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16. Abstract

Freeway bottlenecks are a primary source of congestion, and the removal of several bottlenecks in Dallas has shown a favorable reduction in delay. Solving a freeway bottleneck can be highly complex, and existing analytical tools have been inadequate for congested conditions. Driving behaviors in congestion were observed at several sites on freeways in Dallas and include queue jumping, weaving in congestion, and shoulder driving. These observations have furthered the understanding of freeway operations in congestion.

A survey of what other agencies are using to simulate congested freeway operations showed that FRESIM is the most widely used simulation tool. Several adaptations to the use of FRESIM were identified and tested. These refinements to the application of the FRESIM model allow for better analysis of congestion and bottleneck improvements.

Assessing the benefit a bottleneck removal provides to the motorists remains incomplete. In cases where the bottleneck is simple and well-defined, benefits may be fairly easy to estimate. However, the benefits to motorists are not always obvious. This research enhances the reliability of bottleneck improvement benefits by identifying options to the traditional methodology for assessing benefits.

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HIGHWAY PLANNING AND OPERATIONS FOR THE DALLAS DISTRICT: FREEWAY OPERATIONS UNDER CONGESTED CONDITIONS

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Freeway Operations under Congested Conditions

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IMPLEMENTATION RECOMMENDATIONS

This study was sponsored by the Texas Department of Transportation (TxDOT) because the current era of limited funding for transportation improvements has focused attention on the need to manage transportation systems more efficiently. Freeway bottlenecks are a primary source of congestion, and the removal of several bottlenecks in Dallas have shown a favorable reduction in delay. Solving a freeway bottleneck can be highly complex, and existing analytical tools have been inadequate for congested conditions. The first of three areas of research undertaken to enhance our understanding and approach to bottleneck improvements was the observation of driving behaviors in congestion. The second area of research was to refine the analytical methodology used to evaluate bottlenecks, and the third area was to improve the methodology used to estimate benefits due to bottleneck improvements.

1. Driving behaviors in congestion were observed at several sites on freeways in the Dallas District. Driving behaviors observed include queue jumping, weaving in congestion, and shoulder driving. These observations have furthered our understanding of freeway operations in congested urban areas in Texas and could lead to improved methods for providing construction and maintenance traffic control, as well as refining bottleneck improvements.

    a. Long queue jumps (e.g., Loop 12 and Singleton) have a negative impact on overall throughput and should be actively discouraged through design or operational means.

    b. Unavoidable lane closures, such as those found during pavement rehabilitation on LBJ IH635, should be signed to delay the vacating of the closing lane until the last moment, to maximize throughput.

    c. Weaving in congestion appears to be easier and have higher capacity than high speed weaves, as shown on southbound IH35E near downtown.

    d. Shoulder driving is aggressive driving behavior and should be actively discouraged both by occasional enforcement and by installing rumble strips or raised traffic bumps along shoulders.

2. Traditional tools have proven inadequate for analysis of congestion or bottleneck improvements. A means to simulate congestion is needed by transportation professionals. A survey of what other agencies are using to simulate congested freeway operations showed that FRESIM is the most widely used simulation tool. Several adaptations to the use of FRESIM were identified and tested, and these refinements allow for better analysis of congestion and bottleneck improvements.

    a. Collection of adequate geometry and volume data should be conducted if quality simulation results are expected.

b. It is important to use some method of achieving model outputs for a base case that reasonably match the existing conditions.

c. It appears that a reasonable approach for "calibrating" the model to congested existing operations is by overloading the network (since recorded volumes will be constrained) and allowing the model to react to the excess demand. A proposed methodology for overloading the model is to scale recorded volumes up to a point where the network is saturated (e.g., in 10 percent increments).

d. At the current level of development, FRESIM does not appear to be adequately reliable for estimating absolute future benefits for a freeway bottleneck removal project. However, the use of FRESIM as a simulation tool in bottleneck analysis is reasonable for use in the selection of the best alternative.

3. The ability to fully assess the benefit that bottleneck removal provides to the motorists remains incomplete. In some cases, benefits due to reduction in delay can be estimated as an increase in speed. However, in cases where significant latent demand is present in the system, the benefits to motorists are not as easily measured. Speeds may not increase, but higher volumes indicate that diversion from less attractive routes is occurring. It is seldom possible to fully quantify these benefits. This research enhances the reliability of benefit estimates by identifying options to the traditional methodology for assessing benefits.

a. "Before" data need to be collected beginning outside the region of congestion, both temporal and spatial.

b. Speed and volume data on alternate routes should be collected.

c. "After" data should be collected the same way as "before" data.

d. Increased volumes should be assessed with benefits based on the average speed of the alternate routes.

e. Original volumes should be assessed with benefits based on speed increases or decreases.

f. Throughput increases (i.e., the product of volume and speed) should be identified, even if monetary benefits cannot be estimated.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge was Carol H. Walters, P.E. #51154.

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I. INTRODUCTION

Limited funding for transportation improvements has focused attention on the need to manage transportation systems more efficiently. Of increasing importance is the ability to maximize the efficiency of the existing freeway system, especially with regard to reduction of congestion in areas of air quality non-attainment, such as Dallas. One of the primary sources of freeway congestion are bottlenecks in the freeway system. Numerous bottleneck removal projects have been implemented in the Dallas district, and initial before-and-after studies have indicated a favorable reduction in delay and an increase in efficiency of roadway usage.

Freeway bottlenecks are wasteful of existing capacity in that traffic is prevented from fully utilizing downstream capacity and is subjected to delays and potentially hazardous congestion. It is generally believed that about half of urban congestion is recurrent, and much of that is due to freeway bottlenecks. The other half of urban congestion is due to incidents and is being addressed by a wide variety of ITS programs; however, little attention is currently being paid to finding low cost solutions that might alleviate a substantial portion of recurrent delay. Large reconstruction projects are not always required to make a major difference in recurrent congestion. Rather, detective work and precise analytical methods can often be applied to solve the underlying problems at freeway bottlenecks, and the results can be significant with the expenditure of little money or even the need for public involvement. However, this detective work is highly complex, and existing analytical tools have been inadequate for congested conditions.

Freeway bottleneck improvement projects in Dallas have resulted in measured benefits that exceed cost by 25:1. However, for some bottleneck improvements, the benefits to freeway traffic are difficult to identify because of the limitations of our tools. The most direct method of estimating benefits is from travel time savings. However, if there is no significant change in travel time, despite an increase in volume, there are no estimated benefits. Other factors may also affect the expected benefits, such as hidden downstream bottlenecks or complex weaving movements. A bottleneck improvement may also allow drivers to change their route or trip start times with uncertain effects on the flow of traffic.

DRIVER BEHAVIOR UNDER CONGESTED CONDITIONS

The objectives of this research area are to provide additional evaluation of driver behavior under congested conditions and to further our understanding of freeway operations in congested urban areas in Texas. Researchers observed congested traffic operations at several sites on freeways in the Dallas district. Operations and aberrant driving behaviors at each site were videotaped to obtain volume and movement data. Additional data, such as travel time runs and accident analysis, were obtained where needed. The analysis attempted to identify patterns in driver behavior that may create inefficiencies or hazards in the flow of traffic that may be corrected or avoided through design changes or by different signing, markings, or other traffic control devices.

Some aberrant driver behaviors appear to yield beneficial effects by increasing the capacity or reducing the delay for some drivers without impacting the remaining traffic flow. The results of this research allow for better design of future freeways and a better understanding of congested conditions for improvements on existing freeways for merging and diverging areas, weaving areas, lane drops, and construction zones.

ANALYTIC METHODS USED IN BOTTLENECK ANALYSIS

Traditional tools, such as the Highway Capacity Manual (HCM) and the Highway Capacity Software (HCS), have proven to be inadequate for use in simulating or examining congested conditions on freeways. In many cases, freeways are operating in congested conditions throughout much of the work day. Although engineering judgement and experience are essential in finding potential solutions to freeway flow breakdown, fiscal constraints demand an analysis and justification of the most elementary solutions. Further, major freeway reconstruction in the future (e.g., IH635, LBJ Freeway) will require analysis in terms of congested flow with multiple alternatives. The problem faced by the transportation professional is that it is difficult to model or simulate freeway congestion, and there is a need for examining and calibrating freeway simulation to identify which is best-suited for analyzing congested Dallas freeways.

The primary objective of this area of research is to refine analytic methods used in bottleneck analysis or analysis of congested freeways. Researchers contacted the distributors of simulation software, public agencies, and consultants to determine what others are using to simulate congested freeway operations. FRESIM, a microscopic freeway simulation model, was found to be most widely used for analysis of congestion. Several adaptations to FRESIM were identified and tested with data collected before and after bottleneck improvement projects to better calibrate the model for congested operations.

RELIABILITY OF BENEFIT ESTIMATES FOR BOTTLENECK IMPROVEMENTS

Following the development of analytic methods for bottleneck improvements is the problem of assessing the benefit bottleneck removal provides to the motorists. In some cases, benefits due to reduction in delay can be estimated as speeds increase. However, in cases where significant latent demand is present in the system, speeds may not increase, although volumes do; in this case, the benefits to motorists are more difficult to quantify. In some cases, the benefit may be improving flow for one ramp approach or simply providing capacity for motorists who are stuck in queues. Speeds, in these cases, may not increase significantly, if at all, and the benefits must be estimated using some other method. Another option for these cases might be to recognize from volume and speed data that the system benefits from the improvement, but that a monetary benefit might not be possible to estimate. These are the options and questions addressed in this section of the report.

II. REVIEW OF PREVIOUS WORK

DESIGNING FOR CONGESTION

The TTI Research Report 1483-1F, "Planning for Optimal Roadway Operations in the Design Year" (2), examined the need for designing for congestion for future freeways. In the past, TxDOT has designed highways for freeflow conditions using the 30th highest hourly volume (HHV) for estimating future volumes. However, future designs in urban areas will not be able to satisfy peak hour demands, and a more constrained approach of accepting congestion will be necessary. Designers must consider congestion as a factor in the design of future freeways. Among the recommendations for designing for congestion from the 1483 report are to maintain uniformity in design, to optimize traffic flow under congested conditions with operational aids, to provide access to alternative routes, and to use flexible freeway designs.

Locations where vehicles interact on freeways, such as at merging, diverging, or weaving areas, are often the sites of congestion. The standard designs for freeway elements as recommended by AASHTO operate adequately for most congested conditions. However, some elements are preferred and appear to provide a more orderly flow of traffic. For example, the parallel design single-lane entrance ramp is slightly preferred over the taper design because of the narrow lane width and its compatibility with the introduction of an auxiliary lane.

Examples of the different types of design elements were observed in congestion as part of the 1483 project, and this project has extended the research begun with the 1483 project. The observation of the design elements revealed that much of the behavior exhibited by drivers is more a result of the congestion rather than a typical design element. Common behaviors observed to occur include queue jumping, weaving or frequent lane changing in congestion, shoulder driving, and gore crossing.

- Queue jumping is defined as the bypassing of a queue of vehicles in the through lanes by one or more vehicles from an adjacent lane by waiting to merge into the through lanes at the last possible point. Queue jumping most commonly occurs at lane reductions and is particularly severe approaching work zones where there is a reduction in through lanes, though it has been seen to occur at other design elements, such as exit-only lanes, major forks, and some entrance ramps.

- Weaving areas are locations or elements where recurrent congestion seems to begin or is more problematic and where frequent lane changing is seen when congested. Weaving areas occur wherever entering and exiting vehicles cross paths – most commonly between entrance and exit ramps connected by an auxiliary lane on the right side of the through lanes. Double-sided weaves may occur where vehicles must weave across the through movement to or from a left side entrance or exit.

- Driving on an available shoulder to bypass slower or queued traffic often occurs in conjunction with queue jumping at lane reductions or entrance ramps and with congestion in weaving areas. Shoulder driving most commonly occurs when a driver slows to merge into through traffic, and following vehicles bypass the merging vehicle on the shoulder to merge or exit further downstream.

- Crossing a gore area to bypass slower or queued traffic occurs frequently at congested ramps, most commonly at congested entrance ramps. Vehicles crossing the gore take available gaps in the through traffic lanes from vehicles attempting to merge properly. Both entering and exiting vehicles may weave across the gore approaching congested weaving areas. Gore crossing also occurs in conjunction with queue jumping at congested exits or diverges.

ASSESSING BOTTLENECK IMPROVEMENTS

The TTI Research Report 1232-17 (1), developed through the State Funded Research (SFR) program in the Dallas district, addressed the methods that have been used to assess the feasibility of bottleneck improvement projects. The primary benefit for bottleneck improvements was assumed to be a reduction in delay to the previously congested traffic. Other benefits in emission reductions, reduced fuel consumption, and fewer incidents were also assumed, but the benefits for these factors are usually not estimated since travel time savings are usually more than enough to justify economic feasibility of a project.

