\ pp} + T_{gs,\ ofp})$$
$$= 179.0 \text{ veh-hrs/day}$$

Reasonableness of Results:

The above calculations are somewhat higher than those estimated in the previous study (Nordstrom, 1983). In part this is attributed to the use 1974 traffic in the former study and of which access vehicles were about a third as many as those in 1982. More significant is that intersection time was considered for the access traffic only. The lost time by access vehicles plus the delay added to the base approach volume contributes the most to the total travel time related to the frontage road access option.

The past study estimated daily travel time using the frontage road at 81 vehicle-hours and the daily travel time on the freeway at 45 vehicle-hours. Savings in travel time added to 36 vehicle hours per day which multiplied times 2.8, to approximate 1982 conditions, would add to about 101 vehicle hours per day. The analysis method explained above gives about 75 percent more vehicle hours saved per day, however, a direct comparison is not possible with different assumptions. The secondary benefits at the intersections involved seem reasonable and should be included.

Again, it is recommended that intersection counts should be used to improve accuracy of results, whenever available. Use of actual counts should reflect higher benefits. Running the PASSER III-84 model would properly consider all the variables affecting the at-grade diamond intersection including unbalanced operations, which appear to have a major bearing on intersection delay.

Fuel Consumption

Fuel consumption is a function of vehicle mix, speed and speed changes. Each of the two grade separated ramp functions experience the benefits of improved travel in a somewhat different way.

Removal of a weaving section to improve traffic flow reduces right lane and on-ramp queues. Ramp savings are partially offset by improved flow because at a uniform speed the optimum consumption rate is about 35 mph (AASHTO, 1977). The FREQ8 model incorporates fuel consumption rates adjusted for average speed of all lanes. Thus, fuel consumption of a specific freeway segment affected at some point by a weaving section can be obtained from FREQ8 output tables, as shown in Figure 8. Savings can be calculated subtracting fuel consumed with the weave from that with the grade separated ramp. Consumption tables similar to the ones used for vehicle delay are included in Appendix C but based only on weaving segments 750 feet long. Inspection of the simulated results from the runs made to obtain delay shows that fuel consumption is not directly related to vehicle hours of delay. Figure 18 shows the shape of the fuel consumption curves for off-ramp volumes of 400 vph and three directional freeway mainlanes. The shape of the curves is different from those shown in Figure 9, due in part to the improved fuel efficiency as speed decreases to about 35 mph, or opposite to the effects of delay.

Appendix C data may be used to estimate fuel consumption of a segment operating with a weaving section. Interpolating may be required. The screening method of assessment, to be discussed later, already accounts for fuel consumption in the cost of travel time.

Fuel consumption savings resulting from the use of a grade separated ramp in the access function can be estimated subtracting the consumption using the frontage road from consumption using the freeway. The vehicles provided access multiplied by the fuel consumption rate at frontage road speed, times the distance between at-grade existing and the grade separated

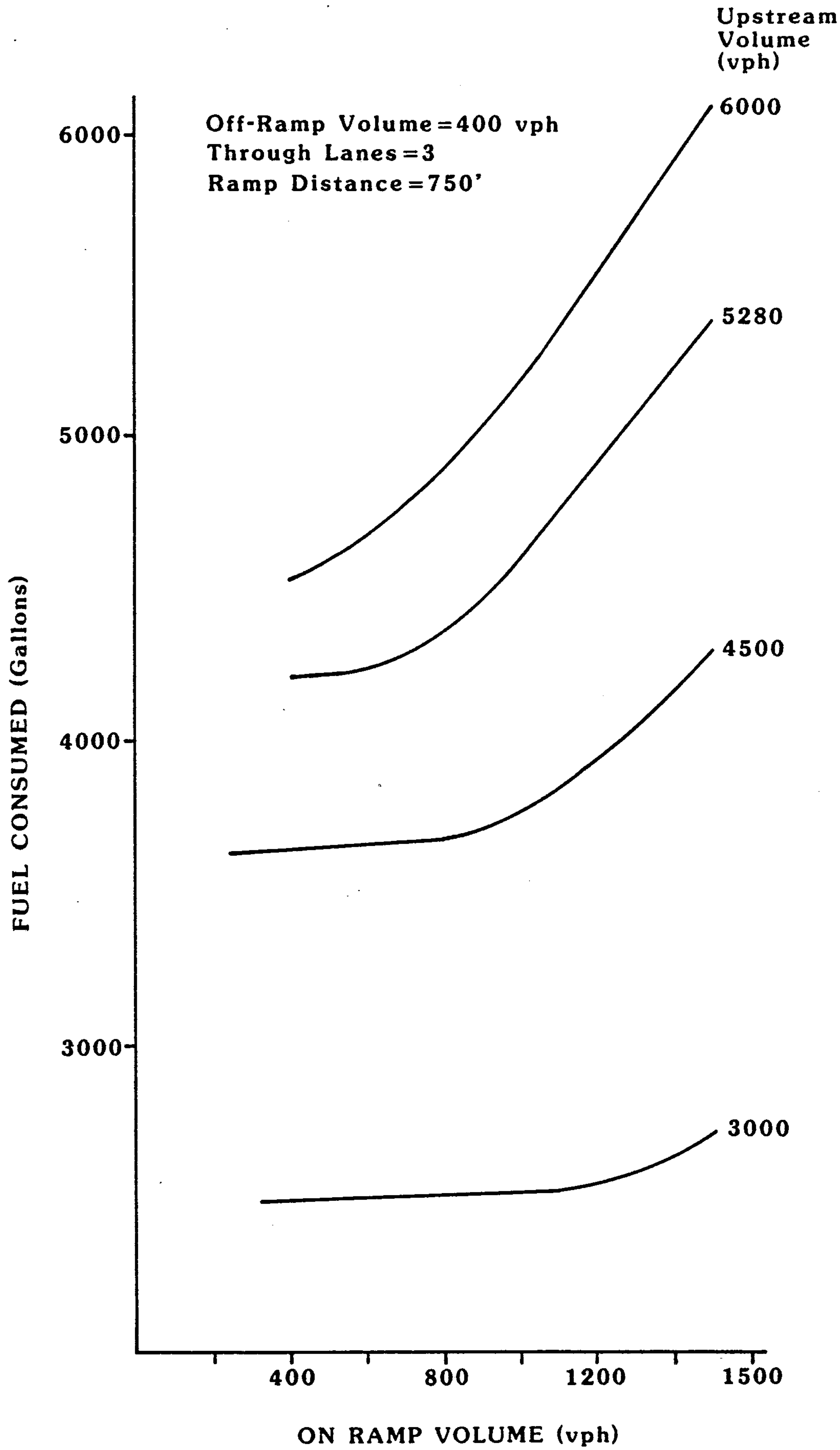


Figure 18. Fuel Consumption on Freeway Segment with Weaving

ramp under consideration provides the fuel consumption for travelling the frontage road. A similar calculation provides the travelling fuel consumption for the freeway once vehicles are provided access through the grade separated ramp.

