Appendix H
Operational Analysis of the C-470 Ramp Complex

PBS&J

An employee-owned company

DRAFT TECHNICAL MEMORANDUM

TO:

FROM:

DATE:

SUBJECT: Operational Analysis of the C-470 Slip Ramp Complex

Introduction

The Express Lane Feasibility Study (ELFS) was conducted in parallel with the C-470 Environmental Assessment (EA), which evaluated potential solutions to congestion and reliability problems on the corridor between South Kipling Parkway and I-25. This study used 2025 as the planning horizon year. The C-470 express lanes (EL) would charge a variable toll to control the facility volume to maintain reliable, free flow traffic conditions. Several different types of ramps were proposed to provide access to and from the express lane to the general purpose lanes (GPL). One such type of access ramp included in the proposed design was slip ramps.

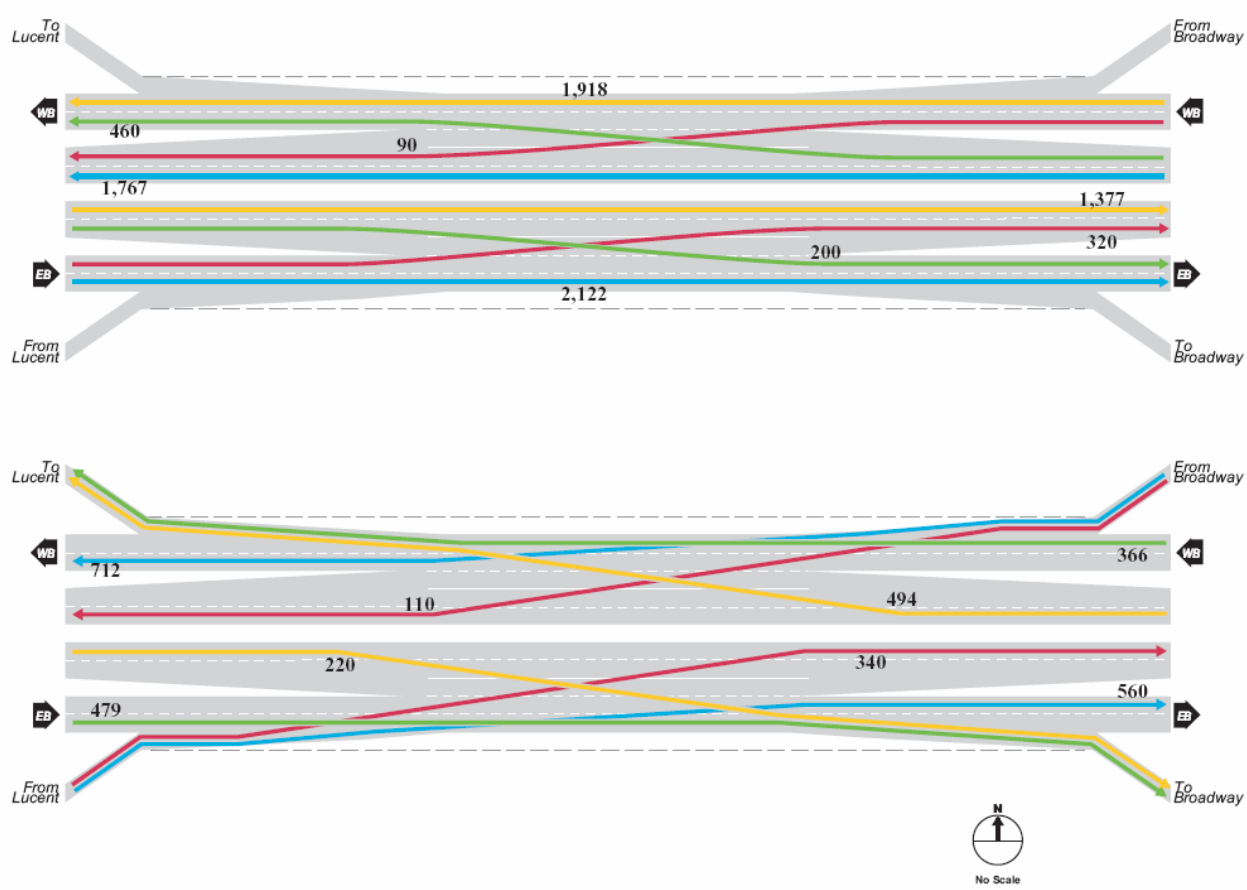
It is our understanding that questions have been raised regarding the capacity of slip ramps on express lane facilities. We also understand that it has been recommended that a threshold established by a Federal Highway Administration (FHWA) sponsored study conducted by Texas Transportation Institute (TTI) should be used to assess the capacity of a slip ramp. Chapter 5 of the TTI study (*Managed Lane Ramp and Roadway Design Issues, FHWA/TX-03/4160-10, January 2003*) suggests that slip ramps can only accommodate between 200-350 vehicles per hour. The intent of this memo is to list the differences between the TTI and C-470 study, discuss the methodology used in the C-470 study and to discuss a few alternative scenarios that were analyzed to answer these questions. Results from the C-470 study indicate that 600 to 1000 vehicles per hour can use the slip ramps with minimal impact to the operation of the express or general purpose lanes.

