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Training Strategies and Materials

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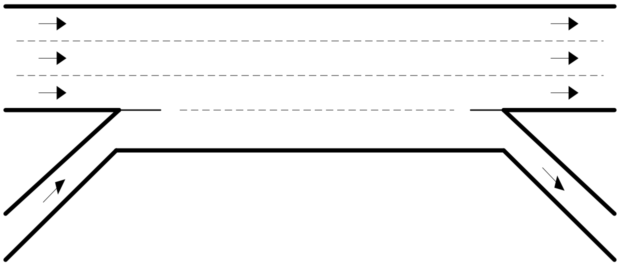

For TxDOT Project 0-6706:

DESIGN AND SCOPE OF IMPACT OF AUXILIARY LANES

by

Yi Qi, Ph.D.
Xiaoming Chen, Ph.D.
Lei Yu, Ph.D., P.E.
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Performed in Cooperation with the Texas Department of Transportation
and the Federal Highway Administration

Published: June 2014

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INTRODUCTION

TxDOT project 0-6706 “Design and Scope of Impact of Auxiliary Lanes” has developed guidelines for implementation of auxiliary lanes including general guidelines on the use of auxiliary lanes and design guidelines for auxiliary lanes. To facilitate the implementation of the guidelines developed by this project, training strategies and materials have been developed for providing a training session for personnel within TxDOT who are involved in the design of freeway interchanges and ramps.

This document consists of two parts. Part I “Training Strategies” provides details on the purpose, method, scheduling, and location for the training. Part II “Training Materials” provides a list of the developed training materials along with the printouts of these training materials.

TRAINING STRATEGIES

Training Objectives and Contents

The goals of the proposed training section are to introduce to traffic engineers the developed guidelines and the use of these guidelines for implementing auxiliary lanes. The training session will cover the following topics:

1. General Guidelines on the Use of Auxiliary Lanes
2. Design Guidelines for Auxiliary Lane

Training Audience

The potential audience for the workshop will be the engineers who are involved in the design of freeway interchanges and ramps. It will include the personnel in TxDOT roadway design sections in different districts and traffic engineers in local Transportation Management Centers (TMCs).

Training Method

Researchers suggest a half-day, two-hour workshop for the proposed training. It is our belief that a half-day course at a TxDOT host district will encourage better participation considering the busy schedules of those individuals targeted to attend.

The workshop will introduce the general guidelines on the use of auxiliary lanes and design guidelines for auxiliary lanes. At the end of the workshop, a workshop evaluation form will be distributed to all attendees and will be reviewed after the workshop. The workshop agenda and materials will be refined, as appropriate, to capitalize on comments and suggestions that will improve the workshop in the future.

Training Scheduling and Coordination

The scheduling of workshops will be coordinated between the university workshop team leader, TxDOT project director, and TxDOT project advisor from the Human Resources Division. The project director will be responsible for coordinating workshops scheduling with TxDOT district training coordinators to ensure that district training facilities will be available for conducting workshops.

Training Location

The workshops are planned to be held in a TxDOT facility within selected host districts. Location selection will be coordinated between the workshop team leader, project director, and project advisors.

TRAINING MATERIALS

PowerPoint materials include:

A presentation for introducing the guidelines developed for the implementation of auxiliary lanes.

Workbook materials include:

Detailed guidelines for the implementation of auxiliary lanes.

- General Guidelines on the Use of Auxiliary Lanes
- Design Guidelines for Auxiliary Lane

Guidelines for Designing and Methods for Assessing Auxiliary Lanes

PowerPoint Presentation for Workshop

Guidelines for Designing and Methods for Assessing Auxiliary Lanes

Dr. Yi Qi, Texas Southern University (TSU)

Dr. Ruey Kelvin Cheu, University of Texas at El Paso (UTEP)

Pilot Workshop

TxDOT 0-6706: Design and Scope of

Impact of Auxiliary Lanes

Outline

- General Guidelines on the Use of Auxiliary Lanes
- Design Guidelines for Auxiliary Lanes

General Guidelines on the Use of Auxiliary Lanes

Guideline 1: When to Consider the Use of Freeway Auxiliary Lanes

Guideline 2: Assessment of Operational and Safety Benefits of Adding an Auxiliary Lane

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Guideline 1–
When to Consider the Use of Freeway Auxiliary Lanes

Auxiliary lane at weaving segments

Continuous auxiliary lane should be provided:

- If the distance between an entrance ramp and an exit ramp<1500 ft (TxDOT Roadway Design Manual).
- If an entrance ramp is less than 2400 ft upstream from a two-lane exit ramp (TxDOT Roadway Design Manual).
- If an exit ramp is less than 2500 ft downstream from a two-lane entrance ramp (TxDOT Roadway Design Manual).
- If local frontage road does not exist (AASHTO Green Book, 2011).

Other factors, such as traffic volumes, speed, grade, and safety/operational issues should also be considered in the use of auxiliary lanes. Engineering studies are desirable on a case-by-case basis in determining the need for an auxiliary lane.

Sources: AASHTO Green Book, 2011, TxDOT RDM

General Guidelines

Guideline 1 –
When to Consider the Use of Freeway Auxiliary Lanes
(continued)

Auxiliary lane at merge/diverge area

- At the isolated entrance/exit ramp, a parallel acceleration/deceleration lane should be considered when:
  - Turbulence in the traffic flow is significant that is caused by vehicles attempting to recover and proceed on the through lanes.
  - Safety issues because of the forced merges at entrance ramp.
  - Traffic volume on freeway mainline and entrance ramp reach to certain levels.

Sources: AASHTO Green Book, 2011, Highway Safety Manual (2010), ITE paper (2013)

Conditions for Adding the Auxiliary Lane at Entrance Ramp

(a) N_F=2 lanes

Minimum L_A (ft) for N_F=2 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	100
1250	-	-	-	-	200	300	400	500	600	700
1500	300	400	500	700	800	900	1000	1100	1200	1400
1750	900	1000	1200	1300	1400	1500	-	-	-	-
2000	-	-	-	-	-	-	-	-	-	-

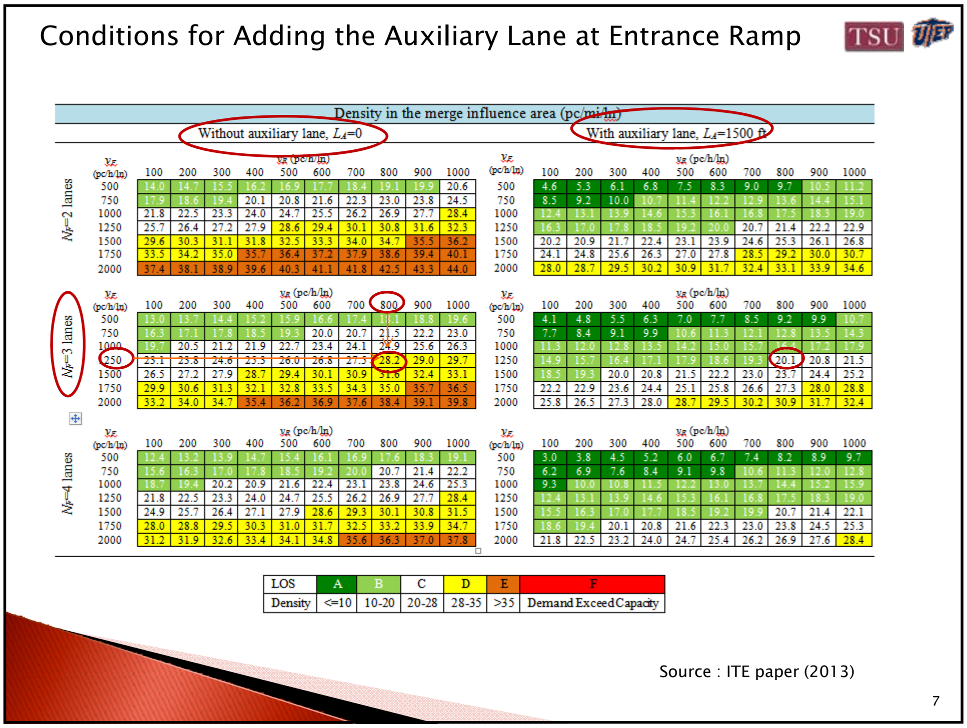
(b) N_F=3 lanes

Minimum L_A (ft) for N_F=3 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	100	200	400
1500	-	-	-	200	300	500	600	700	900	1000
1750	400	600	700	800	1000	1100	1300	1400	-	-
2000	1100	1300	1400	1500	-	-	-	-	-	-

(c) N_F=4 lanes

Minimum L_A (ft) for N_F=4 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	-	-	100
1500	-	-	-	-	-	100	300	400	500	600
1750	100	200	300	400	500	600	800	900	1000	1100
2000	600	700	800	900	1000	1100	1300	1400	1500	-

Source : ITE paper (2013)



Conditions for Adding the Auxiliary Lane at Entrance Ramp

Density in the merge influence area (pc/mi/ln)

Without auxiliary lane, L_A=0

N_F=2 lanes

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	14.0	14.7	15.5	16.2	16.9	17.7	18.4	19.1	19.9	20.6
750	17.9	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5
1000	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
1250	25.7	26.4	27.2	27.9	28.6	29.4	30.1	30.8	31.6	32.3
1500	29.6	30.3	31.1	31.8	32.5	33.3	34.0	34.7	35.5	36.2
1750	33.5	34.2	35.0	35.7	36.4	37.2	37.9	38.6	39.4	40.1
2000	37.4	38.1	38.9	39.6	40.3	41.1	41.8	42.5	43.3	44.0

N_F=3 lanes

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	13.0	13.7	14.4	15.2	15.9	16.6	17.4	18.1	18.8	19.6
750	16.3	17.1	17.8	18.5	19.3	20.0	20.7	21.5	22.2	23.0
1000	19.7	20.5	21.2	21.9	22.7	23.4	24.1	24.9	25.6	26.3
1250	23.1	23.8	24.6	25.3	26.0	26.8	27.5	28.2	29.0	29.7
1500	26.5	27.2	27.9	28.7	29.4	30.1	30.9	31.6	32.4	33.1
1750	29.9	30.6	31.3	32.1	32.8	33.5	34.3	35.0	35.7	36.5
2000	33.2	34.0	34.7	35.4	36.2	36.9	37.6	38.4	39.1	39.8

N_F=4 lanes

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	12.4	13.2	13.9	14.7	15.4	16.1	16.9	17.6	18.3	19.1
750	15.6	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2
1000	18.7	19.4	20.2	20.9	21.6	22.4	23.1	23.8	24.6	25.3
1250	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
1500	24.9	25.7	26.4	27.1	27.9	28.6	29.3	30.1	30.8	31.5
1750	28.0	28.8	29.5	30.3	31.0	31.7	32.5	33.2	33.9	34.7
2000	31.2	31.9	32.6	33.4	34.1	34.8	35.6	36.3	37.0	37.8

With auxiliary lane, L_A=1500 ft

N_F=2 lanes

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	4.6	5.3	6.1	6.8	7.5	8.3	9.0	9.7	10.5	11.2
750	8.5	9.2	10.0	10.7	11.4	12.2	12.9	13.6	14.4	15.1
1000	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
1250	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2	22.9
1500	20.2	20.9	21.7	22.4	23.1	23.9	24.6	25.3	26.1	26.8
1750	24.1	24.8	25.6	26.3	27.0	27.8	28.5	29.2	30.0	30.7
2000	28.0	28.7	29.5	30.2	30.9	31.7	32.4	33.1	33.9	34.6

N_F=3 lanes

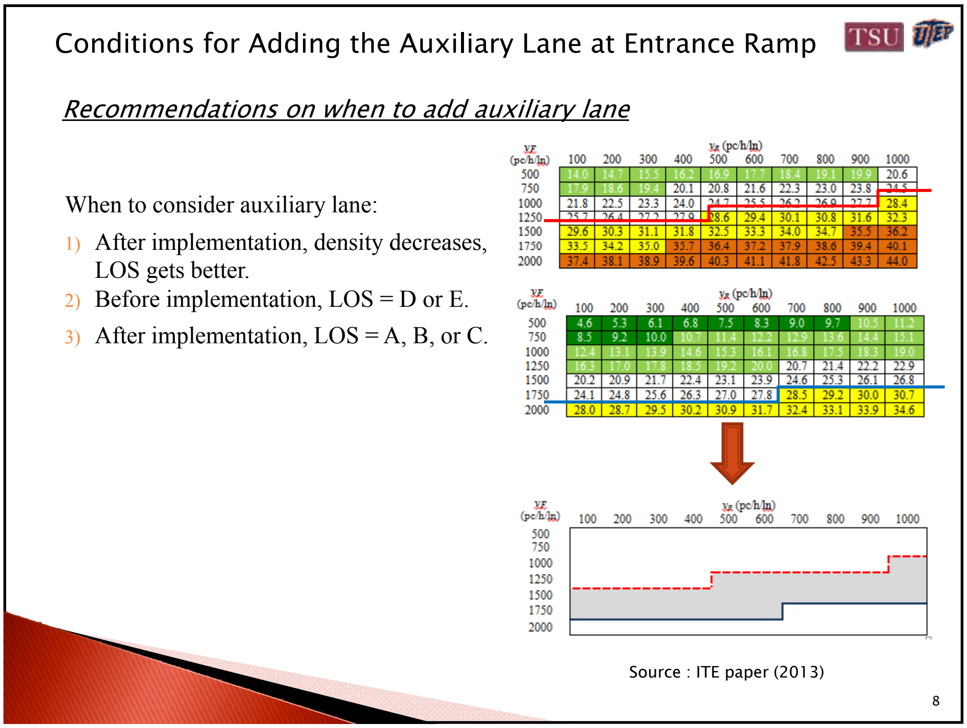
v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	4.1	4.8	5.5	6.3	7.0	7.7	8.5	9.2	9.9	10.7
750	7.7	8.4	9.1	9.9	10.6	11.3	12.1	12.8	13.5	14.3
1000	11.3	12.0	12.8	13.5	14.2	15.0	15.7	16.4	17.2	17.9
1250	14.9	15.7	16.4	17.1	17.9	18.6	19.3	20.1	20.8	21.5
1500	18.5	19.3	20.0	20.8	21.5	22.2	23.0	23.7	24.4	25.2
1750	22.2	22.9	23.6	24.4	25.1	25.8	26.6	27.3	28.0	28.8
2000	25.8	26.5	27.3	28.0	28.7	29.5	30.2	30.9	31.7	32.4

N_F=4 lanes

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	3.0	3.8	4.5	5.2	6.0	6.7	7.4	8.2	8.9	9.7
750	6.2	6.9	7.6	8.4	9.1	9.8	10.6	11.3	12.0	12.8
1000	9.3	10.0	10.8	11.5	12.2	13.0	13.7	14.4	15.2	15.9
1250	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
1500	15.5	16.3	17.0	17.7	18.5	19.2	19.9	20.7	21.4	22.1
1750	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5	25.3
2000	21.8	22.5	23.2	24.0	24.7	25.4	26.2	26.9	27.6	28.4

LOS	A	B	C	D	E	F
Density	<=10	10-20	20-28	28-35	>35	Demand Exceed Capacity

Source : ITE paper (2013)



Conditions for Adding the Auxiliary Lane at Entrance Ramp

Recommendations on when to add auxiliary lane

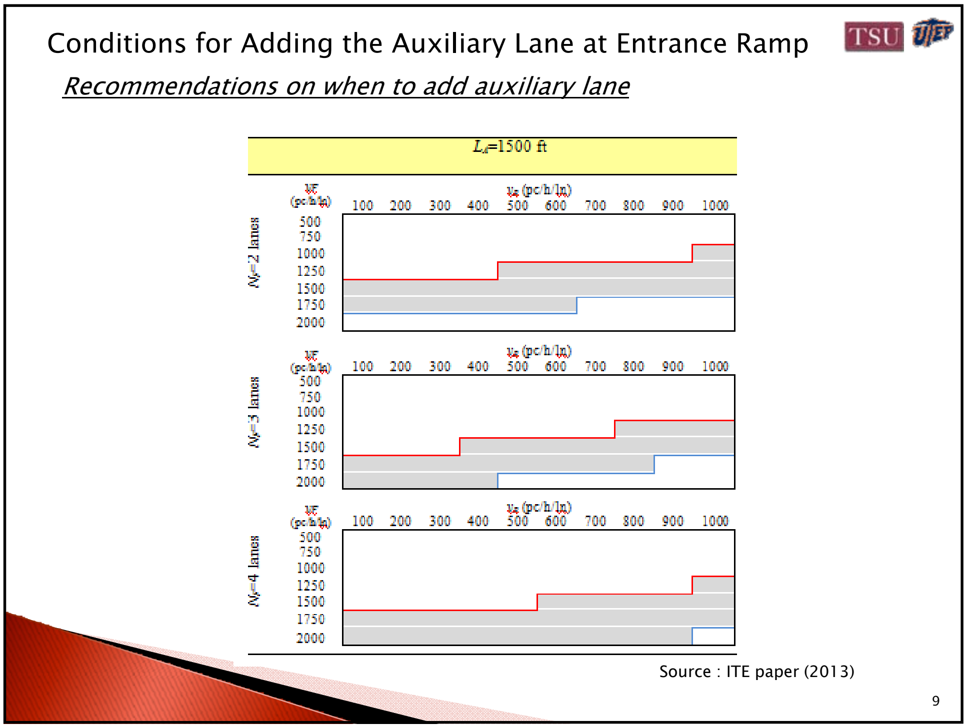
When to consider auxiliary lane:

1) After implementation, density decreases, LOS gets better.
2) Before implementation, LOS = D or E.
3) After implementation, LOS = A, B, or C.