The extra-idle fuel consumption due to the signalized intersection is added to the frontage road travelling consumption to obtain total consumption using the frontage road. Delay savings of the intersection, expressed in vehicle hours, is multiplied by the idle fuel consumption rate. Appendix D displays fuel consumption rates. Fuel consumption by access vehicles required to stop at the signalized intersection and to resume the frontage road speed is estimated to be minor and may be disregarded.

Accidents

Accidents are a rare event and several factors influence them. It is difficult to predict the reduction in accidents that a grade separated ramp will bring without being site specific. Accident rates are provided in this section to account for the principal conditions improved by a grade separated ramp. That is, eliminating the effects of weaving on the mainlanes and the effects of travelling on the freeway versus travelling on a frontage road.

Very limited information is available on the accident rate of weaving sections. Accident analysis conducted in the assessment of a grade separated ramp that replaced a weaving section in San Antonio (Borchardt, 1983) found that over a 0.5 mile segment of the freeway the accident rate went down from 1.69 accidents per million vehicle miles (mvm) to 0.55 accidents per mvm. Prior to grade-separating the ramps about 35 of the accidents resulted in injuries and 65 percent in property damage only. No fatal injuries were reported. The composition of the after improvement accidents was not reported but can be assumed to remain the same.

Access related accidents can be obtained by comparing those attributable to the freeway segment travel and subtracting from those of the frontage road segment. The average freeway has 1.43 accidents per mvm while the frontage road, assumed to have the same rate as a divided urban expressway, averages 3.14 accidents per mvm (AASHTO, 1977).

Total cost per accident on urban roads is estimated at $10,200 on freeways and $9,600 on the frontage road or divided facility (Rollins, 1985).

The above factors may be used to estimate benefits once the number of vehicle miles have been determined. For the weaving case, peak hour directional volume is multiplied by 0.5 mile to obtain vehicle miles. For the access case, the vehicles to be provided grade separated ramp access are multiplied by the distance between the existing ramp and the proposed ramp. However, the screening method to be explained later already accounts for accidents in the cost of travel time.

ASSESSMENT PROCEDURES

The effectiveness of a grade separated ramp to increase the capacity of the mainlanes or the frontage road must be assessed based on quantifiable and non-quantifiable measures. Delay, fuel and safety improvements are the principal measurable benefits. A dollar value should be assigned to those benefits. The impact on adjacent property and neighborhood objectives should also be considered, but in a qualitative manner.

A procedure has been prepared to estimate present worth of benefits and to compare with costs over 5, 10, 15 and 20 year periods. The benefit to cost ratio provides an index that can be used to justify a project based on economic objectives. Ratios above one, together with an acceptable level of non-quantifiable benefits and impacts, can be used to justify a project. Non-quantifiable benefits should be qualitatively assessed in consonance with the detail available.

Figure 19 describes the basic activities and decision points required to justify a grade-separated ramp. This process is applicable once the need for a ramp has been established and a determination has been made that an at-grade solution is not possible nor practical. Also, there is a forseen need to add a through lane and it is not possible to build a grade separated ramp with enough lateral space to accommodate the extra lane.

In general, it is considered impractical to build a grade separated ramp expected to be demolished within a five year period. It takes at least two years to design and build such facility. If programming, budgeting and preliminary engineering is required the ramp may become operational by the time it is scheduled for removal.

Financial justification should be based on a benefit to cost ratio exceeding one, once all pertinent benefits and costs have been quantified. Demolition costs should be considered in all projects scheduled for removal

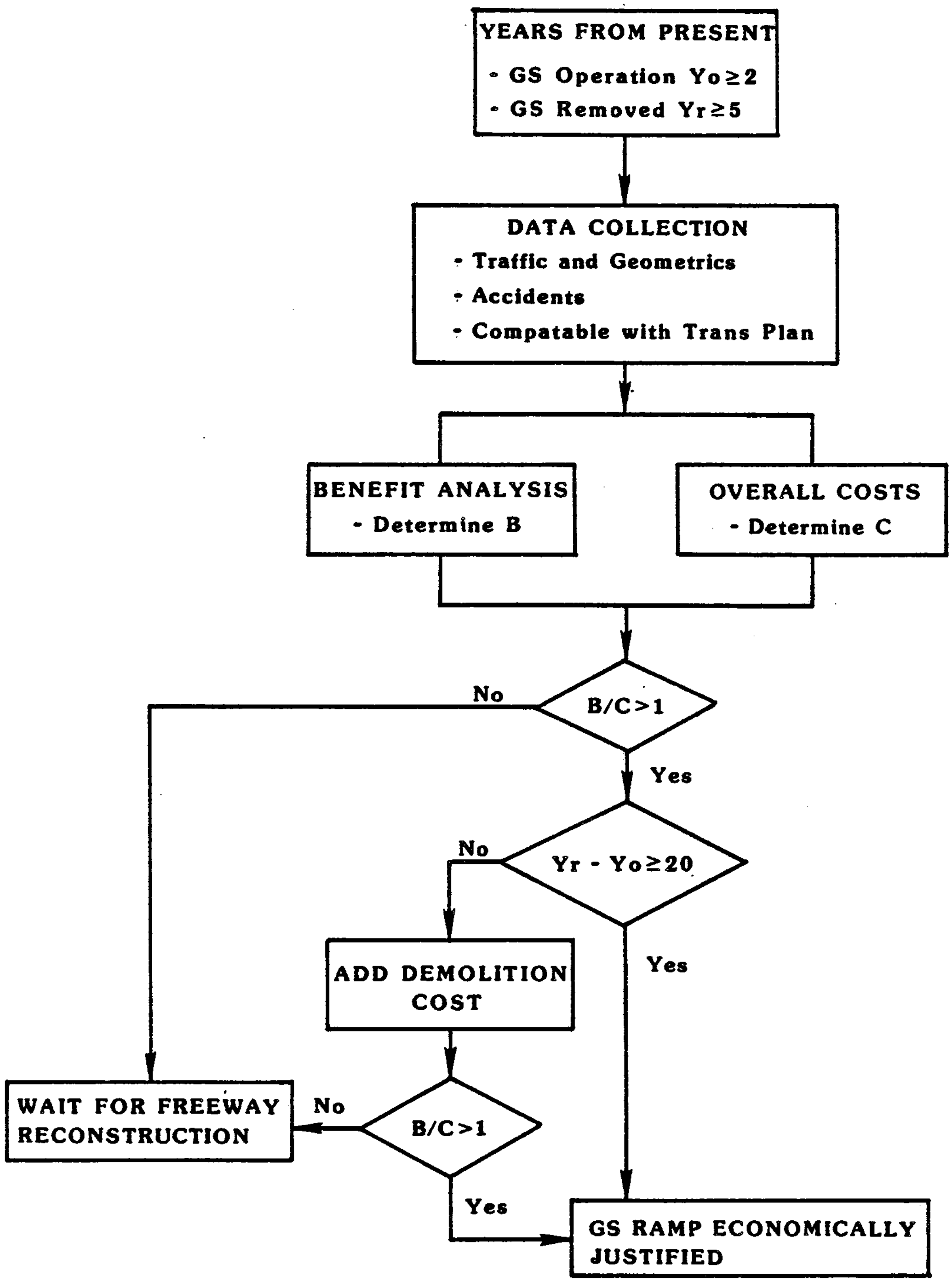


Figure 19. Financial Justification Process

before their 20th year of operation. If the benefit to cost ratio will not exceed one, the project is not justifiable on this basis and should be deferred to wait for freeway reconstruction.