Slip Ramp Analysis (Proposed Configuration)

A micro-simulation model (AIMSUN) was used to model the proposed laneage and express lane configuration on C-470 to assess traffic operations for future volumes. Density and speed were used as the primary measures of effectiveness (MOEs) to determine the quality of operations on the general purpose (non-toll) and express (toll or managed) lanes. A full slip ramp that provides ingress and egress points into and out of the express lanes in both directions of flow was proposed for a roadway segment between Lucent and Broadway interchanges only. Figure 1 lists the projected volumes for this location.

5500 Greenwood Plaza Boulevard, Suite 150, Greenwood Village, Colorado 80111 Telephone: (303) 221-7275 Fax: (303) 221-7276

Figure 1: Projected 2025 PM Volumes for Lucent-Broadway Interchange Slip Ramps



The volumes shown in Figure 1 were obtained from a calibrated micro simulation model that contained travel demand in the form of an origin-destination matrix. Various MOEs including speed, density, queue, discharge and delay time were obtained for these volumes and proposed lane configuration. Figure 2 and Table 1 list the proposed lane configurations and traffic operations.

Figure 2: Proposed Slip Ramp Configuration

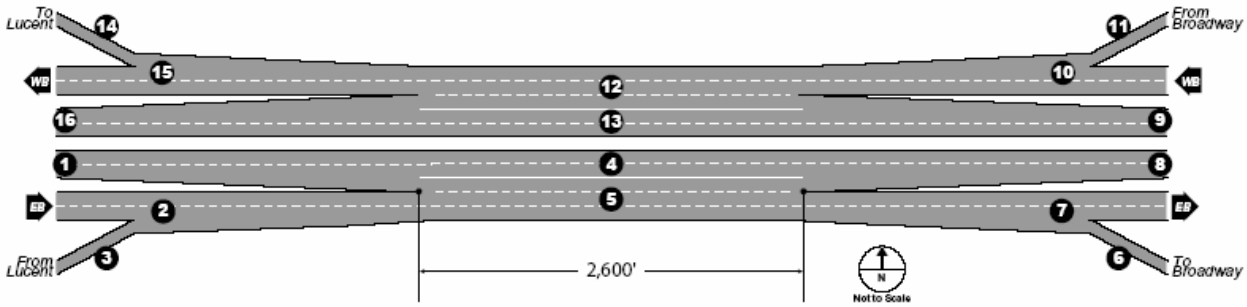


Table 1: Projected 2025 PM Traffic Operations for the Lucent-Broadway Slip Ramp

Section	Flow (vph)	Density (vpm)	Speed (mph)	LOS
1	1797	8.10	64.27	**A**
2	4161	95.40	19.74	**F**
3	909	46.02	19.75	**F**
4	1376	5.59	61.59	**A**
5	4582	43.01	53.26	**E**
6	1026	21.65	47.40	**C**
7	3908	31.17	53.22	**D**
8	2027	17.00	59.62	**B**
9	2712	21.66	62.60	**C**
10	3445	84.31	20.43	**F**
11	861	58.19	14.80	**F**
12	4534	24.14	46.95	**C**
13	1758	7.14	61.59	**A**
14	860	26.00	33.08	**C**
15	4334	58.16	37.26	**F**
16	1968	15.38	63.98	**B**

A detailed discussion of the operations and interaction of various components of a slip ramp was provided in a technical memorandum dated November 18, 2004. The Colorado Department of Transportation (CDOT) reviewed the operational analysis for C-470 in addition to other projects proposing slip ramps in the Denver metro area and had the following comments/concerns:

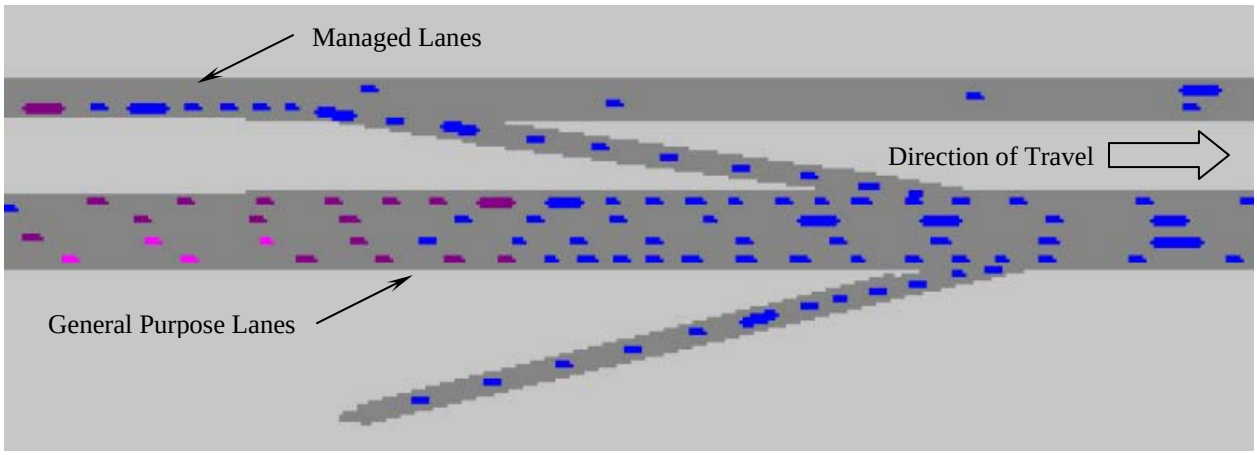
1. Threshold values recommended in the TTI study (350 vph for high volume conditions) shall be used to determine the adoption of slip ramp versus a direct connect (braided) ramp.
2. Slip ramps should be analyzed as a complex and a thorough analysis conducted to assess the turbulence prevalent at a slip ramp location.
3. The projected operations on the managed lanes in the vicinity of the slip ramp would deteriorate once a continuous auxiliary lane is provided between an entry and exit ramp pair on the non-toll lanes at this location. An additional scenario with a continuous auxiliary lane on the non-toll lanes has to be analyzed to assess the impact of the auxiliary lanes on the toll lane operations. An auxiliary lane has to be built to address any bottlenecks prevalent on the non-toll lanes as a part of this alternative.
4. Ramp operations and safety concerns due to the distance from the freeway on and off ramp access to the managed lanes on and off slip ramps should be addressed. It was suggested that the recommended distance separating toll and non-toll lane ramps was to be maintained at 1000 feet per lane with a preferred minimum distance of 2500 feet. It was also indicated that a ramp separation distance of 1.5 to 2 miles suggested by other studies be considered for all slip ramp locations to preserve freeway operations under high volume freeway operating conditions.
5. Both the weaving operation and ramp separation need to be reviewed before slip ramps can be recommended over the improved efficiency, safety and capacity of grade separated ramps to serve the managed lanes.

Review of TTI Slip Ramp Study

Several research and analysis efforts were undertaken as a part of the C-470 study to address all the concerns expressed by reviewing agencies. The TTI managed lanes study was reviewed to reconcile difference between the TTI research effort and the C-470 Environmental Study and to identify revisions that could be performed to the C-470 operational analysis methodologies to address any potential shortcomings. A brief summary of the TTI study review is listed below.

- The basic conclusion of the report is that there is some volume of traffic on a ramp from managed lanes to general purpose lanes that above which direct connect ramps should be considered. That is, below a certain volume one should not bother with assessing direct connect ramps. This research does not present any conclusions regarding identifying a maximum volume above which direct connect ramps must be used.
- The description of the calibration procedures is scant. HCM weaving and capacity problems were used to examine and validate VISSIM results
- The slip ramp and mainline configuration is significantly different from that used for the C-470 project. The configuration assumed for the research effort did not include a receiving lane for the slip ramp from the managed lanes which could significantly influence the outcome of the research analysis.
- The research effort analyzed a 4 lane cross section for the mainline. Vehicles from the managed lanes have to negotiate 4 lanes of freeway traffic before they reach the exit. C-470 mainline has half that number of lanes on the freeway and carries only 40% of the mainline volumes used in the TTI study. The proposed slip ramp configuration for the C-470 study ensures that vehicles from the managed lanes have an opportunity to adjust their speeds before commencing the lane change to reach their destination.
- The TTI research effort assumed that 10% of the vehicles in the traffic stream would be trucks. C-470 corridor experiences low truck percentages in the peak hour (1.5-3%) which results in better operations than that predicted by the TTI research
- A target speed of 50 mph was used for the TTI study which, on a facility that justifies construction of parallel toll facilities seems unrealistic
- Absence of deceleration or acceleration lanes for the managed lanes (as shown by figure 5-4) may lead to inaccurate assessment of the operations on managed lanes and the ultimate capacity of the slip ramp. Figure 5-4 in the TTI report indicates the assumed lane configuration and the resultant congestion on the managed lanes. Figure 3 is directly reproduced from the TTI study and is listed below.
- Comparison of graphs listed in Figures 5-10 and 5-11 for conditions similar to C-470 (volumes of 2000 vphpl, 1000 vph for ramps, 20% weaving, and similar ramp spacing) indicates that the expected drop in speed is minimal.
- The conclusion of the study that “The High-Occupancy Vehicle Facilities: A Planning, Design, and Operations Manual (47) indicates that a direct connect ramp should be considered when ramp volume is 400 veh/hr. The findings from this simulation support that number” is true insofar as that is a threshold to begin to consider a direct connect. However many of the graphs presented in the report indicate that the freeway operates acceptably (45-50 mph) for much higher volumes.