The report noted two complications to assessing potential benefits of any bottleneck improvement project. First, there is difficulty estimating improved speeds due to downstream congestion or hidden bottlenecks downstream or within the queue of congested traffic. If a weave is involved, the HCM procedures will define expected speeds for weaving and non-weaving vehicles. The HCM may also be useful in identifying problematic ramps or weaving areas which may be hidden bottlenecks. Second, there may not be an improvement in travel time but an increase in traffic volume. Where the additional traffic comes from is often uncertain and, therefore, difficult to determine a travel time savings for the additional traffic.

III. DRIVER BEHAVIOR UNDER CONGESTED CONDITIONS

The objectives of this research area are to provide additional evaluation of driver behavior under congested conditions and to further our understanding of freeway operations in congested urban areas in Texas. TTI observed congested traffic operations at several sites on freeways in the Dallas district. The analysis attempted to identify patterns in driver behavior that may create inefficiencies or hazards in the flow of traffic that may be corrected or avoided through design changes or by different signing, markings, or other traffic control devices.

STUDY SITES AND DATA COLLECTION

TTI selected 12 sites for observation of aberrant driving behavior. Researchers selected the sites primarily because recurrent congestion was known to occur at these locations. Analysis of two locations was discontinued due to the fact there was no suitable location to view the driving behavior through the site. Table 1 lists all 12 study sites and gives a brief description of each site and what sort of driving behavior was observed. Figure 1 shows the locations of the study sites.

Researchers used videotape to collect data at each site. Depending on the view through the video camera, a number of different types of data can be collected. TTI counted traffic volumes and the number of aberrant driving maneuvers at each site where suitable video was obtained. Other traffic characteristics can also be taken from the video, such as the density of vehicles, travel time of vehicles, and an estimate of vehicle speed. Other methods of counting volumes, such as manual counts or use of automatic counters, or estimating speeds with the use of travel time runs with distance measuring instruments, were also used when needed to complete the analysis of a site. TTI also used data collected as parts of earlier studies for some of the sites. TTI performed an accident analysis of five of the study sites. At the other sites, such as Site 5 (the ramp connection from eastbound IH30 to northbound IH35E), it was felt that it would be difficult to determine whether or not an accident could be associated with the movement being observed, and no accident analysis was performed at these locations.

Table 1. Driver Behavior in Congestion Site Summary

Site Locations		Type of Facility	When Congested	Videotape Location	Type of Driver Behavior Observed
1	SB IH35E and EB SH183	Branch connection with inside merge	AM	Video from nearby building	Driver lane choice at inside merge and weaving
2	WB Woodall Rodgers across SB IH35E to WB IH30	Double sided weave	PM	Video from bridge and Courts garage	Weaving in congestion
3	NB SRLT IH35E to NB Stemmons IH35E & EB ERLT IH30	Major fork without option lane	AM	Video from diverge gore behind barrier	Queue jumping across gore
4	NB Stemmons IH35E Exit ramp to NB DNT	Tapered exit ramp	AM & PM	PM video from Reunion Tower	Exiting queue in outside lane - speed differential
5	EB IH30 to NB Stemmons IH35E	Non-standard entrance ramp	AM	AM video from Reunion Tower	Queue jumping and shoulder driving
6	Singleton Entrance Ramp to NB Loop 12	Tapered entrance ramp	AM	Video from shoulder north of ramp	Queue jumping, entering across gore, and shoulder driving
7	EB LBJ IH635 at Stemmons IH35E	Lane Drop	AM & PM	No location identified	Queue jumping
8	WB LBJ IH635 Exit to SB US75 and Coit Road	Left hand exit-only lane	AM	Video from TI bridge	Queue jumping and weaving across double white line
9	Hillcrest Entrance Ramp to WB LBJ IH635	Tapered entrance ramp followed by exit	PM	View from Preston Road unsuitable	Bypassing queue on X-ramps
10	Red Bird Entrance Ramp to SB US67	Tapered entrance ramp followed by exit	PM	Video from Red Bird Lane	Entering across gore and shoulder driving
11	EB IH30 and NB IH35E	Branch connection with inside merge	PM	Video from Hotel St.	Driver lane choice at inside merge
12	WB LBJ IH635 DNT Entrance to Midway Road Exit	Type A weaving section	AM & PM	Video from Welch	Weaving in congestion and shoulder driving

Note: Sites 7 and 9 were not studied due to unsuitable locations for videotaping.

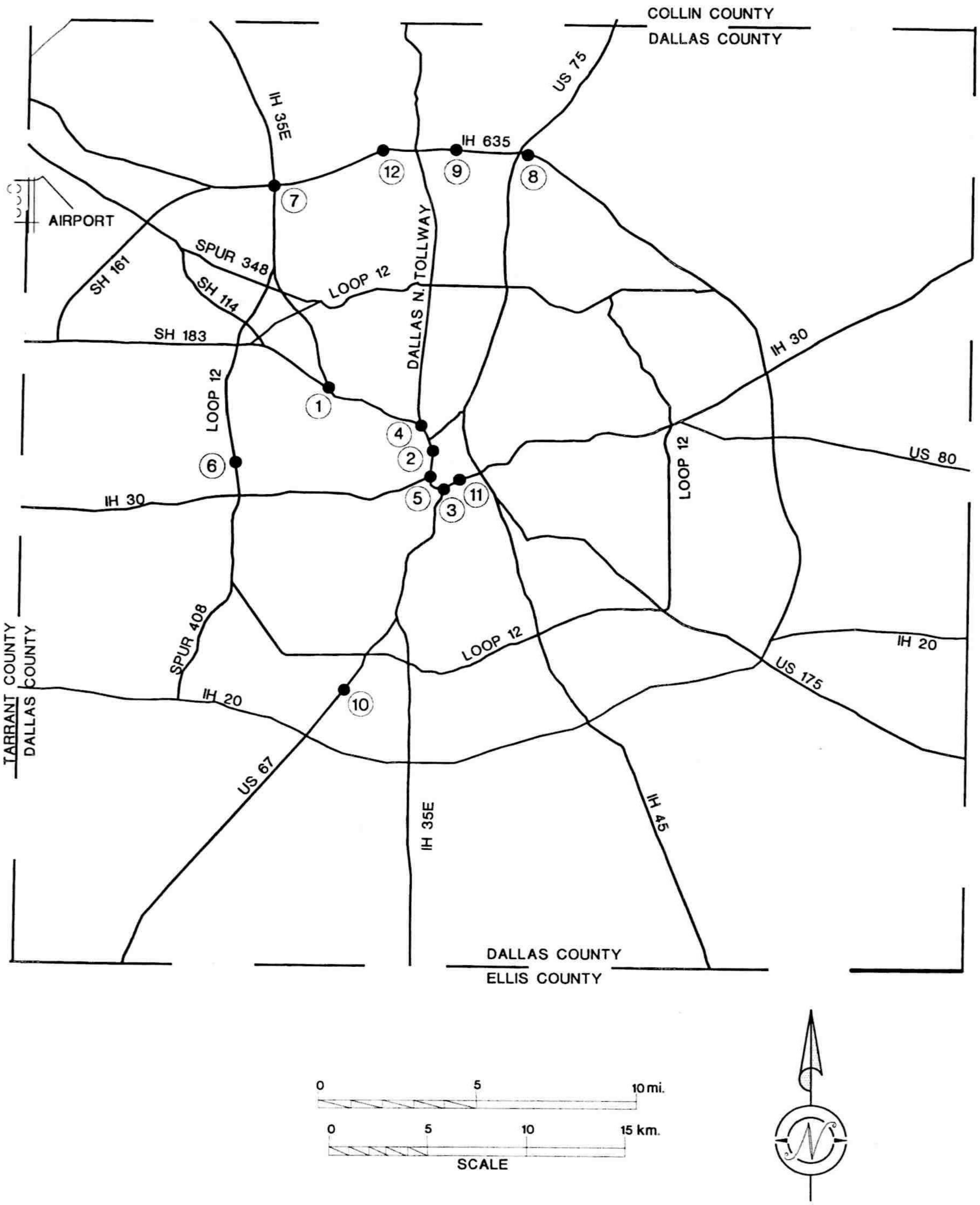


Figure 1. Location of Study Sites

Site 1: The branch connection of southbound IH35E Stemmons and eastbound SH183

IH35E and SH183 are three lanes each approaching the connection and continue beyond the merge as five lanes. The outside lane of IH35E and the inside lane of SH183 continue as the middle lane after the merge. The SH183 approach peaks in the morning. The IH35E approach peaks in the evening; however, the overall peak is in the morning. TTI performed an operational analysis at this location in December of 1992. Data from the 1992 study as well as additional data collected from videotapes were used to examine driver behavior. At Site 1, TTI observed driver lane choice approaching the merge and weaving in congestion from IH35E to the first downstream exit to Commonwealth. From the video, TTI counted each lane prior to the merge and downstream of the merge, and counted the number of vehicles weaving from IH35E to Commonwealth. TTI also estimated the speeds of vehicles in each lane as they moved through the merge area. An accident analysis of this site was conducted as part of the operational analysis in 1992.

Site 2: The weave on IH35E from the Woodall Rodgers entrance to the westbound IH30 exit

The entrance ramp from westbound Woodall Rodgers is a lane addition on the outside of the four main lanes of southbound IH35E to make a five lane section. The inside lane becomes an exit only lane to westbound IH30. The weaving section is about 900 m (3000 ft) in length. The Continental Ave. entrance ramp is on the outside, about 300 m (1000 ft) south of the entrance from Woodall Rodgers. The Elm St. entrance is a lane addition on the inside, about 300 m (1000 ft) upstream of the exit ramp to westbound IH30. Congestion occurs in this weaving area during the evening peak period. TTI videotaped the weaving area from the Woodall Rodgers eastbound lanes looking south. At Site 2, TTI observed congestion in the evening peak and a large amount of lane changing and weaving in congestion. From the Woodall Rodgers video, TTI counted the volume in each lane and the number of lane changes. TTI also performed an accident analysis of this site.

Site 3: The major fork from northbound IH35E to northbound IH35E and eastbound IH30

The five lane section of northbound SRLT IH35E over the Trinity River splits into a two lane connection to northbound Stemmons IH35E on the inside and a three lane connection to eastbound ERLT IH30 on the outside without an option lane. The inside lanes are congested in the morning peak period, while the outer lanes remain in free flow. TTI videotaped the gore area from behind the diverge gore crash barriers. At Site 3, TTI observed congestion in the morning, bypassing queue in the inside lanes from the middle lane, and different speeds on the inside two lanes and the outside three lanes. From the video, TTI counted the volume in lanes 2 and 3, and the number of vehicles that crossed the diverge gore of the major fork.

Site 4: The exit to northbound Dallas North Tollway (DNT) from northbound IH35E

The exit to northbound DNT was a standard tapered exit ramp on the outside of the five lane section of northbound Stemmons IH35E before bottleneck improvements were completed in January of 1997. The exit experienced congestion in both the morning and evening peak periods; however, TTI only videotaped the evening peak period from Reunion Tower looking north towards the exit. At Site 4, TTI observed high exiting volumes in the evening peak period, queuing in the outside lane, lane 5, prior to the exit, and some vehicles exiting from the middle outside lane, lane 4, to bypass the queue in the outside lane. From the video from Reunion Tower, TTI counted the volume in each lane, on the exit ramp, and the number of exiting vehicles from the middle outside lane. TTI also performed an accident analysis of this site.

Site 5: The entrance ramp from eastbound IH30 to northbound Stemmons IH35E

The direct connection from eastbound IH30 is two lanes; the outside lane connects to Commerce St. to downtown, and the inside lane connects to the four main lanes of northbound Stemmons IH35E. Before the bottleneck improvement to northbound Stemmons, the connection to northbound Stemmons was a non-standard tapered entrance ramp. The entrance is followed downstream at about 150 m (500 ft) by an entrance ramp to an auxiliary lane from Commerce St. The IH30 entrance ramp is congested during the morning peak period. TTI videotaped from Reunion Tower the operation of the ramp as well as the downstream entrance ramp from Commerce St. At Site 5, TTI observed congestion in the morning peak period, queue jumping the inside lane of the ramp connection from the outside lane of the ramp connection, and driving on the shoulder from the outside lane of the ramp connection to the downstream auxiliary lane. From the video from Reunion Tower, TTI counted the volume in each lane of the connection, the volume of the main lanes, and the volume from the outside lane of the ramp entering IH35E.

