# Operational Analysis of Terminating Freeway Auxiliary Lanes with One-Lane and Two-Lane Exit Ramps: A Case Study

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This paper summarizes the findings of a case study on the operational analysis of weaving areas created by auxiliary lanes between two successive interchanges. For auxiliary lanes less than 1,500 feet in length, AASHTO lane balance principles permit the termination of the auxiliary lane with a one-lane exit ramp. For auxiliary lanes greater than 1,500 feet in length, the lane balance principles require that the auxiliary lane be dropped with a two-lane exit ramp or tapered into the through roadway downstream of a one-lane exit ramp. The operational analyses of the case study were conducted as part of a Major Investment Study (MIS) in Dallas, Texas. As part of the study, auxiliary lanes were recommended at various locations along two major freeway corridors. At twenty of these locations, additional analyses were conducted to compare the quality-of-service provided by a one-lane exit ramp versus a two-lane exit ramp. The range of traffic and geometric conditions among the twenty sites varied. The analyses were conducted using three software packages: the Highway Capacity Software (HCS), CORSIM and Synchro/Simtraffic. The findings of the case study suggest that a one-lane exit ramp may provide the best traffic operations regardless of weaving length. The experience gained from the case study is presented to aid practitioners in the design of safe and efficient freeway facilities and to aid researchers in current and future efforts to define and understand the operational effects of geometric design. Key words: traffic operations, simulation, lane balance, auxiliary lanes, weaving.

## INTRODUCTION

Few would argue that the urban freeway corridors throughout the United States are becoming increasingly congested. Inadequate capacity, substantial traffic volume growth, aging infrastructure, and the presence of nonstandard design features are all contributing factors to this growing problem.

The challenge ahead for today's engineers and planners is amplified by lessons learned that we cannot always build our way out of a problem. Right-of-way constraints, funding limitations and the public's growing sensitivity to the environmental impacts of roadway projects have forced the transportation industry to do more with less. For freeway systems, this means less dependence on expensive widening projects and a greater emphasis on managing demand and implementing cost-effective improvements to eliminate bottlenecks. Auxiliary lanes and the principles of lane balance are excellent examples of the latter. They play an important role in the ability of a freeway system to efficiently and safely accommodate higher traffic volumes without the addition of basic freeway lanes.

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## GUIDELINES FOR AUXILIARY LANES

The American Association of State Highway and Transportation Officials (AASHTO) *(1)* 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. 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.

This paper focuses on auxiliary lanes between two successive interchanges. Under these conditions, the auxiliary lane serves both as an acceleration lane for entering traffic and as a deceleration lane for exiting traffic. The auxilary lane is typically added with a single entrance ramp lane while the termination of the auxiliary lane is subject to the principles of lane balance.

## PRINCIPLES OF LANE BALANCE

To realize efficient traffic operation through and beyond an interchange, AASHTO recommends that there be a balance in the the number of traffic lanes on the freeway and ramps. For auxiliary lanes between two successive interchanges, two conditions are possible:

- Condition 1: For auxiliary lanes less than 1,500 feet in length (e.g., between closely spaced interchanges or between the loop ramp entrance and the loop ramp exit of a cloverleaf interchange), the lane balance principles permit the termination of the auxiliary lane with a one-lane exit ramp as shown in Figure 1.
- Condition 2: For auxiliary lanes greater than 1,500 feet in length, the lane balance principles state that the number of approach lanes on the freeway must be equal to the number of lanes on the exit, less one.

Under Condition 2, the auxiliary lane may be terminated by one of two methods. The first method, shown in Figure 2, drops the auxiliary lane with a two-lane exit. In this configuration, traffic in the auxiliary lane must exit. Traffic in the basic lane to the left of the auxiliary lane may exit or may proceed along the mainline. The second method, shown in Figure 3, provides a one-lane exit ramp, but carries the auxiliary lane through the exit before it is tapered into the through roadway. This design provides a recovery lane for drivers who inadvertantly remain in the discontinued lane.