Figure 3: Slip Ramp Configuration Assumed in the TTI Study
(Source: Managed Lane Ramp and Roadway Design Issues, FHWA/TX-03/4160-10, January 2003)



The review of the TTI managed lane study indicates that the methods used for the C-470 study is satisfactory and that the conclusion of the TTI study holds good only for a specific set of lane configurations, weaving patterns and traffic patterns. The recommendations of the TTI study cannot be directly applied to the C-470 EA due to significant differences in lane configurations, travel patterns and magnitude of volumes as summarized above. Detailed analysis of the slip ramps for the C-470 study indicates that the managed lanes operate acceptably while the non-toll lanes operate at some degree of congestion as expected, and that operations on the non-toll lanes do not cause queues to extend into the managed lanes. The vehicles on the non-toll lanes operate at a speed that allows for acceptable weave movements and lower speed differential between exiting managed lane traffic and non-toll lane traffic. Detailed analysis of the proposed configuration through a calibrated micro simulation model serves as a better tool for determination of type of access at a location. Generic trigger values serve as a good thumb rule for a few specific configurations but are unable to account for the intricate traffic interaction encountered in a typical slip ramp complex.

AIMSUN and CORSIM Comparison

The proposed slip ramp configuration was also analyzed using CORSIM to validate the results obtained by AIMSUN. Figure 4 shows the configuration of the slip ramp analyzed in AIMSUN and CORSIM, while Table 2 compares the AIMSUN and CORSIM predicted speeds for various sections in the slip ramp complex.

Figure 4: Proposed Slip Ramp Configuration

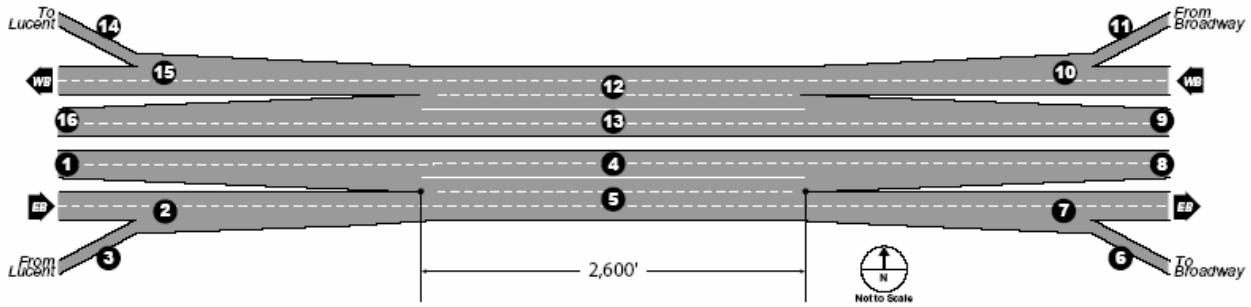


Table 2: Comparison of CORSIM and AIMSUN Operational Analysis

Section	Speed (mph)	
	AIMSUN	CORSIM
1	64.27	63.61
2	19.74	19.32
3	19.75	32.00
4	61.59	63.00
5	53.26	52.00
6	47.40	61.00
7	53.22	58.40
8	59.62	62.00
9	62.60	63.03
10	20.43	57.15
11	14.80	63.50
12	46.95	36.73
13	61.59	63.57
14	33.08	55.80
15	37.26	45.79
16	63.98	62.70