Measurable Benefit

The primary benefit of grade separated ramps is reduced motorists travel time. Examples 1 and 2 explained the procedure to estimate time savings of a grade separated ramp replacing a weaving section. Examples 3 and 4 presented a procedure to calculate time savings of the access case. However, project benefits need to be assessed a dollar value to compare between options and with the total cost of implementation.

The value of time for passenger cars has been estimated at $9.75 per hour and that of trucks at $20.15 per hour (Chui, 1985). This value already considers vehicle occupancy and includes vehicle operating expenses, accidents, motorists time, traffic violations and other non-quantifiable costs such as comfort and convenience. These values have been used, as requested by the SDHPT project review staff.

Two methods will now be reviewed that may be used to quantify benefits. These are a screening method and a detailed analysis method. The one to be used depends on the level of prior planning and decisions made. The screening method is described below and makes use of previous examples to explain its application.

Screening Method

Measurable benefits are determined by time period. Peak period benefits may be expressed on an hourly basis and need to be multiplied times the number of peak hours per day. Off-peak period is the remaining time and benefits are normally accounted for using an 18 hour day, as explained in the Operations and Procedures Manual (SDHPT, 1981). Peak period benefits, here taken as four hours per day, are multiplied times 253 to obtain yearly benefits. Off-peak yearly benefits are the balance of weekday hours or 14 (18 hours per day minus 4 peak hours) multiplied times 365, plus 112 times 18 to account for weekends and holidays.

Future projections should be based on the programmed and planned network, adjusted as required to apply at the project level. Sometimes such projections are not available, particularly those for less than 20 years. A method frequently employed is to multiply current traffic by a growth factor based on past trends. For instance, a yearly growth rate of 2-percent may be applied to freeway through traffic while a 1-percent rate may be appropriate for ramp growth. With these or similar factors future traffic can be estimated. Travel time multiplied by the value of time gives the current and future dollar benefits. Table 5 shows the estimated benefits of the four examples previously presented.

Table 5. Current and Future Benefits Per Year

(1985 $ millions)

Example	Current Year	Projected Year 5	10	15	20
1[1]	1.147	2.749	3.661[3]	NA[4]	NA[4]
2[1]	6.182	7.194	8.078[3]	NA[4]	NA[4]
3[2]	0.235	0.714	1.086	1.475	NA[5]
4[2]	0.500	1.014	1.678	2.458	NA[5]

[1]Future benefits based on a yearly traffic growth of 2% for freeway mainlanes and 1% for on- and off-ramps.

[2]Future benefits based on a yearly traffic growth of 2% for access traffic to be diverted from the frontage road to the freeway, and 1% for other traffic approaching a signalized intersection.

[3]Downstream mainlanes operate beyond capacity and travel time estimates include these effects.

[4]Upstream mainlanes operate beyond capacity and travel time estimates are misleading.

[5]Intersection operates beyond capacity, total delay not calculated by model.

Once current and future benefits are estimated this is converted to present worth. Savings accrued during 1985 are accounted for as a single payment on January 1, 1986, assuming that the grade separated ramp was open to the public a year earlier. Savings accrued during 1989, 1994, 1999 and 2004 are accounted for as a single payment on January 1, of the following year. Further, it is assumed that savings increased at a uniform rate per year through the period considered.

The present worth of each project benefits is calculated with the following formula.

$$P = A\left[\frac{(1 + i)^n - 1}{i(1 + 1)^n}\right] + \frac{G}{i}\left[\frac{(1 + i)^n - 1}{i(1 + i)^n} - \frac{n}{(1 + i)^n}\right] \quad \text{eq. (2)}$$

where,

A = uniform series of "n" end-of-year benefits,

G = arithmetic gradient increase in funds at the end of each year for "n" years, and

i = discount rate compounded at the end of each year.

The above formula has two expressions: the first accounts for the base year savings, as expressed in the uniform series "A"; the second accounts for the marginal increase in yearly savings including the effect of the discount rate, as expressed in the arithmetic gradient series "G". In graphic form, benefits accrued may be expressed as shown in Figure 20. Other methods are available, as explained in the Red Book (AASHTO, 1977), but results are essentially the same.

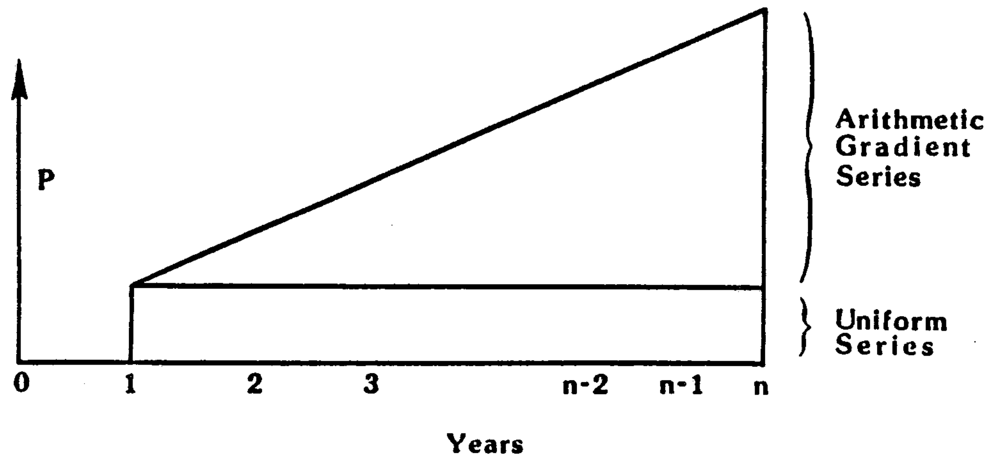


Figure 20. Present Worth of Benefits Received

A simple way to go through this computation is to use readily available interest tables from various economics texts such as Engineering Cost Analysis (Collier, 1982). If P/A and P/G tables are available, then present worth can be expressed as:

$$P = A\ (P/A) + G\ (P/G)$$

Commonly used P/A and P/G factors are included in Appendix E. The analyst may also consider use of the nomograph in Figure E-7 of the Operations and Procedures Manual (SDHPT, 1981) to estimate present worth.

Using a discount rate of 8-percent, the present worth of the examples previously presented are shown in Table 6.

Table 6. Present Worth of Benefits[1]

(1985 $ million)

Example No.	Years			
	5	10	15	20
1	7.53	14.95	NA	NA
2	26.55	46.95	NA	NA
3	1.82	4.03	6.25	NA
4	2.94	6.76	10.98	NA

[1]Eight percent discount rate.

Benefits for the first five years, range from a low of $1.82 million to a high of $26.55 million. Benefits for 10 and 15 year periods increase substantially.

