

AN INVESTIGATION OF OPERATIONAL PERFORMANCE
ON TWO-LANE HIGHWAYS

by

Amirhossein Jafari

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2018

©COPYRIGHT

by

Amirhossein Jafari

2018

All Rights Reserved

DEDICATION

To my dearest parents who always motivated me and supported me.

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor, Dr. Ahmed Al-Kaisy, for his support and guidance throughout the progress of this study. I would also like to thank my committee members, Dr. Yiyi Wang, Dr. Steve Perkins, and Dr. Joel Cahoon for their valuable comments. Further, I would like to acknowledge the financial support provided by the National Cooperative Highway Research Program. Finally, I would like to thank the respective staff at the state departments of transportation for providing the data used in this study.

TABLE OF CONTENTS

1. INTRODUCTION	1
Overview	1
Problem Statement	4
Objective/Scope	5
Research Importance	6
Thesis Organization	7
2. LITERATURE REVIEW	10
Performance Measures on Two-lane Highways	10
HCM Performance Measures on Two-lane Highways: Historical Overview ...	13
HCM Performance Measures	14
Performance Measures Used in Other Countries	16
Alternative Performance Measures Proposed in Literature.....	19
Following Behavior on Two-lane Highways	25
Passing Lanes on Two-lane Highways	29
2 + 1 Highways	38
3. STUDY SITES AND FIELD DATA	43
Overview	43
Study Sites and Field Data Used for Performance Measures Investigation.....	43
Study Sites and Field Data Used for Passing Lanes Investigation.....	51
4. PERFORMANCE MEASURES INVESTIGATION.....	55
Overview	57
Performance Measures on Two-lane Highways: Practice Survey	57
Performance Measures Investigated.....	59
Speed-related Measures.....	59
Flow-related Measures.....	60
Density-related Measures	60
Headway-related Measures.....	60
Passing-related Measures.....	61
Study Results	61
Agency Practice.....	61
Practitioners Perception of Two-Lane Highway Performance Measures	64
Performance Measures on Two-lane Highways: Empirical Investigation.....	70
Study Design	70
Study Sites	72
Research Underlying Hypotheses.....	73
Study Results	74

TABLE OF CONTENTS CONTINUED

Preliminary Assessment of Performance Measures	88
5. Following Status and Percent Followers on Two-Lane Two-Way Highways:	
Empirical Investigation	91
Overview	93
Car-Following Process	93
Study Sites.....	96
Study Results.....	97
Headway Speed Investigation	98
Minimum Safe Headway Investigation	101
Estimating Percent Followers Using Speed Data	104
6. PASSING LANES INVESTIGATION	108
Introduction	110
Effective Length of Passing Lanes.....	111
Research Approach.....	113
Overview.....	113
Swashsim Simulation Program.....	114
Field Data.....	117
Simulation Calibration Process and Results	118
Simulation Experimental Design	126
Passing Lane Effective Length Results	128
Optimum Length of Passing Lanes	132
Study Approach	133
Study Sites and Field Data	134
Calibration and Validation of Simulation Program.....	135
Calibration of Swashsim.....	135
Validation of Swashsim.....	137
Simulation Experimental Design.....	138
Passing Lane Optimum Length Results	140
Traffic Split within Passing Lane Section	140
Maximum Rate of Improvement Over Length Approach	144
Proposed New Approach	147
Evaluation of Passing Lane Design Configuration	152
Study Approach	153
Calibration and Validation of Simulation Model	153
Experimental Design	154
Traffic Performance Investigation.....	157
Economic Effectiveness of Passing Lane Configurations.....	161
Passing Lane Configuration Guidelines	162

TABLE OF CONTENTS CONTINUED

7. 2 + 1 HIGHWAYS	165
Overview	167
Study Approach.....	168
Experimental Design.....	169
Study Results.....	171
Optimal Length of Passing Lane Sections on 2 +1 Roads	176
8. CONCLUSIONS AND RECOMMENDATIONS	178
Overview	178
Performance Measures Investigation	178
Car Following Investigation.....	181
Passing Lanes Investigation	182
REFERENCES CITED.....	186
LIST OF ACRONYMS	196
APPENDICES	197
APPENDIX A SURVEY QUESTIONNAIRE	198
APPENDIX B SITE SPECIFIC REGRESSION RESULTS	208

LIST OF TABLES

Table	Page
1. LOS Criteria for Two-Lane Highways (HCM 2016)	11
2. LOS Criteria for Two-Lane Highways (Oregon, 2014)	18
3. Optimal Length of Passing Lanes (HCM 2016)	30
4. Effective Length of Passing Lane (HCM 2016)	31
5. Recommended Values of Length and Spacing by ADT and Terrain	35
6. Description of Field Data at Study Sites	51
7. Description of Field Data at Study Sites	52
8. Average Ranking Score for Performance Measures	67
9. Results from Multivariate Linear Regression Analysis for Class I Sites	85
10. Results from Multivariate Linear Regression Analysis for Class II Sites	85
11. Results from Multivariate Linear Regression Analysis for Class III Sites	86
12. Number of Times Variable Found Significant Using Class Regression Runs	88
13. Preliminary Assessment Matrix of Performance Measures on Two-Lane Highways	90
14. Description of Field Data at Study Sites	97
15. Percentage of Headways with Relative Speed between the Following and Lead Vehicles of up to ± 1 mi/h for ATR 8	102
16. Calculations for Estimating # of Followers in Transition Range at ATR 32	105

LIST OF TABLES CONTINUED

Table	Page
17. Headway Cut-off Value for Calculating Percent Followers	107
18. SwashSim Vehicle Classification	115
19. Description of Study Sites	117
20. Performance Measures at Different Study Stations (OR 2).....	120
21. Performance Measures at Different Study Stations (OR 17).....	121
22. Traffic Simulation Output and Deviations from Field Measurements (Calibration).....	124
23. Traffic Simulation Output and Deviations from Field Measurements (Validation).....	125
24. Ranges and Levels for Study Variables	126
25. Effective Length of Passing Lane Using Empirical Method (miles).....	131
26. Regression Results for Effective Length	132
27. Traffic Simulation Output and Deviations from Field Measurements (Calibration).....	136
28. Traffic Simulation Output and Deviations from Field Measurements (Validation)	138
29. Traffic Split within Passing Lane	143
30. Percent Reduction in PF to Length of Passing Lane (Harwood Approach)	146
31. Optimum Length of Passing Lane (Harwood).....	146

LIST OF TABLES CONTINUED

Table	Page
32. Percent Reduction in PF (Proposed Approach)	150
33. Lengths of Passing Lane Derived Using the Proposed Approach and for Various PF Reductions	151
34. Ranges and Levels for Study Variables	155
35. Recommended Values of Length and Spacing by Flow Level.....	162
36. Passing Lane Spacing and Effectiveness Index for Different PF Reduction	164
37. Ranges and Levels for Study Variables	170
38. Optimal Length of Passing Lanes (mi) on 2 + 1 Roads.....	176

LIST OF FIGURES

Figure	Page
1. Typical passing lane (Isolated).....	3
2. Operational effect of a passing lane on performance (HCM 2016)	4
3. Theoretical speed distribution with probability P_i represented (Al-Kaisy & Freedman, 2010)	23
4. Passing lane length and spacing (Kirby et al., 2014)	40
5. Aerial photo of 2+1 road in Germany (Source: Google Earth)	41
6. Montana data collection sites	45
7. Idaho data collection sites	47
8. North Carolina data collection sites	48
9. Oregon data collection sites.....	50
10. Study site detector locations, OR 2.....	53
11. Study site detector locations, OR 17.....	54
12. Survey participating agencies in the US and Canada (in gray)	59
13. Performance measures used in two-lane highway operational analysis.....	62
14. Traffic data collected by highway agencies for assessing performance	64
15. Average ranking for characteristics of performance measures.....	65
16. Average ranking score of traffic flow aspects	66
17. Scatterplots of performance measures vs combined flow.....	76

LIST OF FIGURES CONTINUED

Figure	Page
18. Scatterplots of performance measures vs traffic split	77
19. Scatterplots of performance measures vs speed variance	78
20. Scatterplots of performance measures vs percent heavy vehicles	79
21. Correlation results for combined, class I, class II, and class III data.....	82
22. Performance measures rank by class using R^2	87
23. Different states between successive vehicles (Al-Kaisy et al. 2017).....	95
24. Headway speed relationship at selected study sites.....	100
25. Average speed for headways equal or greater than h at selected study sites	101
26. Percentage of headways with relative speeds of ± 1 mi/h for different headway values	103
27. Speed headway curve at ATR 32.....	105
28. Determining % followers headway cut-off value using cumulative frequency diagram for headways in transition range	106
29. Typical Passing Lane (Isolated).....	110
30. Operational effect of a passing lane on performance (HCM 2016).....	112
31. Main network specification screen	115
32. Animation screen of simulated model	116
33. Data collection set up OR 2 (top), OR 17 (bottom).....	117
34. Performance measures along study sites	119

LIST OF FIGURES CONTINUED

Figure	Page
35. Follower density along the highway (%NP = 50).....	128
36. Effective length calculation using empirical method (% NP = 50)	130
37. Data collection setup, OR 2 and OR 17	134
38. Traffic split within passing lane (OR 2)	141
39. Traffic split within passing lane (OR 17)	141
40. Right lane traffic split within the passing lane	144
41. Percent reduction in PF to length of passing lane (Harwood approach).....	145
42. Percent reduction in PF vs length of passing lane	148
43. Percent reduction in PF vs length of passing lane with fitted curves	149
44. Length of passing lane as a function of percent reduction in platooning.....	151
45. Traffic simulation output and field measurements (study site OR 2).....	154
46. Sample experimental set up (2 Passing lanes, Passing lane spacing=21 mi)	156
47. Percent followers along the study site (Flow level=800 veh/hr, Passing lane length=1.5 mi, Passing lane spacing= 6 mi).....	157
48. PF for different configurations of passing lanes	159
49. PF improvement for different configurations of passing lanes.....	159

LIST OF FIGURES CONTINUED

Figure	Page
50. ATS for different configurations of passing lanes.....	160
51. Effectiveness Index for different configurations of passing lanes.....	162
52. 2 + 1 highway	168
53. Sample experimental set up	171
54. Percent reduction in PF vs Flow Level	172
55. Percent improvement in ATS vs flow level.....	174
56. Percent reduction in PF vs % HV	175
57. Percent reduction in PF vs FFS.....	175
58. Optimal length of passing sections on 2 + 1 roads	177

ABSTRACT

A high percentage of the US road networks are two-lane highways. The Highway Capacity Manual (HCM) is the standard reference used in the US for traffic analysis of such highways (HCM 2016). This manual uses a qualitative measure called “Level of Service (LOS)” to show the quality of traffic flow on the highway network. Performance measures are used as indicators of the LOS in the HCM. The current manual uses Average Travel Speed (ATS), Percent Time Spent Following (PTSF), and Percent Free Flow Speed (PFFS) for measuring LOS on two-lane highways. However, several studies reported that the HCM methodology falls short in several aspects including the performance measure used for operational analysis on two-lane highways. Moreover, the current guidelines of the HCM regarding passing lanes are very limited and based on studies conducted more than three decades ago (Harwood and St. John 1985, 1986). Constructing a passing lane is expensive and there is a need to use accurate methods for the design of such facilities. Therefore, the goal of this study is to examine new performance measures for operational analyses of two-lane highways as well as developing new guidelines for the design of passing lanes.

Multiple investigations were conducted using field data from four states in the US as well as microscopic traffic simulation software, SwashSim. Using field data and statistical analysis as well as the results of a survey, the most appropriate performance measures were selected. Additionally, traffic simulation software was used to investigate the operational improvement of passing lanes. Optimum length and effective length of passing lanes were investigated. Optimum length has been used to refer to the length that would bring most operational benefits given the amount of passing lane investments while effective length is defined as the length of two-lane highway over which the effect of a passing lane extends. Moreover, the operational efficiency of different passing lane design configurations were examined to identify the most appropriate length and spacing to be used in the planning and design of passing lanes. In addition, the operational performance of 2+1 roads was investigated in this study and some guidelines for design of these facilities are provided. 2+ 1 highways have one lane in each direction of travel and the middle lane alternates between the two directions.

CHAPTER ONE

INTRODUCTION

Overview

The majority of the United States of America (US) highway networks consists of two-lane, two-way highways. Nationwide, they account for approximately 82% of all highways by centerline mileage (Federal Highway Administration [FHWA], 2018).

On these highways, there is only one lane in each direction of travel. The unique characteristic that separates two-lane highways from other uninterrupted flow facilities is that passing occurs in the opposing lane of traffic. There should be adequate gap and sight distance in the opposite direction that a passing maneuver could take place. Passing opportunities decrease as flow rate and geometric restrictions increase. Lack of passing opportunities typically results in formation of platoons with trailing vehicles subject to additional delay.

The Highway Capacity Manual (HCM) is the standard reference in the US for traffic analysis of highway networks. The Level of Service (LOS) is a qualitative measure used by the HCM to show the quality of traffic flow on a highway facility. Currently, the HCM uses a LOS scale from A to F, with A representing the best traffic conditions and F representing breakdown or congested conditions. A performance measure is an indicator of LOS on highway networks.

Average travel speed (ATS) and percent time spent following (PTSF) are used in the HCM for evaluating performance on class I two-lane highways. Class I highways

include major intercity routes, daily commuter routes, and major links in state or national highway network. The PTSF is defined as “the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of an inability to pass” (HCM 2016). PTSF is also used for class II two-lane highways which involve highways that serve as access routes to class I facilities as well as scenic and recreational routes. On those highways, motorists do not necessarily expect to travel at high speeds. Due to difficulties in measuring the PTSF in the field, the HCM recommends a surrogate measure, percent followers, calculated as the percentage of vehicles following other vehicles with headways smaller than 3 seconds. Percent Free Flow Speed (PFFS) is used for evaluating performance on class III highways. It is the ratio of average travel speed to free flow speed. Class III highways are two-lane highways serving moderately developed areas. They may include portions of class I and class II highways that pass through small towns or developed recreational areas.

High volume of traffic on a highway network causes congestion, delays to drivers, and contributes to air pollution. As traffic volume on two-lane highways increases, highway agencies look for alternatives to accommodate traffic on such highways. In this regard, agencies may turn a two-lane highway into a four lane highway when certain criteria are met. For instance, when the peak hour volume on the highway exceeds a predefined amount, some highway agencies expand the two-lane highway to four lanes to improve LOS. However, the high cost of road construction would justify using other alternatives such as passing lanes. A passing lane is defined as an added lane to one or both directions of travel to increase passing opportunities. Providing a passing lane on a two–

lane highway can improve the operational performance and LOS. Passing lanes are only used in level and rolling terrain, while climbing lanes are used in mountainous areas. On a passing lane section, slow moving vehicles move over to the right allowing faster vehicles to pass using the left lane. Figure 1 shows a typical schematic of an isolated passing lane section.



Figure 1. Typical passing lane (Isolated)

A study by Harwood and St. John (1985) has shown that the operational improvement of passing lanes will last for a distance downstream of those facilities called “Effective Length”. In order to measure the improvement, the current HCM uses Average Travel Speed (ATS) and Percent Time Spent Following (PTSF). Effective length is the distance downstream of the passing lane where the PTSF returns to its original value upstream of the passing lane. This length is used by decision makers for locating the passing lanes as well as their frequency on two-lane highways. Figure 2 shows the operational improvement on a two-lane highway with a passing lane.

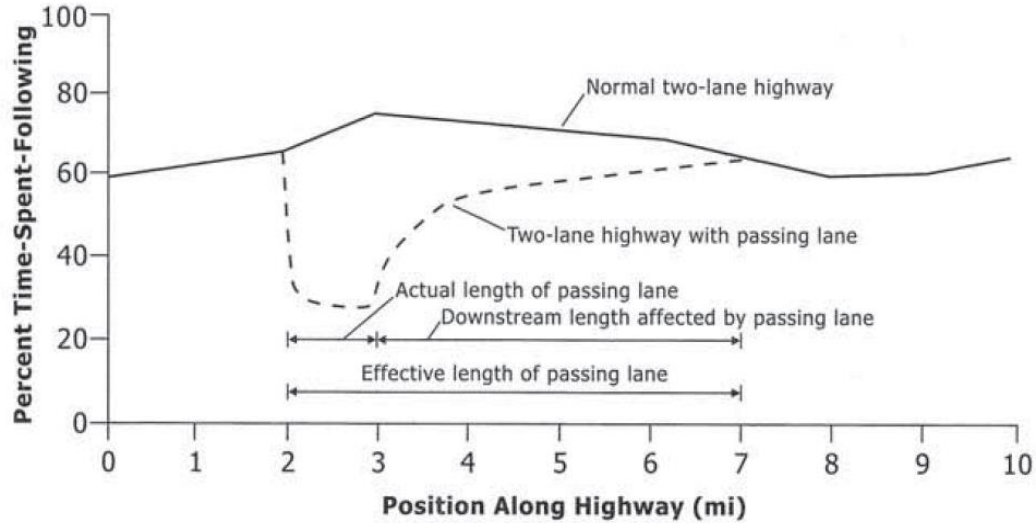


Figure 2. Operational effect of a passing lane on performance (HCM 2016)

Problem Statement

Several studies reported limitations in the current performance measures used by the HCM (Al-Kaisy & Karjala 2008; Van As & Van Niekerk 2004; Catbagan & Nakamura, 2006; Dixon et al. 2002; Luttinnen 2001). The main performance measure, PTSF, is limited in that it is difficult to measure in the field, is not compatible with the service measures of other facilities, does not describe the extent of congestion, and is not very useful in other analyses (e.g. economic, environmental, etc.), (Lutinnen et al 2005). PTSF is also not a good performance measure for indicating if improvements should be made to a highway that has low volumes but a high percentage of heavy vehicles and a few passing opportunities. ATS, on the other hand, is not very informative about the efficiency of the highway. Since the analysis section of a two-lane highway facility is usually several miles long, there could be many changing conditions, such as posted speed limit and roadway alignment that affect ATS, yet it is not related to varying traffic conditions. The PFFS, an

indicator of speed reduction due to traffic, can easily be measured in the field, however, it is not very sensitive to flow level for the uncongested traffic regime (Al-Kaisy & Freedman, 2010).

Lack of passing opportunities on a two-lane highway causes performance to deteriorate and contributes to an increase in platooning level (HCM 2016). Passing lanes are one of the measures that helps to increase passing opportunities and improve performance on two-lane highways. A passing lane is a short length of lane, usually 0.5-2 miles, added to facilitate the breakup of platoons by allowing faster vehicles to pass slower vehicles. Constructing a passing lane is expensive and there is a need to use accurate methods for the design of such facilities. The current guidelines of the HCM regarding passing lanes are very limited and based on studies conducted more than three decades ago (Harwood and St. John 1985, 1986). Driver behavior as well as vehicle performance have gone through some changes since that time. Moreover, traffic simulation tools have significantly changed since that time. Therefore, this study used a recently developed microscopic simulation software program, called SwashSim that has extensive capabilities for modeling traffic operations on two-lane two-way highways (Washburn 2017).

Objective/Scope

This research aims to examine new performance measures for operational analyses of two-lane highways using an empirical investigation of field data as well as results of a survey on two-lane highway operations. Moreover, this study aims to develop new design guidelines for two-lane highways with passing lanes.

This research only investigated two-lane highways that exist in rural or suburban settings where traffic interruptions are infrequent. Moreover, all investigated highways are located in level terrain. The passing lanes located in mountainous areas are called “climbing lanes” (HCM 2016) and are beyond the scope of this study.

Research Importance

The results of this study could help to improve the current guidelines for operational analyses of two-lane highways. Findings from this study provide valuable information about the merits, or lack thereof, of many performance measures that were either used in practice or proposed in the literature. This information is expected to help in revising the current methodology in the HCM.

The study of new performance measures helps to improve the current methodology of the HCM for operational analysis of two-lane highways. The suggested performance measures are easier to measure in the field and are more sensitive to road and traffic conditions. Further, they consider the transportation agencies’ operational objectives for two-lane highways.

Highway agencies spend millions of dollars on expanding two-lane highways to four lane highways each year. However, adding a passing lane may well be more cost effective under a wide range of traffic conditions. There is a need for accurate methods for the design of passing lanes including their location, length and spacing. This research helps to update the current guidelines for the design of passing lanes which could benefit transportation engineers and roadway designers. By knowing the optimum length and

spacing of passing lanes, highway agencies can better make decisions regarding highway upgrades.