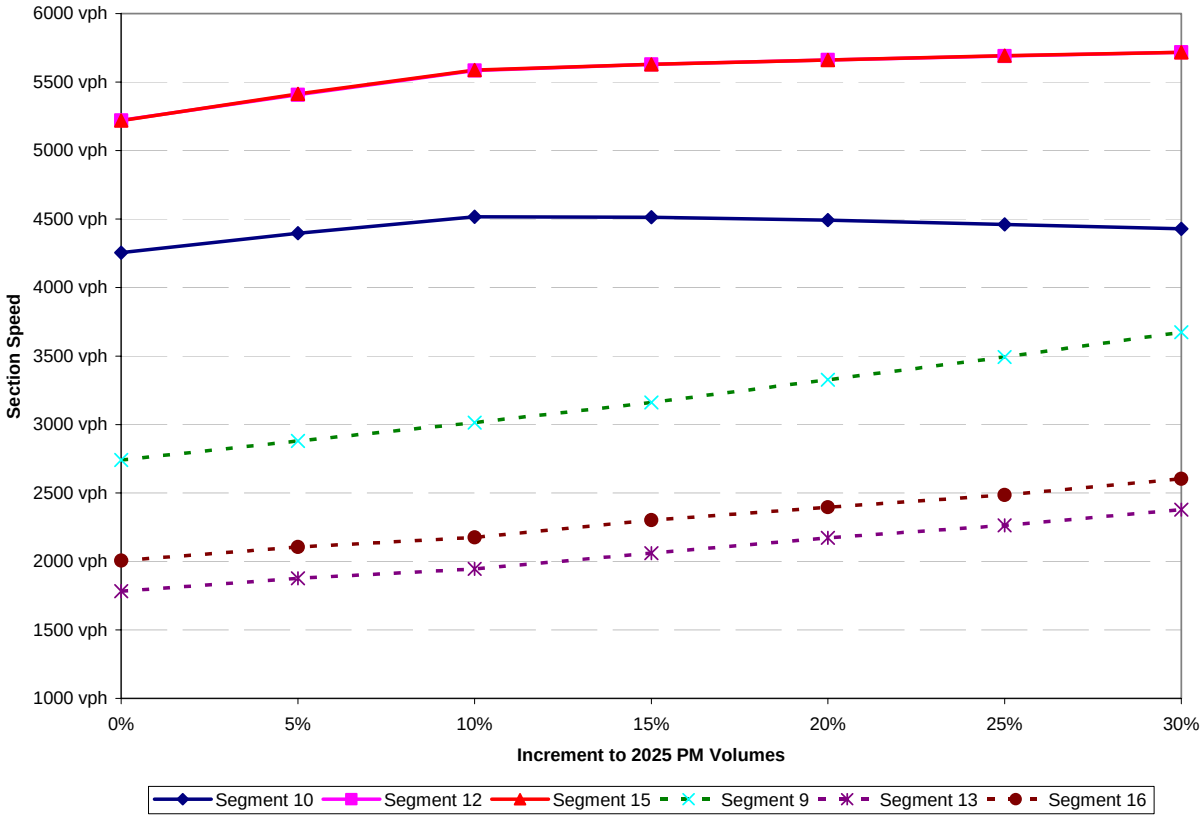
The AIMSUN and CORSIM comparative analysis indicates that AIMSUN yields a conservative analysis of the slip ramp complex and predicts slightly lower speeds for a few sections while the results for the managed lanes are very similar for both softwares. Unlike the AIMSUN model, the slip ramp complex analyzed in CORSIM did not include arterial intersections and adjacent interchanges. Such an "isolated" slip ramp analysis could explain some of the differences in CORSIM predicted speeds.

Reserve Capacity Analysis for Proposed Configuration

A sensitivity analysis was performed to determine the reserve or residual capacity of various elements in the slip ramp system. Year 2025 volume proportions were maintained and volumes were increased in five percent (of year 2025 volumes) increments to assess the impact of increased volumes on the slip ramp system. Variations in throughput PM volume in the peak