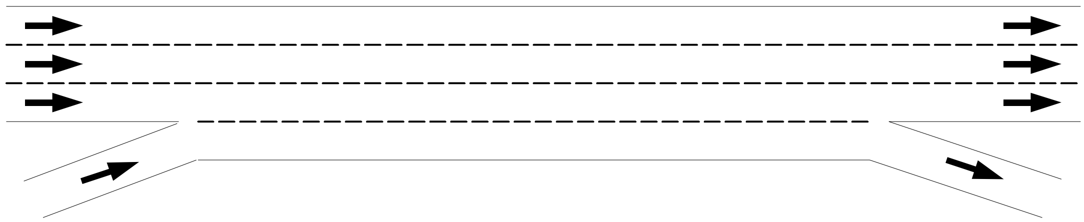

**FIGURE 1 Auxiliary lane terminated with one-lane exit ramp**

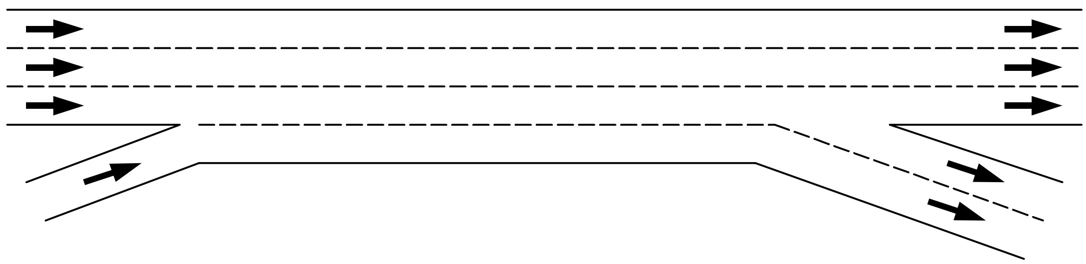

**FIGURE 2 Auxiliary lane terminated with two-lane exit ramp**

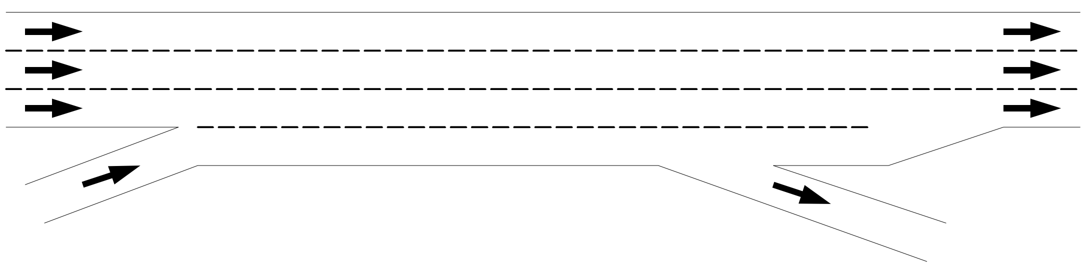

**FIGURE 3 Auxiliary lane terminated with downstream taper**

From personal observations, the application of AASHTO guidelines regarding auxiliary lanes and lane balance seems to vary from state-to-state. This variation is due, in part, to interpretation of the guidelines by agency/consultant staff, differences in the driver characteristics and driving environments that each state must provide for, and the lessons learned from past experiences. Even in cases where AASHTO guidelines are applied consistently, such decisions are oftentimes made during final design activities when it is too late for the appropriate consideration of the operational effects of design decisions.

## OPERATIONAL ANALYSIS – PAST, CURRENT AND FUTURE RESEARCH

The methodologies for analyzing freeway weaving sections that are contained in Chapter 4 of the 1997 Highway Capacity Manual (HCM) *(2)* are based on research conducted in the early 1960s through the early 1980s *(3-7)*. Recent research on basic freeway sections *(8)* and ramp junctions *(9)* has been incorporated but has not resulted in significant changes to the methodology.

In the HCM procedures, the configuration of the weaving section is the critical geometric condition affecting the quality of weaving operations. Three types of configuration (A, B and C) are defined based on the minimum number of lane changes that must be made by weaving vehicles as they travel through the weaving section. A freeway auxilary lane added with a one-lane entrance ramp and terminated with a one-lane exit ramp is defined as a Type A weave. A freeway auxilary lane added with a one-lane entrance ramp and terminated with a two-lane exit ramp or tapered into the through roadway downstream of a one-lane exit ramp is defined as a Type B weave.

On-going research being conducted under the National Cooperative Highway Research Program (NCHRP) will result in improved methods for capacity and quality-of-service analyses of weaving areas *(10)*. In addition to updating the freeway methodologies of the HCM, the findings of the research will address analysis of weaving areas on arterials, collector-distributor roads, and frontage roads. Another key element of the research is the assessment of the applicability and validity of traffic simulation models for analysis of weaving areas. Based on the scheduled completion of the research and, in part, on the controversial nature of the proposed methodologies, the findings of the research are not expected to be included in the 2000 Highway Capacity Manual, scheduled for completion in early 2000. As such, it is unknown when the new methodology will be available to practitioners.