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	14.0	14.7	15.5	16.2	16.9	17.7	18.4	19.1	19.9	20.6
750	17.9	18.6	19.4	20.1	20.8	21.6	22.3	23.0	23.8	24.5
1000	21.8	22.5	23.3	24.0	24.7	25.5	26.2	26.9	27.7	28.4
1250	25.7	26.4	27.2	27.9	28.6	29.4	30.1	30.8	31.6	32.3
1500	29.6	30.3	31.1	31.8	32.5	33.3	34.0	34.7	35.5	36.2
1750	33.5	34.2	35.0	35.7	36.4	37.2	37.9	38.6	39.4	40.1
2000	37.4	38.1	38.9	39.6	40.3	41.1	41.8	42.5	43.3	44.0

v_F (pc/h/ln)	v_R (pc/h/ln) 100	200	300	400	500	600	700	800	900	1000
500	4.6	5.3	6.1	6.8	7.5	8.3	9.0	9.7	10.5	11.2
750	8.5	9.2	10.0	10.7	11.4	12.2	12.9	13.6	14.4	15.1
1000	12.4	13.1	13.9	14.6	15.3	16.1	16.8	17.5	18.3	19.0
1250	16.3	17.0	17.8	18.5	19.2	20.0	20.7	21.4	22.2	22.9
1500	20.2	20.9	21.7	22.4	23.1	23.9	24.6	25.3	26.1	26.8
1750	24.1	24.8	25.6	26.3	27.0	27.8	28.5	29.2	30.0	30.7
2000	28.0	28.7	29.5	30.2	30.9	31.7	32.4	33.1	33.9	34.6

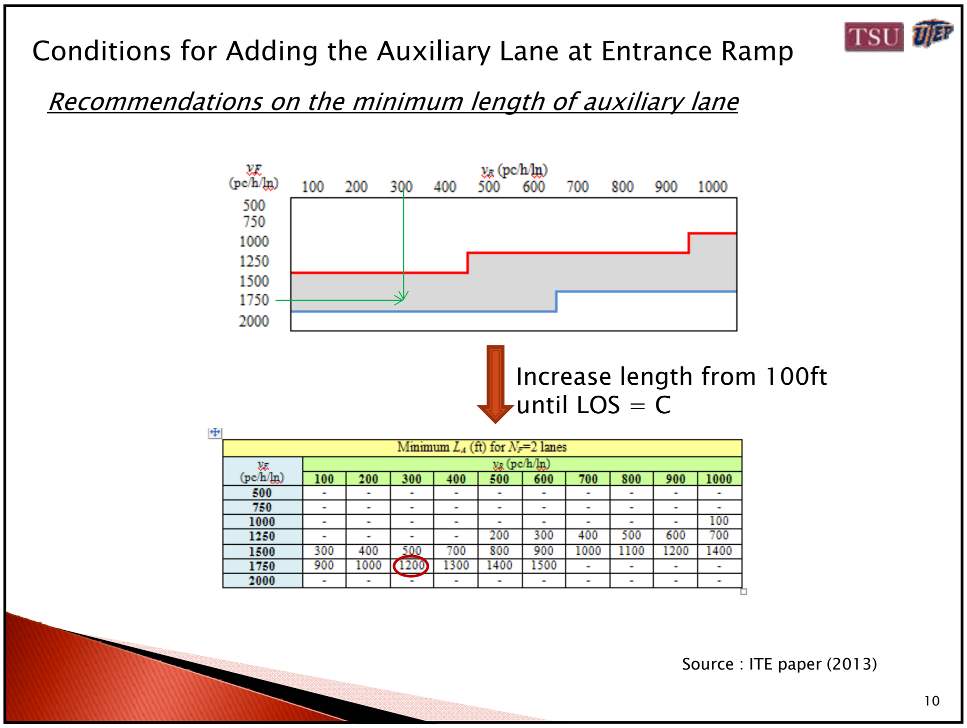
Source : ITE paper (2013)



Conditions for Adding the Auxiliary Lane at Entrance Ramp

Recommendations on when to add auxiliary lane

Source : ITE paper (2013)



Conditions for Adding the Auxiliary Lane at Entrance Ramp

Recommendations on the minimum length of auxiliary lane

Increase length from 100ft until LOS = C

Minimum L_A (ft) for N_F=2 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	100
1250	-	-	-	-	200	300	400	500	600	700
1500	300	400	500	700	800	900	1000	1100	1200	1400
1750	900	1000	1200	1300	1400	1500	-	-	-	-
2000	-	-	-	-	-	-	-	-	-	-

Source : ITE paper (2013)

Conditions for Adding the Auxiliary Lane at Entrance Ramp

(a) N_F=2 lanes

Minimum L_A (ft) for N_F=2 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	100
1250	-	-	-	-	200	300	400	500	600	700
1500	300	400	500	700	800	900	1000	1100	1200	1400
1750	900	1000	1200	1300	1400	1500	-	-	-	-
2000	-	-	-	-	-	-	-	-	-	-

(b) N_F=3 lanes

Minimum L_A (ft) for N_F=3 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	100	200	400
1500	-	-	-	200	300	500	600	700	900	1000
1750	400	600	700	800	1000	1100	1300	1400	-	-
2000	1100	1300	1400	1500	-	-	-	-	-	-

(c) N_F=4 lanes

Minimum L_A (ft) for N_F=4 lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	-	-	100
1500	-	-	-	-	-	100	300	400	500	600
1750	100	200	300	400	500	600	800	900	1000	1100
2000	600	700	800	900	1000	1100	1300	1400	1500	-

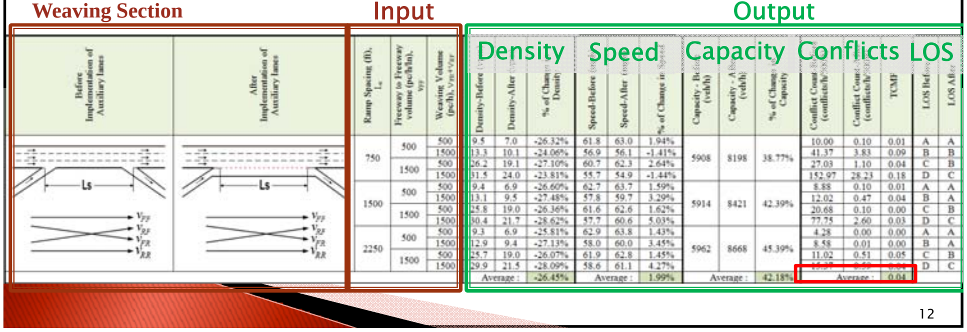
Source : ITE paper (2013)

Guideline 2- Assessment of Operational and Safety Benefits of Adding an Auxiliary Lane

Method: Using Look-up Table Developed Based on Traffic Simulation - VISSIM

Performance Measures Selected: Capacity, Speed, Density, Traffic Conflicts, LOS (based on density thresholds in HCM)

Example Look-up table



Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), V_{FF}	Weaving Volume (pc/h), $V_{RF}+V_{FR}$	Density-Before	Density-After	% of Change Density	Speed-Before	Speed-After	% of Change in	Capacity - Be (veh/h)	Capacity - A (veh/h)	% of Change Capacity	Conflict Count (conflicts/h)	Conflict Count (conflicts/h)	TCMF	LOS Bef	LOS Aft
750	500	500	9.5	7.0	-26.32%	61.8	63.0	1.94%	5908	8198	38.77%	10.00	0.10	0.01	A	A
		1500	13.3	10.1	-24.06%	56.9	56.1	-1.41%				41.37	3.83	0.09	B	B
	1500	500	26.2	19.1	-27.10%	60.7	62.3	2.64%				27.03	1.10	0.04	C	B
		1500	31.5	24.0	-23.81%	55.7	54.9	-1.44%				152.97	28.23	0.18	D	C
1500	500	500	9.4	6.9	-26.60%	62.7	63.7	1.59%	5914	8421	42.39%	8.88	0.10	0.01	A	A
		1500	13.1	9.5	-27.48%	57.8	59.7	3.29%				12.02	0.47	0.04	B	A
	1500	500	25.8	19.0	-26.36%	61.6	62.6	1.62%				20.68	0.10	0.00	C	B
		1500	30.4	21.7	-28.62%	57.7	60.6	5.03%				77.75	2.60	0.03	D	C
2250	500	500	9.3	6.9	-25.81%	62.9	63.8	1.43%	5962	8668	45.39%	4.28	0.00	0.00	A	A
		1500	12.9	9.4	-27.13%	58.0	60.0	3.45%				8.58	0.01	0.00	B	A
	1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	0.51	0.05	C	B
		1500	29.9	21.5	-28.09%	58.6	61.1	4.27%				[illegible]	[illegible]	[illegible]	D	C
			Average :		-26.45%	Average :		1.99%	Average :		42.18%	Average :		0.04		

Why Simulation?

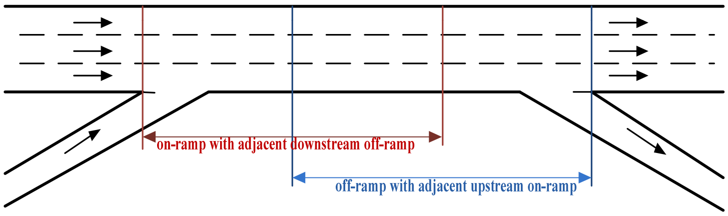
- HCM models/Highway Capacity Software (HCS2010) has the following problems:
  1. Cannot be used directly for the freeway weaving sections without an auxiliary lane.
  2. Will generate unreasonable results for the diverging (off-ramp) sections.

HCM models/HCS2010 can be used for:

- Freeway weaving section with an auxiliary lane (validated).
- Merging (on ramp) sections with and without an auxiliary lane.

Why Simulation? – HCM Problem 1

- HCM models cannot be used directly for the freeway weaving sections without an auxiliary lane.



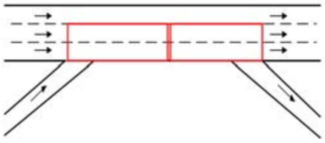
HCM Suggested Method for Weaving Segment without Auxiliary Lanes

Density and speed are computed separately at the on-ramp junction and the off-ramp junction by the ramp module in HCS2010.

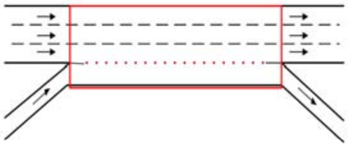
The higher value among of density and the lower value of the speed among the on-ramp and off-ramp was selected.

Why Simulation? – HCM Problem 1

- The HCM models cannot be compared directly between without and with auxiliary lanes → Different number of lanes analyzed.
- The HCM results sometimes were unexplainable for comparison between scenarios without and with auxiliary lanes.



(a) Modeling weaving segments without auxiliary lanes as two joint ramp influence areas as suggested by HCM



(b) Modeling weaving segments with an auxiliary lane using HCM weaving procedures

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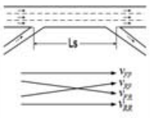
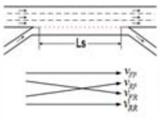
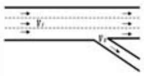
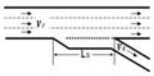
Why Simulation? – HCM Problem 1
Weaving section before and after adding auxiliary lane

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_S	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{FR}+v_{RF}$	Density (V/mi/lane)						Speed(mph)						LOS			
					Calculate by HCM			Simulation			Calculate by HCM			Simulation			Calculate by HCM		Simulation	
					Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	LOS Before	LOS After	LOS Before	LOS After
		750	500	500	15.7	8.6	-45.22%	9.5	7.0	-26.32%	56.1	58.2	3.74%	61.8	63.0	1.94%	B	A	A	A
				1500	20.6	15.0	-27.18%	13.3	10.1	-24.06%	55.1	50.2	-8.89%	56.9	56.1	-1.41%	B	B	B	B
			1500	500	33.9	22.8	-32.74%	26.2	19.1	-27.10%	56	55	-1.79%	60.7	62.3	2.64%	D	B	C	B
				1500	43	31.9	-25.81%	31.5	24.0	-23.81%	50	47.1	-5.80%	55.7	54.9	-1.44%	E	C	D	C
		1500	500	500	14.6	8.6	-41.10%	9.4	6.9	-26.60%	56.1	58.5	4.28%	62.7	63.7	1.59%	B	A	A	A
				1500	19	14.5	-23.68%	13.1	9.5	-27.48%	55.1	51.9	-5.81%	57.8	59.7	3.29%	B	A	B	A
			1500	500	30.1	22.7	-24.58%	25.8	19.0	-26.36%	56	55.3	-1.25%	61.6	62.6	1.62%	D	B	C	B
				1500	38	31.3	-17.63%	30.4	21.7	-28.62%	53	48	-9.43%	57.7	60.6	5.03%	D	C	D	C
		2250	500	500	14.3	8.6	-39.86%	9.3	6.9	-25.81%	56.1	58.5	4.28%	62.9	63.8	1.43%	B	A	A	A
				1500	18.5	14.3	-22.70%	12.9	9.4	-27.13%	55.1	52.5	-4.72%	58.0	60.0	3.45%	B	A	B	A
			1500	500	29.7	22.6	-23.91%	25.7	19.0	-26.07%	56	55.4	-1.07%	61.9	62.8	1.45%	D	B	C	B
				1500	34.8	31.0	-10.92%	29.9	21.5	-28.09%	54	48.4	-10.37%	58.6	61.1	4.27%	D	C	D	C
					Average :		-27.95%	Average :		-26.45%	Average :		-3.07%	Average :		1.99%				

Most of the speed become worse after adding auxiliary lane.

Why Simulation? – HCM Problem 2

Off-ramp section before and after adding auxiliary lane

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_D	Freeway to Freeway volume (pc/h/ln), V_{FF}	Weaving Volume (pc/h), $V_{RF}+V_{FR}$	Density (V/mi/lane)						Speed (mph)						LOS			
					Calculate by HCM			Simulation			Calculate by HCM			Simulation			Calculate by HCM		Simulation	
					Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	LOS Before	LOS After	LOS Before	LOS After
		500	500	250	14	9.5	-32.14%	8.1	6.0	-25.93%	59.2	59.2	0.00%	62.0	63.4	2.26%	B	A	A	A
				750	15.1	10.6	-29.80%	8.4	6.3	-25.00%	57.9	57.9	0.00%	59.6	59.7	0.17%	B	B	A	A
			1500	250	29.6	25.1	-15.20%	26.3	18	-31.56%	59.2	59.2	0.00%	60.5	62.6	3.47%	D	C	C	B
				750	30.5	26	-14.75%	29.7	18.3	-38.38%	57.9	57.9	0.00%	59.4	61.6	3.70%	D	C	C	B
		1000	500	250	14	5	-64.29%	8.1	5.8	-28.40%	59.2	59.2	0.00%	62.0	65.3	5.32%	B	A	A	A
				750	15.1	6.1	-59.60%	8.4	5.9	-29.76%	57.9	57.9	0.00%	59.6	64.3	7.89%	B	A	A	A
			1500	250	29.6	20.6	-30.41%	26.3	17.6	-33.08%	59.2	59.2	0.00%	60.5	64.0	5.79%	D	C	C	B
				750	30.5	21.5	-29.51%	29.7	17.8	-40.07%	57.9	57.9	0.00%	59.4	63.5	6.90%	D	C	C	B
		1500	500	250	14	0.5	-96.43%	8.1	5.8	-28.40%	59.2	59.2	0.00%	62.0	65.6	5.81%	B	A	A	A
				750	15.1	1.6	-89.40%	8.4	5.9	-29.76%	57.9	57.9	0.00%	59.6	63.6	6.71%	B	A	A	A
			1500	250	29.6	16.1	-45.61%	26.3	17.7	-32.70%	59.2	59.2	0.00%	60.5	63.9	5.62%	D	B	C	B
				750	30.5	[illegible]	-44.26%	29.7	17.7	-40.40%	57.9	57.9	0.00%	59.4	63.9	7.58%	D	B	C	B
					Average :		-45.95%	Average :		-31.95%	Average :		0.00%	Average :		5.10%				

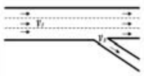
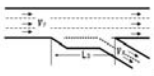
$$D_R = 4.252 + 0.0086v_{12} - 0.009\underline{L_D}$$

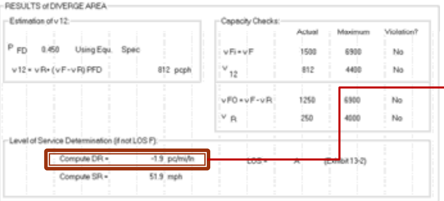
Density estimate is too low for a diverging section with parallel deceleration lanes.

1. There is no difference between before and after adding a parallel deceleration lane.
2. The length of the deceleration lane does not have any impact on the speed of the diverging sections.

Why Simulation? – HCS Problem 2

Off-ramp section before and after adding auxiliary lane

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_D	Freeway to Freeway volume (pc/h/ln), V_{FF}	Weaving Volume (pc/h), $V_{RF}+V_{FR}$	Density (V/mi/lane)						Speed (mph)						LOS			
					Calculate by HCM			Simulation			Calculate by HCM			Simulation			Calculate by HCM		Simulation	
					Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	LOS Before	LOS After	LOS Before	LOS After
		500	500	250	14	6.7	-52.14%	8.1	5.9	-27.16%	59.2	59.2	0.00%	62.0	64.2	3.55%	B	A	A	A
				750	15.1	9.1	-39.74%	8.4	6.0	-28.57%	57.9	57.9	0.00%	59.6	63.4	6.38%	B	A	A	A
			1500	250	29.6	18.3	-38.18%	26.3	17.9	-31.94%	59.2	59.2	0.00%	60.5	62.9	3.97%	D	B	C	B
				750	30.5	20.7	-32.13%	29.7	18.1	-39.06%	57.9	57.9	0.00%	59.4	62.5	5.22%	D	C	C	B
		1000	500	250	14	2.2	-84.29%	8.1	5.7	-29.63%	59.2	59.2	0.00%	62.0	65.7	5.97%	B	A	A	A
				750	15.1	4.6	-69.54%	8.4	5.8	-30.95%	57.9	57.9	0.00%	59.6	65.0	9.06%	B	A	A	A
			1500	250	29.6	13.8	-53.38%	26.3	17.7	-32.70%	59.2	59.2	0.00%	60.5	63.7	5.29%	D	B	C	B
				750	30.5	16.2	-46.89%	29.7	17.7	-40.40%	57.9	57.9	0.00%	59.4	63.7	7.24%	D	B	C	B
		1500	500	250	14	N/A	N/A	8.1	5.7	-29.63%	59.2	59.2	0.00%	62.0	66.0	6.45%	N/A	N/A	A	A
				750	15.1	0.1	-99.34%	8.4	5.8	-30.95%	57.9	57.9	0.00%	59.6	65.4	9.73%	B	A	A	A
			1500	250	29.6	9.3	-68.58%	26.3	17.7	-32.70%	59.2	59.2	0.00%	60.5	63.9	5.62%	D	A	C	B
				750	30.5	11.7	-61.64%	29.7	17.6	-40.74%	57.9	57.9	0.00%	59.4	64.0	7.74%	D	B	C	B
					Average :		-58.71%	Average :		-32.87%	Average :		0.00%	Average :		6.35%				



RESULTS of DIVERGE AREA

Estimation of v 12:

P_{FD} 0.450 Using Equ. Spec

v 12 = vR+ (v F - v R) PFD 812 pcph

Capacity Checks:

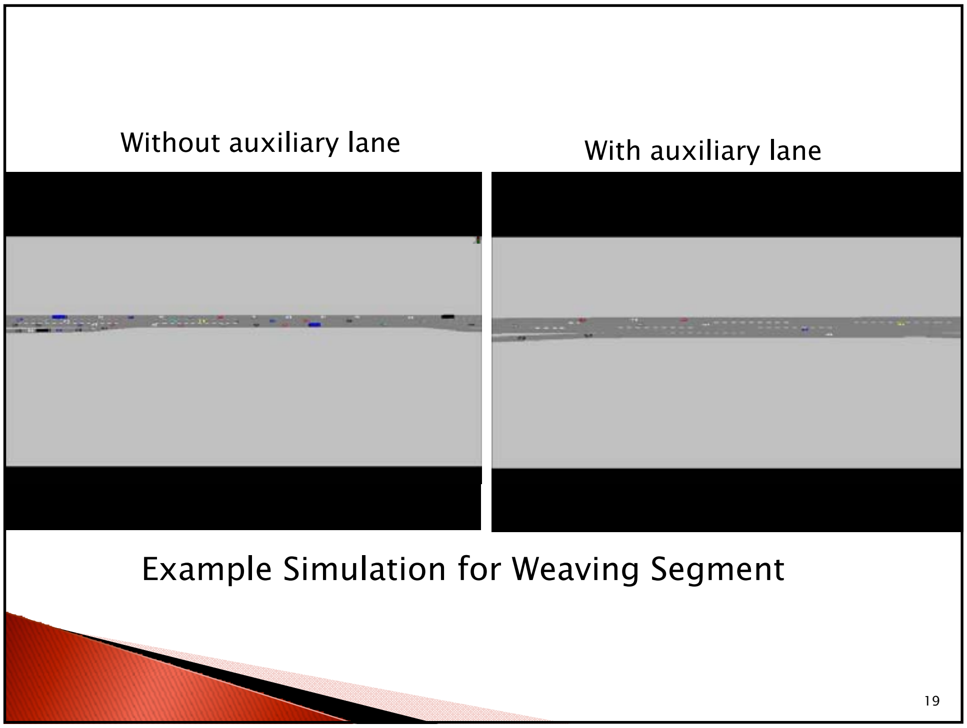
	Actual	Maximum	Violation?
v Fi = v F	1500	6900	No
v_{12}	812	4400	No
v FO = v F - v R	1250	6900	No
v_R	250	4000	No

Level of Service Determination (if not LOS F):

Compute DR = -1.9 pc/mi/ln LOS = A (Exhibit 13-2)

Compute SR = 51.9 mph

Used HCS for the two-lane off-ramp section; it even generates negative density values.