Thesis Organization

This thesis consists of eight chapters. Beyond the introduction, chapter two reviews the literature on performance measures, following behavior, and passing lane design guidelines. Chapter three describes field data and study sites used in this study.

Chapter four, Performance Measures Investigation, presents the results of two separate analyses: a) Practice survey on appropriate performance measures for two-lane highways operational analysis, and b) Empirical investigation of performance measures using field data. Chapter five presents an investigation of following behavior on two-lane highways.

Chapter six includes the results for passing lane investigations. This chapter investigates the optimum and effective length of passing lanes on two-lane highways. Moreover, it examines the operational efficiency of different passing lane design configurations in order to identify the most appropriate length and spacing to be used in the planning and design of passing lanes. Chapter seven provides some guidelines on the design of 2+1 highways. 2+1 highways have one lane per each direction of travel and the middle lane alternates between the two directions. Finally, Chapter eight summarizes the findings from all previous chapters.

CHAPTER TWO

LITERATURE REVIEW

Contribution of Authors and Co-Authors

Manuscript in Chapter 2

Author: Ahmed Al-Kaisy

Contributions: Draft manuscript preparation

Co-Author: Amirhossein Jafari

Contributions: Draft manuscript preparation

Co-Author: Scott Washburn

Contributions: Review the draft

Co-Author: Tapio Lutinen

Contributions: Review the draft

Co-Author: Richard Dowling

Contributions: Review the draft

Manuscript Information

Traffic Operations on Rural Two-Lane Highways: a Review on Performance Measures and Indicators

Ahmed Al-Kaisy, Amirhossein Jafari, Scott Washburn, Tapio Lutinnen and Richard Dowling

Transportation Research Record: Journal of the Transportation Research Board

Status of Manuscript:

☐ Prepared for submission to a peer-reviewed journal

☐ Officially submitted to a peer-reviewed journal

☒ Accepted by a peer-reviewed journal

☐ Published in a peer-reviewed journal

Name of publisher: US National Research Council

Date of submission: (7/29/2017)

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a summary of the relevant literature on two-lane highways. The chapter includes a review of studies on (1) performance measures on two-lane highways, (2) following behavior on two-lane highways, (3) passing lanes on two-lane highways and (4) 2 + 1 highways.

Performance Measures on Two-lane Highways

The Level of Service (LOS) is a qualitative measure used by the Highway Capacity Manual (HCM) to show the quality of traffic flow on a highway facility. Currently, the HCM uses a scale from A to F to show the LOS, with A defined as best and F defined as worst condition for traffic flow (HCM 2016). Performance measures are used to assess operations and LOS. On two-lane highways, they are intended to reflect the level of freedom for drivers to select their desired speeds and pass slow moving vehicles. Measuring performance is important for operational analysis and for upgrade and improvement projects. A low Level of Service (LOS) on a section of two-lane highway may be improved by adding a passing lane or expanding the route into a continuous three lane section or a multilane highway.

Operational analysis on two-lane highways in the US and Canada (and some other countries outside North America) is usually conducted using the procedures outlined in the HCM (HCM 2016). In the most recent edition of the HCM (HCM 2016), average travel speed (ATS) and percent time spent following (PTSF) are used for evaluating performance

on class I two-lane highways. Class I highways include major intercity routes, daily commuter routes, and major links in the state or national highway networks. ATS refers to average speed of all vehicles moving through the highway measured at a point. The PTSF is defined as “the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of an inability to pass” (HCM 2016). PTSF is also used for class II two-lane highways, which involve highways that serve as access routes to class I facilities as well as scenic and recreational routes. On those highways, motorists should not necessarily expect to travel at high speeds. Due to difficulties in measuring the PTSF in the field, the HCM recommends using a surrogate measure, calculated as the percentage of vehicles following other vehicles with headways less than 3 seconds. The third measure, Percent Free Flow Speed (PFFS), is used for evaluating performance on class III highways following recommendations from Washburn et al. (Washburn et al. 2002). It is the ratio of average travel speed to free flow speed. Class III highways are two-lane highways serving moderately developed areas. They may include portions of class I and class II highways that pass through small towns or developed recreational areas. Table 1 shows the LOS criteria for two-lane highways in the 2016 HCM (HCM 2016).

Table 1. LOS Criteria for Two-Lane Highways (HCM 2016)

LOS	Class I Highways		Class II Highways	Class III Highways
	ATS (mi/hr)	PTSF (%)	PTSF (%)	PFFS (%)
A	>55	≤35	≤40	>91.7
B	>50-55	>35-50	>40-55	>83.3-91.7
C	>45-50	>50-65	>55-70	>75.0-83.3
D	>40-45	>65-80	>70-85	>66.7-75.0
E	≤40	>80	>85	≤66.7

Ideally, performance measures used for traffic operations and capacity analysis on any highway facility should meet the following criteria (Luttinen, 2001):

1. A performance measure should reflect the perception of road users on the quality of traffic flow. It is a common understanding that platooning and lack of passing opportunities (and its associated delay) primarily affect the motorists' perception of the quality of service on two-lane highways.
2. A performance measure should be easy to measure and estimate using field data. Specifically, it is expected that the prospective performance measure can be estimated in the field using conventional data collection methods used by highway agencies and the professional community.
3. A performance measure should correlate to traffic and roadway conditions in a meaningful way. On two-lane highways, the prospective performance measure should closely correlate to the platooning phenomenon (and passing opportunities) as well as to traffic level in a logical and meaningful way.
4. It is recommended that the prospective measure be compatible with performance measures used on other facilities. This criterion may be hard to satisfy as it is expected that different aspects of traffic operations are perceived as most important by drivers on different highway facilities. For example, while platooning on two-lane highways is a major determinant of the quality of operation, it is not a major factor in determining the quality of operations on other facilities.
5. A Performance measure should be able to describe both uncongested and congested conditions. While this requirement is applicable to all highway facilities per the

definition of the LOS scheme, it has been perceived to have less significance on two-lane highways, since these facilities are rarely congested and are usually upgraded to four lanes at traffic levels well below capacity.

6. A performance measure should be useful in analyses concerning traffic safety, transport economics, and environmental impacts. Increasingly, the capacity analysis procedures have been used in supporting the aforementioned analyses. To be of use in safety analyses, the prospective measure should correlate well to traffic exposure. On the other hand, for economic and environmental impact analyses, the prospective measure should be useful in estimating delay and its associated fuel consumption and tailpipe emissions.

The six criteria above consider the common operational objectives of most highway agencies, namely: mobility, productivity, safety, reliability and environmental impacts.

A number of alternative performance and/or service measures for two-lane highways have been proposed in the literature. Most of the studies that proposed new performance measures were driven by the obvious limitations of the HCM performance measures mentioned in chapter one. This section provides a review of alternative performance measures that have been proposed in the literature or reported as part of today's practice.

HCM Performance Measures on Two-lane Highways: Historical Overview

The HCM 1950 (HCM 1950) was the first document introducing an analytical method for capacity analysis on two-lane highways. Practical capacity, which corresponds to the capacity under reasonable driving conditions, was used in this manual to assess the

operating conditions on two-lane highways. Operating speed was the indicator for measuring the practical capacity. The concept of level of service was presented in the second edition of the HCM in 1965 (HCM 1965). Operating speed and volume to capacity (v/c) ratio were used to estimate the level of service on two-lane highways. In 1985, the HCM introduced percent time delay (PTD) for measuring performance on two-lane highways besides average travel speed (HCM 1985). It refers to the percentage of time that vehicles are delayed and trapped in platoons due to an inability to pass slower vehicles. Delay refers to situations where drivers travel at speeds lower than their desired speeds. A headway threshold of 5 seconds was used to estimate the PTD in the field. The fourth edition of the HCM introduced PTSF, which is a similar measure to PTD and refers to the percent of time vehicles are following other vehicles on two-lane highways (HCM 2000). The percentage of vehicles with headways less than 3 seconds was used as a surrogate measure for PTSF in this edition of the HCM. The following edition of the HCM was released in 2010 (HCM 2010) and introduced a new classification for two-lane highways: classes I, II and III. Besides PTSF and ATS, the percent free flow speed (PFFS) was the new measure introduced in this edition for operational analysis of class III two-lane highways. The most recent edition of the HCM was released in 2016 (HCM 2016). The analytical methodology including performance measures in this edition is similar to that in the 2010 edition.

HCM Performance Measures

The HCM has been the principal reference for performing capacity analyses in the US and Canada since its inception in 1950. Therefore, the performance measures used by

the current edition of the HCM largely represent the current practice in the US and Canada. As stated earlier in this chapter, three performance measures are used by the current HCM procedures for two-lane highways: percent time spent following (PTSF), average travel speed (ATS), and ATS as a percent of free-flow speed (FFS).

Percent-time-spent-following (PTSF): this performance measure has been in use since the fourth edition of the HCM that was published in 2000 (HCM 2000). PTSF is defined as “the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of an inability to pass.” (HCM 2000). While the PTSF concept correlates well to the platooning phenomenon, which is the major determinant of performance on two-lane highways, it is impractical to measure in the field. Given this limitation in using PTSF, the HCM suggests using the percentage of headways less than 3 seconds as a good estimate for PTSF using field data. However, while PTSF by definition is a spatial measure, (i.e. measured over a stretch of a two-lane highway), the percentage of headways less than 3 seconds can only be measured at a point location.

Average travel speed (ATS): The vast majority of two-lane highways can be thought of as “uninterrupted flow facilities”, thus enjoying relatively higher travel speeds. This is particularly true for the HCM class I highways, which represent important arterials and major collectors in rural areas. On these highways, *ATS* has long been used by the HCM as a performance measure with the premise that average speed is affected by traffic level and, thus, the amount of platooning due to limited passing opportunities. However, two-lane highways have different levels of classifications, a wide range of geometric standards, and consequently, a wide range of operating speeds. Therefore, using average

speed alone may not provide enough information about the level of traffic performance (in the absence of a reference point) to make performance comparison across sites practical. A recent survey of practice found that average travel speed is perceived to be the most relevant traffic flow aspect to two-lane highway operations by HCM users (Al-kaisy et al. 2016).

ATS as a percent of FFS: This performance measure has been in use since the HCM fifth edition published in 2010 for use on class III two-lane highways (HCM, 2010). Using *ATS* as a percentage of free-flow speed was viewed as a good indicator of the amount of speed reduction due to traffic and the amount of vehicular interaction in the traffic stream. However, evaluations using field data in the US, Egypt and Spain (Al-Kaisy and Karjala 2008, Hashim and Abdel-Wahed 2011, Moreno et al. 2014) showed that the speed measures did not exhibit good correlations with platooning variables compared to other performance measures investigated in these studies. Further, Luttinen (Luttinen, 2001) reported on an older study by Kiljunen & Summala (1996) which proposed the use of *ATS/FFS* as a performance measure on Finnish two-lane highways.

Performance Measures Used in Other Countries

In this section, the major performance measures used in other countries are presented and discussed (Al-Kaisy et al. 2018).

In their article on the German experience, Brilon and Weiser (Brilon & Weiser, 2006) reported that the current German Capacity Handbook (HBS 2001) utilizes density as the primary service measure for two-lane highways. The rationale for using density as a performance measure on two-lane highways in Germany is that efficiency is given

preference over user experience (perception) of the quality of service (HBS 2001). Further, this performance measure is compatible with other facility types, mainly freeways and multi-lane highways, when those highway types are analyzed as part of a larger system. For this purpose, density is calculated as the ratio of traffic volume and the *ATS* of only passenger cars (i.e., ATS_{pc}). Average speed of passenger cars is measured over a longer stretch of highway, averaged over both directions. Truck speeds are not very sensitive to increases in traffic volume, but traffic volume is the main factor affecting the *ATS* of passenger cars (HBS 2001). In their investigation of two-lane highway performance measures, Al-Kaisy and Karjala (Al-Kaisy & Karjala, 2008) argued that average travel speed of passenger cars may more accurately describe speed reduction due to traffic, since passenger car speeds are more affected by high traffic volumes than heavy vehicle speeds.

The v/c ratio, or degree of capacity utilization, has been used as the main performance measure on two-lane highways in Japan, China and Denmark (Nakamura & Oguchi 2006, Rong et al. 2011, Vejdirektoratet 2010). It is important to note that the two-lane expressways in Japan are different from the conventional two-lane highways in the US and most other countries in that they have limited access (no at-grade intersections) and a median barrier present in all sections along the entire length of the roadway (Nakamura & Oguchi 2006). Further, the v/c ratio has been used as an additional performance measure in Sweden (TRV 2013). This performance measure was also used for estimating the level of service along with operating speed in the second edition of the HCM (HCM 1965).

Followers density (FD) is another performance measure , which was originally adopted by the South African National Roads Agency more than a decade ago (Van As and Van Niekerk 2004, Van As 2003) and was later investigated in other studies (Al-Kaisy and Karjala 2008, Hashim and Abdel-Wahed 2011, Moreno et al. 2014, Catbagan and Nakamura 2006, Ghosh et al. 2013). Follower density is defined as the product of percent followers (PF) and traffic density; therefore, this measure is derived using two important flow characteristics: traffic flow and density. Again, *PF* is estimated using time headway, which is a microscopic flow characteristic. FD provides a better indication for warranting highway upgrades and improvements. Besides HCM performance measures, the Oregon Department of Transportation (ODOT) has used FD in operational analysis of two-lane highways in recent years because it has the advantage of capturing the effect of platooning and traffic level (Oregon, 2014). Table 2 shows the LOS criteria as a function of FD for class I, and II highways that was developed by Oregon DOT.

Table 2. LOS Criteria for Two-Lane Highways (Oregon, 2014)

LOS	Class I Highways	Class II Highways
	FD (veh/mi/lane)	FD (veh/mi/lane)
A	≤ 2	≤ 2.5
B	>2-3.5	>2.5-4.0
C	>3.5-6	>4.0-6.5
D	>6.0-9.0	>6.5-10.0
E	>9.0	>10.0

Alternative Performance Measures Proposed in Literature

Given the reported limitations in the current HCM performance measures, several alternative performance measures have been proposed by studies here in the US and abroad.

A study by Al-Kaisy and Karjala (Al-Kaisy & Karjala, 2008) investigated a new speed-related performance measure among other performance measures on two-lane highways in the US. The new measure is calculated as the average travel speed of passenger cars (ATS_{PC}) divided by the free-flow speed of passenger cars (FFS_{PC}), expressed as a percentage. The researchers argued that average travel speed of passenger cars may more accurately describe speed reduction due to traffic, since passenger car speeds are more affected by high traffic volumes than heavy vehicle speeds. Further, using *ATS* as a percentage of free-flow speed was viewed as a good indicator of the amount of speed reduction due to traffic and the amount of vehicular interaction in the traffic stream. However, evaluations using field data showed that the speed measures did not exhibit good correlations with platooning variables as compared to other performance measures investigated in this study. Later studies by Hashim and Abdel-Wahed (Hashim & Abdel-Wahed, 2011) and Moreno et al. (Moreno et al., 2014) reported similar results using field data in Egypt and Spain. In his study on *PTSF* in Finland, Luttinen (Luttinen, 2001) reported on another old study by O.K. Normann, who suggested the use of speed differences between successive vehicles on two-lane highways among other proposed performance measures.

A couple of studies in the literature proposed the use of passing maneuvers in measuring performance on two-lane highways. The platooning phenomenon on two-lane highways and the associated delay are directly related to passing opportunities and the ability of platoon vehicles to pass slower vehicles and increase their speeds. As such, a few performance measures were proposed for assessing performance on two-lane highways that are related to passing maneuvers.

A study by Morrall and Werner (Morrall and Werner 1990) proposed the use of overtaking ratio as a supplementary indicator of the level of service on two-lane highways. This measure is obtained by dividing the number of passes achieved by the number of passes desired. According to the study, the number of passes achieved is the total number of observed passes for a given two-lane highway, while the number of passes desired is the total number of passes for a two-lane highway with continuous passing lanes with similar vertical and horizontal geometry. The overtaking ratio considers the effect of the percentage of no-passing zones and passing lanes. The researchers showed that the effect of passing lanes as measured by overtaking ratio is greater than percent time delay used by the 1985 HCM. Overtaking ratio, along with the average number of passes per vehicle, were also proposed by O.K. Norman, as reported by McLean (McLean 1989), and Luttinen (Luttinen, 2001).

Another measure that has been used extensively both in practical applications as well as in published research is time headway, a microscopic traffic flow characteristic. For various practical reasons, time headway has been used solely for identifying platoons using empirical traffic data and field measurements. One important reason for using time

headway is that this measure can readily be extracted from the output of conventional traffic recorders, which have the ability to provide raw data (i.e., timestamp records for individual vehicle arrivals). The second equally important reason is the fact that time headway is a good indicator of the interaction between successive vehicles in the traffic stream and, thus, in determining the status of a vehicle being in a following mode (i.e. being part of a vehicular platoon).

Most of the proposed headway-related measures involve the estimation of the percentage of headways less than a pre-specified cut-off value, a measure more recently called percent followers (PF). The percent of headways less than 3 seconds has been used by the HCM as a surrogate measure for PTSF using field data (HCM 2000). A few recent studies have examined this along with other proposed performance measures to evaluate their suitability for use on two-lane highways (Al-Kaisy and Karjala 2008; Hashim and Abdel-Wahed 2011; Moreno et al. 2014; Catbagan and Nakamura 2006; Van As and Van Niekerk 2004; Penmetsa et al. 2015; Oregon 2014). This performance measure does not necessarily reflect the effect of traffic level, i.e. there could be a two-lane highway with low volume of traffic but still a high percentage of short headways. Therefore, this measure could be misleading in highway improvement and upgrade decisions. Various headway cut-off values were proposed to estimate the percentage of vehicles in following mode in the traffic stream (Van As 2003; Al-kaisy et al. 2017; Penmetsa et al. 2015).

Besides PF, a few other measures have been proposed in the literature that are associated with more than one traffic stream parameter, and as such, they are described in this discussion as compound measures. The merit of using compound measures is the fact

that those measures usually combine the advantages of more than one indicator of traffic performance on two-lane highways (e.g., amount of platooning and traffic level) (Al-Kaisy et al. 2018). One such measure that was proposed in the literature is follower flow, which was investigated by the South African National Roads Agency (Van As 2003). Follower Flow is defined as the hourly rate of vehicles in following mode that pass a point along a two-lane highway. This measure can easily be estimated as the product of PF and flow rate. Follower flow was investigated among several other performance measures in the development of the current South African two-lane highway methodology.

Penmtsa et al. (2015) proposed another compound measure for Indian two-lane highways under mixed traffic condition. The new measure is called number of followers (NF), which represents the number of vehicles moving in the same lane of two-lane highways with gaps less than 2.6 s. This measure showed a strong correlation with traffic volume. Penmtsa et al. (2015) argued that NF alone is not able to show the congestion condition on a highway network. Therefore, number of followers as a proportion of capacity (NFPC) was introduced as a new performance measure. The new measure exhibited a very strong correlation with traffic volume and it was found to explain the quality of traffic flow in a better way.

Another compound measure that was proposed in the literature is percent impeded (PI). This measure was originally proposed by Al-Kaisy and Freedman (Al-Kaisy & Freedman, 2010) and was later investigated by Hashim and Abdel-Wahed (Hashim & Abdel-Wahed, 2011), Ghosh et al. (Ghosh et al. 2013), and Moreno et al. (Moreno et al., 2014). PI is defined as percentage of vehicles impeded by slower-moving vehicles in a

directional traffic stream measured at a point location. PI is calculated as the probability of desired speeds being greater than the average speed of platoon leaders (P_i) multiplied by the percent of vehicles with headways less than a pre-specified threshold value (P_p). For establishing the distribution of desired speeds, vehicles with headway more than 8 seconds were used by Al-Kaisy and Freedman (Al-Kaisy & Freedman, 2010). Platoon leaders were used as a representative sample of slow moving vehicles. This measure is derived using flow and speed characteristics. Figure 3 shows the probability P_i assuming a normal distribution for desired speeds.