## AN OPERATIONAL ANALYSIS CASE STUDY

This paper summarizes the findings of a case study on the operational analysis of the weaving areas created by auxiliary lanes between two successive interchanges. The operational analyses of the case study were conducted as part of a Major Investment Study (MIS) in Dallas, Texas.

### Study Background

The Northwest Corridor Major Investment Study was initiated by Dallas Area Rapid Transit (DART) in the Spring of 1998. The Northwest Corridor extends in a northwesterly direction from downtown Dallas and includes portions of the I-35E (15.7 miles) and SH 114 (8.9 miles) freeway corridors. Mobility elements evaluated as part of the MIS include rail transit, HOV lanes, general freeway improvements, bus service improvements, Transportation System Management (TSM), Travel Demand Management (TDM), and Advanced Transportation Management Systems (ATMS)/Intelligent Transportation Systems (ITS).

A key element of the study was the identification of freeway bottleneck improvements in the I-35E and SH 114 corridors to be included in the TSM/TDM alternative. Bottleneck locations were identified as those areas with poor level of service (LOS E or F) and/or poor accident ratings. In each of the bottleneck areas, improvement alternatives that were considered to be within the context of a TSM alternative were identified and assessed. Additional basic lanes or other major capacity-adding measures were not considered. Based on operational analyses (which are not addressed in this paper), auxiliary lanes were recommended at various locations within the study area to improve the level of service between two successive interchanges and to assist in accommodating high entering and/or exiting traffic volumes.

### Auxiliary Lanes Alternatives

For auxiliary lanes added to existing freeways, tapering the auxiliary lane downstream of a one-lane exit ramp of a diamond interchange configuration can be cost-prohibitive. For elevated freeways (e.g., cross-street under the freeway), this taper would likely occur on structure. For depressed freeways (i.e., cross-street over the freeway), this taper is oftentimes constrained by bridge piers or abutments. Since the purpose of the bottleneck analysis was to identify low-cost improvements for inclusion in a TDM/TSM alternative, tapering the auxiliary lane downstream of a one-lane exit ramp was eliminated from further consideration.

On the surface, eliminating the option of tapering the auxiliary lane downstream of the exit ramp would appear to simplify the decision-making process to the following:

- For auxiliary lane length < 1,500 feet – Terminate auxiliary lane with one-lane exit ramp.
- For auxiliary lane length > 1,500 feet – Terminate auxiliary lane with two-lane exit ramp.

The AASHTO guidelines *(1)* imply that the provision of lane balance is necessary for efficient traffic operations. Are we sure? Is it possible that terminating auxiliary lanes of less than 1,500 feet with a two-lane exit ramp provides the best traffic operations? Similarly, is it possible that terminating auxiliary lanes of greater than 1,500 feet with a one-lane exit ramp provides the best traffic operations? To provide insight to this question, further operational analyses were conducted at 20 locations where auxiliary lanes were recommended. At each location, the analyses compared the quality-of-service provided by a one-lane exit ramp versus a two-lane exit ramp.

### Site Characteristics

Ten sites from the I-35E corridor (five southbound sites and five northbound sites) and ten sites from the SH 114 corridor (five eastbound site and five westbound sites) were evaluated. The analyses were conducted using existing peak hour traffic volumes. The range of traffic and geometric conditions among the 20 sites varied as follows:

- Number of directional freeway lanes (upstream of the weaving section): 2-3
- Number of directional freeway lanes in the weaving section: 3-4
- Weaving section length (feet): 1,100-3,600
- Freeway volume (per lane) upstream of the weaving section (vph): 1,590-2,295
- Entrance ramp volume (vph): 330-1,420
- Exit ramp volume (vph): 150-1,200

Other key assumptions included:

- Mainline free flow speed: 60 mph on I-35E; 70 mph on SH 114
- Ramp speed: 45 mph
- No ramp-to-ramp traffic
- All other conditions ideal

### Methodology

Three software packages were utilized to assess the quality-of-service provided in the weaving section for one-lane exit ramps versus two-lane exit ramps.