Site 6: The Singleton entrance ramp to northbound Loop 12

This entrance ramp is a standard tapered entrance ramp from Singleton Blvd. to northbound Loop 12. The entrance ramp experiences congestion during the morning peak period. Traffic travels northbound on the frontage road, which ends at Singleton, to bypass congestion on the Loop 12 through lanes upstream of the Singleton entrance ramp. TTI videotaped from the shoulder downstream from the ramp looking south and from upstream of the entrance gore looking north to have two views of the operation of the entrance ramp. At Site 6, TTI observed congestion in the morning peak period on northbound Loop 12, heavy volumes on the Singleton entrance ramp, entering traffic bypassing traffic queued on the ramp upstream across the gore, and entering traffic bypassing the queue downstream on the shoulder. From the videos, TTI counted the entering traffic, the traffic entering across the gore or from the shoulder, and the traffic in the outside lane, lane 3. A manual traffic count of each main lane was also made. TTI also performed an accident analysis of this site.

Site 8: The inside exit-only lane from westbound IH635 to southbound US75 and Coit Road

Before restriping as part of the LBJ HOV project, the inside main lane of the four main lanes of westbound LBJ IH635 ended as an exit only lane to southbound Central Expressway US75 and Coit Road. The other three lanes continued past Central Expressway. Congestion at this location, as well as on the through lanes of LBJ, occurred during the morning peak period. TTI videotaped the operation of the westbound through lanes and the exit from the TI bridge looking west. At Site 8, TTI observed congestion in the morning peak period, bypassing the queue in the three through lanes from the inside exit only lane, and weaving across the double white line into and out of the exit only lane. From the video, TTI counted the volume of the main lanes and the exiting traffic, and the number of vehicles crossing the double white line. TTI also performed an accident analysis of this site.

Site 10: The Hampton Road and Red Bird Lane entrance ramp to southbound US67

The Hampton and Red Bird ramp is a nearly standard tapered entrance ramp to the two main lanes of southbound US67. The entrance ramp has a short parallel section of about 60 m over a creek bridge followed by a standard taper. The end of the entrance ramp taper is closely followed downstream at about 50 m by a tapered exit to Camp Wisdom Road. Congestion occurs at this entrance ramp in the evening peak period. TTI videotaped the operation of the entrance ramp from Red Bird Lane looking south. At Site 10, TTI observed congestion in the evening peak hour, a high volume on the entrance ramp, entering traffic bypassing entering queue upstream across the gore and downstream on the shoulder, and exiting traffic bypassing main lanes by using the entrance ramp taper and the following shoulder to get to the exit. From the video, TTI counted each main lane, the entering and exiting volumes, the number of vehicles entering across the gore or from the shoulder, and the number exiting onto the entrance taper or shoulder.

Site 11: The branch connection with inside merge of eastbound IH30 and northbound IH35E

Two lanes from eastbound IH30 and two lanes from northbound IH35E merge into three lanes entering the Canyon of eastbound IH30. The inside lane of eastbound IH30 continues as the inside lane, and the outside lane of northbound IH35E continues as the outside lane. The outside lane of eastbound IH30 and the inside lane of northbound IH35E merge to become the middle lane through the Canyon. Congestion occurs at this location during the evening peak period. TTI videotaped the operation of the merge from the Hotel St. overpass. At Site 11, TTI observed driver lane choice approaching the merge and congestion in the evening peak. From the video, TTI counted each lane prior to the merge and the number of lane changes prior to merge. TTI also performed an accident analysis of this site.

Site 12: The weave on westbound IH635 between the DNT Entrance and the Midway Exit

An auxiliary lane on the outside of the four main lanes of westbound LBJ extends about 500 m (1600 ft) between the entrance ramp from the Dallas North Tollway and Dallas Parkway and the exit to Midway Road. Congestion occurs in the weaving area through the evening peak period. TTI videotaped the operation of the weave from the Welch overpass. At Site 12, TTI observed congestion in the evening peak, weaving in congestion, shoulder driving, and gore crossing. From the video, TTI counted the outside lanes of LBJ prior to the weaving area, the entering and exiting (weaving) traffic, the vehicles crossing the gore in both directions, and the vehicles passing entering queue on the shoulder.

DISCUSSION OF DRIVING BEHAVIOR

Generally, aberrant driving behavior will occur wherever there is enough clear pavement to do so and whenever a driver feels it is to his advantage to do so. Most likely, the driver perceives a time savings that is significant enough to warrant the driving behavior. The negative aspects of the aberrant driving behavior, such as possible collisions with other vehicles or roadside structures, delaying other vehicles, or possible citations from law enforcement, are likely either not perceived or are viewed at such a low risk that they can be ignored.

There appears to be a full range of driving behaviors from aggressive to apprehensive, with most drivers falling somewhere in between. However, as congestion increases, drivers appear to become more aggressive. For example, at Site 6, the Singleton entrance ramp to northbound Loop 12, we see an increase of shoulder driving as the volume of traffic on the ramp increases. The volume of the ramp and the number of shoulder drivers is shown in Figure 2.

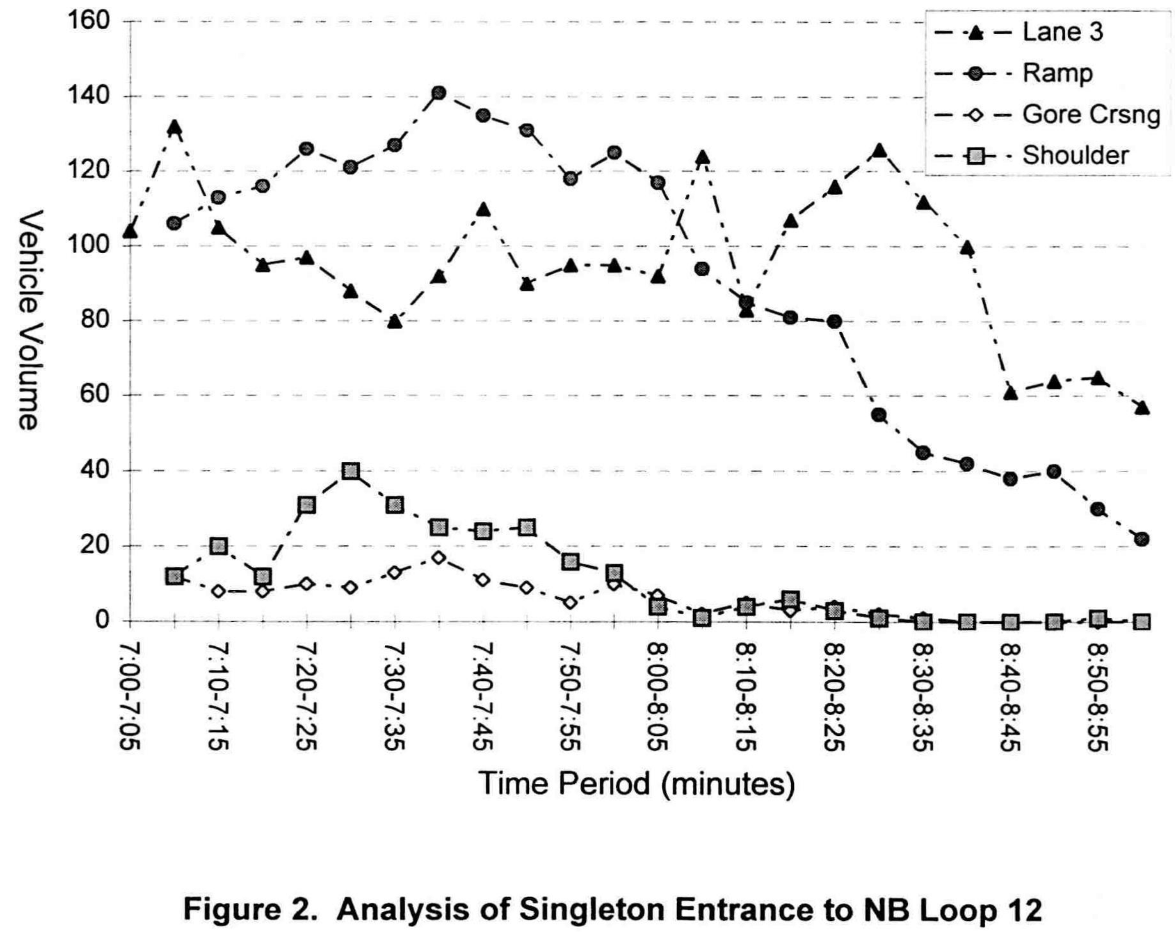


Figure 2. Analysis of Singleton Entrance to NB Loop 12

All of the aberrant driving behaviors seen at the sites described above can be termed as aggressive driving behavior. The shoulder driving behavior was seen most frequently at the entrance ramp sites: at Site 10, the entrance ramp to southbound US67 from Hampton Road and Redbird Lane; at Site 12, the weaving area between the entrance from DNT and the exit to Midway Road on westbound LBJ; and at Site 6, the Singleton entrance ramp discussed above.

Some drivers appear to imitate aggressive behaviors of other drivers. At most of the sites for much of the time, there are no aberrant driving maneuvers; however, when a single driver behaves aggressively several following drivers may repeat the behavior. This imitative behavior seemed to occur most often at sites where driving on the shoulder was observed, but it was also observed with gore crossings. Obviously, many drivers are either unaware of the possible maneuver until they see another driver complete the maneuver to their apparent advantage, or they are unwilling to violate traffic laws unless someone else does so first.

At all the sites observed, large vehicles, such as 18-wheel trucks and buses, were seen as part of the traffic stream. In the peak period, the percentage of trucks per 15 minute period observed ranged from less than 1 percent on US67 at Site 10 to 13 percent on Loop 12 at Site 6. Generally, at each site, the truck percentage is lowest when the congestion or demand is highest. This may indicate that trucks know when to avoid the worst congestion. Trucks were rarely seen performing aberrant maneuvers, though they appear to have a strong influence on the traffic stream in congestion. Due to the low performance characteristics of large vehicles, such as slow acceleration and long stopping distance, many drivers will maneuver to get around a large vehicle in congestion. A common, though potentially hazardous maneuver is when small vehicles merge into the gap in front of a large vehicle. A large vehicle requires a relatively long gap for safe stopping, and small vehicles that move into this gap may cut the available stopping distance for the large vehicle in half. Most drivers who do this maneuver are probably unaware of the danger. This maneuver was most widely seen in weaving areas, such as the weaving area on southbound IH35E at Site 2. There was also a strong cooperative behavior observed among trucks. One truck will often slow to allow another to merge in front of it, forcing all the following traffic to slow as well.

At all but one of the sites where accident rates were studied, the peak hour accident rates are higher than the daily rates. TTI collected accident rates for each site from 1991 to 1995. The average 1994 daily accident rate for the Dallas area was 0.73 accidents per million vehicle-kilometers traveled (1.17 accidents per million vehicle-miles traveled). Each site had a daily accident rate higher than the average for the area. The results of the accident analysis are shown in Table 2. The higher accident rates in the peak hour indicate that congestion increases the number of accidents at these sites. The detail of this accident analysis did not allow the level of severity of each accident to be determined. A more detailed analysis may show that the accidents that occur in congested conditions are less severe due to the slower speeds and more familiar drivers.

Table 2. Accident Data Summary

Site	Study Length kms (miles)	Average Annual Accidents	Average Daily Volume veh/day	Average Daily Acc. Rate acc/mvkt (acc/mvmt)	Average Annual Peak Hour Accidents	Average Peak Hour Volume veh/hour	Average Peak Hour Acc. Rate acc/mvkt (acc/mvmt)
2. Weave on SB IH35E	1.6 (1.0)	63	90,152	1.2 (2.0)	4.8	7,032	1.6 (2.6)
4. NB IH35E Exit to NB DNT	1.4 (0.87)	52	132,206	0.74 (1.2)	4.0	8,329	1.3 (2.1)
6. NB Loop 12 at Singleton Entrance	1.1 (0.68)	8	53,006	0.37 (0.59)	1.2	5,937	0.72 (1.2)
8. WB IH635 Exit to SB US75 and Coit	1.0 (0.62)	50	113,813	1.3 (2.1)	2.0	8,081	1.0 (1.6)
11. Merge of EB IH30 and NB IH35E	0.6 (0.37)	37	82,950	1.9 (3.1)	1.9	5,392	2.1 (3.4)

Note: The average 1994 daily accident rate for the Dallas area was 0.73 accidents per million vehicle-kms traveled (1.17 accidents per million vehicle-miles traveled)

One question this research was trying to answer was: What is the effect of queue jumping or any of the identified aberrant driving behaviors on the throughput of a traffic stream? At Site 6, the Singleton entrance ramp to northbound Loop 12, we can see the effects of the larger queue jump that is occurring. About two-thirds of the volume at the Singleton entrance ramp are using the frontage road as a queue jump to bypass the congestion on Loop 12, further aggravating congestion. The vehicles are exiting Loop 12 upstream as well as coming from IH30 and bypassing the IH30 entrance ramp by going downstream on the frontage road through the signal at Singleton and onto the Singleton entrance ramp. Figure 3 shows the effect of the queue jumping on the throughput of traffic; as the entrance ramp volume increases, the overall throughput is decreased.