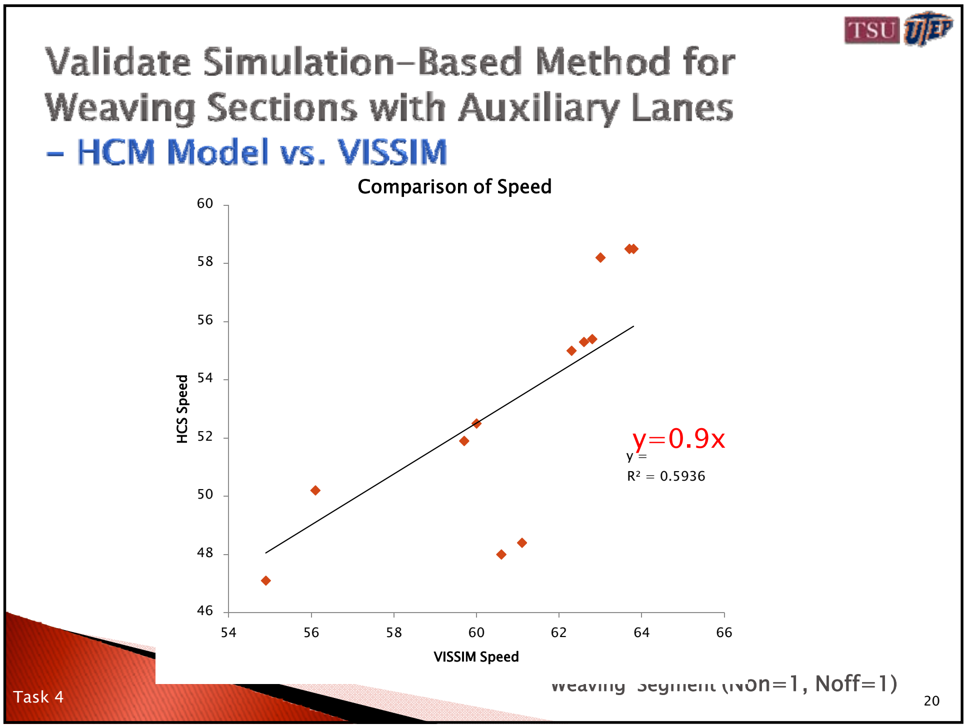


Without auxiliary lane

With auxiliary lane

Example Simulation for Weaving Segment

19

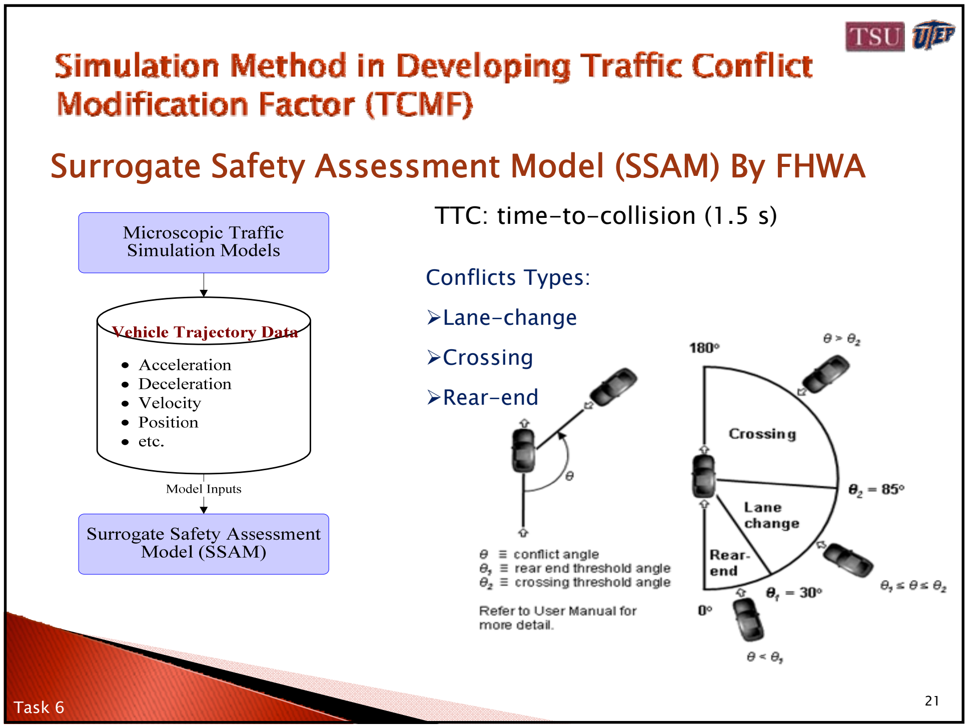


Validate Simulation-Based Method for Weaving Sections with Auxiliary Lanes – HCM Model vs. VISSIM

Weaving Segment (Non=1, Noff=1)

Task 4

20



TSU UTEP

Simulation Method in Developing Traffic Conflict Modification Factor (TCMF)

Surrogate Safety Assessment Model (SSAM) By FHWA

Microscopic Traffic Simulation Models

Vehicle Trajectory Data

- Acceleration
- Deceleration
- Velocity
- Position
- etc.

Model Inputs

Surrogate Safety Assessment Model (SSAM)

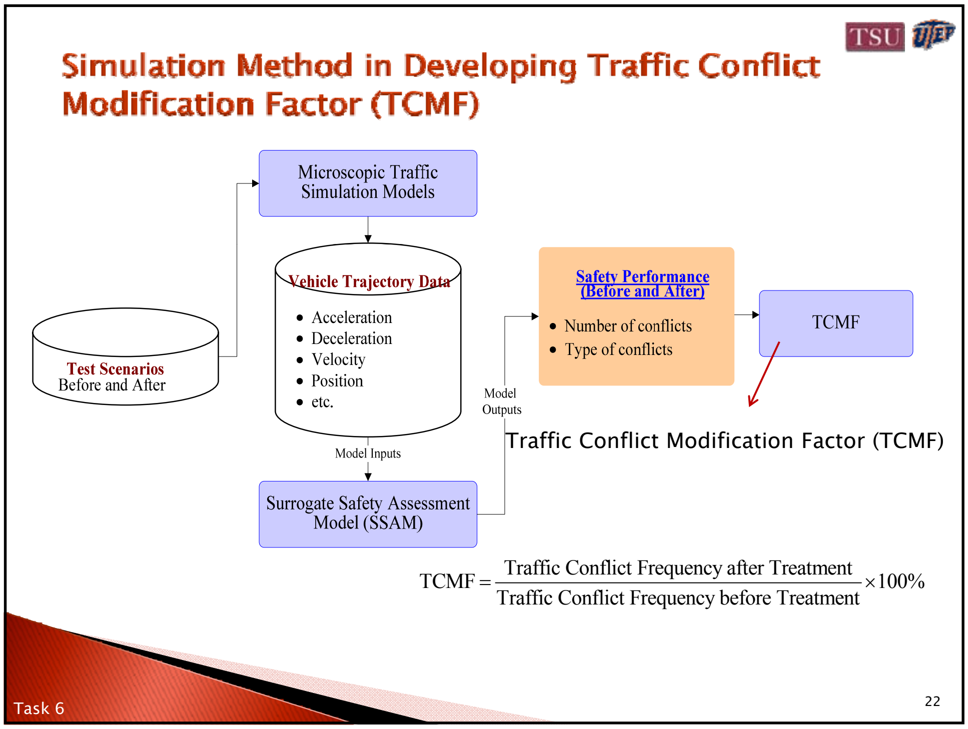
TTC: time-to-collision (1.5 s)

Conflicts Types:

- Lane-change
- Crossing
- Rear-end

θ ≡ conflict angle
θ_1 ≡ rear end threshold angle
θ_2 ≡ crossing threshold angle

Refer to User Manual for more detail.



TSU UTEP

Simulation Method in Developing Traffic Conflict Modification Factor (TCMF)

Test Scenarios
Before and After

Microscopic Traffic Simulation Models

Vehicle Trajectory Data

- Acceleration
- Deceleration
- Velocity
- Position
- etc.

Model Inputs

Surrogate Safety Assessment Model (SSAM)

Model Outputs

Safety Performance (Before and After)

- Number of conflicts
- Type of conflicts

TCMF

Traffic Conflict Modification Factor (TCMF)

$$\text{TCMF} = \frac{\text{Traffic Conflict Frequency after Treatment}}{\text{Traffic Conflict Frequency before Treatment}} \times 100\%$$

Guideline 2–

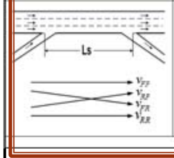
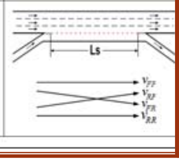
Assessment of Operational and Safety Benefits of Adding an Auxiliary Lane

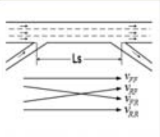
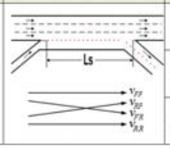
Weaving Section

Input

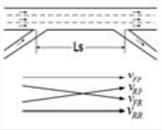
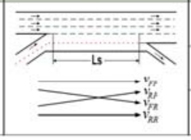
Output

Density Speed Capacity Conflicts LOS

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $V_{FR}+V_{RF}$	Density-Before	Density-After	% of Change in Density	Speed-Before	Speed-After	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	7.0	-26.32%	61.8	63.0	1.94%	5908	8198	38.77%	10.00	0.10	0.01	A	A
				1500	13.3	10.1	-24.06%	56.9	56.1	-1.41%				41.37	3.83	0.09	B	B
			1500	500	26.2	19.1	-27.10%	60.7	62.3	2.64%				27.03	1.10	0.04	C	B
				1500	31.5	24.0	-23.81%	55.7	54.9	-1.44%				152.97	28.23	0.18	D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.7	1.59%	5914	8421	42.39%	8.88	0.10	0.01	A	A
				1500	13.1	9.5	-27.48%	57.8	59.7	3.29%				12.02	0.47	0.04	B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.6	1.62%				20.68	0.10	0.00	C	B
				1500	30.4	21.7	-28.62%	57.7	60.6	5.03%				77.75	2.60	0.03	D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	63.8	1.43%	5962	8668	45.39%	4.28	0.00	0.00	A	A
				1500	12.9	9.4	-27.13%	58.0	60.0	3.45%				8.58	0.01	0.00	B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	0.51	0.05	C	B
				1500	29.9	21.5	-28.09%	58.6	61.1	4.27%				15.37	0.59	0.04	D	C
						Average :	-26.45%		Average :	1.99%		Average :	42.18%		Average :	0.04		

Before implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft)	Freeway to freeway volume (pc/h/ln)	Weaving volume (pc/h) $V_{FR}+V_{RF}$	Before Density	After Density	% of Density	Before Speed (mph)	After Speed (mph)	% of Speed	Before Capacity (veh/h)	After Capacity (veh/h)	% of Capacity	Before (conflicts/h/500ft)	After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	6.9	-27.37%	61.8	63.5	2.75%	5908	8249	39.62%	10.00	0.00	0.00	A	A
				1500	13.3	9.6	-27.82%	56.9	59.3	4.22%				41.37	0.08	0.00	B	A
			1500	500	26.2	19.1	-27.10%	60.7	62.5	2.97%				27.03	0.96	0.04	C	B
				1500	31.5	22.4	-28.89%	55.7	58.9	5.75%				152.97	13.40	0.09	D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.8	1.75%	5914	8631	45.94%	8.88	0.05	0.01	A	A
				1500	13.1	9.5	-27.48%	57.8	60.0	3.81%				12.02	0.14	0.01	B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.7	1.79%				20.68	1.09	0.05	C	B
				1500	30.4	21.7	-28.62%	57.7	60.7	5.20%				77.75	1.91	0.02	D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	64.0	1.75%	5962	8665	45.34%	4.28	0.05	0.01	A	A
				1500	12.9	6.9	-46.51%	58.0	63.4	9.31%				8.58	0.00	0.00	B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	2.50	0.23	C	B
				1500	29.9	18.0	-36.79%	58.6	62.9	7.34%				15.37	2.35	0.15	D	B
						Average :	-29.62%		Average :	4.01%		Average :	43.63%		Average :	0.05		

Weaving Section

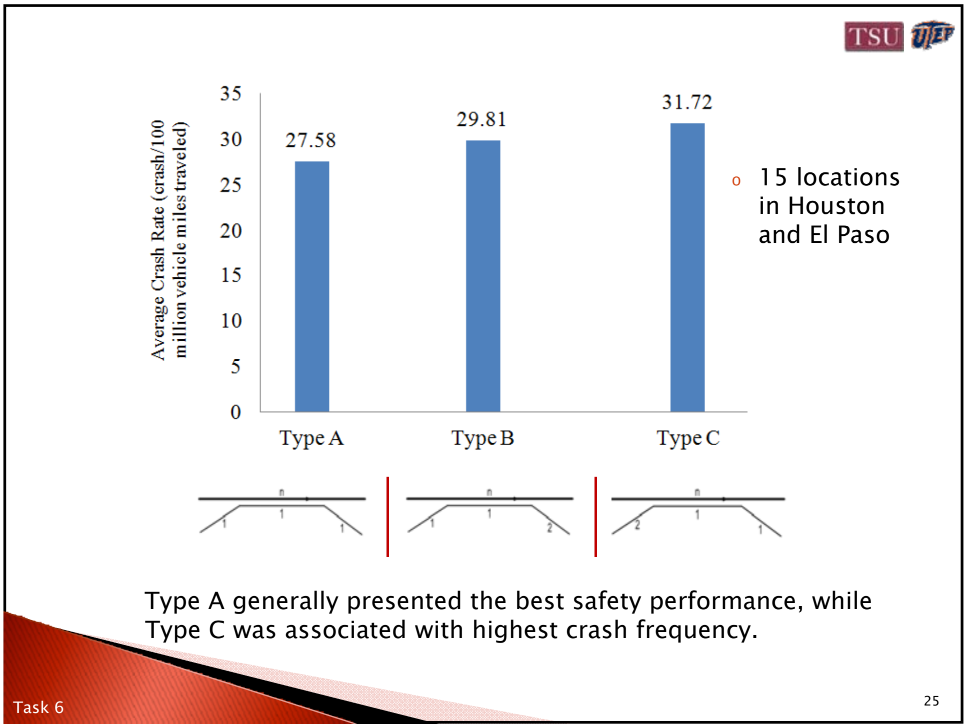
Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{ff}	Weaving Volume (pc/h), $V_{FR}+V_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	5.5	-42.11%	61.8	63.5	2.75%	5908	8767	48.39%	10.00	0	0.00	A	A
				1500	13.3	7.9	-40.60%	56.9	57.1	0.35%				41.37	3.05	0.07	B	A
			1500	500	26.2	15.1	-42.37%	60.7	63.0	3.79%				27.03	0.65	0.02	C	B
				1500	31.5	17.7	-43.81%	55.7	59.6	7.00%				152.97	22	0.14	D	B
		1500	500	500	9.4	5.5	-41.49%	62.7	63.6	1.44%	5914	9441	59.64%	8.88	0.05	0.01	A	A
				1500	13.1	7.5	-42.75%	57.8	60.2	4.15%				12.02	0.8	0.07	B	A
			1500	500	25.8	15.1	-41.47%	61.6	63.3	2.76%				20.68	2.6	0.13	C	B
				1500	30.4	17.0	-44.08%	57.7	62.0	7.45%				77.75	6.7	0.09	D	B
		2250	500	500	9.3	5.5	-40.86%	62.9	64.0	1.75%	5962	9539	60.00%	4.28	0.05	0.01	A	A
				1500	12.9	7.4	-42.64%	58.0	61.1	5.34%				8.58	0.65	0.08	B	A
			1500	500	25.7	14.9	-42.02%	61.9	63.8	3.07%				11.02	2	0.18	C	B
				1500	29.9	16.8	-43.81%	58.6	62.6	6.83%				15.37	4.95	0.32	D	B
						Average :	-42.33%		Average :	3.89%		Average :	56.01%		Average :	0.09		

Operational Performance Comparison: Speed, Capacity, Density, LOS all improved after adding AL:

- ❑ Density reduced by 26–42%.
- ❑ Speed increased by 2–4%.
- ❑ Capacity of weaving segments increased by 42–56%.

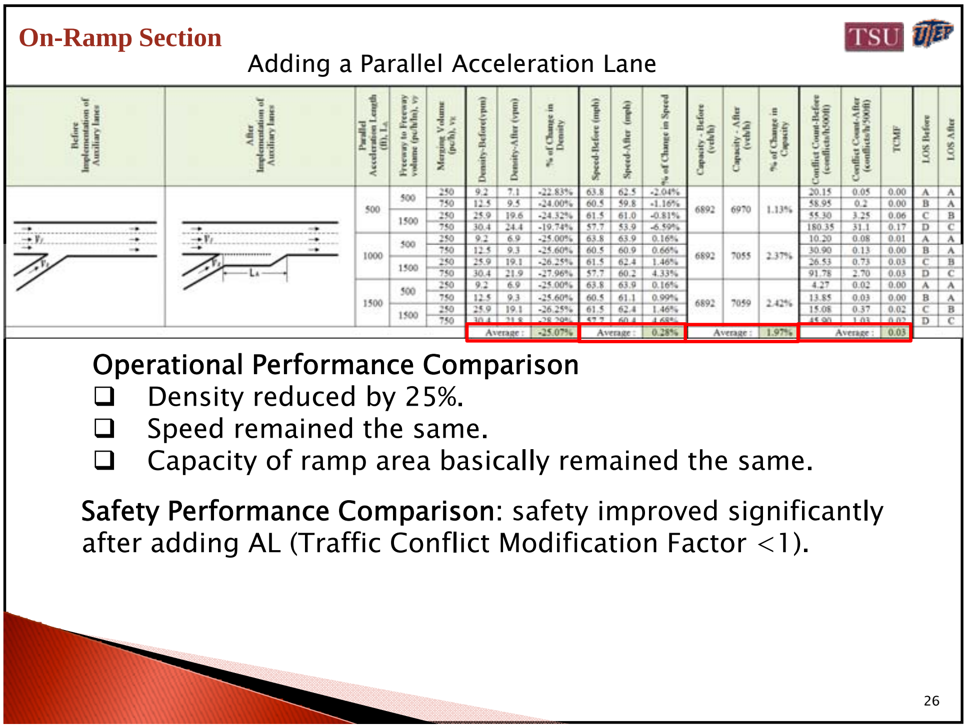
Safety Performance Comparison: safety improved significantly after adding AL (Traffic Conflict Modification Factor <1).

Safety Results Validation: the results of TCMF analysis is consistent with the results of crash data analysis– two-lane entrance ramp section has worst safety performance (TCMF=0.09), followed by two-lane exit ramp section (TCMF=0.05).



- 15 locations in Houston and El Paso

Type A generally presented the best safety performance, while Type C was associated with highest crash frequency.



