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16. Abstract

Many urban freeways in Texas experience congested traffic conditions during peak periods. Freeway system expansion is very expensive and time-consuming. Consequently, alternatives other than construction of new facilities are desired. The Texas Department of Transportation has been implementing comparatively inexpensive methods to improve existing freeways such as grade-separated (i.e., braided) ramps and modified ramp configurations via X-ramp interchanges and ramp reversals.

Ramp reversal, replacement of an entrance ramp with an exit ramp or vice versa, is an improvement strategy occasionally recommended by outside constituencies. The basis for this research was driven by Texas Department of Transportation (TxDOT) engineers' need to have an updated methodology and evaluation results from previously implemented ramp reversal projects to assist in future decision-making.

This research project investigated the benefits and impacts of X-ramp and ramp reversal projects. Impacts that were evaluated include operational, safety, and basic economic benefits. Case study evaluations of 15 projects implemented throughout the state were performed and generally showed that ramp modification projects are a worthwhile effort.

The final product of this research was the development of guidelines for TxDOT staff to assist in the evaluation and implementation of ramp modification projects. The framework for the guidelines was based on the three themes for the Texas access management program: (1) improve safety and mobility, (2) provide reasonable access to developments, and (3) promote local government partnerships. Based on this framework, the 21 guidelines for successful implementation were further divided into five categories: educational, encouragement, engineering, enforcement, and evaluation.

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RAMP REVERSAL PROJECTS: GUIDELINES FOR SUCCESSFUL IMPLEMENTATION

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LIST OF ABBREVIATIONS

ADT	Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ABL	Abilene District
AMA	Amarillo District
APTS	Advanced Public Transportation System
ATL	Atlanta District
ATIS	Advanced Traveler Information System
ATMS	Advanced Traffic Management System
AUS	Austin District
AVCSS	Advanced Vehicle Control and Safety System
AVI	Automatic Vehicle Identification
AVO	Average Vehicle Occupancy
B/C	Benefit-Cost
BMT	Beaumont District
BPR	Bureau of Public Roads
BWD	Brownwood District
BRY	Bryan District
CAD	Computer Aided Drawing
CBD	Central Business District
CBP	Commercial Building Permits
CCSJ	Control Section Job Number
C/D	Collector-Distributor
CHS	Childress District
CRP	Corpus Christi District
CTR	Center for Transportation Research
CVO	Commercial Vehicle Operation
DAL	Dallas District
DFW	Dallas/Fort Worth
DMI	Distance Measuring Instrument
DOT	Department of Transportation
DPS	Department of Public Safety
EB	Eastbound
ELP	El Paso District
FHWA	Federal Highway Administration
FM	Farm-to-Market
FTW	Fort Worth District
GETT	GPS-based Evaluation of Travel Time
GIS	Geographic Information System
GPS	Global Positioning Satellite
HCM	Highway Capacity Manual
HOU	Houston District
HOV	High-Occupancy Vehicle
IAC	Interagency Contract

LIST OF ABBREVIATIONS (continued)

IAJ	Interstate Access Justification
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
LBB	Lubbock District
LCI	Lane Changing Intensity
LFK	Lufkin District
LOS	Level-of-Service
LRD	Laredo District
MCL	Medical Center of Lewisville
MOE	Measure of Effectiveness
MPO	Metropolitan Planning Organization
MUTCD	Manual on Uniform Traffic Control Devices
MVM	Million Vehicle-Miles
MVMT	Million Vehicle-Miles Traveled
NAFTA	North American Free Trade Agreement
NB	Northbound
NCTCOG	North Central Texas Council of Governments
NHTSA	National Highway Traffic Safety Administration
ODA	Odessa District
PAR	Paris District
PCE	Passenger Car Equivalent
PHR	Pharr District
PHT	Person-Hours of Travel
PMC	Project Monitoring Committee
PMT	Person-Miles Traveled
RMC	Research Management Committee
ROW	Right-of-Way
RRX	Railroad Crossing
SAT	San Antonio District
SB	Southbound
SH	State Highway
SJT	San Angelo District
SOV	Single Occupant Vehicle
SPID	South Padre Island Drive
TDM	Travel Demand Management
TP&P	Transportation Planning and Programming
TRIS	Transportation Research Information System
TT	Travel Time
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
US	United States
UTA	University of Texas at Arlington
VHT	Vehicle-Hours Traveled
VMT	Vehicle-Miles Traveled

LIST OF ABBREVIATIONS (continued)

WAC	Waco District
WB	Westbound
WFS	Wichita Falls District
YKM	Yoakum District

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE OF RESEARCH

Urban growth in Texas has placed tremendous demands on freeway systems. The cost of constructing new facilities or of expanding existing ones has increased at a rate greater than inflation. With main lane expansion becoming an ever-diminishing possibility, many TxDOT districts have modified various freeway elements to maximize efficiency and safety. As development within freeway corridors increases, several changes to the transportation system occur, including increased traffic congestion and crash potential. In response, TxDOT has implemented improvements such as new ramps, grade-separated ramps, and frontage road u-turn lanes. In addition, TxDOT has modified ramp configurations via ramp relocations and ramp reversals, often for the purpose of reducing vehicle queues at critical locations. The common purpose for each of these improvements is to maximize vehicular movement while minimizing cost. It is generally accepted that these improvements can be effective in mitigating freeway congestion. However, because of funding and personnel constraints, it is crucial that the various improvement strategies can be easily prioritized according to their expected cost-effectiveness.

The general questions motivating this research were:

- When and where should TxDOT consider the use of ramp reversals?
- How should ramp reversal projects be evaluated?
- When and where should TxDOT use an X-ramp pattern as opposed to diamond ramp design for freeway interchanges?
- Under what conditions are braided ramps worthwhile?

Ramp Reversal

This study focused on the use of ramp reversal, i.e., replacing an exit ramp with an entrance ramp or vice versa. Ramp reversal can help solve congestion issues between the exit ramp/frontage road intersection and the downstream cross street. Ramp reversal becomes an important consideration, especially when the situation involves traffic spilling back from an exit ramp onto the freeway main lanes. The reasons for studying ramp reversals are:

- to examine all benefits and impacts using a case study approach and
- to develop guidelines to aid decision makers in the implementation of successful projects.

X-Ramp Pattern Interchanges

A second major element of this study focuses on the use of X-ramp interchanges. Due to the presence of frontage roads on the majority of freeway facilities in Texas, the two predominant interchange types are the diamond (see Figure 1-1) and X (see Figure 1-2) interchanges. The X-ramp design has an exit ramp located upstream of an entrance ramp both upstream and downstream of the arterial street. The Y-ramp interchange, commonly called a diamond, is the more popular of the two designs; however, scenarios exist where it may be more beneficial to the traveling public to use an X-ramp pattern as opposed to the conventional Y-ramp design. Table 1-1 lists some of the issues of converting from diamond ramp configuration to X-ramps.

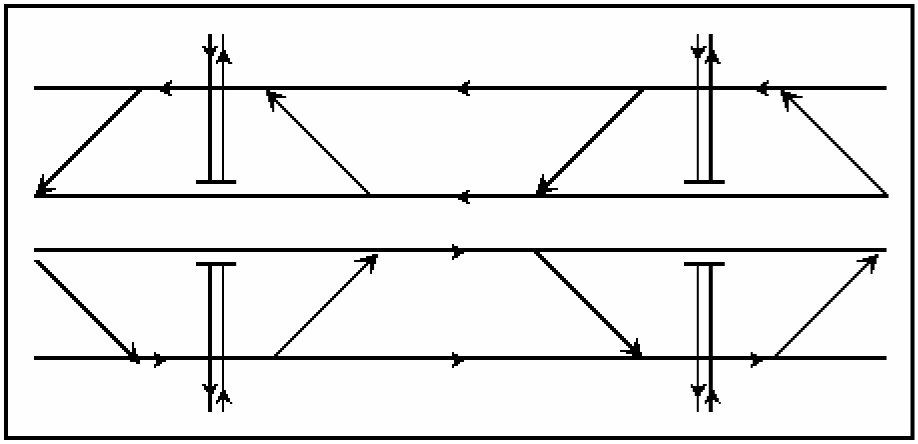

Figure 1-1. Y-Ramp Diamond Interchange Layout (Not to Scale).

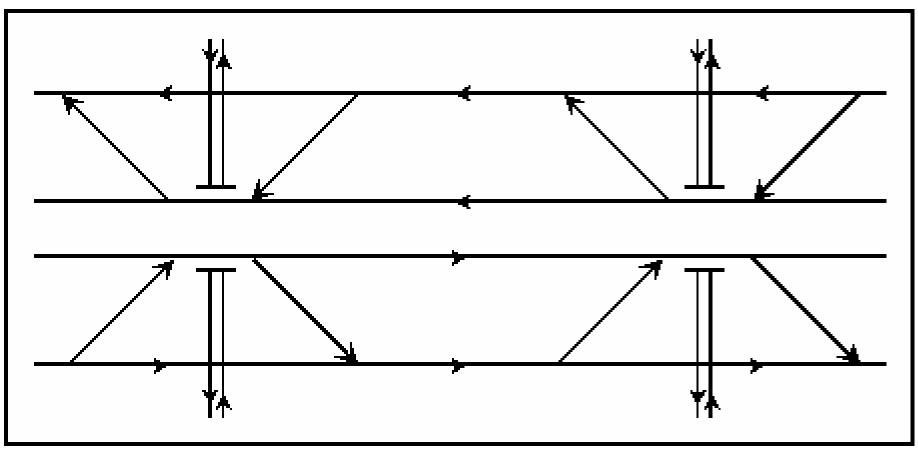

Figure 1-2. X-Ramp Interchange Layout (Not to Scale).

This study will develop guidance on when and where it is desirable to use X-ramp interchanges based on previous studies and case studies performed during this project. One topic that has not been adequately addressed in previous studies is the safety impacts of X-ramp versus diamond designs. The TxDOT Roadway Design Manual offers the following guidance on X-ramps: "*Has primary application to locations with significant development along the frontage road. It provides access between interchanges and exiting queues do not back up onto the freeway. However, entering vehicles may have to accelerate on an upgrade and exiting maneuvers occur just beyond the crest vertical curve where weaving also takes place. The "X" ramp pattern also encourages frontage road traffic to bypass the frontage road signal and weave with the main lane traffic. The "X" ramp pattern may cause some drivers to miss an exit located well in advance of the cross street.*"

Table 1-1. Generic Pros and Cons of Converting from Diamond to X-Ramps.

PROS	CONS
+ ***Increased development*** along frontage road	– ***Costly*** means of improving signal operation
+ ***Reduced through demand*** on frontage road approach to intersection	– Construction activities will ***disrupt business*** along frontage road
+ ***Move the weaving area*** between an entrance ramp and exit ramp from the main lanes to the frontage road, where speeds and volumes are lower	– Invites ***sling-shot maneuvers*** allowing motorists to bypass cross-street signals; this poses safety and capacity problems on frontage road
+ ***Increased storage area*** for cross-street intersection queuing	– Addresses the queue storage problem but ***queuing delay will not be remedied***
+ Better opportunity to use frontage road as alternate route as part of ***incident management*** if auxiliary lanes are provided	– Likely increase in ***short trips*** on the freeway
	– Construction of auxiliary lanes may require ***major reconstruction*** at cross-streets

Braided Ramps

The final topic of this study focuses on the use of braided ramp designs. A braided ramp is a design feature where two nearly parallel ramps cross each other and use a grade separation to avoid weaving (Figure 1-3). Most often this occurs when an on-ramp from one nearby interchange is braided to avoid interfering with an off-ramp for the next one. This treatment would normally be applied in areas where weaving has created significant operational problems or has produced a serious accident history. It is not anticipated that this topic will receive as much attention as ramp reversal and X-ramps; however, this study provides guidance on what conditions make braided ramps a worthwhile improvement option.

Figure 1-3. Braided Ramps.

1.2 RESEARCH WORK PLAN

In order to conduct a research project that produces useful and implementable results, the work plan needs well-defined objectives that are used to measure progress and to determine necessary tasks. The overall goal established for this project is:

Develop guidelines to assist TxDOT staff in the evaluation of ramp reversal projects and X-ramp interchanges.

This work plan provides TxDOT and other interested stakeholders (e.g., municipalities, business owners, land developers, motoring public, etc.) useful, practical, and reliable information on the subject of ramp reversal, X-ramps, and braided ramps. The work plan consisted of the following tasks:

- Task 1. Perform State-of-the-Practice Literature Review
- Task 2. Develop Project Website
- Task 3. Survey Existing Guidelines and Practices
    - Task 3.1. Survey Other State DOTs
    - Task 3.2. Survey TxDOT Districts
- Task 4. Identify and Select Study Sites
- Task 5. Develop Proposed Project Evaluation Process
- Task 6. Conduct Project Case Studies
    - Task 6.1. Evaluate Safety Benefits and Impacts
    - Task 6.2. Assess Operational Benefits and Impacts
- Task 7. Develop Recommended Guidelines and Policies
- Task 8. Prepare Project Deliverables

1.3 REPORT ORGANIZATION

The focus of this project is to develop guidelines to assist TxDOT staff in the evaluation of ramp reversal projects and X-ramp interchanges. Chapter 1 (Introduction) contains the background and significance of research and the basic tasks included in the research work plan.

Chapter 2 (State-of-the-Practice Literature Review) provides a brief summary of the state-of-the-practice literature review performed during Task 1 of the project. The review included findings on ramp reversal, X-ramp interchanges, braided ramps, frontage road operations, weaving analysis, access management, and simulation modeling.

Chapter 3 (Survey of Existing Guidelines and Practices) explains the results of interviews and surveys conducted as part of Task 3 with TxDOT district staff throughout the state. The survey focused on obtaining information on planned and previously implemented projects that involved ramp reversal components.

Chapter 4 (Project Case Studies) presents the sites selected by the research team and Project Monitoring Committee (PMC) as part of Task 4 for detailed evaluation. Case study evaluations of 15 sites were performed to assess the operational, safety, and basic economic impacts resulting from the ramp modification projects.

Chapter 5 (Project Evaluation Process) outlines a project evaluation process that can be used by TxDOT engineers. The process is based on relevant evaluation criteria, the results of previous research, case study findings, and simulation data.

Chapter 6 (Guidelines for Ramp Reversal and X-ramp Projects) describes the development of the guidelines framework for ramp modification projects. The chapter outlines the 21 guidelines and provides a checklist that should aid advance project development engineers in the planning and implementation of successful ramp reversal and X-ramp corridor projects.

CHAPTER 2
STATE-OF-THE-PRACTICE LITERATURE REVIEW

This chapter summarizes some of the important research that relates to ramp reversal, braided ramps, and X-ramps. Other topics that prominently relate to the three already mentioned are weaving analysis, ramp spacing, access management, and use of traffic simulation for ramp and frontage road operations. This state-of-the-practice literature review briefly addresses each of these topics.

2.1 RAMP REVERSAL STUDIES

While few studies have addressed "ramp reversal," the most prominent ramp reversal-related study found was conducted by Borchardt, et al., from the Texas Transportation Institute (TTI) in 1984. Two main reasons for studying ramp reversal are "to identify, quantify, and document all road user benefits that accrue from reversing the ramps; and to develop a streamlined procedure for estimating the cost-effectiveness of a particular ramp reversal project before its implementation" (*1*).

Benefits obtained from ramp reversal include reductions in vehicle running costs, travel time costs, delay and idling costs, and crash costs. Quantification of these elements involved placing dollar values on these activities. Running cost savings are based on the difference between costs of operating a vehicle before and after the ramp reversal construction. Travel time cost savings is a function of the vehicle occupants' time value expressed in dollars. Delay and idling cost savings are derived from the decrease in standing delay experienced at study area intersections. The average delay and idling times per delayed vehicle are recorded before construction; however, the delay and idling times per delayed vehicle after the construction are determined by assuming a linear relationship between pre-construction delays and volumes. The ratio of these values is applied to the estimated post-construction volumes to determine post-construction delay. Crash cost savings is the difference between numbers of crashes before and after construction.

After ramp reversal construction, some motorists accrue disbenefits because they are forced to drive through an additional intersection, which they had not traveled through before the construction. Other disbenefits include slower operating speeds on the frontage road than on the main lanes and delay at the intersection between frontage road and cross street. The daily volume, peak hour volume, percentage of trucks, vehicular delay, and rerouted traffic volume are collected to quantify the benefits as well as the disbenefits.

There are different types of ramp reversal projects. One of these types was a ramp reversal project between US 90 and Wallisville Road on IH 610 in Houston. There was no exit ramp to the northbound frontage road or entrance ramp from the southbound frontage road between these arterials. This geometry forced northbound drivers bound for US 90 to take the Wallisville Road exit and drive through the Wallisville intersection. Moreover, southbound drivers had to pass through the Wallisville intersection before entering the highway. Consequently, construction of ramp reversals will benefit both northbound and southbound drivers. To determine the benefit-cost (B/C) ratio, a service life of 20 years and a capital recovery rate of 10 percent are assumed.

The overall benefit/cost ratio is 3.8, which means that this project on IH 610 is cost-effective and should be implemented (*1*).

The first ramp reversal study conducted by the TxDOT Dallas District could be classified as the second class of ramp reversal. This project converted a little-used exit to an entrance ramp from the eastbound collector paralleling the main lanes on IH 30 near downtown Dallas. This improvement reversed an existing exit ramp to an entrance ramp, allowing entering vehicles to bypass a constrained weave section that was backing up onto IH 35E southbound. Additionally, the weave occurred on a section with fairly tight horizontal curvature, a contributor to rollover problems for trucks during off-peak time periods (*2,3*). A post-implementation evaluation of this ramp reversal project determined the following:

- truck-rollover crashes were eliminated;
- crash rate in the weave area is down 39 percent (and overall crash rate declined by 14 percent);
- volumes and traffic speeds increased during the PM peak hour; and
- project cost was $660,000 with benefits of $700,000 per year based on delay improvement only.

The second ramp reversal project in the Dallas area was an emergency exit ramp, built across an existing entrance ramp, allowing for reversal of the ramp when a crash occurs along westbound IH 30 in the "Canyon," south of downtown Dallas. It could be the third class of ramp reversal. The entrance ramp is from a collector road that is underutilized during the morning peak period. The primary function of the collector is to unload traffic from downtown Dallas during the evenings. Just downstream of this location is the IH 35E/IH 30 "mixmaster" interchange, which is the junction of several freeways in downtown Dallas where many crashes occur, some involving heavy trucks. These crashes tend to shut down the entire freeway main lanes for several hours. When a crash occurs, TxDOT field personnel or law enforcement officials are able to open the emergency exit ramp and close the entrance ramp, allowing motorists to access the collector-distributor road, thus bypassing the crash location (*2*).

2.2 BRAIDED RAMP STUDIES

The most prominent braided ramp study was conducted by TTI as part of a multi-year freeway operations research project. This treatment would normally be applied in areas where weaving creates significant operational problems or has produced a serious crash history. This project is a case study of ramp repair in San Antonio at the Fredericksburg Road entrance ramp to IH 410 and the connector to IH 10 eastbound in northwest San Antonio. Since this project was implemented before the inception of this research study, all the analyses are based on historical data.

Operating speeds in the right lane of IH 410 were typically 30 miles per hour (mph) for at least 1000 feet upstream of the merge. Moreover, entrance ramp traffic from Fredericksburg frequently queued into the intersection. The average speed for entrance ramp traffic is assumed to be about 20 mph during the peak hour. While travel time savings is important, crash reduction is more important. Separating the flows resulted in a 71 percent reduction in crash frequency;

furthermore, over this 0.5-mile section of freeway, the crash rate dropped from 1.69 crashes per million vehicle-miles (MVM) to 0.55 crashes per MVM for the main lanes alone (*1*).

When an on-ramp connected with an auxiliary lane is very close to an off-ramp, traffic cannot discharge to the freeway main lanes. This situation often causes a queue to form for motorists on the freeway and frontage road. Grade-separated ramps are a possible alternative to solve the problem by making the off-ramp traffic exit before the on-ramp traffic enters the freeway. However, grade-separated structures located between the freeway main lanes and frontage road may delay or prevent the addition of exterior freeway lanes to increase the main lane capacity. One of the primary benefits of grade-separated ramps is removal of main lane weaving problems, which restores main lane capacity and eliminates queues in the outside lane and entrance ramp. However, construction costs for braided ramps are high; thus, these ramps should be limited to locations where they can be justified based on function and economics. As a result, eight warrants are proposed by Bonilla and Urbanik as guidelines in the selection of grade-separated ramp projects (*4*).

2.3 X-RAMP STUDIES

Tipton and Pinnel investigated the performance of three ramp designs: stacked ramps, diamond ramps, and X-ramps. This research studied the movement of both entering and exiting traffic and the effect of each design on the acceptable gap time available to those vehicles entering the highway. Tipton and Pinnel concluded that standard interchange design could not always satisfy drivers' desires. Thus, individual consideration would be needed at each interchange design to satisfy travelers' desires. Moreover, they also concluded that X-ramp design is the most desirable in terms of acceptable gap time available to enter the freeway. However, a diamond configuration should be considered in cases where the freeway main lane capacity is reduced as the freeway crosses the arterial street *(5)*.

A 1986 report by Borchardt and Chang documented the results of a TTI research study of diamond versus X-ramp pattern interchange operations. The study used the combined results of a field study, aerial photographic study, and an extensive simulation analysis, which evaluated the operational trade-offs of both ramp designs *(6)*.

Results of the operational field studies showed that the merge of the entrance ramp traffic with that of the freeway main lanes in the case of the diamond ramp was considered to be more critical. On the other hand, for the X-ramp design, no particular problems were noted concerning the operation of the merge area. This conclusion is based on time-lapse photography, which recorded the merge points of each design. Moreover, smoother yielding of the frontage road traffic to exiting traffic occurs in the X-ramp design than in the diamond ramp design. A survey on US 59 North in Houston during the peak periods showed that a large proportion of exiting traffic re-enters the freeway at the downstream entrance ramp at X-ramp sites. This provides additional throughput during peak periods. The results of the aerial photographic survey concluded:

- Auxiliary lanes on the freeway between the entrance and exit ramp pairs on the X-ramp design provide a bypass around the signalized intersection.

- A continuous freeway section with several pairs of ramps in the X-ramp design and auxiliary lanes provides added throughput capacity during peak traffic periods. Motorists driving in a "sling-shot" pattern can avoid delay, but this type of operation should not be encouraged due to increased yielding conflicts and potential delay to frontage road traffic.
- Land-use patterns vary significantly for each of the two designs. Both designs exhibit significant commercial development at the intersection of the freeway frontage roads and the arterial street. However, the majority of the sites of diamond ramp design, which were observed, had sufficient development along the arterial street. Sites with an X-ramp possessed extensive development along the frontage road between the arterial streets.
- The law stated that the frontage road traffic must yield to those on-ramp vehicles desiring to exit the freeway. The result of survey operations proved that this is less of a problem at the X-ramp due to limited visibility of exiting traffic and the proximity of the junction to the signal that often exists in diamond interchange.

The simulation analysis was performed as a two-step process to provide a comparison of the traffic operation effects on both ramp designs. The first step used the PASSER III ™ simulation model to select an optimum signal-timing pattern. The second step used NETSIM ™ to provide the primary means of comparing the operational trade-offs of both ramp designs. The results of simulation revealed that similar study sites consisting of the X-ramp design result in less overall delay than those of the diamond interchange design. However, this difference is not statistically significant, nor does it impose the benefit of favoring one particular design over the other ramp design. The major benefit of the X-ramp is its capability to remove traffic load at several upstream locations without requiring drivers to pass through a series of signalized intersections. It also effectively reduces traffic demands for frontage road intersections and the likelihood of intersection and network failure. In contrast, the diamond interchange utilizes the adjacent frontage road to access nearby facilities but requires motorists to pass through signalized intersections. In this manner, the diamond ramp provides direct access to the intersection of the nearby arterial facilities and keeps the vehicles on the freeway main lanes for a longer distance *(6)*.

A 1995 report by Klaver, et al., evaluated US 83 and cross-street interchange operation at Conway Avenue, Bryan Road, Shary Road, and Ware Road in Pharr, Texas. Entrance and exit ramps at these interchanges were reversed from the existing diamond interchanges to X-ramp interchanges. This reversal led to a notable improvement in expressway operations and improvement in operational level-of-service (LOS), which could be attributed to the selection of ramp reversals in order to maintain expressway weaving distances of at least 600 meters (2000 feet) *(7)*.

An advantage of the X-ramp is the benefit of providing increased expressway access to frontage road development. Expressway traffic can exit, access the frontage development, and then re-enter the expressway without having to negotiate a cross-street signalized intersection. However, several aspects of expressway ramp location must be considered when alternative geometrics are proposed: the distance between an entrance and exit ramp, distance between the exit ramp terminus and the cross street, and location of the frontage road access points in relation to the ramp terminus. The TxDOT *Roadway Design Manual* indicates that the acceptable distance between ramps is dependent on the merge, diverge and weaving operations that take place between ramps as well as the distances required for signing. The manual does specify minimum distances between ramps for various ramp configurations, with a minimum distance of 600 meters (2000 feet) should be used between entrance and exit ramps without an auxiliary lane and 450 meters (1500 feet) with an auxiliary lane present *(8)*.

The conversion of ramp designs to an X-ramp on US 83 places a greater amount of traffic on the frontage road; as a result, the travel speed and LOS on the frontage road decreased slightly. On the other hand, the X-ramp configuration significantly decreased weaving conflicts on the freeway main lanes. With regard to main lane and frontage road operations, the proposed design is estimated to result in a benefit of approximately $34 million—producing an estimated system-wide benefit of approximately $150 million (*7*).

Other advantages when converting from diamond ramp to X-ramp configuration include:

- increasing development along the frontage road,
- reducing through demand on the frontage road,
- increasing storage area for cross-street intersection queuing, and
- providing better opportunities to use the frontage road as alternate route as part of incident management if auxiliary lanes are provided.

Unfortunately, converting a diamond ramp to an X-ramp also forms some disadvantages. First, improved signal operation at the cross streets is the result of the reduction in through demand on the frontage road. Second, construction of needed auxiliary lanes may require major reconstruction over/under cross streets. Last, queue storage increases, but queuing delays will not be remedied.

2.4 WEAVING ANALYSIS

Weaving areas exist on all types of highway facilities, ranging from freeways to arterials. The current procedure in the *Highway Capacity Manual* was developed for weaving areas on freeways, and little has been done for other facility types. This section of the literature review begins with a history of weaving procedures as prescribed in the various editions of the *Highway Capacity Manual* and related documents. Next, other freeway models are reviewed. Lastly, an overview of weaving research on frontage roads is presented.

Weaving Areas by the Book

The 1950 edition of the *Highway Capacity Manual* defined *weaving* as "the act performed by a vehicle moving obliquely from one lane to another, thus crossing the path of other vehicles moving in the same direction." Furthermore, a *weaving section* was defined as "a length of one-way roadway serving as an elongated intersection of two one-way roads crossing each other at an acute angle in such a manner that the interference between cross traffic is minimized through substitution of weaving for direct crossing of vehicle pathways." This edition also divided traffic in the weaving section into weaving and non-weaving flows, and considered only Type A configurations. The weaving capacity (i.e., the maximum number of weaving vehicles) was taken to be equivalent to the flow in a single lane (since the number of vehicles crossing the crown line could be no greater than the number that could crowd into a single lane). For very short weaving sections (less than 100 feet), the capacity was 1200 vehicles per hour, with many vehicles stopping before entering the weaving section. A 900-foot weaving section could accommodate about 1500 passenger cars per hour at about 40 mph, and a 450-foot weaving section could accommodate the same number at 30 mph. These flows represent *possible* capacities for weaving traffic. The 1950 HCM also recommended that additional lanes be added to each side of the weave to fully accommodate non-weaving traffic *(9)*.

The 1965 edition of the *Highway Capacity Manual* defined a *weaving section* as "a length of one-way roadway at one end of which two one-way roadways merge and at the other end of which they separate. A multiple weaving section involves more than two entrance and/or exit roadways." The basic design and analysis tools from the 1950 HCM were carried over into the new HCM but were considerably amplified with additional data (33 observations at 27 sites are listed in the appendix, selected from the 1963 Bureau of Public Roads [BPR] urban weaving area capacity study). Lane configuration is not specifically considered; all sketches showing lane lines are Type A, but the crown line is defined as a real or imaginary line connecting the merge and diverge gores. The weaving methodology is considered applicable to simple and multiple weaves, as well as one- and two-sided weaving, although the reader is referred to the material in the chapter on ramps when one-sided weaving results from an entrance ramp followed by an exit ramp *(10)*.

Published in 1985, the third edition of the *Highway Capacity Manual* reflected the extensive research on weaving areas conducted since the release of the 1965 HCM. Weaving was defined as "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway, without the aid of traffic control devices. Weaving areas are formed when a merge area is closely followed by a diverge area, or when an on-ramp is closely followed by an off-ramp and the two are joined by an auxiliary lane." Weaving areas are defined in terms of three principal geometric characteristics: weaving length (defined as in the 1965 HCM), lane configuration (relative placement and number of entry and exit lanes, generalized to three types), and width (number of lanes) *(11)*.

While this procedure represented a major improvement, particularly with the explicit consideration of lane configuration, which has a major effect on the number of required lane changes in the weaving area, its use is awkward in design. Both the model for speed estimation and the test for constrained operation require an assumption of the weaving area's length, width, and configuration, thus requiring a trial-and-error approach in design. When the revised edition of the 1985 HCM was released in 1994, the weaving area chapter was unchanged *(12)*.

The procedure for the analysis of weaving areas in the 1985 and 1994 HCM is a synthesis of three different procedures developed in the 1970s and 1980s *(13)*. The first was developed at the Polytechnic Institute of New York using the 1963 BPR data and additional data collected as part of the study and introduced the use of lane configuration as a major determinant of operating quality *(14)*. The procedure was later revised largely to simplify its use *(15)*. The second procedure was developed by Leisch *(16)*, and was designed to be used with the 1965 HCM or with Leisch's reformatting and expansion of the 1965 HCM *(17)*. Although the same data were used to develop both procedures (Polytechnic and Leisch), they yielded substantially different results in many cases (13). In an effort to get input from practicing engineers, both procedures were published in TRB's *Circular 212: Interim Materials on Highway Capacity (18)*.

Inconclusive results from the users of *Circular 212* led the FHWA to sponsor additional research, conducted by JHK and Associates *(19)*. This study developed the speed estimation equations but discarded the concepts of lane configuration and constrained operation. In order to develop the procedure eventually adopted in the 1985 HCM, the basic form of the speed estimation equations was retained, the concepts of lane configuration and constrained vs. unconstrained operation were reintroduced, and the equations were recalibrated (13).

Other Freeway Weaving Studies

Harkey and Robertson applied the 1985 HCM weaving methodology to two curved freeway segments in North Carolina. They noted that geometry affected traffic operation in the weaving areas but did not quantify it. The authors were satisfied with the results of the HCM method; however, their recommended solution included an internal merge *(20)*.

Kuwahara et al. collected data from three weaving areas on Japanese freeways and compared the measured results with the 1965 and 1985 HCMs, and the methods proposed by Polytechnic, JHK, and Leisch (all three discussed above regarding the development of the 1985 HCM). The authors found the 1965 HCM to be inadequate for the particular weaving areas selected, the Polytechnic and Leisch methods underestimated speeds, and the 1985 HCM and JHK methods provided relatively good estimates, with the 1985 HCM slightly outperforming the JHK method. While the 1985 HCM speed estimates deviate from observed speeds when lane flows are greater than 1200 pcu/hour-lane in the United States, this deviation was not noted in Japan. The authors provide capacity flows, volume ratios, weaving ratios, length, and configurations in the paper for the six weaving areas studied *(21)*.

Alexiadis et al. observed that existing speeds in weaving areas in Boston exceeded those predicted by the 1985 HCM weaving method. They re-estimated the coefficients for the speed equations using data collected from 11 sites in the Boston area, resulting in improved speed prediction, which passed a *t*-test at a 95 percent confidence level. Because only overall average speed was collected at the freeway sites, a single speed equation representing the average of weaving and non-weaving speeds was estimated *(22)*.

Alexiadis et al. also estimated two speed equations (weaving and non-weaving speeds) using data from Logan airport access roads. Data from two sites at the airport were used; both were two-sided, Type C weaves, and typical speeds were much lower than normal freeway speeds. Again, the estimated speeds were much closer to the observed speeds than those predicted by the 1985 HCM equations and parameters. However, when selecting LOS, the cutoff speeds in the 1985 HCM were used in spite of the low operating speeds (compared to that on freeways). In the re-estimated equations, the numerator was unchanged, resulting in a potential range of 15 to 65 mph, the same as the 1985 HCM *(22)*.

Vermijs used simulation to evaluate capacity for several Type A major weaves and ramp weaves. Four specific factors were considered to have an impact on weaving area capacity: (1) weaving section length, (2) weaving flow, (3) traffic mix, and (4) entering speed. The first three factors were examined in this paper *(23)*.

The capacity of a weaving section was expected to increase with increasing length, up to "a certain length." Vermijs noted that most lane changes take place within the first 350 meters (1150 feet) of a weaving section based on limited observations in The Netherlands and speculated that longer weaving sections would not increase capacity. While the study design apparently included weaving areas as short as 100 meters (330 feet), the shortest weaving length reported was 400 meters (1310 feet). The simulation studies showed that weaving section length ranging from 400 to 1,000 meters (1310 to 3280 feet) had no significant impact on weaving capacity *(24)*.

Increasing weaving flow decreased the capacity of the weaving section. Furthermore, the percentage of trucks had a profound impact on capacity, with lower values in terms of vehicles per hour for higher truck percentages. The truck passenger car equivalents (PCE) ranged from 2.5 to 3.6, depending on the weaving section configuration and the level of congestion. In addition, the truck PCE was higher for weaving sections than basic freeway segments.

Stander and Tichauer examined a 220 meter (720 feet) Type A ramp weave in South Africa. The weave consisted of two through lanes plus an auxiliary lane. Traffic volumes entering from the ramp at the beginning of the weave were nearly as high as the entering through traffic. Exiting traffic was much smaller. The weave was divided into three longitudinal segments of 73 meters (240 feet) each. The bulk of the lighter weaving movement took place in the first segment in all traffic conditions reported. Under moderate traffic conditions, most of the heavier weaving movement also took place in the first segment, but as traffic increased, there were roughly the same number of lane changes in the third segment as seen in the first *(25)*.

Weaving on Frontage Roads

Weaving on frontage roads can be similar to freeway-type weaving when an exit ramp is followed by an entrance ramp connecting the freeway main lanes to a parallel one-way frontage road. However, the speed-based methodology in Chapter 4 of the 1985 HCM (*11*,*12*) is inappropriate, as the typical operating speeds correspond only to the poorer levels of service regardless of the volume levels. At-grade intersections and driveways introduce arterial-like weaving characteristics on frontage roads. Two recent studies emphasizing the freeway-type weaving on frontage roads are discussed in this section, while arterial weaving is covered in the next section.

Frederickson and Ogden examined Type A weaves on frontage roads, which were formed by an auxiliary lane between the exit ramp to the frontage road and the entrance ramp back to the freeway main lanes. Their procedure was based on data collected at six sites and tested with data from two additional sites, all in Texas. They rejected speed as a measure of the quality of service since it was found to be insensitive to flow. Although they found density to be strongly related to flow (both on a per-lane basis), it, too, was rejected, due to the close relationship between density, flow, and speed. It should be noted that flow and density were directly measured from video-taped data, and speed was calculated from the flow and density. Instead, Frederickson and Ogden selected lane changing intensity (LCI) as their principal measure of quality of service. LCI is defined as the number of lane changes per hour divided by the number of lanes in the weaving section and the length of the weaving section. A linear model relating LCI to flow and the number of lanes in the weaving section was developed for each of three weaving section lengths (400 to 600 feet, 600 to 900 feet, and 900 to 1200 feet). Three LOS were subjectively identified by observation of the videotapes: unconstrained (0 to 3,000 lane changes per hour per mile per lane, or lcphpmpl), constrained (3000 to 6000 lcphpmpl), and undesirable (more than 6000 lcphpmpl). LOS A and B were associated with the unconstrained range, LOS C and D with constrained, and LOS E and F with undesirable *(26)*.

The Texas Transportation Institute developed procedures for the Texas Department of Transportation to estimate the LOS on freeway frontage roads. Their focus was on one-way frontage roads, but they also examined delays at ramp junctions on two-way frontage roads. Two weaving types were considered: one- and two-sided weaves.

The one-sided weave is the same as the Type A weave in Fredericksen and Ogden (*26*). Fitzpatrick and Nowlin used NETSIM™ to develop a procedure to evaluate LOS and used the field data from Frederickson and Ogden to calibrate the model *(27)*. They examined weaving sections of 100 to 500 meters (330 to 1640 feet). The weaving volume was taken to be the sum of the exiting and entering traffic, implying that no exiting traffic re-entered the freeway (this was not specifically stated). No sources of interruption to the frontage road traffic (such as driveways and cross streets) were assumed within the weaving section.

Weaving speed was found to decrease with increased weaving volume, but it was more sensitive to the number of lane changes than the volume. (The weaving volume was also found to be linearly related to the number of lane changes.) Speed was selected as the principal measure of the quality of service—the authors noted that speed is also used in the HCM (*12*) for arterials, that it is easily understood, and it is easily measured.

The speed was also found to be sensitive to the length of the weave for weaving sections less than 300 meters (980 feet). The LOS mentioned above were selected for weaving sections greater than 300 meters; as such, the authors recommended a desirable minimum weaving length of 300 meters, with a 200 meter (660 foot) absolute minimum. These results were validated at a single site in Houston with data in the unconstrained and constrained regions only. A visual inspection of some of the calibration data was used to verify the breakpoint between constrained and undesirable operations.

Jacobson et al. defined a two-sided weaving section as the distance between an exit ramp to the frontage road and the downstream intersection *(28)*. Since the exit ramp typically enters the frontage road from the left, traffic turning right at the downstream intersection was considered to be the weaving traffic; in effect, this is an example of arterial weaving. None of the sites included a frontage road lane created by the off ramp. The distance required for right-turning drivers to move into the right lane of the frontage road along with the difficulty each driver had in changing lanes was recorded. In addition, the study team recorded the length of queues from the signalized intersection at three of the sites. Then the regression equations for speed and density were developed. Speed was found to be highly sensitive to the total volume, the fraction of the ramp volume turning right (thus weaving across the frontage road), and the weaving distance, and was thus discarded as the measure to determine LOS. Density was found to be dependent on the total volume and the fraction of traffic turning right but not the length (since density is defined in terms of unit length).

Examination of the speed-density relationship revealed slope changes at 40 and 100 veh/km-lane (65 to 160 veh/mile-lane), and these slope changes delimited unconstrained, constrained, and undesirable levels of operation, which were again associated with LOS A and B, C and D, and E and F, respectively. These cutoffs were developed assuming moderate cross street traffic and optimally timed traffic signals.

Desirable and minimum ramp-to-intersection spacings were found by solving the regression equations for weaving section length and using densities of 40 and 100 veh/km-lane (65 and 160 veh/mile-lane), respectively. While the American Association of State Highway and Transportation Officials (AASHTO) recommends an overall minimum of 105 meters (340 feet) for the length of a weaving section, field studies indicated that the majority of drivers use 60 to 120 meters (200 to 400 feet) to weave across the frontage road. In addition, the queue started to have serious effects on weaving drivers when it backed up to within 90 meters (300 feet) of the ramp. Thus, an overall minimum spacing of 150 meters (490 feet) was recommended, with tables showing minimum and desirable spacings for a range of frontage road and ramp volumes, the fraction of ramp volume turning right, and the number of frontage road lanes.

Next, Chapter 11 (Urban and Suburban Arterials) of the HCM (*12*) was used as a basis for a procedure to estimate LOS on frontage roads *(29)*. Arterial capacity is controlled by signalized intersections, which are covered separately in Chapter 9 of the HCM. The significant sources of delay along frontage roads were found to be the cross street intersections (with either signal or stop control on the frontage road) and the ramps. Earlier, Gattis et al. *(30)* developed delay equations for ramp junctions on one- and two-way frontage roads and found negligible additional delay when auxiliary lanes were used.