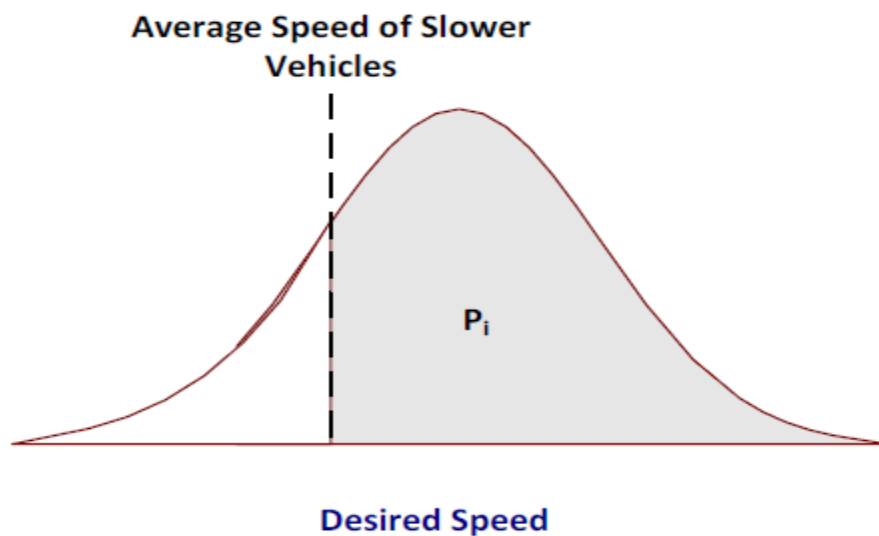


Figure 3. Theoretical speed distribution with probability P_i represented (Al-Kaisy & Freedman, 2010)

Percent impeded was further used to develop other combined measures. Impeded flow, which shows the hourly rate of vehicles impeded by slow-moving vehicles, i.e. platoon leaders, was suggested by Al-Kaisy et al. (Al-kaisy et al. 2017). It is calculated as the product of PI and the hourly rate of traffic flow. They also proposed impeded density,

which refers to number of vehicles impeded per mile per lane in one direction of travel. It is calculated as the product of PI and traffic density. These measures along with other performance measures were investigated by Al-Kaisy et al. (Al-kaisy et al. 2017) for operational analysis on two-lane highways in Montana, Idaho, Oregon and North Carolina. Among all compound measures, follower flow followed by follower density exhibited the highest correlations with traffic variables.

A study by Yu and Washburn (Yu and Washburn 2009) and Li and Washburn (Li & Washburn, 2014) proposed the percent delay service measure for two-lane highway facilities (i.e., a combination of two-lane highway segments and intersections). This service measure is based on the difference between free-flow travel time and actual travel time. The use of a speed-based measure allows the service measure to be applied to both two-lane highway segments and intersections, which individually use delay as the service measure.

Freedom of flow is another performance measure proposed for use on two-lane highways (Polus & Cohen, 2009). Polus and Cohen used the M/M/1 queuing to model vehicular platoons on two-lane highways. In their approach, a platoon is considered as a queue system with random arrivals (vehicles joining the back of queue), random departures (vehicles passing platoon leader), and a single processing channel. To identify platooned vehicles, the researchers used a 3-second follower headway threshold. In their research, two proposed traffic parameters were introduced: traffic intensity and freedom of flow. Similar to queuing analysis, traffic intensity (ρ) in the context of platoon analysis refers to the ratio between the average time spent in the first position when waiting for an

appropriate gap and the average inter-arrival times at the back of the queue. On the other hand, freedom of flow (η) refers to the ratio of the time of undisturbed driving (between platoons) to the time interval in which the driver is in first position behind a slower moving vehicle while waiting to pass. This ratio may reflect the perception of tension experienced by drivers in a more representative way. Freedom of flow can be estimated using equation 1 below.

$$\eta = \frac{N_o}{\rho} \quad (1)$$

Where:

- η = Freedom of flow
- ρ = Traffic intensity
- N_o = Average number of headways between platoons

Following Behavior on Two-lane Highways

Car following interaction (or lack thereof) is highly dependent on the proximity of successive vehicles in the traffic stream, typically measured using time headway. While the headway at which vehicular interaction starts is believed to be a stochastic variable and is largely dependent on driver characteristics, a single cut-off value has often been used in practice in identifying vehicles in following mode from those in free-flow mode. A brief overview of studies that utilized headways solely in identifying the following status or percent followers is presented in this section (Al-Kaisy et al. 2017).

Different thresholds have been identified by researchers to separate following vehicles from non-following vehicles. Several studies have suggested a headway cut-off value between 3 and 4 seconds in identifying vehicles that are in following mode (Van As 2006, Hoban 1984, Guell and Virkler 1988, Pasanen and Salmivaara 1993, Dijker et al.

1998; Shiomi et al. 2011). Dijker et al. (Dijker et al. 1998) proposed a headway cut-off value of 5 seconds for identifying trucks in following mode.

Wasielewski investigated drivers' car following patterns on a single lane of an urban freeway. A semi-Poisson model was applied to a database of 42,000 observed headways. It was found that the followers' headway distribution is independent from the traffic flow with a mean of 1.32 seconds and a standard deviation of 0.52 second (Wasielewski 1979).

Lay (Lay 1986) suggested three distinct states in regard to car-following interaction and vehicles proximity in the traffic stream. He used 2.5 seconds as a headway threshold for following vehicles, headways between 2.5 and 9 seconds for vehicles that are either in a following or free-flow state, and a headway greater than 9 seconds for vehicles in a free-flow state.

Bennet et al. (Bennet et al. 1994) investigated critical headways at 58 study sites in New Zealand. Critical headway was defined as "the headway below which a vehicle's speed is affected by the preceding vehicle". Different techniques were used to establish the critical headway. Among them, the mean of relative speeds, the mean relative speed ratio and the exponential headway model were identified as the best techniques. Using those techniques, critical headway was found to be in the range of 3 to 4.5 seconds.

Van As (Van As 2014) investigated the car following behavior using field data in South Africa. A new methodology was proposed. A vehicle was tracked over a length of highway to check if the following gap changed over the observation distance. If the gap remained constant, it was likely that vehicle was following. The study suggested two

criteria for the classification of vehicles as followers; a following gap shorter than 3 seconds and a speed differential less than 20 km/h. The study found an average following headway of 1.2 seconds for light vehicles and 1.8 seconds for heavy vehicles.

Penmetsa et al. (Penmetsa et al. 2015) studied two-lane intercity highways under mixed traffic conditions in India. The study utilized the clear gap between two consecutive vehicles in analyzing the following status. It was assumed that vehicles traveling in the same lane with a relative speed of 2 km/h or less to be in car-following mode. The probability of not following was plotted against time gap using the 2 km/h rule. The gap corresponding to 50% probability was chosen as the critical gap, which was found to be 2.6 seconds.

Al-Kaisy and Durbin (Al-Kaisy and Durbin 2009) investigated vehicular platoons on two-lane highways in Montana. Average travel speed was plotted against individual time headways at several study sites. The results showed that the increase in speeds is more notable at short headways and it diminishes when headways reach a value in the range of 5 to 7 seconds.

Evans and Wasielewski (Evans and Wasielewski 1983) suggested a headway threshold of 2.5 seconds for vehicles in car-following mode on freeways. The value of 2.5 seconds was suggested for traffic flow of less than 1450 vehicles per hour per lane, while 3.5 seconds was suggested for higher flow levels.

In a study by Vogel (Vogel, 2002), the speed, distance headway and time headway data of more than 100,000 vehicles on urban roads in Sweden were analyzed. The study found that the speed of two successive vehicles are linearly dependent on time headway

for headways up to 6 seconds. A similar finding has been reported in a few other studies (Al-Kaisy & Karjala, 2010; Hoogendoorn, 2005; Lobo et al. 2011). Some other studies have reported the use of 5 seconds as the headway cut-off value for identifying free-flowing vehicles in the traffic stream (Fitzpatrick et al. 2005; Abdul-mawjoud and Sofia 2008; Polus et al. 2000; Figueroa and Tarko 2005; Hashim 2011).

Catbagan and Nakamura (Catbagan and Nakamura 2010) developed a new method for identifying the following behavior. The current method of the Highway capacity Manual (HCM 2016) for identifying followers is based on the 3 second threshold, but this procedure does not account for driver variability or changes in roadway conditions. Also, a certain driver may have a different desired headway based on weather conditions, pavement conditions, the time of day, and other factors that affect the drivers' comfort level.

Probability-based follower identification takes a stochastic approach that incorporates both speed and headway into determining when a driver is following. This procedure uses a mixed distribution model of headways known as the Semi-Poisson Model (SPM) to separate following and free vehicles based only on the headway portion of this method. As headways increase, the probability that a vehicle is following decreases until a critical headway is reached at which point no vehicles should be considered as followers. The speed-based portion of this method is hindered by the difficulty in collecting data on the ever-changing desired speeds of different drivers. This procedure assigns different desired speeds to certain conditions and if a vehicle's speed drops below the assumed desired speed, then it is considered to be in the following state. The unified speed

distribution method was used to approximate the desired speeds (Catbagan and Nakamura 2010).

Passing Lanes on Two-lane Highways

Several researchers have studied the operational effects of passing lanes on two-lane highways to understand passing lane requirements such as length, spacing and configuration. Following is a summary of studies on passing lanes, including effective and optimum length of passing lanes and passing lane design configuration.

Harwood and St. John (Harwood and St. John 1985) investigated the operational and safety benefits of passing lanes on two-lane highways using data collected from 12 passing lanes. Three measures of effectiveness, including traffic speed, percentage of platooned vehicles (vehicles with headways of 4 seconds or less), and passing rate, were used to evaluate the effect of those facilities on operational improvements of two-lane highways. The results showed that the percentage of followers reduced from an average of 35.1 percent at upstream of the passing lane to 20.7 percent within and 29.2 percent immediately downstream for an average flow rate of 245 veh/hr. Further, the results showed that the operational benefit, in terms of PTSF, lasts for several miles downstream of the end of the passing lane. The amount of improvement was found to be a function of the level of platooning upstream of the passing lane as well as the length of passing lane. Traffic speed was found to be only slightly affected by the presence of a passing lane. The passing rate ranged from 0 to 219.3 passes per hour per mile. Passing rate was found to be a function of traffic volume, length of passing lane, and percent followers upstream of the

passing lane. The results of safety analysis indicated that the installation of a passing lane may reduce the accident rate by 25 percent.

In another study, Harwood and St. John (Harwood and St. John 1986) evaluated the operational improvement of passing lanes on two-lane highways using the TWOPAS simulation program. Reduction in percent time delay was used to measure the operational improvement of a passing lane. The results showed that passing lanes had minimal effect on vehicles speeds, but a dramatic effect on platooning.

The optimum length varied in the range between 0.5 and 2 mi and was found to be a function of traffic level. The results from this study are currently being used as part of the Highway Capacity Manual (HCM) guidelines on passing lane planning and design (HCM 2016). Table 3 shows the optimal length of passing lane as a function of traffic flow rate in the HCM.

Table 3. Optimal Length of Passing Lanes (HCM 2016)

Directional Demand Flow Rate (pc/h)	Optimal Passing Lane Length (mi)
≤ 100	≤ 0.5
$>100 \leq 400$	$>0.5 \leq 0.75$
$>400 \leq 700$	$>0.75 \leq 1$
≥ 700	$>1 \leq 2$

The effective length of a passing lane was found to be a function of traffic flow rate and passing lane length. The effective length was found to be in the range of 3 to 8 miles depending on passing lane length, traffic flow and composition, and downstream passing opportunities. The study found no consistent trend regarding the effect of traffic composition on effective length. Moreover, the effect of terrain was minimal. It was

suggested that other geometric and traffic control features such as steep grades, narrow lanes and no-passing zones may reduce the effectiveness of a passing lane.

Table 4 shows the effective length of passing lanes in the HCM based on two performance measures: Average Travel Speed (ATS) and PTSF. The effective length of the passing lane for ATS in all cases is limited to 1.7 miles. For the PTSF, the effect is a function of directional demand flow rate. An increase in the flow rate is associated with a decrease in the effective length of a passing lane. As shown in this table, the effective length varies between 3.6 and 13 miles.

Table 4. Effective Length of Passing Lane (HCM 2016)

Directional Demand Flow Rate (pc/h)	Downstream Length of Roadway Affected (mi)	
	PTSF	ATS
≥ 200	13.0	1.7
300	11.6	1.7
400	8.1	1.7
500	7.3	1.7
600	6.5	1.7
700	5.7	1.7
800	5.0	1.7
900	4.3	1.7
≥ 1000	3.6	1.7

May (May 1991) conducted a study on traffic performance and design of passing lanes using field data from five sites in California as well as the TRARR simulation program. Data from three study sites were used to calibrate the software. The length of passing lane for each study site was altered in simulation and the effect on traffic performance was measured. The number of passes, reduction in percent time delay and estimated annual travel time savings were used to assess the effect of passing lane length on traffic performance. Vehicles with headways less than 5 seconds were considered to be

delayed. The analysis of data showed that passing lanes of 0.25 to 0.75 miles are the most effective for platoon break up. Spacing of 2 to 5 miles between passing lanes was found to be appropriate depending on downstream roadway and traffic conditions. Moreover, hourly flow rate and percent heavy vehicles were found to affect number of passes, percent time delay and mean travel speed.

Gattis et al. (Gattis et al. 2006) studied the operational benefits of continuous three-lane sections with alternating passing lanes in Arkansas. Field data from four sites in Arkansas were used in this study. Four operational parameters including platooning, passing rate, speed and safety were used to investigate the effectiveness of these facilities. The results showed that greatest benefits of passing lanes occurred in the first 0.9 miles. For high traffic volumes, the platooning tended to stabilize after 1.9 miles into the passing lane. Moreover, passing maneuvers increased as volume increased.

Brewer et al. (Brewer et al. 2011) investigated the operational characteristics of super 2 highways in Texas. A Super 2 highway is where a periodic passing lane is added to a two-lane rural highway to allow passing of slower vehicles and the dispersal of traffic platoons. Data from two super 2 locations in Texas were used in this study. Field data were used to calibrate the Traffic Analysis Module (TAM) within the FHWA Interactive Highway Safety Design Model (IHSDM). The measures of effectiveness including PTSF, average total delay and number of passes were used to compare different simulation scenarios. The results showed that most passing maneuvers occur within the first mile of passing lane. Terrain and percentage of heavy vehicles did not have much effect on the

results. The PTSF and average total delay increased with the increase in Average Daily Traffic (ADT). Moreover, passing lanes reduced the delay and PTSF.

Al-Kaisy and Freedman (Freedman and Al-Kaisy 2013) investigated the operational performance within a passing lane using field data from one site in Montana. Per lane analysis of performance measures and lane utilization were used to examine passing maneuvers and lane changes within the passing lane. The results indicated that traffic performance became stable beyond half a mile into the passing lane. Based on this, it was concluded that most passing maneuvers occurred before the half mile station and the optimum length of the passing lane should be around 0.5 miles for this site. The traffic volume for the study site was 275 vehicles per hour.

Enberg and Pursula (Enberg and Pursula 1997) investigated traffic flow characteristics of three-lane rural highways in Finland. Field data from a 14 miles three-lane highway in Finland was used for this study. Moreover, TRARR simulation software was used to evaluate different designs of three-lane highways. The results showed that three-lane highways increase the average travel speed and number of passings. Moreover, platooning was decreased on these facilities. Simulation results indicated that optimum length of passing lane is between 0.3 and 1.6 miles depending on traffic volume and measure of effectiveness. For the field data, passing lanes in the range of 0.6 to 0.9 miles had the most benefits.

Potts and Harwood (Potts & Harwood, 2004) studied the operational benefits of passing lanes on two-lane highways in Missouri. Field data from 28 passing lanes were used in this study. TWOPAS simulation software was used to model the highways

considering sites with and without passing lanes. The results showed that two-lane highways with passing lanes could reduce the PTSF from 10 to 31 percent compared to two-lane highways without passing lanes.

In a study by Al-Kaisy and Freedman (Al-Kaisy and Freedman 2010), the operational improvements downstream of passing lanes were investigated. Field data were collected from two passing lane sites in Montana using automatic traffic recorders. The results showed that platoon level decreases beyond the downstream end of the passing lane due to merge effect at the end of the passing lane. This distance could be as long as 1.5 mi after the taper end of the passing lane. The improvement downstream of passing lanes was a function of passing lane length and traffic flow. Moreover, it was shown that, at one study site, an approximately 30% operational improvement, in terms of percent followers, was observed at a point 6.6 miles downstream of the end of the passing lane for a traffic volume of 155 veh/h. Based on this observation, it was suggested that the effective length of the passing lane at this site might extend more than 10 mi downstream of the passing lane.

Wooldridge et al. (Wooldridge et al., 2001) investigated the optimum length and spacing of passing lanes using TWOPAS simulation software. A hypothetical two-lane highway with varying length and spacing of passing lanes was modeled using the software. Different traffic volumes and vehicle mix were investigated in the analysis. The optimum length of passing lane varied from 0.8 to 2 miles and the optimum spacing was found to be from 3.5 to 11 miles depending on traffic volume as shown in Table 5. These values were found based on minimizing the cost and percent time delay.

Table 5. Recommended Values of Length and Spacing by ADT and Terrain

ADT (vpd)		Recommended Passing Lane Length (mi)	Recommended Distance Between Passing Lanes (mi)
Level Terrain	Rolling Terrain		
≤1950	≤1650	0.8-1.1	9.0-11.0
2800	2350	0.8-1.1	4.0-5.0
3150	2650	1.2-1.5	3.8-4.5
3550	3000	1.5-2	3.5-4.0

Morall et al. (Morall et al. 1995) planned and designed passing lanes for two-lane highways in southern California. Three hundred and fifty miles of two-lane highways in Imperial, San Diego and Riverside counties were investigated. TRARR simulation software was used to evaluate a range of passing lane alternatives (including length and location) for different traffic volumes. One hundred and seventeen new passing lanes and four turnouts were suggested for the routes investigated in this study. The analysis method included adding a passing lane to different segments with the objective of maintaining LOS C for the design year. In order to locate passing lanes, other criteria were also considered such as minimizing costs, avoiding intersection and slow speed areas, and providing adequate sight distance at the beginning and end of passing lanes. The designed system assured having passing opportunities no greater than approximately every 6 miles. The average spacing between passing lanes was between 4.5 to 6 miles. Passing lane length as a percentage of total analysis length for each route varied between 14.8 and 22.9 %.

Mutabazi et al. (Mutabazi et al. 1999) studied different configurations of passing lanes as well as effect of intersections within passing lane sections. Field data from two sites in Kansas were used to calibrate and validate TWOPAS. A hypothetical two-lane highway with varying percentage of heavy vehicles (% HV), directional distribution

volumes, and passing lane configurations were created in TWOPAS. Percent time delay was used to compare different scenarios. Using 5 seconds for identifying vehicles in platoon, there was no difference between the proportions of vehicles in platoon from upstream to downstream. However, there was a reduction in percentage of headways less than 2 seconds. Different configurations including tail to tail, side by side, and head to head passing lanes were modeled in the software. Side by side and head to head showed a better performance than others. Overall, a small difference in percent time delay was observed among different configurations. The study also recommended four considerations for locating passing lanes on two-lane highways including: safety, traffic performance, consistency with driver expectations, and minimizing construction costs.

Passing zones on two-lane highways are designed to allow the faster vehicles to do the passing maneuvers, and thus level of service on the highway will be improved. Passing sight distance is used in the design and marking of the passing zones on two-lane highways.

Moreno et al. (Moreno et al. 2013) studied the operational effectiveness of passing zones depending on length and traffic volume. Data from 1600 passing maneuvers on four passing zones in Spain were used to model passing frequency and passing rate as a function of traffic volume and length of passing zone. The results showed that a higher length of passing zone is associated with higher passing frequency. The results stabilized for lengths above 0.68 miles. Moreover, two-way traffic volumes between 600 and 700 vph optimized the number of passes.

Moreno et al. (Moreno et al. 2015) investigated the minimum length of passing zones considering both operational and safety impacts. Field data from 1750 passing

maneuvers on two-lane highways in Spain were used to calibrate and validate Aimsun software, after which, 44,000 directional scenarios were generated using different length of passing zones and traffic volume. A free flow speed of 62 mph, traffic split of 50/50, and 100 % passenger cars were used for all scenarios. A reliability analysis was used to find the probability that passing zone length is shorter than the required passing distance. The results showed that passing zones shorter than 0.16 miles have very little effect on operation of the highway. They suggested minimum passing zone lengths of 0.17 mi, 0.19 mi, and 0.22 mi for high, medium and low traffic volumes, respectively. These lengths are longer than the minimum passing zone length of 0.075 mi suggested by the MUTCD (FHWA 2009) and Green book (AASHTO 2011).