On-Ramp Section

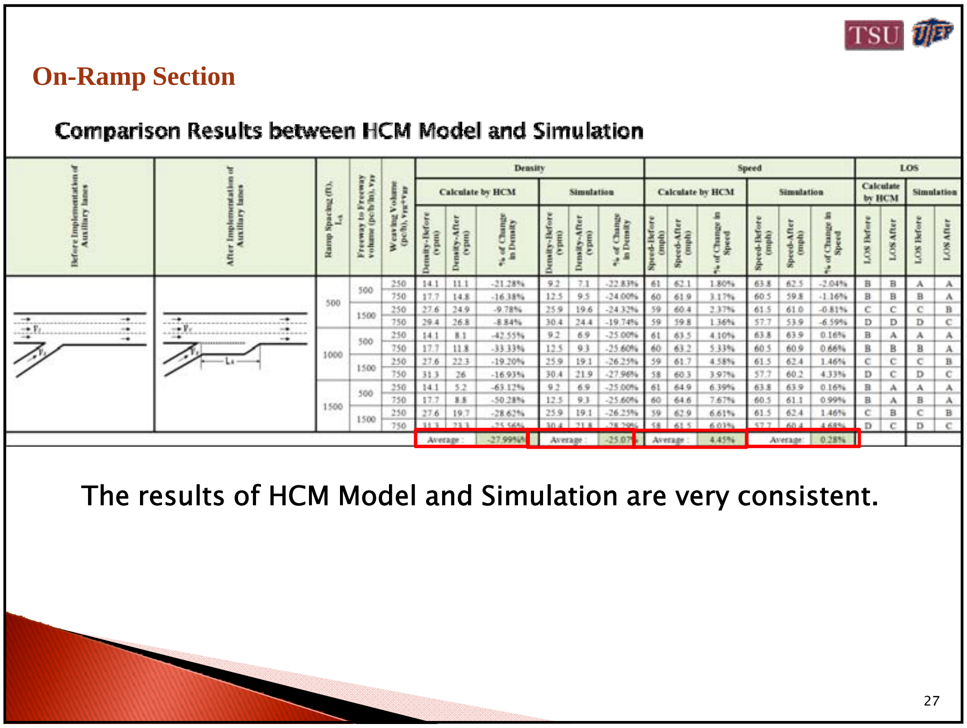
Adding a Parallel Acceleration Lane

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Acceleration Length (ft), L_A	Freeway to Freeway volume (pc/h/ln), v_F	Merging Volume (pc/h), v_R	Density-Before(vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		500	500	250	9.2	7.1	-22.83%	63.8	62.5	-2.04%	6892	6970	1.13%	20.15	0.05	0.00	A	A
				750	12.5	9.5	-24.00%	60.5	59.8	-1.16%				58.95	0.2	0.00	B	A
			1500	250	25.9	19.6	-24.32%	61.5	61.0	-0.81%				55.30	3.25	0.06	C	B
				750	30.4	24.4	-19.74%	57.7	53.9	-6.59%				180.35	31.1	0.17	D	C
		1000	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7055	2.37%	10.20	0.08	0.01	A	A
				750	12.5	9.3	-25.60%	60.5	60.9	0.66%				30.90	0.13	0.00	B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				26.53	0.73	0.03	C	B
				750	30.4	21.9	-27.96%	57.7	60.2	4.33%				91.78	2.70	0.03	D	C
		1500	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7059	2.42%	4.27	0.02	0.00	A	A
				750	12.5	9.3	-25.60%	60.5	61.1	0.99%				13.85	0.03	0.00	B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				15.08	0.37	0.02	C	B
				750	30.4	21.8	-28.29%	57.7	60.4	4.68%				45.90	1.03	0.02	D	C
					Average :		-25.07%	Average :		0.28%	Average :		1.97%	Average :		0.03		

Operational Performance Comparison

- ❑ Density reduced by 25%.
- ❑ Speed remained the same.
- ❑ Capacity of ramp area basically remained the same.

Safety Performance Comparison: safety improved significantly after adding AL (Traffic Conflict Modification Factor <1).



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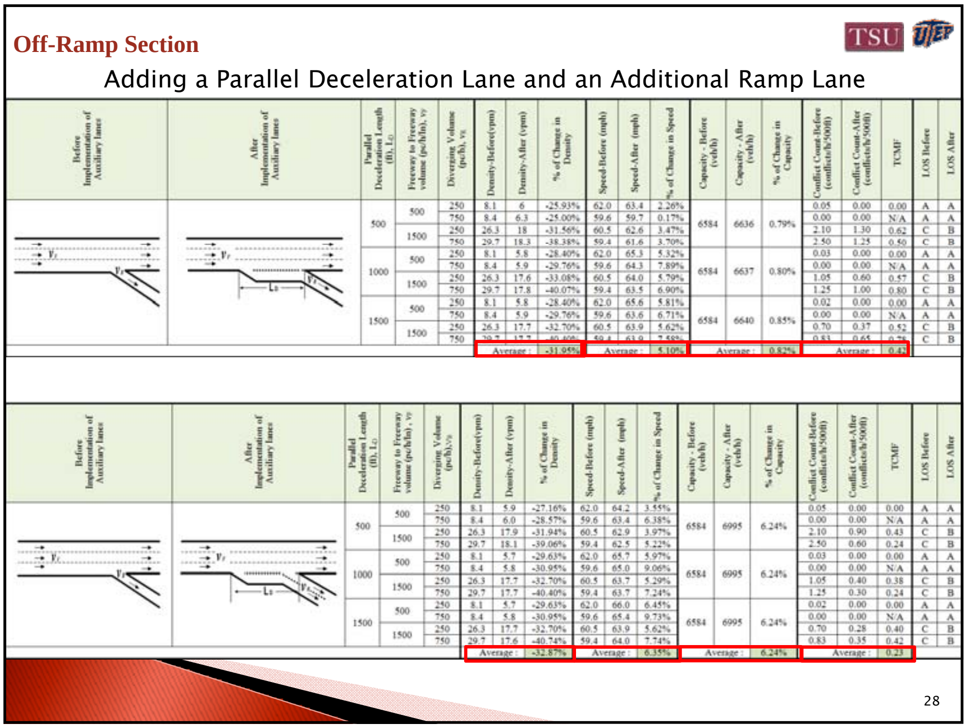
On-Ramp Section

Comparison Results between HCM Model and Simulation

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_A	Freeway to Freeway volume (pc/h/ln), V_{FF}	Weaving Volume (pc/h), V_{RF}*V_{FR}	Density						Speed						LOS			
					Calculate by HCM			Simulation			Calculate by HCM			Simulation			Calculate by HCM		Simulation	
					Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	LOS Before	LOS After	LOS Before	LOS After
		500	500	250	14.1	11.1	-21.28%	9.2	7.1	-22.83%	61	62.1	1.80%	63.8	62.5	-2.04%	B	B	A	A
				750	17.7	14.8	-16.38%	12.5	9.5	-24.00%	60	61.9	3.17%	60.5	59.8	-1.16%	B	B	B	A
			1500	250	27.6	24.9	-9.78%	25.9	19.6	-24.32%	59	60.4	2.37%	61.5	61.0	-0.81%	C	C	C	B
				750	29.4	26.8	-8.84%	30.4	24.4	-19.74%	59	59.8	1.36%	57.7	53.9	-6.59%	D	D	D	C
		1000	500	250	14.1	8.1	-42.55%	9.2	6.9	-25.00%	61	63.5	4.10%	63.8	63.9	0.16%	B	A	A	A
				750	17.7	11.8	-33.33%	12.5	9.3	-25.60%	60	63.2	5.33%	60.5	60.9	0.66%	B	B	B	A
			1500	250	27.6	22.3	-19.20%	25.9	19.1	-26.25%	59	61.7	4.58%	61.5	62.4	1.46%	C	C	C	B
				750	31.3	26	-16.93%	30.4	21.9	-27.96%	58	60.3	3.97%	57.7	60.2	4.33%	D	C	D	C
		1500	500	250	14.1	5.2	-63.12%	9.2	6.9	-25.00%	61	64.9	6.39%	63.8	63.9	0.16%	B	A	A	A
				750	17.7	8.8	-50.28%	12.5	9.3	-25.60%	60	64.6	7.67%	60.5	61.1	0.99%	B	A	B	A
			1500	250	27.6	19.7	-28.62%	25.9	19.1	-26.25%	59	62.9	6.61%	61.5	62.4	1.46%	C	B	C	B
				750	31.3	23.3	-25.56%	30.4	21.8	-28.29%	58	61.5	6.03%	57.7	60.4	4.68%	D	C	D	C
					Average :		-27.99%	Average :		-25.07%	Average :		4.45%	Average:		0.28%				

The results of HCM Model and Simulation are very consistent.



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Off-Ramp Section

Adding a Parallel Deceleration Lane and an Additional Ramp Lane

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway to Freeway volume (pc/h/ln), V_F	Diverging Volume (pc/h), V_R	Density-Before(vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		500	500	250	8.1	6	-25.93%	62.0	63.4	2.26%	6584	6636	0.79%	0.05	0.00	0.00	A	A
				750	8.4	6.3	-25.00%	59.6	59.7	0.17%				0.00	0.00	N/A	A	A
			1500	250	26.3	18	-31.56%	60.5	62.6	3.47%				2.10	1.30	0.62	C	B
				750	29.7	18.3	-38.38%	59.4	61.6	3.70%				2.50	1.25	0.50	C	B
		1000	500	250	8.1	5.8	-28.40%	62.0	65.3	5.32%	6584	6637	0.80%	0.03	0.00	0.00	A	A
				750	8.4	5.9	-29.76%	59.6	64.3	7.89%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.6	-33.08%	60.5	64.0	5.79%				1.05	0.60	0.57	C	B
				750	29.7	17.8	-40.07%	59.4	63.5	6.90%				1.25	1.00	0.80	C	B
		1500	500	250	8.1	5.8	-28.40%	62.0	65.6	5.81%	6584	6640	0.85%	0.02	0.00	0.00	A	A
				750	8.4	5.9	-29.76%	59.6	63.6	6.71%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				0.70	0.37	0.52	C	B
				750	29.7	17.7	-40.40%	59.4	63.9	7.58%				0.83	0.65	0.78	C	B
					Average :		-31.95%	Average :		5.10%	Average :		0.82%	Average :		0.42		

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway to Freeway volume (pc/h/ln) , V_F	Diverging Volume (pc/h),V_R	Density-Before(vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		500	500	250	8.1	5.9	-27.16%	62.0	64.2	3.55%	6584	6995	6.24%	0.05	0.00	0.00	A	A
				750	8.4	6.0	-28.57%	59.6	63.4	6.38%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.9	-31.94%	60.5	62.9	3.97%				2.10	0.90	0.43	C	B
				750	29.7	18.1	-39.06%	59.4	62.5	5.22%				2.50	0.60	0.24	C	B
		1000	500	250	8.1	5.7	-29.63%	62.0	65.7	5.97%	6584	6995	6.24%	0.03	0.00	0.00	A	A
				750	8.4	5.8	-30.95%	59.6	65.0	9.06%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.7	5.29%				1.05	0.40	0.38	C	B
				750	29.7	17.7	-40.40%	59.4	63.7	7.24%				1.25	0.30	0.24	C	B
		1500	500	250	8.1	5.7	-29.63%	62.0	66.0	6.45%	6584	6995	6.24%	0.02	0.00	0.00	A	A
				750	8.4	5.8	-30.95%	59.6	65.4	9.73%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				0.70	0.28	0.40	C	B
				750	29.7	17.6	-40.74%	59.4	64.0	7.74%				0.83	0.35	0.42	C	B
					Average :		-32.87%	Average :		6.35%	Average :		6.24%	Average :		0.23		

Off-Ramp Section

For exit ramp influence areas, adding a parallel auxiliary/deceleration lane can:

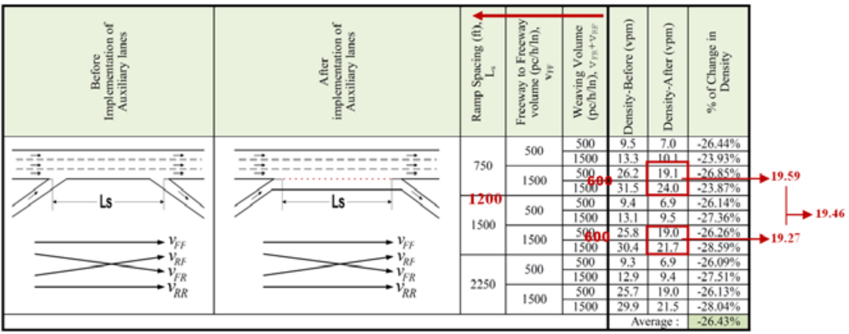
- ☐ Density reduced by about 30%.
- ☐ Speed slightly increased by approximately 5%.
- ☐ Capacity of ramp area remained the same for one-lane off-ramps and slightly increased by 6% for two-lane off-ramps.

General Guidelines

Use of the Look-Up Tables (Interpolation Method)

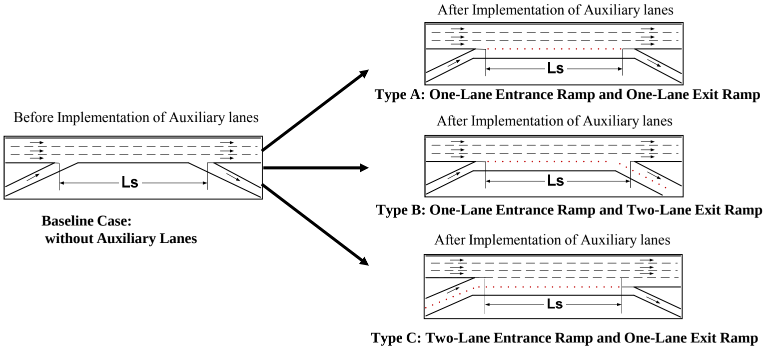
To estimate the traffic density after the auxiliary lane is installed at a weaving segment with one-lane entrance ramp and one-lane exit ramp:

- Ramp Spacing (L_S) – 1200 ft.
- Freeway to Freeway volume (V_{FF}) = 1500 vph.
- Weaving Volume ($V_{FR}+V_{RF}$) = 600 vph.



Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h/ln), $v_{FR}+v_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density
		750	500	500	9.5	7.0	-26.44%
				1500	13.3	10.1	-23.93%
			1500	500	26.2	19.1	-26.85%
				1500	31.5	24.0	-23.87%
		1500	500	500	9.4	6.9	-26.14%
				1500	13.1	9.5	-27.36%
			1500	500	25.8	19.0	-26.26%
				1500	30.4	21.7	-28.59%
		2250	500	500	9.3	6.9	-26.09%
				1500	12.9	9.4	-27.51%
			1500	500	25.7	19.0	-26.13%
				1500	29.9	21.5	-28.04%
					Average :		-26.43%

Tools for Using the Look-Up Tables

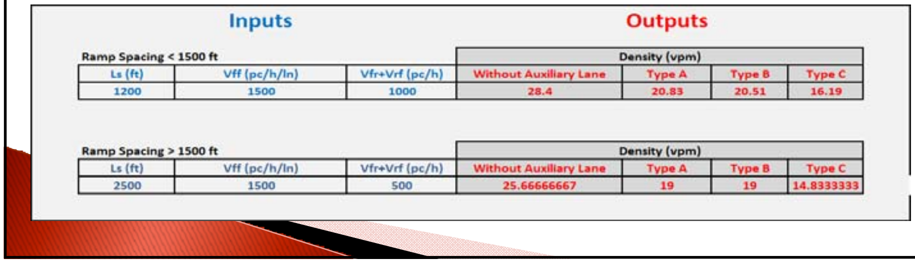


Type A: One-Lane Entrance Ramp and One-Lane Exit Ramp

**Baseline Case:
without Auxiliary Lanes**

Type B: One-Lane Entrance Ramp and Two-Lane Exit Ramp

Type C: Two-Lane Entrance Ramp and One-Lane Exit Ramp



Inputs **Outputs**

Ramp Spacing < 1500 ft

			Density (vpm)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
1200	1500	1000	28.4	20.83	20.51	16.19

Ramp Spacing > 1500 ft

			Density (vpm)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
2500	1500	500	25.66666667	19	19	14.8333333

Guidelines for Design of Auxiliary Lanes

Guideline 3: General Principles for Lane Arrangement Where
Auxiliary Lanes Are Used

Guideline 4: Methods for Dropping an Auxiliary Lane from Mainline

Guideline 5: Length of Parallel Acceleration/Deceleration Lanes
Auxiliary Lanes at Merge/Diverge Area

Guideline 6: Design of Auxiliary Lanes at Two-Lane Ramps

Guideline 7: Width of Auxiliary Lanes and Shoulders

Guideline 3–
General Principles for Lane Arrangement Where Auxiliary Lanes Are Used

- Consistency of basic number of lanes

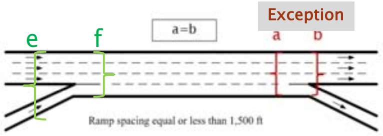
  The basic number of lanes should be consistent for a substantial length of freeway, irrespective of changes in traffic volume.

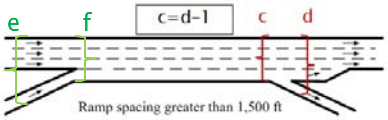
- Principles of lane balance

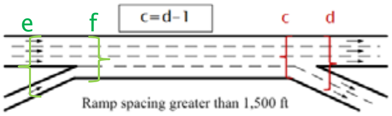
  There should be a balance in the number of lanes on the freeway and ramps.

f≥e-1
f = e
f=e-1

Exception



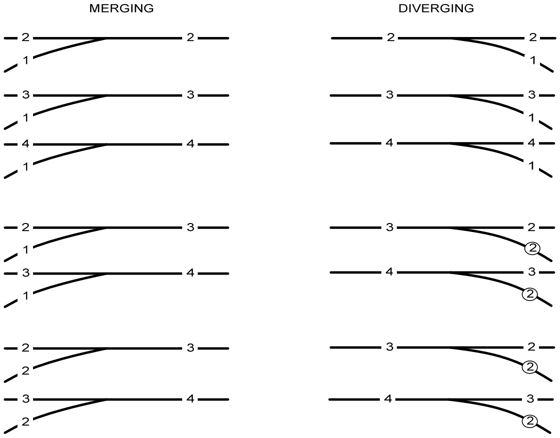




Sources: AASHTO Green Book, 2011

- Examples of Lane Balance

  There should be a balance in the number of lanes on the freeway and ramps.



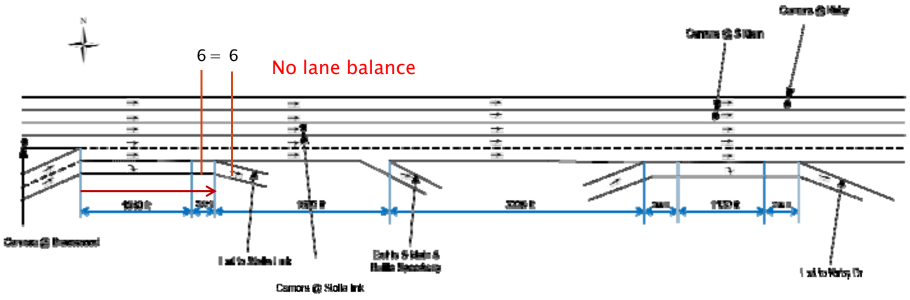
② ONE LANE UNDER SPECIAL CONDITIONS OF PRINCIPLE 2 UNDER THE SECTION "COORDINATION OF LANE BALANCE AND BASIC NUMBER OF LANES"

Sources: AASHTO Green Book, 2011

Design of Auxiliary Lanes

Example of Effectiveness of Lane Balance Principle

Location: I-610 Freeway and Stella Link Rd (Eastbound)



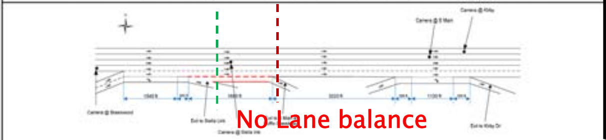
Three comparative cases with lane balance were developed to testify the effects of lane balance design.