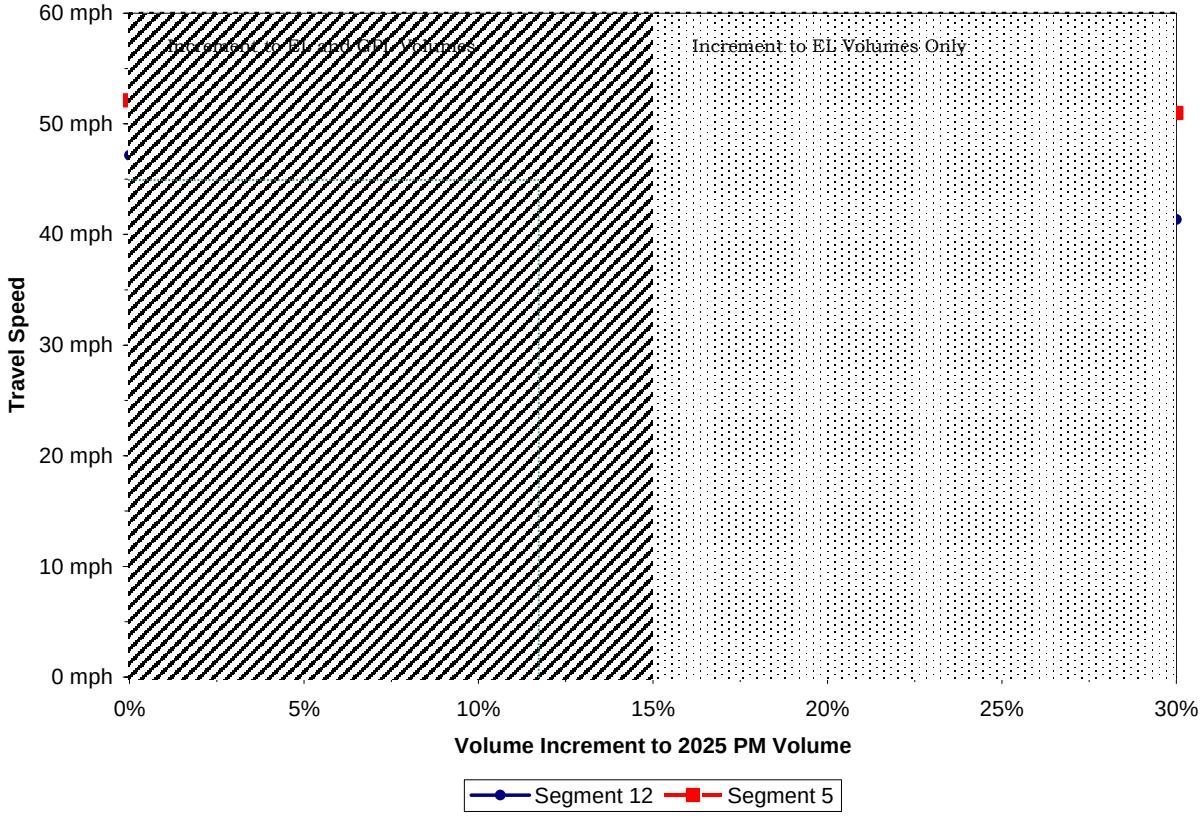
direction (westbound direction) for various elements of the slip ramp are shown in Chart 1.

Chart 1: Variation in Throughput Volume for Various Levels of Increased Traffic



The reserve capacity analysis indicated that a maximum throughput volume of 4500 vph (2250vphpl) is reached attained for a volume increment of 15%. Any further increase in GPL volumes translated to additional queues upstream of section 10 (merge section on GPL) instead of increased throughput to section 12. So, the GPL volumes were held at 1.15 times the 2025 volumes while only the EL volumes were increased beyond the 15% volume increment. The express lanes attained the maximum allowed volume limit (1600 to 1800 vphpl) on the EL facility for volumes that were 27% higher than the 2025 volume level. Hence, the maximum increase in volume was limited to 30% of year 2025 volumes since the maximum volumes that could be realized in a slip ramp of this configuration would be approximately 27% more than the 2025 volume (while maintaining 2025 volume proportions). Chart 2 shows the variation of realized speeds on segments 5 and 12 for various levels of volume.

Chart 2: Variation in Segment Speeds for Various Levels of Increased Traffic



As can be seen from Chart 2, segment 5 (eastbound GPL) experiences very little drop is operating speeds as volumes are increased since the eastbound direction is the off-peak direction for PM peak and so carries lower volumes. Travel speeds on section 12 (westbound GPL) remains above the 40 mph level for all volume levels and above 45 mph for volumes that are 12% higher than 2025 PM peak volumes. This 12% value translates to approximately 1068 vph entering the GPL from the EL via the slip ramp. However, the lowest speeds observed for segment 12 was approximately 42 mph and sections 9 and 13 operated at approximately 62 mph to 65 mph for all volume levels. The slip ramp system operated acceptably for all volume levels without exhibiting any breakdowns due to queues. The section of freeway upstream of section 10 did experience queues and delays when volumes exceeded the maximum capacity of that section as expected, but did not adversely influence operations of the slip ramp. In summary, increasing volumes on the general purpose lanes causes breakdowns prior to the slip ramp location. However, the slip ramp complex works satisfactorily despite increase in either the general purpose or express lane volumes.

Auxiliary Lane Analysis

A few additional scenarios were analyzed to determine the influence of managed and non-toll lanes on operations along both facilities. Auxiliary lanes were added on non toll lanes between

Lucent and Broadway. The auxiliary lane was introduced to attempt to remove the bottlenecks which would help assess the impact of a free flowing section on the operations of the slip ramp. Figure 5 shows the assumed lane configuration and the results of the analysis are listed in Table 3.