The effect of other aberrant behaviors on vehicle throughput is uncertain. Shoulder driving and gore crossing observed at the Singleton entrance ramp, shown in Figure 2, appear to increase the capacity of the ramp. While the ramp capacity might be lower if there were no shoulder driving or gore crossing, there might be a positive influence on the overall throughput - similar to ramp metering. In any case, shoulder driving or gore crossing has a disruptive effect on the traffic, which is potentially hazardous due to the unexpected nature of the behavior and should be discouraged. Occasional police enforcement of problem areas and the installation of rumble strips or raised traffic bumps along the problem shoulders should be effective in discouraging the behavior without impeding the use of the shoulder for vehicle breakdowns.

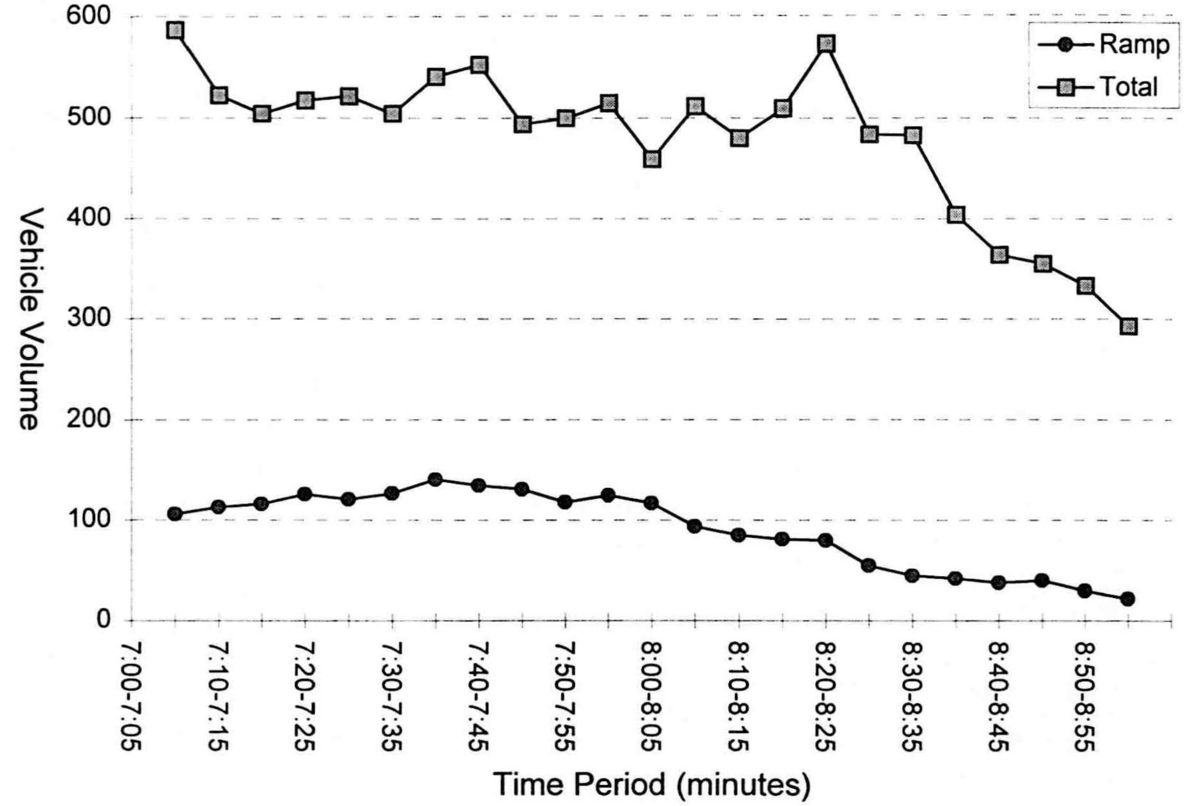


Figure 3. Total Volume of NB Loop 12 and Singleton Entrance

Often, weaving areas are directly associated with recurrent congestion, and at these sites, it may be feasible to eliminate the weave through design changes, such as braided ramps or collector distributor roads. However, many weaving areas are located in areas where there are additional sources of congestion downstream. This was the case for the observed weaving areas at Site 2 (the weave from westbound Woodall Rodgers on southbound IH35E to westbound IH30) and at Site 12 (the weaving area on westbound IH635 between the DNT entrance ramp and the exit to Midway Road). At both sites, weaving at the slower speeds due to congestion appears easier and is accomplished in a shorter distance than at higher free flow speeds. At the southbound IH35E site, the number of lane changes observed indicates that the capacity for weaving in congestion is higher than the capacity expected for normal weaves. The amount of weaving at this site exceeds the expected maximum level of weaving for a type C weave by 60 percent. The volume and number of lane changes observed on southbound IH35E are shown in Figure 4.

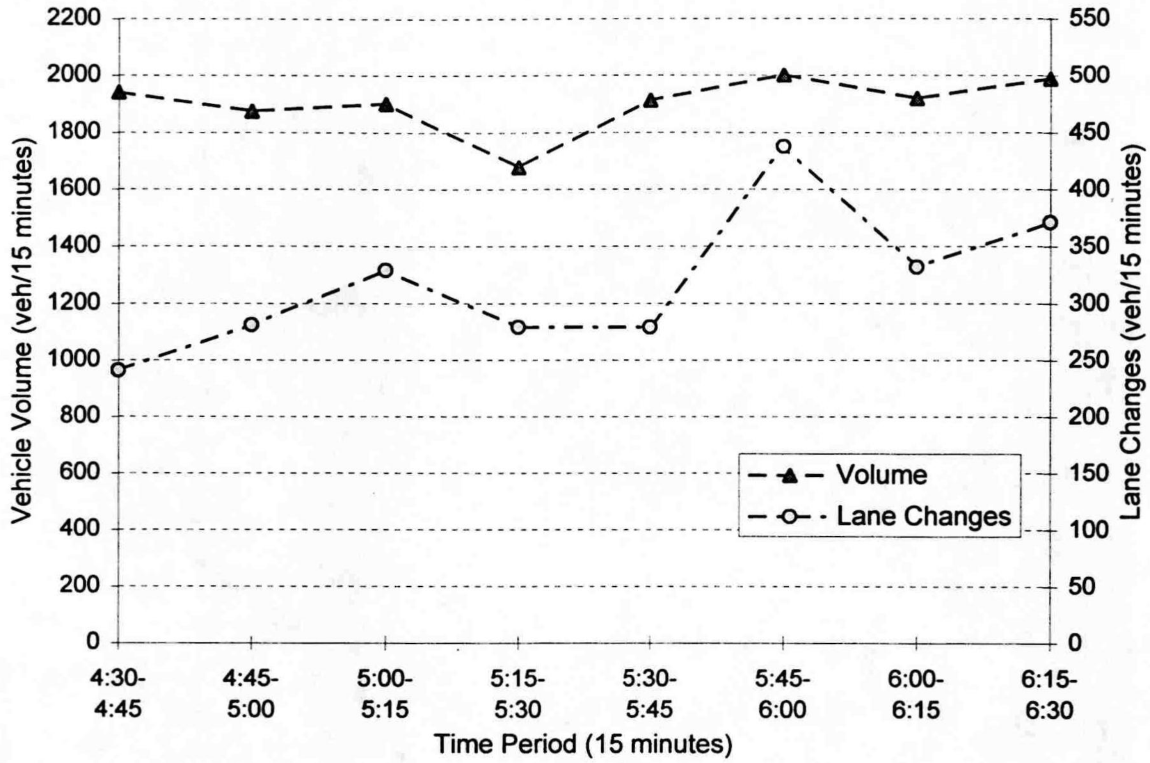


Figure 4. Analysis of Weave from Woodall Rodgers to WB IH30 on SB IH35E

To gain a better understanding of queue jumping, TTI observed lane closures on LBJ Freeway. On Saturday, May 10, 1997, the three outside lanes of LBJ IH635 were closed for pavement rehabilitation near Midway Road, and on Saturday, May 17, 1997, the three inside lanes of westbound LBJ were also closed for pavement rehabilitation near Preston Road. The eastbound lanes were observed from the Rosser Road overpass looking east toward the third lane closure and exit to Midway Road. The westbound lanes were observed from the Preston Road overpass, also looking east toward the third lane closure. From the videotapes made at the two sites, the volume in each lane and the number of queue jumps were counted for one minute intervals. The number of short queue jumps and the corresponding lane volume in the affected lane are plotted in Figures 5 and 6. The volumes for both sites were counted between 11:00 and 11:30 in the morning. Both sites show an increase in through volume with an increase in short queue jumping, though a slight decrease in through volume was expected for an increase in queue jumping. This may be because the video was actually catching only minor variations in merge maneuvers, not the lengthy, deliberate queue jumping as noted at the Singleton entrance ramp.