Design of Auxiliary Lanes

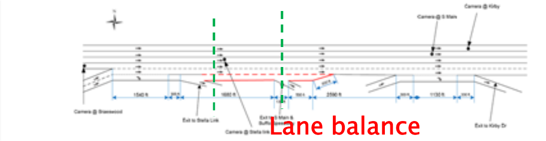
Example of Effectiveness of Lane Balance Principle (Cont'd)

Base Case II - Continuous auxiliary lane along the corridor studied

Comparative Case II (a) - Auxiliary lane dropped within an interchange

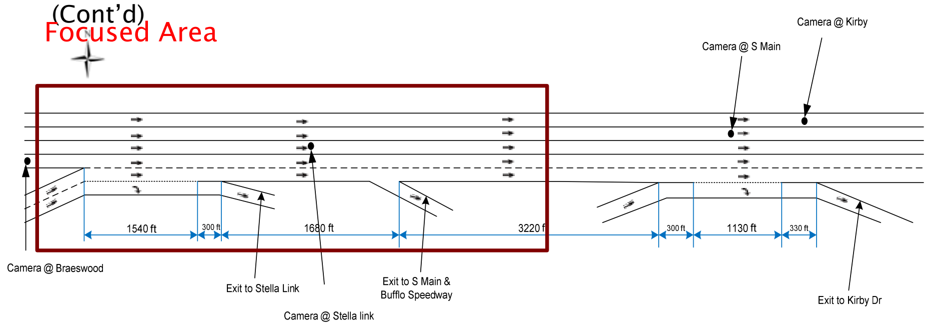


Comparative Case II (b) - Auxiliary lane continued to the next interchange



Comparative Case II (c) - Auxiliary lane continued to the next interchange and dropped within the interchange downstream

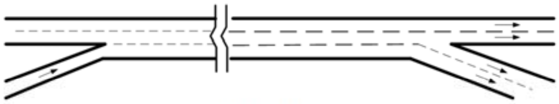
Example of Effectiveness of Lane Balance Principle (Cont'd)



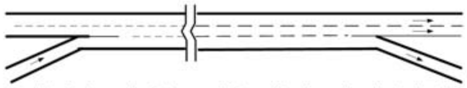
Case	No. of lanes with speed < 45 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)		No. of lanes with speed lower than 50 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 50 mph)	
		Relative length	Actual length		Relative length	Actual length
Base Case II	3	Base	1960 ft	3	Base	2955 ft
Case II (a)	2-3	-1010 ft	950 ft	3	-155 ft	2800 ft
Case II (b)	2	-240 ft	1720 ft	2-3	-155 ft	2800 ft
Case II (c)	1-2	-1110 ft	850 ft	2-3	-955 ft	2000 ft

Guideline 4–

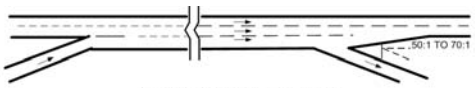
Methods for Dropping an Auxiliary Lane from Mainline



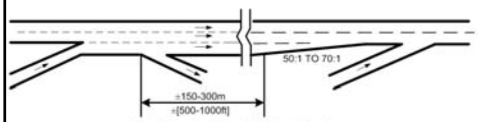
(a) Auxiliary lane dropped on exit ramp



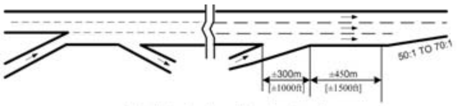
(b) Auxiliary lane between cloverleaf loops or closely spaced interchanges dropped on single exit lane



(c) Auxiliary lane dropped at physical nose



(d) Auxiliary lane dropped within an interchange



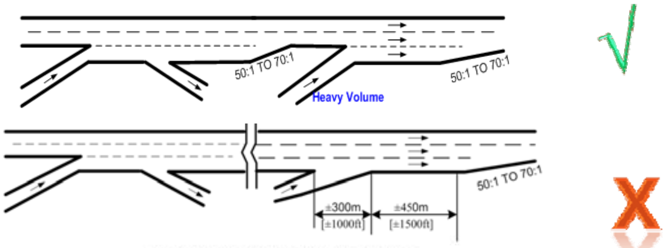
(e) Auxiliary lane dropped beyond an interchange

Source: AASHTO Green Book, 2011

Guideline 4–

Methods for Dropping an Auxiliary Lane from Mainline

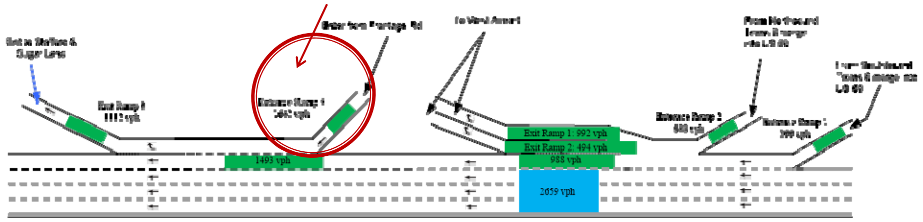
- **Special notes:** If the next entrance ramp has a high traffic volume, it is desirable to drop the auxiliary lane before the next entrance as shown in the following figure.



(e) Auxiliary lane dropped beyond an interchange

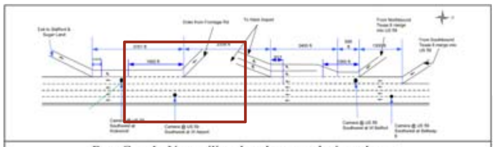
Guideline 4–Example of Lane Drop Methods

Location: US 59 Southwest Freeway & W. Airport Blvd. (Southbound)

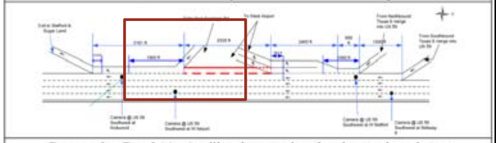


high traffic demand

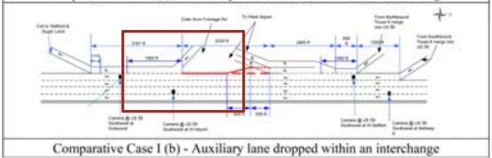
Guideline 4-Example of Lane Drop Methods（Cont'd)



Base Case I - No auxiliary lane between the interchanges



Comparative Case I (a) - Auxiliary lane continued to the next interchange

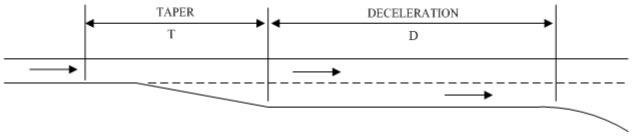


Comparative Case I (b) - Auxiliary lane dropped within an interchange

Comparison Results

Case	No. of lanes with speed < 45 mph (cross-sectional)	Length of influence area due to interchange (longitudinal, speed < 45 mph)	No. of lanes with speed < 50 mph (cross-sectional)	Length of influence area due to interchange (longitudi nal, speed < 50 mph)
		Actual		Actual
Base I	4	1395 ft	4	1620 ft
I (a)	3	1395 ft	3	1620 ft
I (b)	3	1195 ft	3	1320 ft

Guideline 5-
Length of Parallel Acceleration/Deceleration Lanes Auxiliary Lanes at Merge/Diverge Area

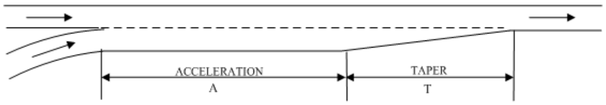


HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	DECELERATION LENGTH, D (ft)				
		Ramp Speed				
		30	35	40	45	50
50	230	315	285	225	175	-
55	250	380	350	285	235	-
60	265	430	405	350	300	240
65	285	470	440	390	340	280
70	300	520	490	440	390	340
75	330	575	535	490	440	390

Source: TxDOT Roadway Design Manual

Guideline 5–

Length of Parallel Acceleration/Deceleration Lanes Auxiliary Lanes at Merge/Diverge Area (continued)



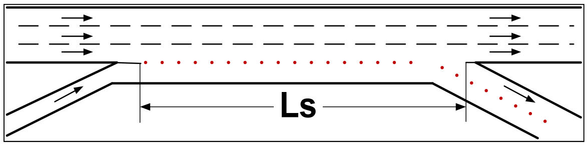
HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	ACCELERATION LENGTH, A (ft)							
		Entering Speed							
		15	20	25	30	35	40	45	50
50	230	660	610	550	450	350	130	-	-
55	250	900	810	780	670	550	320	150	-
60	265	1140	1100	1020	910	800	550	420	180
65	285	1350	1310	1220	1120	1000	770	600	370
70	300	1560	1520	1420	1350	1230	1000	820	580
75	330	1730	1630	1580	1510	1420	1160	1040	780

Source: TxDOT Roadway Design Manual

Guideline 6–

Design of Auxiliary Lanes at Two-Lane Ramps

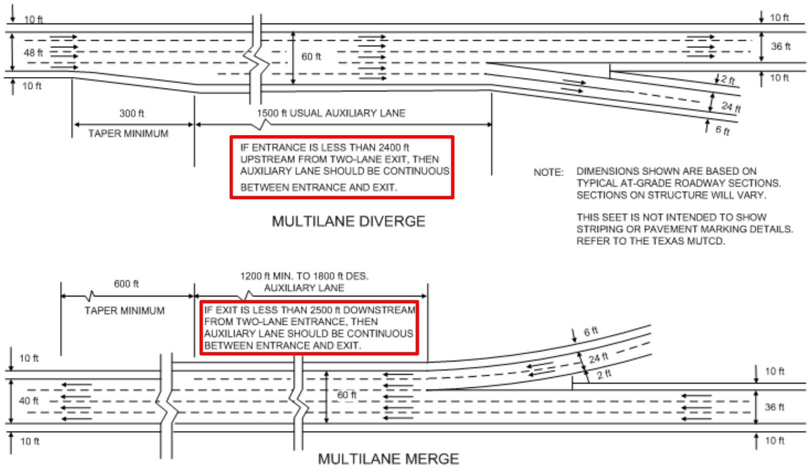
- Where operational problems are caused by **high diverging demand at an exit ramp**, a **two-lane exit ramp** is recommended to increase the diverging capacity and reduce the number of lane-changes mandated for the diverging vehicles.



- For parallel acceleration/deceleration lanes at two-lane ramps, the design of auxiliary lanes can refer to the following figure (TxDOT Roadway Design Manual, 2010).

Guideline 6–

Design of Auxiliary Lanes at Two-Lane Ramps



IF ENTRANCE IS LESS THAN 2400 ft UPSTREAM FROM TWO-LANE EXIT, THEN AUXILIARY LANE SHOULD BE CONTINUOUS BETWEEN ENTRANCE AND EXIT.

MULTILANE DIVERGE

NOTE: DIMENSIONS SHOWN ARE BASED ON TYPICAL AT-GRADE ROADWAY SECTIONS. SECTIONS ON STRUCTURE WILL VARY.

THIS SEET IS NOT INTENDED TO SHOW STRIPING OR PAVEMENT MARKING DETAILS. REFER TO THE TEXAS MUTCD.

IF EXIT IS LESS THAN 2500 ft DOWNSTREAM FROM TWO-LANE ENTRANCE, THEN AUXILIARY LANE SHOULD BE CONTINUOUS BETWEEN ENTRANCE AND EXIT.

MULTILANE MERGE

Source: TxDOT Roadway Design Manual

Guideline 7–

Width of Auxiliary Lanes and Shoulders

- ❑ Desirably, the width of auxiliary lanes should be equal to that of mainline lanes (normally 12 ft).
- ❑ Where auxiliary lanes are provided along freeway mainlines, the adjacent shoulder should desirably be 8-12 ft in width or the same width as mainline lanes, with a minimum shoulder width of 6 ft.

Sources:
- AASHTO Green Book (2011)
- Massachusetts DOT Project Development & Design Guide (2007)
- Utah DOT Roadway Design Manual of Instruction (2007)
- Oregon DOT Highway Design Manual (2003)

Exercise of Look-up Table

Exercise 1: The Weaving Segment

PHF =0.92 (all movements)

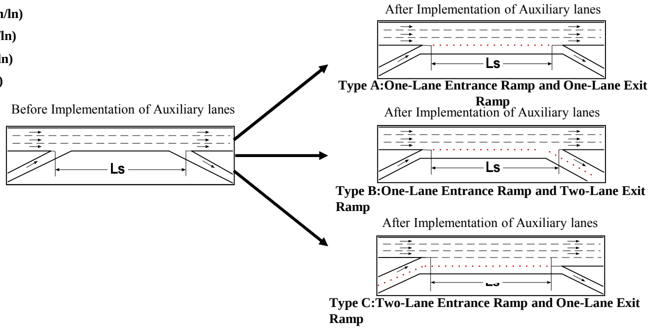
V_{FF} = 1125 (pc/h/ln)

V_{FR} = 550 (pc/h/ln)

V_{RF} =645 (pc/h/ln)

V_{RR} = 0 (pc/h/ln)

L_S = 1350 ft

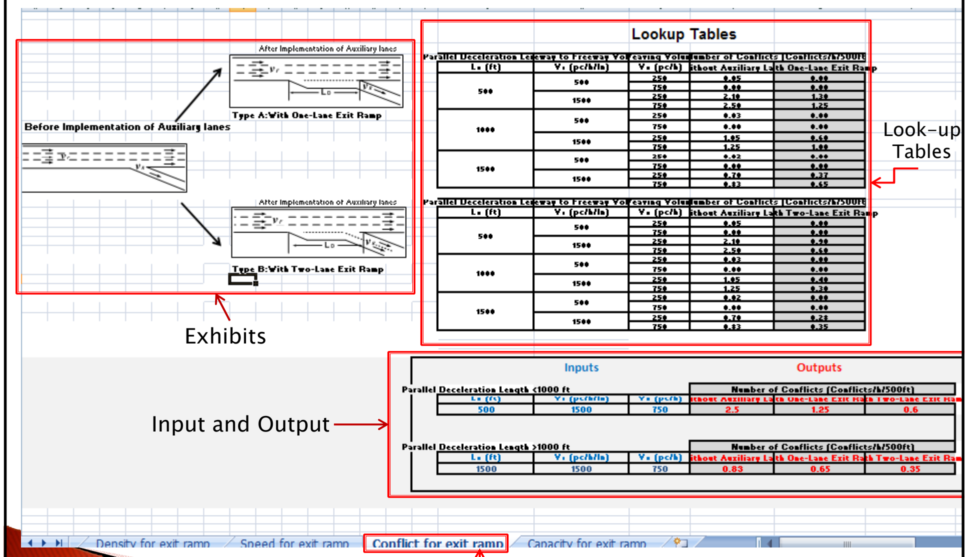


Type A:One-Lane Entrance Ramp and One-Lane Exit Ramp

Type B:One-Lane Entrance Ramp and Two-Lane Exit Ramp

Type C:Two-Lane Entrance Ramp and One-Lane Exit Ramp

What are the expected density, speed, capacity, and conflicts for the each type of weaving segment? What is the difference between the before implementation of auxiliary lanes and after?



Lookup Tables

Parallel Deceleration Le	eway to Freeway Vo	eaving Volu	umber of Conflicts	(Conflicts/h/500ft
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	ithout Auxiliary La	th One-Lane Exit Ramp
500	500	250	0.05	0.00
		750	0.00	0.00
	1500	250	2.10	1.30
		750	2.50	1.25
1000	500	250	0.03	0.00
		750	0.00	0.00
	1500	250	1.05	0.60
		750	1.25	1.00
1500	500	250	0.02	0.00
		750	0.00	0.00
	1500	250	0.70	0.37
		750	0.83	0.65

Parallel Deceleration Le	eway to Freeway Vo	eaving Volu	umber of Conflicts	(Conflicts/h/500ft
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	ithout Auxiliary La	th Two-Lane Exit Ramp
500	500	250	0.05	0.00
		750	0.00	0.00
	1500	250	2.10	0.90
		750	2.50	0.60
1000	500	250	0.03	0.00
		750	0.00	0.00
	1500	250	1.05	0.40
		750	1.25	0.30
1500	500	250	0.02	0.00
		750	0.00	0.00
	1500	250	0.70	0.28
		750	0.83	0.35

Inputs Outputs

Parallel Deceleration Length <1000 ft

			Number of Conflicts (Conflicts/h/500ft)		
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	ithout Auxiliary La	th One-Lane Exit Ra	th Two-Lane Exit Ra
500	1500	750	2.5	1.25	0.6

Parallel Deceleration Length >1000 ft

			Number of Conflicts (Conflicts/h/500ft)		
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	ithout Auxiliary La	th One-Lane Exit Ra	th Two-Lane Exit Ra
1500	1500	750	0.83	0.65	0.35

Step 1: Volume Adjustment

Key volume parameters are:

v_{FF} = 1223 (pc/h/ln)
v_{FR} = 598 (pc/h/ln)
v_{RF} = 701 (pc/h/ln)
v_{RR} = 0 (pc/h/ln)
$v_{FR}+v_{RF}$ = 1299 (pc/h/ln)

Step 2: Determine the Speed

Select worksheet "Speed" in Excel, estimated using Ramp Space > 1000ft, then input the key volume and length of weaving segment (Ls).

Inputs

Ramp Spacing < 1500 ft

Outputs

			Speed (mph)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
1350	1223	1299	58.3	60.0	60.8	61.5

Type A: ΔSpeed = +1.7 (mph)
Type B: ΔSpeed = +2.5 (mph)
Type C: ΔSpeed = +3.2 (mph)

Using the similar way to calculate Density, Capacity and Conflicts in Step 3 to 5
Step 3: Determine the Density
Step 4: Determine the Capacity
Step 5: Determine the Conflicts

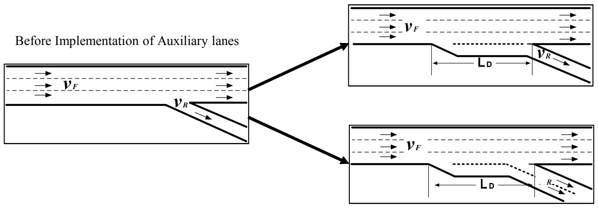
Exercise of Lookup Table

Exercise 2: The Diverging Segment

PHF =0.92 (all movements)
v_{FF} = 1219 (pc/h/ln)
v_R = 216 (pc/h/ln)
L_D = 1500ft

Before Implementation of Auxiliary lanes

After Implementation of Auxiliary lanes
Type A: One -Lane Exit Ramp



Type B: Two-Lane Exit Ramp

What are the expected density, speed, capacity, and conflicts for each type of weaving segment? What is the difference between the before implementation of auxiliary lanes and after?

Step 1: Volume Adjustment

Key volume parameters are:

v_{FF} = 1325 (pc/h/ln)
v_{R} = 235 (pc/h/ln)

Step 2: Determine the Speed

Select worksheet "Speed" in Excel, estimated using Ramp Space > 1000ft, then input the key volume and length of weaving segment (Ls).

Inputs

Parallel Deceleration Length >1000 ft

Outputs

			Speed (mph)		
L_s (ft)	V_F (pc/h/ln)	V_R (pc/h)	Without Auxiliary Lane	With One-Lane Exit Ramp	With Two-Lane Exit Ramp
1500	1325	235	60.9	64.2	64.3

Type A: ΔSpeed = +3.3 (mph)
Type B: ΔSpeed = +3.4 (mph)

Using the similar way to calculate Density, Capacity and Conflicts in Step 3 to 5
Step 3: Determine the Density
Step 4: Determine the Capacity
Step 5: Determine the Conflicts

Thanks. Any Questions ?