Figure 5: Proposed Lane Configuration

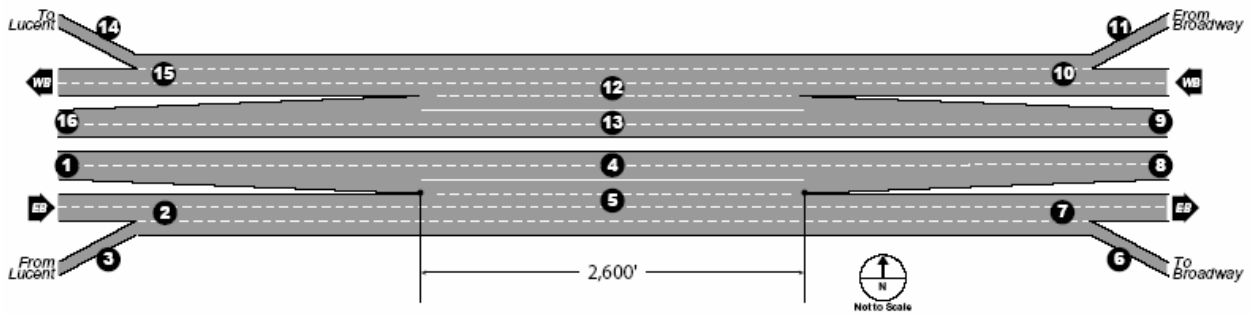


Table 3: Traffic Operations for the Lucent-Broadway Slip Ramp With an Auxiliary Lane

Section	Flow (vph)	Density (vpm)	Speed (mph)	LOS
1	1567	12.06	64.97	**B**
2	4667	65.90	35.41	**F**
3	1216	37.53	32.40	**E**
4	1176	9.69	60.71	**A**
5	5058	42.81	59.08	**E**
6	992	19.00	52.22	**C**
7	4485	41.92	53.50	**E**
8	1749	14.35	60.93	**B**
9	2146	16.50	65.03	**B**
10	4153	39.37	52.74	**E**
11	1180	29.37	40.18	**D**
12	5282	27.49	48.03	**D**
13	1381	5.29	65.23	**A**
14	1317	40.32	32.66	**E**
15	4657	43.05	54.09	**E**
16	1642	12.71	64.58	**B**

The analysis indicates that the auxiliary lanes benefit non-toll lanes and non-toll lane ramps to and from both the interchanges by accommodating additional volumes and hence reducing delay. The operations for some of these sections improve due to addition of one lane which is accompanied by slight increase in link volumes. However, the volumes on the Express Lanes and its ramps change slightly with no change in Level of Service for the toll lane facility. In fact the auxiliary lane slightly increases volumes on the toll lane on-ramps and does not cause the slip ramps to fail due to delays or queues. The slip ramp system works well with or without the auxiliary lane, while inclusion of the auxiliary lane increases right-of-way and environmental impacts.

Slip Ramp Elimination Analysis

An alternative scenario which provided no access to express lanes from the non toll lanes between Lucent and Broadway interchanges was analyzed. Access to and from the express lanes was eliminated to isolate the effects of managed lane ramps on operations along non toll lanes. Alternate access points between Broadway and University interchanges were provided to serve the prevalent express lane demand. Figure 6 illustrates the assumed lane configuration for this scenario and Table 4 lists the results of the operational analysis.

Figure 6: Assumed Lane Configuration for the Slip Ramp Elimination Analysis

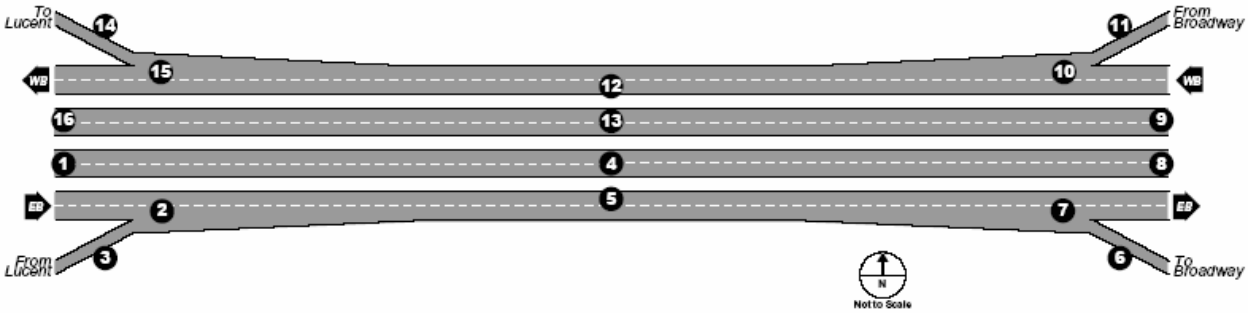


Table 4: Traffic Operations for the Lucent-Broadway Slip Ramp Without an Express Lane Access

Section	Flow (vph)	Density (vpm)	Speed (mph)	LOS
1	1296	10.65	60.86	A
2	4496	68.76	23.11	F
3	751	42.59	17.72	E
4	1296	10.65	60.86	A
5	4487	28.26	51.23	D
6	841	19.21	37.61	C
7	4496	68.76	23.11	F
8	1296	10.65	60.86	A
9	2244	18.59	61.92	C
10	4247	61.25	25.90	F
11	823	85.82	17.02	F
12	4262	28.62	52.55	D
13	2228	11.96	66.29	B
14	995	30.06	32.99	D
15	4247	61.25	25.90	F
16	2213	17.28	64.46	B