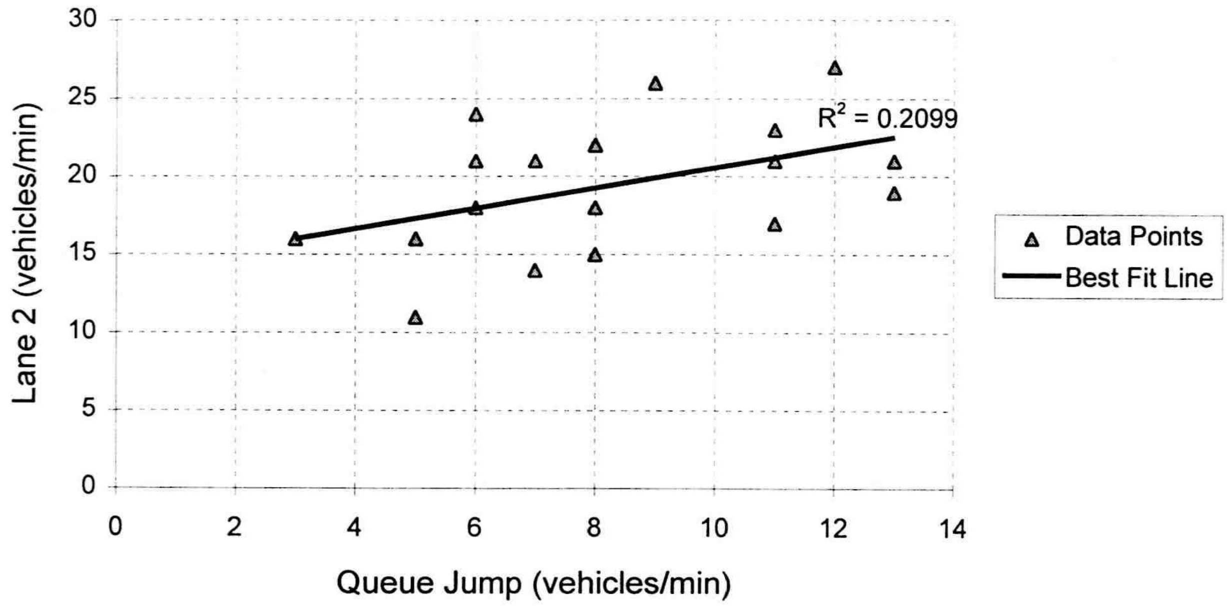


Figure 5. Queue Jump Analysis - EB LBJ IH635 Lane Closures

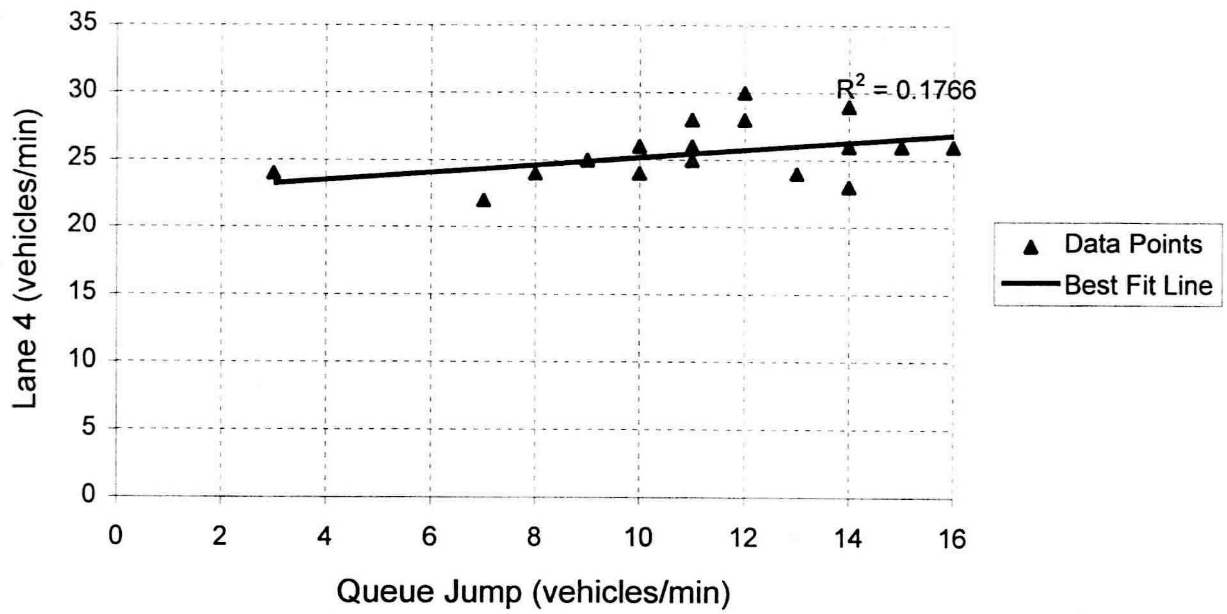


Figure 6. Queue Jump Analysis - WB LBJ IH635 Lane Closures

Statistically, there is little to no relationship between short queue jumping and lane throughput at these sites; however, the interesting result is in the different throughputs seen at the two sites. The eastbound site which had an exit to Midway Road near the lane closure had a lower and less uniform lane volume for the affected lane than the westbound site. In Figure 5, it can be seen that the lane volume of lane 2 (the middle inside lane 1 is the inside lane or HOV lane) ranged between 11 and 27 vehicles per minute. However, in Figure 6, it can be seen that the lane volume of lane 4 (the middle outside lane) ranged between 24 and 30 vehicles per minute. The middle lane of the eastbound site appeared to have a higher speed and throughput compared to the adjacent through lane due to the exit at the end of the lane. This results in a more random arrival rate for queue jumps at the lane closure as well as less delay for the queue jumping vehicles, while at the westbound site the vehicles in the ending lane and the adjacent through lane appear to have little difference in speed and a near uniform pattern of merging at the end of the lane. These observances have led to the hypothesis that it is best to have each lane full with uniform speed approaching a lane closure with all the merging at the end of the lane being closed. However, additional sites will need to be observed, as well as field test performed, with different signing to verify this hypothesis.

SUMMARY OF DRIVING BEHAVIOR OBSERVATIONS

The objectives of the driver behavior research, to provide additional evaluation of driver behavior under congested conditions and to further our understanding of freeway operations in congested urban areas in Texas, have been satisfied. Though no specific recommendations for design changes have been made, this analysis has identified patterns in driver behavior that may create inefficiencies or hazards in the flow of traffic. The aberrant driving behaviors discussed above may all create inefficiencies or hazards for the flow of traffic.

Aberrant driving behaviors appear to be more common at locations where there are clear and adequate shoulders and entrance and exit gores. Despite a potential increase in shoulder driving or other aberrant driving behaviors in congested conditions, full width and full strength shoulders, with rumble strips or traffic bumps where needed to discourage shoulder driving, are an important safety feature for when traffic flow conditions are not congested. Signing did not appear to be a problem at any of the locations observed for this study. As traffic slows for congested conditions, most drivers probably have a better chance to recognize and heed roadway signs than when they are traveling at higher speeds. Similarly, roadway markings did not appear to be a problem at any of the locations observed for this study, despite the fact that at many sites, drivers were observed ignoring the roadway markings - gore crossing or crossing double white lines. The effect of other traffic control devices, such as lane control signals or changeable message signs, were not observed at any of the study sites. However, the use of lane control signals may exacerbate the problems associated with queue jumping approaching lane closures.

Queue jumping, in many cases, may be avoided through careful design and proper lane balance at freeway to freeway interchanges. Of course, with the approaches to construction zones or other temporary lane closures and with existing overcapacity ramps and connections, queue jumping may be unavoidable. The observances at the work zones on eastbound and westbound LBJ suggest there may be ways to sign the approaches to a lane closure in such a way as to minimize early lane changes and promote a more uniform speed and flow in the affected lanes. However, more research at construction zone approaches will be needed to form any recommendations to minimize the problems associated with queue jumping.

CONCLUSIONS

- Long queue jumps (e.g., Loop 12 and Singleton) have a negative impact on overall throughput and should be actively discouraged through design or operational means, such as improved signal timing at the intersection of Singleton and the Loop 12 frontage road.

- Unavoidable lane closures, such as those found during pavement rehabilitation on LBJ IH635, should be signed to delay the vacating of the closing lane until the last moment, to maximize throughput.

- Weaving in congestion appears to be easier and has higher capacity than high speed weaves, as shown on southbound IH35E near downtown.

- Shoulder driving is aggressive driving behavior and should be actively discouraged both by occasional enforcement and by installing rumble strips or raised traffic bumps along shoulders.

IV. REFINING ANALYTICAL METHODS FOR BOTTLENECK ANALYSIS

Traditional tools have proven to be inadequate for use in simulating or examining congested conditions on freeways. In many cases, freeways are operating in congested conditions throughout much of the work day. Although engineering judgment and experience are essential in finding potential solutions to freeway flow breakdown, fiscal constraints demand an analysis and justification of the most elementary solutions. Further, major freeway reconstruction in the future (e.g., IH635, LBJ Freeway) will require analysis in terms of congested flow with multiple alternatives. The problem faced by the transportation professional is that it is difficult to model or simulate freeway congestion, and there is a need for examining and calibrating freeway simulation to identify which is best-suited for analyzing congested Dallas freeways.

PHONE SURVEY

The primary distributors for the simulation software being examined by this research are the Center for Microcomputers in Transportation (McTrans) and PC-TRANS. McTrans distributes transportation-related microcomputer software, provides technical assistance, and is a full service software support center serving the transportation engineering and planning community. PC-TRANS also distributes and provides technical support for a wide range of transportation-related microcomputer software. Both distributors were contacted and asked which is the most widely used software for macroscopic or microscopic simulation of freeway operations. Both said CORFLO was the most widely used macroscopic software and that FRESIM was the most widely used microscopic software, as well as the most widely used simulation software overall. McTrans, when asked who uses the software, said mostly consultants use FRESIM, while PC-TRANS said that the use of FRESIM is fairly uniform among state departments of transportation, research organizations, consultants, and local governments.

TTI contacted the Dallas and Houston districts of TxDOT to determine what was being used to analyze freeway operations in congested conditions. At the district level, only the Highway Capacity Software has been used for level of service analysis; no simulation of congestion has been done. The Houston office of TTI has assisted the Houston district by analyzing some corridors with the FREQ model. Contact with Parsons Transportation Group and Kimley-Horn and Associates confirmed the findings at the state DOT level that simulation modeling is rarely performed, and that FRESIM is the primary model chosen for simulating congested conditions.

CORFLO (7, 8) is a component model of the TRAF simulation system designed for the integrated urban network or corridor analysis at a macroscopic level with traffic assignment capabilities. CORFLO consists of three submodels: FREFLO, NETFLO1, and NETFLO2. FREFLO, a macroscopic freeway simulation model, represents traffic in terms of aggregate measures on each section of freeway. NETFLO1 and NETFLO2 simulate urban streets at different levels of detail. Each of the submodels can be run independently or on a specific subnetwork. CORFLO, prior to the availability of CORSIM, was the only traffic model to explicitly handle cars, trucks, buses, and carpools on freeways and surface streets in a single integrated environment.

FRESIM (7, 8) is also a component model of the TRAF simulation system. FRESIM, however, is designed for microscopic freeway simulation of freeway networks. The INTRAS model was the predecessor to FRESIM. Enhancements included improvements to the geometric and operational capabilities of the model. FRESIM can simulate one to five through freeway lanes and one to three freeway auxiliary lanes, as well as grades, curves, superelevation, lane additions and drops, incidents, and work zones. The operational features include lane changing, ramp metering, surveillance systems, six different vehicle types, different driver habits, and warning signs for lane drops, incidents, and exits.

CORSIM is the FHWA's new microscopic simulation model. It is a sophisticated model based on the FRESIM and NETSIM models. CORSIM simulates a real-world traffic network by moving individual vehicles across a combined surface street and freeway network using accepted vehicle and driver behavior models and simulating various traffic control devices. Unfortunately, CORSIM has just recently become available and was not included as part of this research.

ADJUSTMENTS MADE TO FRESIM

The motivation for pursuing this section of this research report was to make an effort to improve the bottleneck analysis methodology. Further, based on previous experience with simulation programs, researchers believed that some good could be gained through simulation if it could be incorporated into the methodology. Previous experience has also taught that there are problems with the available simulation packages when used to model congested freeway conditions. As the survey indicated, FRESIM is the most likely package to simulate congested conditions since it is a highly developed microscopic simulation package, and the problems with simulating congested conditions seem to be the vehicle interactions that take place (i.e., weaving, queue jumping, turbulence, etc.). Microscopic simulation would intuitively offer the best tool to capture these interactions.

Given the results of the survey and previous experience, an effort was made to begin incorporating the use of FRESIM in a bottleneck analysis methodology. The first problem was to establish a reasonable method of calibrating the model to existing conditions. This is a problem in that the existing conditions in bottleneck cases are congested conditions: speeds are low, demand is high, recorded volumes are constrained (low), and vehicle interactions are increased. The decision that must be made is a procedural one: to adjust the model parameters to meet the observed conditions (low speed, low volumes) or to adjust the model input data and allow the model to react as the actual freeway does. In the case of bottleneck locations, the most reasonable approach appears to be to "overload" the system with volume (which is likely the case, given queuing and latent network demand) until the model measures of effectiveness more closely match the observed measures (speed, volume).

This methodology may not be best in unconstrained conditions where the flow has not broken down. In these cases, adjusting the model parameters (headway parameters, etc.) to calibrate to existing conditions may be best, using recorded volumes and geometry as inputs. Then the same parameters could be used to estimate future operations if changes in geometry are made. This approach does not work for constrained conditions. If constrained conditions exist, changing the model parameters to match the observed conditions will require "artificially" reducing the capacity of the model by changing the model parameters so that the low (constrained) input volumes will result in lower simulated speeds. Either method results in constrained simulated conditions, but by "overloading" the system, the user is allowing the simulation package to react to saturated conditions instead of artificially constraining the system.

The next question is how to go about "overloading" the simulated system. In most cases, bottlenecks are a product of small sections where there is an imbalance between demand and capacity, along with other elements like weaves, heavy merges, etc. The speed profile that results from these combined problems is generally distinct in terms of peaks and valleys. The speed profile is important in helping determine where the bottleneck is located, where traffic flow starts recovering, and hopefully if there are any minor bottlenecks hidden in the congestion. It is, therefore, important to be able to increase volumes such that the simulated speed profile will have the same basic shape as the actual speed profile. In other words, it is important to be able to examine section-by-section speeds, not just the average speed over the entire bottleneck. In order to meet this need, the methodology begins by running FRESIM with the existing geometry and recorded volumes as a base case. Subsequent runs are then made, increasing the input volume in 10 percent increments (e.g., base*1.1, base*1.2, etc.) until the simulated speed profile most closely matches the actual speed profile. These calibration runs are meant to put the simulation tool into constrained conditions and respond by moving as many vehicles as possible through at constrained speeds. The assumption in this methodology is that this model is basically a robust model and should give reasonable results, given the proper inputs.

It also follows that the volume input to reach the best calibration is then used as input to help understand the operations if any geometric changes are made. The calibrated run is used as the new "base" case for purposes of comparison. The tool then can be used to judge if a given lane addition, auxiliary lane, or weave will improve operations and how much. Again, the calibrated run is used as the basis for comparison and only for judging relative improvements, not absolute measures of effectiveness. Additionally, the results should be examined for reasonableness using engineering judgment.