Benefit to Cost Ratio

Once the quantifiable benefits are obtained and the construction costs estimated, a benefit to cost ratio can be prepared to assess cost effectiveness of each project. Cost estimates for a short and long bridge version of grade separated ramps were estimated in the Benefit Analysis section; typical cost were given as $1.24 million for the first and $1.79 million for the latter. Demolition costs may be estimated at 20 percent of the construction cost. Maintenance for each option should be considered, if available at this level of analysis.

Table 7 shows the benefit to cost ratio of the above examples. Examples 1, 2 and 4 can be justified in a period less than 5-years, when the ratio would be one. However, example 3 would not be economically viable until sometime in between the 10th and the 15th year.

Table 7. Benefit to Cost Ratio[1]

Example No.	Years			
	5	10	15	20
1	3.5	7.0	NA	NA
2	12.3	21.8	NA	NA
3	0.8	1.9	2.9	NA
4	1.4	3.1	5.1	NA

[1]The more expensive of the two typical configurations has been used here. Initial construction, estimated at $1.79 million, plus 20% for demolition totals $2.15 million. If the grade separated ramp does not need to be demolished during the specific period, the B/C ratio would be higher.

The viability of each of the above examples should not be emphasized. Rather, the methodology and the values indicating that it does not take fully saturated conditions to justify the cost of building a grade-separated ramp, should be regarded as important.

Detailed Method

A detailed analysis of a grade separated ramp as an option for freeway weaving or to frontage road access is more involved and is likely to be used after preliminary screening and analysis of alternatives. It includes data collection, concept design, simulation of operations, benefits estimation, cost estimation and assessment including benefit cost ratio and other possible impacts. Figure 21 shows an activity chart of major tasks and relationship to each other.

Data collection include obtaining design plans of the proposed grade separated ramp, utilities, dedicated right of way and some geometrics upstream and downstream from the site. A site visit supplements design plans and aerial photos, plus gives a perspective on operations and adjacent land uses. Current traffic counts involved in weaving and freeway traffic speed is required for the weaving option. Upstream ramp counts should be obtained

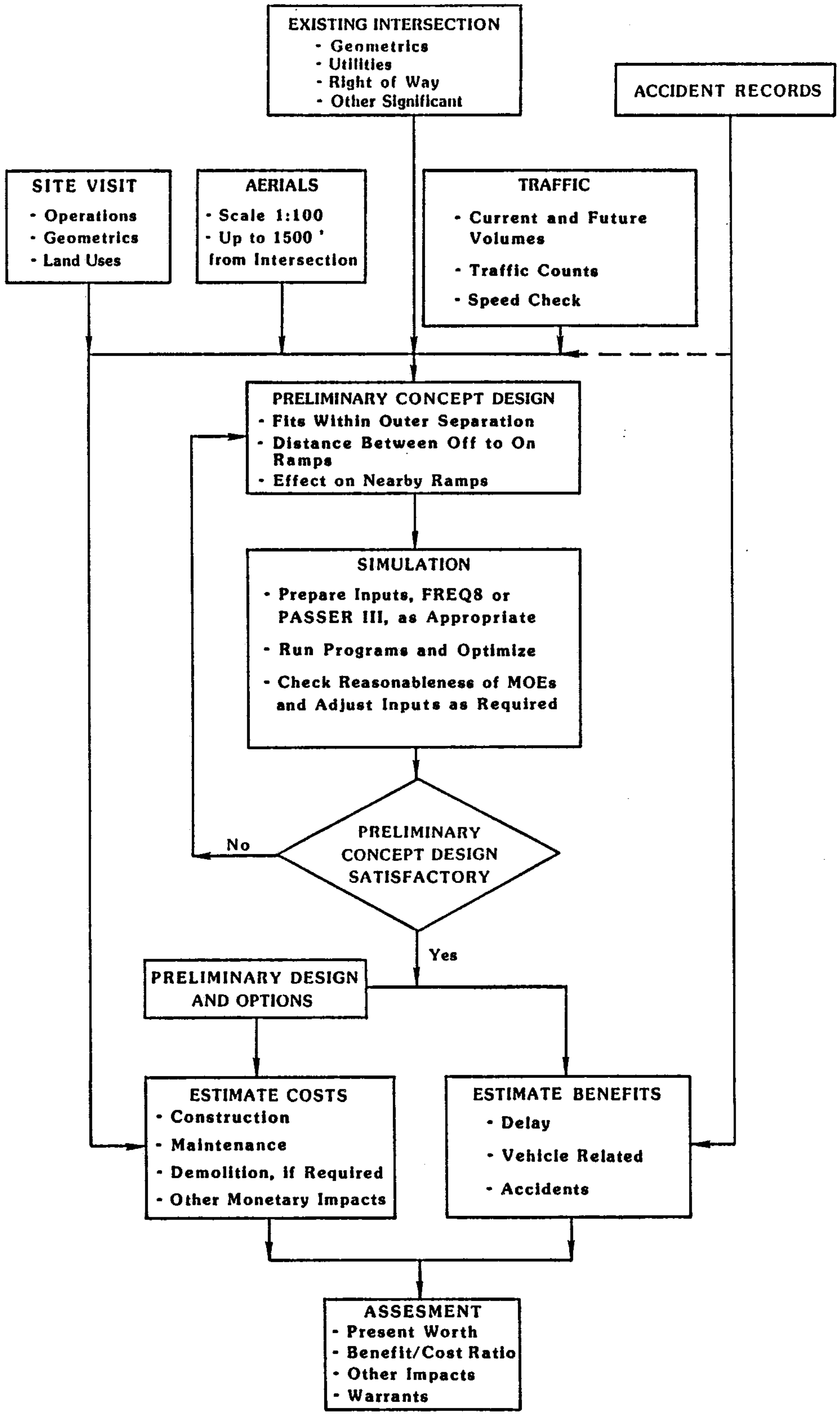


Figure 21. Flowchart For Detailed Method of Assessment

within a mile, and 1500 feet downstream. The access option needs to count access traffic and intersection traffic. Speed on the freeway and on the frontage road is required. Accident records should be retrieved, preferably for a period of four years.

With the above information a preliminary concept design is developed. The location with respect to the freeway, to other ramps and to the frontage road nearby intersection are investigated. Every attempt should be made to allow the possible accommodation of an extra lane on the freeway. Possible low cost improvements to the intersection or frontage road are considered in the access case. Preliminary cost estimates of the selected options should be prepared at this time.

Pertinent data and concept design information are input to the models. If the FREQ8 model is used for the weaving case, data should be input by time slices approximately 15 minutes each for a period beginning before queues formation and preferably ending after queues dissipate; a period of 3-hours is generally satisfactory. If the PASSER III model is used for the access case, the model should be run for at least a peak and an off-peak hour. Because of the integral nature of the two sides of a diamond intersection, where delay on one side means delay on the other side, all approaches on both sides should be considered.

If the simulation suggests minor changes to improve operations such as beginning a ramp further downstream or adding a turning lane to an intersection (where possible), this should be considered as the base condition to compare with the grade separated ramp option.

The design is refined and construction and other related costs estimated. If construction requires significant delay of existing traffic, this should be analyzed. Other monetary impacts such as may occur with detours affecting commercial property should be considered at this time, if significant. Maintenance costs should be included.