Fitzpatrick et al. examined the effects of link length, volume, access density (number of access points, such as driveways, per kilometer), and link type on the link running time. Link type was determined by the downstream terminal of the link: traffic signal, stop sign, exit ramp, or entrance ramp (*29*). The dependence of running time on link type was reduced by excluding links with speeds less than 8 km/hour (5 miles/hour). The excluded links were largely those with downstream signals or stop signs; the delay on these links can be estimated using techniques in Chapters 9 and 10 (signalized and unsignalized intersections, respectively) of the HCM. Average speed was unrelated to the number of access points with less than 20 access points/km (32 access points/mile) on a one-way frontage road (16 access points/km, or 26 access points/mile, on a two-way frontage road). Greater numbers of access points resulted in reduced speed.

The LOS over an extended section of frontage road can be determined through a speed estimate based on link travel times (developed in Fitzpatrick et al. [*29*]), delays around ramps (developed in Gattis et al. [*30*]), and intersection delays (from the current HCM). The LOS boundaries recommended are those for Class I arterials from Chapter 11 of the HCM (range of free-flow speeds: 35-45 mph; 40 mph typical free-flow speed).

The procedures for analysis of one- and two-sided weaving on frontage roads, LOS evaluation of extended frontage road sections, and spacing to metered entrance ramps (from Sharma and Messer *[31]*) were summarized in Fitzpatrick et al. (*32*), along with worksheets similar in format to those found in the *Highway Capacity Manual*.

2.5 RAMP SPACING

The distance between successive ramp terminals should be long enough to provide sufficient weaving length and adequate space for signing. AASHTO defines this distance as a function of ramp pairs (entrance or exit), the classification of the interchanges involved, and weaving potential. When an entrance ramp is followed by an exit ramp in a cloverleaf loop ramps, the distance between entrance/exit ramp noses is primarily dependent on loop ramp radii and roadway and median widths. When the distance between the successive noses is less than 1500 ft (450 m), the speed-change lanes should be connected to provide an auxiliary lane *(33)*. Similarly, Figure 3-37 in TxDOT *Roadway Design Manual* also shows the minimum distances between ramps for various ramp configurations *(8)*.

Barnes et al. conducted a case study on a section of IH 610 in Houston following the installation of collector-distributor facilities. Based on this case study and general studies of frontage road operations, it was determined that sufficient right-of-way should be obtained, spacing between major cross streets should be ample, and existing intersection configurations are appropriate to handle expected traffic demand. Barnes et al. also recommended that ramps have one entrance lane and two exit lanes, interchange distance should equal or exceed 3000 ft (915 m), and weaving section lengths on frontage roads should be at least 1000 ft (305 m) in length *(34)*. In another research study, Kockelman et al. found that frontage roads with a diamond design seem preferred in intense commercial development areas. X-interchanges are preferred in residential development areas because X-interchanges reduce frontage road weaving conflicts. They also noted that frequent ramps impact flow and safety *(35)*.

Jacobson et al. conducted research to develop improved guidelines for driveway to entrance ramp spacing along freeway frontage roads (*28*). The analyses utilized in this research consisted of operational and safety assessments, both of which were based upon field and historical data specifically collected at several locations in Austin and San Antonio. The new guidelines doubled the distance in the existing guidelines in relation to both upstream and downstream placement of driveways in relation to entrance ramps. This change specifically entailed going from an absolute minimum of 100 feet (30.3 m) to a desirable spacing of 200 feet (60.6 m) upstream of the ramp and an absolute minimum of 50 feet (15.1 m) to a spacing of 100 feet (30.3 m) downstream from the ramp.

2.6 ACCESS MANAGEMENT

Kockelman et al. *(36)* provides a comprehensive evaluation of frontage road design policies by:

- summarizing research results about public access to roadways,
- discussing access policies and practices across the states,
- comparing land development and operation of corridors with and without frontage roads,
- summarizing studies on access right valuation, and
- comparing total construction costs.

The primary finding is that the number of access points or access density impacts frontage road operations; specifically, density of more than 16 access points/mile on one-way and more than 20 access points/mile on two-way frontage roads degrade operations. They computed an "access density" variable as the ratio of access length to overall section length. These values ranged from a low of zero (in the case of IH 35 at Parmer Lane) to 0.52 (along IH 35 at 38 ½ Street). These access-point densities correspond to driveway spacing (on center) of 330 and 264 feet (100 and 80 m). Research results from Minnesota show that X-configured interchanges are more favorable than diamond interchanges because they tend to force frontage road traffic to freeway main lanes instead of cross-street intersections, thus reducing intersection traffic. X-configuration interchanges need relatively frequent ramp spacing so that the resulting travel paths are not too circuitous.

The number of driveways and unsignalized intersections per mile has a significant impact on frontage road operations. According to Fitzpatrick et al. (*32*), the total number of driveways and unsignalized intersections cannot exceed 16 access points per mile on one-way frontage roads or 20 access points per mile on two-way frontage roads. These access point densities correspond to driveway spacing of 330 and 264 feet (100 and 80 m), which are much larger than those generally observed in developed corridors. The operation and safety of frontage roads heavily depend on access-provision policies. "Driveway design, spacing and location, ramp positioning, merge and diverge policies, and other requirements may ameliorate unsafe and congested situations on freeway corridors that already have frontage roads" (*37*).

Kockelman et al. discuss recommendations for design policies and procedures for revising frontage roads with actual case studies in Texas (*37*). The following steps for policy and procedure are introduced in order to evaluate frontage road inclusion in new and upgraded freeway facilities:

1. The first stage needs agreement to provide frontage roads from local government, metropolitan planning organization (MPO), or property owners. Alternative access options should be accepted and consulted by these entities.
2. Consider existing access to the facility, the land owner can continue to access to the facility or if the right to access is not permitted, frontage road or comparable alternative access method is required.
3. Compare the cost to purchase access rights from landowners with the cost of building frontage road. If the cost of purchasing access rights is much higher, the design must be considered this situation.

4. Consider the distance between interchanges and determine if frontage road is needed based on safety, traffic operation, and geometric design.
5. Consider proper frontage road and access density. Sixteen access points per mile or less is recommended.
6. Evaluate the effect of the facility: cause land lock, traffic circuit, intersection lost LOS or capacity.
7. Consider the lack of a frontage would cause longer distance to access the facility.

The authors applied the design policies and recommendations to three projects upgrading existing highway in the near future: US 290, US 281, and SH 71. Based on analysis performed using the design decision policy, a frontage road is recommended for only US 281.

In addition, the TxDOT *Roadway Design Manual* (*8*) considers the placement of streets and driveways in the vicinity of freeway ramp/frontage road intersection critical because this increases the weaving that occurs on the frontage road and may lead to the operational problems. Table 3-16 (*8*) of the *Roadway Design Manual* shows the spacing to be used between the exit ramps and driveways, side streets, or cross streets. Furthermore, Figure 3-13 and Figure 3-14 (*8*) also recommend access control at exit ramp and entrance ramp junctions with the frontage road. Table 2-1 in the TxDOT *Access Management Guidebook for Texas* gives the minimum connection spacing criteria for frontage roads, and this value depends on the posted speed and characteristic of frontage road (one-way or two-way) (*38*). The separation between frontage road intersections in diamond interchanges is also significant, and the minimum value is set to be at least 300 ft (90 m) for a diamond interchanges in urban or suburban areas (*8*).

2.7 TRAFFIC SIMULATION FOR RAMP AND FRONTAGE ROAD OPERATIONS

A variety of existing microscopic traffic models are candidates for consideration for frontage road and ramp operations being examined under different schemes for ramp placement, including X-ramp and Y-ramp designs. As a minimum, the model selected for the analysis for Project 0-5105 must be capable of modeling interrupted flow facilities (i.e., arterials and freeway frontage roads), freeway operations (including lane changing and weaving), static or dynamic route assignment, and appropriate vehicle classes so that realistic types and percentages of autos, buses, and heavy vehicles are included. Route assignment features are necessary for the investigation of ramp operations so that vehicles can be routed from the freeway to the frontage road, or vice-versa, in such a manner that unrealistic turning movements are avoided.

Applicable Models

Among publicly or commercially available microscopic simulation models, several are full-featured applications that have a reasonably broad user base in the United States and have been applied to studies similar to the ramp operations in this proposal. These models include CORSIM ™ *(39)*, Paramics ™ *(40)*, VISSIM ™ *(41)*, Integration ™ *(42)*, and SimTraffic ™ *(43)*. When route assignment is introduced as a criterion in the selection process, SimTraffic ™ is removed from contention. When cost is factored into model choice, Paramics ™ is removed in that it is nearly 10 times more costly than the next most expensive model. Finally, Integration ™ is removed because of inconsistent technical support in the last several years. Only two models appear to be practical candidates for modeling ramp and frontage road operations: CORSIM™ and VISSIM™. Both models have been used for project analysis in Texas for a multitude of freeway, frontage road, and arterial studies.

CORSIM™

CORSIM™ was developed for the Federal Highway Administration in the late 1970s and has been in use as a simulation tool since that time. CORSIM™ is composed of two largely separate programs, FRESIM™, which simulates freeway main lanes and exits, and NETSIM™, which simulates arterial and frontage road environments. Interface modes are used when simulations (such as the type being proposed here) involve both freeway and frontage road/arterial components. A limitation on these simulations is that CORSIM™ does not (using the normal user interface) allow for vehicle routing (i.e., using origin-destination data, for instance) along a path from FRESIM™ to NETSIM™. In other words, there is no way using the normal model features to "tell" a specific freeway vehicle that it must exit and then turn right at a driveway on the frontage road. Vehicle routing is necessary for evaluation of ramp modification projects because analysts must be able to know for each simulation how many vehicles are weaving on both the main lanes and frontage roads. Such data are a key component to reaching conclusions about safe and/or desirable weaving volumes and weaving distances between ramps and along frontage roads.

Outside of its normal user interface, CORSIM™ includes the routing capabilities mentioned above. Undocumented features exist that allow CORSIM™ to read extra input files that give vehicle volume, mix, and path information. However, these additional input files must be created for each simulation case. For the multitude of simulations that can be involved in a ramp modification evaluation, this process can become tedious. Further, the corporation maintaining CORSIM™ has no intention of creating a user interface for this functionality or supporting it further *(44)*.

A means of circumventing the routing limitations of CORSIM™ for simulating frontage roads is to use only the NETSIM™ component of the model. Used by itself, NETSIM™ includes all of the routing features necessary for the proposed research. However, if any freeway simulation is necessary for specific cases, the NETSIM™ model must also be used to simulate freeway segments. This is not desirable in terms of modeling real-world behavior, since NETSIM™ does not have FRESIM's™ built-in capabilities to model the lane changing maneuvers and vehicle behavior on freeways.

Another limitation of CORSIM™ as it pertains to evaluation of ramp modification projects is that vehicles within NETSIM™ do not "know" which lane to be in for a downstream turning maneuver until they are within two links (roadway segments between ramps, driveways or intersections) of their turn. For the different scenarios in the proposed research, this limitation can produce unrealistic weaving maneuvers if the spacing along the frontage road between ramps and driveways is short. This issue with CORSIM™ can be mitigated if careful attention is paid to model calibration and coding. One such calibration was performed in recent research of freeway weaving areas *(42)*.

Calibrated and field-verified CORSIM TM models have been used by TTI in research analyzing many aspects of weaving operations, including X-ramp type weaving (35), weaving between ramps and interchanges (28), and weaving between ramps and frontage road driveways (28). CORSIM TM was also used by CTR in a more general study (37) of the overall economic, land use, and operations impacts of frontage roads, which included both X- and Y-ramp configurations. Moreover, CORSIM TM can also used for ramp metering and provides the specific capability to model five ramp-metering strategies through the information on record types 28 (surveillance specification), 37 (freeway metering), and 38 (freeway metering detector specification). The five strategies are:

- Clock Time Metering. This is a fixed-rate metering, and the user specifies the metering rate (vehicles/hour) or the headway between vehicles (seconds/vehicle).
- Demand/Capacity Metering. The freeway capacity downstream of the ramp is evaluated, and, if demand is less than capacity, the ramp is metered at a rate so as to not exceed the downstream capacity. Surveillance detectors on the freeway main lanes provide input to the metering algorithm.
- Speed Control Metering. Different metering rates may be specified based on the speed of the freeway main lanes. Surveillance detectors must be placed immediately upstream (typically) of the ramp to gather speed information.
- Multiple Threshold Occupancy Metering. The user can specify the metering rate based on the main lane occupancy. Defaults are provided which range from 12 vehicles/minute for main lane occupancies of less than 10 percent to 3 vehicles/minute for main lane occupancies of greater than 34 percent.
- ALINEA Metering. The ALINEA algorithm is incorporated as an option in CORSIM TM. This algorithm also uses main lane occupancy to determine the metering rate and requires surveillance detectors in the freeway main lanes.

Kockelman et al. conducted three CORSIM TM simulation networks including a freeway with frontage road and diamond interchanges, a freeway with frontage roads and X-type interchanges, and a freeway with diamond interchanges but no frontage roads (36). The simulated-bases research focused primarily on stopped and total/travel delay, queue length, and speed especially on the freeway main lanes. The results indicated that the non-frontage road configuration performs as well as or better than the frontage road configuration if traffic demands do not saturate signalized intersections to which freeway exit ramp lead. The frontage road X configuration was shown to be the most robust operational concept. Because X-ramp configurations divert freeway-entering traffic from signalized intersections, they effectively reduce traffic demands for the frontage road intersections, reducing the likelihood of intersection and network failure. One disadvantage associated with the X-ramp is the speed reduction of the freeway main lanes caused by weaving between entry and exit ramps.

VISSIM TM

VISSIM TM is a simulation model developed in Germany to analyze complex traffic and transit operations. An English-language version has been available for about 10 years, and the user base is both established and expanding. As with CORSIM TM, VISSIM TM has a graphical user interface which allows the user to create networks over scaled background aerial photography or computer-aided drawing layouts. VISSIM's TM sophisticated vehicle simulation model allows the user to accurately analyze traffic interactions such as weaving sections and merges *(45)*.

VISSIM TM can analyze traffic operations considering factors such as traffic composition, signals, lane layout, transit stops, weaving, variable message signs, and other traffic control phenomena. For results presentation, VISSIM TM generates customizable output files. Information contained in these files can include travel time and delay statistics, queue lengths, signal timing, graphical output of space diagrams and speed profiles, and environmental indicators. Unlike CORSIM TM, which bases primary outputs on how vehicles perform on roadway links (i.e., average rather than individual vehicle statistics), VISSIM TM allows the user to define which outputs are desired. This flexibility makes it easy to generate a speed profile of a vehicle exiting the freeway, merging onto the frontage road, and (for instance) accessing a driveway. CORSIM TM can only generate such profiles using third-party processing software; in VISSIM TM, these capabilities are built-in.

VISSIM TM contains static and dynamic vehicle routing, which allow the user to control vehicle paths. Whereas this capability is provided in CORSIM TM as an experimental and unsupported feature, in VISSIM TM it is built-in. Thus, VISSIM TM can be programmed for experiments involving varying volumes and weaving intensity for the ramps and driveways along frontage roads.

The user is allowed to specify the vehicle's response to downstream turning as a calibration feature, which permits realistic simulation of vehicle lane changing as freeway vehicles approach exit ramps or as vehicles on a frontage road approach a driveway, entrance ramp, or cross-street interchange. Calibrated VISSIM TM models have been used by TTI recently in a study of the effects of ramp volume and spacing on freeway weaving for managed lanes *(46)* and in a study of the overall corridor impacts of ramp volume and spacing where managed lanes are present *(47)*. Even though VISSIM TM is the most powerful simulation package on the market, it is time consuming and very expensive to use.

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CHAPTER 3
SURVEY OF EXISTING GUIDELINES AND PRACTICES

This chapter summarizes the activities accomplished within Task 3 of the research work plan. The information presented includes the methodology and results of a survey of TxDOT district staff to gather information on existing guidelines, policies, and practices related to ramp modification projects. The survey focused on obtaining information on planned and previously implemented projects that involved ramp reversals.

Within the original Task 3 work plan, the research team envisioned surveying staff from both of the other state departments of transportation (DOTs) and the 25 TxDOT districts. During the Task 1 literature review, researchers determined that the concept of ramp reversal is almost exclusively being applied in Texas. This finding is directly related to the prevalent use of frontage road facilities in Texas versus other states. Due to this finding, it was decided that the survey effort would concentrate solely on obtaining information from the 25 TxDOT districts.

3.1 TXDOT DISTRICT SURVEY METHODOLOGY

One of the first decisions during the development of the survey instrument was to develop it in a format for electronic distribution. Researchers believed that a greater response rate would be obtained using electronic mail versus traditional mail distribution. Researchers also used a second technique to boost the overall response rate by having the survey distributed directly from the TxDOT Program Coordinator instead of from a member of the research team. The survey was sent via e-mail attachment to district engineers for each of the 25 districts.

The survey instrument contained seven total pages. The first page provided some general background information on the research project and instructions for completing and returning the survey. Respondents filled in fields to provide their name, title, district, e-mail address, and phone number on this page. The second page provided three figures to illustrate the types of projects being considered in the research. Pages three thru seven provided respondents with the ability to provide data on up to five total projects.

The questions on the project pages asked respondents for basic information such as type of project, date of implementation, control section job number (CCSJ), location (city, main highway, direction of flow, upstream cross street, and downstream cross street), project cost, project rationale, and whether or not any studies were performed to evaluate the project.

Question 1 - Type of Project
For the type of project question, the survey respondent used a drop-down box to select one of the four options below to describe the ramp modification based on the figures provided on the second page:

- Single ramp reversal (on → off),
- Single ramp reversal (off → on),
- Ramp reversal pair (on → off to off → on), or
- X-ramp corridor.

Question 2 – Date of Implementation
Next, the survey asked for the date of implementation of the project. Since the survey focused on obtaining information on planned and previously implemented projects that involved ramp reversals, the drop-down box allowed respondents to select a month (January – December) and year (1990 – 2010).

Question 3 – Control Section Job Number (CCSJ)
Respondents were then asked to type in the CCSJ for the project being described. The CCSJ is a unique project number that would be useful to the research team in gaining copies of the plan sets for each project. The control section is also important because it is the reference system used for crash data which would be useful for safety evaluation.

Question 4 - Location
The survey then had space for respondents to type in important information describing details of the project location, including the city, roadway, direction of flow, and project limits. This would allow researchers to further pinpoint the exact location and mile point limits of the project for detailed safety evaluation if it was necessary.

Question 5 – Project Cost
The total project cost was also gathered from respondents. Many of the ramp modification projects included in the survey were part of larger corridor reconstruction projects or involved other significant work such as new drainage structures and other miscellaneous items. This question did not attempt to single out the cost attributable to the ramp modification, just the overall project cost.

Question 6 – Project Rationale
One of the most important parts of the survey was obtaining the rationale for the ramp modification project. Respondents were provided a list of seven rationale developed by the research team. Respondents were told to check all of the rationale boxes that applied to the ramp modification project being reported. The default project rationale included:

- high traffic volumes,
- inadequate ramp spacing,
- main lane weaving,
- safety issues,
- frontage road weaving,
- land access, and
- political/developer request.

Respondents could also select a checkbox labeled "Other" and manually type in a reason in the space provided.

Question 7 – Evaluation Studies
The final portion of the survey asked respondents whether any studies were performed to evaluate and/or justify the project. If an affirmative answer was selected, the survey respondent was asked to provide a source where the research team could obtain the studies results.

3.2 TXDOT DISTRICT SURVEY RESULTS

The research team received completed surveys from 18 of the 25 TxDOT districts. This high response rate (72 percent) can be attributed primarily to electronic distribution and also the level of interest in ramp modification projects throughout the state. Table 3-1 lists the survey respondents, and Figure 3-1 provides a graphical representation of those TxDOT districts.

Table 3-1. Listing of TxDOT District Survey Respondents.

District	Abbreviation	Name of Survey Respondent	Title of Survey Respondent
Abilene	ABL	Blair Haynie	Dir. of Transportation Planning & Development
Amarillo	AMA	Mark Tomlinson	District Engineer
Atlanta	ATL	Lance Simmons	District Bridge/Special Projects Engineer
Austin	AUS	Carmen Ramos	Planner – Advance Project Development Office
Beaumont	BMT	Janet Manley	Dir. of Transportation Operations
Brownwood	BWD	Lynn Passmore	District Engineer
Bryan	BRY	Chad Bohne	Advance Planning Engineer
Corpus Christi	CRP	Victor Vourcos	Advance Project Development Engineer
El Paso	ELP	Gerardo Leos	Advance Project Development/ROW Engineer
Houston	HOU	Pat Henry	Dir. of Transportation Planning & Development
Laredo	LRD	Jo Ann Garcia	Dir. of Transportation Planning & Development
Lufkin	LFK	Cheryl Flood	Dir. of Transportation Planning & Development
San Angelo	SJT	John DeWitt	Dir. of Transportation Planning & Development
San Antonio	SAT	Judy Friesenhahn	District Transportation Planning Director
Tyler	TYL	Randy Redmond	Dir. of Transportation Planning & Development
Waco	WAC	Larry Colclasure	Dir. of Transportation Operations
Wichita Falls	WFS	Davis Powell	Transportation Engineering Supervisor
Yoakum	YKM	Paul Frerich	Dir. of Transportation Operations

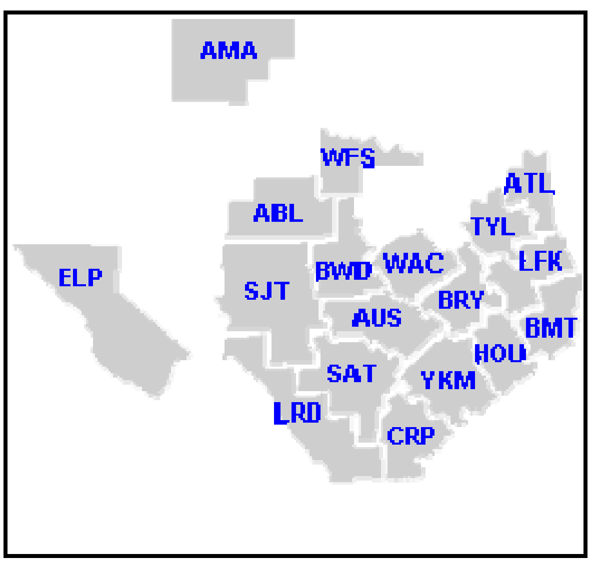


Figure 3-1. Graphical Representation of TxDOT District Survey Respondents.

The seven districts that did not respond to the survey included:

- Childress (CHS),
- Dallas (DAL),
- Fort Worth (FTW),
- Lubbock (LBB),
- Odessa (ODA),
- Paris (PAR), and
- Pharr (PHR).

It should be noted that while the Dallas, Fort Worth, and Odessa districts did not complete and return the formal survey instrument, members of the project monitoring committee provided detailed information for projects in those jurisdictions during committee meetings and phone conversations. It is also worth mentioning that four of the responding districts (Amarillo, Brownwood, San Angelo, and Yoakum) indicated that they did not have any implemented or planned ramp modification projects.

Results for Question 1 - Type of Project
The 14 districts that had information on existing, ongoing, or planned ramp modification projects submitted detailed responses for 36 projects. Figure 3-2 provides the project frequency by category of ramp modification. Half of the projects classified by respondents were X-ramp corridor. Thirty-six percent involved the reversal of an entrance/exit ramp pair, and 14 percent entailed the reversal of a single ramp.

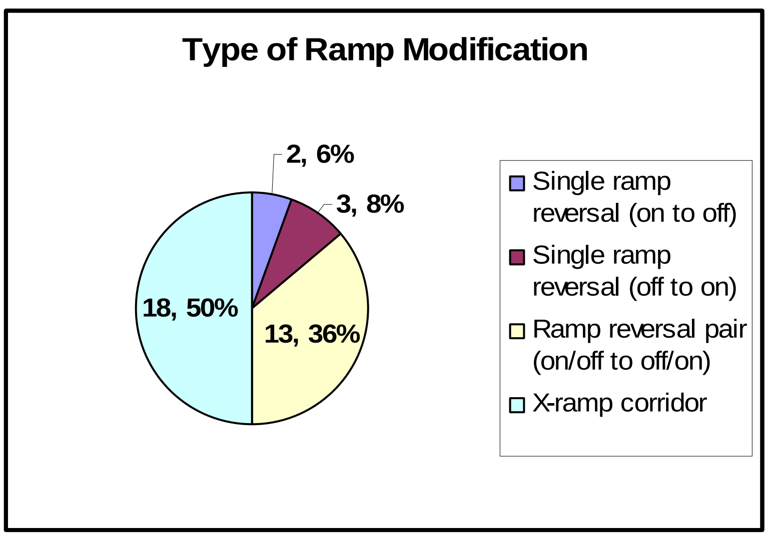


Figure 3-2. Classification of Type of Ramp Modification Project.

Results for Question 2 – Date of Implementation
The research team used the date of implementation data provided by respondents to determine whether projects were existing (i.e., construction complete), ongoing (i.e., still under construction as of February 2006), or planned (i.e., construction and/or letting had not started as

of February 2006). Researchers used the TxDOT website and the CCSJ information and date of implementation information to make this determination. The TxDOT website provides monthly estimates of construction status for current and previously completed projects.

Based on this analysis, researchers determined that there was a relatively even dispersion of projects based on their implementation status. Figure 3-3 shows the frequency of ramp modification projects classified as existing, ongoing, or planned based on the definitions provided in the previous paragraph. It is important to note that approximately 30 percent of the ramp modification projects are planned for future implementation. These are the projects that can benefit from the findings and guidance provided in this research.

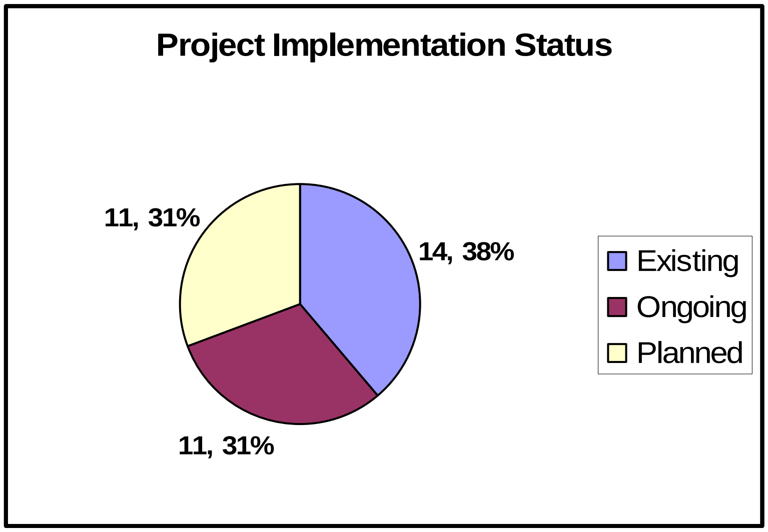


Figure 3-3. Implementation Status of Ramp Modification Projects.

Results for Question 4 – Location

The survey question asking for location information revealed that the almost 2/3 of the ramp modification projects were to interstate facilities. Ramp modification projects were reported on Interstates 10, 20, 30, 35, 45, and 410. Figure 3-4 shows the frequency of ramp modification projects by the major roadway type.

Results for Question 5 – Project Cost

The responses for project cost produced a wide distribution. Thirty of the thirty-six projects reported in the survey provided a project cost. Of the 30, the low project cost was $1,200,000 for a ramp reversal pair project. The highest cost reported project totaled $274,000,000 for an X-ramp corridor in the San Antonio District. This project involved eight separate construction jobs in the 1990s. The average cost of the projects was almost $41 million; however, the several large future X-ramp corridor projects in the Houston District skewed the average to this high number. When looking at projects that solely involve either single or pair ramp reversals, the typical costs seem to range in the $1 to $5 million range.

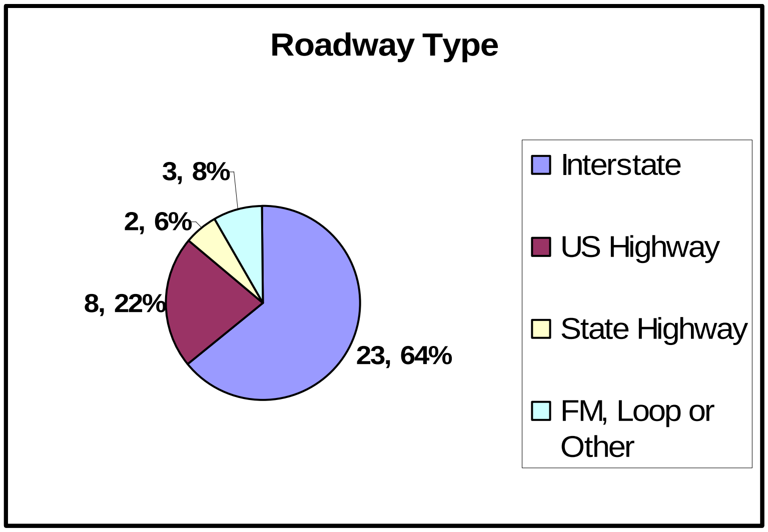


Figure 3-4. Roadway Type Distribution of Ramp Modification Projects.

Results for Question 6 – Project Rationale

The analysis of responses to the question regarding project rationale produced some interesting results. Respondents were allowed to check multiple rationales for each of their reported projects. In general, the overwhelming majority (80 percent) of respondents cited multiple rationales for implementation of the ramp modification project. The remainder of respondents indicated that only one rationale was significant to the consideration of the ramp modification project.

Further analysis of the rationale showed that safety issues (68 percent) and high traffic volumes (60 percent) were the most frequently cited by respondents. Table 3-2 provides the citation frequency for all seven default rationale included on the survey instrument.

Table 3-2. Analysis of Default Project Rationale Frequency.

Default Rationale	Number of Citations	Percentage of Projects
Safety issues	25	69
High traffic volumes	22	61
Inadequate ramp spacing	16	44
Main lane weaving	16	44
Political/developer request	15	42
Land access	11	30
Frontage road weaving	4	11

Some of the respondents did utilize the option to submit other rationale in addition to the defaults contained in the survey. The most popular other rationale was that ramp modifications were implemented while the frontage road was being converted from two-way to one-way operation. Respondents indicated that six reversal projects were sparked by the frontage road conversion decision. Five projects specifically mentioned the issue of queue spillback on an exit ramp onto the freeway main lanes as a rationale for ramp modification. It is interesting to note that the safety issues rationale was not selected for any of those five projects. Two respondents indicated that ramp modifications were implemented to better utilize the available capacity on the frontage road facility. Finally, other rationale cited by single respondents included: (1) two entrance ramps in a row, (2) construction of an additional overpass, and (3) alleviate frontage road congestion at the arterial cross street.

Results for Question 7 – Evaluation Studies

The final question asked respondents to indicate whether any studies were performed to evaluate and/or justify the ramp modification project. Almost 65 percent (22 of 36) of the ramp modification projects had some form of evaluation study. Respondents indicated the source of the 22 studies. Table 3-3 lists the basic sources including TxDOT, TTI, consultants, value engineering study, and a major investment study. One ramp modification project had studies performed by two different sources.

Table 3-3. Sources of Evaluation Studies of Ramp Modification Projects.

Source	Number of Citations	Percentage of Projects
TxDOT – Transportation Planning & Development	8	22
Texas Transportation Institute	7	19
Private consultants	5	14
TxDOT – Traffic Operations	1	3
Value engineering study	1	3
Corridor improvement study	1	3
None	14	39

The research team obtained copies of many of these studies in order to study methods and types of evaluations. This analysis will help researchers gain insight needed to develop a standard project evaluation process.

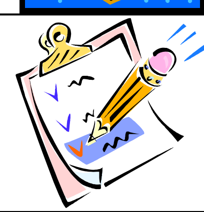
CHAPTER 4
PROJECT CASE STUDIES

This chapter summarizes the activities accomplished within Task 4 of the research work plan. Task 4 involved selecting ramp modification projects throughout the state for case study evaluation. The information presented includes the evaluation framework, methodology used for selection of case study sites, detailed evaluation of individual case study projects, and a synthesis of the case study findings.

4.1 CASE STUDY EVALUATION FRAMEWORK

The first step in the case study process was to develop a framework to guide the individual case study evaluations. The basic objective of the case study process is to assess the benefits and impacts of ramp modification projects. The researchers felt that there are three primary evaluation areas that would make the assessment worthwhile – operations, safety, and basic economics. Table 4-1 provides the framework used the in the case study evaluations.

Table 4-1. Case Study Evaluation Framework.

Evaluation Area	Symbol
Operations	
Safety	
Basic Economic	
Lesson Learned	

The remaining subsections provide additional explanation of these three focus areas. It is important to note that researchers employed several different techniques to estimate and analyze each focus area. Some of the evaluation is based on empirical data, some on results from simulation modeling, and some on anecdotal information provided by key project stakeholders.

Operational Evaluation

An important consideration of ramp modification projects is their effect on traffic operations. The survey results presented in Chapter 3 revealed that operational issues such as high traffic volumes and weaving were often cited as rationale for ramp modifications. It is inherent that ramp reversals change traffic patterns, sometimes significantly. The traffic patterns on both the freeway main lanes and adjacent frontage road will adapt to the revised access created by the modified ramps. Previous research has noted that for areas with conventional diamond ramp patterns, the most critical areas for operations are between the exit ramp and the arterial street and between the arterial street and the entrance ramp. In the X-ramp configuration, the most critical area switches between the exit ramp and the subsequent entrance ramp (*1*). Knowing some of the likely traffic pattern changes and the critical areas helped researchers determine what operational impacts to evaluate. The operational impacts considered in the case studies included:

- Systemwide delay – good measure of the overall ability of traffic to move in the area;
- Volume fluctuations
  - Freeway main lanes – how have volumes on the main lanes changed?
  - Frontage road – how have volumes between access ramps changed?
  - Downstream intersection – how have volumes and conditions changed?
- Queuing – what has happened to the presence of queues at the site, particularly if a queue from the exit ramp routinely stacked onto the main lanes?
- Ramp spacing – assessing spacing before and after reversal versus design guidelines.

Safety Evaluation

The evaluation of safety impacts of ramp modifications was also a key issue. The survey results presented in Chapter 3 indicated that safety issues were the most often cited project rationale, at almost 70 percent. This result underscores that evaluation of safety is essential to getting a good assessment of project success. The queuing impact considered in the operational evaluation was a surrogate measure of safety, particularly at sites where ramp modifications were implemented primarily because an existing exit ramp routinely backed up onto the adjacent main lanes causing increased risk of high-speed rear-end collisions. Researchers performed the case study safety evaluation by analyzing the crash frequency and rates before and after the ramp modifications. The safety evaluation documented impacts on main lane, frontage road, and total crashes based on available data. Some sites did not have sufficient data to make a valid assessment; therefore, researchers obtained anecdotal information to compensate for the lack of available crash data.

Basic Economic Evaluation

The operational and safety impacts were the two primary evaluations for the Project 0-5105 case studies. Researchers felt that the basic economic impacts of ramp modifications also needed to be evaluated. The survey results presented in Chapter 3 showed that land access and development were both cited as rationale for many ramp modification projects. The research team developed several indicators to assess the influence of ramp modification projects on the basic economy around the case study area. The three indicators included: (1) sales tax receipts,

(2) property values, and (3) business development. Further explanation is provided in the next subsections.

Sales Tax Receipts

Texas cities finance their public services from a variety of revenue sources such as property taxes, sales taxes, and other sources. Sales tax revenue is a strong indicator of retail activity. Researchers performed surveys with city staff in order to gather information on sales tax receipts for businesses located adjacent to case study sites. The research team asked city staff to indicate whether sales tax receipts increased or decreased for businesses located along the frontage road in the direction that ramps were modified. In some cases, sales tax data for the entire city was used instead of just for the actual case study corridor. It is acknowledged the city responses regarding sales tax receipts cannot always be definitively attributed to the ramp modification project; however, it does provide some measure of basic economic impact.

Property Values

Another indicator of economic activity is the value of properties along a corridor. Researchers also questioned city staff regarding changes in property values along the frontage road in the direction that ramps were modified. These data were not available for all case study sites but do provide a second measure of the basic economic impacts of the ramp modifications.

Business Development

The research team also wanted to gain an understanding of the development activities created by ramp modification projects. The researchers asked city staff to assess whether there had been any new development along the frontage road that could be attributed to the different access created by the ramp reversal project. In addition to the survey responses, Internet searchers of sites that monitor business development activity were also performed to aid in this assessment.

Lesson Learned

After review of the three key evaluation issues, the research team determined the most significant lesson learned from each individual case study. This was done to highlight items both positive and negative issues from the case studies.

4.2 CASE STUDY SITE SELECTION

Based on information gathered in Tasks 1 and 3 and other known resources, researchers developed a list of implemented and planned projects that could be used to investigate the benefits and impacts of ramp reversal projects. In agreement with the Project Monitoring Committee, it was decided to focus the case studies primarily on ramp reversal projects and also some X-ramp corridor projects. The decision was then made to not include braided ramp projects in the case study evaluation. The research team used many factors to determine sites for detailed evaluation. Some of the selection considerations included:

- implementation status – complete, ongoing or planned;
- availability of data (geometric, traffic and crash); and
- availability of evaluation studies.

The overall goal then became to have approximately 15 sites for detailed case study evaluation. Researchers met with the Project Monitoring Committee to discuss potential case study sites. Based on those discussions and the selection considerations, 15 sites were chosen for the case study evaluation. Table 4-2 provides some of the basic data for 12 sites that involved either a single ramp being reversed or a pair of ramps being reversed. Table 4-3 gives the same data for the three X-ramp corridor sites.

Table 4-2. Ramp Reversal Case Study Sites.

Site #	Year	Roadway City TxDOT CCSJ	Project Description	Project Cost
1	2000	SH 114 Grapevine 0353-03-075	Reversed the westbound Business 114 entrance ramp with the Spur 103 (Main Street) exit ramp (PAIR)	$2,025,193
2	1999	IH 20 Arlington 2374-05-054	Switched the westbound Matlock entrance ramp with the Cooper (FM 157) exit ramp (PAIR)	$7,049,023
3	1999	IH 30 Dallas 0009-11-161	Reversed the eastbound Harwood exit ramp to make it an entrance ramp (SINGLE)	$660,000
4	1999	IH 30 Dallas 0009-11-161	Closed the westbound Harwood entrance and converted it to a gated emergency exit ramp that can be used during incidents (SINGLE)	$660,000
5	2002	US 67 Cedar Hill 0261-02-055	Southbound ramp reversal that switched the Pleasant Run Road entrance ramp with the FM 1382 exit ramp (PAIR)	$1,041,783
6	2001	IH 35 Austin 0015-03-078	In the southbound direction, reversed Manor exit to become the 32nd Street entrance and reversed 32nd/26th entrance to become the Manor exit (PAIR)	$2,376,137
7	2001	IH 35 Austin 0015-03-078	In the northbound direction, reversed the 38 ½ exit to become the 32nd Street entrance (SINGLE)	$2,376,137
8	2000	US 190 Killeen 0231-03-102	In the westbound direction, reserved the ramps between W. S. Young and FM 2410 (PAIR)	$1,169,149
9	2005	IH 35E Denton 0196-01-092	Switched the southbound Loop 288 entrance ramp with the State School Road exit ramp (PAIR)	$1,242,529
10	2005	IH 35E Denton 0196-01-093	Reversed the northbound State School Road entrance ramp with the Loop 288 exit ramp (PAIR)	$1,427,790
11	2005	IH 35E Lewisville 0196-02-094	Northbound ramp reversal of the Fox Avenue entrance ramp and the FM 1171 (Main Street) exit ramp (PAIR)	$1,012,278
12	2005	US 190 Harker Heights 0231-03-114	Switched the eastbound FM 3470 (Stan Schlueter) entrance ramp and the FM 2410 exit ramp (PAIR)	$986,747

Table 4-3. X-Ramp Corridor Case Study Sites.

Site #	Year	Roadway / City / TxDOT CCSJ	Project Description	Project Cost
13	2002	US 83 Abilene 0034-01-107	Widened the US 83 main lanes from 4 to 6 lanes between S. 14th Street and FM 89 and switched the ramps from diamond to X-ramp	$19,989,242
14	2001	US 83 Pharr 0039-17-132	Widened the US 83 main lanes from 4 to 6 lanes between Business 83 and FM 2220 and switched the ramps from diamond to X-ramp	$36,598,173
15	2006	SH 358 Corpus Christi 0617-01-169	Will relieve congestion on westbound SH 358 by ramp reversal and addition of auxiliary lanes between Staples Street and Carroll Lane	$10,000,000

4.3 DETAILED CASE STUDIES

This section synthesizes the detailed information collected for each of the individual case study sites. Each site described gives the reader a better understanding of the project scope and the evaluation results.