Moreno (Moreno 2016) investigated the effect of average passing zone length on traffic performance of two-lane highways using TWOPAS simulation software. Average passing zone length was defined as the absolute length of passing zones divided by the number of passing zones. Field data from four passing zones in Spain were used to calibrate the software using a genetic algorithm. Different scenarios were generated by varying the average passing zone length, percentage of no-passing zones, traffic volume, directional split and percentage of heavy vehicles. Two different models were developed for ATS and PTSF. The results showed that average passing zone length has a great effect on traffic performance (i.e. ATS and PTSF). Passing zone lengths less than 0.16 mi had no effect on the operational efficiency of the highway. Passing zone lengths longer than 1.6 mi had similar effects to a length 1.6 mi.

2 + 1 Highways

2 + 1 highways have one lane in each direction of travel and the middle lane alternates between the two directions. Further, passing vehicles always use the center lane. A review of literature showed that the countries listed below are using 2+1 configurations: Austria, Denmark, Finland, France, Germany, Ireland, Italy, Poland, Netherlands, South Korea, Spain, Sweden, United Kingdom and USA (Kirby et al., 2014).

Bergh et al. (2016) investigated the use of 2+1 roads in Sweden. The first 2 + 1 road was opened in 1998 in Sweden. There are around 1,700 miles of 2 + 1 median barrier roads in Sweden. Around 70 % of these roads have a speed limit of 63 mph. The results of this study showed that the level of service on these facilities depends on the share of two-lane segments as well as how the share of two-lane segments are divided. The simulation experiments showed that a length of 0.93 mi for the overtaking segments is reasonable. Moreover, an increase from 20 to 30 overtaking lane percentage would reduce the delay up to 2.4 sec/mi.

Chae et al. (2013) evaluated the application of 2+1 roads for rural two-lane highways in South Korea. The traffic microsimulation software, Vissim, was used to analyze the operational improvements of 2+1 roads compared to two-lane and four-lane highways. Two performance measures were used for this purpose including average travel speed and delay. The results of the study showed that 2+1 roads would improve the average travel speed by 21 percent and the delay was reduced by 39 percent. The construction costs for these facilities was estimated to be 26-40 percent less than conventional four lane highways. In another study by Lee et al. (2013), 17,000 veh/day was calculated as the

maximum traffic volume for Korean 2+1 roads. Choi et al. (2016) proposed a procedure for analysis of 2+1 roads in South Korea. The percent time spent following was suggested for measuring the performance of 2+1 roads. Using the results from TWOPAS simulation software, new criteria for measuring the level of service of 2+1 roads in South Korea were derived.

Cafiso et al. (2015) investigated the safety and operational improvements of 2+1 roads in Poland. Field data from a total of 16, 2 + 1 sections in Poland were used for this study. The results showed that an increase in traffic volume is associated with more platooning on these facilities. The traffic platooning reduced by 6.6 % from upstream to downstream of 2 + 1 segments. The percentage of vehicles with headways less than three seconds was used as a measure of platooning. The vehicles using the passing lane had an average travel speed of 11.2 mi/hr higher than the vehicles in the right lane. The difference between average travel speeds from the start to the end of passing lane was 6.6 mi/hr. It was also concluded that traffic volume and speed dispersion have a significant impact on the operation of passing relief lanes. The platoon reduction was found to be a function of passing segment length and share of heavy vehicles.

Kirby et al. (2014) investigated the operational characteristics of 2+1 roads with or without intelligent transport systems assisted merging in New Zealand. Field data from three existing passing lane locations were used to calibrate and validate the traffic microsimulation model, S-Paramics. The optimum length and spacing of passing lanes under different terrain, AADT flow ranges, and different percentage of heavy vehicles was established. A sample contour plot from the results is shown in Figure 4. The legend values

show the benefit cost ratio (BCR). A BCR is the ratio of the benefits of a project, expressed in monetary terms, relative to its costs,

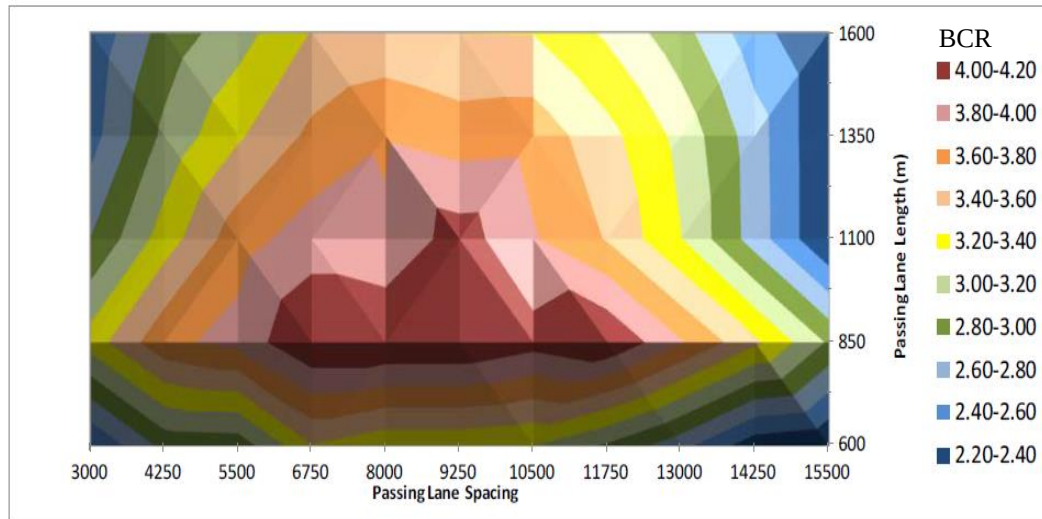


Figure 4. Passing lane length and spacing (Kirby et al., 2014)

The NCHRP 20-17/Task 139 (2003) was focused on the application of 2+1 roadway designs in Europe. The research team assessed whether this design is appropriate for use in the US. The researchers visited Germany, Finland and Sweden to meet with agency staff and observe 2+1 roads and collect operational and safety data for these facilities. Based on the European experience, the researchers suggested the use of 2+1 roads in the US. These facilities should be used on level or rolling terrain where the provision of a four lane highway is not practical. A 2+1 highway will generally operate at two levels of service higher compared to a conventional two-lane highway with the same traffic volume. A length of 0.6 to 1 mi was recommended for these facilities, however, for higher traffic volumes (i.e. 700 veh/hr per each direction) a length of 2 miles is operationally effective.

The 2+1 roads should not be considered where current or projected flow rates exceed 1200 veh/hr per each direction of travel. A summary of findings from different countries is summarized below (NCHRP 20-17/Task 139, 2003).

Germany had 220 miles of these facilities in 2003. These highways operated effectively at average daily traffic volumes of 15,000-25,000 (veh/day). The typical length of a passing lane was 0.6 -0.9 mi with a separation between opposing directions of travel of 1.6 ft. The speed limit on 2+1 roads was 60 mph. The overall section length of a 2+1 should be 2.5 -3.7 mi to be effective, however, 2 +1 road sections have been effective at lengths up to 9.3 mi. Figure 5 shows an aerial photo of a 2+1 road section in Germany. The results of a survey, conducted between 1983 and 1988, showed that most German drivers prefer 2+1 roads to normal two-lane highways due to higher passing opportunities.



Figure 5. Aerial photo of 2+1 road in Germany (Source: Google Earth)

The first 2 + 1 road in Finland was opened in 1991. Finland had 30 mi of 2+1 highways with AADT volumes of up to 14,000 veh/day in 2003. The typical length of a passing lane was 0.9 mi. The optimal length of a passing lane was estimated to be between 0.6 and 0.9 mi. The speed limit on 2+1 roads was 60 mph for passenger cars and 50 mph for trucks. The operational improvement of 2+1 roads would last 2.1 miles downstream of a passing lane with respect to the Percent Time Spent Following (PTSF). The capacity of a 2 + 1 road was measured to be 1,900 veh/hr in one direction.

Sweden had 240 mi of 2 + 1 roads with traffic volumes ranging from 4,000 to 20,000 veh/day in 2003. The revised Swedish guidelines recommend speed limits of 55 or 70 mph for new conventional 2 + 1 roads and 70 mi/h for new 2+1 roads on semi-motorways. The speed limit for trucks on 2 + 1 roads is 50 mi/h. In Sweden, a barrier is included between oncoming passing lanes to divide the traffic in different directions. The common width for 2 + 1 roads is 43 ft.

CHAPTER THREE

STUDY SITES AND FIELD DATA

Overview

This chapter presents the characteristics of the study sites and field data used in this research. To ensure the diversity of two-lane highways represented in the dataset, different types of terrain, traffic volumes and highway classifications from different states were considered.

Study Sites and Field Data Used for Performance Measures Investigation

Different study sites in the states of Montana, Idaho, Oregon and North Carolina were used in this research. This dataset includes areas with extreme winter climates (i.e. Montana and Idaho) as well as mild climates (i.e. Oregon and North Carolina). Traffic volumes, area setting, terrain and number of access points were among the considerations for selecting the sites. All sites are located in rural areas. Data for the sites were provided by the departments of transportation in each state. Individual vehicle data including arrival time, spot speed, and vehicle classification was obtained from automatic traffic recorder output. A brief description of the study sites in each state is provided below.

Montana Sites

1. ATR 43-MT, Highway US 191 near Big Sky, Montana. This site is located about 1.5 mi north of junction of MT-64 and US 191. Data from Automatic Traffic Recorder (ATR) number A-043 was used for this site. The annual average daily

traffic (AADT) at this site is 4,776 vehicles per day in 2014. This site is located in a mountainous area. This site is a principal arterial, which is considered a class I highway for the purpose of this study.

2. WIM 132-MT, Highway MT-200 near Greenough, Montana. This site is located about 6 miles north of Greenough. Data from WIM (Weigh in Motion) station A-132 was used for this site. The annual average daily traffic (AADT) at this site is 2,831 vehicles per day in 2014. This site is a principal arterial which is considered a class I highway for the purpose of this study.
3. ATR 28-MT, Interstate 15 Frontage road near Great Falls, Montana. This site is located about 7 mi west of Great Falls and about 4.2 miles east of Vaughn. Data from ATR (Automatic Traffic Recorder) station A-028 was used for this site. The annual average daily traffic (AADT) at this site is 2,939 vehicles per day in 2014. This site is a major collector which is considered a class II highway for the purpose of this study.
4. ATR 73-MT, Highway MT-35 south of Flathead Lake, Montana. This site is located about 2.8 mi east of the junction of US 93 and MT-35. Data from WIM station A-73 was used for this site. The annual average daily traffic (AADT) at this site is 3,562 vehicles per day in 2014. This site is a minor arterial which is located in a relatively developed recreational area and as such is considered a class III highway for the purpose of this study.

The Study sites for Montana are shown in Figure 6.

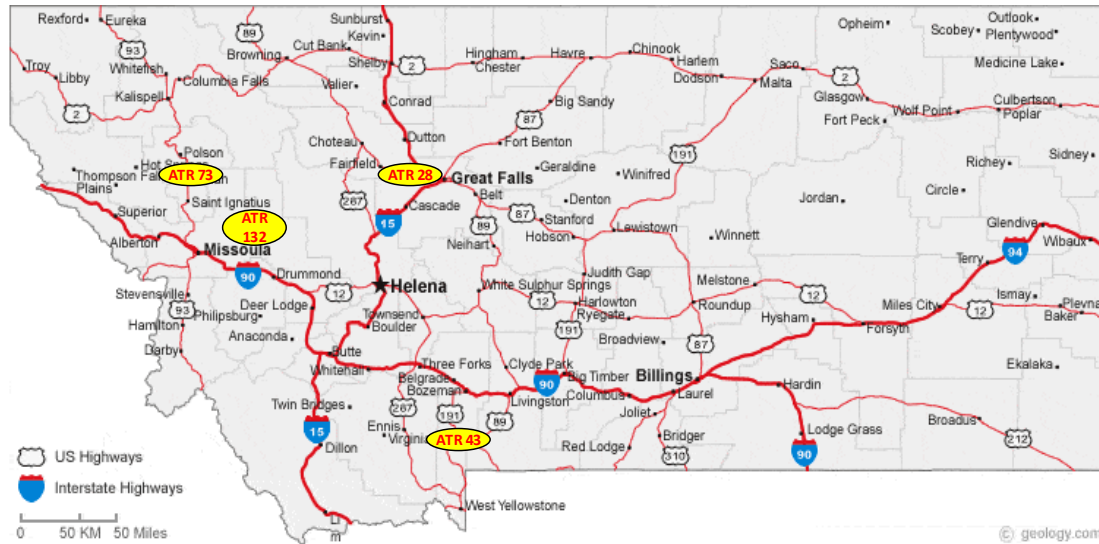


Figure 6. Montana data collection sites

Idaho Sites

5. ATR 47-ID, Highway US 2 near Priest River, Idaho. This site is located about 2.6 mi east of the Idaho-Washington border, on the highway segment that connects Laclede, Idaho to Priest River, Idaho. Data from ATR station A-047 was used for this site. The annual average daily traffic (AADT) at this site is 6,799 vehicles per day in 2014. This site is a principal arterial and is considered a class I highway for the purpose of this study.
6. ATR 44-ID, Highway US 95 near Weiser, Idaho. This site is located about 3.8 mi south of Main Street of Weiser, on the highway segment that connects Wood, Idaho to Weiser, Idaho. Data from ATR station A-044 was used for this site. The annual average daily traffic (AADT) at this site is 5,206 vehicles per day in 2014. This site is a principal arterial and is considered a class I highway for the purpose of this study.

7. ATR 147-ID, SH 57 road near Priest River, Idaho. This site is located about 8.4 mi north of Priest River, Idaho. Data from ATR station A-147 was used for this site. The annual average daily traffic (AADT) at this site is 1,582 vehicles per day in 2014. This site is a major collector and is considered a class II highway for the purpose of this study.
8. ATR 126-ID, Highway US 95 near Moscow, Idaho. This site is located about 0.4 mi north of the junction of Brent Dr. and US 95. Data from ATR station A-126 was used for this site. The annual average daily traffic (AADT) at this site is 6,391 vehicles per day in 2014. This site is a principal arterial located in a relatively developed area and is therefore considered a class III highway for the purpose of this study.

The Study sites for Idaho are shown in Figure 7.

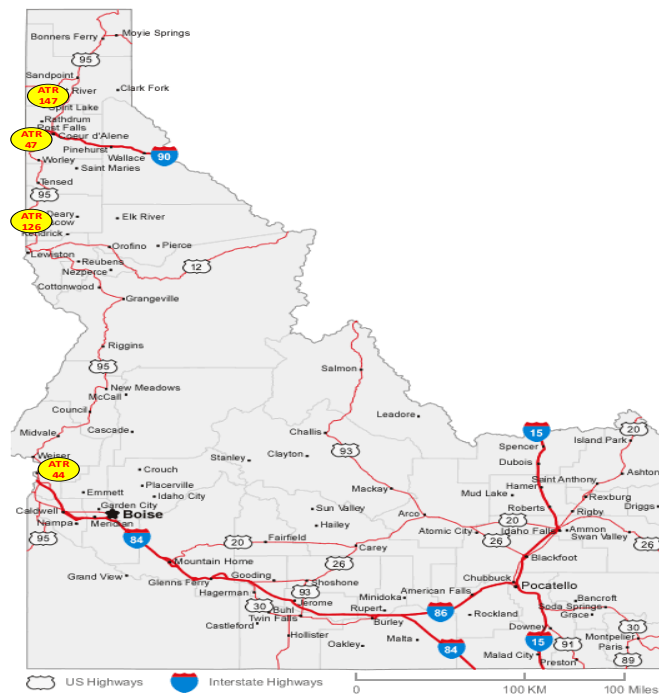


Figure 7. Idaho data collection sites

North Carolina Sites

9. Site 1-NC, Highway US 17 near Maysville, North Carolina. This site is located about 2.6 mi north of Maysville. The annual average daily traffic (AADT) at this site is 9,600 vehicles per day in 2014. This site is a major collector and is considered a class I highway for the purpose of this study.
10. Site 3-NC, Highway US 64 near Manns Harbor, North Carolina. This site is located about 2.5 mi west of Manns Harbor. The annual average daily traffic (AADT) at this site is 3,300 vehicles per day in 2014. This site is a principal arterial and is considered as a class 1 highway for the purpose of this study.
11. Site 4-NC, Highway US 43 near New Bern, North Carolina. This site is located about 8.2 mi north of New Bern. The annual average daily traffic (AADT) at

this site is 2,700 vehicles per day in 2014. This site is a principal arterial and is considered as a class 1 highway for the purpose of this study.

12. Site 7-NC, Highway US 43 near Vanceboro, North Carolina. This site is located about 3 mi south of Vanceboro. The annual average daily traffic (AADT) at this site is 7,700 vehicles per day in 2014. This site is a principal arterial and is considered a class I highway for the purpose of this study.

The Study sites for North Carolina are shown in Figure 8.



Figure 8. North Carolina data collection sites

Oregon Sites

13. Site 2-OR, Highway US 97 near Chiloquin, Oregon. This site is located about 19.5 mi north of Vanceboro. The annual average daily traffic (AADT) at this site is 3,900 vehicles per day in 2014. This site is a major collector and is considered a class I highway for the purpose of this study.

14. Site 11-OR, Highway US 126 near Cloverdale, Oregon. This site is located about 2.5 mi east of Cloverdale. The annual average daily traffic (AADT) at this site is 5,000 vehicles per day in 2014. This site is a principal arterial and is considered a class I highway for the purpose of this study.
15. Site 13-OR, Highway US 97 near Grass Valley, Oregon. This site is located about 4.9 mi north of Grass Valley. The annual average daily traffic (AADT) at this site is 2,700 vehicles per day in 2014. This site is a major collector and is considered as a class I highway for the purpose of this study.
16. Site 17-OR, Highway US 26 near Warm Springs, Oregon. This site is located about 15.8 mi north of Warm Springs. The annual average daily traffic (AADT) at this site is 4,900 vehicles per day in 2014. This site is a principal arterial and is considered a class I highway for the purpose of this study.

The Study sites for Oregon are shown in Figure 9.

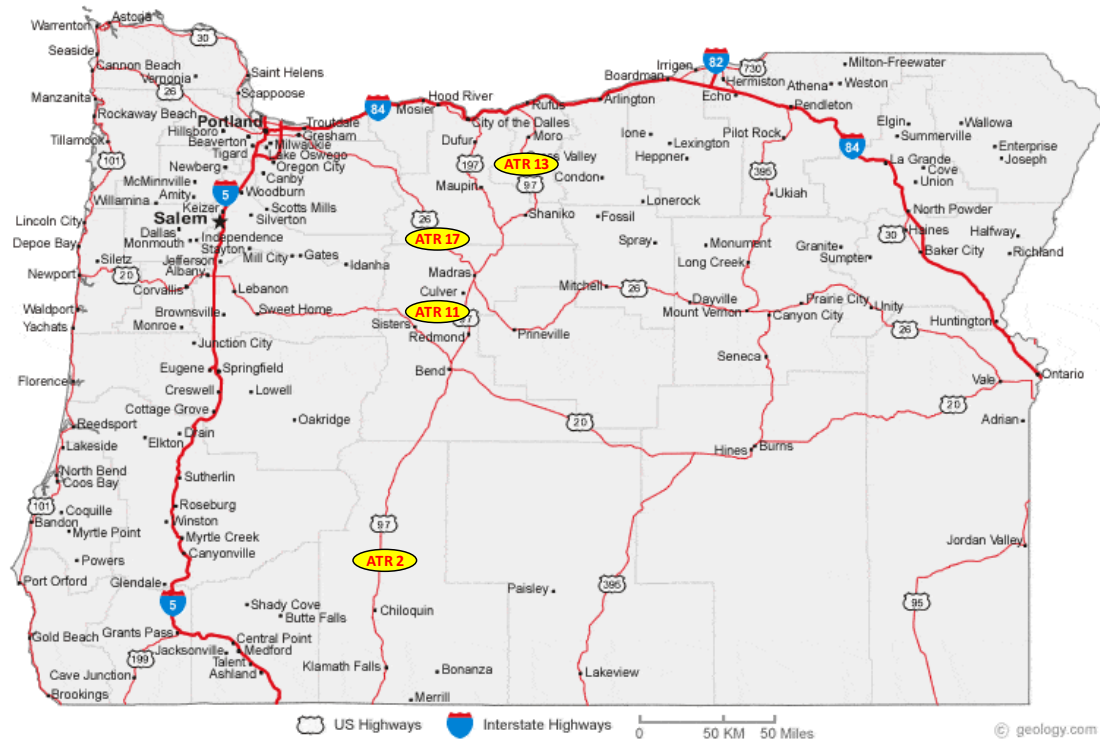


Figure 9. Oregon data collection sites

According to the 2016 HCM, study sites 1,2,5,6, and 9 to 16 can be classified as class I, sites 3 and 7 are class II and sites 4, and 8 are class III.. A description of the data collected at the 16 study sites is provided in Table 6. General traffic data contains 1) direction, 2) headway, 3) speed, and 4) vehicle type. The percent no passing zones shows the percentage of the road in which passing is not allowed. This percentage was found for 3 miles upstream and downstream of the location of traffic counters.