CASE STUDY

Eastbound LBJ Freeway (I-635) at Central Expressway (US75)

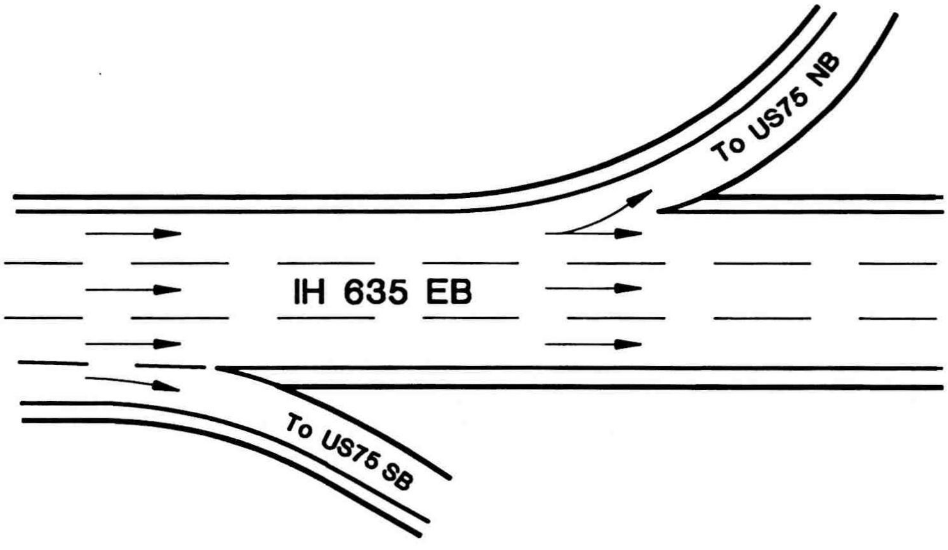
The following section presents a test case for this methodology at a bottleneck located in Dallas, Texas. The case study is a location along the congested IH635 LBJ Freeway in Dallas, Texas. The specific location is eastbound LBJ at the US75 Central Expressway interchange. Before conditions included four mainlanes, with a one-lane merge from Hillcrest, followed by a single-lane diverge to Coit, then followed by a one-lane exit to southbound US75 with a lane drop. Through the interchange, there is a left-side diverge to northbound US75 and then an entrance from northbound US75 with a lane addition, leaving four mainlanes heading east out of the interchange. The bottleneck improvement is shown in Figure 7.

The change in geometry designed to relieve the bottleneck addressed both reasons for the bottleneck. First, the lane drop to the southbound US75 exit ramp was removed, and a fourth lane was carried through to the northbound exit. There, a lane drop was utilized to better serve the connection.

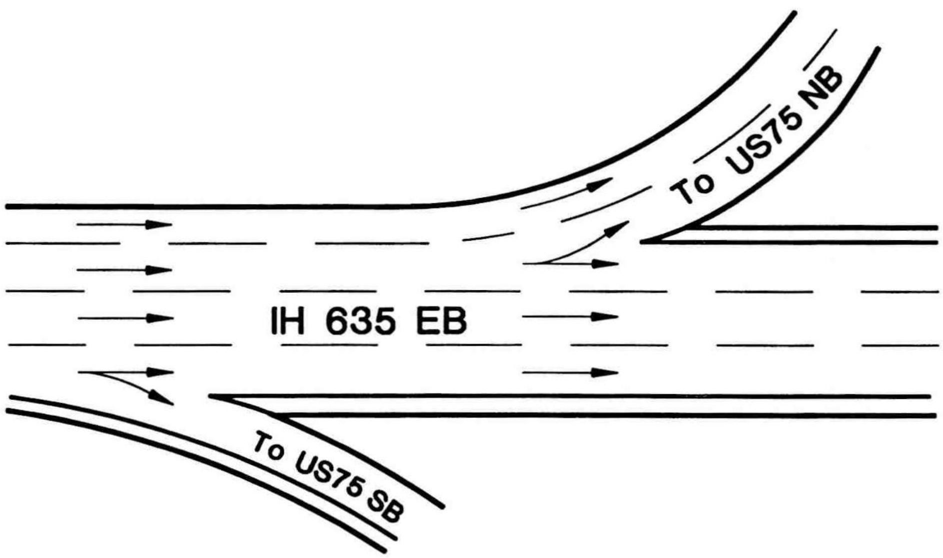
The main bottleneck was located between the exit to southbound US75 and the exit to northbound US75. This section was just downstream of the lane drop from four to three lanes. Operationally, the demand for the southbound exit was not sufficient for a lane drop, while the left-side northbound exit had more than enough demand for a lane drop, yet was served only by a diverge. The unwarranted lane drop to southbound US75 left too much demand on the three mainlanes downstream, exacerbated by the heavy northbound diverge. The bottleneck location is easily identified in the speed profile shown on Figure 8, as slow speeds upstream of the section indicate queuing, and the increased speeds downstream indicate the excess capacity available downstream of the "metered" freeway section.

A total of five FRESIM runs were made with the "before" improvement geometry, one with the recorded flowrates, and four other runs with increased flowrates up to an increase of 40 percent (recorded flowrates*1.4). Again, the idea was to overload the network with volume and let FRESIM react to the excess demand, hopefully, in a manner consistent with real-world networks. Figures 8, 9, and 10 are plots of speed, volume, and an aggregate of speed and volume termed total travel, with length of freeway in meters along the x-axis (1 meter = 3.3 feet). Each plot consists of separate data series for the actual before condition, and then one series for each of the FRESIM runs, with input volume ranging from the actual recorded volume (V100) to 140 percent of the recorded volume (V140). Also included on the plots are separate series depicting the actual after improvement conditions along with the FRESIM results for after improvement.

The plot of volume versus length of freeway shows several things to support that this approach is a reasonable approach and that FRESIM responds to the inputs in a logical manner. First, as input volumes are increased for the existing geometry, the FRESIM volume increases until the 40 percent increase in volume is used as an input. The result of the V140 case was that the volume handled by FRESIM actually dropped compared to the V130 case. This is an indication that the capacity had been exceeded or met, and the network was operating under saturated conditions. Also significant in these plots is the fact that the FRESIM after volumes closely match the actual after volumes, again supporting the reasonable nature of this methodology. Finally, the shapes of the volume profiles are all very similar, with a general shift upward where input volumes were increased, supporting the nature in which input volumes are scaled upward in percentage increments.

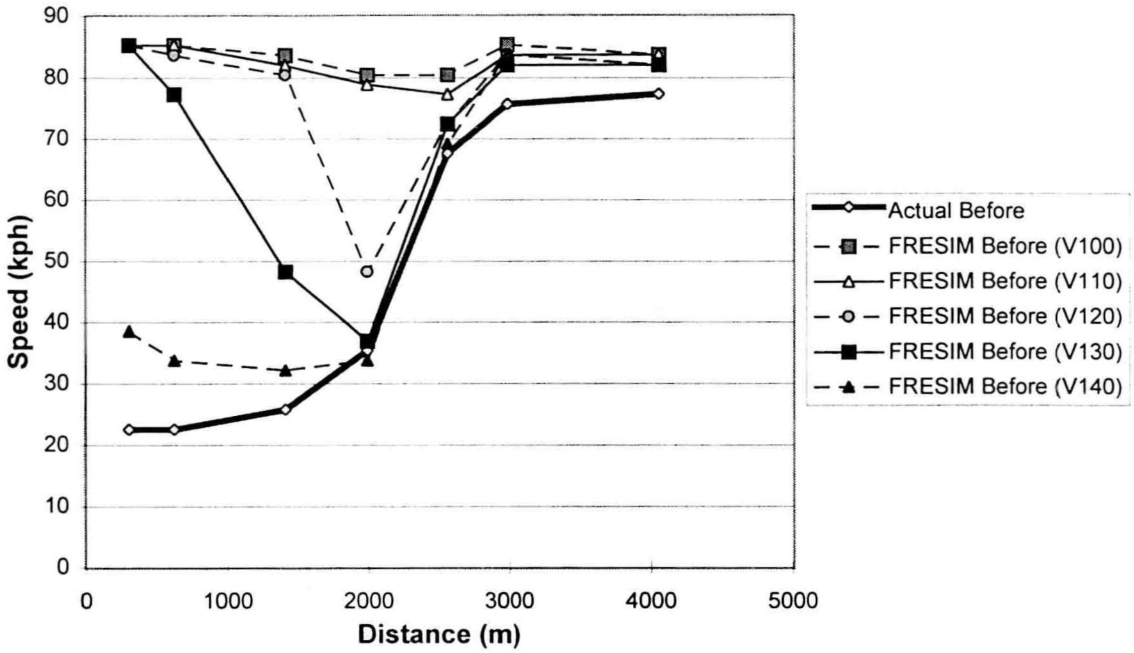


BEFORE BOTTLENECK IMPROVEMENT



AFTER BOTTLENECK IMPROVEMENT

Figure 7. Eastbound IH635 LBJ Bottleneck Improvement



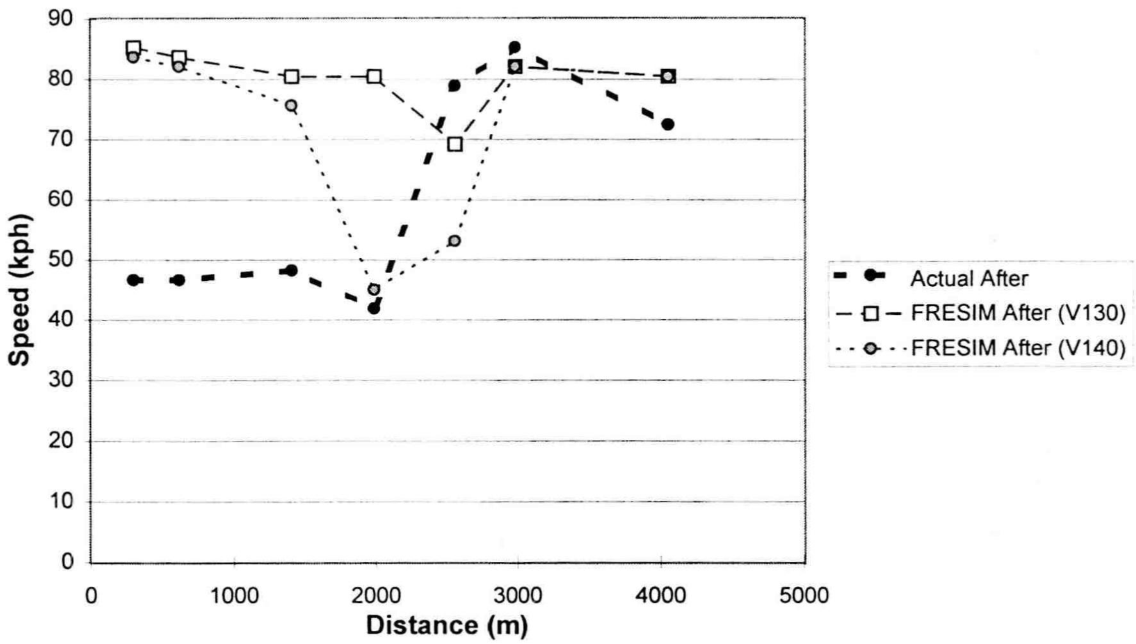
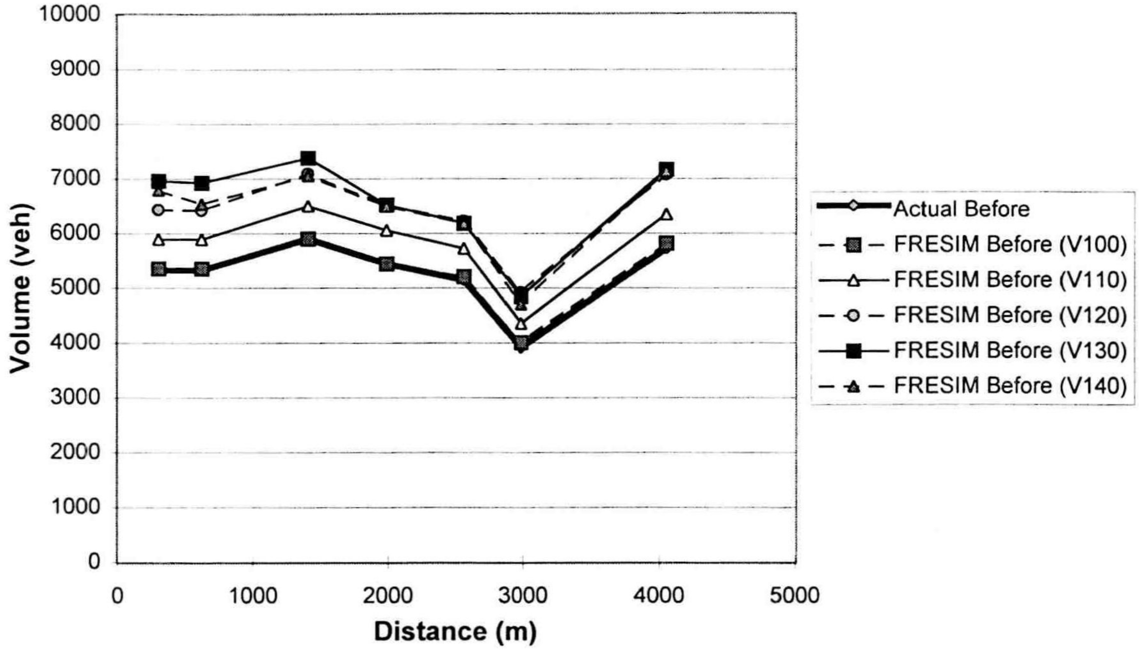