Site 1 – SH 114 in Grapevine

The first case study site involved a ramp reversal pair on SH 114 in the City of Grapevine. This $2 million project reversed the westbound Business 114 entrance ramp and the Spur 103 (Main Street) exit ramp. Figure 4-1 shows an aerial photograph of the site before the reversal project. Some key information on the project construction schedule is provided in the list below:

- Letting date: August 2000 – Fort Worth District;
- Date work began: October 17, 2000; and
- Date work completed: August 26, 2003.

According to Grapevine officials, improved access to properties along the westbound SH 114 frontage road was the driving force behind the ramp reversal project. Property owners along the frontage road included several automobile dealerships (Lexus, Cadillac, and Ford), three fast food restaurants, a chain printing business, and a gas station. The property owners contributed to the project financing by paying for the engineering design services of a Dallas-Fort Worth (DFW) area consulting firm.

Evaluation Results

Because this project was constructed prior to the start of Project 0-5105, researchers were forced to primarily rely on anecdotal data to evaluate the operational and basic economic impacts of the ramp reversal. The research team utilized crash data from the Department of Public Safety (DPS) database and from the City of Grapevine Police Department to assess the safety impacts.

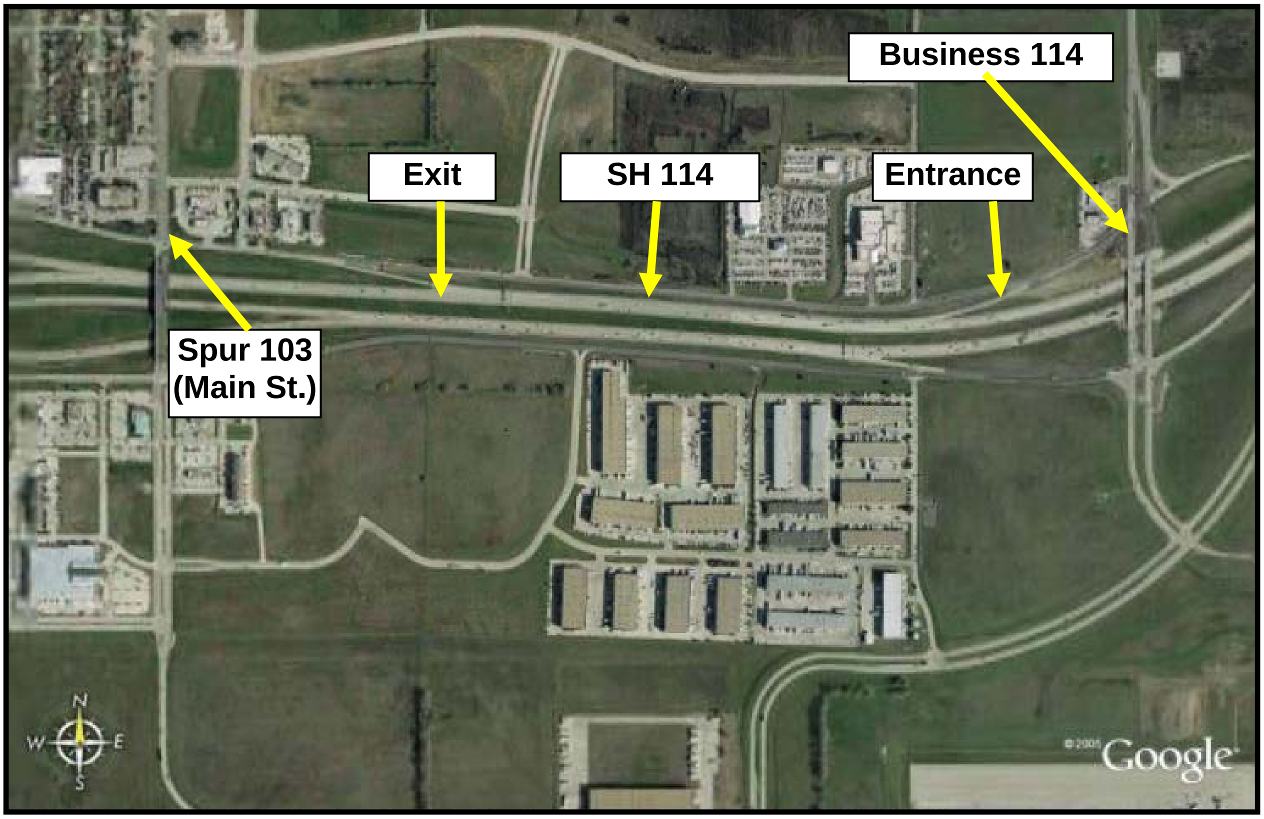
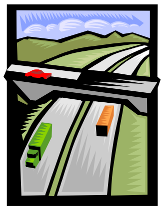


Figure 4-1. Aerial Photograph of Site 1 – SH 114 in Grapevine (2).



Operational. This section of SH 114 is commonly referred to as the funnel. The average daily traffic (ADT) prior to the project (year 2000) was 162,000 vehicles per day (vpd). Traffic volumes along both the main lanes and frontage road have continued to increase as has traffic delay. The Assistant Director of Engineering Services for the City of Grapevine indicates that the positive operational benefit of the reversal project was that it did improve access to the frontage road and the private development abutting the frontage road (3). The reversal is also credited with greatly improving the access to a newly widened city street serving surrounding light industrial properties and a hotel.

Safety. Researchers obtained crash records from the City of Grapevine. The city maintains a geographic information system (GIS) of city roadways with a link to individual crash reports. The analysis revealed that main lane crashes in the westbound direction have been reduced following the ramp reversal. The frontage road crash rate was basically unchanged.

Basic Economic. An economic development specialist with the City of Grapevine indicated that the ramp reversal has not created a discernable economic impact with the seven businesses that along the westbound frontage road between Business 114 and Main Street (4).

<u>Lesson Learned</u>. After completion of this project, Grapevine engineering staff began to receive complaints regarding the revised signing on SH 114. The specific issue was the ability of motorists to see the sign for the Spur 103 exit ramp and have enough time to react to the new ramp location. TxDOT maintenance staff ultimately moved the exit ramp warning sign farther east on SH 114 to allow motorists more time to react to the location of the new ramp.

Site 2 – IH 20 in Arlington

Site 2 involved a ramp reversal pair on IH 20 in the City of Arlington. This $7 million project reversed the westbound Matlock entrance and the Cooper Street (FM 157) exit ramp. The project also included rebuilding and widening of the westbound frontage road, adding an auxiliary lane between the new ramps, and converting the Cooper Street exit ramp from a single lane to a two-lane ramp. Figure 4-2 shows aerial photographs of the site before the reversal project. Some key information on the project construction schedule is provided in the list below:

- Letting date: March 2000 – Fort Worth District;
- Date work began: May 24, 2000; and
- Date work completed: February 27, 2002.

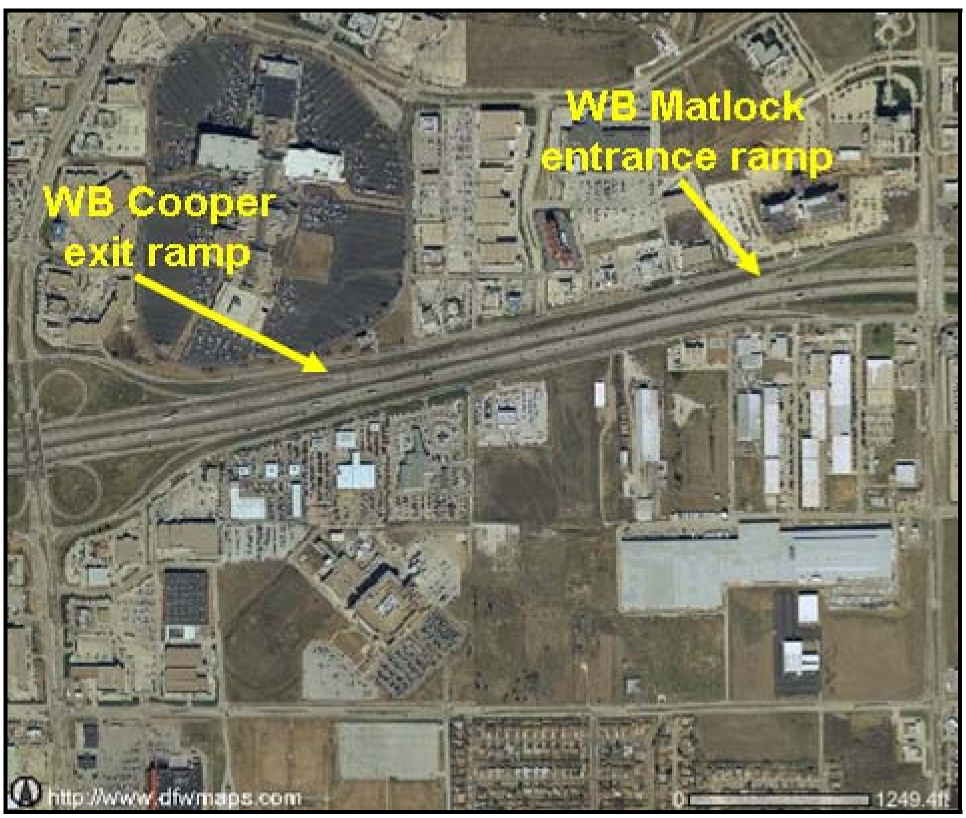
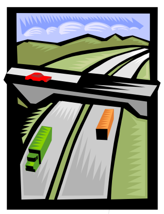


Figure 4-2. Aerial Photograph of Site 2 – IH 20 in Arlington (5).

According to local officials, improved access and traffic flow to the Parks at Arlington Mall was the driving force behind the ramp reversal project (*6*,*7*). A secondary consideration was to eliminate backup of vehicles onto the IH 20 main lanes that routinely occurred during afternoon peak periods and the holiday shopping season. This project involved a joint construction funding effort between the FHWA ($5,500,000), City of Arlington ($1,000,000), and TxDOT ($600,000). The City of Arlington also paid an additional $290,000 for design services.

Evaluation Results

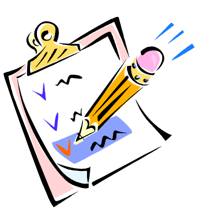
Because this project was constructed prior to the start of project 0-5105, researchers were forced to rely primarily on historical and anecdotal data to evaluate the operational and basic economic impacts. The research team utilized crash data from the DPS database and from the City of Arlington Police Department to assess the safety impacts.



Operational. The average daily traffic (ADT) on IH 20 prior to the project (year 2000) was 162,000 vpd. Data collected by TxDOT before and after the reversal project indicated a dramatic increase in daily traffic volumes along the westbound IH 20 frontage road. ADT increased from approximately 5,300 vehicles per day (vpd) to 31,600 vpd. Many of these vehicles access the Parks Mall or other retail developments and do not proceed to Cooper Street. The operational performance of the Cooper interchange has improved since engineers are now able to provide more green time to thru movements instead of the frontage road.

Safety. The safety evaluation revealed that the frontage road crash rate decreased by 41 percent following the ramp reversal project (3.9 crashes per MVM before to 2.3 crashes per MVM after). The queue spillback that existed under the old ramping configuration has also been eliminated, a positive safety improvement.

Basic Economic. The ramp reversal project created a significant positive economic benefit – in terms of sales tax revenues, property values, and new development (*8*,*9*). In November of 2002, a new 400,000 square foot expansion was opened at the Parks Mall. The expansion was located on the south side of the mall property – directly adjacent to the improved access to the westbound Interstate 20 frontage road. The expansion was anchored by an 18-screen AMC theatre, a new ice rink, and Dick's Sporting Goods store.



Lesson Learned. After completion of this project, TxDOT and City of Arlington officials began to receive complaints regarding vehicle speed along the westbound frontage road and on the new two-lane Cooper exit ramp. The frontage road section has a different look and feel than most because of the four-lane cross section and the presence of overhead sign bridges across the roadway (see Figure 4-3). A number of different actions were taken including increased routine enforcement, addition of flashers and reduced speed advisory warning signs on the Cooper exit ramp, and periodic deployment of a portable speed trailer to provide motorists with real-time feedback of their speed. These concerns for vehicle speed and safety were not foreseen; however, implementation of future projects should learn that coordination with local police for enforcement is an important part of a successful project.

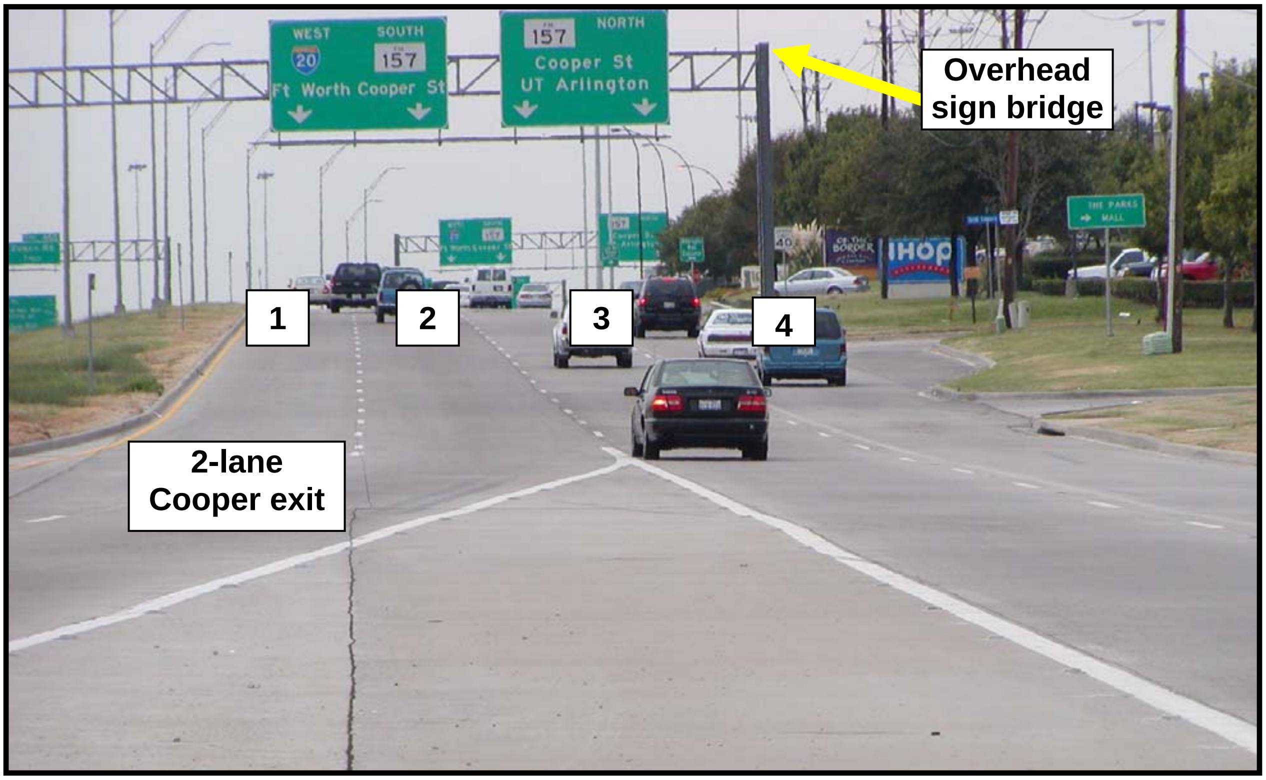


Figure 4-3. Improved IH 20 Frontage Road in Arlington.

Site 3 – Eastbound IH 30 in Dallas

Site 3 involved the reversal of a single ramp on IH 30 in the City of Dallas (*10*,*11*). This case study site is located on the southern edge of downtown Dallas and is commonly referred to as the "Canyon." This $660,000 project eliminated the eastbound Harwood exit ramp and converted it to an entrance ramp. The location of this ramp is just downstream of the "mixmaster" IH 35E/IH 30 interchange. An auxiliary lane was also added between the entrance ramp and the IH 45 exit ramp as part of the project. The main problem investigated was a significant slowdown in southbound traffic on IH 35E near downtown during the afternoon, lasting up to four hours. While there was congestion downstream due to heavy merging volumes just prior to the Trinity River Bridge, about half of the southbound traffic was headed east, trying to access IH 30. This traffic was congested due to a short weaving section, only 1200 feet in length, handling hourly traffic volumes as shown in Figure 4-4. An additional problem in the weave area was that it is located on a horizontal curve to the left. Trucks were rolling over frequently, as they tried to both drive the curve to the left and change lanes, with little time or space to make the maneuver. Loads were dumped at this point almost monthly, snarling traffic for hours.

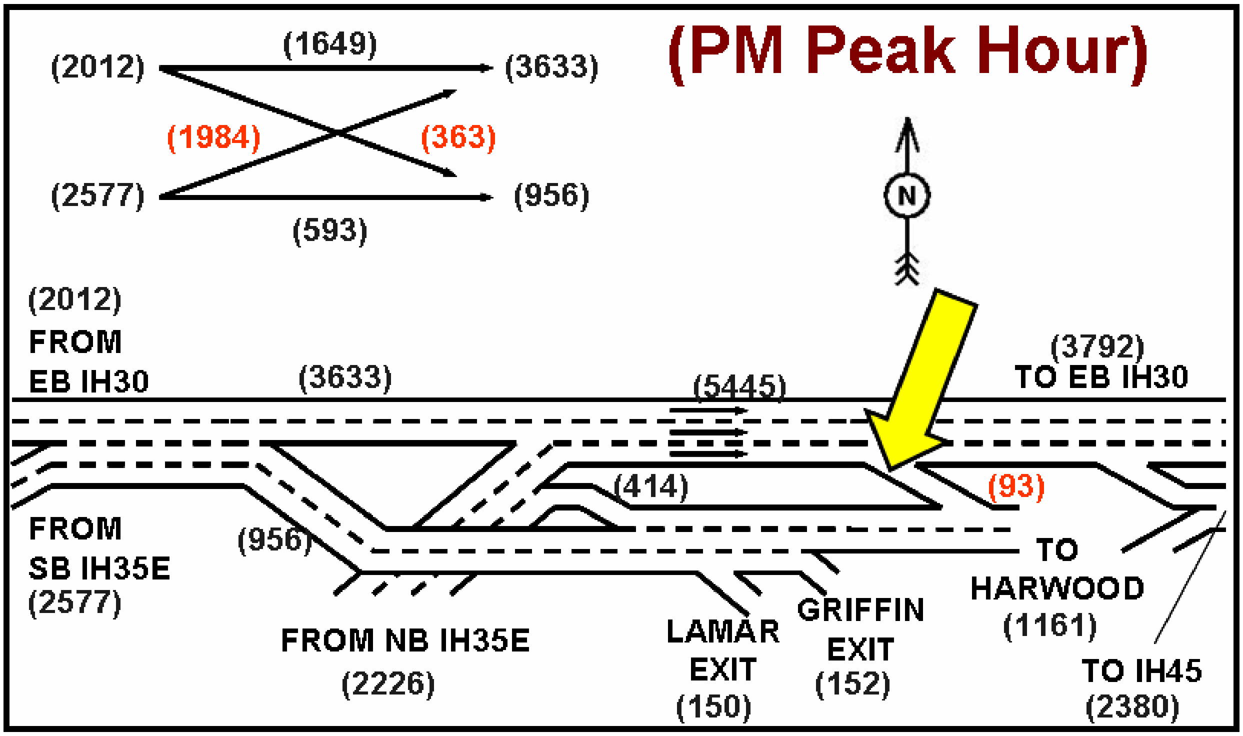


Figure 4-4. Site 3: Eastbound IH 30 in Dallas – Before Layout.

Figure 4-5 is the lane layout after the ramp reversal was implemented. A collector-distributor (C/D) road parallels IH 30 through the Canyon, which ends at an arterial street, Harwood, serving the downtown. An exit ramp from the main lanes of IH 30 also accessed Harwood, and it carried less than 100 vehicles during either the morning or evening peak hour—probably because it was redundant. TxDOT decided to replace the little-used exit ramp with an entrance ramp from the C/D road to the main lanes, allowing traffic to IH 30 to avoid the congested weave mentioned earlier and yet still make the required entrance to IH 30 downstream of it. There was concern that too many drivers would divert to the C/D road, causing problems with the exits to Lamar and Griffin, two other major downtown streets. Accordingly, TxDOT decided not to sign the new pathway and to let truckers find it and tell one another. Some key information on the construction schedule is provided in the list below:

- Letting date: August 1998 – Dallas District;
- Date work began: October 1998; and
- Date work completed: October 1999.

The driving force behind this project was improving the safety and operations of a bottleneck location. The Dallas District used interstate maintenance funds to pay for this project.

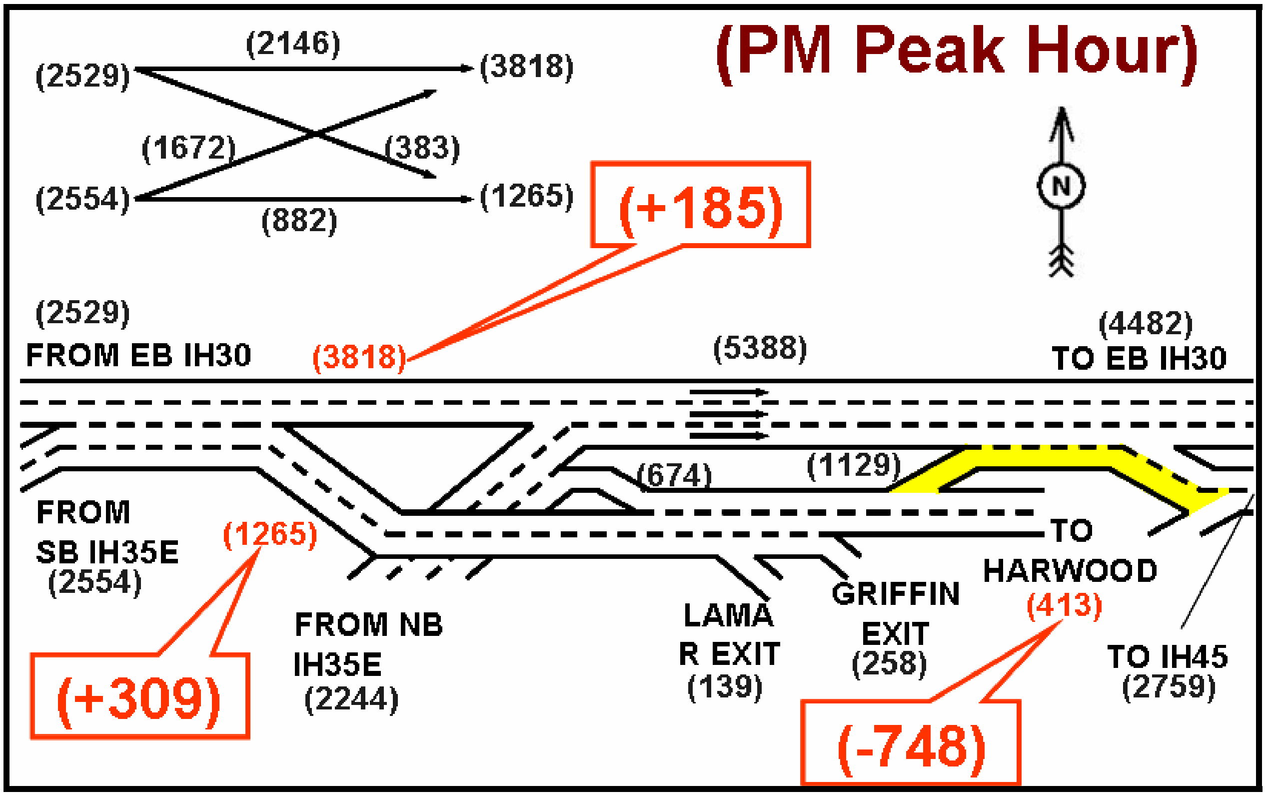
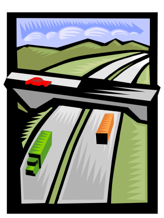


Figure 4-5. Site 3: Eastbound IH 30 in Dallas – After Ramp Reversal Layout.

Evaluation Results

This project was evaluated by TTI for the TxDOT Dallas District. Both the operational and safety performance were assessed; however, the basic economic impacts were not because of the difficulty of obtaining anecdotal or historical data from almost eight years ago.



Operations. The construction cost for this reversal was $660,000, including the new auxiliary lane to the IH 45 exit. TTI found improved speeds and increased volumes; the resulting delay reduction was calculated to be $700,000 per year. Not taking into account the injury crash savings or reductions in delay due to them, the B/C ratio for a projected 10-year life is 9:1. This project paid for itself in less than one year *(11)*.

Safety. The overall injury crash rate at the site showed a 31 percent decrease from 93.0 crashes per 100 million vehicle miles traveled (MVMT) to 64.5 MVMT. Looking at just crashes in the weaving section, there was a 43 percent reduction in the injury crash rate with truck-related crashes falling by 60 percent. Rollovers in that section have all but ceased *(11)*.

Basic Economic. The objective of this ramp reversal project was to improve operations and safety, which it successfully accomplished. The research team did not contact City of Dallas officials to get information on economic impacts.

The site is adjacent to the Dallas Central Business District (CBD), which has experienced an economic upturn since the reversal project was completed in late 1999. The upturn in economic activity is attributed to many factors including light rail service, residential development (primarily condominiums), arts district improvements, and other positive market forces.

Lesson Learned. This project showed that reversal of even a single access ramp can produce significant benefits. The evaluation showed that this was a very successful project in improving mobility and safety of the traveling public at a relatively low cost.

Site 4 – Westbound IH 30 in Dallas

At this case study site, TxDOT constructed an emergency exit ramp along westbound IH 30 in the Canyon. This emergency exit ramp, which is closed with a traffic gate during non-incident conditions, was constructed across the existing westbound Harwood entrance ramp (*10*). The entrance ramp is from a collector-distributor (C/D) road that is underutilized during the morning peak period. The primary function of the collector-distributor road is to unload the downtown Dallas area during the evenings. Just downstream of this location is the mixmaster interchange. This interchange is the location of numerous crashes, some involving heavy trucks. These crashes tend to shut down the entire freeway for several hours. When a crash occurs, TxDOT opens the gate to the emergency exit ramp, allowing motorists to access the C/D road, thus bypassing the crash location. This project was constructed as part of the same construction job as Site 3.

Evaluation Results
This project has never been formally evaluated. Both the operational and safety performance were assessed based on anecdotal information provided by key project stakeholders. Since this project did not have any economic objective, the basic economic impacts were not assessed. The emergency exit ramp created by the reversal project has been used during incidents and has provided significant time savings for westbound traffic through incident scenes.

Site 5 – US 67 in Cedar Hill

Site 5 involved a ramp reversal pair on US 67 in the City of Cedar Hill. This $1 million project reversed the southbound Pleasant Run entrance ramp and the FM 1382 exit ramp. The project also included several other improvements, including:

- auxiliary lane on the southbound US 67 main lanes between the new Pleasant Run entrance ramp and the next downstream exit ramp to Belt Line Road and
- auxiliary lane on the southbound frontage road between the new FM 1382 ramp and the Pleasant Run entrance ramp.

Figure 4-6 shows aerial photographs of the site layout before the reversal project. Some key information on the project construction schedule is provided in the list below:

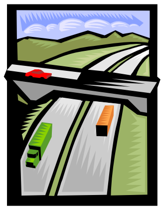
- Letting date: November 2001 – Dallas District;
- Date work began: February 7, 2002; and
- Date work completed: November 11, 2002.

According to local officials, improved safety was the driving force behind the project (*12*,*13*). The proximity of the FM 1382 exit ramp to the intersection (less than 600 feet) did not provide enough stacking room and traffic would frequently back up onto the highway. A secondary motivation was to improve access to a substantial amount of undeveloped property along the frontage road. Cedar Hill used local municipal bonds to assist TxDOT in the project funding.

Figure 4-6. Aerial Photograph of Site 5 – US 67 in Cedar Hill (5).

Evaluation Results

Because this project was constructed prior to the start of project 0-5105, researchers were forced to primarily rely on historical and anecdotal data to evaluate the operational and basic economic impacts of the ramp reversal. The research team utilized crash data from the DPS database and from the Dallas County Sheriff's Department to assess the safety impacts.



Operations. The Director of Public Works for the City of Cedar Hill indicated that the ramp reversal had a positive impact on both the southbound US 67 main lanes and frontage road (*12*). The reversal also eliminated the routine backup of vehicles onto the main lanes from the FM 1382 exit ramp that occurred during peak periods before the ramp was moved almost 1700 feet to the south.

Safety. Researchers obtained crash records from the Dallas County Sheriff's Department and the DPS database. The analysis revealed that main lane crash rate in the southbound direction was basically unchanged. The frontage road crash rate decreased after the ramp reversal. This finding was supported by anecdotal information provided City of Cedar Hill officials.

Basic Economic. The ramp reversal project is credited with having a significant positive economic impact, according to the Director of Finance at the City of Cedar Hill (*13*). The reversal has resulted in increased sales tax receipts and property values for businesses located along the southbound frontage road. The implementation of Pleasant Run Towne Crossing, a 410,000 square-foot shopping center, is credited to the cooperation between TxDOT and Cedar Hill to expedite the reversal of the entrance ramp to US 67 at Pleasant Run to ensure adequate traffic flow into and out of the development. This shopping center creates $70 million in annual sales and has an assessed value of $26 million, generating $1.6 million in tax benefits and more than 500 jobs for the city (*14*).

Lesson Learned. Ramp reversal projects can spur substantial economic activity and development. The revised accessed created by the approximately $1 million project is generating significant tax revenue and employment benefits.

Site 6 – Southbound IH 35 in Austin

Case study site number 6 was a $2.4 million bottleneck improvement project on IH 35 in the city of Austin (*15*). This case study site is located on the lower level of IH 35 adjacent to the University of Texas campus (Figure 4-7).

In the southbound direction, the improvements on IH 35 included:

- Eliminate the Hancock Plaza and 38½ Street entrance ramps.
- Reverse the 26th Street exit and make it the 32nd Street entrance.
- Add an auxiliary lane.
- Reverse the 26th Street entrance and make it the Manor exit.

Also included in the project were intersection improvements at 38th Street and 32nd Street. These improvements included more through lanes at the intersections and an extra turn lane on the southbound frontage road at 32nd Street during the morning peak. Figure 4-8 shows the basic lane layouts before and after the improvement project.

Figure 4-7. Picture of IH 35 Lower Level in Austin.

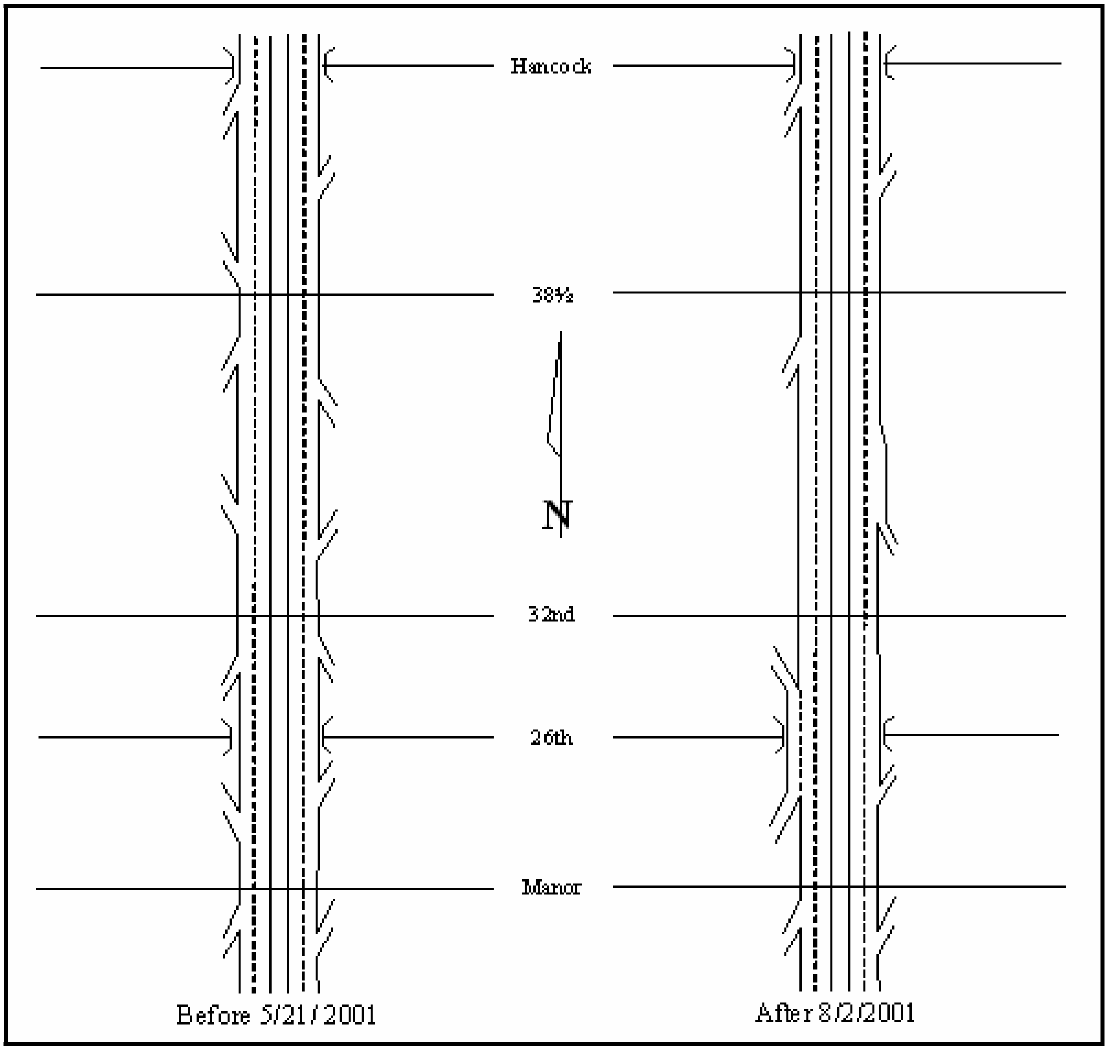


Figure 4-8. Before and After Lane Layouts for IH 35 Ramp Reversal Projects in Austin *(17)*.

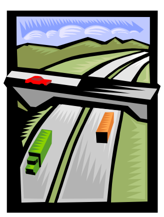
Some key information on the project construction schedule is provided in the list below:

- Letting date: August 2000 – Austin District;
- Date work began: May 1, 2001; and
- Date work completed: October 1, 2001.

The driving force behind this project was improving the safety of a well-known bottleneck location. A December 2000 article in the *Austin American Statesman* provided an assessment of why the project was needed *(16)*:

"The nastiest stretch of the toughest road in Central Texas is about to get its comeuppance. Interstate 35 from Manor Road to 41st Street offers some of the region's wildest driving moments, with merging drivers forced to floor it and fit into interstate traffic on ramps barely two cars long, while other drivers screech off on too-short exits. The entire lower deck acts as a stage for more wrecks than any other point of I-35's journey through Austin."

Evaluation Results
This project was evaluated by TTI as part of an interagency contract with the TxDOT Austin District *(17)*. Both the operational and safety performance were assessed; however, the basic economic impacts were not assessed because development was not a primary project motivation.



Operations. Two primary measures of effectiveness (MOE) were used for alternatives comparison and selection at the time the lower level improvements were analyzed using the CORSIM traffic simulation model: throughput (or volume) and speed. Throughput indicates how many vehicles the roadway network can process under traffic-loaded conditions. An improvement in speed but a reduction in throughput may not increase overall mobility, and may indicate that an upstream bottleneck has been created. Maintaining throughput means that mobility is preserved for the demand, and increasing throughput means that more capacity has been created or released due to removing artificial constraints in geometry or signal operations.

Speed is used to indicate level of performance as a departure from very congested conditions (i.e., low speed and high volume), with a target of free-flow speed, or the speed that motorists desire to drive under uncongested, prevailing conditions. Speed and throughput must be considered together in evaluating performance, but where throughput remains constant, higher speed is indicative of improved performance.

Throughput data were obtained from loop detectors installed in each of the southbound IH 35 main lanes at 15th Street. These detectors collect volume and speed data each day. Fifteen-minute summarized data were used in this analysis. It should be noted that these detectors were the only source of continuous volume information in the vicinity of the lower level on IH 35. It would have been more desirable to collect throughput information within the lower level rather than at its extremes (where these detectors are located), but such data were not available. Based on this constraint, data were obtained from the detectors at 15th Street for southbound IH 35 to record traffic conditions for the vehicle stream leaving the lower level.

Figures 4-9 and 4-10 for southbound IH 35 are nearly identical for before and after conditions throughout most of the day. This result is not unexpected, since any potential throughput increases in the major PM peak period that could be realized in the lower level would be masked by downstream congestion and queuing.

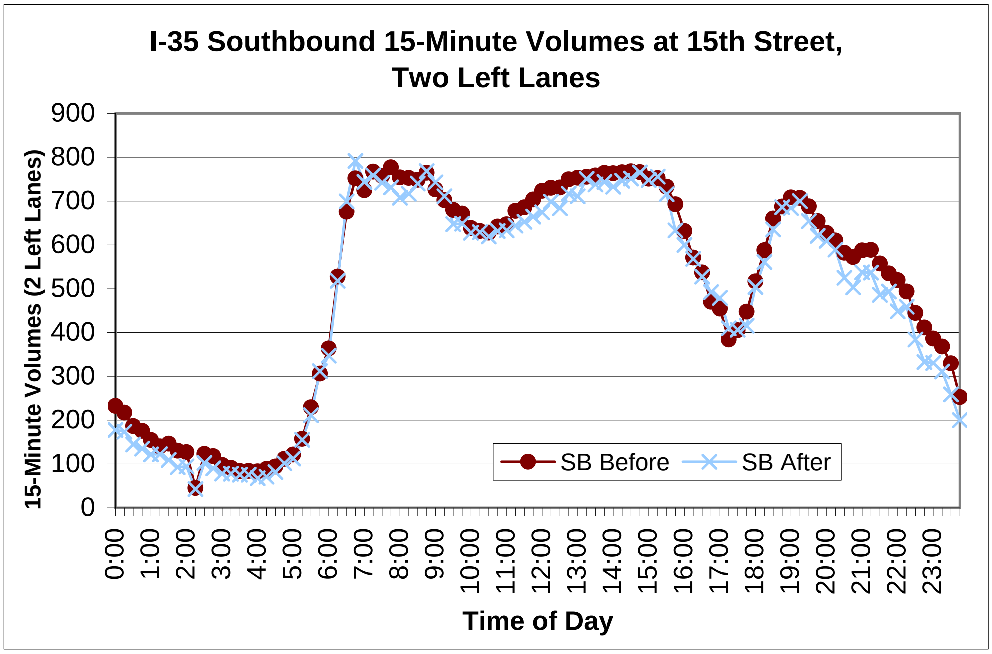


Figure 4-9. IH 35 Southbound Volumes at 47th Street (*17*).