Table 6. Description of Field Data at Study Sites

Site #	Site name	Dates	Class	Duration of data collection (hours)	Total vehicle count (veh)	Speed Limit(mph)	Direction of analysis	Percent No-Passing Zones
1	ATR 43-MT	July 20, 2014- July 26, 2014	I	168	23,676	60	South-bound	93
2	WIM 132-MT	July 9, 2014- July 24, 2014	I	384	31,653	70, 60 (trucks)	West-bound	56
3	ATR 28-MT	July 16, 2015 - July 30, 2015	II	360	24,311	70, 60(trucks)	North-bound	40
4	ATR 73-MT	July 16, 2015 - July 30, 2015	III	360	47,052	60	North-bound	66
5	ATR 47-ID	June 16, 2015 - June 30, 2015	I	360	62,643	60	West-bound	33
6	ATR 44-ID	June 15, 2015 - June 30, 2015	I	384	49,737	65	North-bound	13
7	ATR 147-ID	September 12,2015- September 20,2015	II	216	8,727	50	North-bound	86
8	ATR 126-ID	September 12,2015- September 20,2015	III	216	33,300	45	South-bound	30
9	Site 1-NC	June 8, 2015- June 16, 2015	I	185	91,790	55	South-bound	37
10	Site 3-NC	June 15, 2015- June 23, 2015	I	172	50,334	55	East-bound	3
11	Site 4-NC	June 9, 2015- June 17, 2015	I	188	93,700	55	North-bound	68
12	Site 7-NC	June 8, 2015- June 16, 2015	I	171	88,082	55	North-bound	30
13	Site 2-OR	July 9, 2015- July 12 2015	I	96	21,932	55	South-bound	17
14	Site 11-OR	May 28,2015- May 31,2015	I	96	19,657	55	East-bound	50
15	Site 13-OR	June 4, 2015- June 7, 2015	I	96	12,596	55	South-bound	30
16	Site 17-OR	June 11 2015- June 14, 2015	I	96	26,757	55	South-bound	55

Study Sites and Field Data Used for Passing Lanes Investigation

To investigate the effective and optimum length of a passing lane, data should be collected at one detector location upstream, as well as several locations downstream of the

passing lanes. Field data from two study sites in Oregon were used for this study, as shown in Table 7. Traffic volumes, area settings, terrain type and number of access points were among the considerations for selecting the sites. The data were collected by the Oregon Department of Transportation using Automatic Traffic Recorders for a period of 4 days in July 2015. Per-vehicle data including time stamps, speed, and vehicle classification were extracted from the detector's output.

Table 7. Description of Field Data at Study Sites

Site Number	Site Name	Data Collection Dates	Length of Passing Lane (mi)	Duration of Data Collection (hours)	Annual Average Daily Traffic (veh/day)	Speed Limit (mi/h)	Direction of Analysis
1	Oregon 2	July 9, 2015-July 12 2015	2.2	96	3900	55	South-bound
2	Oregon 17	June 11 2015-June 14, 2015	1.6	96	4900	55	South-bound

The first study site is located on Highway US 97 near Chiloquin, Oregon. This site is located about 19.5 miles north of Chiloquin between mileposts 229 and 232. There is a 2.2-mi long passing lane in each direction of travel. Only the southbound direction was investigated in this study. The total length of the study site is 10.7 miles, including the length of the passing lane and a total of 11 detectors. Data were collected at one location immediately upstream of the passing lane, and other detectors located downstream at 0.5 miles, 1.5 miles, 3.5 miles, 6.5 miles and 8.5 miles after the taper end of the passing lane. This enables assessing the operational benefits of the passing lane. Moreover, there are four detectors within the passing lane at 0.25 miles, 0.35 miles, 0.5 miles and 0.75 miles, respectively. There are no major driveways or intersections upstream of the passing lane.

However, there is another passing lane 8.3 miles upstream of the study site. A relatively long distance downstream of the passing lane is also free from major driveways or intersections. A schematic of the study site locations is shown in Figure 10.

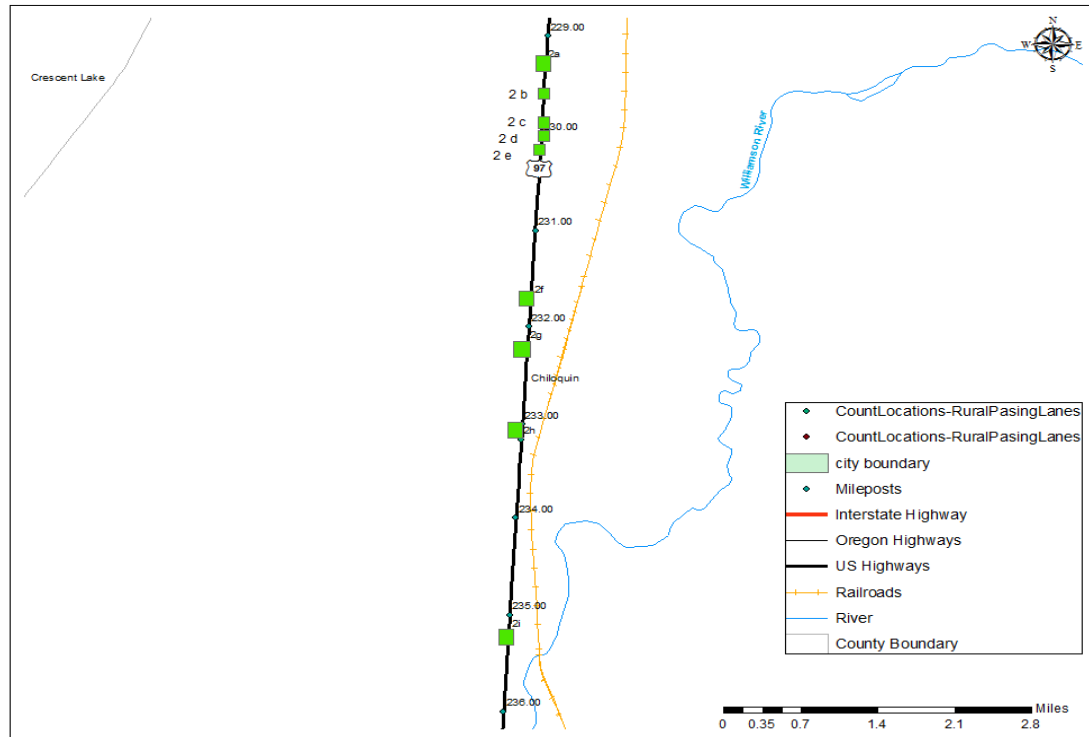


Figure 10. Study site detector locations, OR 2

The second study site is located on Highway US 26 about 15.8 mi north of Warm Springs, Oregon. The annual average daily traffic (AADT) at this site was 4,900 vehicles per day in 2014. There is a 1.6 mile long passing lane in each direction of travel. Only the southbound direction was investigated in this study. Data were collected at one detector location upstream of the passing lane, and other detectors located downstream at 0.5 miles, 1.5 miles, 3 miles, 4.7 miles and 7 miles after the taper end of the passing lane. Moreover,

there are four detector locations within the passing lane at distances 0.15, 0.25, 0.4 and 0.65 mi, respectively. There is another passing lane 4.9 miles after the taper end of the first passing lane. The length of the second passing lane is 1.5 miles. Figure 11 shows the study area for this site.

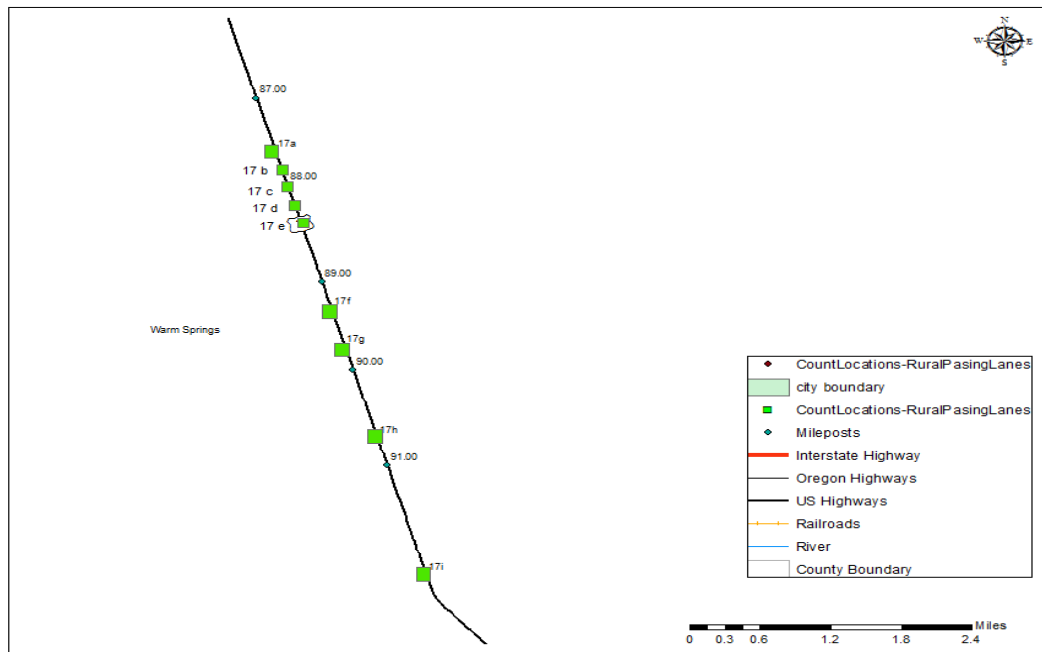


Figure 11. Study site detector locations, OR 17

CHAPTER FOUR

PERFORMANCE MEASURES INVESTIGATION

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

Author: Ahmed Al-Kaisy

Contributions: Draft manuscript preparation

Co-Author: Amirhossein Jafari

Contributions: Draft manuscript preparation

Co-Author: Scott Washburn

Contributions: Review the draft

Co-Author: Tapio Lutinnen

Contributions: Review the draft

Co-Author: Richard Dowling

Contributions: Review the draft

Manuscript Information

Performance on Two-Lane Highways: Empirical Investigation

Ahmed Al-Kaisy, Amirhossein Jafari, Scott Washburn

Transportation Research Record: Journal of the Transportation Research Board

Status of Manuscript:

☐ Prepared for submission to a peer-reviewed journal

☐ Officially submitted to a peer-reviewed journal

☐ Accepted by a peer-reviewed journal

☒ Published in a peer-reviewed journal

Name of publisher: US National Research Council

Date of submission: (7/29/2016)

Issue in which manuscript appears:2615

CHAPTER FOUR

PERFORMANCE MEASURES INVESTIGATION

Overview

As discussed earlier, the current performance measures for evaluating level of service on two-lane highways have some limitations. These limitations were the main motive behind this study. Specifically, this chapter aims to examine the suitability of some proposed performance measures for use in two-lane highway capacity analysis using both field data examination and survey results. The survey aims to achieve an understanding of US state and Canadian province transportation agencies' perception of the applicability of various performance measures for the analysis of two-lane highways. Specifically, the survey attempts to determine what constitutes a good performance measure for two-lane highways from the perspective of the transportation agencies. This information is critical in identifying the most appropriate service measure(s) to be used in an improved two-lane highway operational analysis methodology. The responses from the survey, as well as results of empirical investigation, were used to select the most appropriate performance measure for operational analysis of two-lane highways.

Performance Measures on Two-lane Highways: Practice Survey

In order to better understand the perceptions and preferences of transportation agencies with regard to performance measures on two-lane highways, an online survey was designed as part of the NCHRP Project 17-65. The survey was sent to all state DOTs and

to the ministries of transportation in all Canadian provinces. The survey subjects were transportation engineers with key roles in evaluating two-lane highway operations in their agencies. As might be expected, these engineers represent the technical expertise in two-lane highway operations within their agencies, and as such, largely represent the agencies' perspective on the various questions included in the survey. The survey included a total of 17 questions, some of which were concerned with agency practice while others were more concerned with participants' perceptions and preferences. A total of 41 responses were received, representing transportation agencies at 25 states and 4 Canadian provinces. The response rates for the US and Canada were 49% and 40%, respectively. There were three states with more than one response--Oregon, California and Texas with 4, 3 and 2 responses, respectively. It should be noted that 6 survey subjects submitted the survey without answering any of the questions and therefore, were excluded from the analysis. Figure 12 identifies the responding US states and Canadian provinces (Al-Kaisy et al. 2016). The survey questions are presented in Appendix A.



Figure 12. Survey participating agencies in the US and Canada (in gray)

Performance Measures Investigated

The survey questionnaire included questions on all performance measures that are currently used by the HCM, as well as those from the literature that have been proposed or reported as being used. In general, performance measures for two-lane highways fall into one of the following categories (Al-Kaisy et al 2016):

Speed-related Measures. Several speed-related measures have been used in practice or proposed in the literature for measuring performance on two-lane highways. The current HCM methodology uses ATS for class I two-lane highways and PFFS for class III two-lane highways. The PFFS is defined as the ratio of average travel speed to free-flow speed multiplied by 100. Other speed-related measures include average travel speed of passenger

cars, average travel speed of passenger cars as a percentage of free-flow speed of passenger cars (PFFS_{PC}) (Al-Kaisy and Karjala 2010, Brilon and Weiser 2006) and speed variance (Luttinen 2001).

Flow-related Measures. The perception by transportation agencies of the quality of service and the level of vehicular interaction (following or passing slower vehicles) is believed to be a function of traffic flow. The use of volume-to-capacity (v/c) ratio on two-lane highways was reported as the primary performance measure in Denmark, China and Japan (Vejdirektoratet 2010, Rong et. al 2011, Nakamura and Oguchi 2006) and as a secondary performance measure in Sweden (TRV 2013). Follower flow is another flow-related performance measure, which was investigated by the South African National Roads Agency (Van As 2004). Follower flow is defined as the flow rate multiplied by the percentage of vehicles with short headways, that is, headways smaller than a pre-specified threshold value. Those vehicles are assumed to be in following mode.

Density-related Measures. Density has been reported as a performance measure used in Germany for two-lane highway analysis (Brilon and Weiser 2006). In this particular application, density is estimated as the ratio of traffic flow (vehicles per hour) to the average speed of passenger cars. Follower density is another measure introduced by the South African National Roads Agency and is calculated as the product of percent followers (PF), defined earlier, and traffic density (Van As 2004).

Headway-related Measures. Time headway, which is a microscopic traffic flow characteristic, is another measure used in practical applications as well as in published

research. An important measure in this category is PF. Percent impeded (PI) is another measure in this category, which is defined as the product of PF and the probability of desired speeds being greater than the average speed of platoon leaders (Al-Kaisy and Freedman 2011).

Passing-related Measures. Limited passing opportunities are believed to contribute to the formation of platoons and increased delay on two-lane highways. Overtaking ratio and the average number of passes per vehicle are two proposed measures in this category (Luttinen 2001, Morrall and Werner 1990, McLean 1989). The overtaking ratio is estimated by dividing the number of passes achieved by the number of passes desired (Morall and Werner 1990).

Study Results

As was mentioned before, the survey included questions about the agency practice as well as other questions that are more related to respondents' perceptions and preferences. A summary of survey results is provided in this section.

Agency Practice

When asked about the use of HCM 2010 methodology for two-lane highways, all responding agencies in the US and Canada confirmed the use of the HCM methodology, except one state agency. That agency reported the use of crash analysis and Synchro/Simtraffic software packages for their analysis, and the HCM procedures are used as a supplementary tool if more information is required. The aforementioned response does not seem to be accurate, especially since the question is concerned with operational

analysis and that Synchro/Simtraffic does not have the capability to model two-lane highway operations. Further, the *Interactive Highway Safety Design Model (IHSDM)* TWOPAS was mentioned as a supplemental analysis tool besides the HCM by another state. Oregon utilizes follower density for analysis of class I and class II highways; however, the HCM is used for analysis of class III highways.

Survey participants were also asked about the performance measures used by their agency in the operational analysis of two-lane highways. These results are shown in Figure 13.

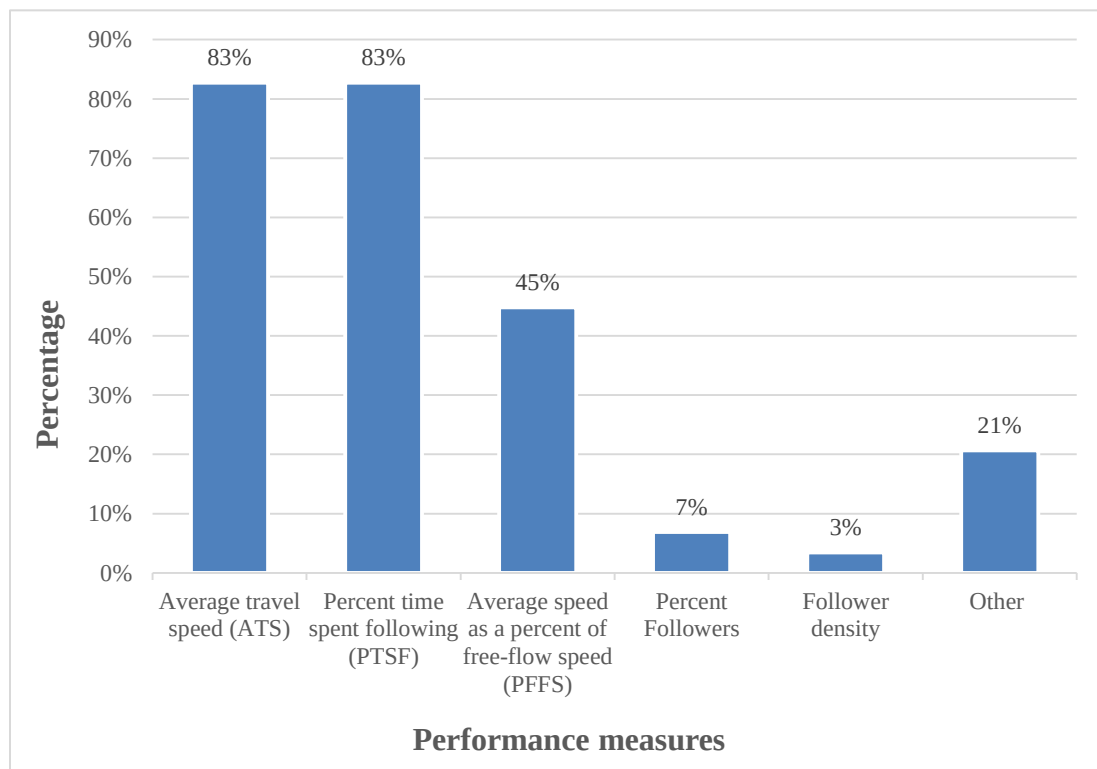


Figure 13. Performance measures used in two-lane highway operational analysis

ATS and PTSF, followed by PFFS, are used the most for performance analysis on two-lane highways. Only Oregon reported the use of follower density for performance analysis on two-lane highways. Percent followers for vehicles traveling at headways of less than 2 seconds is used by the ministry of Transportation and Infrastructure in British Columbia, Canada. The use of traffic counts, delay, and speed differential for two-lane highway operational analysis was also mentioned by another state agency. Several other performance measures were reported in the survey and they include: annual average daily traffic (AADT), the ratio of AADT to capacity (AADT/c), volume-to-capacity ratio (v/c) and the location and size of available passing areas.

The survey participants were further asked about the data collected by their respective agencies that is used in assessing performance on two-lane highways. The results are summarized in Figure 14. As shown in this figure, almost all highway agencies in the US and Canada use binned vehicle counts as part of their regular data collection programs on two-lane highways. Per vehicle data, which is critical in estimating some performance measures on two-lane highways, is only collected by 17% of the responding agencies. Maine reported the use of speed-delay runs in assessing two-lane highway performance. The Ministry of Transportation and Infrastructure in British Columbia, Canada reported the use of per-vehicle data on two-lane highways on an ad-hoc basis.