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Guidelines for Designing and Methods for Assessing Auxiliary Lanes

Workbook Materials for Workshop

GUIDELINES FOR DESIGNING AND METHODS FOR ASSESSING AUXILIARY LANES

The purpose of this document is to present guidelines for the conditions under which auxiliary lanes should be considered and guidelines for the geometric design of auxiliary lanes. These guidelines were developed based on the results of the literature review, the survey of traffic engineers, and the traffic simulation and crash data analysis.

1 FRAMEWORK OF DEVELOPED GUIDELINES

The proposed guidelines include two parts: (1) general guidelines on the use of auxiliary lanes, and (2) guidelines for design of auxiliary lanes. The recommended guidelines were highlighted in shaded text boxes for easy reference.

2 GENERAL GUIDELINES ON THE USE OF AUXILIARY LANES

This part of the guidelines aims to provide general guidelines regarding the conditions under which the use of auxiliary lanes is suggested.

Guideline 1 – When to Consider the Use of Freeway Auxiliary Lanes:

Auxiliary lane at weaving segments

- If the distance between an entrance ramp and an exit ramp is less than 1500 ft, a continuous auxiliary lane is strongly recommended.
- If an entrance ramp is less than 2400 ft upstream from a two-lane exit ramp, a continuous auxiliary lane between the entrance and the exit should be provided.
- If an exit ramp is less than 2500 ft downstream from a two-lane entrance ramp, a continuous auxiliary lane between the entrance and the exit should be provided.
- If a local frontage road does not exist, a continuous auxiliary lane is strongly recommended.

Auxiliary lane as parallel acceleration/deceleration lanes

If interchanges are widely spaced (e.g., greater than 2500 ft in length), continuous auxiliary lanes between them might not be practical or necessary. In this case, parallel acceleration/ deceleration should be considered when

- Turbulence is significant in the traffic flow because it is caused by vehicles attempting to recover and proceed on the through lanes.
- Safety issues arise because of the forced merges at an entrance ramp.
- Traffic volumes on freeway mainline and entrance ramp meet the conditions provided in Table 1.

Generally, traffic volumes, speed, grade, and safety/operational issues should be analyzed to determine the need for auxiliary lanes. Engineering studies are desirable on a case-by-case basis in determining the need for an auxiliary lane.

Auxiliary Lane at Weaving Segments

Generally, according to *AASHTO Green Book (2011),* operations may be improved by using a continuous auxiliary lane between the entrance and exit ramps where (1) interchanges are closed spaced, (2) the distance between the end of the taper on the entrance terminal taper and the beginning of the taper on the exit terminal taper is short, and/or (3) a local frontage road does not exist. Note that the first two conditions are related to the weaving distance. Several state DOT designs provide more specific guidelines regarding the desired weaving distance for the use of auxiliary lanes as follows:

- According to the *TxDOT Roadway Design Manual (2010*), the provision regarding auxiliary lanes is a major determinant of the spacing required between an entrance ramp and a following exit ramp. It suggests the minimum spacing shall be 2000 ft (600 m) without an auxiliary lane and 1500 ft (450 m) with an auxiliary lane. Therefore, an auxiliary lane is desirable for a spacing of 1500 ft.
- The *Arizona DOT Roadway Design Guidelines (2007)* suggest that, within the metropolitan areas and all other urban/suburban areas throughout the state, mainline auxiliary lanes should be provided on controlled-access highways between ramp entrances and exits of nominally one mile (5280 ft).
- The *California DOT Highway Design Manual (2001)* states that auxiliary lanes should be provided in all cases when the weaving distance is less than 2000 ft (600 m).
- The *Illinois DOT Bureau of Design and Environment Manual (2010),* the *Ohio DOT Location and Design Manual (2011)*, and the *Minnesota DOT Roadway Design Manual (2001)* suggest that an auxiliary lane should be provided where the distance between the taper end of the entrance terminal and the beginning taper of the exit terminal is less than 1500 ft.
- According to the *Montana DOT Road Design Manual (2007),* an auxiliary lane should be provided where the distance between the end of the entrance terminal and the beginning of an exit terminal is less than 1600 ft.

Based on the literature, it is strongly recommended that, if the distance between a one-lane entrance ramp and a one-lane exit ramp is less than 1500 ft, an auxiliary lane be used.

In addition, according to the *TxDOT Roadway Design Manual (2010),* if an entrance ramp is less than 2400 ft upstream from a two-lane exit ramp, an auxiliary lane should be continuous between the entrance and the exit. If an exit ramp is less than 2500 ft downstream from the two-lane entrance ramp, an auxiliary lane should be continuous between the entrance and the exit.

Moreover, according to the design manuals of some state DOTs, several other factors, including traffic volume, grade, speed, etc., should be analyzed to determine the need for auxiliary lanes. The *Illinois DOT Bureau of Design and Environment Manual (2010)*, Indiana DOT's *Indiana Design Manual (2011)* and the *Montana DOT Road Design Manual (2007)* recommend that traffic volumes be analyzed to determine the need for auxiliary lanes. The *California DOT Highway Design Manual (2001)* requires analyzing grade when considering auxiliary lanes.

Furthermore, in the nationwide survey performed in this project, other factors were identified that should be involved in the decision on use of auxiliary lanes. They included traffic density, safety or operational issues, percentage of trucks, and Level of service (LOS).

Auxiliary Lane as Parallel Acceleration/Deceleration Lanes

When interchanges are widely spaced (e.g., greater than 2,500 ft in length), it might not be practical or necessary to extend the auxiliary lane from one interchange to the next. Under such circumstances, parallel acceleration/deceleration lanes are needed if turbulence is significant in the traffic flow caused by vehicles attempting to recover and proceed on the through lanes *(AASHTO Green Book, 2011).*

In addition, the *AASHTO Highway Safety Manual (2010)* indicated that the installation of parallel acceleration lanes at an entrance ramp could improve the safety performance. Therefore, a parallel acceleration lane is preferable when there are traffic safety issues because of forced merges that already exist at the entrance ramp. Furthermore, according to a newly published literature (Wang et al., 2011), traffic volume conditions for adding an auxiliary lane (parallel acceleration lane) with minimum required length at an entrance ramp were provided in Table 1. In this table, the row index v_F is the traffic volume on the freeway mainline (pc/h/ln) and the column index v_R is the traffic volume on the entrance ramp (pc/h/ln). The cells correspondent to these two indexes indicate, under the given traffic volume conditions, if an auxiliary lane (a parallel acceleration lane) is needed or not and how long it should be. A cell with the actual number indicates that an auxiliary lane is needed and the value of this number is the minimum required length of this auxiliary lane (parallel acceleration lane) at this ramp.

Table 1: Traffic Volume Conditions for Adding an Auxiliary Lane with Minimum Required Length

Minimum L_A^* (ft) for $N_F^* = 2$ lanes										
v_F^* (pc/h/ln)	v_R^* (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	100
1250	-	-	-	-	200	300	400	500	600	700
1500	300	400	500	700	800	900	1000	1100	1200	1400
1750	900	1000	1200	1300	1400	1500	-	-	-	-
2000	-	-	-	-	-	-	-	-	-	-

Minimum L_A (ft) for $N_F = 3$ lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	100	200	400
1500	-	-	-	200	300	500	600	700	900	1000
1750	400	600	700	800	1000	1100	1300	1400	-	-
2000	1100	1300	1400	1500	-	-	-	-	-	-

Minimum L_A (ft) for $N_F = 4$ lanes										
v_F (pc/h/ln)	v_R (pc/h/ln)									
	100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
500	-	-	-	-	-	-	-	-	-	-
750	-	-	-	-	-	-	-	-	-	-
1000	-	-	-	-	-	-	-	-	-	-
1250	-	-	-	-	-	-	-	-	-	100
1500	-	-	-	-	-	100	300	400	500	600
1750	100	200	300	400	500	600	800	900	1000	1100
2000	600	700	800	900	1000	1100	1300	1400	1500	-

∗ N_F: Number of lanes on freeway (mainline).
∗ L_A: Length of auxiliary lane.
∗ v_F: Volume on freeway(mainline).
∗ v_R: Volume on on-ramp.

Generally, these guidelines are useful rules of thumb to trigger the consideration for an auxiliary lane. For a specific application, engineering studies are desirable on a case-by-case basis in the final decision on the use of auxiliary lanes.

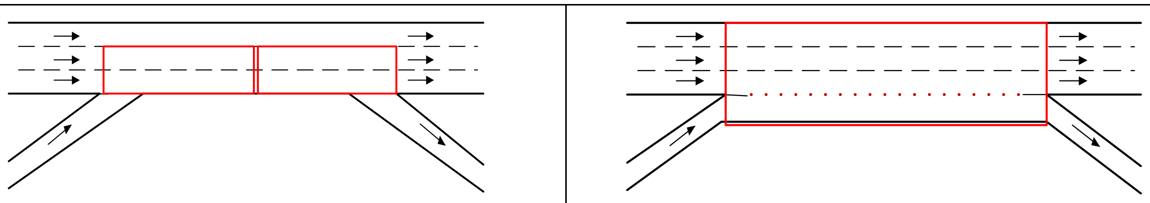
Guideline 2 – Assessment of Operational and Safety Benefits of Adding an Auxiliary Lane:

Look-up tables presented in Table 2 to Table 7 can be used to preliminarily analyze the operational and safety impacts of adding an auxiliary lane.

To facilitate analysis performed by engineers, a set of look-up tables was developed in this project. The tables covered a wide range of combinations of typical geometric and traffic conditions. They allowed the users to perform a preliminary analysis without having to conduct the complex calculation (such as Highway Capacity Manual [HCM] procedures) or a detailed traffic simulation-based analysis.

Note that the results of this study showed that the HCM methods might be limited in analyzing a weaving segment without an auxiliary lane for following two reasons:

- The HCM model for weaving segments is only for the segments with an auxiliary lane and it yields results (e.g., density and speed) for all lanes within the weaving segment (please see Figure 1[b]). For the weaving segments without auxiliary lanes, the HCM suggested modeling them as two joint ramp influence areas (please see Figure 1[a]). However, this approach yielded results (e.g., density and speed) only for the two mainline lanes next to the shoulder (i.e., two ramp influence areas). Thus, the modeling results of these two cases cannot be compared directly.
- The results (e.g., density and speed) of Case A (without auxiliary lanes, modeled as two joint ramp influence areas) sometimes were better than those of Case B (with auxiliary lanes, modeled by HCM standard method), which is not reasonable because installing an auxiliary lane should not make the segment performance become worse and the two outer lanes next to the shoulder should be affected more by the diverging and merging traffic than the inner lanes.



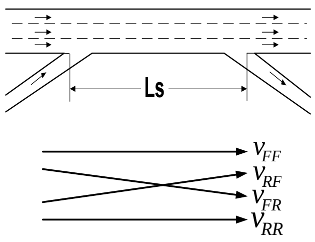
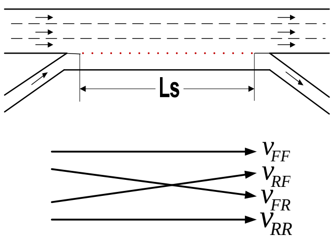
(a) Modeling weaving segments without auxiliary lanes as two joint ramp influence areas as suggested by HCM

(b) Modeling weaving segments with an auxiliary lane using HCM weaving procedures

Figure 1: HCM Analysis for Weaving Segment without and with an Auxiliary Lane

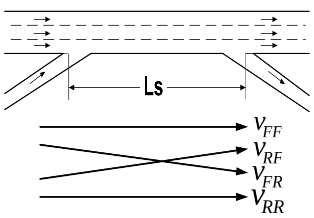
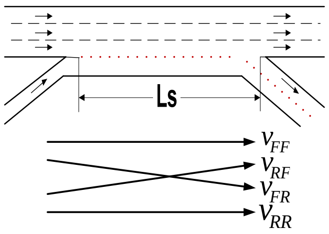
Therefore, in this study, the traffic simulation-based approach was used to develop the look-up tables for analyzing the operational and safety impacts of adding an auxiliary lane. Please note, for developing the proposed look-up tables, there were several assumptions implicitly used in the simulation studies, besides the traffic and geometric conditions shown in Tables 2 to 7. Considerations should be given to adjust the estimates of the performance measures listed in the look-up tables for a specific case that deviates from these assumptions. These assumptions include: Peak hour factor = 1.0; Percentage for heavy-vehicle = 0 percent; Lane width and auxiliary lane width = 12 ft; Grade = 0; Driver population is assumed as regular commuters.

Table 2: Look-Up Table for Weaving Segments (One-Lane Entrance Ramp and One-Lane Exit Ramp)

Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $v_{FR}+v_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	7.0	-26.32%	61.8	63.0	1.94%	5908	8198	38.77%	10.00	0.10	0.01	A	A
				1500	13.3	10.1	-24.06%	56.9	56.1	-1.41%				41.37	3.83	0.09	B	B
			1500	500	26.2	19.1	-27.10%	60.7	62.3	2.64%				27.03	1.10	0.04	C	B
				1500	31.5	24.0	-23.81%	55.7	54.9	-1.44%				152.97	28.23	0.18	D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.7	1.59%	5914	8421	42.39%	8.88	0.10	0.01	A	A
				1500	13.1	9.5	-27.48%	57.8	59.7	3.29%				12.02	0.47	0.04	B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.6	1.62%				20.68	0.10	0.00	C	B
				1500	30.4	21.7	-28.62%	57.7	60.6	5.03%				77.75	2.60	0.03	D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	63.8	1.43%	5962	8668	45.39%	4.28	0.00	0.00	A	A
				1500	12.9	9.4	-27.13%	58.0	60.0	3.45%				8.58	0.01	0.00	B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	0.51	0.05	C	B
				1500	29.9	21.5	-28.09%	58.6	61.1	4.27%				15.37	0.59	0.04	D	C
					Average :		-26.45%	Average :		1.99%	Average :		42.18%	Average :		0.04		

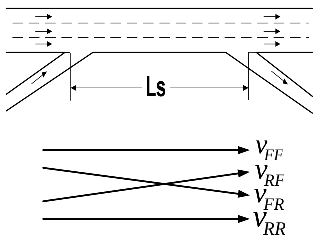
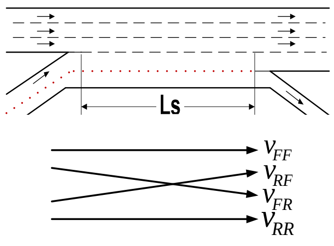
Note: Weaving Volume=Volume of Ramp to Freeway + Volume of Freeway to Ramp

Table 3: Look-Up Table for Weaving Segments (One-Lane Entrance Ramp and Two-Lane Exit Ramp)

Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft)	Freeway to freeway volume (pc/h/ln)	Weaving volume (pc/h) $V_{FR}+V_{RF}$	Before Density	After Density	% of Density	Before Speed (mph)	After Speed (mph)	% of Speed	Before Capacity (veh/h)	After Capacity (veh/h)	% of Capacity	Before (conflicts/h/500ft)	After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	6.9	-27.37%	61.8	63.5	2.75%	5908	8249	39.62%	10.00	0.00	0.00	A	A
				1500	13.3	9.6	-27.82%	56.9	59.3	4.22%				41.37	0.08	0.00	B	A
			1500	500	26.2	19.1	-27.10%	60.7	62.5	2.97%				27.03	0.96	0.04	C	B
				1500	31.5	22.4	-28.89%	55.7	58.9	5.75%				152.97	13.40	0.09	D	C
		1500	500	500	9.4	6.9	-26.60%	62.7	63.8	1.75%	5914	8631	45.94%	8.88	0.05	0.01	A	A
				1500	13.1	9.5	-27.48%	57.8	60.0	3.81%				12.02	0.14	0.01	B	A
			1500	500	25.8	19.0	-26.36%	61.6	62.7	1.79%				20.68	1.09	0.05	C	B
				1500	30.4	21.7	-28.62%	57.7	60.7	5.20%				77.75	1.91	0.02	D	C
		2250	500	500	9.3	6.9	-25.81%	62.9	64.0	1.75%	5962	8665	45.34%	4.28	0.05	0.01	A	A
				1500	12.9	6.9	-46.51%	58.0	63.4	9.31%				8.58	0.00	0.00	B	A
			1500	500	25.7	19.0	-26.07%	61.9	62.8	1.45%				11.02	2.50	0.23	C	B
				1500	29.9	18.9	-36.79%	58.6	62.9	7.34%				15.37	2.35	0.15	D	B
						Average :	-29.62%		Average :	4.01%		Average :	43.63%		Average :	0.05		

Note: Weaving Volume=Volume of Ramp to Freeway + Volume of Freeway to Ramp

Table 4: Look-Up Table for Weaving Segments (Two-Lane Entrance Ramp and One-Lane Exit Ramp)

Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h), $V_{FR}+V_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density	Speed-Before (mph)	Speed-After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h500ft)	TCMF	LOS Before	LOS After
		750	500	500	9.5	5.5	-42.11%	61.8	63.5	2.75%	5908	8767	48.39%	10.00	0	0.00	A	A
				1500	13.3	7.9	-40.60%	56.9	57.1	0.35%				41.37	3.05	0.07	B	A
			1500	500	26.2	15.1	-42.37%	60.7	63.0	3.79%				27.03	0.65	0.02	C	B
				1500	31.5	17.7	-43.81%	55.7	59.6	7.00%				152.97	22	0.14	D	B
		1500	500	500	9.4	5.5	-41.49%	62.7	63.6	1.44%	5914	9441	59.64%	8.88	0.05	0.01	A	A
				1500	13.1	7.5	-42.75%	57.8	60.2	4.15%				12.02	0.8	0.07	B	A
			1500	500	25.8	15.1	-41.47%	61.6	63.3	2.76%				20.68	2.6	0.13	C	B
				1500	30.4	17.0	-44.08%	57.7	62.0	7.45%				77.75	6.7	0.09	D	B
		2250	500	500	9.3	5.5	-40.86%	62.9	64.0	1.75%	5962	9539	60.00%	4.28	0.05	0.01	A	A
				1500	12.9	7.4	-42.64%	58.0	61.1	5.34%				8.58	0.65	0.08	B	A
			1500	500	25.7	14.9	-42.02%	61.9	63.8	3.07%				11.02	2	0.18	C	B
				1500	29.9	16.8	-43.81%	58.6	62.6	6.83%				15.37	4.95	0.32	D	B
					Average :		-42.33%	Average :		3.89%	Average :		56.01%	Average :		0.09		

Note: Weaving Volume=Volume of Ramp to Freeway + Volume of Freeway to Ramp

Table 5: Look-Up Table for Merge Segments with a One-Lane Entrance Ramp

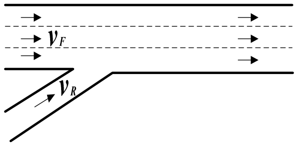
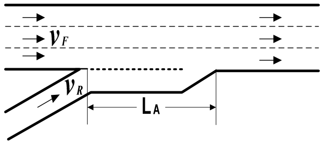
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Acceleration Length (ft), L_A	Freeway to Freeway volume (pc/h/ln), v_F	Merging Volume (pc/h), v_R	Density – Before (vpm)	Density - After (vpm)	% of Change in Density	Speed - Before (mph)	Speed - After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count-Before (conflicts/h/500ft)	Conflict Count-After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		500	500	250	9.2	7.1	-22.83%	63.8	62.5	-2.04%	6892	6970	1.13%	20.15	0.05	0.00	A	A
				750	12.5	9.5	-24.00%	60.5	59.8	-1.16%				58.95	0.2	0.00	B	A
			1500	250	25.9	19.6	-24.32%	61.5	61.0	-0.81%				55.30	3.25	0.06	C	B
				750	30.4	24.4	-19.74%	57.7	53.9	-6.59%				180.35	31.1	0.17	D	C
		1000	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7055	2.37%	10.20	0.08	0.01	A	A
				750	12.5	9.3	-25.60%	60.5	60.9	0.66%				30.90	0.13	0.00	B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				26.53	0.73	0.03	C	B
				750	30.4	21.9	-27.96%	57.7	60.2	4.33%				91.78	2.70	0.03	D	C
		1500	500	250	9.2	6.9	-25.00%	63.8	63.9	0.16%	6892	7059	2.42%	4.27	0.02	0.00	A	A
				750	12.5	9.3	-25.60%	60.5	61.1	0.99%				13.85	0.03	0.00	B	A
			1500	250	25.9	19.1	-26.25%	61.5	62.4	1.46%				15.08	0.37	0.02	C	B
				750	30.4	21.8	-28.29%	57.7	60.4	4.68%				45.90	1.03	0.02	D	C
					Average :		-25.07%	Average :		0.28%	Average :		1.97%	Average :		0.03		