Figure 8. Eastbound LBJ at Central - Actual and FRESIM Output Speeds



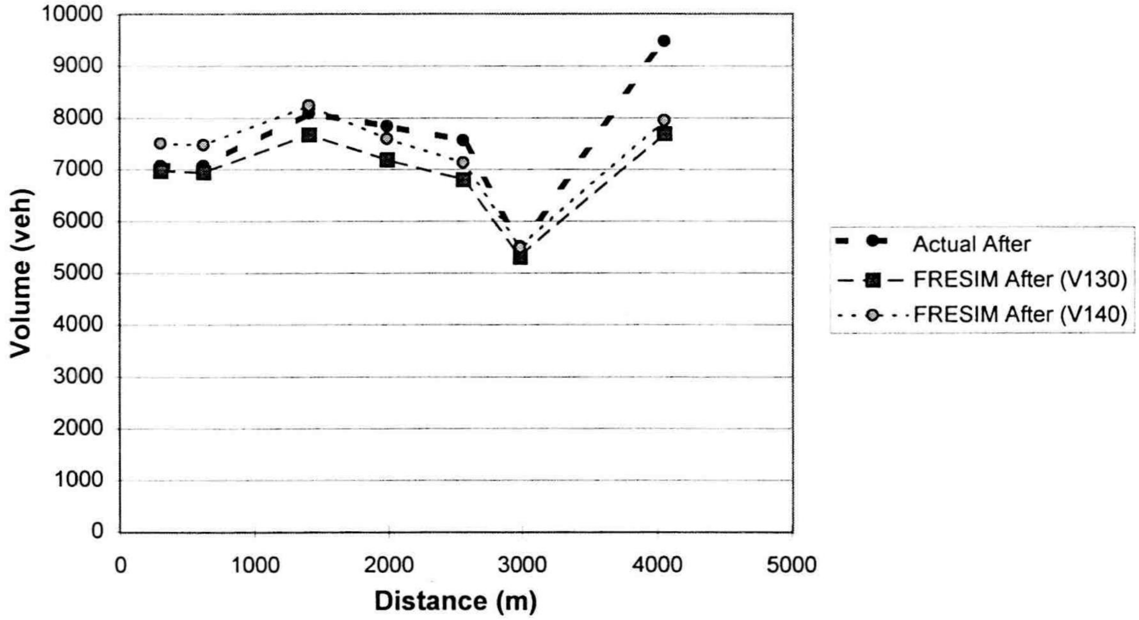


Figure 9. Eastbound LBJ at Central - Actual and FRESIM Output Volumes

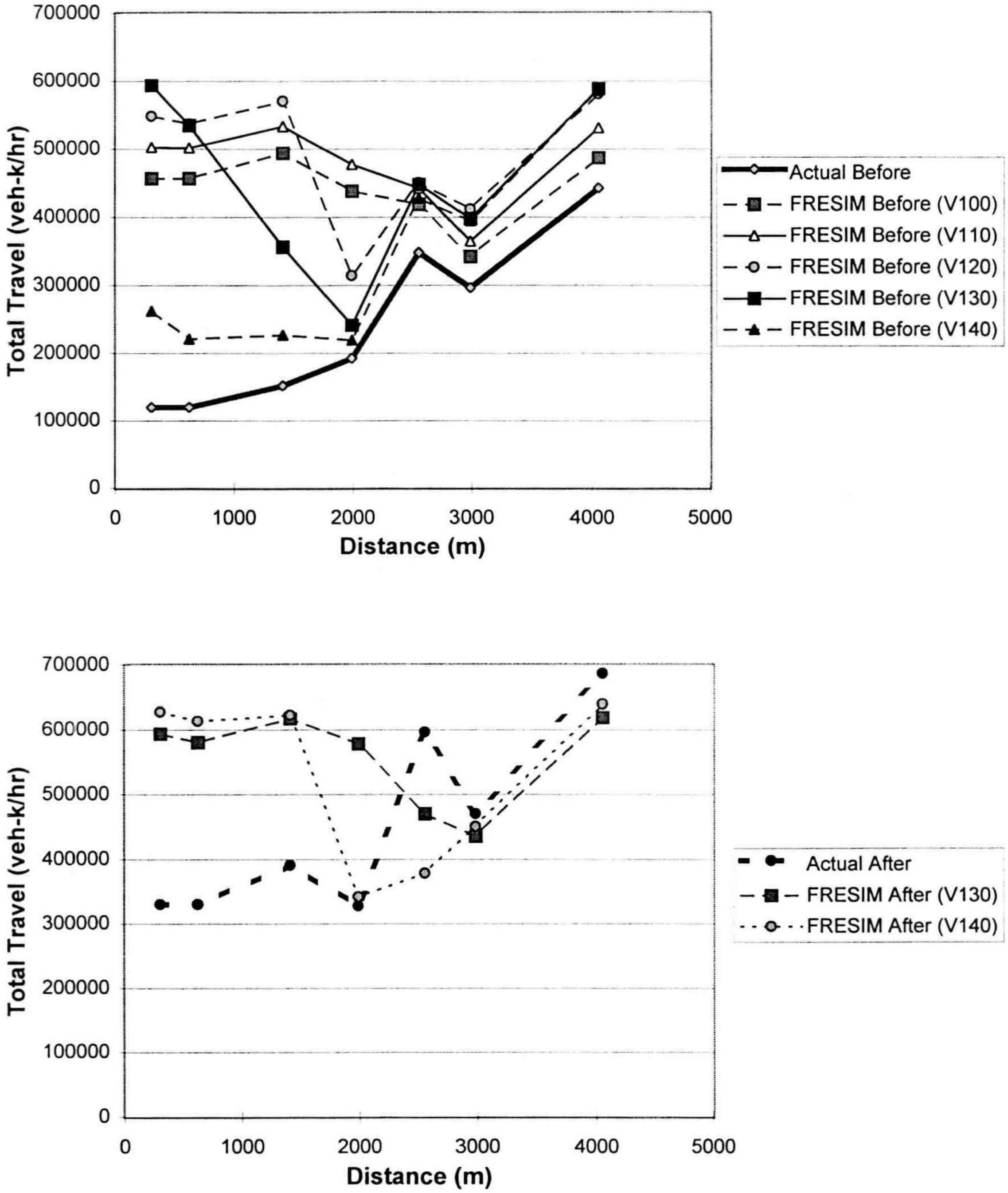


Figure 10. Eastbound LBJ at Central - Actual and FRESIM Output Total Travel

The plot of speeds versus length of freeway is a more significant plot since this is one of the primary measures of effectiveness used in operational analysis. The series on the speed plot represent the same series included on the volume plot: actual speed before improvement, five FRESIM speed plots for before improvement (V100-V140), actual speed after improvement, and two after-improvement speed profiles.

The calibration speed plots (before improvement) indicate several things that support this methodology. First, as is expected, FRESIM speeds generally decrease as the input volume is increased. However, for the V100 case through the V130 case, the entry boundary condition does not match the actual speed. This corresponds to the results of the volume plot that indicated volumes continuing to increase through the V130 case (indicating non-saturated conditions). However, the boundary speed for the V140 case matches the actual entry speed much more closely, further supporting that fully-saturated conditions were met.

The speed plots for after conditions showed similar trends to the calibration speed plots. As input volume is increased, speeds decrease. However, it seems as though FRESIM lacks the sensitivity to model the complex vehicle interactions in place after the bottleneck improvement. Again, the entry boundary condition is not met accurately. However, all profiles, including the after-improvement profiles, match the actual profiles surprisingly well at the bottleneck and downstream. This is an area where judgment needs to be used to determine if the FRESIM results seem reasonable or if there is simply a problem meeting the boundary conditions.

The final set of plots is of a measure termed total travel, which is an aggregate of speed and volume. Total travel is being explored as an appropriate measure since it may capture the benefits of bottleneck improvements when significant latent demand exists in the network. Under these conditions, speeds may not improve significantly, but more motorists may be using the freeway, reducing their travel times. By accounting for speed and volume, total travel may capture some of these hidden benefits.

The plots on Figure 10 represent the total travel for the actual recorded data before and after improvement and the FRESIM runs using the different input volume cases. These plots reveal some of the advantages and disadvantages of using total travel as a measure of effectiveness. First, it is evident that when the volume profiles match the true volume plots reasonably well, the shape of the speed profiles dominate the shape of the total travel profile. It is also evident that the boundary conditions of the different series are controlled by the volume data. Hence, the shape of the profile is controlled more by speed, in this case, and the magnitude of the total travel values is controlled more by volume. These observations may not hold true in more complex, more highly saturated cases. In this case, it appears that an examination of the volume and speed separately is a better approach.

This case study was a relatively simple bottleneck improvement that moved a lane drop from one exit ramp downstream to the next exit ramp. The bottleneck location was well-defined in the freeway system, and the improvement was evident as speeds went up noticeably. In this case, the volume and speed profiles for the FRESIM runs matched the actual profiles reasonably well at the appropriate volume level. It appears that this methodology for analysis would have worked reasonably well for the before/after analysis, provided the appropriate volume level was reached (i.e., increase input volume until the output volume stops increasing). It is also important to remember that a base case (the calibrated case with before-improvement geometry) would be used as a means of comparison for any alternatives being considered. Although the absolute values for speed may not be reliable enough at this point of model development for projecting monetary benefits, relative changes in operation can be estimated using this methodology.

DISCUSSION OF CASE STUDY

The case study that has been discussed is ideal for research study in that before and after-improvement data are available for analysis. The practitioner can use both datasets as guides to what does and does not work when using computer simulation. However, real-world applications involve only before data and a set of potential after-improvement geometry scenarios. The problem that faces the engineer, in these cases, is whether or not the simulated after-improvement measures of effectiveness are reliable. It is apparent through analysis of the case study that the simulated speeds reasonably reflect the actual after speeds. In all cases, bottleneck locations will operate under saturated conditions, and it is important to calibrate FRESIM to reflect those conditions. Further, it is important to restate that the calibrated before-improvement case should be used as the base case for comparison. The relative improvement should be compared for each alternative to help in understanding what will and will not work to relieve the bottleneck, and which alternative will provide the most relief. At this stage of FRESIM development, the results do not lend themselves to use in determining absolute benefits after the improvement is made. The results do not appear reliably accurate for this application. In other words, the FRESIM outputs are consistent and reasonable from an intuitive standpoint but not necessarily accurate in terms of absolute measures of effectiveness.

Although a discussion of this methodology has been given in previous paragraphs, a summary of the use of FRESIM in congested conditions is useful. First, accurate before data, including volume, geometry, and speed data, are necessary. Also, an understanding of the operation of the bottleneck is necessary to lend engineering judgment to the analysis and to make sure the FRESIM measures of effectiveness make sense.

The calibration of the model should be performed as an iterative process. It is proposed in this methodology that an "overloading" process be used to ensure that saturated conditions are being modeled (recorded volumes will be constrained and, if used as direct input, will not result in saturated simulation conditions). The approach used in this research was to first use the recorded volumes as inputs (which will likely result in uncongested conditions). Subsequent simulation runs will use increments of the recorded volumes as inputs (e.g., in 10 percent increments). Eventually, the FRESIM output volumes will stop increasing, indicating saturated conditions. Comparison of the FRESIM output speeds should match the actual before speeds reasonably well (if they do not, adjustments to FRESIM model parameters may be explored). This should serve as the base case for comparing the relative improvement with different bottleneck removal alternatives. The level of volume input should be used as input to test the relative improvement with different alternatives. In other words, once the model is calibrated to existing conditions, the geometry is changed, using the same volume inputs to test the merits of different alternatives.

As has been discussed, there is some doubt as to the reliability of the absolute measures of effectiveness reported by FRESIM. There is evidence that provides good reason to use FRESIM for helping compare different sets of alternatives, given some baseline FRESIM run as a standard. Similar evidence is not apparent for the use of FRESIM to absolutely predict the benefits of a given improvement. One reason for this is that if the calibration is off slightly, the measures of effectiveness output from FRESIM for bottleneck improvement options will also be off. However, for comparison of the different alternatives, a minor error in calibration should not be as critical, as they will all be based on the same calibration. In other words, if absolute certainty of calibration was possible, it might be more reasonable to use FRESIM as a means to estimate benefits. But, since future conditions are unknown, it should most reasonably be used only to compare different construction alternatives.

CONCLUSIONS

- Collection of adequate geometry and volume data should be conducted if quality simulation results are expected.

- It is important to use some method of achieving model outputs for a base case that reasonably match the existing conditions.

- It appears that a reasonable approach for "calibrating" the model to congested existing operations is by overloading the network (since recorded volumes will be constrained) and allowing the model to react to the excess demand.

- A proposed methodology for overloading the model is to scale recorded volumes up to a point where the network is saturated (e.g., in 10 percent increments).

- At the current level of development, FRESIM does not appear to be adequately reliable for estimating absolute future benefits for a freeway bottleneck removal project.

- The use of FRESIM as a simulation tool in bottleneck analysis is reasonable for use in the selection of the best alternative.