Benefits are estimated in detail based on reduced travel time to motorists, reduced fuel consumption and accidents prevented. Outputs from the computer models are the primary source of data to estimate travel time saved. If detailed peak and off-peak data is available, as for the access option, a spreadsheet microcomputer program may be used to estimate present worth (Bonilla, 1986). The economic assessment of the grade separated ramp project should be based on a favorable benefit to cost ratio, and meeting most of the warrants proposed below for grade separated ramps.

Warrants

A grade separated ramp can increase the effective capacity of the freeway mainlanes or improve access to points on the frontage road. But because of the high capital cost, it's use should be limited to locations where it can be justified based on function and on economics. The conditions to be considered in selecting a specific grade separated ramp project are the proposed warrants. These are:

1. The existence of nearby ramps precludes the addition of an extra at-grade ramp without severely affecting the operation of existing ramps.
2. The outer separation is at least 63 feet wide and freeway geometrics allow the grade separated ramp to operate efficiently.
3. Traffic volume is not expected to exceed 1600 vehicles per hour within the design life of the on- or the off-ramp of the grade separated pair.
4. If mainlane addition on the outer separation is considered within the design life of the project and the grade separated ramp cannot be built within the existing outer separation leaving enough space for eventual mainlane expansion, options considered include:

    - reject grade separated-ramp in favor of eventual mainlane expansion,
    - build a grade separated ramp and demolish when freeway expansion is necessary, and

- build a lower design type grade-separated ramp and/or modify frontage road to leave enough space for eventual mainlane expansion.

5. An on-ramp followed closely by an off-ramp (short weave) have enough traffic to constitute a bottleneck on the freeway mainlanes and low cost traffic engineering improvements such as restriping to add a lane, are not possible or cannot resolve the capacity problem.
6. A significant amount of motorists (200 vph or more) want to exit at a downstream point where there is no ramp and instead leave the freeway early to travel on the frontage road and at least through one signalized intersection.
7. Access traffic using the frontage road add enough traffic to a signalized intersection to induce excessive delay. Low cost traffic engineering measures cannot relieve congestion.
8. The accident rate (accidents per vehicle mile) 0.5 mile upstream and 0.2 mile downstream of the short weave is significantly higher than on nearby segments of the same freeway. The weaving section can be determined to be the main contributing factor.
9. Benefit to cost ratio is greater than three based on the screening method incorporated in this report or as approved by the SDHPT. Ratios above one may be justified but a detailed analysis should be conducted to include all benefits and costs.

The above warrants are proposed as a guideline in the selection of grade separated ramp projects. Several assumptions are incorporated into the assumptions of an economic analysis, such as the value of time, and judgement should still prevail. Solutions not requiring the grade separated ramp, such as routing traffic further upstream or downstream from the site or closing an existing ramp, should be considered in the early planning stage.

FINDINGS AND CONCLUSION

The documented use of grade separated ramps connecting freeway mainlanes with frontage roads is very limited. Warrants for interchanges do not address specific issues peculiar of grade separated ramps. Interchanges are typically designed with ample right of way to satisfy desirable lateral safety standards and to allow smooth transitions between mainlane traffic and frontage road traffic. However, some compromises may be appropriate in the case with ramps built to satisfy unforeseen traffic growth in urban areas.

A minimum width outer separation must be available to build a grade separated ramp. That is, the distance between the outside lane line of the freeway and the inside lane line of the frontage road. This distance is about 63 feet in order to observe all SDHPT standards. Such separation allows for an at-grade ramp, a second ramp crossing over the first, shoulders and guardrails. If lateral space to build an extra mainlane is considered, an outer separation 75 feet or wider is required.

Desirable width of outer separations within urban areas in Texas is 80 feet or more (SDHPT, 1981) but narrower outer separations exist. If freeway expansion is contemplated and a grade separated ramp is being considered, four options are available.

- reject grade separated ramp in favor of eventual mainlane expansion,
- build a grade separated ramp and remove when mainlane expansion becomes necessary,
- build a lower design type grade-separated ramp and/or modify the frontage road to leave enough space for eventual mainlane expansion, or
- build a grade-separated ramp within the existing outer separation leaving enough space for the eventual addition of a freeway mainlane.

A benefit cost analysis can be used to justify the most satisfactory option. Benefits and costs can be compared based on their present worth.

Estimated construction costs vary between $1.24 million to $1.79 million for a grade separated ramp with a short bridge and a grade separated ramp with a long bridge. However, topography, geometric adjustments required to tie with other ramps or bridges, may make this estimate suitable for planning purposes only.

Using the construction costs above it takes about 503 to 726 vehicle hours in travel time savings to break even, that is, to have a benefit to cost ratio of one. If the grade-separated ramp needs to be demolished to build another freeway lane, it is estimated that 20% more vehicle hours would be required to achieve a benefit to cost ratio of one. Benefits have been separately assessed by function for grade-separated ramps that resolve a freeway weaving problem and/or those that improve access to a cross street or other location along the frontage road.

A short weaving section, 750 feet long, induces slightly more travel time than a standard and acceptable section 1500 feet long. However, this shows up only after the weave reaches capacity. Eliminating the weave with a grade separated ramp, can eliminate ramp induced delay. The weaving delay is attributed to the queues formed on the right most lane of the freeway and the on-ramp queues. Travel times estimated by simulation caused by ramp related queues appear very high and there is a need for validation.

In the access case, the more significant component of travel time is delay induced by the signalized intersection. Delay is not only incurred by access vehicles travelling the intersection but principally by all other vehicles going through the intersection. And unlike the weaving case, the intersection induced delay affects peak as well as off-peak hours. When the intersection reaches capacity, the model used indicates over saturation and will not output travel time. This seems like a drawback but it really means that local conditions will determine the actual delay and the model travel time maybe meaningless.

It can be stated that grade separated ramps can be a cost-effective solution to weaving on the freeway, and access to or from some point on the frontage road, provided that neither the on-ramp nor the off-ramp of a weaving section can neither be eliminated nor moved elsewhere, and no reasonable at-grade solution exist to the access problem. At locations with high weaving or access volumes, removal of a grade separated ramp to expand the freeway can be justified in as little as five years.