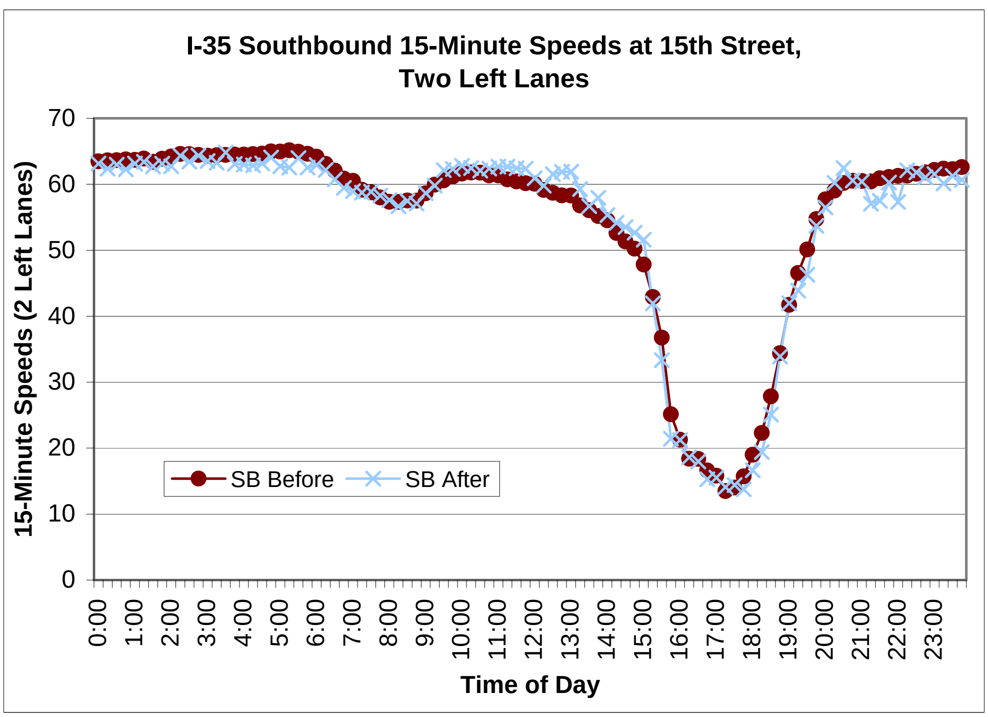


Figure 4-10. IH 35 Southbound Speeds at 47th Street (*17*).

To summarize throughput results, the ramp closure and reversal improvements that were implemented to improve safety have had no detrimental impact on IH 35 operations, and may even be helping improve traffic flow during peak period conditions. Unfortunately, any real-world benefits that might be realized by the geometric changes are masked by downstream peak period congestion along southbound IH 35.

Speed is the primary MOE for bottleneck project improvements, as it is low speed and congestion that identify and help quantify the bottleneck problem being studied. The detector data used in the previous section could not be used for this analysis since those detector stations were located at the extreme ends of the lower level and do not document flow and performance within/along the main lanes in the lower level. To document before conditions, a global positioning satellite (GPS) receiver unit and specialized GIS software, known as GETT (GPS-based Evaluation of Travel Time) were used to collect speed information along the southbound frontage roads and main lanes in February 2001. This data collection effort was repeated in February 2003 to document conditions that existed after the geometric modifications were made. At least six travel time runs were performed during peak periods (6:45 to 8:45 AM, 4:30 to 6:30 PM) in the southbound direction to generate statistically significant samples of operating speed.

The main lane and frontage road impacts of the geometric modifications within the lower level are documented in Table 4-4 and Table 4-5. Where statistically significant differences are found in speed performance, a "Yes" is shown in the appropriate column.

Table 4-4. IH 35 Southbound Main Lane Speed Impacts Due to Improvements (*17*).

Direction	Peak	Section	Speed Before (mph)	Speed After (mph)	Significant Difference?
Southbound	AM	51st – Airport	23.6	32.8	No
		Airport – 38 ½	53.3	52.9	No
		38 ½ – 32nd	55.0	56.3	No
		32nd – 26th	56.2	55.8	No
		26th – Manor	55.8	57.9	No
		Manor – MLK	56.8	58.4	No
	PM	51st – Airport	12.6	19.4	No
		Airport – 38 ½	7.5	11.8	Yes
		38 ½ – 32nd	7.3	10.8	Yes
		32nd – 26th	5.9	12.0	Yes
		26th – Manor	7.8	10.6	No
		Manor – MLK	8.0	11.6	Yes

Review of Table 4-4 and Table 4-5 shows that there are no negative impacts due to the geometric modifications made along the southbound main lanes and frontage roads within the lower level. In fact, some benefits appear to be realized along the congested southbound main lanes in the PM peak. Very low 7 to 10 mph peak period speeds under these stop-and-go conditions (caused by downstream congestion proximate to downtown) actually increased by several miles per hour. Though it would be difficult to attribute the cause of this observed result to the lower level changes (as conditions can fluctuate significantly during congested flow operations), there were no other recent changes to IH 35 in this area.

Table 4-5. IH 35 Southbound Frontage Road Speed Impacts Due to Improvements (*17*).

Direction	Peak	Section	Speed Before (mph)	Speed After (mph)	Significant Difference?
Southbound	AM	51st – Hancock	26.9	41.3	Yes
		Hancock – 38 ½	8.1	10.9	No
		38 ½ – 32nd	17.1	20.5	Yes
		32nd – Manor	27.8	20.6	Yes*
		Manor – MLK	21.3	23.9	No
		MLK – 15th	19.5	36.5	Yes
	PM	51st – Hancock	38.4	38.9	No
		Hancock – 38 ½	5.3	8.3	Yes
		38 ½ – 32nd	18.9	15.9	No
		32nd – Manor	29.9	23.9	Yes*
		Manor – MLK	11.2	18.9	No
		MLK – 15th	25.5	28.4	No

* Significant delay impacts are noticed in the "after" data collection due to the installation of a traffic signal at the Manor interchange along IH 35; these delays are not necessarily related just to the geometric reconfiguration.

Along the frontage roads, there is some improvement in the southbound direction, especially downstream and upstream of the Hancock interchange, that could only be attributed to the change in ramp location and orientation. This improvement was observed despite the fact that traffic wishing to enter the southbound freeway was rerouted (due to entrance ramp closures) several thousand feet down the frontage road.

Safety. DPS crash records were obtained for the Austin District for the years 1996 to 2000. However, since these records contained only half of the crash data for the one year period (April 30, 2000, to May 1, 2001) preceding construction of the auxiliary lanes in the lower level on IH 35 and none of the crash data for the one year period (October 2, 2001, to September 30, 2002) following construction, other sources of crash data were used. A database of collision records was obtained from the City of Austin Police Department for IH 35 for the time period between January 2000 and October 2002.

Crash record information for the "before" period, or April 30, 2000, to May 1, 2001, was pulled from the full data set and sorted by address. Then, only the crash information for the lower level of IH 35 was examined (i.e., only crashes in the 1800 to 4500 block of IH 35 North were examined). A similar procedure was used to isolate crash data for the "after" period, which began after construction on October 2, 2001, and lasted until September 30, 2002.

It is apparent from Table 4-6 that significant reductions in crashes were observed in the one year period following the implementation of the new ramping scheme in the lower level. Though it would be inappropriate to base definitive conclusions on only one year of collision data, the magnitude of the crash reduction certainly supports the rationale of the lower level changes.

Table 4-6. IH 35 Southbound Crash Statistics Before and After Improvements (*17*).

Direction	Condition	Total Crashes	Non-Injury	Minor Injury*	Major Injury or Fatality
Southbound	Before (4/30/00 – 5/1/01)	96	24	69	3
	After (10/2/01 – 9/30/02)	62 (-35%)	27 (+13%)	34 (-51%)	1 (-67%)

* Includes crashes classified as "possible injury"

Reductions in the number of crashes are concomitant with a reduction in the types of injuries that result from those collisions. In all but one category (non-injury crashes), there is an observed reduction in the number of injury crashes, with the smallest reduction being 51 percent. Again, it is the overall number of crashes that is the most meaningful measure of the safety impact of the lower level geometric changes, and this value reduced by an average 35 percent in the lower level between the year preceding the lower level changes and the year after the changes.

Lesson Learned. Properly implemented ramp reversal projects can produce meaningful safety benefits. These benefits are sometimes difficult to quantify because of the difficulty of obtaining timely crash records.

Site 7 – Northbound IH 35 in Austin

Case study site number 7 was part of the same bottleneck improvement project as Site 6 on IH 35 in the city of Austin (*15*). In the northbound direction, the improvements on IH 35 included:

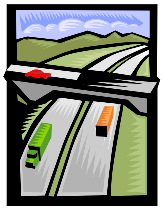
- Eliminate the Manor entrance.
- Reverse the 38½ Street exit and make it the new 32nd Street entrance.
- Add an acceleration lane.
- Eliminate the old 32nd Street entrance.

Also included in the project was the addition of more through lanes at the 38th Street and 32nd Street intersections. Basic lane layouts before and after the improvement project are shown in Figure 4-8. Some key information on the project construction schedule is provided in the list below:

- Letting date: August 2000 – Dallas District;
- Date work began: May 1, 2001; and
- Date work completed: October 1, 2001.

The driving force behind this project was improving safety at a well-known bottleneck location.

Evaluation Results
This project was evaluated by TTI as part of an interagency contract with the TxDOT Austin District (*17*). Both the operational and safety performance were assessed; however, the basic economic impacts were not assessed because development was not a primary project motivation.



Operations. Two primary measures of effectiveness were used for alternatives comparison and selection at the time the lower level improvements were analyzed using the CORSIM traffic simulation model: throughput (or volume) and speed. Throughput indicates how many vehicles the roadway network can process under traffic-loaded conditions. An improvement in speed but a reduction in throughput may not increase overall mobility, and may indicate that an upstream bottleneck has been created. Maintaining throughput means that mobility is preserved for the demand, and increasing throughput means that more capacity has been created or released due to removing artificial constraints in geometry or signal operations.

Speed is used to indicate level of performance as a departure from very congested conditions (i.e., low speed and high volume), with a target of "free flow" speed, or the speed at which motorists desire to drive under uncongested, prevailing conditions. Speed and throughput must be considered together in evaluating performance, but where throughput remains constant, higher speed is indicative of improved performance.

Throughput data were obtained from loop detectors found in each of the IH 35 main lanes for northbound IH 35 at 47th Street. These detectors collect volume and speed data each day. Fifteen-minute summarized data were used in this analysis. It should be noted that these detectors were the only source of continuous volume information in the vicinity of the lower level on IH 35. It would have been more desirable to collect throughput information within the lower level rather than at its extremes (where these detectors are located), but such data were not available. Based on this constraint, data were obtained from the detectors at 47th Street for northbound IH 35 to record traffic conditions for the vehicle stream leaving the lower level.

Figure 4-11 and Figure 4-12 for northbound IH 35 are nearly identical for before and after conditions throughout most of the day. This result is not unexpected, since any potential throughput increases in the major PM peak period that could be realized in the lower level would be masked by downstream congestion and queuing.

To summarize throughput results, the ramp closure and redesign improvements that were implemented to improve safety have had no detrimental impact on IH 35 operations, and may even be helping improve traffic flow during peak period conditions. Unfortunately, any real-world benefits that might be realized by the geometric changes are masked by downstream peak period congestion along northbound IH 35.

Speed is the primary MOE for bottleneck project improvements, as it is low speed and congestion that identify and help quantify the bottleneck problem being studied. The Advanced Traffic Management System (ATMS) detector data used in the previous section could not be used for this analysis since those detector stations were located at the extreme ends of the lower level and do not document flow and performance within/along the main lanes in the lower level.

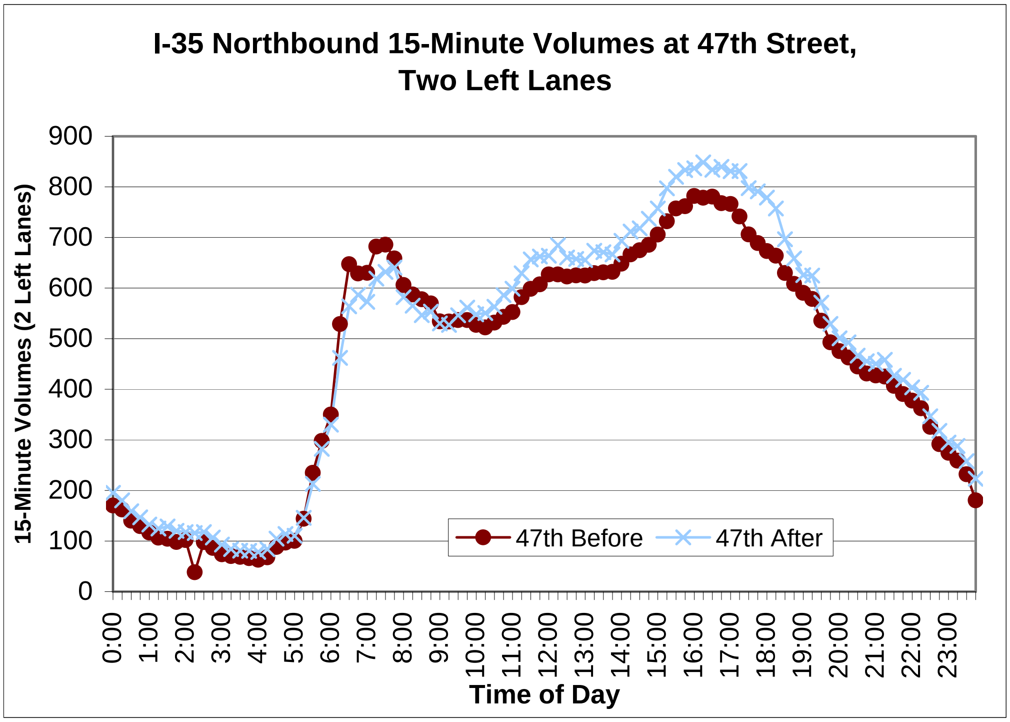


Figure 4-11. IH 35 Northbound Volumes at 47th Street (*17*).

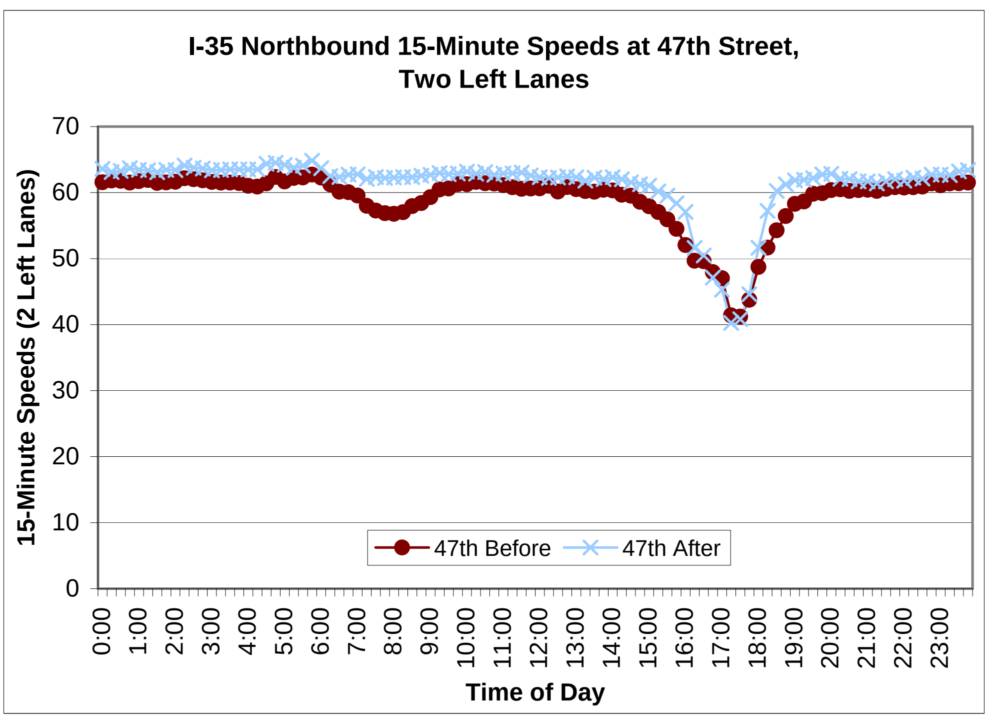


Figure 4-12. IH 35 Northbound Speeds at 47th Street (*17*).

To document "before" conditions, a GPS receiver unit and specialized GIS software, known as GETT, were used to collect speed information along the southbound frontage roads and main lanes in February 2001. This data collection effort was repeated in February 2003 to document conditions that existed after the geometric modifications were made. At least six travel time runs were performed during peak periods (6:45 to 8:45 AM, 4:30 to 6:30 PM) in the northbound direction to generate statistically significant samples of operating speed on the main lanes and frontage roads. The main lane and frontage road impacts of the geometric modifications within the lower level are documented in Table 4-7 and Table 4-8. Where statistically significant differences are found in speed performance, a "Yes" is shown in the appropriate column.

Table 4-7. IH 35 Northbound Main Lane Speed Impacts Due to Improvements (*17*).

Direction	Peak	Section	Speed Before (mph)	Speed After (mph)	Significant Difference?
Northbound	AM	11th – MLK	53.3	56.1	No
		MLK – 26th	57.0	58.0	No
		26th – 38 ½	60.1	61.4	No
		38 ½ – Airport	59.1	60.4	No
		Airport – 51st	54.7	50.4	No
	PM	11th – MLK	23.8	24.2	No
		MLK – 26th	32.8	36.4	No
		26th – 38 ½	36.9	33.5	No
		38 ½ – Airport	37.1	48.3	No
		Airport – 51st	34.3	38.0	No

Table 4-8. IH 35 Northbound Frontage Road Speed Impacts Due to Improvements (*17*).

Direction	Peak	Section	Speed Before	Speed After	Significant Difference?
Northbound	AM	MLK – Manor	26.0	10.5	Yes*
		Manor – 32nd	19.6	15.7	No
		32nd – 38 ½	32.1	35.8	No
		38 ½ – Hancock	16.6	21.1	No
	PM	MLK – Manor	26.2	12.1	Yes*
		Manor – 32nd	19.2	27.5	No
		32nd – 38 ½	30.5	27.0	No
		38 ½ – Hancock	13.3	12.6	No
		MLK – 15th	25.5	28.4	No

* Significant delay impacts are noticed in the "after" data collection due to the installation of a traffic signal at the Manor interchange; these delays are not necessarily related just to the geometric reconfiguration of the lower level.

<u>Safety</u>. DPS crash records were obtained for the Austin District for the years 1996 to 2000. However, since these records contained only half of the crash data for the one year period (April 30, 2000, to May 1, 2001) preceding construction of the auxiliary lanes in the lower level on IH 35 and none of the crash data for the one year period (October 2, 2001, to September 30, 2002) following construction, other sources of crash data were used. A database of collision records was obtained from the City of Austin Police Department for IH 35 for the time period between January 2000 and October 2002. Crash record information for the “before” period, or April 30, 2000, to May 1, 2001, was pulled from the full data set and sorted by address. Then, only the crash information for the lower level of IH 35 was examined (i.e., only crashes in the 1800 to 4500 block of IH 35 North were examined). A similar procedure was used to isolate crash data for the “after” period, which began after construction on October 2, 2001, and lasted until September 30, 2002.

It is apparent from Table 4-9 that significant reductions in crashes were observed in the one year period following the implementation of the new ramping in the lower level. The reductions are indicated in both the northbound and southbound directions, and no other geometric changes were made to IH 35 in this area within the study time frame. Though it would be inappropriate to base definitive conclusions on only one year’s worth of collision data, the magnitude of the crash reduction certainly supports the rationale of the change to lower level geometrics.

Table 4-9. IH 35 Northbound Crash Statistics Before and After Improvements (*17*).

Direction	Condition	Total Crashes	Non-Injury	Minor Injury*	Major Injury or Fatality
Northbound	Before (4/30/00 – 5/1/01)	64	13	50	1
	After (10/2/01 – 9/30/02)	37 (-42%)	9 (-31%)	28 (-44%)	0 (-100%)

* Includes crashes classified as “possible injury”

Reductions in the number of crashes are concomitant with a reduction in the types of injuries that result from those collisions. In all but one category (non-injury crashes), there is an observed reduction in the number of injury crashes, with the smallest reduction being 31 percent. Again, it is the overall number of crashes that is the most meaningful measure of the safety impact of the lower level geometric changes, and this value reduced by 42 percent in the lower level between the year preceding the lower level changes and the year after the changes.

Lesson Learned. When using simulation models to evaluate reversal alternatives, speed and throughput should be considered together in evaluating performance, but where throughput remains constant, higher speed is indicative of improved performance.

Site 8 – US 190 in Killeen

Site 8 involved a ramp reversal pair on US 190 in the City of Killeen. This $1.2 million project reversed the westbound FM 2410 entrance ramp and the W.S. Young exit ramp. The project also included the addition of an auxiliary lane on the westbound frontage road between the new W.S. Young exit ramp and the FM 2410 entrance ramp. Some key information on the project construction schedule is provided in the list below:

- Letting date: May 2000 – Waco District;
- Date work began: June 27, 2000; and
- Date work completed: April 27, 2001.

The motivation behind the ramp reversal project was the desire to commercially develop this area and TxDOT's need to address the increased residential/commercial growth and subsequent traffic in the project vicinity (*18*,*19*). The proximity of the W.S. Young exit ramp to the intersection (less than 700 feet) did not provide enough stacking room or weaving distance for vehicles to make a right turn at W.S. Young. The Killeen Mall, a 560,00 square foot shopping facility that attracts 10 million customers per year, is located at the northeast corner of W.S. Young and the US 190 westbound frontage road (*20*). Figure 4-13 shows a layout of the US 190/W.S. Young intersection prior to the ramp reversal project. The City of Killeen contributed $250,000 to the project funding.

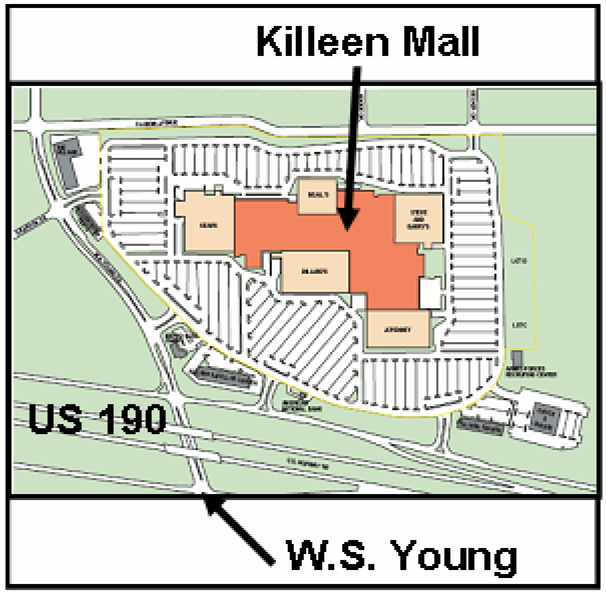


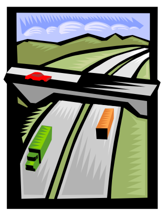
Figure 4-13. Killeen Mall (*20*).

Figure 4-14 is an aerial photograph of Site 8 with yellow arrows depicting the approximate placement of the ramps after the reversal project was completed. The yellow arrow in the center of this figure emphasizes the improved access to the local street located approximately halfway between FM 2410 and W.S. Young. This was particularly helpful for providing secondary access to the Killeen Mall and also improved access to the residential areas.

Figure 4-14. Aerial Photograph of Site 8 – US 190 in Killeen (*2*).

Evaluation Results

Because this project was constructed prior to the start of Project 0-5105, researchers were forced to primarily rely on historical and anecdotal data to evaluate the operational and basic economic impacts of the ramp reversal. The research team utilized crash data from the DPS database and from the City of Killeen Police Department to assess the safety impacts.



Operations. Information obtained from an official familiar with the project revealed that the ramp reversal had a positive impact on the operational performance of the westbound freeway main lanes and frontage road (*19*). The growth of commercial ventures along the frontage road has increased traffic significantly. Additionally, the growth of residential subdivisions along FM 3470 has also fed considerably more traffic onto the frontage road. However, the ramp reversal and widening of the frontage road allows smoother and safer weaving maneuvers and provides effective and efficient management of traffic both on the frontage road and westbound main lanes.

Safety. The safety impacts at this case study site were not evaluated because of the lack of available "after" data. Researchers contacted the City of Killeen Police Department in an effort to obtain these data but were unsuccessful. Anecdotal information provided to the research team indicated that the project had a positive effect on the safety of the westbound main lanes and frontage road (*19*).

Basic Economic. A city finance employee provided a perspective on the economic impacts (*21*). The overall sales tax for the City of Killeen has continuously increased over the last several years; however, data for the businesses specific to the corridor are considered proprietary. The property values have increased with several new developments and existing businesses have expanded. With several new commercial buildings being added to this area beginning in 2000, the property tax values have significantly increased by several million dollars. Further information on new development activity was also provided. There were seven commercial building permits (CBP) issued in 2000 in anticipation of the ramp reversal project. In addition, there have been two CBP issued in 2001, one in 2002, two in 2003, and one in 2004.

Finally, the city employee indicated that traffic congestion affects the quality of life. Quality of life is a key component of the economic development process. The difference in the westbound ramps (reversed) and the eastbound ramps (typical diamond configuration) is significant. The eastbound configuration reduces the use of large sections of frontage road, backs up traffic on US 190, and increases the difficulty in accessing business on the frontage road. None of this seems to occur with the westbound configuration. So, one could conclude that the ramp reversals on the westbound ramps has had a positive economic effect on quality of life, in general, and a positive economic effect on the business along the westbound frontage, in general. The situation with the eastbound ramps has a strong negative impact on economic development in comparison.

<u>Lesson Learned</u>. The information gathered during the economic impact evaluation revealed a significant difference in perception between the side of the freeway where ramps had been reversed versus the other side where ramps were not.

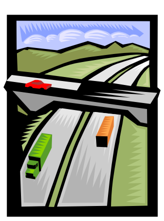
Site 9 – Southbound IH 35E in Denton

Case study site 9 involved a ramp reversal pair on southbound IH 35E in the city of Denton. This $1.2 million project reversed the Loop 288 entrance ramp and the State School Road exit ramp. There were no other improvements made to the frontage road or main lanes. Some key information on the project construction schedule is provided in the list below:

- Letting date: August 2004 – Dallas District;
- Date work began: December 14, 2004; and
- Date work completed: July 20, 2005.

The motivation behind the ramp reversal project was the desire of the city to improve access to a master planned development with retail and residential components *(22,23)*. The Unicorn Lake development built a new city street (Wind River Road) that connected to the IH 35E southbound frontage road approximately halfway between Loop 288 and State School Road *(24)*. The reversal allowed southbound traffic to exit and access Wind River Road without going through a traffic signal. The proximity of the State School exit ramp to the intersection (970 feet) was not a significant issue; however, a driveway to a major employer was located in close proximity to the exit ramp. Drivers would frequently cut across both lanes of the frontage road to enter that driveway, which created safety issues. Figure 4-15 provides an aerial photograph of the site with arrows depicting ramp locations following the reversal project and the improved access to Wind River. The City of Denton paid for the engineering design services.

Evaluation Results
This project was ongoing during project 0-5105, so the research team was able to collect before and after operational data. The safety evaluation relied on anecdotal data because of insufficient after data (6 months) to identify crash trends. Researchers collected the basic economic data from City of Denton officials.



<u>Operations</u>. Researchers analyzed the before and after operational data and found that the overall operational performance has improved. Volumes on the southbound IH 35E main lanes decreased; contributing to better main lane flow. Volumes on the two-lane frontage road significantly increased. There is a concern that capacity at the junction of the State School Road exit ramp with the frontage road will become a bottleneck location in the future because the frontage road is reduced to one lane at this location to allow the ramp traffic to have their own lane.

Figure 4-15. Aerial Photograph for Site 9 – Southbound IH 35E in Denton (2).

Safety. The safety impacts at this case study site were not evaluated because of the lack of available crash data. Since the project ended in the summer of 2005, there was not enough after data to be able to make a valid evaluation. The research team performed observational studies to evaluate safety performance before and after the ramp reversal project. Queue spillback on the southbound State School Road exit ramp was not an issue prior to the reversal. Anecdotal information provided to the research team indicated that the project had a positive effect on the safety of the westbound main lanes and frontage road (*23*).

Basic Economic. The Director of Economic Development for the City of Denton provided a perspective on the economic impacts of the southbound reversal project (*23*). The overall sales tax for the City of Denton has increased from the months before the reversal to the time period after the reversal. The sales tax revenue increase cannot be directly attributed to the ramp reversal; however, the reversed ramps now allow travelers to exit in time to turn in the 130-acre mixed use Unicorn Lake development.

Development activity that can be attributed to the ramp reversal project includes:

- a Cinemark multi-screen theater;
- four new restaurants;
- a branch bank building;
- a small office park; and
- an assisted living facility.

In summary, the Denton official indicated that the Unicorn Lake project would not have worked without the ramp reversals.

Lesson Learned. Successful and timely implementation of ramp reversal projects can be critical in providing access to large development projects. This case study illustrated that close coordination between stakeholders (TxDOT, City of Denton, and Unicorn Lake project developers) resulted in a positive outcome that all parties are happy about.

Site 10 – Northbound IH 35E in Denton

Site 10 involved a ramp reversal pair on northbound IH 35E in the city of Denton. This $1.4 million project reversed the State School entrance ramp and the Loop 288 exit ramp. There were no other improvements made to the frontage road or main lanes. Some key information on the project construction schedule is provided in the list below:

- Letting date: November 2004 – Dallas District;
- Date work began: January 18, 2005; and
- Date work completed: January 17, 2006.

The motivation behind the ramp reversal project was the desire of the City of Denton to improve access to commercial development and relieve congestion at the Loop 288 intersection *(23)*. The City of Denton built a new city street (Brinker Road) that connected to the IH 35E northbound frontage road approximately halfway between State School Road and Loop 288. The reversal allowed southbound traffic to exit and access Brinker Road without going through a traffic signal. The proximity of the Loop 288 exit ramp to the intersection (760 feet) was also a significant motivation, due to frequent queue spillback onto the IH 35 main lanes. Figure 4-16 provides an aerial of the site with arrows depicting ramp locations following the reversal project and the improved access to Brinker Road. The City of Denton paid for the engineering design services.

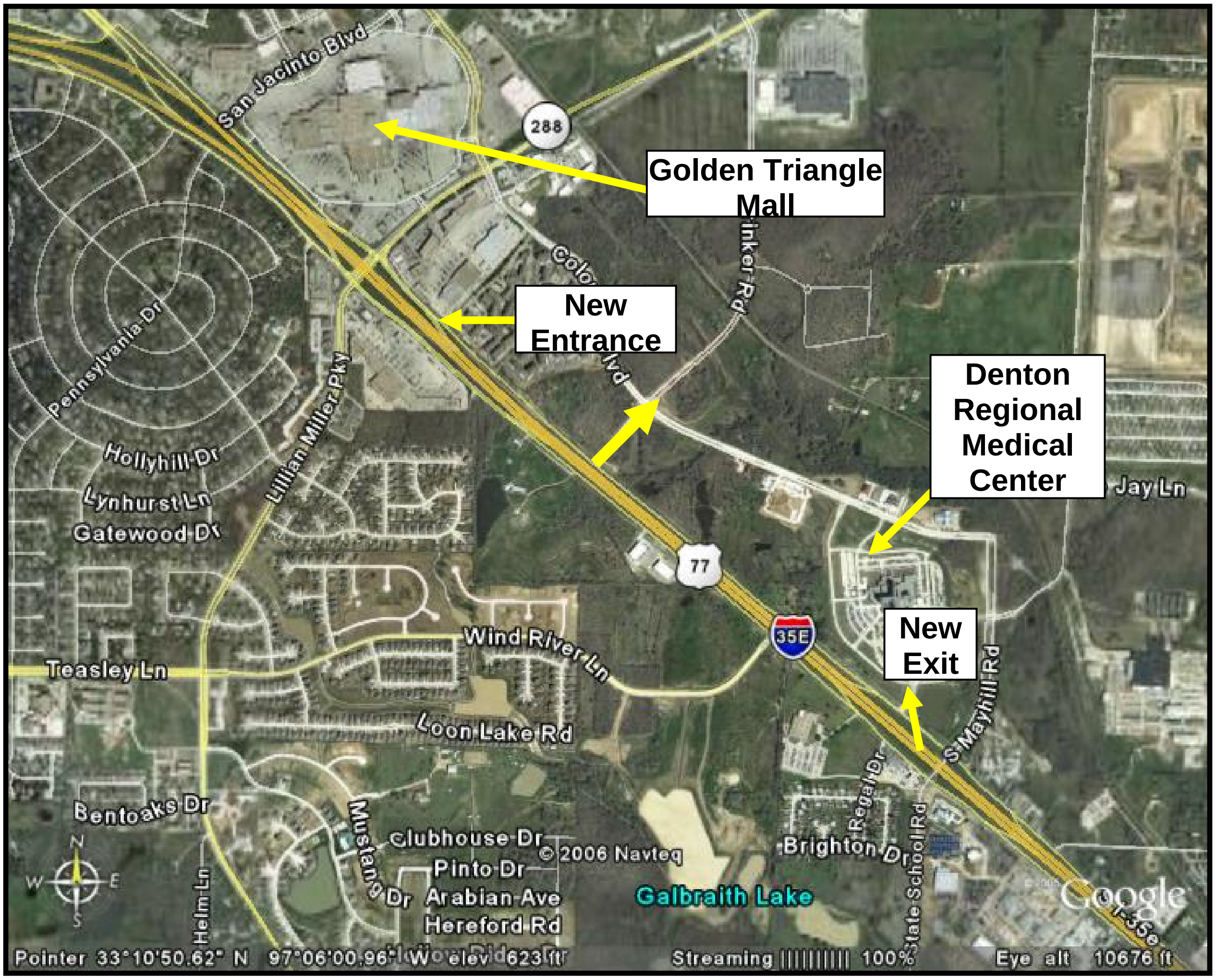
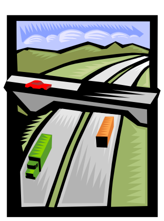


Figure 4-16. Aerial Photograph for Site 10 – Northbound IH 35E in Denton (2).

Evaluation Results

This project was ongoing during project 0-5105, so the research team was able to collect before and after operational data. The safety evaluation relied on anecdotal data because of insufficient after data (3 months) to identify crash impacts. Researchers collected the basic economic data from City of Denton officials.



__Operations__. Researchers analyzed the before and after operational data and found that the overall operational performance has improved. Northbound IH35E main lane volumes decreased; contributing to better main lane flow. Volumes on the two-lane frontage road significantly increased. There is a concern that capacity at the junction of the Loop 288 exit ramp with the frontage road will become a bottleneck location in the future because the frontage road is reduced to one lane at this location to allow the ramp traffic to have their own lane (see Figure 4-17).

Figure 4-17. Picture of Loop 288 Exit Ramp Junction with Northbound Frontage Road.

<u>Safety</u>. The research team performed observational studies to assess queue propagation on the northbound Loop 288 exit ramp before and after the ramp reversal. Prior to the reversal, a queue of vehicles routinely backed up onto the IH 35E main lanes from the Loop 288 exit ramp. After the Loop 288 exit ramp was moved almost one mile (4700 feet) to the south, queue spillback was no longer observed. Another positive safety benefit created by the reversal project was improved access to the Denton Regional Medical Center, which is located on the northeast corner of the State School Road/IH 35E interchange.

<u>Basic Economic</u>. The Director of Economic Development for the City of Denton also provided a perspective on the economic impacts of the northbound reversal project *(23)*. The overall sales tax for the City of Denton has increased from the months before the reversal to the time period after the reversal. The sales tax revenue increase cannot be directly attributed to the ramp reversal; however, the reversed ramps now allow travelers to exit in time to turn on Brinker Road – a road that leads directly to three restaurants and a new 50-acre retail center on Loop 288. The existing Loop 288/IH 35E interchange is already congested because of a regional mall (Golden Triangle) located in the northeast quadrant. The improved access to Brinker Road is spurring additional retail development north of the interstate. There are plans in place to extend Brinker Road to open up a new business park. An additional benefit of the ramp reversal is that Brinker Road will serve as an alternate route during the upcoming construction on Loop 288, which is being widened from a four-lane to a six-lane facility. Finally, several of the developments that benefited from the ramp reversal even went so far as to market the TxDOT project in their marketing materials for lease space *(25)*.

Lesson Learned. Consideration of frontage road capacity is extremely important, particularly if the cross section is only two lanes. If no auxiliary lane is constructed between the exit ramp and entrance ramp on the frontage road, a bottleneck at the exit ramp junction is likely in the future because of having only one through lane available.

Site 11 – IH 35E in Lewisville

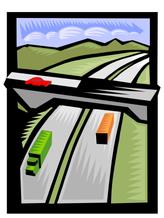
Case study site 11 involved a ramp reversal pair on northbound IH 35E in the City of Lewisville. This $1 million project reversed the Fox Avenue entrance and the FM 1171 (Main Street) exit ramp. An auxiliary lane was added on the frontage road between the new exit and entrance ramps. Some key information on the project construction schedule is provided in the list below:

- Letting date: January 2005 – Dallas District;
- Date work began: May 3, 2005; and
- Date work completed: November 18, 2005.

The motivation behind the ramp reversal project was to improve safety (*26*). The existing FM 1171 exit ramp was only 260 feet from the intersection, well below recommended guidelines.

Evaluation Results

This project was ongoing during project 0-5105, so the research team was able to collect before and after operational data. The safety evaluation relied on anecdotal data because of insufficient after data (4 months) to identify crash impacts. Researchers collected the basic economic data from City of Lewisville officials (*27*).



Operations. Researchers analyzed the before and after operational data and found that the overall operational performance has improved. Volumes on the northbound IH 35E main lanes decreased; contributing to better main lane flow. Volumes on the frontage road significantly increased. City of Lewisville traffic engineering staff indicated that the reversal has created positive operational benefits by allowing them to increase capacity for through traffic (eastbound and westbound) across the FM 1171 bridge.

Safety. Anecdotal information provided by Lewisville traffic engineering staff indicated that prior to the ramp reversal the FM 1171 exit ramp created safety problems due to inadequate storage (*26,28*). Queue spillback typically occurred between the hours of 12:30 PM and 2:00 PM due to high volumes of traffic on all approaches during the lunch hour. The worst backup usually occurred on a daily basis between 5:00 PM and 7:00 PM. Another factor contributing to the backup was the lack of storage on the FM 1171 bridge deck itself. A large volume of traffic stacked in the left-turn pocket on the bridge, which choked down the northbound ramp. Even though the reversal has eliminated the spillback problem for now, the bridge capacity problem still exists with the new exit ramp.

Basic Economic. The Lewisville Director of Economic Development provided a perspective on the economic impacts of the northbound reversal project (*27*). Since the motivation for this project was purely to improve safety, there really was not any economic activity to monitor. The Medical Center of Lewisville (MCL) is located at the southeast corner of the IH 35E/FM 1171 interchange. The MCL facility owns the majority of property along the northbound frontage road down to Purnell Road, and most of the rest is residential development. In addition to the exit ramp spillback problem being eliminated, safety of emergency personnel (particularly ambulance drivers) trying to access MCL has significantly improved. Prior to the ramp reversal ambulance drivers had to exit at Fox Avenue and travel along the frontage road a significant distance prior to getting to the MCL emergency room driveway. These drivers now have a much safer route and more direct access, improving their response time and safety.

Lesson Learned. Safe and efficient access to hospitals and emergency medical facilities are important considerations. This ramp reversal project illustrated that revised access created by ramp reversal can improve the safety and response time of emergency services. While it is difficult to quantify this benefit in pure numbers, it is inherent that this type of improvement is important to overall public safety.

Site 12 – US 190 in Killeen

Site 12 involved a ramp reversal pair on eastbound US 190 in the city of Harker Heights. This $1 million project reversed the FM 3470 (Stan Schlueter Loop) entrance ramp and the FM 2410 exit ramp. The project also added an auxiliary turn lane on the eastbound frontage road between the two relocated ramps. Some key information on the project construction schedule is provided in the list below:

- Letting date: August 2004 – Waco District;
- Date work began: September 14, 2004; and
- Date work completed: June 17, 2005.

The motivation behind the ramp reversal project was the desire of the City of Harker Heights to improve access to a new Wal-Mart Supercenter located on the eastbound US 190 frontage road (*19*,*29*). TxDOT engineers also wanted to do something to deal with the increased traffic created by the new development and were attracted by the opportunity to leverage dollars with monies provided by other stakeholders. This project was funded jointly by the City of Harker Heights ($350,000 advance funding agreement), Wal-Mart ($350,000 donation agreement), and the TxDOT Waco District ($242,000 in discretionary funds) (*30*). Figure 4-18 provides an aerial of the site with the Killeen Regional Airport on the north side of US 190.