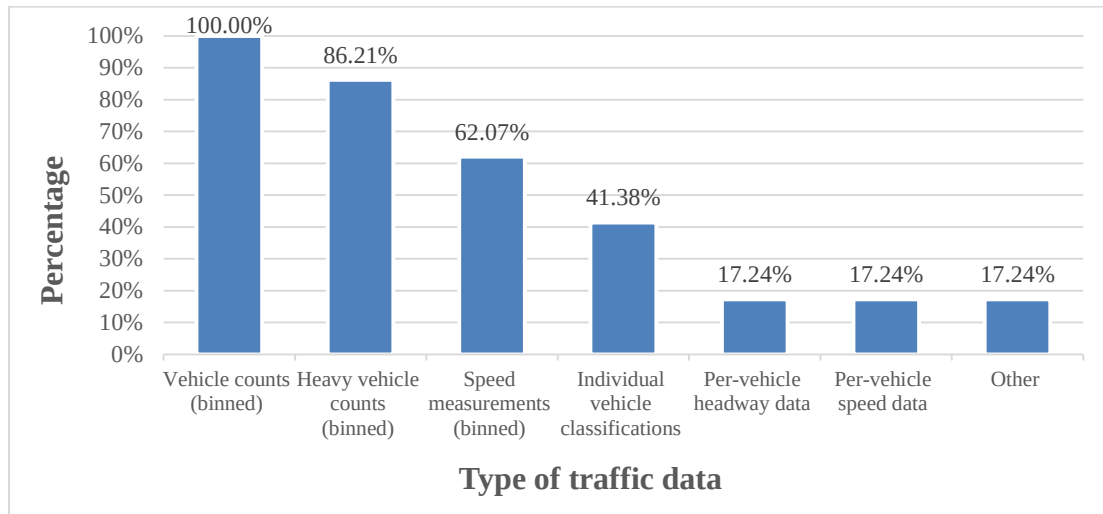


Figure 14. Traffic data collected by highway agencies for assessing performance

Practitioners Perception of Two-Lane Highway Performance Measures

Some of the survey questions asked about participant opinion of the various aspects related to performance measures on two-lane highways. As was mentioned before, there were a total of 35 responses representing 25 states and 4 Canadian provinces. For the analysis of these questions, all responses are considered even if multiple responses came from the same agency, as those responses are more related to individuals' opinions. A discussion of these questions and their responses is provided below.

One survey question attempted to gain a better understanding of what constitutes a good performance measure for two-lane highways. Several characteristics of performance measures were identified in this survey and participants were asked to rank these characteristics based on their relative importance for each class of two-lane highways. The characteristic with the highest importance was given a rank of '1' and the rank increases

with the decrease in importance. A summary of the participants' rankings is presented in Figure 15 for the three classes of two-lane highways.

As shown in this figure, the most important characteristic in a two-lane highway performance measure is being sensitive to traffic conditions, as perceived by survey participants. The second characteristic in importance is being sensitive to road conditions.

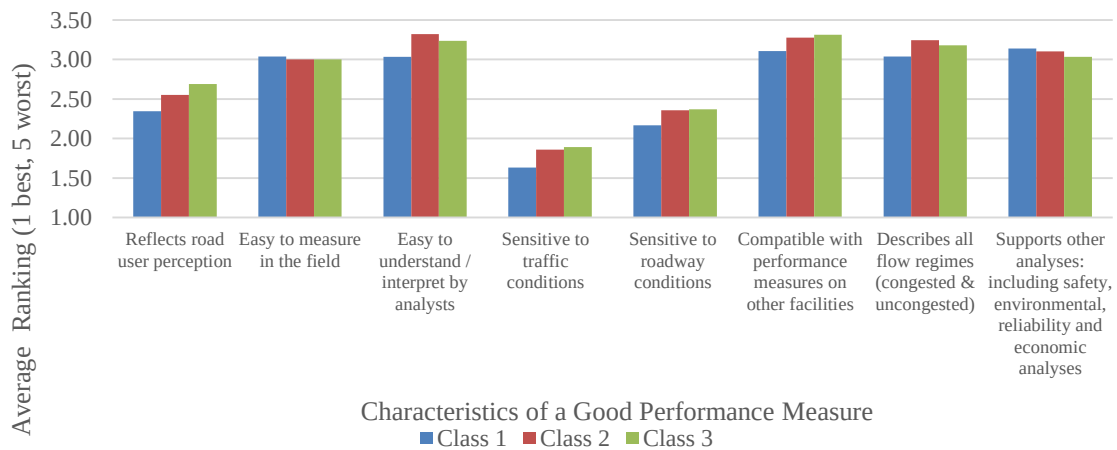


Figure 15. Average ranking for characteristics of performance measures

Road conditions on two-lane highways include features such as horizontal and vertical alignment, lane width and shoulder width. Road user perception of the quality of ride is the third most important characteristic in a performance measure, as ranked by survey participants. The remaining characteristics of performance measures were ranked almost the same with an average ranking of around 3.0. Rankings for different classes of two-lane highways were largely similar, particularly for the three most important characteristics discussed earlier, as clearly shown in Figure 15.

Another survey question asked participants to rank several aspects of traffic flow with respect to their usefulness in assessing performance on two-lane highways. Figure 16 summarizes the responses to this question, with the lowest rank representing the most useful traffic flow aspect, and vice versa.



Figure 16. Average ranking score of traffic flow aspects

As Figure 16 depicts, speed was ranked as the most useful aspect of traffic flow in assessing performance on two-lane highways. The rankings for class I and class II highways are almost identical with the most useful traffic flow aspects ranked in the following order: speed, flow, delay, headways, passing maneuvers and density. The corresponding ranking for class III highways resulted in the following order: speed and delay, followed by flow, headways, density and passing maneuvers respectively. The latter ranking is logical given the fact that delay is an important performance measure for interrupted traffic streams and that passing maneuvers may not represent an important

aspect of traffic operations in relatively developed areas where major driveways, intersections and auxiliary turning lanes exist.

The survey questionnaire presented the participants with a series of questions asking about the most appropriate two-lane highway performance measures, in relation to those traffic flow aspects discussed in the previous question. Table 8 presents the average rankings for each performance measure grouped by different traffic flow aspects (a rank of 1.0 represent the best performance measure).

Table 8. Average Ranking Score for Performance Measures

Traffic Flow Aspect	Performance Measure	Average Ranking Score		
		Class I	Class II	Class III
Flow	Volume-to-Capacity (v/c) Ratio	<u>1.56</u>	<u>1.52</u>	<u>1.63</u>
	Flow Rate	1.61	1.74	1.77
	Follower Flow (FF)	2.14	2.09	2.23
Speed	Average Travel Speed (ATS)	<u>1.54</u>	<u>1.52</u>	<u>1.65</u>
	Average Travel Speed as a Percent of Free-Flow Speed (PFFS)	2.12	2.20	2.09
	Average Travel Speed of Passenger Cars (ATS _{PC})	2.44	2.31	2.43
	Speed Variance	2.33	2.56	2.58
	ATS _{PC} as a Percent of Free-Flow Speed of Passenger Cars (PFFS _{PC})	2.84	2.92	3.10
Density	Traffic Density	1.44	<u>1.56</u>	1.85
	Follower Density (FD)	<u>1.38</u>	1.61	<u>1.65</u>
Platooning / Headways	Average Platoon Length (# of vehicles)	2.29	2.35	2.53
	Percent Time Spent Following (PTSF)	<u>1.44</u>	<u>1.61</u>	<u>1.89</u>
	Percent Followers (PF)	2.19	2.31	2.44
	Percent Impeded (PI)	2.29	2.41	2.41
Passing Maneuvers	Overtaking Ratio	<u>1.15</u>	<u>1.42</u>	<u>1.91</u>
	Average Number of Passes per Vehicle	1.83	2.00	2.30

* Bold underlined values represent the best average ranking for each class by traffic flow aspect

The relative rankings shown in Table 8 suggest a high level of consistency across the three classes of two-lane highways. Among flow-related performance measures, v/c ratio was ranked first followed by traffic flow and FF, respectively. With regard to speed-related measures, average travel speed was ranked first, followed by average travel speed as a percent of free-flow speed (PFFS), average travel speed of passenger cars (ATS_{pc}), speed variance and ATS_{pc} as a percent of free-flow speed of passenger cars ($PFFS_{pc}$), respectively. For density-related measures, traffic density is perceived as a better performance measure on class II highways, while follower density (FD) is perceived as a better measure on class I and class III highways. For headway-related performance measures, the HCM measure percent-time-spent-following (PTSF) is perceived as the best, followed by percent followers (PF), percent impeded and average platoon length, respectively. PF is used in the current HCM as a surrogate measure for estimating PTSF using field data. Finally, for measures related to passing maneuvers, overtaking ratio is perceived as a better performance measure compared to the average number of passes per vehicle on a two-lane highway segment.

While Table 8 is useful in comparing performance measures that belong to the same group/category, it cannot be used to provide objective comparisons across categories. Specifically, the number of measures in each group is different, and therefore, the same average ranking in two different groups could indicate different levels of merit.

When asked about their satisfaction with the HCM performance measures, around 73% of the agencies surveyed mentioned they were satisfied with HCM performance measures used by their agencies. Several issues were raised by survey participants, which

corresponded to what they perceive as limitations in the current performance measures used on two-lane highways. Some of the comments made in this regard are as follows:

- PTSF is difficult to measure in the field.
- The level of service based on PTSF is overestimated, especially in summer peak traffic, in that everyone is following someone else.
- Even if all vehicles are driving at speeds near speed limit or above, level of service based on PTSF would be F.
- The PTSF does not recognize or rate context of a project segment within an entire corridor between control cities.
- For class 1 highways with high volume, the PTSF dictates the LOS results; however the HCM suggests using both the ATS and the PTSF for class 1 highways.

As was mentioned earlier, there are some limitations related to the HCM 2000 methodology for operational analysis of two-lane highways (HCM 2000) as reported in several studies in the literature (Al-Kaisy and Freedman 2011, Al-Kaisy and Freedman 2010, Al-Kaisy and Karjala 2008, Brilon and Weiser 2006, Luttinen 2001). This methodology has not significantly changed in the later HCM editions (HCM 2010, 2016). Survey participants were asked to state their priorities for revisions/additions to the HCM two-lane highway analysis methodology. The following is a summary of their feedback as related to the use of performance measures on two-lane highways.

A few characteristics were mentioned by survey participants as being important for a good performance measure on two-lane highways. One respondent mentioned that the performance measure should be able to describe the whole corridor between control

cities/towns. Overall travel time was mentioned as an example of such performance measures. Other respondents suggested the use of other measures not included in the survey such as travel time reliability. One survey respondent mentioned that the travelers' experience along the whole corridor should be considered by any proposed new measure. Replacing PTSF and ATS with more follower (headway) based measures like follower density was recommended by another survey respondent. Other criteria that were mentioned by survey participants as being important for performance measures are consistency between facilities in different area types (urban, suburban, rural) and the ease with which the measures can be explained to the public.

Performance Measures on Two-lane Highways: Empirical Investigation

As discussed earlier, the current performance measures for evaluating level of service on two-lane highways have some limitations. These limitations were the main motive behind this study. Specifically, this section aims at examining the suitability of some proposed performance measures for use in two-lane highway capacity analysis.

Study Design

In order to assess the suitability of performance measures, the association between several performance measures and traffic variables were investigated in this section. Traffic variables investigated consisted of combined flow in both directions of travel, heavy vehicle percentage (% HV), traffic split (proportion of traffic in travel direction), speed variance and percent no passing zone (Al-Kaisy et. al 2017). Performance measures used in this investigation include:

- Average Travel Speed (ATS): Average speed of all vehicles traveling in the direction of analysis.
- Average Travel Speed to Free Flow Speed (ATS/FFS): The ratio between the average travel speed of all vehicles to free-flow speed. In this study, average speed of vehicles with headway more than 8 seconds was used to establish the free-flow speed.
- Percent Followers (PF): Percentage of vehicles with headways less than 3 seconds (a surrogate measure used by HCM to estimate PTSF using field data).
- Follower Density (FD): The number of vehicles with headways less than 3 seconds per mile per lane in one direction of travel. This measure is calculated as the traffic density (in one direction) multiplied by percent followers (PF).
- Follower Flow (FF): The hourly rate of vehicles with headways less than 3 seconds that passes a point along a two-lane highway in the analysis direction. This measure is calculated as the flow rate multiplied by percent followers (PF).
- Percent Impeded (PI): Percentage of vehicles impeded by slower-moving vehicles in a directional traffic stream measured at a point. PI is calculated as the probability of desired speeds being greater than the average speed of platoon leaders multiplied by the percent of vehicles with headways less than a pre-specified threshold value. A threshold value of 3 seconds was used in this study (same as PF). For establishing the distribution of desired speeds, vehicles with headway more than 8 seconds were used. Platoon leaders were used as a representative sample of slow moving vehicles.

- Impeded Flow (IF): The hourly rate of vehicles impeded by slow-moving vehicles, i.e. platoon leaders. It is calculated as the product of PI and the hourly rate of traffic flow.
- Impeded Density (ID): Number of vehicles impeded per mile per lane in one direction of travel. It is calculated as the product of PI and traffic density.

As defined above, performance measures are either speed-related (ATS, PFFS), headway related (PF) or composite measures (FD, FF, PI, ID, IF). Traffic variables investigated in this study include:

- Combined flow (veh/hr): The hourly flow rate in both directions of travel.
- Traffic split: The proportion of hourly flow rate in the direction of analysis to combined flow.
- Percent heavy vehicles (% HV): The percentage of heavy vehicles in the direction of analysis.
- Speed variance: The square of standard deviation of all vehicle speeds measured at a specific location in the direction of analysis.
- Percent no passing: The percentage of road by length in which passing is not allowed in the direction of analysis. This percentage was found for 3 miles upstream and downstream of the location being investigated.

Study Sites

Sixteen study sites in the states of Montana, Idaho, Oregon and North Carolina were used in this study (four sites in each state). A description of the data collected at the 16

study sites was provided in Table 6 of chapter three. Data were aggregated into one hour intervals for use in the analysis.

Research Underlying Hypotheses

In this section, the major hypotheses underlying the relationship between performance measures and traffic variables are discussed (Al-Kaisy et al 2017).

- Combined flow: This is traffic flow in the two directions of travel expressed as an hourly flow rate. As combined flow increases, ATS and ATS/FFS are expected to decrease. On the other hand, all other performance measures (PF, FD, FF, PI, ID, and IF) are expected to increase.
- Traffic split: This is the proportion of traffic flow in the analysis direction. The hypotheses here are similar to those of combined flow. As traffic split increases, ATS and ATS/FFS are expected to decrease while all other performance measures (PF, FD, FF, PI, ID, and IF) are expected to increase.
- Percent heavy vehicles: Heavy vehicles are generally associated with lower performance and thus lower speeds compared to passenger cars. As heavy vehicle percentage increases, ATS and ATS/FFS are expected to decrease while all other performance measures are expected to increase.
- Speed variance: Similar to percent heavy vehicles, this variable is not generally perceived as being related to traffic level, however, it may well be associated with the level of platooning in the traffic stream. The relationship between speed variance and performance measures may not be as straightforward as with the other three traffic variables. On one hand, high speed variance could mean faster formation of

platoons due to faster vehicles quickly catching up with slower vehicles forming platoons (a.k.a. bunches, groupings, etc.). On the other hand, a traffic stream consisting of high percentage of platooned vehicles may exhibit more uniformity in speeds due to following vehicles roughly traveling at speeds of platoon leaders (thus smaller speed variance). Therefore, the validity of either hypothesis may well be a function of traffic level and passing opportunities.

Study Results

To investigate the relationship between performance measures and traffic variables, a graphical examination of the relationships between the two was conducted first. This step is expected to reveal some of the patterns and trends that underlie those relationships. Correlation and regression analyses were conducted to assess the level of association between performance measures and traffic variables.

As was mentioned earlier, data were collected from 16 different sites, of which 12 are class I, two class II and two class III sites. In this analysis, sites ATR 47, ATR 147 and ATR 73 were chosen to represent class 1, class 2 and class 3 two-lane highways, respectively.

Figure 17 shows the relationship between the eight performance measures investigated in this study and combined flow at the three study sites. In general, all relationships are consistent with the research hypotheses discussed earlier particularly those related to PF, FD, FF, PI, ID, and IF. The trends for the speed-related performance measures (ATS and ATS/FFS) generally show lower sensitivity between those measures and combined flow. It is also important to notice that ATS/FFS exhibited very little

sensitivity (if any) on class I highways and a relatively higher sensitivity on class II and III, respectively.

A similar set of graphs showing the relationship between the performance measures and traffic split is shown in Figure 18. With the exception of ATS at class I and class II study sites, all relationships exhibited trends that are in agreement with the research hypotheses. ATS shows almost no sensitivity whatsoever to traffic split at sites ATR47 and ATR 147.

Figure 19 shows the relationships between performance measures and speed variance. In regards to speed-related measures, all relationships showed decline in the two performance measures as speed variance increases, with the exception of ATS/FFS at class I study site. As for headway-related and composite measures, all relationships at class I and class III sites (ATR 47 and ATR 73) showed decline in performance measures with the increase in speed variance. The relationships at class II study site (ATR 147) showed trends that are inconsistent with those at the other two study sites. Specifically, performance measures showed almost no sensitivity to speed variance for the most part. It is important to remember that traffic level at this study site is notably lower than that at the other study sites as shown in **Error! Reference source not found..**

Figure 20 shows the relationships between performance measures and percentage of heavy vehicles. Overall, the majority of relationships showed very little to no sensitivity of performance measures to the percent of heavy vehicles. The only exception are those relationships at site ATR 73 (class III) where headway-related and composite measures

(PF, FD, FF, PI, ID, and IF) showed noticeable decline with the increase in heavy vehicle percentage.