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Appendix A
Peaking Patterns Used For Input to FREQ8

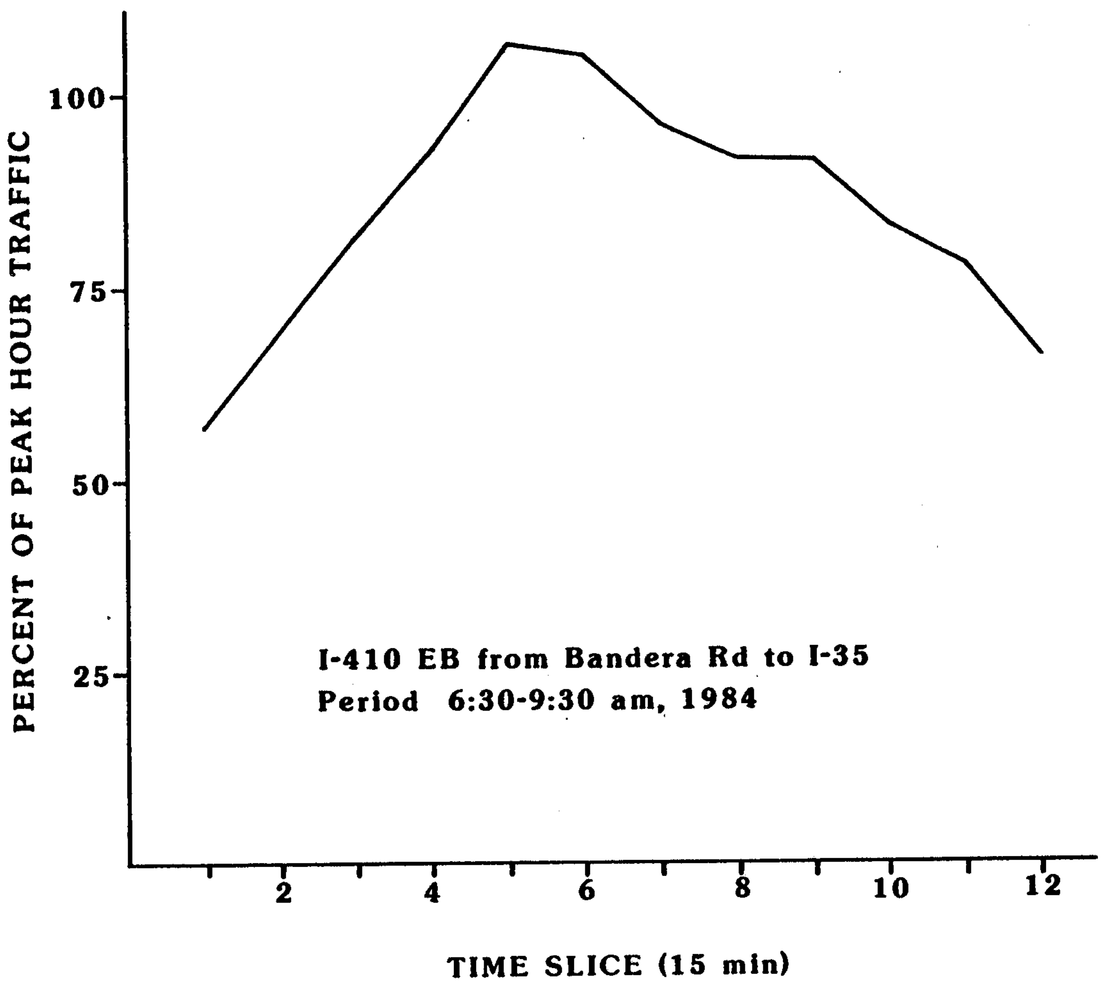

Figure A-1. I-410 Mainlanes Peak Pattern

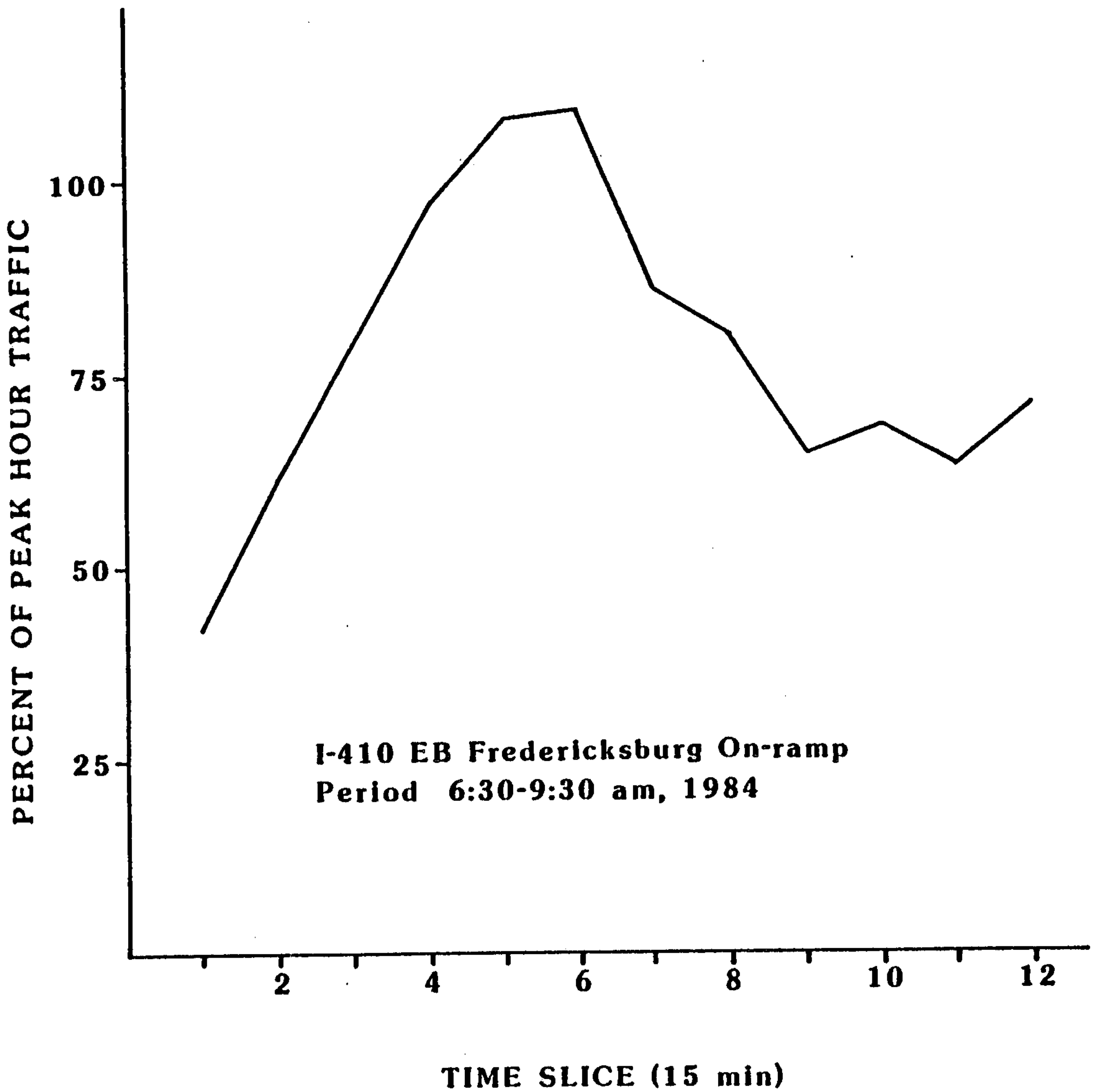

Figure A-2. I-410 On-Ramp Peak Pattern

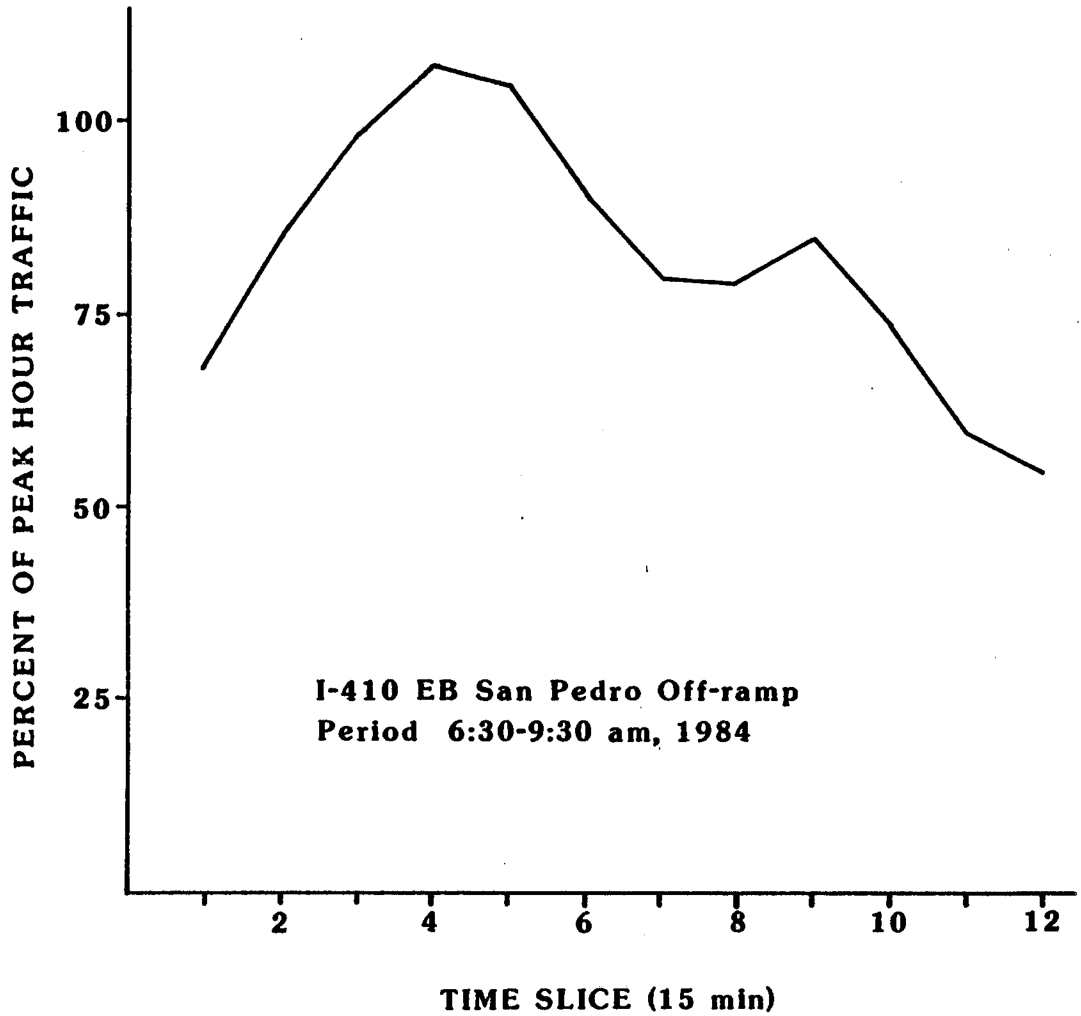

Figure A-3. I-410 Off-Ramp Peak Pattern

Appendix B

Travel Times on the Freeway With Weaving Ramps and With a Grade Separated Ramp Pair

Table B.1. Travel Time Savings for 3-Lane Segment with Grade Separated Ramp Instead of 750 Feet of Weaving

Through Traffic Volume	On-Ramp Volume	Off-Ramp Volume			
		400	800	1200	1500
3000	400	0	0	0	0
	800	0	922 (922)	1478 (1478)	
	1200	15 (15)	2582 (2582)		
	1500	298 (298)			
4500	400	0	0	0	0
	800	29 (29)	1436 (1436)	1818 (1818)	
	1200	449 (449)	3134 (3134)		
	1500	1042 (1042)			
5250	400	17 (17)	26 (26)	0	0
	800	259 (274)	2173 (2173)	2296 (2296)	
	1200	1107 (1204)	2534 (2537)		
	1500	1722 (1822)			
6000	400	21 (40)	63 (63)	54 (54)	45 (45)
	800	91 (630)	2641 (2702)	2984 (2986)	
	1200	737 (1632)	3894 (4421)		
	1500	1088 (2180)			

Note: Numbers in parentheses are the contribution of the grade separated ramp to travel time savings. When ramp travel time savings exceed total savings, downstream congestion on mainlanes offsets some benefits of grade separated ramp. See page 25 for further explanation.