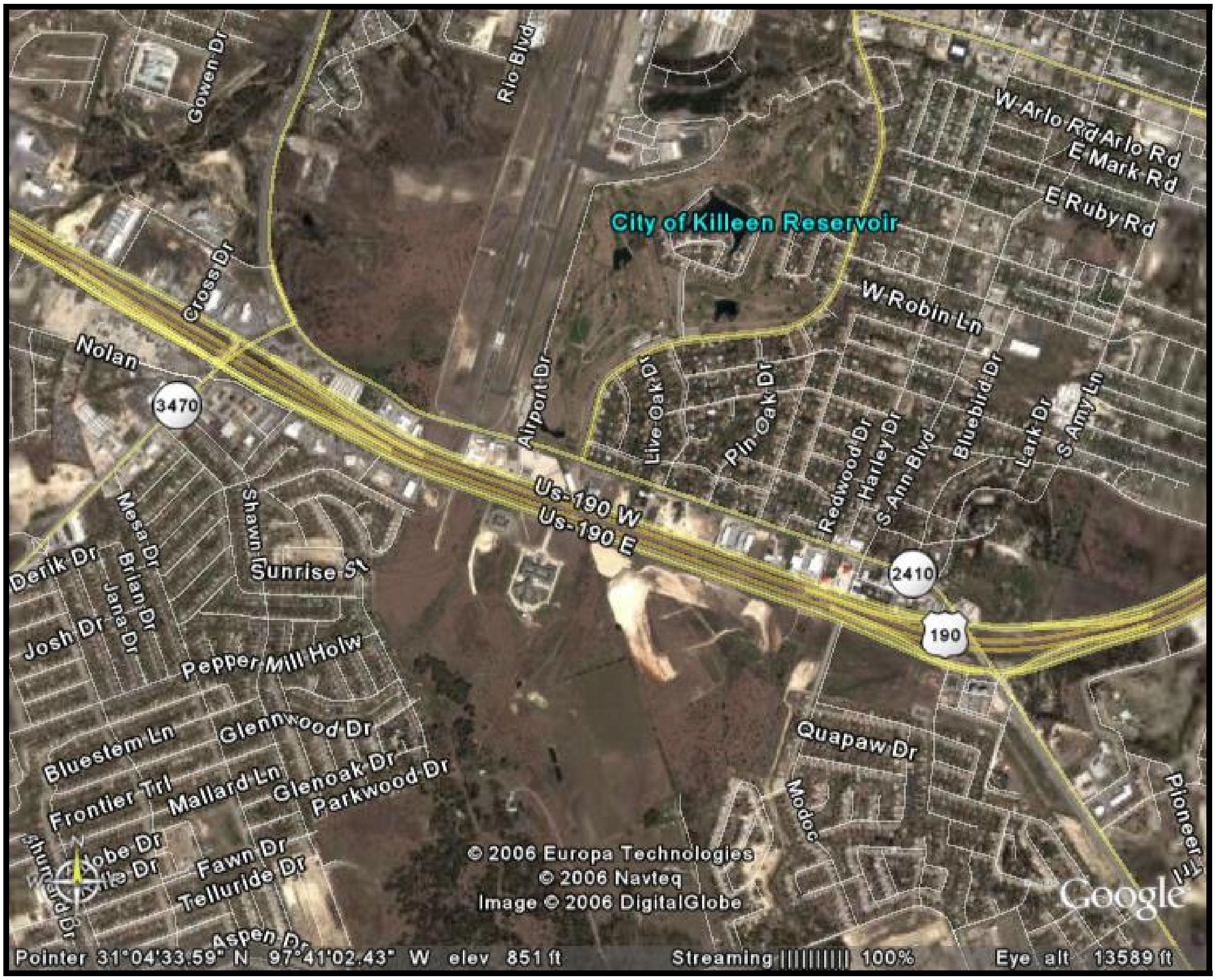
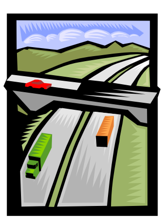


Figure 4-18. Aerial Photograph for Site 12 – Eastbound US 190 in Harker Heights (2).

Evaluation Results

This project was ongoing during project 0-5105; however, the research team did not know about it in enough time to schedule any before data collection. Researchers were forced to primarily rely on historical and anecdotal data to evaluate the operational, safety, and basic economic impacts of the ramp reversal. Crash data from the Harker Heights Police Department were not made available, so only an anecdotal safety evaluation could be performed.



Operations. Both city and TxDOT officials indicated that traffic operations in the project vicinity have improved (*19*,*29*). The reversal project has produced highly efficient flow and management of the increased frontage road traffic and also the eastbound main lane traffic at both the exit and entrance locations. Another operational outcome is that the reversal has allowed for positive traffic flow at the FM 2410 junction. Prior to the ramp reversal, vehicles exiting from US 190 would have to traverse over several lanes of traffic if they were turning left onto FM 2410. The new configuration allows drivers to gradually position themselves into the correct lanes over a longer stretch of frontage road.

Safety. The safety impacts at this case study site were not evaluated because of the lack of available after data. Researchers e-mailed the Harker Heights Police Department in an effort to obtain these data but were unsuccessful. Anecdotal information provided to the research team indicated that the project had a positive effect on the safety of the eastbound main lanes and frontage road *(19)*.

Basic Economic. The Director of Planning and Development for the City of Harker Heights provided information on the economic impacts of the reversal project *(29)*. The full impact of the reversal project has not been felt; however, it is already having a major impact on the sales tax receipts for the city. Wal-Mart is now the sales tax-producing leader in Harker Heights. Other smaller businesses have been constructed next to Wal-Mart, adding additional sales tax inputs. The ramp reversal also continues to place positive pressure on the development of properties along the frontage road. Vacant commercial properties are now much more attractive to potential businesses. Developers are also platting their undeveloped frontage road properties in an effort to be prepared for potential businesses. In fact, a Ford automobile dealership placed an intent to construct sign on a piece of property along the frontage road after the construction was complete. The overall economic impact has been extremely positive, and this type of project will be embraced in the future.

Lesson Learned. Agreements to share funding of ramp reversal projects can help accelerate implementation. This case study showed that joint funding by TxDOT, the city, and a private developer produced a project that was constructed in approximately 9 months and was ready in time for access to the new major traffic generator.

Site 13 – US 83 in Abilene

Site 13 is an X-ramp corridor project on US 83 (Winters Freeway) in the City of Abilene. This $20 million project widened the basic freeway cross section from four to six main lanes and reversed the existing diamond ramp configuration to X-ramps between South 14th Street and FM 89 (Buffalo Gap Road). It is important to note that while one lane was added in each direction on the US 83 main lanes, the frontage road capacity was unchanged (they remained a basic two-lane cross section). Some key information on the project construction schedule is provided in the list below:

- Letting date: April 2002 – Abilene District;
- Date work began: June 17, 2002; and
- Date work completed: November 19, 2004.

Winters Freeway is a key corridor in the Abilene area that serves several key facilities – Dyess Air Force Base on the northern end and the Mall of Abilene on the southern end. The motivation behind this project was to improve traffic flow and access to businesses located along the corridor. Figure 4-19 is an aerial photograph of Site 13.

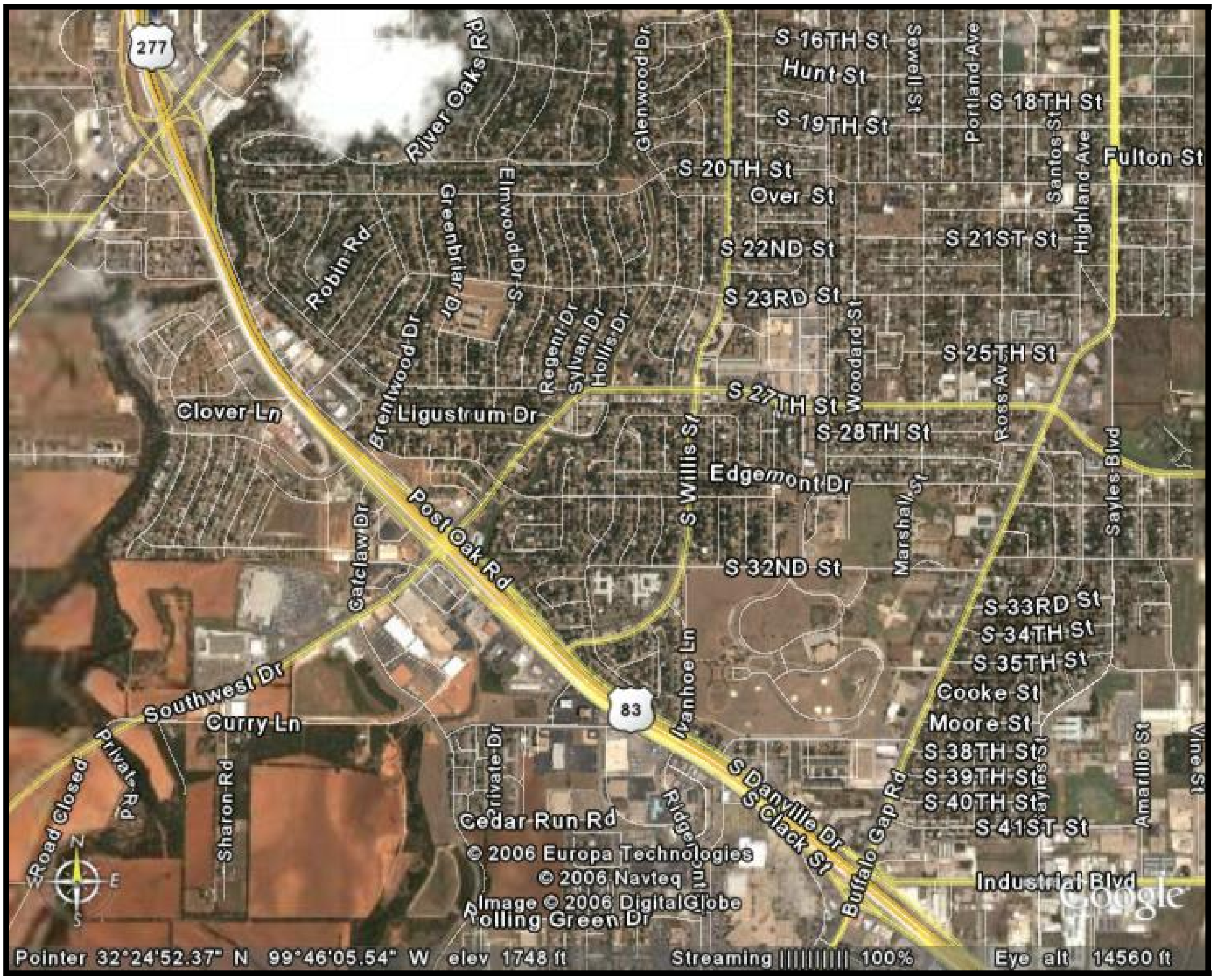
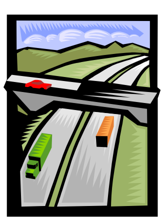


Figure 4-19. Aerial Photograph for Site 13 – US 83 in Abilene (2).

Evaluation Results

This project was basically complete prior to project 0-5105, starting in September of 2004. Researchers were forced to primarily rely on anecdotal data to evaluate the operational and basic economic impacts of the X-ramp corridor. Crash data from the Abilene Police Department and the DPS were used to conduct the safety evaluation.



<u>Operations</u>. Since this project was completed prior to the onset of project 0-5105, the operational evaluation relied on anecdotal information and media reports in the local newspaper (*Abilene Reporter-News*). This project was a major undertaking and took almost 2 ½ years to complete the construction. This factor and the resulting operational performance after completion both generated a substantial outcry from the public. The *Abilene Reporter-News* archive produced a number of citations about the Winters Freeway X-ramp corridor project (*31*). Most of the comments were negative in nature and focused on the dissatisfaction of the operational performance of the frontage roads after the ramp modifications. The list below provides some of the headlines that show the sentiment about the project:

- freeway mess,
- freeway ramps confuse drivers,
- engineers working to fix signal timing, and
- tough exits.

Anecdotal information about this project suggests that main lane volumes have decreased and frontage road volumes and congestion have substantially increased. This information seems to be supported by the 24-hour ADT maps produced by the TxDOT Transportation Planning and Programming (TP&P) Division in Austin. These maps are produced for each of the 25 districts each year and provide a good measurement of traffic volumes throughout the state. Table 4-10 provides a history of the 24-hour traffic volumes in the Winters Freeway corridor.

It is apparent that the volumes on the Winters Freeway significantly decreased in the study section during the construction period (56,000 vehicles per day in 2002 to 30,000 in 2003). The overall volume has not returned to the before level with approximately 7,000 fewer vehicles in 2004.

Table 4-10. Daily Traffic Volumes on US 83 in the Abilene District.

Location	Year/Volume (vehicles per day)				
	2004	2003	2002	2001	2000
North of US 277	42,000	47,000	50,000	42,000	39,000
Between US 277 and FM 89	49,000	30,000	56,000	52,000	51,000
South of FM 89	23,000	22,000	22,000	21,000	18,800

* Traffic volumes based on annual maps produced by the TxDOT Transportation Planning & Programming Division

Safety. Researchers obtained crash records from the Abilene Police Department and the DPS database *(32)*. Frontage road crash data were available; however, main lane information was not. The analysis revealed that the frontage road crash rate was basically unchanged after X-ramp implementation.

Basic Economic. The research team did not have sufficient time or resources to evaluate the basic economic impacts of this case study site. The Mall of Abilene is located on the southwest corner of the busiest intersection in Abilene, Buffalo Gap Road (FM 89) and the Winters Freeway. This mall has an estimated 9.2 million visitors per year and is the largest shopping destination and retail hub for an area consisting of 22 counties called the "Big Country" *(33)*. Following the X-ramp corridor project, the Mall of Abilene was sold to an Atlanta, Georgia, based real estate advisory and development firm who has proceeded to make the first extensive renovations in the 25-year history of the facility *(34)*.

Lesson Learned. The most significant lesson learned in this corridor is that an X-ramp corridor causes a substantial shift in volume from the main lanes to the frontage road, and this reality needs to be planned for accordingly. In this case study, it is apparent that by not providing any additional capacity on the frontage road congestion grew worse. Figure 4-20 shows the basic layout created by the X-ramp configuration in the Winters Freeway corridor – the two-lane frontage road is reduced to one-way at the exit ramp junction. This is where the operational problems were concentrated.

Figure 4-20. Aerial Photo of US 83 Frontage Road Typical Exit Ramp Junction (2).

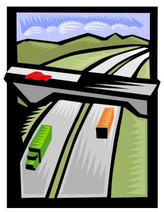
Site 14 – US 83 in Pharr District

The TxDOT Pharr District is implementing a series of X-ramp corridor projects on US 83 in the cities of Mission, McAllen, and Pharr. Site 14 is a $36.6 million project that widened the basic freeway cross section from four to six main lanes and reversed the existing diamond ramp configuration to X-ramps between Conway Avenue and Sugar Road. Some key information on the project construction schedule is provided in the list below:

- Letting date: January 2001 – Pharr District;
- Date work began: April 13, 2001; and
- Date work completed: September 3, 2004.

The Pharr District programmed improvements on US 83 because of the rapid growth in the area and the projected decrease in the quality of traffic operations in the near future.

Evaluation Results
This project was basically complete prior to project 5105, starting in September of 2004. Researchers were forced to primarily rely on anecdotal data to evaluate the operations, safety, and basic economic impacts of the ramp reversal.



Operations. The operational analysis of US 83 was performed by TTI as part of research project 0-2903 *(35)*. This study was done prior to project implementation to assess the operational effects of ramp reversals and relocations. While the existing ramps in the area were a mixture of diamond and X-ramp configurations, the pre-implementation analysis supported the transition to uniform X-ramp configurations. An assessment of the total system-wide benefits associated with the X-ramp configuration was also conducted. This analysis quantified the difference between traffic operations during the morning and evening peak hours under existing conditions versus the all X-ramp configuration. Table 4-11 summarizes the results of this analysis.

The analysis showed that the primary benefits projected to be gained along the study area were associated with signal-timing and minor geometric improvements at the cross-street interchanges. These improvements alone were estimated to generate benefits well over $100 million. The conversion of ramp designs to an X-ramp configuration placed a greater amount of traffic on the frontage roads, which created minor increases in frontage road travel speeds and LOS. However, the X-ramp configuration significantly decreased the weaving conflicts that would otherwise exist on the freeway main lanes. With regard to the main lane and frontage road operations, the X-ramp configuration was estimated to result in a benefit of approximately $34 million – producing an estimated system-wide benefit of approximately $150 million.

Table 4-11. Net Benefits of Pharr District X-Ramp Corridor Improvement Project *(35)*.

Corridor Component	Net Present Cost Due to Delay, $Millions[1]		Net Benefits $Millions
	Existing Geometrics	Proposed Improvements	
Freeway main lanes	38.8	1.3	37.5
Cross-street interchanges	142.3	25.9	116.4
Frontage roads	0.2	4.1	-3.9
TOTAL	$181.3	$31.3	$150.0

[1] The net present cost of delay during the peak hours (AM plus PM) over 20 years, assuming a discount rate of 4%, 250 working days per year, and a value of time of 10.78 per vehicle-hour

Safety. The safety impacts at this case study site were not evaluated due to a lack of available data.

Basic Economic. No formal information was collected on the basic economic impacts for this site. In general, the entire "Valley" region in Texas has experienced a considerable upturn in economic activity, largely attributable to the North America Free Trade Agreement (NAFTA). US 83 is a vital local facility with a regional mall and significant retail development along the study corridor and also a significant international facility serving cross border truck traffic.

<u>Lesson Learned</u>. X-ramp corridor projects can produce significant operational benefits compared to diamond or hybrid interchange configurations, particularly for improving the traffic flow along cross-street facilities.

Site 15 – SH 358 in Corpus Christi

Site 15 is a planned X-ramp corridor project on SH 358 in the TxDOT Corpus Christi District. One phase of this $10 million project is currently scheduled in the June 2006 letting (section between Staples Street and Carroll Lane). This project is included in the case studies because of an extensive study performed by TTI to evaluate alternative operational improvements on the SH 358 Freeway, also known as South Padre Island Drive (SPID) (*36*). The study site limits were from the SH 286 Crosstown Expressway interchange to ½ mile east of Airline Drive (see Figure 4-21).

Figure 4-21. Aerial Photograph for Site 15 – SH 358 in Corpus Christi (2).

This section of SPID has the largest ADT in the Corpus Christi area and serves over 140,000 vpd. The corridor provides Corpus Christi with several vital functions. As an example, SPID serves as the only continuous roadway route to North Padre Island/Mustang Island and its respective beaches, piers, and tourist destinations. Another route to reach the island, SH 361, is located on the north side of the Corpus Christi Bay and is serviced by a 24-hour ferry operation.

The SPID corridor also serves one of the largest retail centers in the area, located along both sides of the freeway between Weber and Airline. Major retail anchor stores and shopping malls are also accompanied by smaller ancillary stores and dining locations. The result is a major retail destination for the region.

Additionally, SPID serves as one of the major commuter routes in the area. Generally, the majority of jobs in the region have been located in north Corpus Christi along the IH37 corridor and downtown, while the majority of the residential areas are located on the south side and are continuing to develop southward.

SPID is currently a controlled-access facility with a typical section consisting of three main lanes and two frontage road lanes in each direction. The posted speed for the freeway main lanes is 60 mph, while the posted speed on the frontage road is 40 mph from the Crosstown interchange to just east of Everhart and 45 mph from east of Everhart to Airline. Driveway access points and interchanges are permitted along the frontage road right-of-way (ROW). The driveway access points vary with regard to design speed, spacing, and safety characteristics. All of the crossing arterials except Carroll Lane are four- or five-lane facilities which widen for various turning bays at the interchanges with SPID. Carroll Lane is two lanes and widens to four lanes at its interchange with SPID.

The SPID congestion relief project has received considerable attention from the public and media. TxDOT has several motivations for implementation of the X-ramp corridor project in this location. One of the primary factors is safety considerations, particularly at the cross-street/frontage road intersections. The *Corpus Christi Caller Times* has written several articles on the safety performance of the SPID, noting that the top five crash locations all fall within the study corridor (see Figure 4-22).

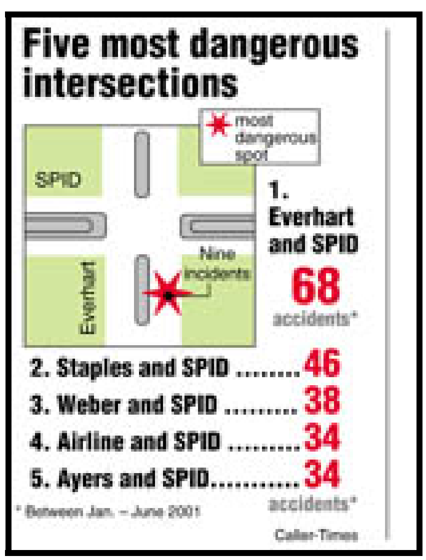


Figure 4-22. Publicity of Safety Issues on SH 358.

Improving traffic operations is another significant motivation. Figure 4-23 shows a graphical representation that appeared in the local newspaper to illustrate the concept of ramp reversal to the general public.

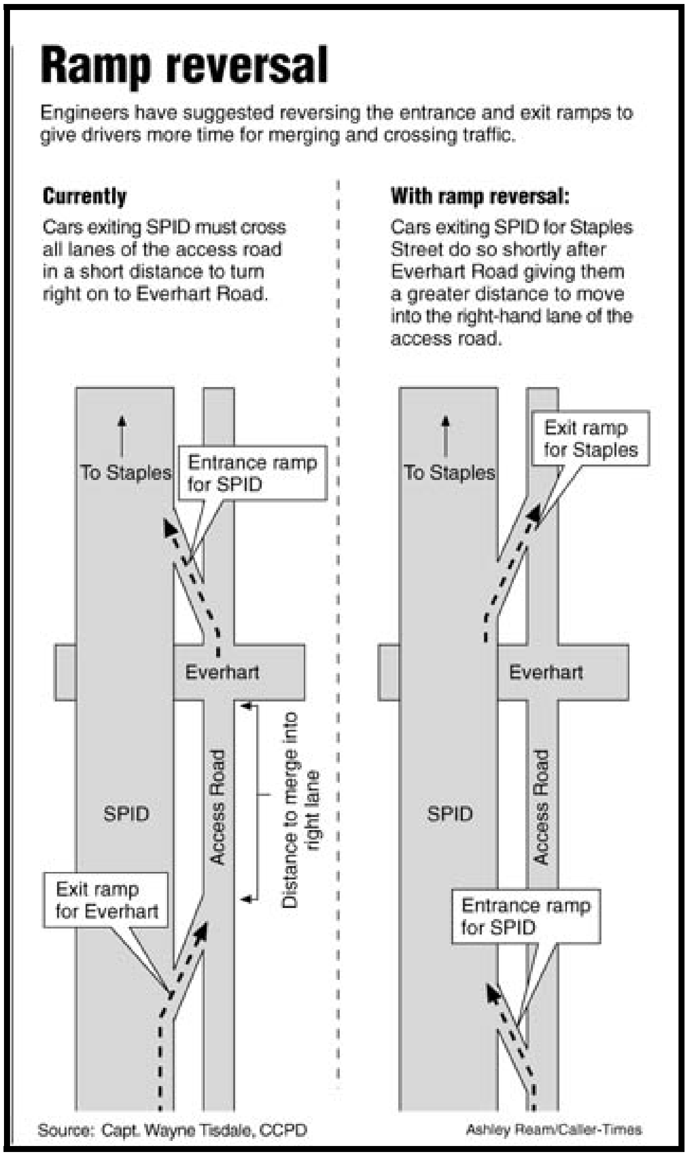
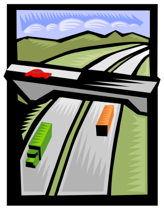


Figure 4-23. Conceptual Illustration of Ramp Reversals on SH 358.

Evaluation Results

This project has not been implemented by TxDOT but TTI did a pre-project evaluation study to document the operational and safety performance of the proposed switch to an X-ramp corridor. The basic economic impacts at this site have not been assessed.



<u>Operations</u>. The December 2004 TTI study utilized the VISSIM simulation model to compare various improvement alternatives, including conversion to an X-ramp corridor *(36)*. This analysis determined that the ramp reversals and the improvements to cross-street intersections produced considerable operational benefits. One of the primary benefits of the X-ramp configuration can be observed by examining screen captures from the VISSIM modeling. In Figure 4-24, the VISSIM simulation model during the evening peak hour is illustrated in the vicinity of Everhart for the existing "diamond" ramp configuration. As shown in Figure 4-24, the eastbound frontage road queue spills back onto the Everhart exit ramp and contributes to congestion on the freeway main lanes – this is a known regular occurrence at present. Conversely, Figure 4-25 illustrates the VISSIM model for the X-ramp configuration for the same location and time period. While the demands are still high for the eastbound frontage road approach, the X-ramp configuration allows a greater storage area for queuing vehicles such that the end of the queue does not spill back onto the exit ramp or terminal gore area.

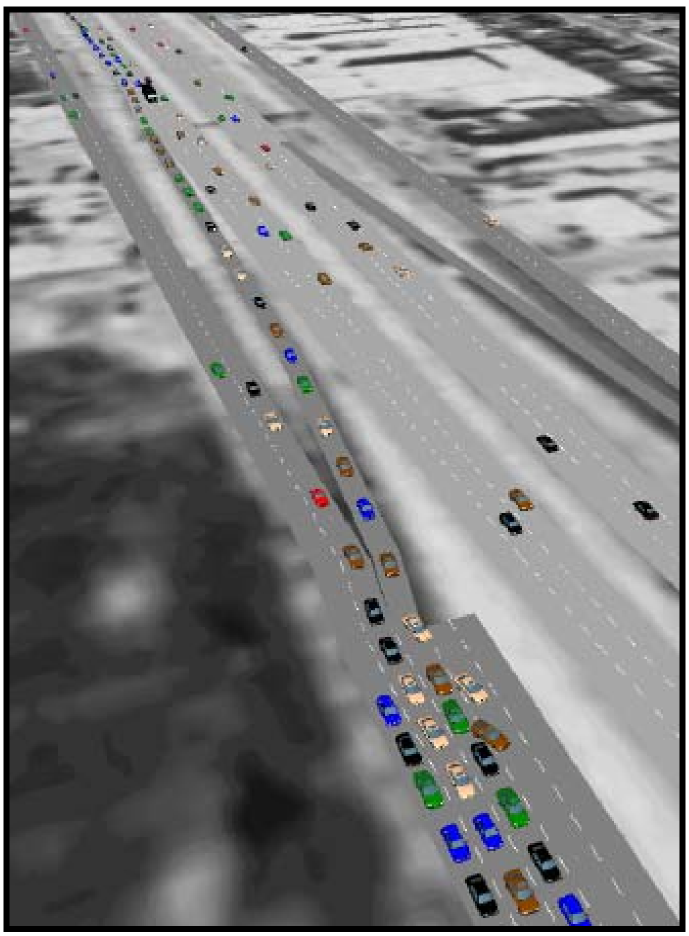


Figure 4-24. VISSIM Model during PM Peak Hour with Diamond Ramp at Everhart *(36)*.

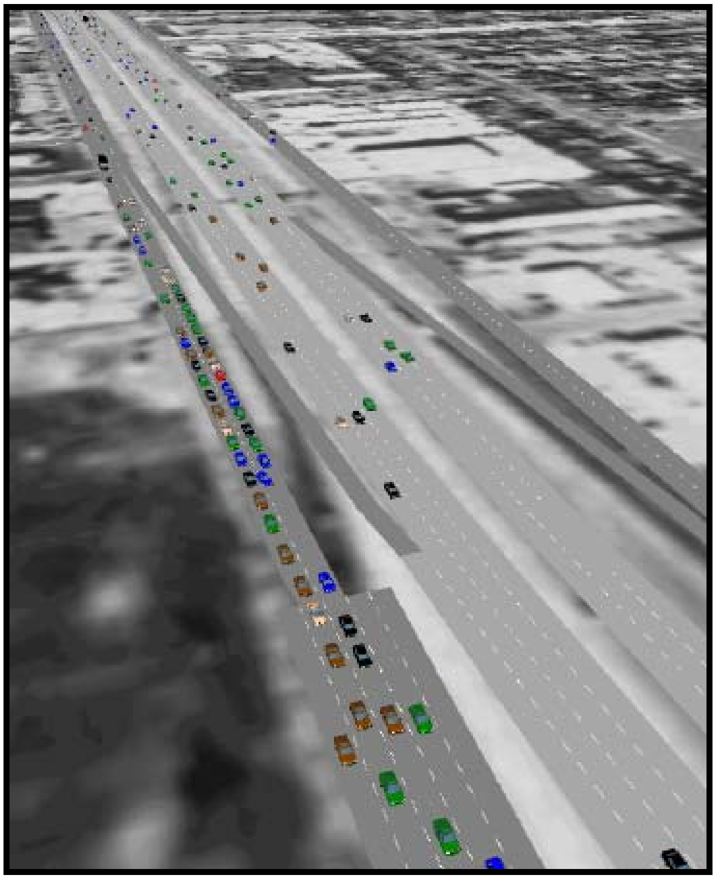


Figure 4-25. VISSIM Model during PM Peak Hour with X-Ramp at Everhart *(36)*.

Safety. Crash data were obtained from TxDOT and the City of Corpus Christi as an additional means of problem identification and analysis *(36)*. The TxDOT data included the main lanes, exit ramp, and frontage road data for the years 1997 -1999. The city data were from 1999 to 2001 and consisted of intersection crash location diagrams and "hotspot" crash locations in Corpus Christi for the most crash-prone locations. In 2001, eight (8) of the top 11 crash locations were located in the SPID corridor. Two of the eight locations were mid-block near the westbound Everhart and Staples exit ramp gores. Figure 4-26 shows an example of the city crash data for the Staples exit ramp.

The TxDOT crash data were analyzed for each tenth of a mile for SPID from the Crosstown Freeway interchange to the Cayo De Oso Causeway by direction, location, crash type, and crash severity. The data showed 60 percent of the crashes occurred in the eastbound direction. This finding is a reflection of the longer and more congested evening peak hour in this direction of flow.

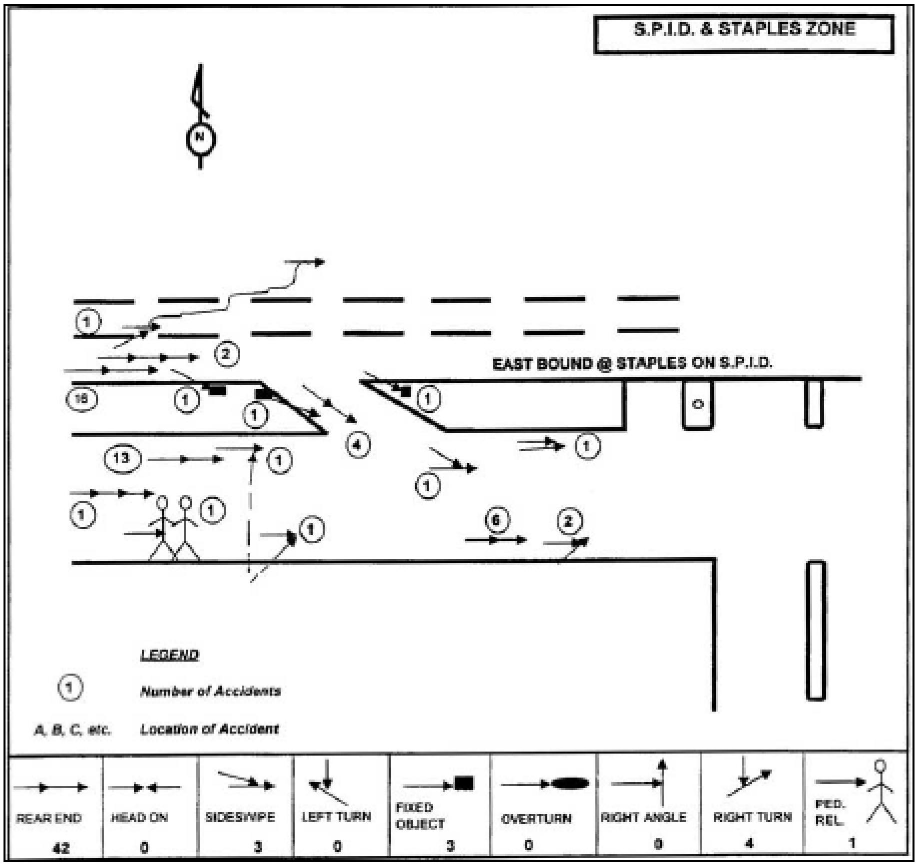


Figure 4-26. City of Corpus Christi Crash Diagram at Staples Exit Ramp (*36*).

Figure 4-27 shows a summary of the crash data by location (i.e., main lane, ramp, or frontage). The graph shows that the section of the SPID corridor from the Crosstown Freeway interchange to Airline has a higher crash density than the corridor from Airline to the Cayo De Oso Causeway. The crash location graph also shows that most of the frontage road crashes occurred near the intersections of the frontage roads and the major arterials. The only other prominent frontage road crash location was located at mile point 10.3, the section between Staples and Airline. This is the only location in the corridor where two ramps are located between major arterials that have only ½-mile spacing with SPID.

The high traffic volumes and tight ramp spacing are contributing factors to the high crash rate at this location. The short weaving distance of 825 feet in the eastbound direction and 950 feet in the westbound direction are below the recommended minimum weaving distance for current design guidelines. The crash data also show the westbound exit ramp areas at Everhart and Staples to be overrepresented when compared to the other ramp locations in this corridor. The greatest concentration of crashes that occurred on the main lanes is near these two noted eastbound exit ramps and in the vicinity of the vertical curves associated with the cross-street interchange overpasses.

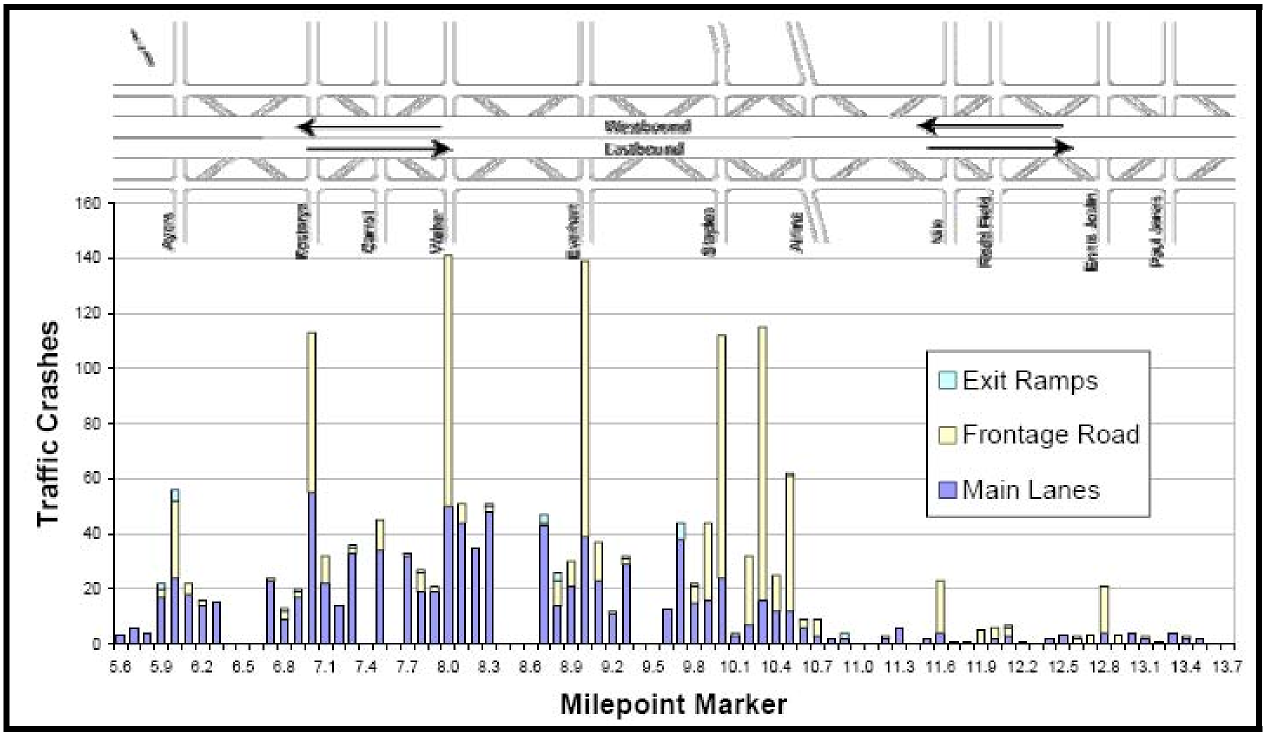


Figure 4-27. Summary of Crash Data by Location for Case Study Site 15 (*36*).

The statewide average crash rate for urban one-way frontage roads was 395.8 (2000) and 407.7 (2001) crashes per 100 MVMT. The three-year average crash rate calculated for the 8.1-mile SPID corridor was 438.5 per 100 MVMT. As noted earlier, it is clear that the queue backup from the cross streets onto upstream exit ramps is a contributing factor to this “higher than average” rate. These particular types of crashes are troublesome, as traffic approaching the exit ramp area is typically traveling at a high rate of speed (50+ mph). The prevailing exit ramp to cross-street spacing along SPID results in exiting vehicles commonly encountering queues in the ramp and/or ramp gore areas. This condition creates a more severe high-speed to low-speed vehicle crash scenario that typically results in more severe injuries. Using the crash data, the average yearly economic cost of crashes for the corridor is $25.8 million (*37*). As such, the magnitude and types of crashes within this corridor were a primary factor considered in the development of alternative improvements analyzed in this study.

Basic Economic. No formal information was collected on the basic economic impacts for this site.

Lesson Learned. This project has not been implemented yet. However, this case study revealed that thorough evaluation and well-planned public education can lead to project implementation even in complex corridors.

4.4 SYNTHESIS OF CASE STUDY FINDINGS

This section synthesizes the findings of the project 0-5105 case studies. The synthesis is provided in three tables – one for operations, a second for safety, and a third for basic economic impacts.

Synthesis of Operational Case Study Findings

Table 4-12 summarizes the findings of the evaluation of operational impacts for all of the case study sites. The operational impacts that were evaluated included system delay, traffic volumes – on the main lanes (ML), on the frontage road between access ramps (FRBR), and at the downstream frontage road intersection (FRINT), queuing, and the overall assessment based on sum of the other impacts. The footnotes at the bottom of the table explain the rationale used by the research team to assess whether the operational impact was positive, no change, negative, or not evaluated.

Table 4-12. Synthesis of Operational Case Study Evaluations.

Site Description	Delay/ Speed	Volumes			Queuing	Anecdotal/ Overall
		ML	FRBR	FRINT		
1. WB SH 114 in Grapevine	« »	+	—	+	« »	+
2. WB IH 20 in Arlington	+	+	—	+	+	+
3. EB IH 30 in Dallas	+	« »	—	« »	« »	+
4. WB IH 30 in Dallas	+	« »	« »	« »	« »	+
5. SB US 67 in Cedar Hill	« »	« »	—	« »	+	« »
6. SB IH 35 in Austin	+	« »	« »	« »	« »	+
7. NB IH 35 in Austin	+	« »	« »	« »	« »	+
8. WB US 190 in Killeen	+	« »	—	+	« »	+
9. SB IH 35E in Denton	+	+	—	+	+	+
10. NB IH 35E in Denton	+	+	—	+	+	+
11. NB IH 35E in Lewisville	+	+	—	+	+	+
12. EB US 190 in H. Heights	+	+	—	+	« »	+
13. US 83 in Abilene	Ø	+	—	+	« »	« »
14. US 83 in Pharr	+	+	—	+	+	+
15. SH 358 in Corpus Christi	+	+	—	+	+	+

ML Main lane volume impact
FRBR Frontage road volume impact between the access ramps
FRINT Frontage road volume impact at the downstream cross-street intersection

+ Positive operational benefit (e.g., improved travel delay/speed in corridor, decreased main lane volume between the two cross streets, decreased frontage road volume between ramps, and decreased frontage road volume approaching the downstream signalized intersection)

— Negative operational benefit (e.g., increased main lane or frontage road volume between ramps)

« » No measurable change in the operational performance measure

Ø This impact was not or could not be evaluated

Synthesis of Safety Case Study Findings

Table 4-13 summarizes the findings of the evaluation of safety impacts for all of the case study sites. The safety impacts that were included in the evaluation were main lane crash rate, frontage road crash rate, total crash rate, and anecdotal assessment. The footnotes at the bottom of the table explain the rationale used by the research team to assess whether the safety impact was positive, no change, negative, or not evaluated.