V. RELIABILITY OF BENEFIT ESTIMATES FOR BOTTLENECK IMPROVEMENTS

It is generally accepted that bottleneck removal projects are worthwhile and contribute to better overall freeway flow. However, simply acknowledging that these types of projects are beneficial is not sufficient in terms of fund allocation. It is important to have a methodology to estimate the benefits of a project based on some projected performance improvement. These types of estimates rely almost entirely on the assumptions made in their calculation. For instance, one methodology might be to assume a percentage increase in speed, based on previous experience, or to use a simulation program to estimate after-construction speeds as the basis for benefit estimation. Whatever the methodology, the reliability of the estimate is only as sound or reliable as the assumptions upon which they are based. The objective of this portion of the research project was to examine the traditional approaches to estimating benefits, examine a case study of before/after performance at a bottleneck location, and offer some recommendations to help in the estimation of benefits.

APPROACH FOR ASSESSING THE BENEFITS OF BOTTLENECK IMPROVEMENTS

Traditional benefit/cost analysis for bottleneck improvements uses delay as its basis, assigning a certain value to person or vehicle hours of delay. The problem with this methodology, in certain instances, is that the assumptions or methodology used to estimate future speeds (and travel times) may turn out to be inaccurate. As was shown above, even the best simulation models can have varying results, depending on the quality of the calibration. Additionally, the after-construction improvements may not be evident in the data. In an effort to examine this problem, a case study of the northbound IH35E bottleneck improvement was performed. The following paragraphs describe that case study and the findings of this portion of the research.

Case Study: Northbound IH35E (Stemmons) Bottleneck Improvement

The geometrics of this case study are presented in Figure 11. The methodology used for determining benefits for this bottleneck improvement was to look at speeds and volumes for the before and after cases for different approaches and different freeway sections. In most cases, the speeds changed very little, but volumes increased in almost every case. This can be explained by the nature of the improvement (adding auxiliary lanes or short sections of mainlane in strategic places) and in the fact that there was sufficient latent demand on the network to "fill in the gaps" created by the added capacity. The problem with determining appropriate benefits, before or after the improvement is actually made, is that the latent demand increases the volume on the freeway but keeps speeds from increasing. There is obviously some benefit being provided to those drivers who either were using a different facility before the improvement or were waiting in queues on the freeway. A methodology for assigning some monetary value to that benefit, or to determine whether or not this is possible, is the focus of this case study.

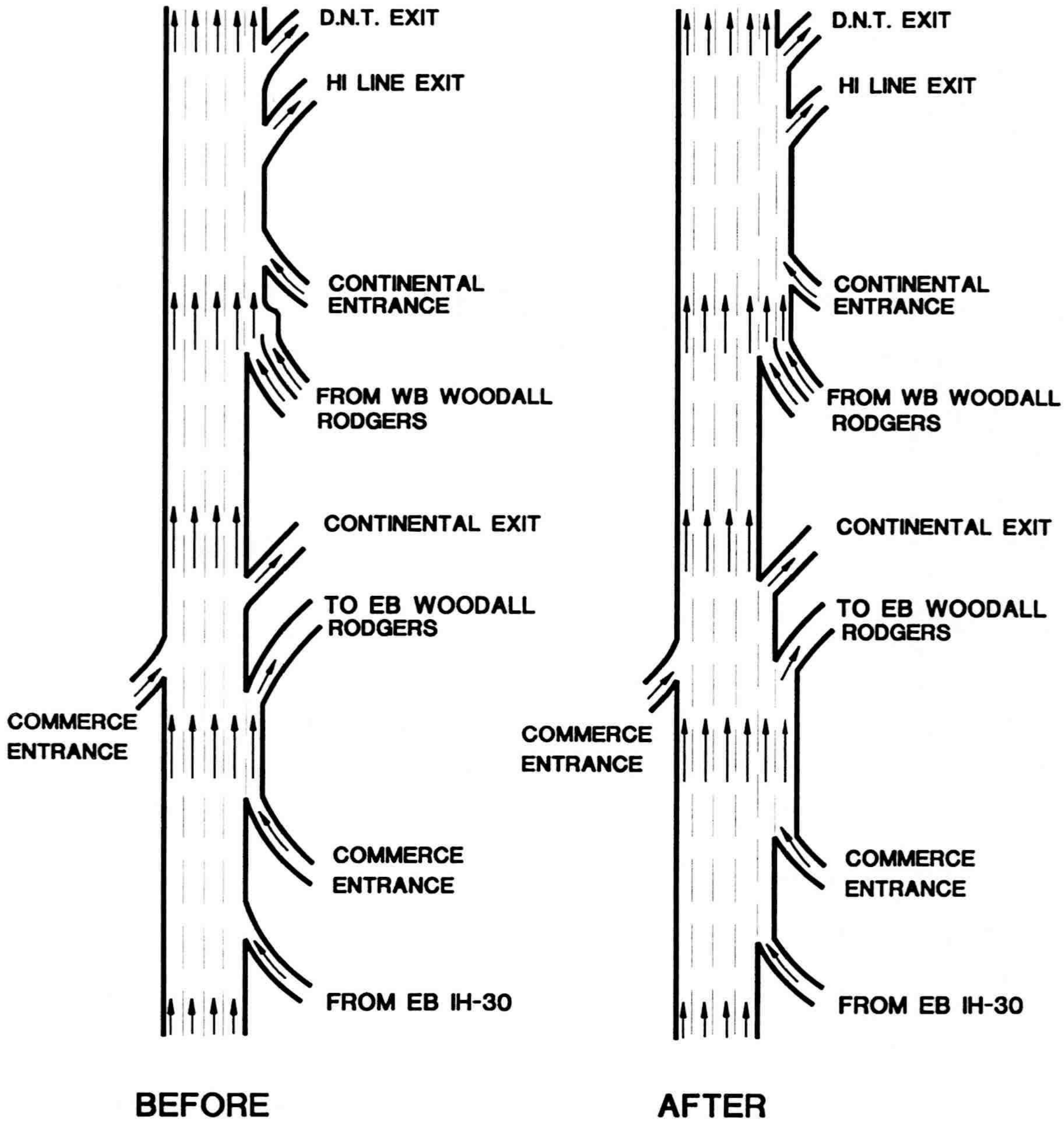


Figure 11. Northbound IH35E Stemmons Bottleneck Improvement

Table 3. Northbound IH35E Stemmons Before and After Bottleneck Evaluation Morning Peak Period

Roadway	Measures of Effectiveness	Before (1/96)	After (3/97)	Percent Change
NB IH35E SRLT to Stemmons (NB to NB)	Average Speed (kph (mph))	37 (23)	36 (22)	-2.9%
	Volume (vehicles)	9,266	10,101	9.0%
	Total travel (veh-kph (veh-mph))	342,800 (213,000)	363,600 (225,700)	5.8%
EB IH30 to Stemmons (EB to NB)	Average Speed (kph (mph))	66 (41)	60 (37)	-8.8%
	Volume (vehicles)	5,429	6,900	27.1%
	Total travel (veh-kph (veh-mph))	358,300 (222,600)	414,000 (257,200)	16.0%
WB IH30 to Stemmons (WB to NB)	Average Speed (kph (mph))	41 (25)	45 (28)	11%
	Volume (vehicles)	8,335	8,393	0.7%
	Total travel (veh-kph (veh-mph))	341,700 (212,300)	377,700 (234,700)	11.9%
NB IH35E: EB IH30 Ent. to Woodall Rodgers	Average Speed (kph (mph))	38 (24)	34 (21)	-11%
	Volume (vehicles)	26,594	30,241	13.7%
	Total travel (veh-kph (veh-mph))	1,010,600 (628,000)	1,028,200 (638,900)	1.4%
Woodall Rodgers to Stemmons (WB to NB)	Average Speed (kph (mph))	51 (32)	67 (42)	31%
	Volume (vehicles)	8,367	9,249	10.5%
	Total travel (veh-kph (veh-mph))	426,700 (265,100)	619,700 (385,100)	44.8%
NB IH35E: Woodall Rodgers to NB DNT Exit	Average Speed (kph (mph))	54 (34)	52 (32)	-3.3%
	Volume (vehicles)	19,423	22,176	14.2%
	Total travel (veh-kph (veh-mph))	1,040,900 (646,800)	1,148,800 (713,800)	10.4%

Table 3 contains the before and after measures of effectiveness for the northbound Stemmons bottleneck project. Each of the four freeway approaches are represented in the table. Again, it is important to note that this bottleneck improvement was primarily intended to improve operations on the eastbound IH30 and Woodall Rodgers approaches. Most importantly in the table are the values indicated for before and after speeds and volumes for each approach. Traditionally, the before-improvement speed would be recorded and the after speed estimated. The changes in these speeds would then be used for each section to estimate the benefit to be derived from the project and to compare the benefit to the estimated cost. It was initially expected that all approaches and northbound IH35E would be improved. The actual result was that volumes went up on all segments, but speeds only went up on two of the approaches. Therefore, it is more appropriate to assign benefits based on the increase in volume on the freeway. In other words, there was latent demand on the surrounding network or in queues that contributed to the additional volume while keeping speeds at before-improvement levels.

The real problem is that speed, or travel time, can be used to determine delay savings, which can be converted to a monetary benefit. In cases where there is sufficient latent demand that speeds do not increase through the bottleneck (but some benefit is being derived by the motorists who could not get through before the improvement), the problem is how to assess the level of benefit. It may be apparent visually and by inspecting the before and after data that some improvement was made, but monetary benefits need to be assessed.

One option is to assume some before speed (be it sitting in queue or on an arterial) for the motorists who were able to use the facility after the improvement was made. If you assume that the motorists were sitting still, then a benefit can be assessed based on the after-improvement average speed and the additional volume.

Another option would be to use a different measure of effectiveness that takes into account both speed and volume. One measure that is available is termed total travel and is simply the product of speed and volume. The problem with using another measure of effectiveness is that it is not easily converted to monetary benefits.

For examples of the merits of using an aggregate measure of effectiveness, Table 3 reports total travel in vehicle distance per hour. It is obvious that the use of total travel captures any improvement in speed that may take place but also includes any vehicles that were not able to get through the bottleneck before improvement. Again, although this may capture any capacity benefits provided by the bottleneck improvement, it is difficult to assign a monetary value to total travel.

The bottleneck improvement used for this case study is a complex example of a bottleneck improvement. First, there were actually a series of bottlenecks causing congestion (the merge at the eastbound IH30 entrance ramp, the merge at the Woodall Rodgers entrance, and a deficiency in the number of through lanes). Only two of these problems were addressed by this bottleneck improvement project. Second, there is sufficient demand on this network to justify a new freeway, which is in the planning stages. Some motorists sit in queues on a daily basis, and others use the arterial network to bypass this section of Stemmons. It was, therefore, quite difficult to estimate what the benefits of this bottleneck would have been beforehand and, likewise, difficult to assess benefits after construction. The best description of the improvement is that more people are using the freeway, and we can assume the additional motorists are gaining some benefit over the before-construction conditions.

DISCUSSION OF BENEFIT ESTIMATES

It is obvious after examining the northbound IH35E bottleneck project that assessing benefits is not always as simple as collecting speeds and assessing a dollar value to the delay savings. This methodology may work quite well for simpler bottleneck projects where the demand is not as high and removal of the bottleneck is obvious. However, the traditional benefit-cost analysis does not always work out for reasons described earlier. The benefits are apparent to the motorist as flow is improved and operations seem safer. But the real benefit to the system is that more motorists are using the appropriate facility for their commuting trip. So, delay savings may be assessed to those motorists who could not use the facility before the improvement, assuming that they were stopped (or traveling slowly) before the improvement. The only other alternative would be to adopt the use of some other measure of effectiveness to assess the benefit.

Some bottleneck improvement projects may not work as well as the designer intended due to influences such as latent demand or hidden bottlenecks within the system. But when motorists report improved conditions after the improvement is made (as was the case with the Stemmons bottleneck), it is necessary to try and understand why the data reflect little or no improvement. One explanation is that the improvement allowed additional motorists on certain approaches to enter the facility. These motorists see an improvement because they are moving on the freeway instead of sitting in a queue on the approach ramp. It is logical to examine the benefits in these terms and realize that the demand on the system is such that no small bottleneck improvement will result in free flow conditions, but the improvement does result in smoother flow and a benefit to some of the motorists. Otherwise, some monetary value for increased total travel needs to be developed as part of future research.

CONCLUSIONS

- "Before" data need to be collected beginning outside the region of congestion, both temporal and spatial.
- Speed and volume data on alternate routes should be collected.
- "After" data should be collected the same way as "before" data.
- Increased volumes should be assessed benefits based on the average speed of the alternate routes.
- Original volumes should be assessed benefits based on speed increases or decreases.
- Throughput increases should be identified, even without monetary benefits.

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