Results of the analysis indicate that elimination of an express lane access improves the operation slightly for the merge areas on the non toll lanes and degrades the operations for the non toll lane on-ramps. Elimination of the express lane access also degrades the non-toll lane operations in the peak direction. However, some of the perceived improvements caused due to elimination of express lane access are due to bottlenecks on ramps. Absence of express lane access leads to sustained congestion at the merge point which in turn does not allow volumes from arterials to enter the freeway. Hence, elimination of an express lane access is not accompanied by

overwhelming operational benefits. A comparison of travel speeds and densities along various sections of the Lucent-Broadway interchange complex for various express lane access configurations is listed in Table 5.

Table 5: Comparison of Speeds and Density for Various Express Lane Access Configurations

Section	Without Auxiliary Lane		With Auxiliray Lane		Without Express Lane Acces	
	Speed (mph)	Density (vpm)	Speed (mph)	Density (vpm)	Speed (mph)	Density (vpm)
1	64.27	8.10	64.97	12.06	60.86	10.65
2	19.74	95.40	35.41	65.90	23.11	68.76
3	19.75	46.02	32.40	37.53	17.72	42.59
4	61.59	5.59	60.71	9.69	60.86	10.65
5	53.26	43.01	59.08	42.81	51.23	28.26
6	47.40	21.65	52.22	19.00	37.61	19.21
7	53.22	31.17	53.50	41.92	23.11	68.76
8	59.62	17.00	60.93	14.35	60.86	10.65
9	62.60	21.66	65.03	16.50	61.92	18.59
10	20.43	84.31	52.74	39.37	25.90	61.25
11	14.80	58.19	40.18	29.37	17.02	85.82
12	46.95	24.14	48.03	27.49	52.55	28.62
13	61.59	7.14	65.23	5.29	66.29	11.96
14	33.08	26.00	32.66	40.32	32.99	30.06
15	37.26	58.16	54.09	43.05	25.90	61.25
16	63.98	15.38	64.58	12.71	64.46	17.28

Conclusion

It was recognized early in the traffic analysis process that adequate operations on slip ramps and non-toll lanes was essential to the success of toll lanes. To this end, all slip ramps were carefully analyzed and all ramps that caused deterioration in traffic operations were altogether eliminated or replaced with direct connections (ex: Quebec and I-25 access). The only location where a true slip ramp is being recommended is between Lucent Boulevard and Broadway interchanges in the eastbound and westbound directions. The slip ramps were developed based on CALTRANS highway design standards and allows for a distance of approximately 3300’ between the slip ramp exit gore and the non-toll lane on-ramp merge point which is much higher than the preferred 2500’ spacing. Similarly, the distance between the slip ramp merge point to the non-toll lane off ramp gore is approximately 3300’. It is not possible to provide a 2.5 mile spacing between the managed lane and non toll lane ramps since the average interchange spacing along C-470 is approximately one mile.

Direct connect ramps are not always a better solution as compared slip ramps. Direct connect ramps help separate exiting/entering toll lane traffic from non toll lane traffic. Direct connect ramps can be constructed only at locations where the ramp terminals have the required reserve capacity to allow for relatively high speed weaving traffic. Direct connect ramps have been provided at locations (Quebec interchange ramps and I-25 interchange ramps) where such ramps

have proved valuable in alleviating congestion on non toll lanes caused due to toll lane traffic. Despite their advantages, direct connect ramps pose additional concerns at merge points on interchange ramps where additional merge movements are created due to vehicles from toll and non toll lanes desiring to turn right and left at the ramp terminal intersection. This issue is further magnified by the significant speed differential in toll lane and non toll lane traffic on the interchange ramp along with queuing on ramps due to signals. Direct connect ramps limit access to the vehicles oriented to/from a specific interchange, pose additional safety issues as noted above in addition to encouraging out-of-way travel on local streets.

Inspection of MOEs from analysis of various alternatives, using various softwares, indicates that the slip ramps and toll lanes operate acceptably for the Lucent to Broadway section of C-470. However, the non toll lane on-ramp merge sections on the non-toll lanes operate poorly due to heavy merging volumes (similar to existing conditions). The turbulence points do not interact with or are not influenced by the toll lane slip ramps. A weaving analysis was conducted at the only location with a true slip ramp which indicated that the speed differential was not highly significant and that the weave section does not pose safety concerns for the express lanes. Provision of a slip ramp access was determined to be the optimal solution for the prevalent traffic conditions and was recommended due to all the factors listed above.