1. ***Highway Capacity Software (HCS) Version 3.1a*** - HCS is a macroscopic, deterministic model which replicates the procedures of Chapter 4 of the 1997 HCM. In these procedures, the quality-of-service within a weaving section is based on the average density of all vehicles in the section. With the exception of weaving section length, all of the analysis locations of the case study reflect geometric and operational conditions within the limitations of the HCM procedures. The weaving length limitations of the HCM represent the range of the data used in the calibration of the HCM methodology. However, input values beyond the limitations do not necessarily result in erroneous findings. Although the HCM recommends the application of Chapter 5 (Ramp Junction) procedures for these cases, the weaving procedures were applied for comparison purposes. For the purposes of the case study, the configuration providing the lowest average density in the weaving section was assumed to provide the best traffic operations.
2. ***CORSIM (TSIS Version 4.2)*** - Sponsored by the Federal Highway Administration, CORSIM is a microscopic, stochastic simulation model for analyzing urban networks. In microsimulation each vehicle is individually tracked through the model, and com-

**TABLE 1 Operational Analysis Summary**

| Facility | Direction | Location | Number of Upstream Basic lanes | Number of Lanes in Weaving Section | Length of Weaving Section (ft) | Peak Hour Volume (vph): Up-stream Freeway | En-trance Ramp | Exit Ramp | Down-stream Freeway | Exit Ramp Configuration Providing Best Operations: HCS | CORSIM | Synchro/ Simtraffic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I-35E | Northbound | Mockingbird to Empire Central | 3 | 4 | 1,400 | 4,760 | 510 | 270 | 5,000 | 1-lane | 1-lane | 1-lane |
| I-35E | Northbound | Regal Row to Raceway | 3 | 4 | 2,100 | 5,680 | 1,010 | 790 | 5,900 | 1-lane | 2-lane | 1-lane |
| I-35E | Northbound | Northside to Whitlock | 3 | 4 | 1,900 | 5,730 | 1,030 | 440 | 6,320 | 1-lane | 1-lane | 1-lane |
| I-35E | Northbound | Hebron Pkwy to Corporate Drive | 3 | 4 | 2,200 | 5,690 | 1,120 | 590 | 6,220 | 1-lane | 1-lane | 1-lane |
| I-35E | Northbound | Corporate Drive to SH 121 | 3 | 4 | 1,900 | 6,220 | 630 | 1,000 | 5,850 | 1-lane | 1-lane | 1-lane |
| I-35E | Southbound | SH 121 to Corporate Drive | 3 | 4 | 1,900 | 6,000 | 940 | 940 | 6,000 | 1-lane | 2-lane | 1-lane |
| I-35E | Southbound | Corporate Drive to Hebron Pkwy | 3 | 4 | 2,300 | 6,000 | 520 | 1,200 | 5,320 | 1-lane | 1-lane | 1-lane |
| I-35E | Southbound | Vista Ridge to Frankford | 3 | 4 | 2,700 | 4,930 | 810 | 1,010 | 4,730 | 1-lane | 1-lane | 1-lane |
| I-35E | Southbound | Regal Row to Empire Central | 3 | 4 | 2,000 | 5,280 | 460 | 800 | 4,940 | 1-lane | 1-lane | 1-lane |
| I-35E | Southbound | Empire Central to Mockingbird | 3 | 4 | 1,500 | 4,940 | 450 | 1,140 | 4,250 | 1-lane | 1-lane | 1-lane |
| SH 114 | Eastbound | Freeport to Esters | 3 | 4 | 1,400 | 6,170 | 330 | 500 | 6,000 | 1-lane | 1-lane | 1-lane |
| SH 114 | Eastbound | Esters to Belt Line | 3 | 4 | 3,600 | 6,000 | 440 | 1,060 | 5,380 | 1-lane | 1-lane | 1-lane |
| SH 114 | Eastbound | Belt Line to Valley View | 3 | 4 | 3,500 | 5,380 | 1,250 | 230 | 6,400 | 1-lane | 1-lane | 1-lane |
| SH 114 | Eastbound | Valley View to Walnut Hill | 3 | 4 | 2,100 | 5,090 | 710 | 410 | 5,390 | 1-lane | 1-lane | 1-lane |
| SH 114 | Eastbound | O'Connor to Rochelle | 2 | 3 | 1,900 | 4,300 | 420 | 800 | 3,920 | 1-lane | 2-lane | 1-lane |
| SH 114 | Westbound | Rochelle to O'Connor | 2 | 3 | 1,100 | 3,880 | 870 | 290 | 4,460 | 1-lane | 2-lane | 1-lane |
| SH 114 | Westbound | O'Connor to Hidden Ridge | 2 | 3 | 1,100 | 4,460 | 1,420 | 150 | 5,730 | 1-lane | 2-lane | 1-lane |
| SH 114 | Westbound | Valley View to Beltline | 3 | 4 | 2,200 | 6,850 | 900 | 840 | 6,910 | 1-lane | 2-lane | 1-lane |
| SH 114 | Westbound | Belt Line to Esters | 3 | 4 | 2,600 | 6,710 | 790 | 620 | 6,880 | 1-lane | 1-lane | 1-lane |
| SH 114 | Westbound | Esters to Freeport | 3 | 4 | 1,600 | 6,880 | 400 | 700 | 6,580 | 1-lane | 2-lane | 1-lane |