Table B.2. Travel Time Savings for 3-Lane Segment with Grade Separated Ramp Instead of 1500 Feet of Weaving

Through Traffic Volume	On-Ramp Volume	Off-Ramp Volume			
		400	800	1200	1500
3000	400	0	0	0	0
	800	0	814 (814)	1605 (1605)	
	1200	0	2363 (2363)		
	1500	77 (77)			
4500	400	0	0	0	0
	800	11 (11)	1354 (1354)	1949 (1949)	
	1200	205 (205)	2931 (2931)		
	1500	607 (607)			
5250	400	0	30 (30)	15 (15)	21 (21)
	800	66 (82)	2066 (2066)	2411 (2411)	
	1200	752 (849)	3615 (3618)		
	1500	1220 (1321)			
6000	400	-7	58 (65)	118 (125)	136 (143)
	800	67 (172)	2525 (2592)	2915 (2920)	
	1200	346 (1254)	2567 (4249)		
	1500	429 (1535)			

Note: Numbers in parentheses are the contribution of the grade separated ramp to travel time savings.

Table B.3. Travel Time Saving for 4-Lane Segment with Grade Separated Ramp Instead of 750 Feet of Weaving

Through Traffic Volume	On-Ramp Volume	Off-Ramp Volume			
		400	800	1200	1500
4000	400	0	0	0	0
	800	0	1278 (1278)	1789 (1789)	
	1200	116 (116)	2993 (2993)		
	1500	630 (630)			
6000	400	0	0	0	0
	800	28 (28)	1880 (1880)	2274 (2274)	
	1200	600 (600)	3614 (3614)		
	1500	1389 (1389)			
7000	400	0	0	0	0
	800	69 (69)	2228 (2228)	2606 (2606)	
	1200	890 (974)	3958 (3964)		
	1500	1608 (1721)			
8000	400	5	14 (5)	6 (4)	5 (5)
	800	6 (112)	2297 (2363)	2721 (2718)	
	1200	305 (1202)	3678 (4291)		
	1500	612 (1838)			

Note: Numbers in parentheses are the contribution of the grade separated ramp to travel time savings.