Table 4-13. Synthesis of Safety Case Study Evaluations.

Site Description	Safety Impacts			
	ML	FR	Total	Anecdotal
1. WB SH 114 in Grapevine	✚	« »	✚	✚
2. WB IH 20 in Arlington	« »	✚	✚	✚
3. EB IH 30 in Dallas	✚	✚	✚	✚
4. WB IH 30 in Dallas	Ø	Ø	Ø	✚
5. SB US 67 in Cedar Hill	« »	✚	✚	✚
6. SB IH 35 in Austin	✚	✚	✚	✚
7. NB IH 35 in Austin	✚	✚	✚	✚
8. WB US 190 in Killeen	Ø	Ø	Ø	✚
9. SB IH 35E in Denton	Ø	Ø	Ø	✚
10. NB IH 35E in Denton	Ø	Ø	Ø	✚
11. NB IH 35E in Lewisville	Ø	Ø	Ø	✚
12. US 190 in Harker Heights	Ø	Ø	Ø	✚
13. US 83 in Abilene	Ø	« »	Ø	Ø
14. US 83 in Pharr	Ø	Ø	Ø	Ø
15. SH 358 in Corpus Christi	Ø	Ø	Ø	Ø

ML Main lane safety impact within project limits
FR Frontage road safety impact within project limits
✚ Positive safety benefit (e.g., the crash rate per 100 million vehicle-miles traveled decreased and the perception of safety from local officials was that safety got better)
— Negative safety benefit (e.g., the crash rate per 100 million vehicle-miles traveled increased and the perception of safety from local officials was that safety got worse)
« » No measurable change in the safety performance
Ø This impact was not or could not be evaluated

Synthesis of Basic Economic Case Study Findings

Table 4-14 summarizes the findings of the evaluation of basic economic impacts for all of the case study sites. The economic impacts that were included in the evaluation were sales tax receipts, property value, business development, and overall assessment. The footnotes at the bottom of the table explain the rationale used by the research team to assess whether the basic economic impact was positive, no change, negative, or not evaluated.

Table 4-14. Synthesis of Basic Economic Case Study Evaluations.

Site Description	Economic Impacts			
	Sales Tax	Property Value	Business Development	Overall
1. WB SH 114 in Grapevine	+	« »	« »	+
2. WB IH 20 in Arlington	+	+	+	+
3. EB IH 30 in Dallas	Ø	Ø	Ø	Ø
4. WB IH 30 in Dallas	Ø	Ø	Ø	Ø
5. SB US 67 in Cedar Hill	+	+	+	+
6. SB IH 35 in Austin	Ø	Ø	Ø	Ø
7. NB IH 35 in Austin	Ø	Ø	Ø	Ø
8. WB US 190 in Killeen	+	+	+	+
9. SB IH 35E in Denton	+	+	+	+
10. NB IH 35E in Denton	+	+	+	+
11. NB IH 35E in Lewisville	Ø	Ø	Ø	Ø
12. US 190 in Harker Heights	+	+	+	+
13. US 83 in Abilene	Ø	Ø	+	+
14. US 83 in Pharr	Ø	Ø	Ø	Ø
15. SH 358 in Corpus Christi	Ø	Ø	Ø	Ø

+ Positive economic benefit (the sales tax receipts in the city increased, the property values along the affected corridor increased, and business development – commercial permits and facility expansion – increased)

– Negative economic benefit (e.g., the sales tax receipts in the city decreased, the property values along the affected corridor decreased, and business development decreased)

« » No measurable or perceived change in the basic economic performance

Ø This impact was not or could not be evaluated

Synthesis of Lessons Learned

Table 4-15 summarizes the lessons learned for all of the case study sites except Site 4. After review of the three key evaluation issues, the research team determined the most significant lesson learned from each individual case study. This was done to highlight both positive and negative issues from the case studies.

Case Study Conclusions

The research team included 15 ramp modification projects in the case study evaluation that consisted of an evaluation framework concentrating on four elements. Each case study site was evaluated based on operational performance, safety, and basic economic impacts. Researchers also developed a lesson learned for each case study site to highlight important knowledge.

Table 4-15. Synthesis of Lessons Learned from Case Study Evaluations.

Site Description	Lesson Learned
1. WB SH 114 in Grapevine	Guide signing for revised ramps needs to be carefully considered so that motorists can safely find their destination.
2. WB IH 20 in Arlington	Higher vehicle speeds on frontage roads after ramp reversals might become an issue so coordination with law enforcement is important.
3. EB IH 30 in Dallas	Reversal of even a single access ramp can produce significant benefits and improve mobility and safety of the traveling public at a relatively low cost.
5. SB US 67 in Cedar Hill	Ramp reversal projects can spur substantial economic activity and development. The revised accessed created by the project is generating significant tax revenue and employment benefits.
6. SB IH 35 in Austin	Properly implemented ramp reversal projects can produce meaningful safety benefits. These benefits are often difficult to quantify because of the lack of available crash records.
7. NB IH 35 in Austin	When using simulation models to evaluate reversal alternatives, speed and throughput should be considered together in evaluating performance, but where throughput remains constant, higher speed is indicative of improved performance.
8. WB US 190 in Killeen	There can be a significant difference in perception between the side of the freeway where ramps had been reversed (positive) versus the other side where ramps were not (not as positive).
9. SB IH 35E in Denton	Successful and timely implementation of ramp reversal projects can be critical in providing access to large development projects. Close coordination between stakeholders can result in a project that all parties are happy about.
10. NB IH 35E in Denton	Consideration of frontage road capacity is extremely important, particularly if the cross section is only two lanes. If no auxiliary lane is constructed between the exit ramp and entrance ramp on the frontage road, a bottleneck at the exit ramp junction is likely in the future because of having only one thru lane available.
11. NB IH 35E in Lewisville	Revised access created by a ramp reversal can improve the safety and response time of emergency services. While it is difficult to quantify this benefit in pure numbers, it is inherent that this type of improvement is important to public safety.
12. US 190 in Harker Heights	Agreements to share funding of ramp reversal projects can help accelerate implementation. Joint funding by TxDOT, the city, and a private developer produced a project that was constructed in approximately 9 months and was ready in time for access to the new major traffic generator.
13. US 83 in Abilene	An X-ramp corridor causes a substantial shift in volume from the main lanes to the frontage road, and this reality needs to be planned for accordingly. In this case study, it is apparent that by not providing any additional capacity on the frontage road congestion grew worse.
14. US 83 in Pharr	X-ramp corridor projects can produce significant operational benefits compared to diamond or hybrid interchange configurations, particularly for improving the traffic flow along cross-street facilities.
15. SH 358 in Corpus Christi	Thorough evaluation and well-planned public education can lead to project implementation even in complex corridors.

Overall, it appears that the operational, safety, and basic economic impacts of ramp modification projects are primarily positive in nature. The detailed case study evaluations support further implementation of ramp reversal and X-ramp corridor projects by TxDOT.

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CHAPTER 5
PROJECT EVALUATION PROCESS

This chapter summarizes the activities accomplished within Task 5 of the research work plan. Task 5 involved the development of a proposed analytical approach/process for evaluation of projects involving ramp reversals or X-ramps. The first subsection provides some of the evaluation criteria that are important to ramp modification projects. The second subsection outlines some of the data collection activities that might be needed to support project evaluation. The third subsection includes some guidance on the use of traffic analysis tools for project evaluation. The fourth subsection delineates the proposed project evaluation framework.

5.1 EVALUATION CRITERIA

The research team considered a wide range of criteria that affect the performance of ramp modification projects. It is important to note that operational performance was the focus of this research, since the project was funded by TxDOT Research Management Committee (RMC) 4, which is devoted to the subject of traffic operations. Some of the operational criteria considered in the evaluation include:

- Traffic volumes;
    - Freeway main lanes
    - Freeway ramps
    - Frontage roads
    - Peak hour/period versus daily

- Ramp spacing;
    - Distance between successive ramps
    - Spacing between exit ramps and driveways, side streets, or cross streets
    - Access control at entrance and exit ramp junctions with the frontage road
    - Grade-separation/braided ramps

- Weaving;
    - On the freeway main lanes
    - On the frontage road
    - Weaving volumes
    - Section length
    - Type
    - Constrained versus unconstrained

- Capacity/level-of-service;
    - Basic freeway sections
    - Ramp merge and diverges
    - Weaving areas
    - Frontage road sections

- Freeway interchange type;
    - Diamond
    - Reverse diamond or X-pattern
    - Stacked diamond
    - Hybrid

- Cross-street intersection layout and operation;
    - Signal timing
    - Number and assignment of lanes
    - Presence of Texas turnaround lanes

- Presence of auxiliary lanes;
    - Between ramps on the freeway main lanes
    - Between ramps of the cross street on the frontage road

- Frontage road operation;
    - One-way versus two-way traffic flow

- Revised freeway access;
    - Interstate versus non-interstate (e.g., US, state highway, loop, etc.) facilities

- Vehicle queuing; and
    - Sight distance issues created by roadway curvature or topography
    - Queue spillback from frontage roads back onto the freeway main lanes

- Traffic control and signing
    - Presence of ramp metering in the corridor
    - Placement issues – particularly provision of adequate distance for destination guide signs (i.e., decision sight distance)
    - Driver expectancy.

Most of the criteria in the previous list already have existing guidelines, standards, or procedures to assist in the operational evaluation. Table 5-1 provides a list of the evaluation criteria with their corresponding primary guidance sources and a quick reference within each source for further detailed guidance.

5.2 DATA COLLECTION ACTIVITIES

Proper collection of relevant traffic data is an important part of any project evaluation process. In the evaluation of ramp modification projects, four primary categories of data are relevant:

- traffic volumes;
- travel times;
- queue lengths; and
- physical inventory.

Table 5-1. Guidance Sources and Information for Operational Evaluation Criteria.

Evaluation Criteria	Primary Guidance Source	Detailed Information
Distance between successive ramps	TxDOT *Roadway Design Manual* (*1*)	• Figure 3-37
	AASHTO *Green Book* (*2*)	• Exhibit 10-68
Spacing between exit ramps and driveways, side, or cross streets	TxDOT *Roadway Design Manual*	• Table 3-16
	AASHTO *Green Book*	• Exhibit 10-2
Access control at exit ramp junction with frontage road	TxDOT *Roadway Design Manual*	• Figure 3-13
	TTI Research Report 2927-1 (*3*)	• Entire document
Access control at entrance ramp junction with frontage road	TxDOT *Roadway Design Manual*	• Figure 3-14
	TTI Research Report 2927-2 (*4*)	• Figures 7 and 8
Grade-separation/braided ramps	TTI Research Report 376-2F (*5*)	• Entire document
	AASHTO Green Book	• Chapter 3 and 10
Freeway weaving	*Highway Capacity Manual* 2000 (*6*)	• Chapter 24
Frontage road weaving	TxDOT *Roadway Design Manual*	• Chapter 3 – Sect. 6
	TTI Research Report 1393-1, 2 (*7,8*)	• Entire document
Freeway capacity and LOS	*Highway Capacity Manual* 2000	• Chapter 23
Frontage road capacity and LOS	TxDOT *Roadway Design Manual*	• Chapter 3 – Sect. 6
	TTI Research Report 1393-3, 4F (*9,10*)	• Entire documents
Interchange type	TxDOT *Access Management Manual* (*11*)	• Section 5
	TxDOT *Roadway Design Manual*	• Chapter 3 – Sect. 6
	CTR Research Report 1873-2 (*12*)	• Table 1
	TTI Research Reports 210-12F (*13*) and 335-1F (*14*)	• Entire documents
Cross street configuration – lane grouping/assignment	*Highway Capacity Manual* 2000	• Chapter 16
	TTI Research Report 2910-S (*15*)	• Entire document
Texas turnaround lanes	TxDOT *Roadway Design Manual*	• Figure 3-38
Freeway auxiliary lanes	TxDOT *Roadway Design Manual*	• Figure 3-37
Frontage road auxiliary lanes	TxDOT *Access Management Manual*	• Chapter 2 – Sect. 7
	TTI Research Reports 1393-1,2,3 and 4F	• Entire documents
Frontage road operation	TxDOT *Roadway Design Manual*	• Chapter 3 – Sect. 6
Revised freeway access – interstate facility	TxDOT *Roadway Design Manual*	• Chapter 1 – Sect. 4
	TxDOT *Project Development Manual* (*16*)	• Chapter 2 – Sect. 5
Queue spillback/queue storage	TxDOT *Roadway Design Manual*	• Chapter 3 – Sect. 6
	TTI Research Report 4538-1 (*17*)	• Figure 2-22
Decision sight distance	TxDOT *Roadway Design Manual*	• Chapter 2 – Sect. 3
Traffic control and signing	Texas MUTCD (*18*)	• Entire document

Traffic Volumes

Traffic counts are the most basic of all traffic engineering data. The first important consideration in evaluating ramp modification projects is to collect traffic volume data on the freeway main lanes (Figure 5-1), ramps (Figure 5-2 and 5-3), and frontage road sections (Figure 5-4) that will be impacted by the proposed reversal(s). Field data collection can be expensive and time consuming, so every effort should be made to use available data before collecting new data. Sources of available volume data on freeway main lanes and frontage road facilities may include:

- intelligent transportation system (ITS) field devices;
- TxDOT saturation counts;
- city traffic counts; and
- regional travel model counts.

If the collection of new data is necessary, the Institute of Transportation Engineers (ITE) *Manual of Transportation Engineering Studies* is an excellent resource and how to guide for conducting field studies with appendices on data analysis and presentation *(19)*.

The second important consideration for the collection of traffic volume data for evaluation of ramp modification projects is to concentrate on the peak hour/period rather than daily volumes. The majority of ramp modifications will have the greatest impact on traffic operations during the peak travel periods, which is why resources should be dedicated to collection of peak period data. It is also significant to note that if the ramp modification is found to work well with peak hour volumes, then it is inherent that it will also perform well during the rest of the day.

Figure 5-1. Collection of Main Lane Volume Data Using Pneumatic Tube Counter.

Figure 5-2. Collection of Exit Ramp Volume Using Pneumatic Tube Counter.

Figure 5-3. Collection of Entrance Ramp Volume Using Pneumatic Tube Counter.

Figure 5-4. Collection of Frontage Road Volume Using Pneumatic Tube Counter.

Travel Times

Travel time data are collected to measure the prevailing speed at which a traffic stream traverses a section of roadway. It is an important measure in determining the amount and location of motorist delay and traffic congestion at a study location.

The collection of travel time data is important to gauge the effectiveness of a ramp modification project. There are several different methods for collecting travel times, including a floating car technique using either a distance measuring instrument (DMI) or GPS device. If the study corridor has automatic vehicle identification (AVI) or other tag-based systems, these data can also be used to collect travel times.

The *Travel Time Data Collection Handbook* is a comprehensive reference that is available online at http://www.fhwa.dot.gov/ohim/timedata.htm (*20*). This handbook provides guidance to transportation professionals and practitioners for the collection, reduction, and presentation of travel time data.

Queue Lengths

The location, duration, and extent of traffic queues at a study site are important parameters to consider, especially for ramp modification projects. Queuing data are most often collected by focused field observation during peak traffic periods. In the evaluation of ramp modification projects, it is particularly important to observe locations where traffic queues spill back from the frontage road facilities onto the adjacent freeway main lanes.

Physical Inventory

The last time of data collection activity relates to conducting a physical inventory of the study site by field personnel. Some of the types of inventory data useful in the project evaluation process include:

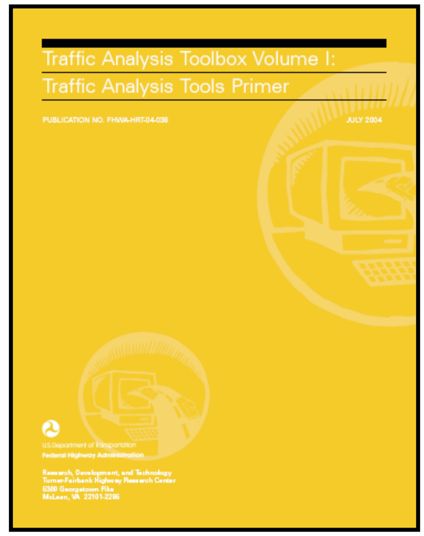
- roadway (number of lanes, driveway locations, ramp spacing, turnaround lanes, etc.);
- traffic control (exit ramp junctions, traffic signal timings, etc.); and
- adjacent land uses and businesses (type, location, vacancies, etc.).

Some inventory data may be available in other databases (aerial photographs, GIS databases, etc.) and manual sources (project plans, roadway inventory logs, etc.); however, field verification is important.

5.3 USE OF TRAFFIC ANALYSIS TOOLS FOR PROJECT EVALUATION

In order to assess the potential effectiveness of a particular ramp modification project, it must be analyzed using traffic analysis tools or methodologies. "Traffic analysis tools" is a collective term used to describe a variety of software-based analytical procedures and methodologies that support different aspects of traffic and transportation analyses. Traffic analysis tools include methodologies such as:

- sketch-planning,
- travel demand modeling,
- traffic signal optimization, and
- traffic simulation.



There are numerous traffic analysis tools available for use; however, little comprehensive guidance has existed to aid transportation professionals in selecting and applying these tools – particularly for simulation models. The FHWA recently developed a series of materials in the *Traffic Analysis Toolbox* that provide extensive guidance that is directly applicable to ramp modification project evaluation (*21*).

Model Selection

The *Traffic Analysis Toolbox – Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools* report is an excellent resource to make an informed decision on the model that is most appropriate for analysis of a particular project (*22*). This resource identifies seven criteria that should be considered when selecting a type of traffic analysis tool. These criteria include:

- geographic scope,
- facility types,
- travel modes,
- traffic management strategies and applications,
- traveler responses,
- performance measures, and
- tool/cost-effectiveness.

Figure 5-5 shows these criteria and some of the basic considerations. An automated tool that implements the guidance can be found at the FHWA Traffic Analysis Tools Web site at: http://ops.fhwa.dot.gov/trafficanalysistools/index.htm.

Comparison of Simulation and Highway Capacity Software

One very important consideration early in the evaluation process is to decide whether the use of traffic simulation is more appropriate than *Highway Capacity Manual*-based methods or tools. If the decision is that microscopic simulation is needed or desirable, further guidance is provided in the following section.

Analysis Context: Planning, Design, or Operations/Construction						
1	2	3	4	5	6	7
Geographic Scope	**Facility Type**	**Travel Mode**	**Management Strategy**	**Traveler Response**	**Performance Measures**	**Tool/Cost-Effectiveness**
What is your study area?	Which facility types do you want to include?	Which travel modes do you want to include?	Which management strategies should be analyzed?	Which traveler responses should be analyzed?	What performance measures are needed?	What operational characteristics are necessary?
• Isolated Location • Segment • Corridor/ Small Network • Region	• Isolated Intersection • Roundabout • Arterial • Highway • Freeway • HOV Lane • HOV Bypass Lane • Ramp • Auxiliary Lane • Reversible Lane • Truck Lane • Bus Lane • Toll Plaza • Light Rail Line	• SOV • HOV (2, 3, 3+) • Bus • Rail • Truck • Motorcycle • Bicycle • Pedestrian	• Freeway Mgmt • Arterial Intersections • Arterial Mgmt • Incident Mgmt • Emergency Mgmt • Work Zone • Spec Event • APTS • ATIS • Electronic Payment • RRX • CVO • AVCSS • Weather Mgmt • TDM	• Route Diversion – Pre-Trip – En-Route • Mode Shift • Departure Time Choice • Destination Change • Induced/ Foregone Demand	• LOS • Speed • Travel Time • Volume • Travel Distance • Ridership • AVO • v/c Ratio • Density • VMT/PMT • VHT/PHT • Delay • Queue Length • # Stops • Crashes/ Duration • TT Reliability • Emissions/ Fuel Consump • Noise • Mode Split • Benefit/Cost	• Tool Capital Cost • Effort (Cost/ Training) • Ease of Use • Popular/Well-Trusted • Hardware Requirements • Data Requirements • Computer Run Time • Post-Processing • Documentation • User Support • Key Parameters User Definable • Default Values • Integration • Animation/ Presentation

Figure 5-5. Criteria for Selecting a Traffic Analysis Tool (22).

Microscopic Simulation for Ramp and Frontage Road Operations

Many existing traffic simulation models are oriented toward analysis of freeway main lane operations. The evaluations of ramp modification projects also need models that are capable of realistic and dependable for simulation of ramp and frontage road operations. This research project helped the research team to gain an understanding of the strengths and limitations of microscopic traffic simulation models for evaluation of ramp modification projects. One of the most important considerations was that route assignment features were necessary for the investigation of ramp operations so that vehicles can be routed from the freeway to the frontage road, or vice-versa, in such a manner that unrealistic turning maneuvers are avoided.

Applicable Models

Among publicly or commercially available microscopic simulation models, several are full-featured applications that have a reasonably broad user base in the United States and have been applied to situations similar to ramp modification projects. These models include CORSIM™ *(23)*, Paramics™ *(24)*, VISSIM™ *(25)*, Integration™ *(26)*, and SimTraffic™ *(27)*. When route assignment is introduced as a criterion in the selection process, SimTraffic™ is removed from contention. When cost is factored into model choice, Paramics™ is removed in that it is nearly 10 times more costly than the next most expensive model. Finally, Integration™ is removed because of inconsistent technical support in the last several years. Only two models appear to be practical candidates for modeling ramp and frontage road operations: CORSIM™ and VISSIM™. Both models have been used for project analysis in Texas for a multitude of freeway, frontage road, and arterial studies.

CORSIM™

CORSIM™ was developed for the FHWA in the late 1970s and has been in use as a simulation tool since that time. Figure 5-6 shows an exit ramp model. CORSIM™ is composed of two largely separate programs, FRESIM™, which simulates freeway main lanes and exits, and NETSIM™, which simulates arterial and frontage road environments. Interface modes are used when simulations (such as the type being proposed here) involve both freeway and frontage road/arterial components. A limitation on these simulations is that CORSIM™ does not (using the normal user interface) allow for vehicle routing (i.e., using origin-destination data, for instance) along a path from FRESIM™ to NETSIM™. In other words, there is no way using the normal model features to "tell" a specific freeway vehicle that it must exit and then turn right at a driveway on the frontage road. Vehicle routing is necessary for evaluation because analysts must be able to know for each simulation how many vehicles are weaving on both the main lanes and frontage roads.

Figure 5-6. CORSIM Model of Exit Ramp.

Outside of its normal user interface, CORSIM™ includes the routing capabilities mentioned above. Undocumented features exist that allow CORSIM™ to read extra input files that give vehicle volume, mix, and path information. However, these additional input files must be created for each simulation case, which can become tedious. Further, the corporation maintaining CORSIM ™ has no intention of creating a user interface for this functionality or supporting it further.

A means of circumventing the routing limitations of CORSIM™ for simulating frontage roads is to use only the NETSIM™ component of the model. Used by itself, NETSIM™ includes all of the routing features necessary for the proposed research. This is not desirable in terms of modeling real-world behavior, since NETSIM™ does not have FRESIM's™ built-in capabilities to model the lane changing maneuvers and vehicle behavior on freeways.

Another limitation of CORSIM™ as it pertains to the ramp modification project evaluation is that vehicles within NETSIM™ do not "know" which lane to be in for a downstream turning maneuver until they are within two links (roadway segments between ramps, driveways or intersections) of their turn. This limitation can produce unrealistic weaving maneuvers if the spacing along the frontage road between ramps and driveways is short. This issue with CORSIM™ can be mitigated if careful attention is paid to model calibration and coding. One such calibration was performed in recent research of freeway weaving areas (*28*). Calibrated and field-verified CORSIM™ models have been used by TTI in research analyzing many aspects of weaving operations, including X-ramp type weaving (*7*), weaving between ramps and interchanges (*9*), and weaving between ramps and frontage road driveways (*3*). CORSIM™ was also used by CTR in a more general study (*12*) of the overall economic, land use, and operations impacts of frontage roads, which included both X- and diamond ramp configurations.

Further guidance on the use of CORSIM™ is available from TTI with training course materials produced as part of the TRICOM research project (*29*). The Minnesota Department of Transportation has also created an Advanced CORSIM training manual that provides further instruction on how to effectively use the model for project evaluation (*30*).

VISSIM™

VISSIM™ is a simulation model developed in Germany to analyze complex traffic and transit operations. An English-language version has been available for about 10 years and the user base is both established and expanding. As with CORSIM™, VISSIM™ has a graphical user interface which allows the user to create networks over scaled background aerial photography or computer-assisted design (CAD) layouts (see Figure 5-7). VISSIM's™ sophisticated vehicle simulation model allows the user to accurately analyze traffic interactions such as weaving sections and merges (*26*).

VISSIM™ can analyze traffic operations considering factors such as traffic composition, signals, lane layout, transit stops, weaving, variable message signs, and other traffic control phenomena. For results presentation, VISSIM™ generates customizable output files. Information contained in these files can include travel time and delay statistics, queue lengths, signal timing, graphical output of space diagrams and speed profiles, and environmental indicators. Unlike CORSIM™, which bases primary outputs on how vehicles perform on roadway links (i.e., average rather than individual vehicle statistics); VISSIM™ allows the user to define which outputs are desired. This flexibility makes it easy to generate a speed profile of a vehicle exiting the freeway, merging onto the frontage road, and (for instance) accessing a driveway. CORSIM™ can only generate such profiles using third-party processing software; in VISSIM™, these capabilities are built-in.

VISSIM™ contains static and dynamic vehicle routing, which allow the user to control vehicle paths. Whereas this capability is provided in CORSIM™ as an experimental and unsupported feature, in VISSIM™ it is built-in. Thus, VISSIM™ can be programmed for experiments involving varying volumes and weaving intensity for the ramps and driveways along frontage roads.

The user is allowed to specify the vehicle's response to downstream turning as a calibration feature, which permits realistic simulation of vehicle lane changing as freeway vehicles approach exit ramps or as vehicles on a frontage road approach a driveway, entrance ramp, or cross-street interchange. Calibrated VISSIM™ models have been used by TTI recently in a study of the effects of ramp volume and spacing on freeway weaving for managed lanes and in a study of the overall corridor impacts of ramp volume and spacing where managed lanes are present *(26)*.

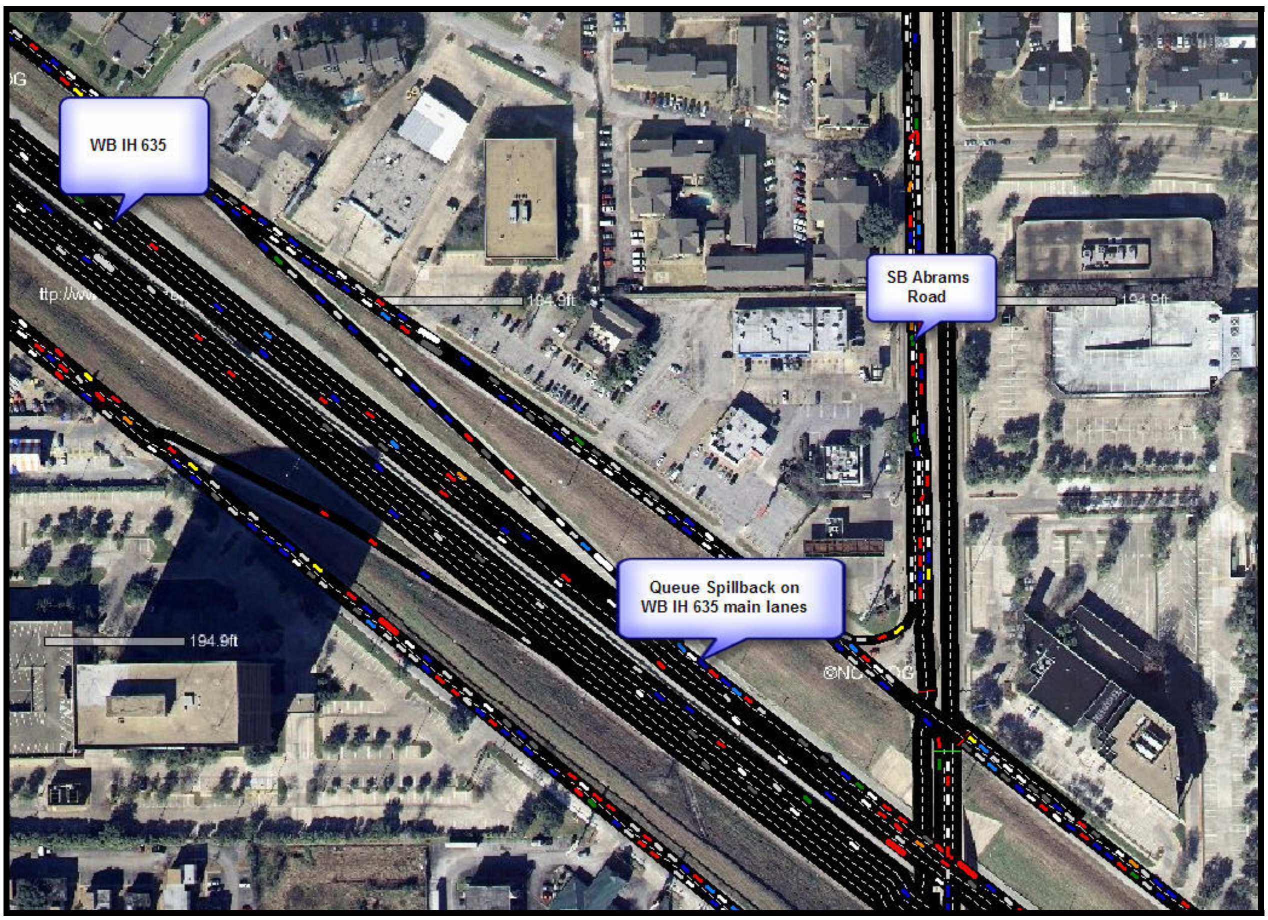


Figure 5-7. Example of VISSIM Model with Aerial Photograph as Background Image.

5.4 PROJECT EVALUATION FRAMEWORK

The research team developed a five-step process as a framework for evaluating potential ramp modification projects shown in Table 5-2. This framework serves as a high-level guide for determining whether or not a ramp reversal or X-ramp project is worthwhile to implement.

Table 5-2. Project Evaluation Framework for Ramp Modification Projects.

#	Step	Description
1	Define Purpose and Need	Define the scope of the study area for the ramp modification project under consideration. Once this has been determined, it is important to consider the purpose and need for ramp modifications. Use of the operational evaluation criteria and guidance sources contained in Table 5-1 can help a project manager determine the purpose and need. The research team provided information on the driving force/project motivation for each of the case study sites in Chapter 4 in order to highlight the purpose and need for implementation of those ramp modification projects.
2	Collect Data	Collect the necessary data for the defined study area. The information contained in Section 5.2 of this chapter describes appropriate data collection activities.
3	Select Analysis Tool(s)	Select the appropriate traffic analysis tools for evaluation of traffic operations. The information presented in Section 5.3 of this chapter provides some guidance on the analysis tool and model selection process.
4	Perform Analysis	Perform the analysis of the ramp modification alternatives under consideration. Some of the guidance contained in Section 5.3 is also helpful in this step, and further guidance is presented in Section 6.5 of the following chapter.
5	Assess Viability	Assess the viability and whether to implement a ramp modification project. Project viability can probably best be assessed using a cost-effectiveness evaluation such as B/C ratio. Other important considerations are availability of project funding from traditional sources and potential contribution from other sources such as local governments or private developers.

Figure 5-8 on the following page provides a ramp modification decision flowchart developed as a tool to complement the basic framework in Table 5-2. This flowchart starts at the top with the basic premise of deciding whether a ramp reversal, X-ramp, or braided ramp project is worthwhile. The second decision level deals with data collection items. The next two levels outline some basic questions that are aimed at helping to determine project purpose and need. Finally, the last two steps involve the alternatives analysis and use of a cost-effectiveness procedure developed in previous research.

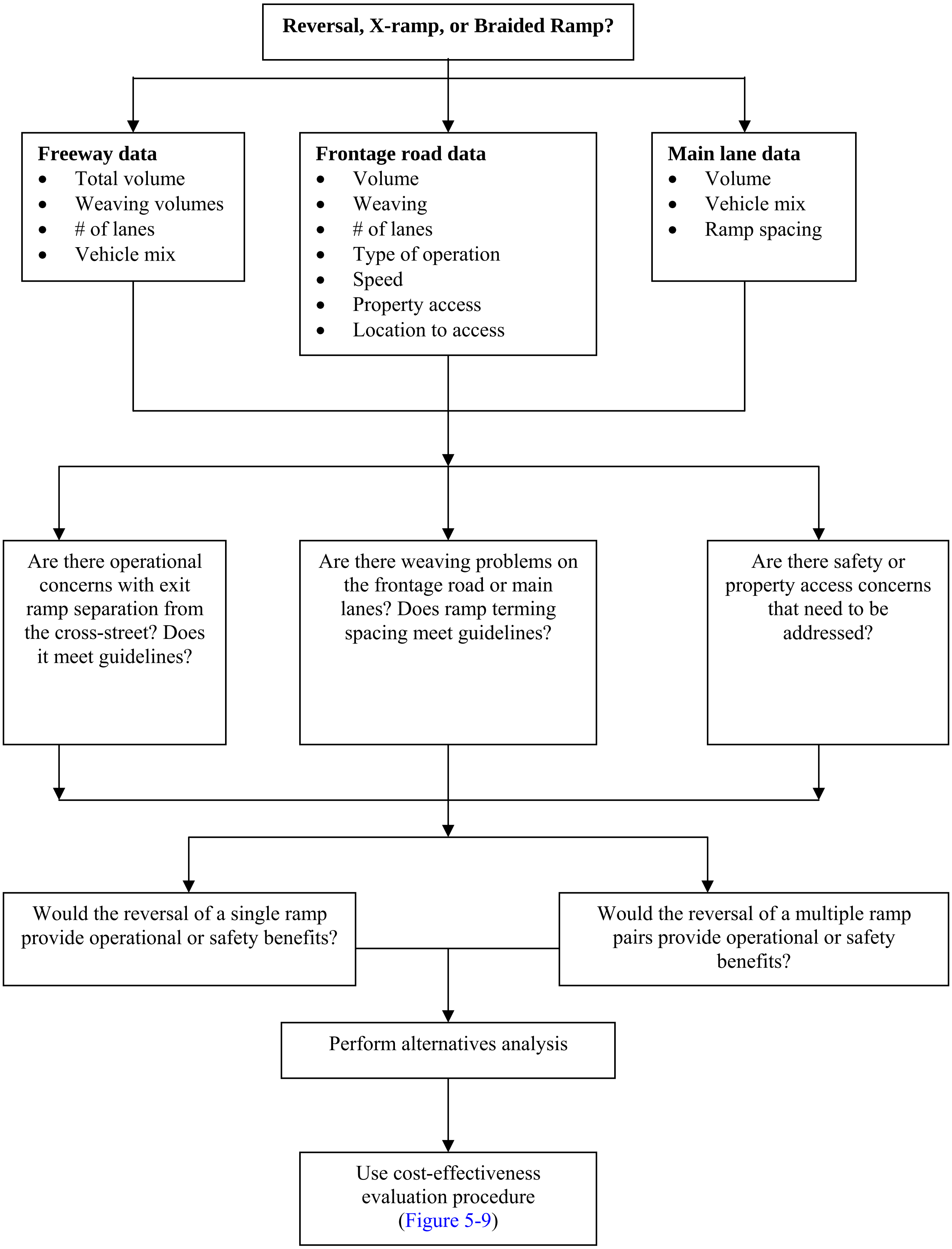


Figure 5-8. Ramp Modification Project Decision Flowchart.

Streamlined Cost-Effectiveness Evaluation Procedure for Ramp Reversal Projects

A previous TTI research project number 210, *An Analysis of Urban Freeway Operations and Modifications*, developed a streamlined procedure for estimating the cost-effectiveness of a particular ramp reversal project before its implementation (*13*). Figure 5-9 shows the cost-effectiveness evaluation procedure in the form of a flowchart.

The cost-effectiveness procedure developed by Borchardt et al. is based upon parameters required to determine whether a ramp reversal project is worthwhile. These parameters include traffic data such as vehicular delay, peak-period volume, daily volume, percent trucks, and estimated volume of rerouted vehicles. These data provide the basis for determining the benefits and disbenefits expected to result from the reversal of the ramps. An estimate of the construction costs, coupled with the net benefit, provides a B/C ratio that quantifies the cost-effectiveness. For roadway construction projects such as ramp reversals, a 20-year life and 10 percent interest rate are default values if more specific information is unavailable. With this information, the B/C ratio can be calculated. If the ratio is greater than one, the project will save more money than it costs and should be implemented, as illustrated at the bottom of Figure 5-9.

Evaluation Procedure for Grade-Separated Ramps

Another previous TTI research project number 376, *Increased Capacity of Highway and Arterials Through the use of Flyovers and Grade Separated Ramps*, analyzed the use of braided ramps serving frontage roads to investigate operational and geometric requirements, to prepare guidelines on benefit-cost analysis and to propose warranting conditions (*5*). A grade-separated ramp can increase the effective capacity of the freeway main lanes or improve access to points on the frontage road. But because of the high capital cost, their use should be limited to locations where it can be justified based on function and economics. The analysis procedure developed by this research is suited for screening 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.

Warrants

The conditions to be considered in selecting a specific grade-separated ramp project are the proposed warrants developed in project 376 (*5*). 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 off-ramp of the grade-separated pair.
4. If main lane 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 main lane expansion, options considered include:

- reject grade-separated ramp in favor
- reject grade-separated ramp in favor of eventual main lane expansion,
- build a grade-separated ramp and demolish when freeway expansion is necessary,
- build a lower design type grade-separated ramp and/or modify frontage road to leave enough space for eventual main lane expansion.

5. An on-ramp followed closely by an off-ramp (short weave) has enough traffic to constitute a bottleneck on the freeway main lanes 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 vehicles per hour 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 through at least one signalized intersection.
7. Access traffic using the frontage road adds enough traffic to a signalized intersection to induce excessive delay. Low-cost traffic engineering measures cannot relieve congestion.
8. The crash rate (crashes 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 TxDOT. Ratios above one may be justified but a detailed analysis should be conducted to include all benefits and costs.

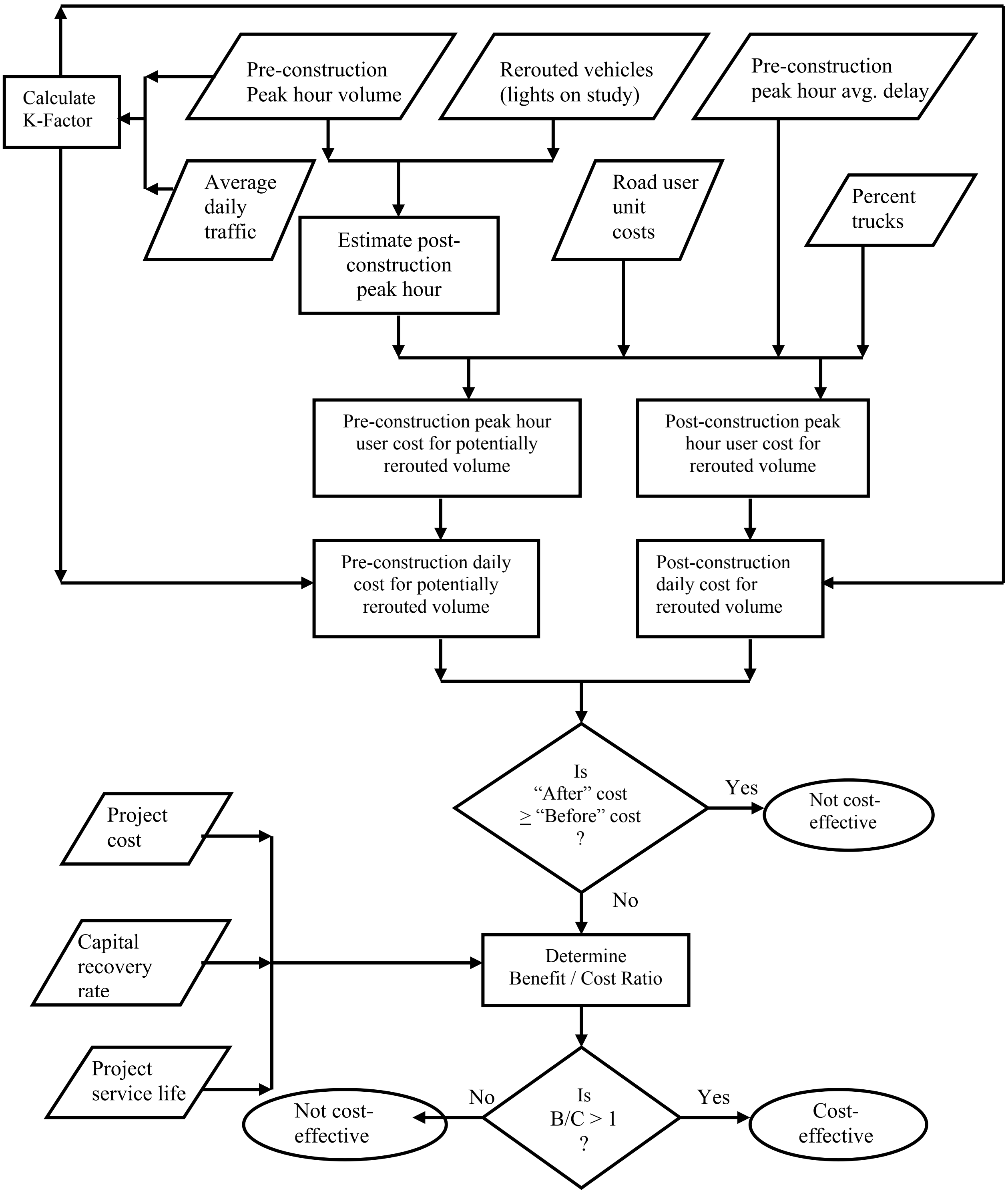


Figure 5-9. Cost-Effectiveness Evaluation Procedure for Ramp Reversal Projects (*13*).