prehensive operational measures of effectiveness are collected on every vehicle in the model for every second of model simulation. A wide variety of link and system-wide operational measurement statistics can be generated. For each analysis location, a simple model network representing the weaving section was created. In the comparison of one-lane exit ramps and two-lane exit ramps, all input parameters except the exit ramp configuration were held constant. For the purposes of the case study, the configuration providing the lowest overall delay for the entire system was assumed to provide the best traffic operations.

3. ***Synchro/Simtraffic Version 4.0*** - Synchro/Simtraffic is also a microsimulation package. Originally developed for intersection and arterial traffic flow, Synchro/Simtraffic has been updated to now model freeways including high speed merges and weaving sections. Similar to the CORSIM methodology, a simple model network representing the weaving section was created for each analysis location. In the comparison of one-lane exits and two-lane exits, all input parameters except the exit ramp configuration were held constant. For the purposes of the case study, the configuration providing the lowest overall delay for the entire system was assumed to provide the best traffic operations.

## Findings

The results of the assessment are summarized in Table 1. The key input data and the configuration providing the best traffic operations for the three methodologies are summarized in Table 1 for each methodology. Key observations from the findings include:

- Based on results of the HCS analyses, a one-lane exit ramp provided better traffic operations than a two-lane exit ramp at all twenty locations. In each case, the two-lane exit ramp (analyzed as a Type B weave configuration) resulted in higher average density within the weaving section than did a one-lane exit ramp (analyzed as a Type A weave configuration). The increase in density ranged from 12.8% to 29.5% and averaged 21.6%.

- Based on the results of the CORSIM analyses, a one-lane exit ramp provided better traffic operations at thirteen of the twenty locations. However, at all twenty locations the change in total system delay between the one-lane exit ramp configuration and the two-lane exit ramp configuration was not substantial, ranging from –2.4% (where the two-lane exit ramp provided the best traffic operations) to 3.7% (where the one-lane exit ramp provided the best operations). Of the five locations with weaving length of 1,500 feet or less, three locations operated best with a one-lane exit ramp while two locations operated best with a two-lane exit ramp. Of the fifteen locations with weaving length greater than 1,500 feet, ten locations operated best with a one-lane exit ramp while five locations operated best with a two-lane exit ramp.
- Based on results of the Synchro/Simtraffic analyses, a one-lane exit ramp provided better traffic operations than a two-lane exit ramp at all twenty locations. In each case, the two-lane exit ramp resulted in higher total system delay than did a one-lane exit ramp. The increase in total system delay ranged from 0.4% to 309.9% and averaged 33.7%.

## CONCLUSIONS

For auxiliary lanes less than 1,500 feet in length, AASHTO lane balance principles permit the termination of the auxiliary lane with a one-lane exit ramp. For auxiliary lanes greater than 1,500 feet in length, the lane balance principles require that the auxiliary lane be dropped with a two-lane exit or tapered into the through roadway downstream of a one-lane exit. The findings of the case study suggest that a one-lane exit ramp may provide the best traffic operations, regardless of weave length. Observations using the animation feature of the simulation models provided a possible explanation for these findings. With a one-lane exit ramp, all of the exiting traffic must utilize the auxiliary lane. With a two-lane exit ramp, a portion of the exiting traffic remains in the basic lane to the left of the auxiliary lane. This was observed to result in a higher density for the basic lane and additional delay for through traffic.

This paper presents the findings of a case study. No field data to collaborate or refute the findings of the case study were collected. Although all of the analysis sites are located in the Dallas metropolitan area, it is important to note that the analyses were conducted based on assumed rather than measured driver characteristics. Thus, the relevance of the findings is not restricted to a specific geographical area.

The experience gained from the case study is presented to aid practitioners in the design of safe and efficient freeway facilities and to aid researchers in current and future efforts to define and understand the operational effects of geometric design. To the latter, the findings of the case study support the need for additional research on the operational effects of auxiliary lanes and lane balance.

## ACKNOWLEDGEMENT

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