Table B.4. Travel Time Savings For 4-Lane Segment with Grade Separated Ramp Instead of 1500 Feet of Weaving

Through Traffic Volume	On-Ramp Volume	Off-Ramp Volume 400	800	1200	1500
4000	400	0	0	0	0
	800	0	1193 (1193)	1916 (1916)	
	1200	25 (25)	2782 (2782)		
	1500	243 (243)			
6000	400	0	0	1 (1)	8 (8)
	800	8 (8)	1771 (1771)	2373 (2373)	
	1200	278 (278)	3415 (3415)		
	1500	842 (842)			
7000	400	0	2 (2)	18 (18)	38 (38)
	800	24 (24)	2109 (2109)	2533 (2533)	
	1200	484 (568)	3766 (3772)		
	1500	1080 (1193)			
8000	400	-7	-4 (4)	40 (47)	76 (84)
	800	12 (39)	2175 (2250)	2937 (2946)	
	1200	40 (787)	3480 (4102)		
	1500	240 (1334)			

Note: Numbers in parentheses are the contribution of the grade separated ramp to travel time savings.

Appendix C

Fuel Consumption of Weaving Vehicles

Table C.1. Fuel Consumption for 3-Lane Segment with 750 Feet of Weaving and with Grade Separated Ramp

Through Traffic Volume	On-Ramp Volume	Ramp Type	Off-Ramp Volume 400	800	1200	1500
	200	W	2538	2526	2514	2502
		GS	2538	2526	2514	2502
	400	W	2495	2484	2473	2465
		GS	2495	2485	2474	2466
3000	800	W	2513	3005	3284	
		GS	2513	2488	2456	
	1200	W	2539	3926		
		GS	2532	2478		
	1500	W	2714			
		GS	2549			
	200	W	3708	3698	3687	3679
		GS	3708	3698	3687	3679
	400	W	3645	3634	3624	3616
		GS	3645	3635	3624	3617
4500	800	W	3678	4430	4616	
		GS	3662	3624	3597	
	1200	W	3930	5373		
		GS	3679	3615		
	1500	W	4292			
		GS	3704			
	200	W	4273	4262	4252	4244
		GS	4273	4262	4252	4244
	400	W	4209	4204	4179	4171
		GS	4199	4189	4180	4173
5250	800	W	4369	5382	5430	
		GS	4212	4163	4142	
	1200	W	4909	6298		
		GS	4234	4162		
	1500	W	5380			
		GS	4356			
	200	W	4588	4579	4568	4561
		GS	4589	4579	4568	4561
	400	W	4533	4543	4527	4515
		GS	4498	4509	4499	4492
6000	800	W	4890	5983	6214	
		GS	4430	4446	4528	
	1200	W	5528	7076		
		GS	4720	4489		
	1500	W	6086			
		GS	5190			

Table C.2. Fuel Consumption for 4-Lane Segment with 750 Feet of Weaving and with Grade Separated Ramp

Through Traffic Volume	On-Ramp Volume	Ramp Type	Off-Ramp Volume			
			400	800	1200	1500
4000	200	W	3382	3371	3360	3351
		GS	3382	3371	3360	3351
	400	W	3391	3389	3369	3360
		GS	3391	3389	3369	3361
	800	W	3409	4096	4354	
		GS	3409	3373	3342	
	1200	W	3493	5057		
		GS	3428	3364		
	1500	W	3795			
		GS	3440			
6000	200	W	4945	4934	4923	4915
		GS	4945	4934	4923	4915
	400	W	4953	4942	4932	4924
		GS	4952	4942	4932	4925
	800	W	4986	5984	6180	
		GS	4970	4920	4894	
	1200	W	5321	6957		
		GS	4982	4910		
	1500	W	5790			
		GS	5004			
7000	200	W	5696	5684	5675	5667
		GS	5696	5684	5675	5667
	400	W	5704	5692	5683	5675
		GS	5703	5692	5683	5678
	800	W	5760	6924	7112	
		GS	5718	5662	5637	
	1200	W	6274	7898		
		GS	5710	5648		
	1500	W	6757			
		GS	5772			
8000	200	W	6117	6109	6100	6092
		GS	6117	6109	6100	6092
	400	W	6108	6118	6109	6102
		GS	6103	6120	6109	6103
	800	W	6129	7418	7594	
		GS	6010	6052	6061	
	1200	W	6856	8512		
		GS	6145	5897		
	1500	W	7342			
		GS	6474			

Appendix D
Fuel Consumption Rates

Table D.1 Fuel Consumption Rates for Vehicle Type 1 on Freeways, by Level of Service and Average Speed[a]

Average Speed Miles Per Hour	Level of Service A	B	C	D	E	F
	---- Gallons Per Vehicle Mile ----					
5						.3970
10						.1649
15						.1028
20						.0772
25						.0641
30					.0433	.0574
35				.0420	.0428	.0431
40			.0426	.0429	.0444	
45		.0427	.0443	.0450	.0465	
50	.0438	.0454	.0471	.0486		
55	.0468	.0489	.0512			
60	.0494	.0519				
65	.0567					

[a]Buffington, 1981

Table D.2. Fuel Consumption Rates For Vehicle Types 2 & 4 on Freeways, by Level of Service and Average Speed[a]

Average Speed Miles Per Hour	Level of Service A	B	C	D	E	F
	---- Gallons Per Vehicle Mile ----					
5						.6765
10						.3491
15						.2249
20						.1772
25						.1635
30					.1139	.1577
35				.1250	.1281	.1319
40			.1329	.1346	.1395	
45		.1412	.1457	.1486	.1528	
50	.1486	.1542	.1603	.1654		
55	.1613	.1687	.1769			
60	.1782	.1862				
65	.1981					

[a]Buffington, 1981

Table D.3. Fuel Consumption Rates for Vehicle Type 3 on Freeways, by Level of Service and Average Speed[a]

Average Speed Miles Per Hour	Level of Service A	B	C	D	E	F
	- - - - Gallons Per Vehicle Mile - - - -					
5						3.1346
10						1.055
15						.5660
20						.3784
25						.2963
30					.1567	.2445
35				.1503	.1552	.1613
40			.1529	.1566	.1646	
45		.1613	.1676	.1722	.1745	
50	.1778	.1860	.1951	.2026		
55	.1928	.2041	.2167			
60	.2017	.2128				
65	.2208					

[a]Buffington, 1981

Table D.4. Idling Fuel Consumption, by Vehicle Type

Vehicle Type	Idling Fuel Consumption Per Hour[a] Gallons Per Hour[a]
1	.370
2 & 4	.650
3	.400

[a]To convert gallons per hour to liters per hour, multiply by 3.7854.

Source: Winfrey, Robley, Economic Analysis for Highways, International Textbook Co., Scranton, Pennsylvania, 1969.

Appendix E
Present Worth Factors Commonly Used in Highway Projects

Table E.1. Present Worth Factors for Uniform Series (P/A) and Arithmetic Gradient (P/G)[1]

i	Years from Present							
	5		10		15		20	
(%)	P/A	P/G	P/A	P/G	P/A	P/G	P/A	P/G
4	4.4518	8.5546	8.1109	33.881	11.1184	69.735	13.590	111.560
6	4.2124	7.9345	7.3600	29.602	9.7122	57.554	11.469	87.230
8	3.9927	7.3724	6.7100	25.976	8.5595	47.885	9.8181	69.089

Source: AASHTO, A Manual on User Benefit Analysis of Highway and Bus-Transit Improvement, American Association of State Highway and Transportation Officials, Washington, D.C. 1977.

[1]The arithmetic gradient factors assume an increase in funds at the end of each period.