Table 6: Look-Up Table for Diverge Segments with a One-Lane Exit Ramp

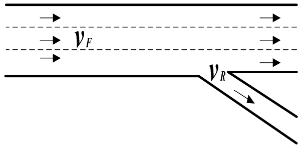
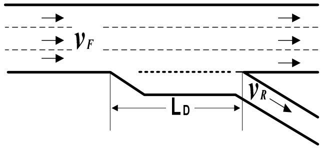
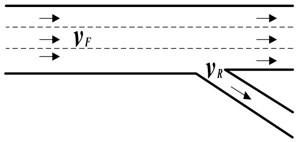
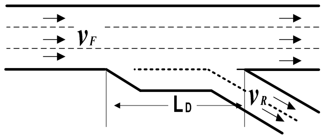
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway to Freeway volume (pc/h/ln), v_F	Diverging Volume (pc/h), v_R	Density - Before (vpm)	Density - After (vpm)	% of Change in Density	Speed - Before (mph)	Speed - After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count - Before (conflicts/h/500ft)	Conflict Count - After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
 	 	500	500	250	8.1	6	-25.93%	62.0	63.4	2.26%	6584	6636	0.79%	0.05	0.00	0.00	A	A
				750	8.4	6.3	-25.00%	59.6	59.7	0.17%				0.00	0.00	N/A	A	A
			1500	250	26.3	18	-31.56%	60.6	62.6	3.30%				2.10	1.30	0.62	C	B
				750	29.7	18.3	-38.38%	60.6	61.6	1.65%				2.50	1.25	0.50	C	B
		1000	500	250	8.1	5.8	-28.40%	62.0	65.3	5.32%	6584	6637	0.80%	0.03	0.00	0.00	A	A
				750	8.4	5.9	-29.76%	59.6	64.3	7.89%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.6	-33.08%	60.6	64.0	5.61%				1.05	0.60	0.57	C	B
				750	29.7	17.8	-40.07%	60.6	63.5	4.79%				1.25	1.00	0.80	C	B
		1500	500	250	8.1	5.8	-28.40%	62.0	65.6	5.81%	6584	6640	0.85%	0.02	0.00	0.00	A	A
				750	8.4	5.9	-29.76%	59.6	63.6	6.71%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.6	63.9	5.45%				0.70	0.37	0.52	C	B
				750	29.7	17.7	-40.40%	60.6	63.9	5.45%				0.83	0.65	0.78	C	B
						Average :	-31.95%		Average :	4.53%		Average :	0.82%		Average :	0.42		

Table 7: Look-Up Table for Diverge Segments with a Two-Lane Exit Ramp

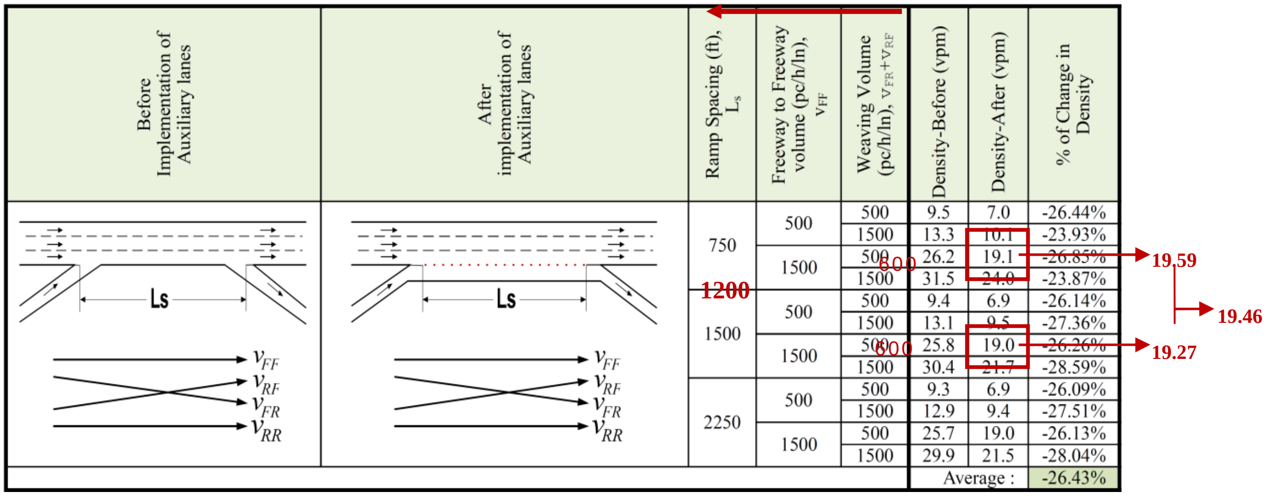
Before Implementation of Auxiliary lanes	After Implementation of Auxiliary lanes	Parallel Deceleration Length (ft), L_D	Freeway to Freeway volume (pc/h/ln), v_F	Diverging Volume (pc/h), v_R	Density - Before(vpm)	Density - After (vpm)	% of Change in Density	Speed - Before (mph)	Speed - After (mph)	% of Change in Speed	Capacity - Before (veh/h)	Capacity - After (veh/h)	% of Change in Capacity	Conflict Count - Before (conflicts/h/500ft)	Conflict Count - After (conflicts/h/500ft)	TCMF	LOS Before	LOS After
		500	500	250	8.1	5.9	-27.16%	62.0	64.2	3.55%	6584	6995	6.24%	0.05	0.00	0.00	A	A
				750	8.4	6.0	-28.57%	59.6	63.4	6.38%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.9	-31.94%	60.5	62.9	3.97%				2.10	0.90	0.43	C	B
				750	29.7	18.1	-39.06%	59.4	62.5	5.22%				2.50	0.60	0.24	C	B
		1000	500	250	8.1	5.7	-29.63%	62.0	65.7	5.97%	6584	6995	6.24%	0.03	0.00	0.00	A	A
				750	8.4	5.8	-30.95%	59.6	65.0	9.06%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.7	5.29%				1.05	0.40	0.38	C	B
				750	29.7	17.7	-40.40%	59.4	63.7	7.24%				1.25	0.30	0.24	C	B
		1500	500	250	8.1	5.7	-29.63%	62.0	66.0	6.45%	6584	6995	6.24%	0.02	0.00	0.00	A	A
				750	8.4	5.8	-30.95%	59.6	65.4	9.73%				0.00	0.00	N/A	A	A
			1500	250	26.3	17.7	-32.70%	60.5	63.9	5.62%				0.70	0.28	0.40	C	B
				750	29.7	17.6	-40.74%	59.4	64.0	7.74%				0.83	0.35	0.42	C	B
					Average :		-32.87%	Average :		6.35%	Average :		6.24%	Average :		0.23		

Example for Using the Look-up Tables

Interpolated values may be used for a rough estimation based on the tables. For the following instance:

- Ramp Spacing (L_S) = 1200 ft.
- Freeway to Freeway volume (V_{FF}) = 1500 vph.
- Weaving Volume (V_{FR}+V_{RF}) = 600 vph.

Assuming an analyst needs to estimate the traffic density after the auxiliary lane is installed at a weaving segment with a one-lane entrance ramp and a one-lane exit ramp, Table 2 can be used as shown in Figure 2.



Before Implementation of Auxiliary lanes	After implementation of Auxiliary lanes	Ramp Spacing (ft), L_s	Freeway to Freeway volume (pc/h/ln), v_{FF}	Weaving Volume (pc/h/ln), $v_{FR}+v_{RF}$	Density-Before (vpm)	Density-After (vpm)	% of Change in Density
		750	500	500	9.5	7.0	-26.44%
				1500	13.3	10.1	-23.93%
			1500	500	26.2	19.1	-26.85%
				1500	31.5	24.0	-23.87%
		1500	500	500	9.4	6.9	-26.14%
				1500	13.1	9.5	-27.36%
			1500	500	25.8	19.0	-26.26%
				1500	30.4	21.7	-28.59%
		2250	500	500	9.3	6.9	-26.09%
				1500	12.9	9.4	-27.51%
			1500	500	25.7	19.0	-26.13%
				1500	29.9	21.5	-28.04%
						Average :	-26.43%

Figure 2: Demo of Analyzing the Weaving Segment Performance without and with an Auxiliary Lane Based on the Look-Up Tables

Since the ramp spacing is given as 1200 ft, the freeway-to-freeway volume is given as 1500 vph, and the weaving volume is 600 vph, the analyst should look at the two red-outlined areas. The interpolated values of the percentage of changes should be calculated by the following equation:

$$y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0}$$

Where: y_1 is the upper bound performance measure (e.g., density, speed, capacity, or conflicts).

y_0 is the lower bound performance measure.

x_1 is the upper bound input variable (e.g., L_S, V_{FF} or $V_{FR}+V_{RF}$).

x_0 is the lower bound input variable.

The interpolated value is calculated based on the values of the input variables listed from the right to left in the look up table. Therefore, for the Weaving Volume ($V_{FR}+V_{RF}$) = **600 vph**, Freeway to Freeway volume (V_{FF}) = 1500 vph, Ramp Spacing (L_S) = 750 ft, the interpolated traffic density after installing auxiliary lane is equal to:

$$19.1+ (600-500)*(24-19.1)/(1500-500) = 19.59 \text{ vpm}$$

Likewise, for the Weaving Volume ($V_{FR}+V_{RF}$) = **600 vph**, Freeway to Freeway volume (V_{FF}) = 1500 vph, Ramp Spacing (L_S) = 1500 ft, the interpolated traffic density after installing auxiliary lane is equal to:

$$19+ (600-500)*(21.7-19.0)/(1500-500) = 19.27 \text{ vpm}$$

Finally, for Weaving Volume ($V_{FR}+V_{RF}$) = **600 vph**, Freeway to Freeway volume (V_{FF}) = 1500 vph, Ramp Spacing (LS) = **1200 ft**, the interpolated value can be calculated as follows:

$$19.27+ (1200-750)*(19.59-19.27)/(1500-750) = 19.46 \text{ vpm}$$

3 GUIDELINES FOR DESIGN OF AUXILIARY LANES

This part of the guidelines aims to synthesize and recommend guidelines regarding geometric design of auxiliary lanes. For guidelines regarding design of signage and pavement marking, please refer to the latest version of the *TXDOT Freeway Signing Handbook* and the *Texas Manual on Uniform Traffic Control Devices (TMUTCD - Chapter 3).*

Guideline 3 – General Principles for Lane Arrangement where Auxiliary Lanes Are Used:

Two basic principles are generally recommended to balance the traffic load and maintain a uniform level-of-service along the freeway with an auxiliary lane:

- Consistency of basic number of lanes
- Principles of lane balance

These two general principles were recommended based on the *AASHTO Green Book (2011)*.

Consistency of Basic Number of Lanes

The basic number of lanes is the minimum number of traffic lanes designated and maintained over a significant length of a freeway. It is often determined based on the traffic demand on freeway mainlines. According to the *AASHTO Green Book (2011)*, the basic number of lanes should be consistent for a substantial length of freeway, irrespective of changes in traffic volume and lane balance needs.

Principles of Lane Balance

To realize efficient traffic operation through and beyond an interchange, the *AASHTO Green Book (2011)* recommends that there be a balance in the number of lanes on the freeway and ramps. The *Roadway Design Manuals* of Illinois, Indiana, Massachusetts, Minnesota, Montana, Nevada, Ohio, Utah, and Washington explicitly mention that the principles of lane balance should be followed.

> For auxiliary lanes less than 1,500 ft in length (e.g., between closely spaced interchanges or between the loop ramp entrance and the loop ramp exit of a cloverleaf interchange), lane balance principles permit the termination of the auxiliary lane with a one-lane exit ramp as shown in Figure 3.

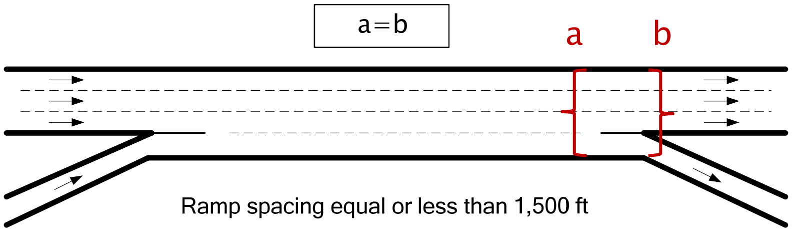
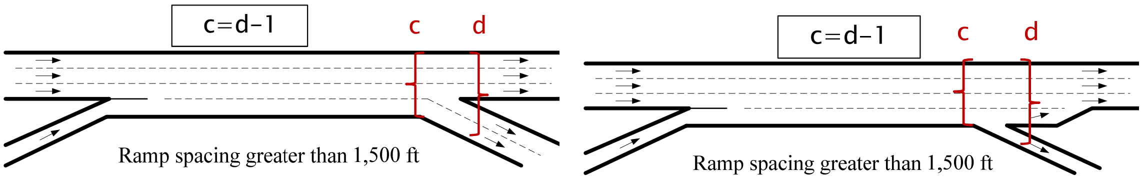


Figure 3: Principles of Lane Balance for Ramp Spacing Less than 1,500 ft

(Source: AASHTO Green Book, 2011)

Condition 2: For auxiliary lanes greater than 1,500 ft in length, lane balance principles state that the number of approach lanes on the freeway must be equal to the number of lanes on the freeway beyond the exit plus the number of lanes on the exit, minus one, as shown in Figure 4.

Under Condition 2, the auxiliary lane may be terminated by one of two methods shown in Figures 4 (a) and 4 (b). The first method, shown in Figure 4 (a), 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 4 (b), 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 inadvertently remain in the discontinued lane.



(a) Auxiliary lane terminated with two-lane exit ramp

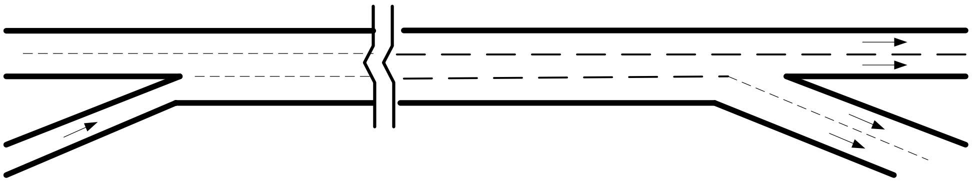
(b) Auxiliary lane terminated with downstream taper

Figure 4: Principles of Lane Balance for Ramp Spacing Greater than 1,500 ft

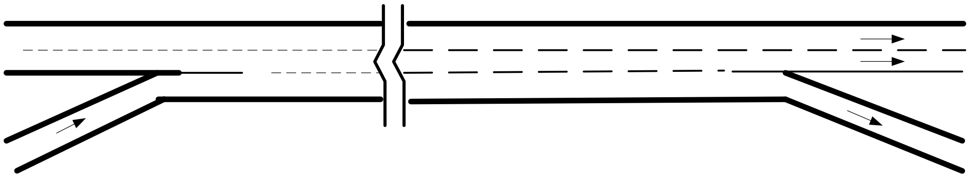
(Source: AASHTO Green Book, 2011)

Guideline 4 – Methods for Dropping an Auxiliary Lane from Mainline:

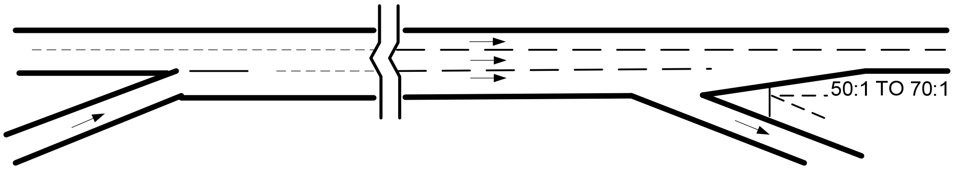
When it is not practical or necessary to extend the auxiliary lane from one interchange to the next, the following alternative methods can be considered for dropping an auxiliary lane from the mainline as shown in Figure 5.



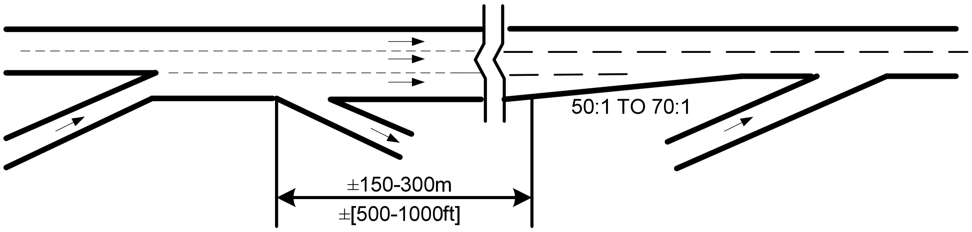
(a) Auxiliary lane dropped on exit ramp



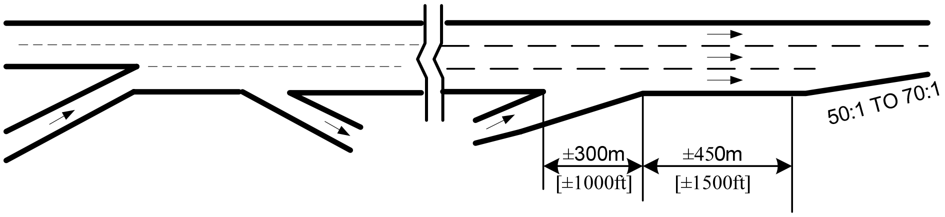
(b) Auxiliary lane between cloverleaf loops or closely spaced interchanges dropped on single exit lane



(c) Auxiliary lane dropped at physical nose



(d) Auxiliary lane dropped within an interchange



(e) Auxiliary lane dropped beyond an interchange

Figure 5: Alternative Methods to Drop Auxiliary Lanes

(Source: AASHTO Green Book, 2011)

Please note, the findings of this project showed that extending the auxiliary lane beyond an interchange (Figure 5 [e]) is preferable only if the entrance ramp downstream has a low traffic volume or volume-of-capacity. If the next entrance ramp has a high traffic volume, it is desirable to drop the auxiliary lane before the next entrance as shown in Figure 6.