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CHAPTER 6
GUIDELINES FOR RAMP REVERSAL AND X-RAMP PROJECTS

6.1 BACKGROUND INFORMATION

Many freeways in Texas experience congested traffic conditions during peak periods. Freeway system expansion is very expensive and time-consuming. Consequently, improvement alternatives other than construction of new facilities are desired. The Texas Department of Transportation has been implementing comparatively inexpensive methods to improve the existing freeways such as grade-separated (i.e., braided) ramps and modified ramp configurations via X-ramp interchanges and ramp reversals. As a matter of background, it is important to understand the basic tradeoffs between the use of X-ramp versus traditional diamond interchanges. Table 6-1 lists some of the generic pros and cons associated with a decision to utilize the X-ramp configuration. Figure 6-1 illustrates the conceptual definitions of the X-ramp and diamond ramp configurations.

Table 6-1. Generic Pros and Cons of Converting from Diamond to X-Ramps.

PROS	CONS
+ ***Increased development*** along frontage road	– ***Costly*** means of improving signal operation
+ ***Reduced through demand*** on frontage road approach to intersection	– Construction activities will ***disrupt business*** along frontage road
+ ***Move the weaving area*** between an entrance ramp and exit ramp from the main lanes to the frontage road, where speeds and volumes are lower	– Invites ***sling-shot maneuvers*** allowing motorists to bypass cross-street signals; this poses safety and capacity problems on frontage road
+ ***Increased storage area*** for vehicles queuing from the cross-street intersection	– Addresses the queue storage problem but ***queuing delay will not be remedied***
+ Better opportunity to use frontage road as alternate route as part of ***incident management*** if auxiliary lanes are provided	– Likely increase in ***short trips*** on the freeway
	– Construction of auxiliary lanes may require ***major reconstruction*** at cross-streets

Ramp reversal, or X-ramp configuration, is an improvement strategy that has seen a significant amount of interest throughout the state, particularly in the last five years. Project 0-5105 provides TxDOT engineers with an updated methodology and evaluation results from previously implemented ramp reversal projects to assist in decision-making for future projects.

The project investigated the benefits and impacts of X-ramp and ramp reversal projects. Impacts evaluated include operational, safety, and basic economic benefits. Case study evaluations of 15 projects implemented throughout the state were performed. These case studies and existing guidance contained in TxDOT manuals was used to determine when it is advisable to consider the use of reversed and/or X-pattern ramps. The culmination of the project is guidelines to assist TxDOT staff in the evaluation and implementation of X-ramp and ramp reversal projects.

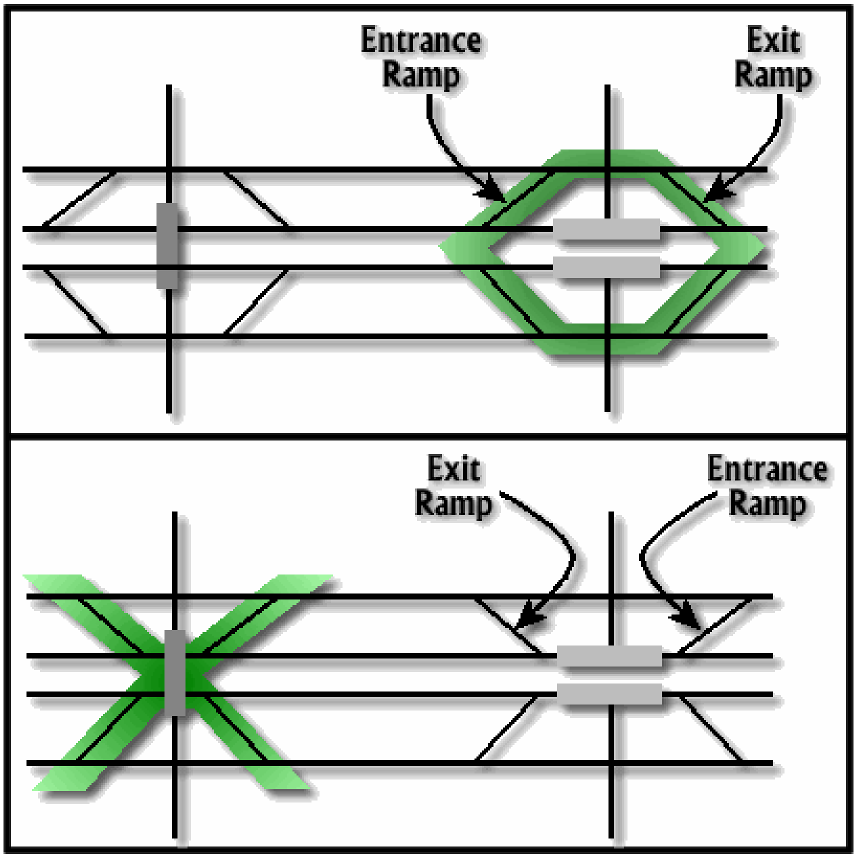


Figure 6-1. Conceptual Illustration of Diamond vs. X-Ramp Interchanges.

6.2 GUIDELINES FOR SUCCESSFUL IMPLEMENTATION OF RAMP REVERSAL AND X-RAMP PROJECTS

Guidelines Framework

One of the challenges of developing guidelines is making sure that they are clear, concise, and practical. The research team reviewed a number of guidebooks and manuals to try and identify formats that were successful in meeting that challenge.

After much review, researchers determined that some of the recently completed research on the topic of access management was a good area to emulate (*1*, *2*). While access management is normally thought of as the management of traffic on arterial facilities, there is also a strong linkage to frontage road and ramp management. The synergy between access management goals and themes and ramp modification projects became apparent throughout the Project 0-5105 research. Based on the shared aims, the development of guidelines for ramp reversal and X-ramp projects is based on the themes (Figure 6-2) developed for the TxDOT Access Management program:

- Theme #1 – Improve safety and mobility;
- Theme #2 – Provide reasonable access to developments; and
- Theme #3 – Promote local government partnerships.

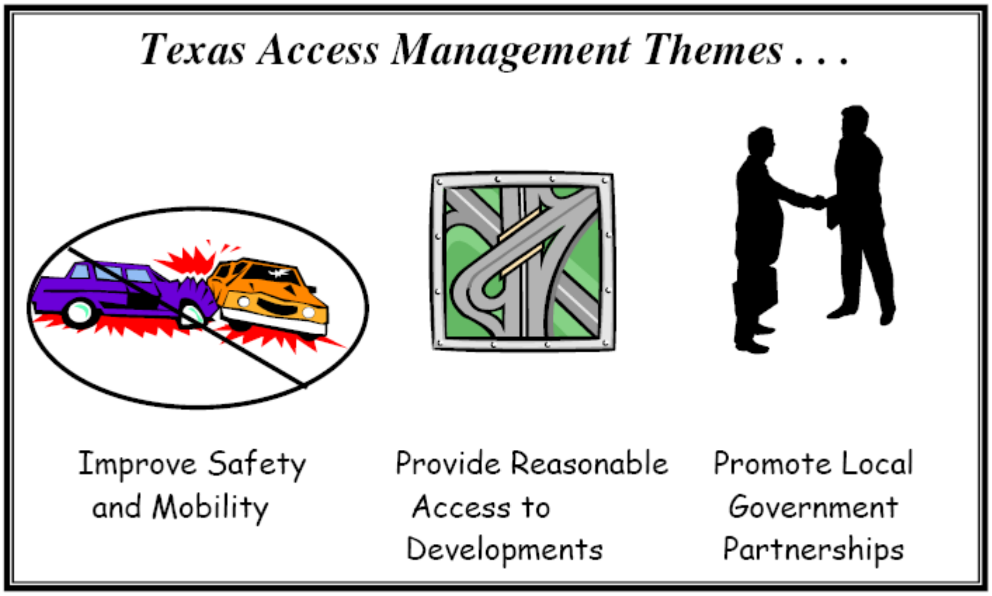


Figure 6-2. Texas Access Management Themes (*1*).

In essence, ramp management techniques such as ramp reversal, ramp closure, and even ramp metering are freeway access management techniques. These three themes all strongly relate to the overall research objective and the 21 guidelines developed during project 0-5105.

In addition to the three theme areas, the research team felt that further structure for the guidelines was necessary. Researchers decided that the 5Es would constitute a good framework for guidelines development. The 5Es – Education, Encouragement, Engineering, Enforcement, and Evaluation – are based on the national *Safe Routes to School* program guidance being developed by the Federal Highway Administration (3). Furthermore, the *Guidelines for Successful Implementation of Ramp Reversal and X-Ramp Projects* contained in this document are sorted into five major categories based on the 5Es:

- **Educational** – teaching, promoting, and involving the public and stakeholders about the impacts and benefits of potential projects;
- **Encouragement** – allowing stakeholders to participate in project funding;
- **Engineering** – implementing projects that meet existing standards, improve mobility and safety, provide reasonable access to developments, and promote local government partnerships;
- **Enforcement** – partnering with local law enforcement to ensure traffic laws are obeyed in the vicinity of project improvements; and
- **Evaluation** – using proper evaluation methods to justify implementation of worthwhile projects and monitoring and documenting outcomes, trends, and lessons learned after project implementation.

Guidelines Format

The research team developed a typical format for presentation of the 21 guidelines contained in this document. Each guideline is numbered and presented in a text box. Text supporting and explaining the guideline is then provided. For most guidelines, an example that highlights the practical implementation of that guideline is also included. Finally, links and references to supporting information are provided when appropriate.

6.3 EDUCATIONAL GUIDELINES

This section documents the three educational guidelines for ramp reversal and X-ramp corridor projects. The educational guidelines primarily support the third theme of promoting partnerships.

<u>Guideline 1</u>: Use the local media, department resources, and other innovative techniques to promote projects prior to construction, during construction, after completion, and following evaluation.

Examples of Effective Project Promotion

As stated in Guideline 1, effective project promotion can occur during different stages of the project implementation process. Opportunities for project promotion can occur prior to construction, during construction, after the completion of construction, and even following project evaluation. The following subsections document some good examples of project promotion by the local media, TxDOT, and local partners for each phase of the project implementation process. Many examples were observed from case studies of TxDOT projects throughout the state; however, representative examples are presented.

Interstate 20 Ramp Reversal in Arlington

The IH 20 ramp reversal project in Arlington is a good example of promotion at each phase of the project implementation process (CCSJ 2374-05-054). Most of the promotion was positive in nature; however, there was one negative media story after a project evaluation.

<u>Prior to Construction</u>. An article that appeared in the University of Texas at Arlington (UTA) student newspaper, *The Shorthorn*, was a good example of effective media coverage prior to construction *(4)*. The *Shorthorn* article did an excellent job of promoting the upcoming ramp reversal of the Matlock Road entrance ramp and Cooper Street exit ramp on westbound IH 20 (see Figure 6-3). The article alluded to each of the three themes for successful projects:

- <u>Improve safety and mobility</u> – headline trumpeted the aim to reduce traffic congestion and a quote stated the goal of the project to help by making it “safer than before”;
- <u>Provide reasonable access to roadside developments</u> – TxDOT spokesperson was quoted as indicating the ramp reversal would “alleviate the back-up on the freeway and improve traffic flow, which benefits the mall and other businesses”; and
- <u>Promote local government partnerships</u> – the *Shorthorn* writer mentioned that the project was a cooperative effort between the City of Arlington, The Parks of

Arlington Mall, the contractor, and TxDOT and even provided information on funding contributions from this partnership.

Figure 6-3. Effective Project Promotion Prior to Construction (*4*).

The article also provided a graphic detailing the proposed improvements so that the scope of the project was easy to convey. This graphic is shown in Figure 6-4.

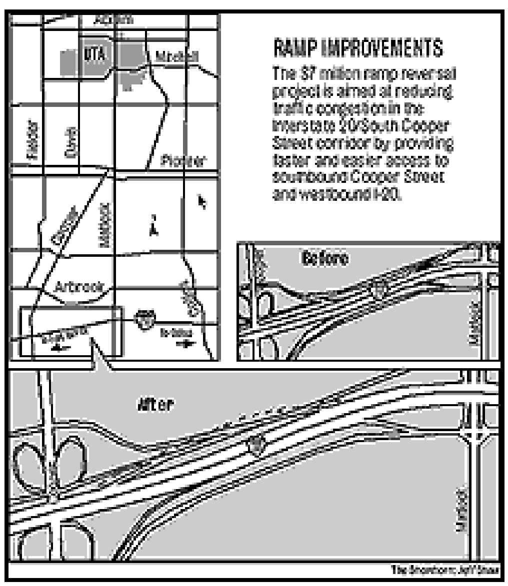


Figure 6-4. Project Graphic Detailing Before and After Improvements (*4*).

<u>During Construction</u>. A City of Arlington press release was a good example of effective promotion during construction (5). The press release celebrated the completion of a significant project milestone (opening of a collector-distributor road) and gave an update on future project phases.

After Project Evaluation. One newspaper story created some negative publicity after the IH 20 ramp reversal project in Arlington. A Fort Worth Star-Telegram reporter wrote an article with the headline *Accidents up on Improved IH 20 Frontage Road* (6). The report asserted that "traffic accidents are on the rise on the westbound IH 20 frontage road near The Parks at Arlington mall, an area that police say is more dangerous despite an $8 million project intended to ease traffic congestion. Police recorded 28 crashes on the frontage road between Matlock Road and Cooper Street from November 2001 to November 2002—a 65 percent increase from the 12 months before construction was complete." The article only reported the increase in frequency of crashes on the westbound frontage road and did not account for the volume increase on the frontage road from approximately 6000 vehicles per day before the project to over 32,000 after the project (see Figure 6-5). A comparison of before and after crash rates on the westbound frontage road revealed that safety was actually improved with a 41 percent reduction from 3.9 to 2.3 crashes per million vehicle miles (Figure 6-6). This example shows why it is important to use crash rate instead of crash frequency because traffic volumes (and crash exposure) typically increase significantly following ramp modifications.

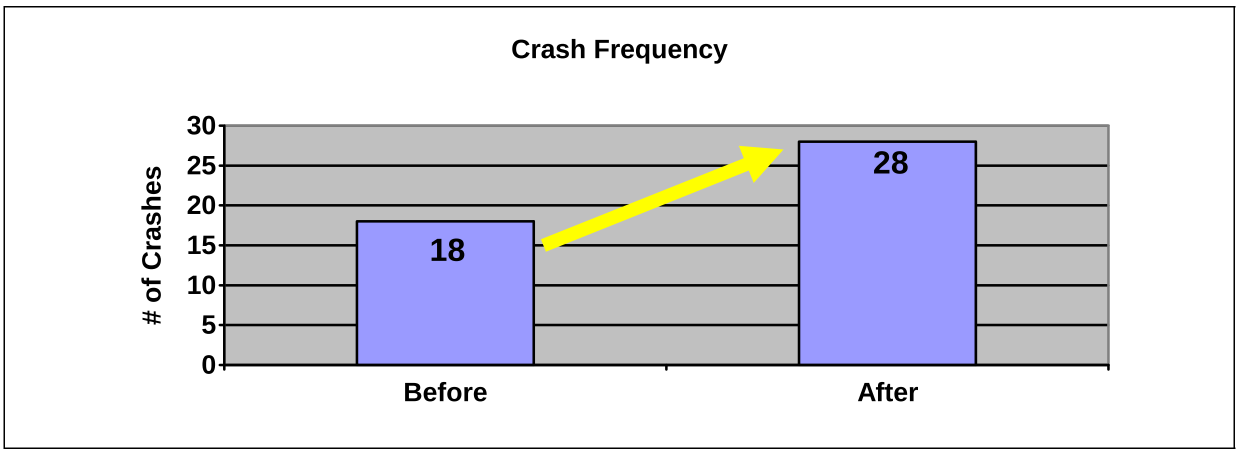


Figure 6-5. IH 20 WB Frontage Road Crash Frequency Before and After Ramp Reversal.

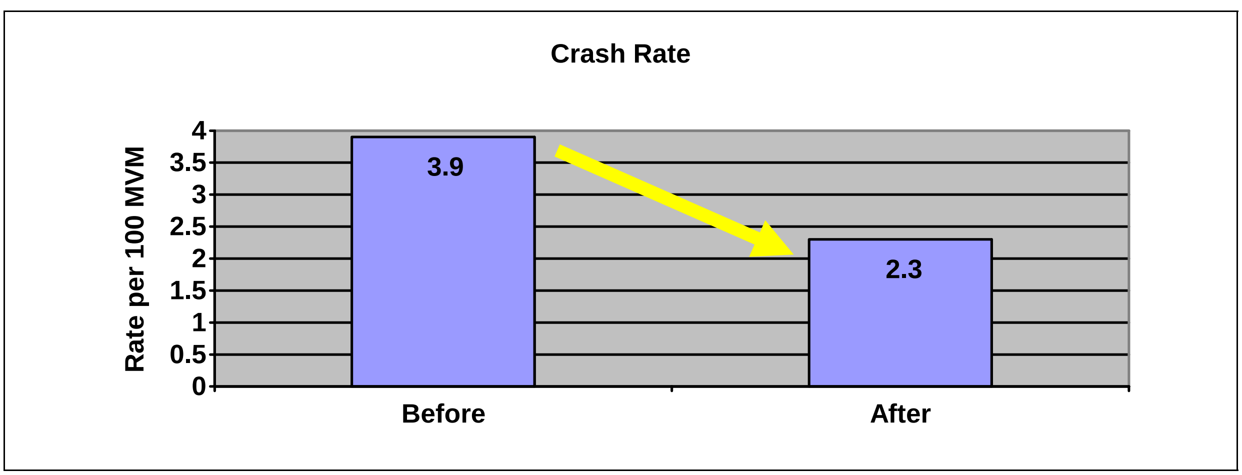


Figure 6-6. IH 20 WB Frontage Road Crash Rate Before and After Ramp Reversal.

Guideline 2: Develop fact sheets, brochures, newsletters, or other media to educate the public and stakeholders of the proposed project.

Researchers formulated Guideline 2 to encourage the use of communications techniques to inform the public and stakeholders of proposed ramp modifications. Fact sheets, brochures, newsletters, or other media can all be used effectively. The following subsections provide some good examples.

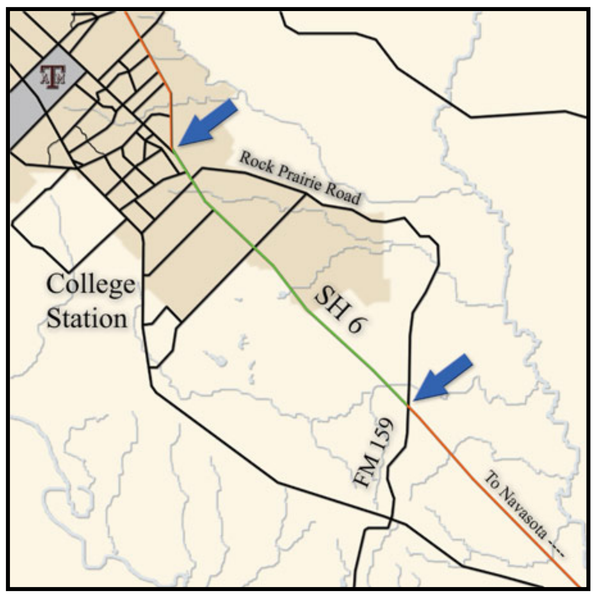
Fact Sheet Example

State Highway 6 Ramp/Frontage Road Improvement Project

Many TxDOT districts make effective use of the Internet for project education and promotion. The Bryan District has produced online fact sheets for three projects that involve ramp reversals. One of the projects, the State Highway 6 Ramp Frontage Road Improvement Project, is a representative example (Figure 6-7) of a concise and informative project fact sheet.

SH 6 (Earl Rudder Freeway) Ramp / Frontage Road Improvements - From Greens Prairie Road to FM 159

Brazos County



The Bryan District is currently developing a project to improve traffic flow within the SH 6 corridor. The improvements will include adjustment or addition of access ramps, conversion of the frontage roads to one-way operation and construction of additional turn-around interchanges. Public meetings were held to assist in determining the preferred improvements.

No new right-of-way acquisition is required for this project.

Construction is anticipated to begin in 2006.

Additional information about this project can be obtained by contacting:

Mr. Robert L. Richardson, P.E.
Bryan District Design Engineer

Phone: 979-778-9727
Fax: 979-778-9702
E-mail: brichar@dot.state.tx.us

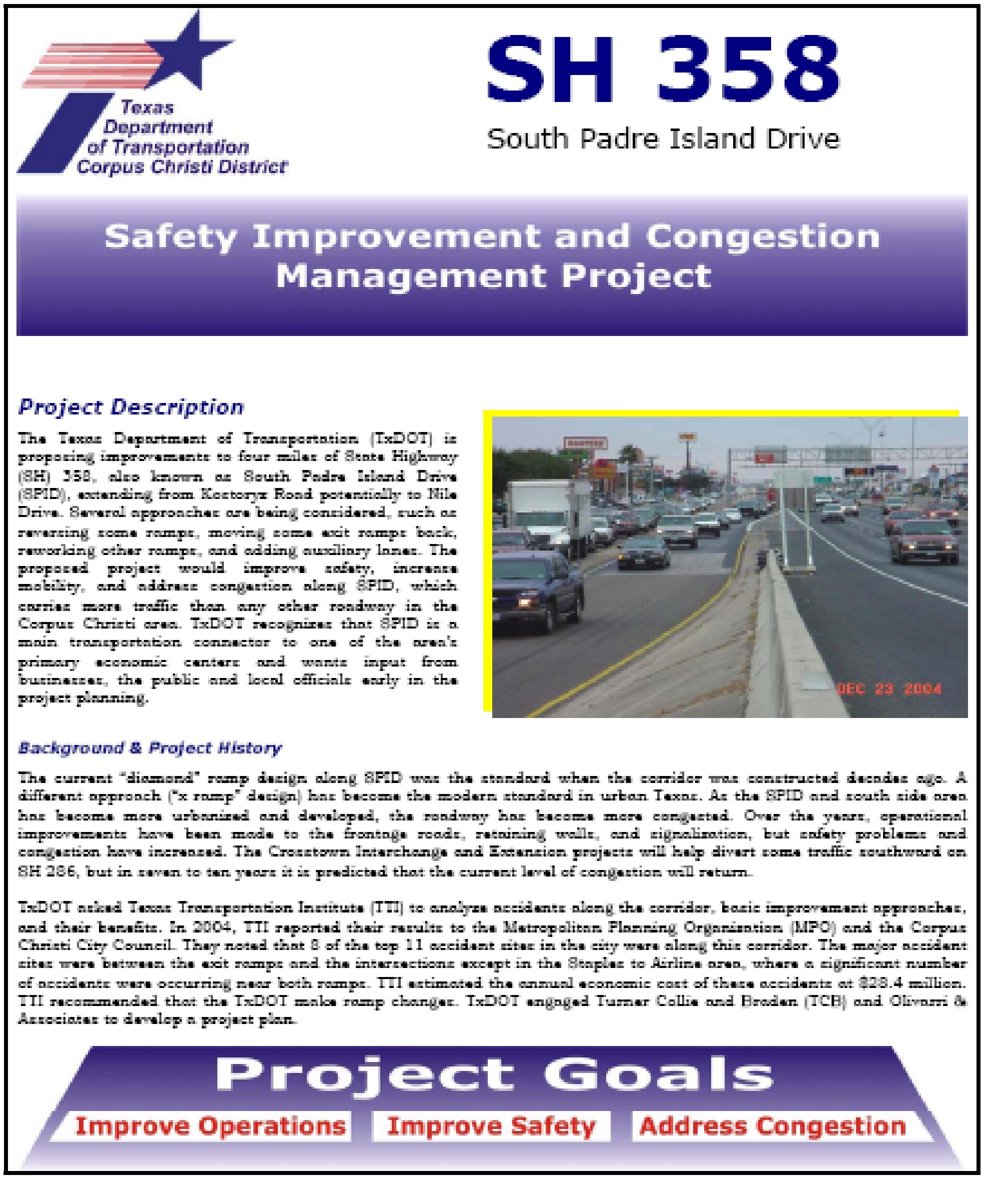
Bryan District Design Office
On Texas Avenue (one block south of SH 21) - In Bryan

Figure 6-7. State Highway 6 Internet Project Fact Sheet (7).

Newsletter Example

State Highway 358 Corridor Project

A project that has done an admirable job of producing high-quality promotion materials is the State Highway 358 Safety Improvement and Congestion Management Project. The Corpus Christi District is promoting proposed improvements on SH 358 (also known as South Padre Island Drive) using newsletters (Figure 6-8), press releases (*8*), presentations (*9*), and other tools.



Texas Department of Transportation Corpus Christi District

SH 358

South Padre Island Drive

Safety Improvement and Congestion Management Project

Project Description

The Texas Department of Transportation (TxDOT) is proposing improvements to four miles of State Highway (SH) 358, also known as South Padre Island Drive (SPID), extending from Kostoryz Road potentially to Nile Drive. Several approaches are being considered, such as reversing some ramps, moving some exit ramps back, reworking other ramps, and adding auxiliary lanes. The proposed project would improve safety, increase mobility, and address congestion along SPID, which carries more traffic than any other roadway in the Corpus Christi area. TxDOT recognizes that SPID is a main transportation connector to one of the area's primary economic centers and wants input from businesses, the public and local officials early in the project planning.

Background & Project History

The current "diamond" ramp design along SPID was the standard when the corridor was constructed decades ago. A different approach ("x ramp" design) has become the modern standard in urban Texas. As the SPID and south side area has become more urbanized and developed, the roadway has become more congested. Over the years, operational improvements have been made to the frontage roads, retaining walls, and signalization, but safety problems and congestion have increased. The Crosstown Interchange and Extension projects will help divert some traffic southward on SH 286, but in seven to ten years it is predicted that the current level of congestion will return.

TxDOT asked Texas Transportation Institute (TTI) to analyze accidents along the corridor, basic improvement approaches, and their benefits. In 2004, TTI reported their results to the Metropolitan Planning Organization (MPO) and the Corpus Christi City Council. They noted that 8 of the top 11 accident sites in the city were along this corridor. The major accident sites were between the exit ramps and the intersections except in the Staples to Airline area, where a significant number of accidents were occurring near both ramps. TTI estimated the annual economic cost of these accidents at $28.4 million. TTI recommended that the TxDOT make ramp changes. TxDOT engaged Turner Collie and Braden (TCB) and Olivarri & Associates to develop a project plan.

Project Goals

Improve Operations | Improve Safety | Address Congestion

Figure 6-8. Example of Effective Project Newsletter (*10*).

Guideline 3: Develop educational and promotional messages consistent with the three access management program themes.

Educational and promotional messages about ramp reversal projects should be consistent with the three themes for successful projects (see Figure 6-2). As previously mentioned, the IH 20 project is a good example of how a media effort prior to construction effectively consistent with each of the three themes – (1) improve safety and mobility, (2) provide reasonable access to developments, and (3) promote local government partnerships.

6.4 ENCOURAGEMENT GUIDELINES

This section documents one guideline in the encouragement category for ramp reversal and X-ramp corridor projects.

Guideline 4: Encourage funding contributions from local government entities and private developers to offset project implementation costs.

Funding Contributions

Guideline 4 indicates that TxDOT should encourage funding contributions to offset project implementation costs. The contributions can be from local government entities (e.g., cities, counties, or metropolitan planning organizations) and/or private developers and can be in the form of money, right-of-way donations, or engineering design. Many of the case study examples documented funding contributions. Positive benefits for TxDOT include reduced project costs to the state and often expedited project delivery. The following subsection highlights examples of some of the funding contributions observed from project case studies throughout the state.

Private Developer Contributions

Researchers found several examples of private developer contributions to ramp reversal projects. A ramp reversal project on eastbound US 190 in Killeen/Harker Heights between FM 3470 and FM 2410 was implemented at a total cost of just under $1 million. The driving force behind this project was the announcement that Wal-Mart would build a Supercenter along the eastbound frontage road. The anticipated increase in traffic caused local officials to consider the benefits of ramp modifications. The project was funded jointly with the following breakdown:

- TxDOT Waco District - $242,000 (discretionary funding);
- City of Harker Heights - $350,000 (advance funding agreement); and
- Wal-Mart - $350,000 (donation agreement).

Half of the ramp reversal projects included in the case study evaluation included some type of funding contribution to aid TxDOT in project implementation.

Guideline 5: Encourage local government entities and business owners to consider access revisions of frontage road driveways as part of the ramp modification project.

Access Revisions
Guideline 5 supports the notion that local government entities and business owners should consider access revisions of frontage road driveways as part of the ramp modification project. A ramp modification project is an opportunity to look at both existing and planned driveway connections along the section of frontage road within the project area. To the extent possible, existing and planned driveways should conform to guidelines contained in the TxDOT *Access Management Manual* (*2*). The ramp reversal project on eastbound US 190 in Killeen/Harker Heights is also a good example of following Guideline 5. In this case, both city officials and business owners agreed to consolidate several existing driveways to achieve proper spacing and to enhance the safety of motorists on the frontage road.

6.5 ENGINEERING GUIDELINES

This section documents five engineering guidelines for ramp reversal and X-ramp corridor projects. The engineering-related guidelines provide direction on design and operational considerations that are important to successful project implementation. These guidelines are the result of a number of important considerations:

- existing standards and guidelines from TxDOT manuals:
  - Roadway Design Manual (*11*),
  - Access Management Manual (*2*),
  - Project Development Process Manual (*12*),
- the state-of-the-practice literature review;
- case study findings;
- project evaluation methodology; and
- the collective judgment and experience of the research team.

Queue Storage

A major safety concern on freeways is traffic flowing at normal speed encountering unexpected slow or stopped traffic ahead. Traffic can queue due to recurrent congestion, work zones, or collisions and/or other incidents. Queue spillback from exit ramps is a common occurrence in urban areas, particularly at locations where there is inadequate storage available to prevent vehicles from stacking onto the main lanes. TxDOT districts indicated that safety issues, namely the existence of or potential for exit ramp spillback, were the number one reason for implementation of previous ramp reversal projects. Figure 6-9 and Figure 6-10 illustrate real-world examples of queue spillback at one of the case study sites on IH 35E in Lewisville.

An example of what can happen when a queue is allowed to spill back onto the freeway main lanes is provided in Figure 6-11. An Internet search about exit ramp spillback produced a link to an article detailing a multi-vehicle collision on the H-1 freeway in Hawaii (*13*). The collision involved a westbound truck on the H-1 freeway losing control and sideswiping multiple vehicles approaching the Makakilo exit ramp. Traffic on this exit ramp frequently queued back onto the freeway during morning and afternoon peak hours. This situation is particularly hazardous because drivers going around a curve at a high rate of speed often do not see the stopped traffic until the last second and sometimes have to quickly stop. The collision involved 11 vehicles and produced 1 fatality and 12 injuries to the vehicle occupants. At the time of the collision, the exit ramp was being renovated partly to prevent queues extending onto the freeway.

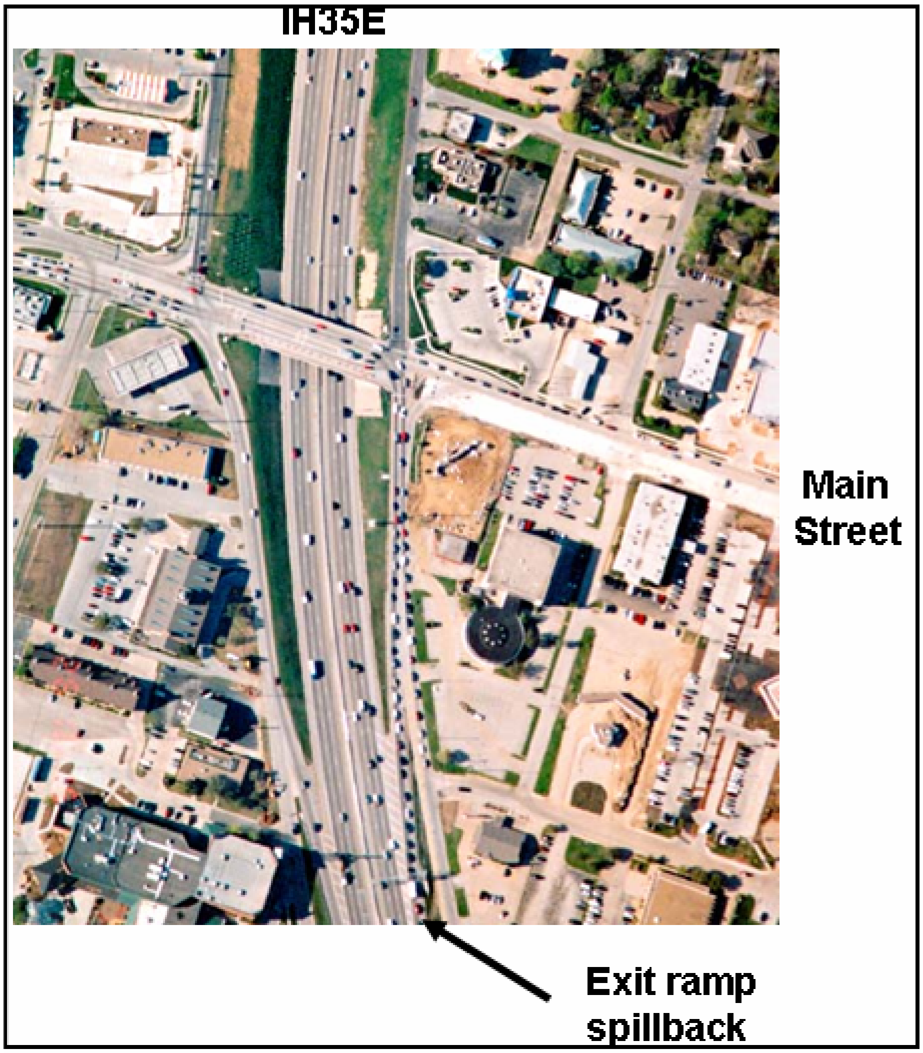


Figure 6-9. Aerial View of Exit Ramp Spillback at Case Study Site 11 (*14*).

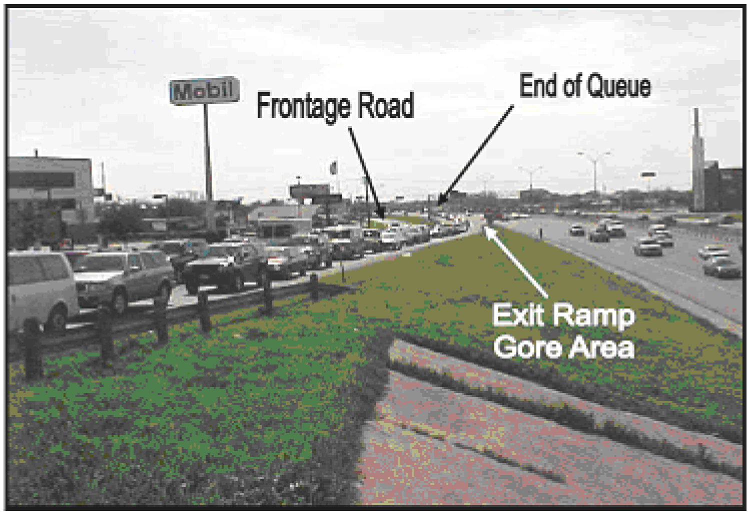


Figure 6-10. Plan View of Exit Ramp Spillback at Case Study Site 11.

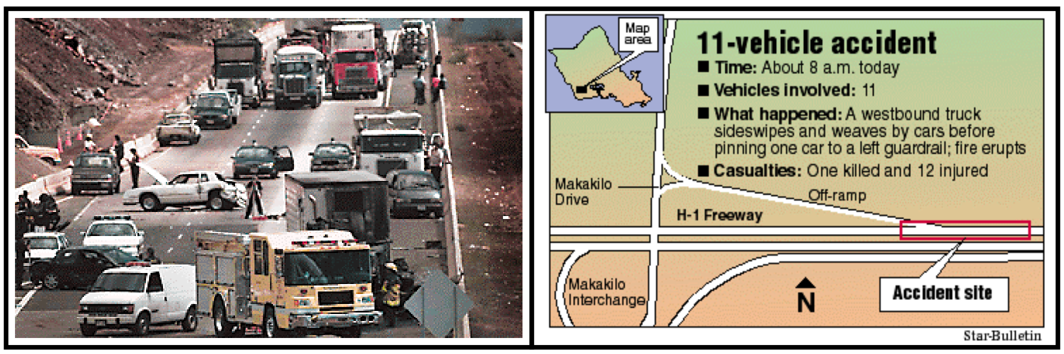


Figure 6-11. Exit Ramp Spillback Incident on H-1 Freeway in Hawaii (*13*).

<u>Guideline 6</u>: Provide adequate storage to prevent vehicles from stacking onto the main lanes.

Researchers developed Guideline 6 to emphasize the need to provide adequate storage to prevent high-speed traffic on the freeway encountering a stack of stationary vehicles from an exit ramp. The TxDOT *Roadway Design Manual* addresses this guideline with desirable spacing between exit ramps, driveways, side streets, or cross streets (*11*). The distance between the exit ramp/frontage road junction and the crossroad is dictated by considerations of queue storage and weaving on the frontage road. Research by Fitzpatrick et al. (*15*) and by Jacobson et al. (*16*) indicates that such distances should range from 300 to 1500 feet (90 to 455 meters) for storage and 300 to 500 feet (90 to 152 meters) for weaving (see Figure 6-12). During the highest demand hours of the day, the weave distance may actually serve as additional queue storage and may prevent spillback onto the freeway.

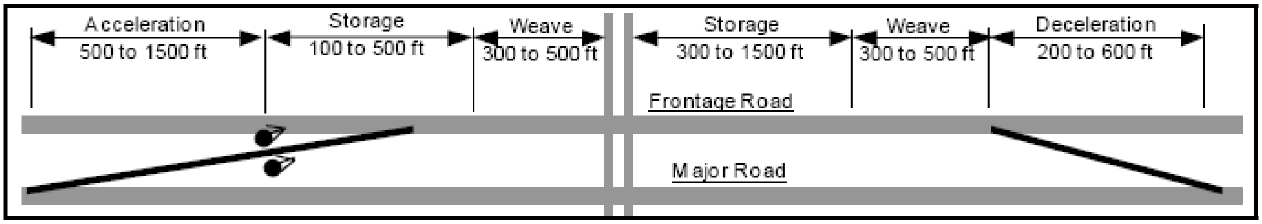


Figure 6-12. Ramp Design Components at Interchanges with Frontage Roads (*17*).

Ramp Spacing

On urban freeways there are frequently two or more ramp terminals in close succession. Provisions of sufficient maneuvering length and adequate space for signing are two key considerations in the determination of ramp spacing. In reality, ramp location and placement are often driven by political, economic, and access considerations rather than engineering standards.