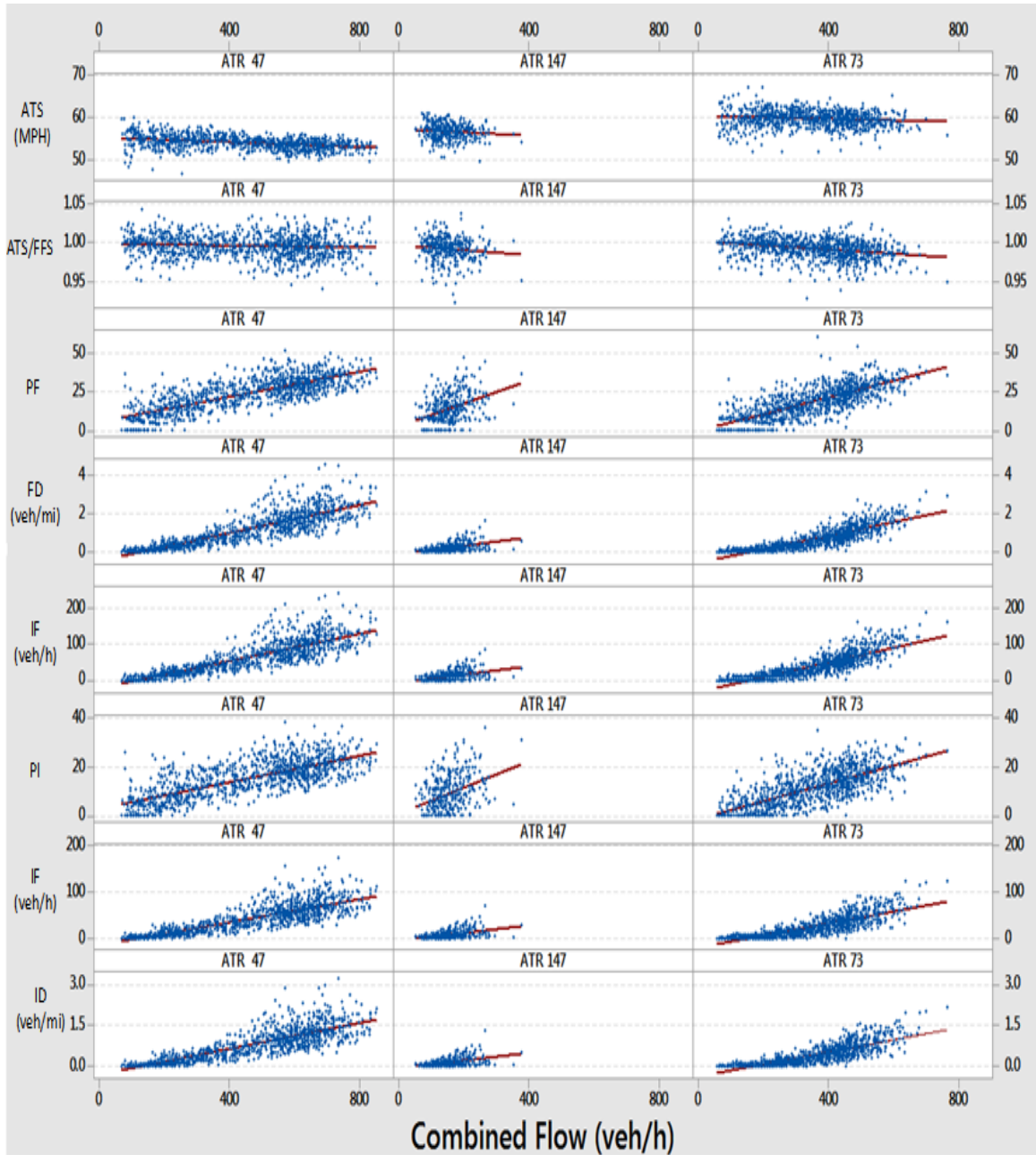


Figure 17. Scatterplots of performance measures vs combined flow

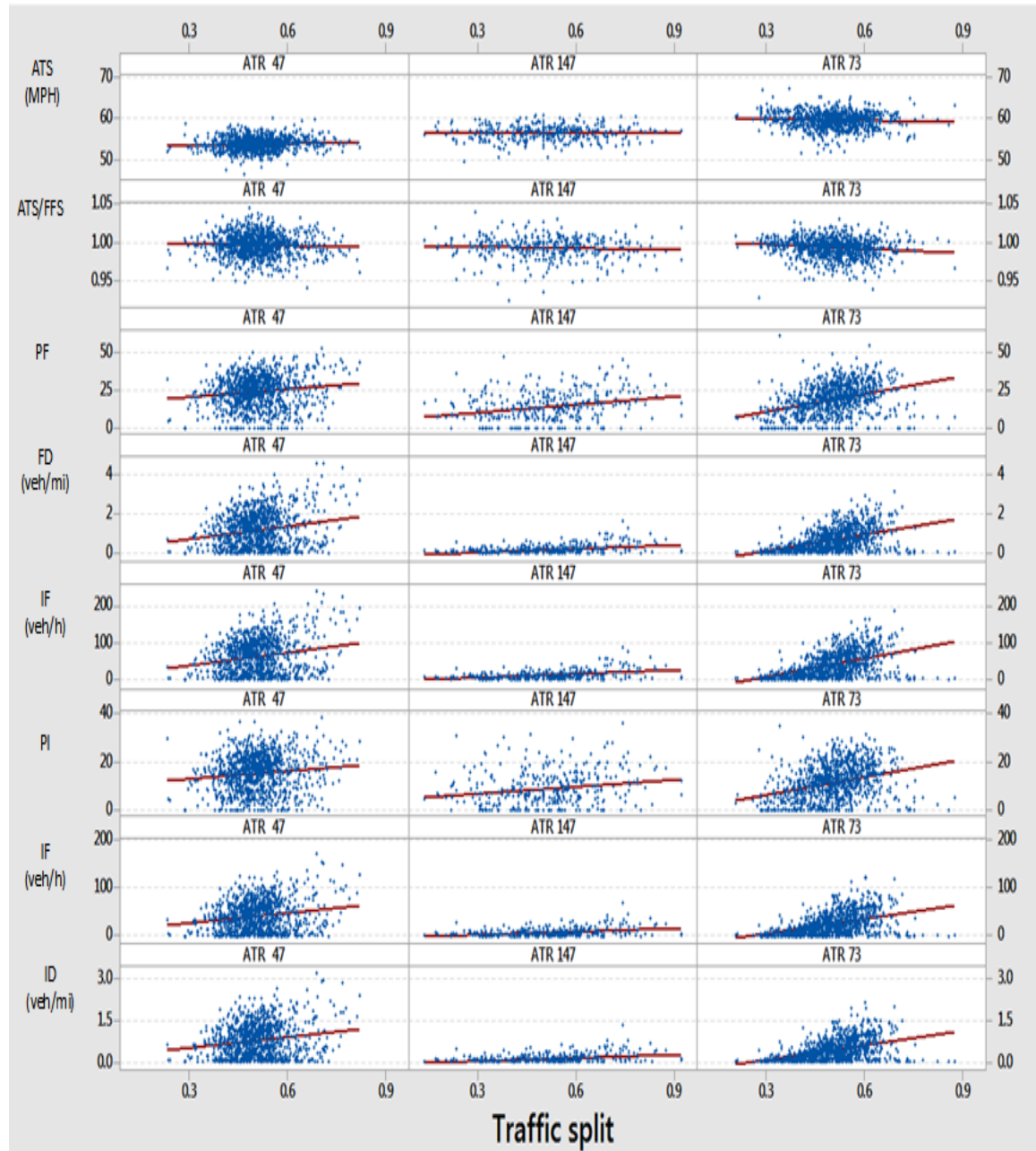


Figure 18. Scatterplots of performance measures vs traffic split

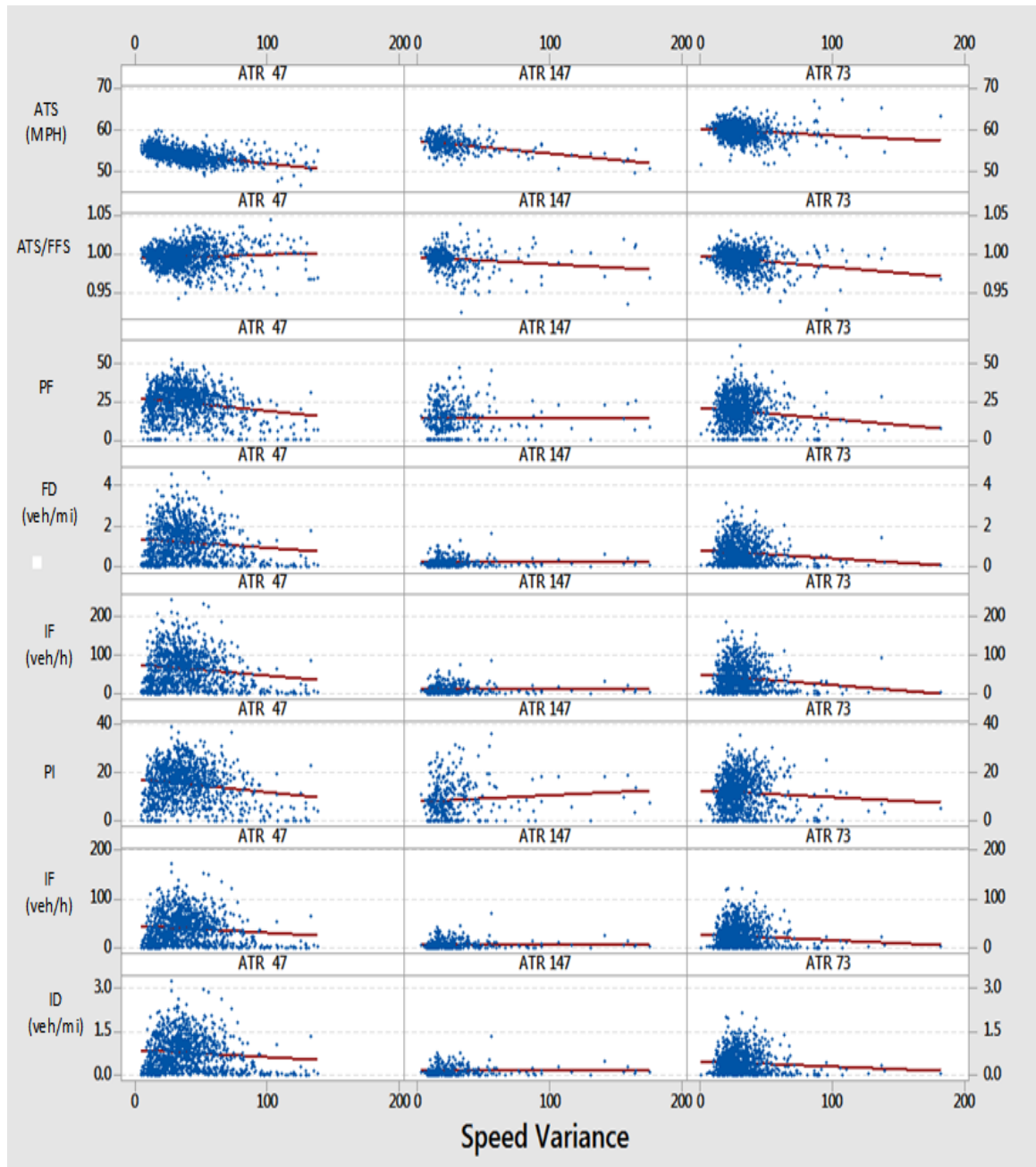


Figure 19. Scatterplots of performance measures vs speed variance

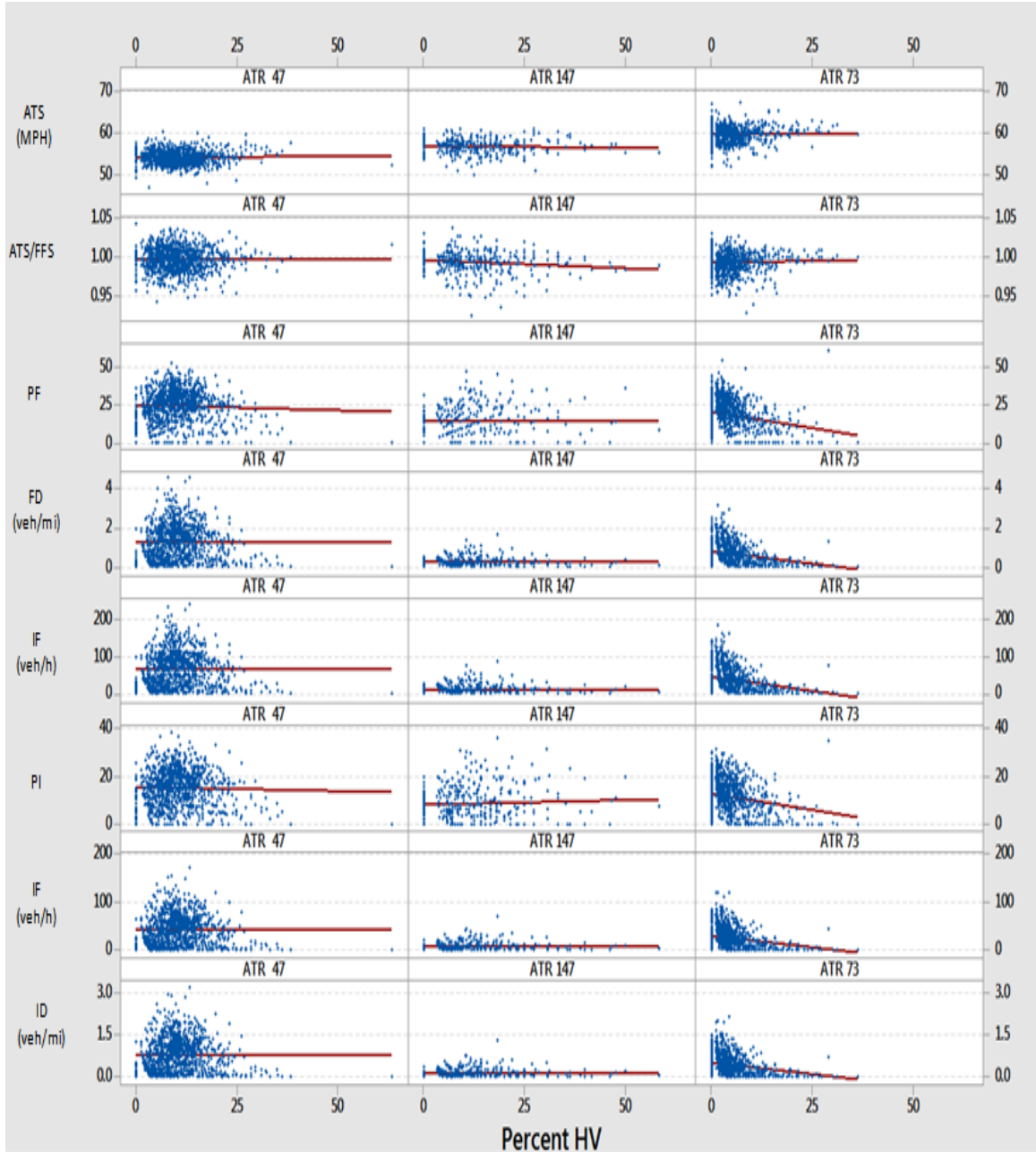


Figure 20. Scatterplots of performance measures vs percent heavy vehicles

To gain insight into the suitability of performance measures on different types of two-lane highways, three levels of analysis (data aggregation) were used in this study. The first level utilized combined data from all study sites in the analysis. The second level of

analysis utilized data aggregated across sites of the same highway class (class I, II or III). The third level involved separate analyses using data from individual study sites.

The relationship between performance measures and traffic variables was also examined using correlation and regression analyses. Figure 21 shows the coefficients of correlation between all performance measures and traffic variables for the combined data at all study sites, as well as class I, II, and III data. The most important observations are summarized below.

For combined and class I data, combined flow shows notably high correlations with performance measures followed by traffic split which is associated with much lower correlation coefficients. Headway-related and composite performance measures generally exhibited high correlations with combined flow, with coefficients higher than 0.8 for FD, FF, ID and IF. Speed variance and percent heavy vehicles generally show very low correlations with performance measures. Percent heavy vehicles exhibits very low correlation coefficients with all performance measures.

For class II data, while combined flow shows again higher correlations with performance measures compared to other traffic variables, those correlations are notably lower than their counterparts on class I highways. Although traffic split exhibited lower correlation coefficients compared with combined flow, those coefficients are generally greater than their counterparts on class I highways. Further, though still considered low in value, percent heavy vehicles exhibit relatively higher correlation coefficients compared with their counterparts on class I highways. Speed variance and percent heavy vehicles

exhibit relatively weak correlations with performance measures except for the correlation between ATS and percent heavy vehicles.

For class III data, combined flow shows highest correlations with performance measures compared to other traffic variables. Again, while traffic split exhibits lower correlation coefficients compared with combined flow, those coefficients are generally greater than their counterparts on class I highways. Headway-related and composite performance measures exhibit relatively high correlations with combined flow, with coefficients around 0.80 or greater for PF, FD, FF, ID and IF. For speed-related measures, ATS/FFS shows higher correlation with combined flow, traffic split and speed variance while ATS shows higher correlation with percent heavy vehicles.

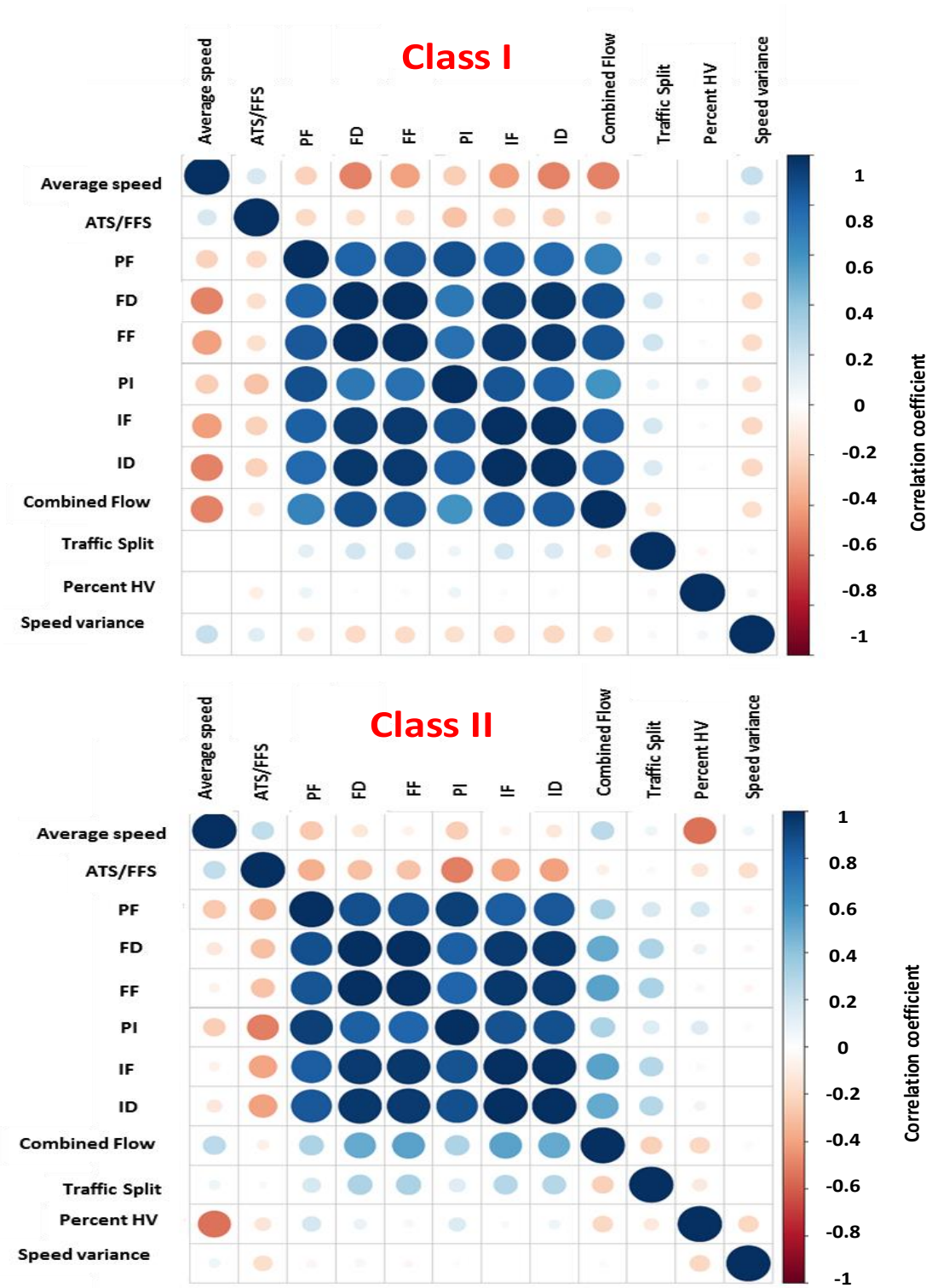


Figure 21. Correlation results for combined, class I, class II, and class III data

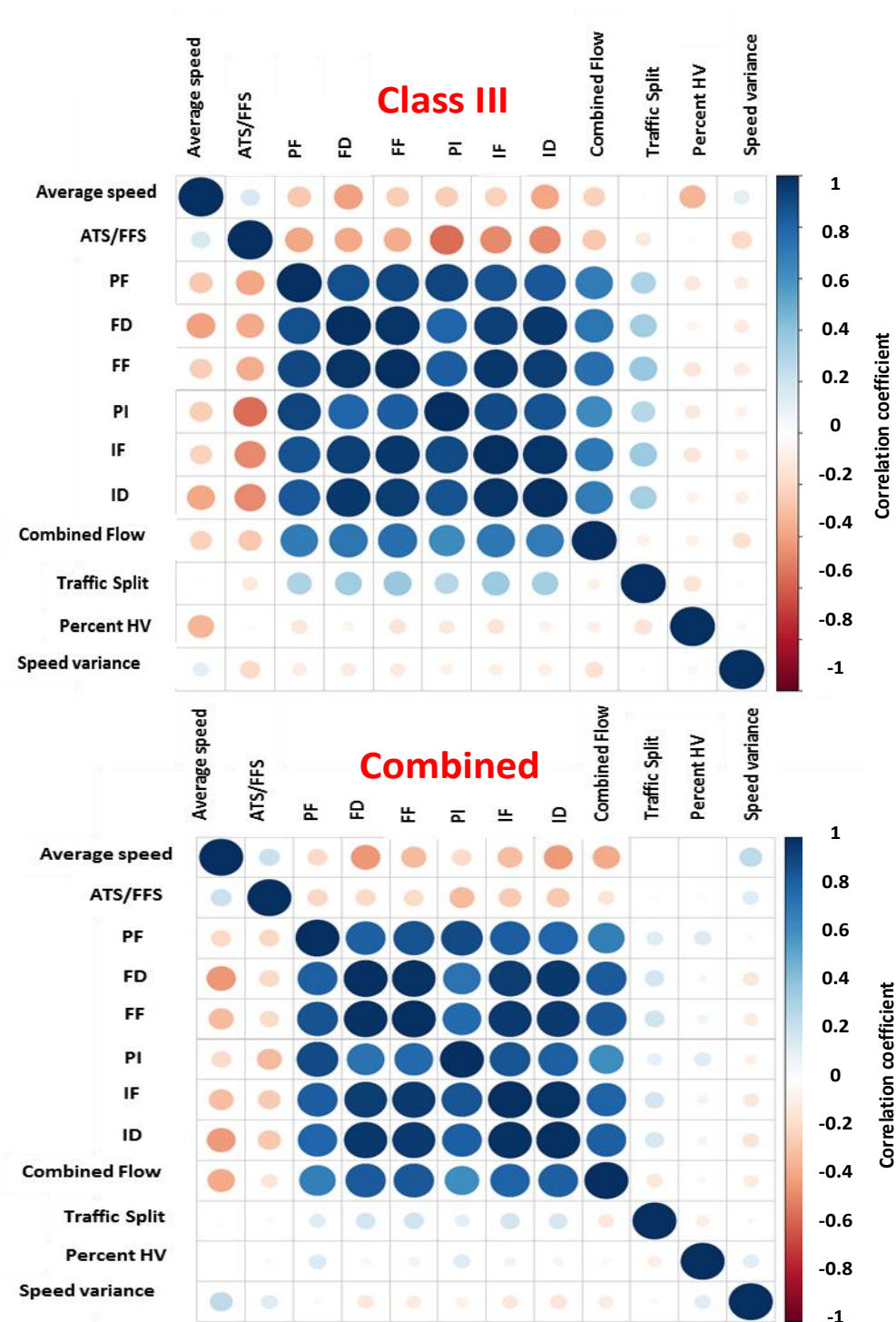


Figure 21. (Continued). Correlation results for combined, class I, class II, and class III data

In order to explore the relationships between performance measures and traffic variables, multiple linear regression was also performed using the data for each class type. Table 9, Table 10 and table 11 summarize the results of regression analysis for each class using 95% confidence level. In these models, performance measures represented the response (dependent) variable and traffic variables were used as predictor (independent) variables. Values not found significant were removed from the results. Appendix B includes the results for all sites.