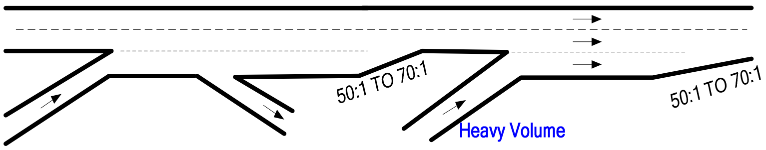
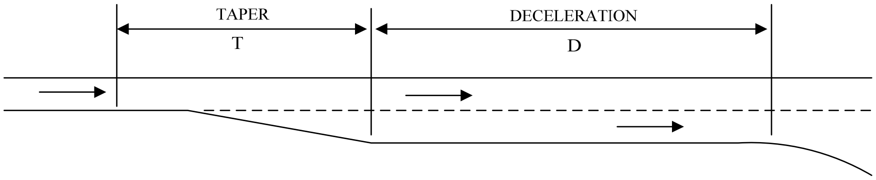


Figure 6: Scenario when Auxiliary Lane Dropped within an Interchange Is Preferred

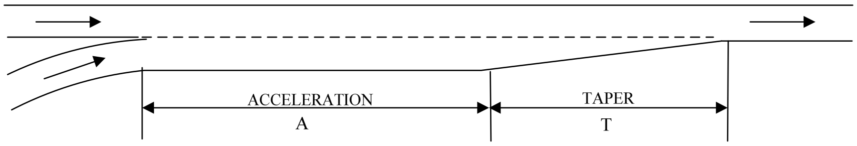
<u>Guideline 5 – Length of Parallel Acceleration/Deceleration Lanes Auxiliary Lanes at Merge/Diverge Area:</u>

Refer to Figure 7 for lengths of taper and parallel acceleration/deceleration lanes, where design speed represents the mainline speed and entrance-curve design speed represents the desired speed at the street-ramp junction.

For parallel acceleration/deceleration lanes, the lengths can be determined based on the provisions in the *TxDOT Roadway Design Manual (2010).*



HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	DECELERATION LENGTH, D (ft)				
		Ramp Speed				
		30	35	40	45	50
50	230	315	285	225	175	-
55	250	380	350	285	235	-
60	265	430	405	350	300	240
65	285	470	440	390	340	280
70	300	520	490	440	390	340
75	330	575	535	490	440	390



HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	ACCELERATION LENGTH, A (ft)							
		Entering Speed							
		15	20	25	30	35	40	45	50
50	230	660	610	550	450	350	130	-	-
55	250	900	810	780	670	550	320	150	-
60	265	1140	1100	1020	910	800	550	420	180
65	285	1350	1310	1220	1120	1000	770	600	370
70	300	1560	1520	1420	1350	1230	1000	820	580
75	330	1730	1630	1580	1510	1420	1160	1040	780

Figure 7: Lengths of Parallel Acceleration/Deceleration Lanes at Entrance/Exit Ramp

(Source: TxDOT Roadway Design Manual)

Guideline 6 – Design of Auxiliary Lanes at Two-Lane Ramps:

- Where operational problems are caused by high entrance/exit ramp demand, a two-lane entrance/exit ramp is recommended to increase the capacity for the merging/diverging vehicles.
- If a two-lane entrance ramp is installed because of high merging traffic demand and the next ramp that is within the 2500 ft distance with low or moderate traffic volume, it is recommended to extend the auxiliary lane that originated from the two-lane entrance ramp beyond the next ramp.
- For parallel acceleration/deceleration lanes at two-lane ramps, the design of auxiliary lanes can refer to Figure 8 (*TxDOT Roadway Design Manual, 2010*).

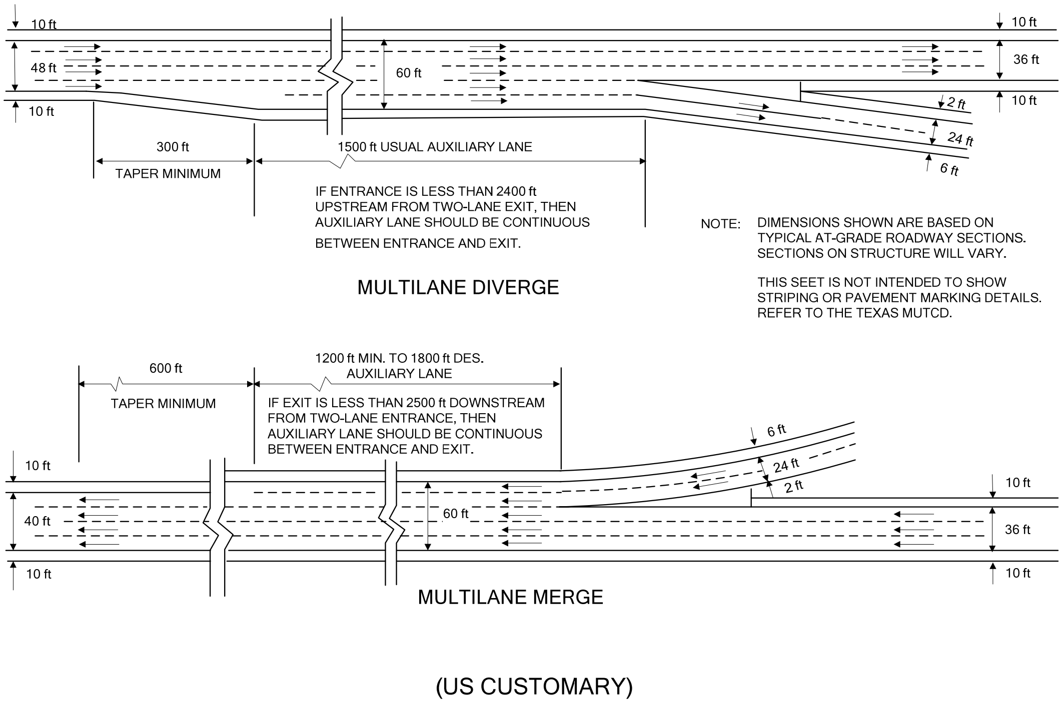


Figure 8: Lengths of Parallel Acceleration/Deceleration Lanes at Entrance/Exit Ramp

(Source: TxDOT Roadway Design Manual)

This guideline is based on the *AASHTO Green Book (2011)* and the *TxDOT Roadway Design Manual (2010)* - Chapter 3. In addition, the results of the simulation analysis in this study indicated that operational benefits were achieved by extending two-lane entrance ramp to the next ramp if they are closely spaced. For parallel acceleration/deceleration lanes at two-lane ramps, the design of auxiliary lanes can refer to Figure 8 (*TxDOT Roadway Design Manual, 2010*).

Guideline 7 – Width of Auxiliary Lanes and Shoulders:

- Desirably, the width of auxiliary lanes should be equal to that of mainline lanes (normally 12 ft).
- Where auxiliary lanes are provided along freeway mainlines, the adjacent shoulder should desirably be 8–12 ft in width or the same width as mainline lanes, with a minimum shoulder width of 6 ft.

This guideline is based on the *AASHTO Green Book (2011),* as well as the *Massachusetts DOT Project Development & Design Guide (2007)*, the *Utah DOT Roadway Design Manual of Instruction (2007)*, and the *Oregon DOT Highway Design Manual (2003)*.

According to the *AASHTO Green Book (2011),* where auxiliary lanes are provided along freeway main lanes, the adjacent shoulder should desirably be 8 ft–12 ft wide, with a minimum 6-ft-wide shoulder considered.

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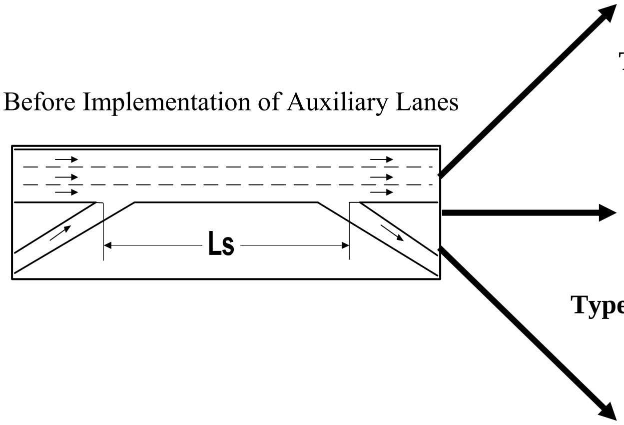
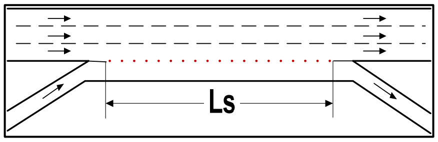
Wang, Y., R. Cheu, Y. Qi, and X. Chen. *Use of Auxiliary Lanes at Isolated Freeway On-Ramp Junctions*. Accepted to be published at *Journal of Transportation of ITE*, 2013.

Exercise 1:

Before Implementation of Auxiliary Lanes

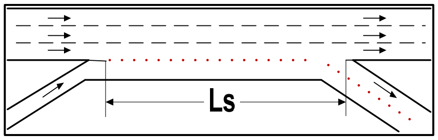


After Implementation of Auxiliary Lanes



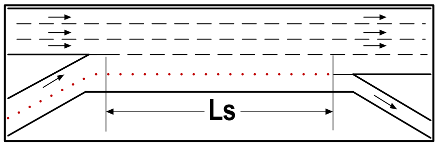
Type A: One-Lane Entrance Ramp and One-Lane Exit Ramp

After Implementation of Auxiliary Lanes



Type B: One-Lane Entrance Ramp and Two-Lane Exit Ramp

After Implementation of Auxiliary Lanes



Type C: Two-Lane Entrance Ramp and One-Lane Exit Ramp

The Weaving Segment

What are the expected density, speed, capacity, and conflicts for the each type of weaving segment? What is the difference between the before implementation of auxiliary lanes and after?

The Facts

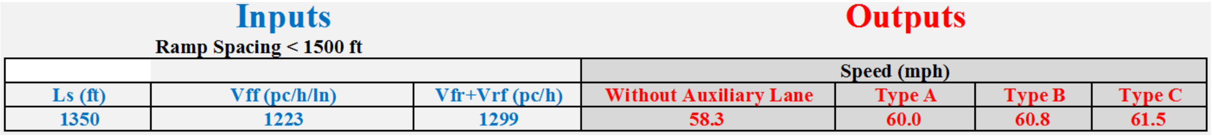
PHF =0.92 (all movements)
v_{FF} = 1125 (pc/h/ln)
v_{FR} = 550 (pc/h/ln)
v_{RF} =645 (pc/h/ln)
v_{RR} = 0 (pc/h/ln)
L_s = 1350 f

Step 2: Volume Adjustment

Key volume parameters are:
v_{FF} = 1223 (pc/h/ln)
v_{FR} = 598 (pc/h/ln)
v_{RF} =701 (pc/h/ln)
v_{RR} = 0 (pc/h/ln)
$v_{FR} + v_{RF}$ = 1299 (pc/h/ln)

Step 3: Determine the Speed

Select worksheet “Speed” in Excel , estimated using Ramp Space < 1500ft , then input the key volume and length of weaving segment (L_s).



Inputs

Ramp Spacing < 1500 ft

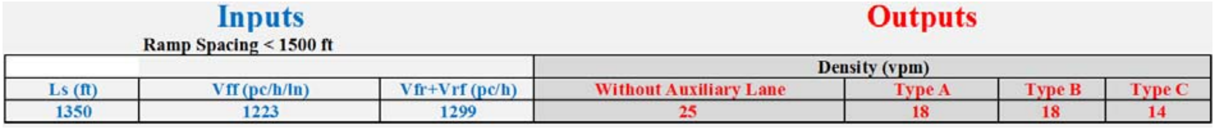
Outputs

			Speed (mph)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
1350	1223	1299	58.3	60.0	60.8	61.5

Type A: ΔSpeed = +1.7 (mph)
Type B: ΔSpeed = +2.5 (mph)
Type C: ΔSpeed = +3.2 (mph)

Step 4: Determine the Density

Select worksheet "Density" in Excel , estimated using Ramp Space < 1500ft , then input the key volume and length of weaving segment (L_S).



Inputs

Ramp Spacing < 1500 ft

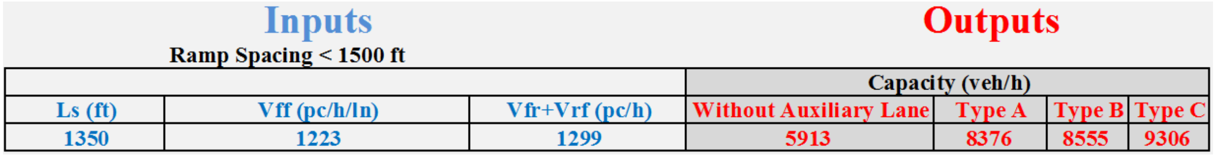
Outputs

			Density (vpm)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
1350	1223	1299	25	18	18	14

Type A: ΔDensity= -7 (vpm)
Type B: ΔDensity= -7 (vpm)
Type C: ΔDensity = -11 (vpm)

Step 5: Determine the Capacity

Select worksheet "Capacity" in Excel , estimated using Ramp Space < 1500ft , then input the key volume and length of weaving segment (L_S).



Inputs

Ramp Spacing < 1500 ft

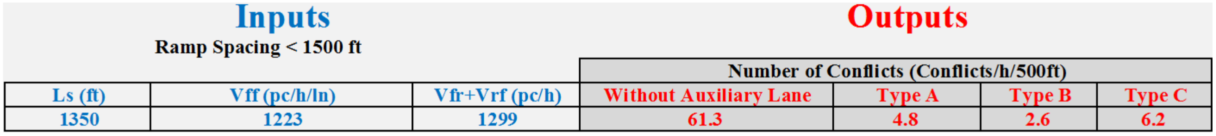
Outputs

			Capacity (veh/h)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
1350	1223	1299	5913	8376	8555	9306

Type A: ΔCapacity = +2463 (veh/h)
Type B: ΔCapacity= +2642 (veh/h)
Type C: ΔCapacity = +3393 (veh/h)

Step 6: Determine the Conflicts

Select worksheet "Conflicts" in Excel , estimated using Ramp Space < 1500ft , then input the key volume and length of weaving segment (L_S).



Inputs

Ramp Spacing < 1500 ft

Outputs

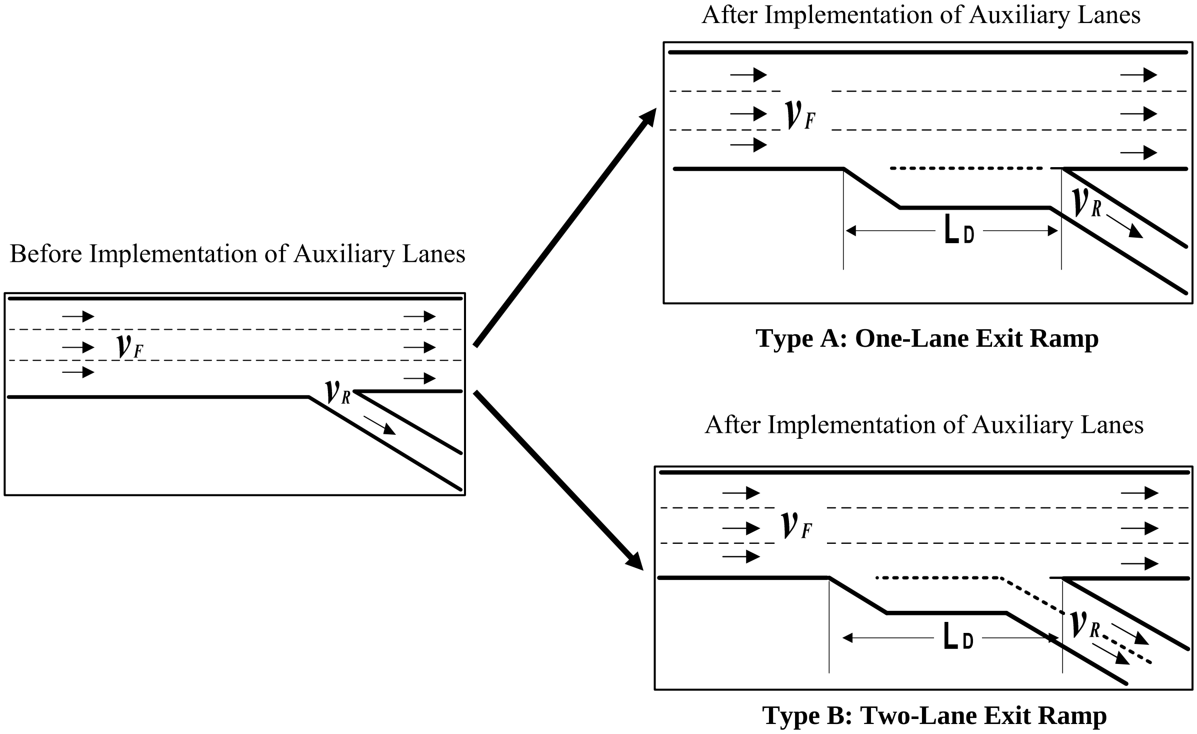
			Number of Conflicts (Conflicts/h/500ft)			
Ls (ft)	Vff (pc/h/ln)	Vfr+Vrf (pc/h)	Without Auxiliary Lane	Type A	Type B	Type C
1350	1223	1299	61.3	4.8	2.6	6.2

Type A: ΔDensity= -56.5 (conflicts/h/500ft)
Type B: ΔDensity= -58.7 (conflicts/h/500ft)
Type C: ΔDensity = -55.1 (conflicts/h/500ft)

Exercise 2:

The Weaving Segment

The weaving segment that is the subject of this example problem is show in Exhibit-2.


Before Implementation of Auxiliary Lanes

After Implementation of Auxiliary Lanes

Type A: One-Lane Exit Ramp

After Implementation of Auxiliary Lanes

Type B: Two-Lane Exit Ramp

Exhibit-2

What are the expected density, speed, capacity and conflicts for the each type of weaving segment? What is the difference between the before implementation of auxiliary lanes and after?

The Facts

PHF =0.92 (all movements)
v_F = 1219(pc/h/ln)
v_R = 216(pc/h/ln)
L_D = 1500 ft

Step 1: Volume Adjustment

Key volume parameters are:
v_F = 1325 (pc/h/ln)
v_R = 235 (pc/h/ln)

Step 2: Determine the Speed

Select worksheet “Speed” in Excel , estimated using Ramp Space > 1000ft, then input the key volume and length of weaving segment (L_s).

Inputs **Outputs**

Parallel Deceleration Length >1000 ft

			Speed (mph)		
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	Without Auxiliary Lane	With One-Lane Exit Ramp	With Two-Lane Exit Ramp
1500	1325	235	60.8	64.2	64.2

Type A: ΔSpeed = +3.4 (mph)
Type B: ΔSpeed = +3.4 (mph)

Step 3: Determine the Density

Select worksheet "Density" in Excel , estimated using Ramp Space > 1000ft , then input the key volume and length of weaving segment (L_S).

Inputs **Outputs**

Parallel Deceleration Length >1000 ft

			Density (vpm)		
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	Without Auxiliary Lane	With One-Lane Exit Ramp	With Two-Lane Exit Ramp
1500	1325	235	23.0	15.6	15.6

Type A: ΔDensity= -7.4 (vpm)
Type B: ΔDensity= -7.4 (vpm)

Step 4: Determine the Capacity

Select worksheet "Capacity" in Excel , estimated using Ramp Space > 1000ft , then input the key volume and length of weaving segment (L_S).

Inputs **Outputs**

Parallel Deceleration Length > 1000 ft

			Capacity (veh/h)		
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	Without Auxiliary Lane	With One-Lane Exit Ramp	With Two-Lane Exit Ramp
1500	1325	235	6584	6640	6995

Type A: ΔCapacity = +56 (veh/h)
Type B: ΔCapacity= +441 (veh/h)

Step 5: Determine the Conflicts

Select worksheet "Conflicts" in Excel , estimated using Ramp Space > 1000ft , then input the key volume and length of weaving segment (L_S).

Inputs **Outputs**

Parallel Deceleration Length >1000 ft

			Number of Conflicts (Conflicts/h/500ft)		
L_D (ft)	V_F (pc/h/ln)	V_R (pc/h)	Without Auxiliary Lane	With One-Lane Exit Ramp	With Two-Lane Exit Ramp
1500	1325	235	0.6	0.3	0.2

Type A: ΔDensity= -0.3 (conflicts/h/500ft)
Type B: ΔDensity= -0.4 (conflicts/h/500ft)