Distance between Successive Ramps

The minimum acceptable distance between ramps depends upon the merge, diverge, and weaving operations that take place between ramps as well as distances required from proper signing. The *Highway Capacity Manual* governs analysis procedures of these requirements (*18*).

Guideline 7: Provide adequate distance between successive ramps to facilitate safety and mobility.

Researchers developed Guideline 7 to reinforce the need to provide adequate spacing between adjacent ramps to facilitate safe and efficient traffic operations. The TxDOT *Roadway Design Manual* addresses this guideline with detailed guidance in a section entitled "Distance Between Successive Ramps" (*11*). The *Roadway Design Manual* provides spacing criteria for four cases that are explained in additional detail in the following subsections.

Case 1 – Entrance Ramp Followed by Exit Ramp

This ramp configuration corresponds to the traditional diamond interchange pattern. For Case 1, the minimum weaving length without an auxiliary lane is recommended as 2000 feet (600 meters) and 1500 feet (450 meters) if an auxiliary lane is present. Figure 6-13 shows Case 1.

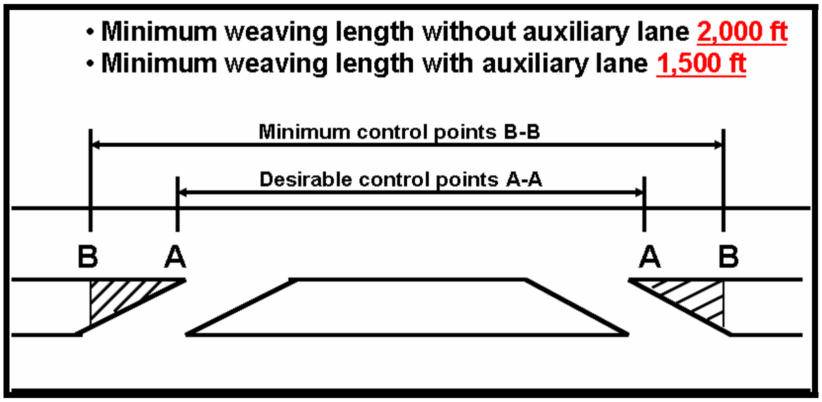


Figure 6-13. Distance between Successive Ramps - Case 1 (*11*).

Case 2 – Exit Ramp Followed by Exit Ramp
Case 2 typically occurs in the field when a diamond pattern is followed by a section where a pair of ramps has been reversed. The minimum distance between consecutive exit ramps is recommended to be 1000 feet (300 meters) (see Figure 6-14).

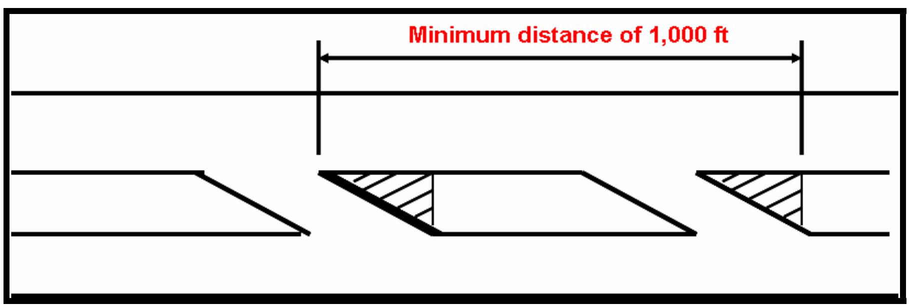


Figure 6-14. Distance between Successive Ramps – Case 2 (11).

Case 3 – Entrance Ramp Followed by Entrance Ramp
This case typically occurs in the field where a pair of ramps that has been reversed is followed by a section with a diamond pattern. The *Roadway Design Manual* states that this situation will be encountered only on infrequent occasions and special design treatment is required (*11*). No minimum or desirable distance is provided in the manual for this case; however, further guidance indicates that an added freeway lane will usually be required and that reference should be made to the AASHTO *Green Book* (*19*) and the *Highway Capacity Manual* (*18*) for more specific information since operational aspects are influenced by traffic volumes and may require longer distances. A minimum distance of 1000 feet (300 meters) is recommended by AASHTO (*19*).

Case 4 – Exit Ramp Followed by Entrance Ramp
Case 4 corresponds to the X-ramp interchange pattern. The *Roadway Design Manual* indicates that the distance between an exit ramp followed by an entrance ramp is governed by the geometrics of the connections to the adjacent roadway or connecting roadway (Figure 6-16). No minimum or desirable distance is provided in the manual for this case; however, the distance is likely to be governed by the desirable spacing between ramps and driveways and/or side streets. The manual does provide the spacing to be used for exit ramps (see Table 6-2 and Figure 6-27)

and entrance ramps to driveways, side streets, or cross streets where practical (Figure 6-28). Based on these spacings, a minimum distance of 800 feet (460 feet exit to driveway + 40 feet driveway + 300 feet driveway to entrance) would be required for Case 4.

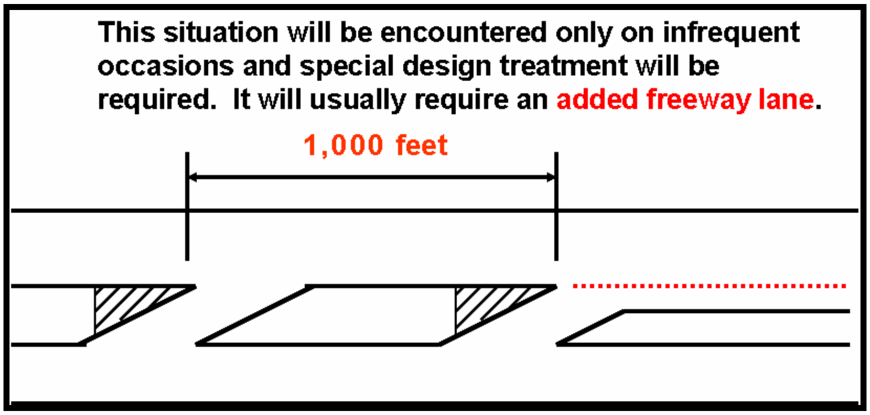


Figure 6-15. Distance between Successive Ramps – Case 3 (*11*).

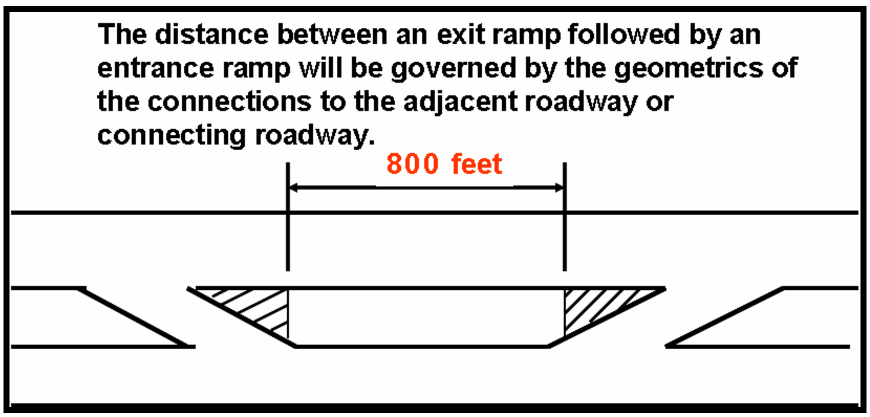


Figure 6-16. Distance between Successive Ramps – Case 4 (*11*).

Table 6-2. Desirable Spacing between Exit Ramps and Driveways, Side Streets, or Cross Streets (*11*).

Total Volume (Frtg rd + Ramp) (vph)	Driveway or Side Street Volume (vph)	Spacing (ft [m]) Number of Weaving Lanes * 2	3	4
< 2500	< 250	460 [140]	460 [140]	560 [170]
	> 250	520 [160]	460 [140]	560 [170]
	> 750	790 [420]	460 [140]	560 [170]
	> 1000	1000 [300]	460 [140]	560 [170]
> 2500	< 250	920 [280]	460 [140]	560 [170]
	> 250	950 [290]	460 [140]	560 [170]
	> 750	1000 [300]	600 [180]	690 [210]
	> 1000	1000 [300]	1000 [300]	1000 [300]

* Number of weaving lanes is defined as the total number of lanes on the frontage road downstream from the ramp

Grade-Separated Ramps

Grade-separated ramps connecting with a frontage road have the potential to eliminate ramp weaving creating main lane congestion and/or to improve access to or from some point on the frontage road in a cost-effective manner (*20*). However, a tradeoff may exist because grade-separated structures located between the freeway main lanes and frontage roads may delay or prevent the addition of exterior freeway lanes to increase the main lane capacity.

When weaving or access problems cannot 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 assessed:

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

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.

Guideline 8: Consider the use of braided ramps when economic, geometric, and operational conditions are favorable.

The research team developed Guideline 8 because grade-separated (also commonly referred to as braided) ramps should be considered when economic, geometric, and operational conditions are favorable. Previous research by the Texas Transportation Institute came up with warrants and analysis procedures to use for selection of specific grade-separated ramp projects (*20*). These procedures were provided in detail in Chapter 5 of this report. Previous guidance indicated that desirably, ramp terminals should be spaced 2500 to 3000 feet apart. Occasionally, closer spacing may be necessary. In these situations, the operational efficiency may be improved by using a continuous auxiliary lane between the entrance and exit terminals. A more expensive alternative for high-volume locations is to provide a grade separation between the two ramps. ***Grade-separated ramps should be considered when the volume on the entrance and exit ramps exceeds 1600 vehicles per hour per lane*** (see section 5.4). The impact of grade-separated ramps on future widening should be considered prior to implementation. Figure 6-17 shows braided ramps in the Houston area. Figure 6-18 is an aerial photograph of braided ramps in Fort Worth.

Figure 6-17. Braided Ramps in Houston, Texas.

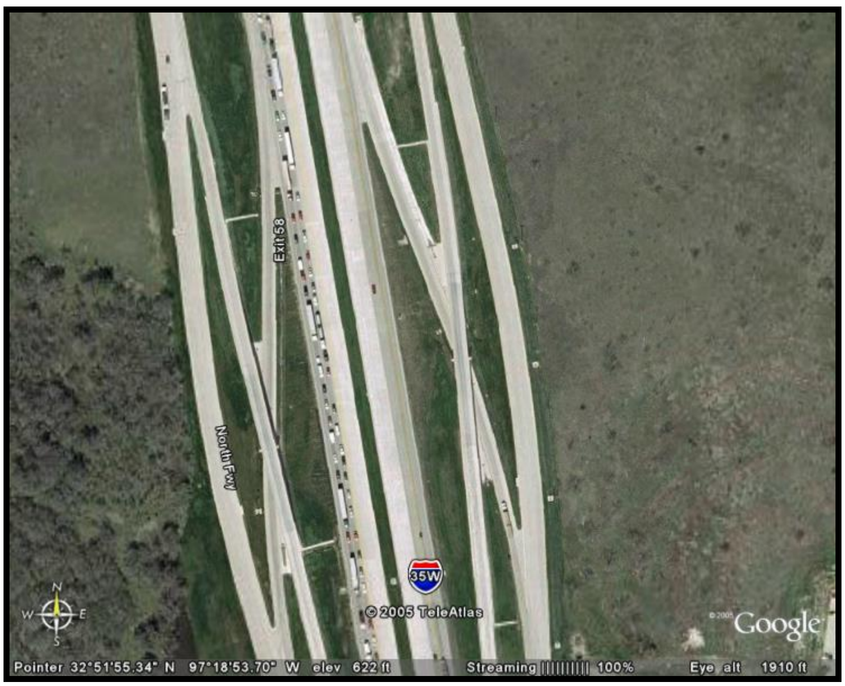


Figure 6-18. Aerial View of Braided Ramps in Fort Worth, Texas (*21*).

Auxiliary Lanes

Auxiliary lanes are an important design feature to accommodate lane balance and operational continuity at strategic locations. The American Association of State Highway and Transportation Officials defines an auxiliary lane as the portion of the roadway adjoining the traveled way for parking, speed change, turning, storage for turning weaving, truck climbing, and other purposes supplementary to through-traffic movements (*19*). In a freeway environment, auxiliary lanes may be provided downstream of an entrance ramp to accommodate merging traffic, upstream of an exit ramp to accommodate diverging traffic, or between two closely spaced interchanges to accommodate weaving traffic. In addition, auxiliary lanes may be carried through one or more interchanges to serve one or more of the listed purposes.

Guideline 9: Provide auxiliary lanes to mitigate merging impacts and provide operational continuity at strategic locations.

The research team focused attention on what situations dictate the need for an auxiliary lane in ramp reversal and X-ramp corridor projects. Researchers developed Guideline 9 to accentuate the need to provide auxiliary lanes to mitigate the potential negative operational impacts of forced merges or lane drops and provide continuity at strategic locations. The presence of any type of merge condition indicates a reduction in capacity. Lanes located downstream of a merge may operate very close to capacity for a short distance downstream of the merge point. This is due to the mixing of two streams into one lane. As the traffic flows downstream, it redistributes to other lanes. The capacity of lanes located upstream of a merge is restricted by the capacity of the merge itself (*20*).

Freeway Auxiliary Lanes

Freeway auxiliary lanes are used extensively throughout the state of Texas (see Figure 6-19 and 6-20). In general, auxiliary lanes on freeways are considered when interchanges are spaced at 1 mile or less. If the spacing exceeds 1 mile, the addition of a freeway lane is not normally considered as an auxiliary lane. As previously outlined, the TxDOT *Roadway Design Manual* provides some guidance on the use of auxiliary lanes on the freeway (*11*):

- the minimum weaving length without an auxiliary lane is recommended as 2000 feet (600 meters) and 1500 feet (450 meters) if an auxiliary lane is present and
- the situation where an entrance ramp is followed by an entrance ramp usually requires an added freeway lane (likely an auxiliary lane to the downstream exit ramp).

Figure 6-19. Freeway Auxiliary Lane.

Figure 6-20. Picture Showing Construction of New Auxiliary Lane on Freeway Main Lanes.

Frontage Road Auxiliary Lanes

The *Access Management Manual* indicates that the most critical area for traffic operations for the X-ramp pattern is between the exit ramp and the subsequent entrance ramp. This area along the frontage road must be closely considered because more traffic will use the exit ramp since a greater distance of frontage road destinations is now available. The addition of auxiliary lanes on frontage roads between the exit ramp and entrance ramp is often part of ramp reversal projects (see Figure 6-21 and 6-22). Further information and guidance about operational analysis on the frontage road will be presented in Guidelines 10, 11, 13, 16, and 21.

Figure 6-21. Picture of Construction of New Frontage Road Auxiliary Lane.

Figure 6-22. Frontage Road Auxiliary Lane.

Guideline 10: Provide adequate capacity on the frontage road to service anticipated traffic demands.

Capacity Considerations

It is important to consider basic capacity, based on an analysis of current and future traffic demand, in an effort to make sure that facility operations are not significantly impacted.

The research team developed Guideline 10 to highlight the importance of providing adequate capacity on the frontage road to service anticipated traffic demands. During the case studies, it became evident that many of the evaluation studies (normally in the form of Interstate Access Justification [IAJ] reports) do not account for capacity considerations on the frontage road. Most IAJ reports do a good job of assessing the required level-of-service on the ramp junctions with the main lanes and any main lane weaving sections. In a ramp reversal situation, weaving shifts to the frontage road, and traffic volumes significantly increase on the frontage road. These factors point to the need to routinely consider and assess frontage road LOS, ***particularly when the frontage road has a two-lane typical cross section*** (see Figure 6-23). One phenomenon that should be considered when a corridor is converted to an X-ramp configuration is the propensity of motorists to perform a slingshot or queue jumping maneuver. Figure 6-24 shows an example of this practice on a north Dallas freeway with X-ramps.

Guideline 11: Adjust signalized intersection operations to account for traffic pattern changes caused by the ramp modifications.

Adjustment of signalized intersection operations in the vicinity of the ramp reversal project is an important activity (Figure 6-25). Several of the case studies and review of previous evaluation studies revealed that volumes on the frontage road at the cross street significantly decrease. This is one of the benefits of X-ramp and ramp reversal projects and it should be taken full advantage of. The agency responsible for the signal timing at affected intersections should adjust the timing to account for the volume shifts caused by the ramp modifications.

Figure 6-23. Two-Lane Frontage Roads Require Careful Capacity Analysis.

Figure 6-24. Queue Jumping on X-Ramp Corridors Should be Expected.

Figure 6-25. Frontage Road Signals Should be Adjusted Following Ramp Modifications.

Construction Planning

An important step in the project development process is the development of phasing and traffic control plans to guide the construction process. TxDOT has spent considerable resources developing methods and procedures for building and maintaining highways faster and cheaper.

> **<u>Guideline 12</u>: Develop construction staging and traffic control plans to minimize the negative impacts of the ramp modification project.**

In view of the importance of motorists' time, the research team developed Guideline 12 to emphasize the need to develop construction staging and traffic control plans that minimize the negative impacts of the ramp modification project. Ramp reversal projects are typically fairly straightforward; however, if frontage road reconstruction is part of the job it can become complex. TxDOT engineers and their consultants should develop construction schedules that expedite project delivery and maintain as high a level of access as possible.

Access Management

Access management is a set of tools used to balance the needs of mobility on a roadway with the needs of access to adjacent land uses. Access management includes not only the physical treatments on the ground, but the policies to implement them as well. Over the past decade, TxDOT has realized the importance of developing a set of access management policies to guide decisions made on a statewide basis. The three themes noted previously in Figure 6-2 provide the consistency on which the entire access management program is based.

Guideline 13: Consider changes to frontage road driveway access to promote safe and efficient operations with the revised ramp locations.

After considering the role of access management in ramp modification projects, the research team developed Guideline 13. This guideline directs TxDOT to consider changes to frontage road driveway access in order to promote safe and efficient operations with the revised ramp locations (Figure 6-26). The TxDOT *Roadway Design Manual* provides clear guidance on how to control frontage road access (*11*). It states that in the case where frontage roads are provided, access should be controlled for operational purposes at ramp junctions with frontage roads through access restrictions or the use of the state's permitting authority to control driveway location and design.

Figure 6-26. Driveway Access Might Need to be Modified Following Ramp Modifications.

Figures 6-27 and 6-28 show recommended access control strategies for planned entrance and exit ramps, respectively, and should be used where practical.

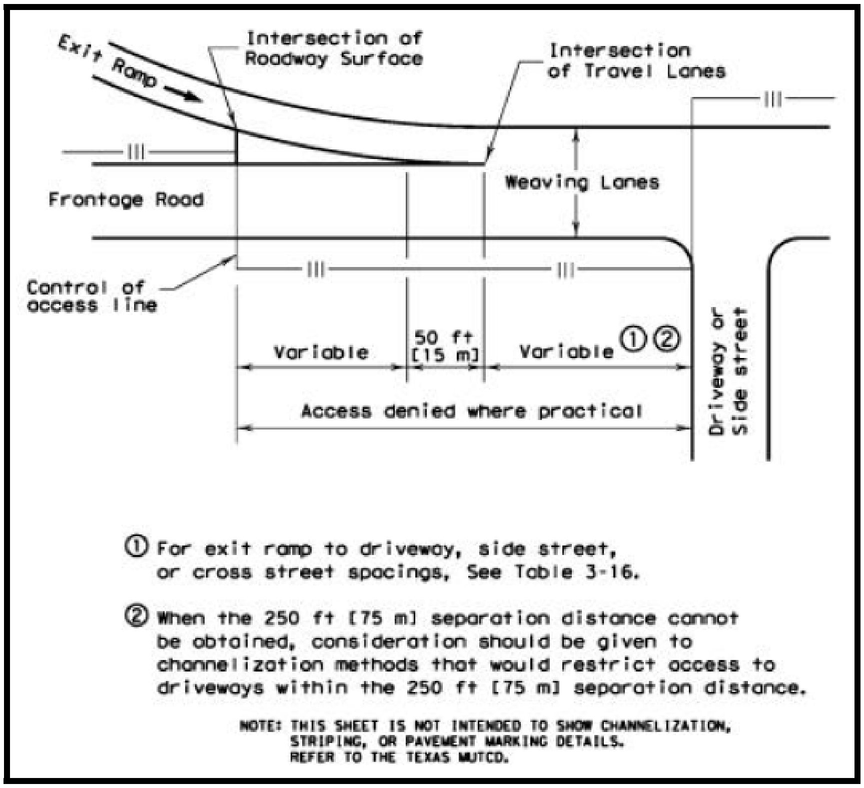


Figure 6-27. Recommended Access Control at Exit Ramp Junction with Frontage Road (*11*).

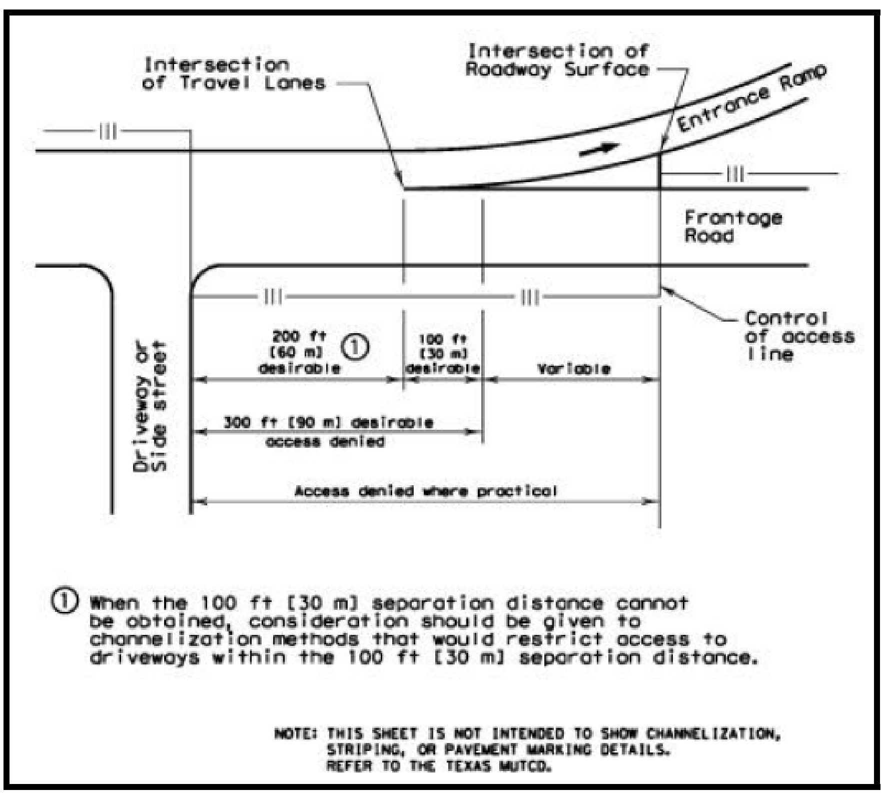


Figure 6-28. Recommended Access Control at Entrance Ramp Junction with Frontage Road (*11*).

Guideline 14: Account for the impacts of revised ramp configuration on access to hospitals and other emergency medical facilities.

The research team developed Guideline 14 based on a lesson learned from one of the sites included in the case study evaluation (see Figure 6-29). Emergency vehicle routing and access are both important considerations for the transportation network because time to treatment is critical in the outcome of medical emergencies. TxDOT staff should account for the impacts of revised ramp configuration on access to hospitals and other emergency medical facilities.

Figure 6-29. Medical Center of Lewisville.

Signing Considerations

Directing motorists to their destination safely and efficiently is the objective of freeway guide signing. Motorists are often creatures of habit and become accustomed to their route being the same as it always has. When a project is constructed that moves the location of freeway ramps, motorists sometimes have a difficult time adjusting.

Guideline 15: Make necessary revisions to guide and wayfinding signing so that motorists can react properly to the ramp modification project.

Similar to the previous guideline, researchers formulated Guideline 15 based on a lesson learned from one of the sites included in the case study evaluation. It is important for TxDOT staff to make necessary revisions to guide and wayfinding signing so that motorists can react properly to the ramp modification project.

Guideline 16: Ramp reversals should be considered when frontage roads are being converted from two-way to one-way operation.

Frontage Road Conversion

The majority of frontage roads in Texas located in urban areas operate as one-way facilities. Some frontage roads located on the urban/suburban fringe still operate with two-way traffic permitted. The TxDOT Design Division has established a policy that outlines conversion of two-way frontage roads to one-way operation when certain conditions are prevalent (*11*). Over the past decade, several districts have been systematically letting projects for frontage road conversion. The case studies and state-of-the-practice literature review both revealed that frontage road conversion is an excellent opportunity to consider other tangential issues such as ramp modifications, u-turn lane additions, and other improvements. Guideline 16 advocates that ramp reversals should be considered when frontage roads are being converted from two-way to one-way operation (see Figure 6-30).

Figure 6-30. Frontage Road Conversion is a Good Opportunity for Ramp Modifications.

6.6 ENFORCEMENT GUIDELINES

This section documents two guidelines in the enforcement category for ramp reversal and X-ramp corridor projects. While it is not necessarily intuitive that there is a relationship between ramp reversals and enforcement, the research team felt that the linkage be acknowledged.

Guideline 17: Coordinate with law enforcement officials for speed enforcement on frontage roads following ramp modifications.

Speed Enforcement and Mitigation

Following ramp reversals, one of the items mentioned anecdotally and also in media accounts was the higher probability for speeding on the frontage road. Since vehicles are on the frontage road a longer distance, the propensity for speeding seems to increase. Knowing this, TxDOT should coordinate with law officials prior to ramp modifications for speed enforcement (Figure 6-31). This is particularly important in the early stages after the project is done.

Figure 6-31. Speed Enforcement is Recommended on Frontage Roads after Ramp Modifications.

Guideline 18: Utilize speed trailers or other speed mitigation techniques to supplement enforcement efforts.

If speeding on the frontage road is identified as a problem, other techniques besides police enforcement might be beneficial. Because police resources for traffic enforcement are limited, TxDOT and local entities could also utilize speed trailers (Figure 6-32) or other speed mitigation techniques to supplement enforcement efforts.

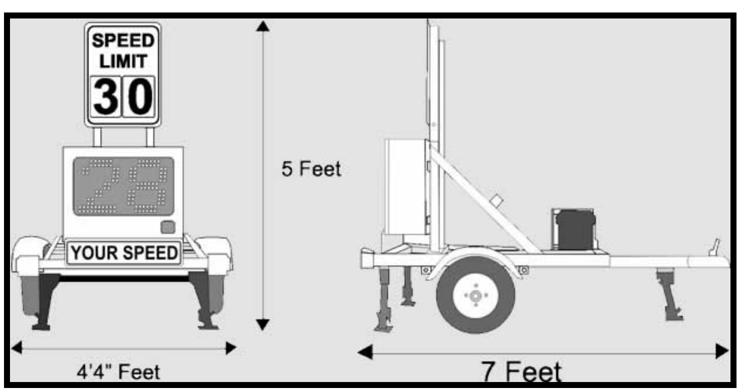


Figure 6-32. Speed Monitoring Trailer.

6.7 EVALUATION GUIDELINES

This section documents three evaluation guidelines for ramp reversal and X-ramp corridor projects. These three guidelines synthesize the essential guidance developed in Chapter 5.

Guideline 19: Utilize traffic simulation models to evaluate and justify complex projects.

Traffic Simulation Models

Simulation models are powerful tools that allow for comparison of project alternatives and evaluation of performance measures. For ramp modification projects, simulation models should be used according to the detailed guidelines provided in Chapter 5. In general, the research team recommends that simulation models be used to evaluate and justify complex projects. It takes a significant amount of time and effort to complete simulation models correctly, so it is not something to use on all projects. Figure 6-33 provides a good example of how simulation model output, in this case a screen capture of peak hour operations approaching a signalized intersection, can visually confirm that real-world conditions can be replicated with good results.

Figure 6-33. Example of Real World vs. VISSIM Model.

Evaluation Studies

The final two guidelines developed by the research team relate to evaluation studies for ramp modification projects. The use of proper techniques for evaluation studies are important because project approval and ultimately project success are dependent on a thorough and accurate evaluation being performed.

Guideline 20: For interstate projects, follow the requirements contained in Section 4 ***Additional Access to the Interstate System*** **of the** ***Roadway Design Manual.***

The TxDOT *Roadway Design Manual* recently added guidance regarding additional access to the interstate system based on coordination with federal authorities. Researchers included Guideline 20 to reinforce the need to consider and follow these requirements, which are applicable to new or revised access points to existing interstate facilities regardless of the funding of the original construction or regardless of the funding of the new access points. The state-of-the-practice literature review revealed additional information produced by other state DOTs with guidance on interstate system access. The FHWA Minnesota Division has prepared a document with some further guidance on the preparation of interstate access requests that is available online (*22*). The Georgia DOT has an online flowchart that outlines the approval process (*23*). Both the Texas and Minnesota guidance is particularly important for interstate ramp reversal projects but could also potentially be applied to evaluation of these projects on state-maintained roadways.

Guideline 21: If evaluation studies are performed prior to project implementation, consider the operational impacts (capacity and level-of-service) on both the freeway main lanes and frontage road facilities.

The research team developed Guideline 21 to highlight the need to consider operational impacts on both the freeway main lanes and frontage road facilities. Although techniques to estimate capacity and LOS on freeways and urban arterials are detailed in the *Highway Capacity Manual* (*18*), these procedures should not be applied directly to frontage roads, as frontage roads have features characteristic of both freeways (i.e., exit and entrance ramps) and urban arterials (i.e., driveways, cross streets, and signalized intersections). The following report was developed to suggest techniques for estimating capacity and level of service on frontage roads (*15*):

> Kay Fitzpatrick, R. Lewis Nowlin, and Angelia H. Parham. *Procedures to Determine Frontage Road Level of Service and Ramp Spacing*. Research Report 1393-4F, Texas Department of Transportation, Texas Transportation Institute, College Station, TX, 1996.

Research Report 1393-4F contains procedures for: (1) determining LOS on a continuous frontage road section; (2) analyzing frontage road weaving sections; and (3) determining spacing requirements for ramp junctions.

The TxDOT *Roadway Design Manual* has adopted this TTI research for evaluation of frontage road capacity and LOS (*11*). Figure 6-34 shows a picture of a frontage road at one of the ramp reversal project case study sites.

Figure 6-34. Evaluation of Frontage Road Operations is Important to Project Success.

6.8 GUIDELINES CHECKLIST

The research team also developed a checklist in Table 6-3 that outlines the 21 guidelines developed as a guide to successful project implementation. The *Guidelines for Successful Implementation of Ramp Reversal and X-Ramp Projects* contained in Table 6-3 are sorted into five major categories: educational (1 – 3); encouragement (4 – 5); engineering (6 – 16); enforcement (17 – 18); and evaluation (19 – 21). This checklist should aid advance project development engineers in planning and implementation of successful ramp reversal and X-ramp corridor projects.

Table 6-3. Checklist of Guidelines for Successful Implementation of Ramp Reversal and X-Ramp Projects.

#	Guideline	√
Educational		
1	Use the local media, department resources, and other innovative techniques to promote projects prior to construction, during construction, after completion, and following evaluation.	
2	Develop fact sheets, brochures, newsletters, or other media to educate the public and stakeholders of the proposed project.	
3	Develop educational and promotional messages consistent with the three access management program themes.	
Encouragement		
4	Encourage funding contributions from local government entities and private developers to offset project implementation costs.	
5	Encourage local government entities and business owners to consider access revisions of frontage road driveways as part of the ramp modification project.	
Engineering		
6	Provide adequate storage to prevent vehicles from stacking onto main lanes.	
7	Provide adequate distance between successive ramps to facilitate safety and mobility.	
8	Consider the use of braided ramps when economic, geometric, and traffic flow conditions are favorable.	
9	Provide auxiliary lanes to mitigate merging impacts and provide operational continuity at strategic locations.	
10	Provide adequate capacity on the frontage road to service anticipated traffic demands.	
11	Adjust signalized intersection operations to account for traffic pattern changes caused by the ramp modifications.	
12	Develop construction staging and traffic control plans to minimize the negative impacts of the ramp modification project.	
13	Consider changes to frontage road driveway access to promote safe and efficient operations with the revised ramp locations.	
14	Account for the impacts of revised ramp configuration on access to hospitals and other emergency medical facilities.	
15	Make necessary revisions to guide and wayfinding signing so that motorists can react properly to the ramp modification project.	
16	Consider ramp reversals when frontage roads are being converted from two-way to one-way operation.	
Enforcement		
17	Coordinate with law enforcement officials for speed enforcement on frontage roads following ramp modifications.	
18	Utilize speed trailers or other speed mitigation techniques to supplement enforcement efforts.	
Evaluation		
19	Utilize traffic simulation models to evaluate and justify complex projects.	
20	For interstate projects, follow the requirements contained in Section 4 *Additional Access to the Interstate System* of the Roadway Design Manual (*11*).	
21	If evaluation studies are performed prior to project implementation, consider the operational impacts (capacity and level-of-service) on both the freeway main lanes and frontage road facilities.	

6.9 WHEN TO CONSIDER REVERSED AND X-RAMP IMPLEMENTATION

This section outlines when to consider the use of reversed and X-ramp interchanges. It is apparent based on the case study evaluations that the operational, safety and basic economic impacts of ramp modification projects such as ramp reversals and X-ramp corridors are primarily positive in nature. Based on this key finding, the research team developed six basic scenarios where the use of reversed and x-ramp interchanges should be considered for implementation. These considerations may include one or more of the following six scenarios:

- At locations where a significant level of existing or planned commercial development is located along the frontage road;
- New construction of a freeway corridor in an urban or suburban setting;
- An existing freeway corridor is undergoing complete reconstruction;
- A lack of adequate spacing between the exit ramp and cross street exists that routinely causes exiting queues to back up onto the freeway main lanes;
- During conversion of frontage roads from two-way to one-way operations; and
- When an evaluation study shows that ramp modifications will significantly improve the overall operational performance and produce a benefit-cost ratio greater than 1.0.

6.10 HOW TO INCORPORATE RESEARCH RESULTS INTO THE ROADWAY DESIGN MANUAL

The final section of this report is dedicated to summarizing how to best incorporate the research results into the TxDOT *Roadway Design Manual* (*11*). Only the most relevant information should be incorporated and it should be clear and concise. The research team believes that three key elements of the 0-5105 research findings should be incorporated into the *Roadway Design Manual* (*11*):

- The five basic scenarios where the use of reversed and x-ramp interchanges should be considered for implementation;
- Further guidance on when to consider the use of grade-separated ramps; and
- A reformatted version of the *Checklist of Guidelines for Successful Implementation of Ramp Reversal and X-Ramp Projects* contained in Table 6-3.

The following subsections provide more specific guidance on how these three key elements can be incorporated into the next edition of the *Roadway Design Manual* (*11*).

Change #1: section entitled Reverse diamond or x-pattern. (Chapter 3, Section 6, pg. 3-86) (*11*)

Existing text – The reverse diamond or "X" interchange pattern (Figure 3 -20 C) has primary application to locations with significant development along the frontage road. It provides access between interchanges and exiting queues do not back up onto the freeway. However, entering vehicles may have to accelerate on an upgrade and exiting maneuvers occur just beyond the crest vertical curve where weaving also takes place. The "X" ramp pattern also encourages frontage road traffic to bypass the frontage road signal and weave with the mainlane traffic. The "X" ramp pattern may cause some drivers to miss an exit located well in advance of the cross street.

Recommended replacement text – Use of the reverse diamond or "X" interchange pattern (Figure 3 -20 C) has primary application when a significant level of existing or planned commercial development is located along the frontage road. Research has shown that the X-pattern ramp configuration typically has better operational performance in medium to high average daily traffic corridors, reduces overall crash rates, and improves basic economic indicators such as sales tax receipts, property values and new business development. Other times to consider application of ramp reversal or X-pattern are when: (1) there is new construction of a freeway corridor in an urban or suburban setting; (2) an existing freeway corridor is undergoing complete reconstruction; (3) a lack of adequate spacing between the exit ramp and cross street routinely causes exiting queues to back up onto the freeway main lanes; (4) frontage roads are being converted from two-way to one-way traffic operation; and (5) when an evaluation study shows that ramp modifications will significantly improve the overall operational performance. Key considerations for successful implementation of reverse diamond or X-pattern interchanges are contained in the *Checklist of Guidelines for Successful Implementation of Ramp Reversal and X-Ramp Projects* in Table 6-4.

There are several design and operational issues with this type of interchange including the case where entering vehicles may have to accelerate on an upgrade and exiting maneuvers occur just beyond the crest vertical curve where weaving also takes place. The "X" ramp pattern also encourages frontage road traffic to bypass the frontage road signal and weave with the main lane traffic. The "X" ramp pattern may cause some drivers to miss an exit located well in advance of the cross street.

Change #2: section entitled Stacked diamond. (Chapter 3, Section 6, pg. 3-86) (*11*)

Existing text **–** Sometimes access to and from the mainlanes is needed on two closely spaced cross streets. Insufficient distance for consecutive entrance and exit ramps can be resolved by using grade-separated ramps, resulting in a "stacked diamond" (Figure 3-20 E).

Recommended replacement text – Sometimes access to and from the main lanes is needed on two closely spaced cross streets. Insufficient distance for consecutive entrance and exit ramps can be resolved by using grade-separated ramps, resulting in a "stacked diamond" (Figure 3-20 E). When weaving or access problems cannot be solved at-grade by ramp elimination or relocation, grade-separated ramps merit consideration. Grade-separated ramps, commonly referred to as braided ramps, should be considered when they have the potential to eliminate ramp weaving creating main lane congestion and/or to improve access to or from some point on the frontage road in a cost-effective manner. Research in Texas has developed a rule-of-thumb that grade-separated ramps should be considered when traffic volumes on both the entrance and exit ramp pair exceed 1600 vehicles per hour. One other important consideration is having an outer separation distance at least 63 feet in width to allow for the grade-separated ramp to operate efficiently.

Table 6-4. Checklist of Guidelines for Successful Implementation of Ramp Reversal and X-Ramp Projects for Roadway Design Manual .

#	Guideline	√
Educational		
1	Use the local media, department resources, and other innovative techniques to promote projects prior to construction, during construction, after completion, and following evaluation.	
2	Develop fact sheets, brochures, newsletters, or other media to educate the public and stakeholders of the proposed project.	
3	Develop educational and promotional messages consistent with the three access management program themes.	
Encouragement		
4	Encourage funding contributions from local government entities and private developers to offset project implementation costs.	
5	Encourage local government entities and business owners to consider access revisions of frontage road driveways as part of the ramp modification project.	
Engineering		
6	Provide adequate storage to prevent vehicles from stacking onto main lanes (Table 3-16).	
7	Provide adequate distance between successive ramps to facilitate safety and mobility (Figure 3-37).	
8	Consider the use of braided ramps when economic, geometric, and traffic flow conditions are favorable (Chapter 3, Section 6).	
9	Provide auxiliary lanes to mitigate merging impacts and provide operational continuity at strategic locations (Figure 3-37).	
10	Provide adequate capacity on the frontage road to service anticipated traffic demands (Chapter 3 – Section 6).	
11	Adjust signalized intersection operations to account for traffic pattern changes caused by the ramp modifications.	
12	Develop construction staging and traffic control plans to minimize the negative impacts of the ramp modification project.	
13	Consider changes to frontage road driveway access to promote safe and efficient operations with the revised ramp locations (Figure 3-13 and Figure 3-14).	
14	Account for the impacts of revised ramp configuration on access to hospitals and other emergency medical facilities.	
15	Make necessary revisions to guide and wayfinding signing so that motorists can react properly to the ramp modification project.	
16	Consider ramp reversals when frontage roads are being converted from two-way to one-way operation (Chapter 3, Section 6).	
Enforcement		
17	Coordinate with law enforcement officials for speed enforcement on frontage roads following ramp modifications.	
18	Utilize speed trailers or other speed mitigation techniques to supplement enforcement efforts.	
Evaluation		
19	Utilize traffic simulation models to evaluate and justify complex projects.	
20	For interstate projects, follow the requirements contained in Section 4 *Additional Access to the Interstate System* of the Roadway Design Manual.	
21	If evaluation studies are performed prior to project implementation, consider the operational impacts (capacity and level-of-service) on both the freeway main lanes and frontage road facilities.	

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