For class 1, all of the 8 regression models are considered statistically significant with R^2 between 0.07 and 0.81. Follower flow and follower density resulted in models with highest R^2 values (0.81 and 0.8, respectively). Regarding the results of class II study sites shown in Table 10, all models were found statistically significant at 95% confidence level. However, the models for headway-related and composite performance measures yielded notably lower R^2 values while those for speed-related performance measures yielded higher R^2 values compared with class I data. Again, Follower flow followed by follower density resulted in models with the highest R^2 values. Further, speed variance was not found significant in six out of eight regression models (at 95% confidence level).

Class III results shown in Table 11 suggest that all regression models are statistically significant at 95% confidence level. Models for headway-related and composite measures yielded R^2 values that are greater than those of class II study sites but lower than those for class I study sites. In regards to speed-related measures, the model for ATS/FFS yielded the highest R^2 compared to other classes. Further, speed variance was not found significant in six out of 8 class III models.

Table 9. Results from Multivariate Linear Regression Analysis for Class I Sites

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	Percent HV	Speed Variance
Class 1							
ATS	0.12	4.7	64.05 0.00	-0.007 0.00	-2.69 0.00	-0.02 0.00	0.004 0.00
ATS/FFS	0.07	0.02	1.01 0.00	-0.00002 0.00	-0.01 0.00	-0.0004 0.00	-0.00001 0.00
% Follower	0.59	11.21	-7.3 0.00	0.05 0.00	29.68 0.00	0.07 0.00	-0.008 0.00
Follower Flow	0.81	36.08	-118.46 0.00	0.29 0.00	164.7 0.00	---	-0.03 0.00
Follower Density	0.80	0.63	-2.09 0.00	0.005 0.00	2.87 0.00	---	-0.0006 0.00
% Impeded	0.50	8.29	-4.78 0.00	0.03 0.00	17.69 0.00	0.06 0.00	---
Impeded Flow	0.76	24.98	-71.81 0.00	0.17 0.00	98.82 0.00	0.06 0.01	-0.01 0.00
Impeded Density	0.75	0.45	-1.28 0.00	0.003 0.00	1.73 0.00	0.001 0.01	-0.0002 0.00

Table 10. Results from Multivariate Linear Regression Analysis for Class II Sites

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	Percent HV	Speed Variance
Class 2							
ATS	0.25	3.27	62.75 0.00	0.006 0.00	-1.63 0.00	-0.23 0.00	-0.007 0.01
ATS/FFS	0.04	0.02	1.009 0.00	-0.00002 0.00	-0.01 0.00	-0.0003 0.00	-0.00004 0.00
% Follower	0.27	7.65	-9.17 0.00	0.05 0.00	18.36 0.00	0.27 0.00	---
Follower Flow	0.54	8.17	-27.18 0.00	0.11 0.00	33.99 0.00	0.26 0.00	---
Follower Density	0.51	0.14	-0.44 0.00	0.002 0.00	0.56 0.00	0.005 0.00	---
% Impeded	0.25	5.62	-7.61 0.00	0.04 0.00	12.69 0.00	0.18 0.00	---
Impeded Flow	0.50	6.05	-19.24 0.00	0.08 0.00	22.89 0.00	0.17 0.00	---
Impeded Density	0.48	0.10	-0.31 0.00	0.001 0.00	0.38 0.00	0.003 0.00	---

Table 11. Results from Multivariate Linear Regression Analysis for Class III Sites

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	Percent HV	Speed Variance
Class 3							
ATS	0.14	6.99	63.37 0.00	-0.01 0.00	-5.96 0.00	-0.29 0.00	---
ATS/FFS	0.16	0.01	1.01 0.00	-0.00003 0.00	-0.01 0.00	---	0.0002 0.00
% Follower	0.62	7.27	-11.71 0.00	0.05 0.00	30.83 0.00	0.08 0.00	-0.04 0.00
Follower Flow	0.75	20.22	-81.66 0.00	0.17 0.00	129.82 0.00	---	---
Follower Density	0.68	0.47	-1.72 0.00	0.003 0.00	2.58 0.00	0.007 0.00	---
% Impeded	0.52	5.58	-8.2 0.00	0.03 0.00	19.26 0.00	---	---
Impeded Flow	0.68	14.58	-52.03 0.00	0.11 0.00	81.52 0.00	---	---
Impeded Density	0.63	0.33	-1.09 0.00	0.002 0.00	1.63 0.00	0.004 0.00	---

Regression results at the sixteen study sites were used to rank performance measures in terms of their relationship with traffic variables investigated in this research. Figure 22 shows the rankings of performance measures by R^2 value for different classes of two-lane highways. As the results show, follower flow and follower density are the first and second ranked performance measures followed by impeded flow and impeded density. Speed-related measures ranked last for all highway classes.

Table 12 shows the number of times traffic variables were found significant for each performance measure using class regression runs. Combined flow and traffic split were consistently found significant in almost all regression runs for all highway classes particularly in models of headway-related and composite performance measures. Speed

variance was found significant more often in ATS models for all highway classes. Percent heavy vehicles was found significant less often compared to all other traffic variables.

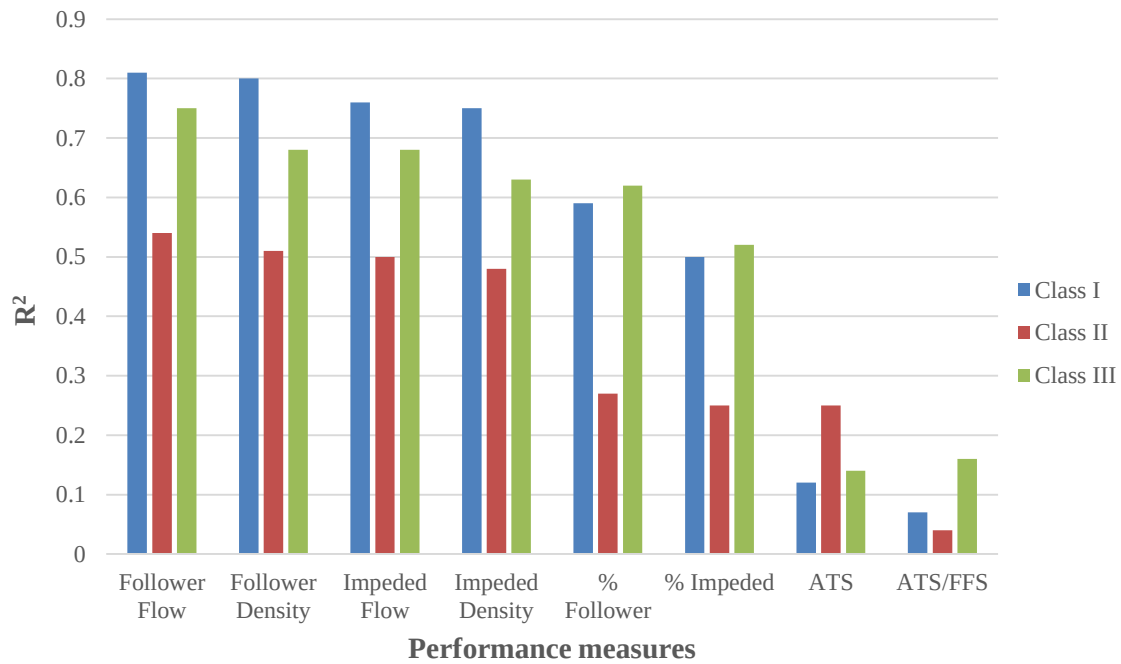


Figure 22. Performance measures rank by class using R²

Table 12. Number of Times Variable Found Significant Using Class Regression Runs

Performance Measure	Sites											
	Class I (12 sites)				Class II (2 sites)				Class III (2 sites)			
	Combined Flow	Traffic Split	% Trucks	Speed Variance	Combined Flow	Traffic Split	% Trucks	Speed Variance	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATS	12	7	7	10	2	1	1	2	1	0	0	2
ATS/FFS	10	4	3	10	2	2	1	2	2	1	0	2
% Follower	12	12	6	4	2	2	1	0	2	2	1	0
Follower Flow	12	12	3	5	2	2	1	0	2	2	1	0
Follower Density	12	12	3	5	2	2	1	0	2	2	1	0
% Impeded	12	12	7	8	2	2	1	1	2	2	1	1
Impeded Flow	12	12	3	7	2	2	1	1	2	2	1	0
Impeded Density	12	12	3	9	2	2	1	1	2	2	1	2

Preliminary Assessment of Performance Measures

In this section, an initial qualitative assessment of the alternative performance measures is presented (Al-Kaisy et al. 2018). The HCM performance measures will also be included in this assessment to help in understanding the merits of the proposed alternative measures. As stated before, it is desired for prospective performance measures on two-lane highways to meet the set of criteria discussed earlier in this study. Table 13 summarizes all performance measures discussed in this study and the degree to which each measure satisfies the aforementioned six criteria. In this subjective assessment, each performance measure is evaluated against the six criteria independently (i.e., assessed assuming it's used solely for measuring performance on two-lane highways). It is important to remember that those criteria do not have the same significance when it comes to conducting two-lane highway operational analysis. For example, to easily measure

performance in the field may have more weight than supporting environmental impact analysis. As the objective of this research is to examine performance measures rather than to recommend a particular measure for operational analysis on two-lane highways, no weights were assigned to the six evaluation criteria.

At a glance, it is apparent that no single measure largely satisfied all evaluation criteria and that each measure satisfied some criteria to a higher degree but scored low on other criteria. While this is applicable to almost all performance measures included in this evaluation, the following observations can be made:

1. The two major HCM performance measures on two-lane highways, PTSF and ATS, do not well satisfy most of the six evaluation criteria.
2. Aside from being easy to measure in the field, speed-related measures scored generally low on all other criteria except for supporting economic and (to a lesser degree) environmental analyses.
3. Performance measures based on passing maneuvers scored notably low on most of the evaluation criteria.
4. Compound measures involving headway and either density or flow rate showed higher degree in satisfying the six criteria particularly follower density and impeded density.

The above discussion suggests that identifying a single performance measure that satisfactorily meets all criteria may prove to be very difficult, and therefore, it may be advantageous to use more than one performance measure in describing performance on two-lane highways.

Table 13. Preliminary Assessment Matrix of Performance Measures on Two-Lane Highways

Performance Measure	(1) Road User Perception	(2) Easy to Measure	(3) Sensitive to Road Conditions	(4) Compatible with Other Facilities	(5) Describes All Flow Regimes	(6) Support Other Analyses			
						Safety	Economic	Environmental	Reliability
HCM – PTSF ^a	XXX ^b	X	X	X	X ^c	X	X	X	X
HCM – ATS	X	XXX	X	XX	X ^c	X	XX	X	X
HCM – (ATS/FFS)	XX	XXX	XX	X	XX ^c	X	XXX	XX	X
ATS _{PC}	X	XXX	X	XX	X	X	XX	XX	X
ATS _{PC} as a percent of FFS of PCs (ATS _{PC} /FFS _{PC})	XX	XXX	XX	X	XX	X	XXX	XX	X
Speed Variance	X	XXX	X	X	X	XX	X	X	X
Demand-to-capacity (d/c) ratio	XX	XXX	X	X	XXX	XX	XX	XX	XX
Traffic Density	X	XXX	XX	XXX	XXX	XX	X	X	XX
Overtaking ratio	X	X	XX	X	X	X	X	X	X
Average # of passes per vehicle	X	X	XX	X	X	XX	X	X	X
% followers (PF)	XX	XXX	XX	X	X	X	X	X	X
Follower flow (FF)	X	XXX	XXX	X	X	XX	X	X	X
Follower density (FD)	XX	XXX	XXX	XX	X	XX	X	X	X
Percent impeded (PI)	XXX	XX	XXX	X	X	XX	X	X	X
Impeded flow (IF)	X	XX	XXX	X	X	XX	X	X	X
Impeded density (ID)	XX	XX	XXX	XX	X	XX	X	X	X
Freedom of flow	X	X	XX	X	XX	XX	X	X	X

a – PTSF is estimated using flow rates in the analytical methodology and using percent followers (PF) as a surrogate measure for field estimation.

b – X = hardly meeting criterion, XX = fairly meeting criterion, XXX = largely meeting criterion

c – Level of service F is not defined for any of the three HCM 2016 performance measures

CHAPTER FIVE

FOLLOWING STATUS AND PERCENT FOLLOWERS ON TWO-LANE TWO-WAY
HIGHWAYS: EMPIRICAL INVESTIGATION

Contribution of Authors and Co-Authors

Manuscript in Chapter 5

Author: Ahmed Al-Kaisy

Contributions: Draft manuscript preparation

Co-Author: Amirhossein Jafari

Contributions: Draft manuscript preparation

Co-Author: Scott Washburn

Contributions: Review the draft

Manuscript Information

Following Status and Percent Followers on Two-lane Highways: Empirical Investigation

Ahmed Al-Kaisy, Amirhossein Jafari, Scott Washburn.

Transportation Research Record: Journal of the Transportation Research Board

Status of Manuscript:

- ☒ Prepared for submission to a peer-reviewed journal
- ☐ Officially submitted to a peer-reviewed journal
- ☐ Accepted by a peer-reviewed journal
- ☐ Published in a peer-reviewed journal

CHAPTER FIVE

FOLLOWING STATUS AND PERCENT FOLLOWERS ON TWO-LANE TWO-WAY
HIGHWAYS: EMPIRICAL INVESTIGATIONOverview

This chapter aims at achieving a better understanding of the car-following interaction between vehicles on two-lane two-way highways. Such an understanding is critical for estimating car-following parameters that have been used in practice for identifying vehicles that are in following mode, an important aspect of operational analyses on two-lane highways (Al-Kaisy et al. 2017).

Car-Following Process

Car-following behavior, i.e., the interaction between successive vehicles sharing the same travel lane, has been the focus of research since early developments in traffic-flow theories. This vehicular interaction becomes especially important on two-lane two-way highways where only one lane is available for each direction of travel. On these facilities, car-following interactions become a major determinant of the quality of service and an indicator of the amount of platooning, i.e., the time during which drivers are forced to travel at a speed less than their desired speed due to being impeded by other vehicles in the same travel lane. Those interactions are expected to increase with the increase in traffic demand, increase in the percentage of slow moving vehicles (e.g., trucks), and as more restrictions exist on passing opportunities.

It is believed that when the time gap (or headway) between two successive vehicles in the traffic stream gets smaller, the car-following interaction begins; reflected by the following vehicle adjusting its speed as it gets closer to the lead vehicle. This introduces an important parameter, referred to here as critical headway (h_{cr}), and is defined as the time headway at which the car-following interaction starts. As the following vehicle continues to approach the lead vehicle, the speed of the following vehicle and the headway between the two vehicles will continue to decrease until a point is reached when the speeds of the two vehicles will be approximately the same. At this point, the headway between the two vehicles represents what is perceived as the minimum safe headway (h_{min}). In this research, time headway and not gap is used to refer to the physical proximity of successive vehicles in the traffic stream on two-lane highways as it can directly be measured in the field.

Like many other traffic phenomena, it is rational to assume that both h_{cr} and h_{min} are stochastic variables that are mainly a function of driver characteristics. An important question this research attempts to answer is how close the following vehicle needs to be from the lead vehicle for this interaction to take effect; or in other words, what is the value of critical headway on two-lane highways? It is expected that this headway is primarily a function of the driver of the following vehicle. Specifically, more aggressive drivers may start to interact with the lead vehicle and adjust their speeds when they are very close to the lead vehicle (i.e., very small critical headway, h_{agg}), while on the other hand, more conservative drivers may start to interact with the lead vehicle and adjust their speeds at a relatively large distance from the lead vehicle (i.e., very large critical headway, h_{con}). In following other vehicles, the majority of drivers start interacting with the lead vehicle at

headways that fall between the critical headways for the former two driver types; i.e., the very aggressive and the very conservative drivers. This concept is shown in Figure 23. This figure clearly demarks the two boundaries: h_{agg} and h_{con} . Vehicles that travel at headways less than h_{agg} can generally be described as being in following state while those with headways greater than h_{con} can be described as being independent or in free-flow state. Typical values for the critical headway are expected to be in this range; i.e., between the boundary values h_{agg} and h_{con} (Al-Kaisy et al. 2017).

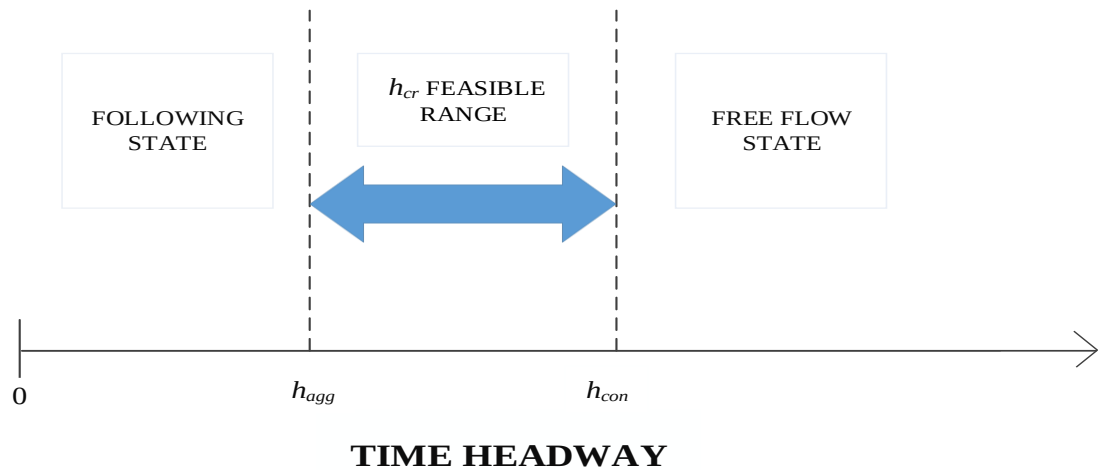


Figure 23. Different states between successive vehicles (Al-Kaisy et al. 2017)

A similar argument can be assumed for the minimum safe headways (h_{min}) between successive vehicles in platoons that are in following mode (i.e., not in passing mode) traveling roughly at the same speed as that of the platoon leader. Specifically, the “perceived” minimum safe headway is believed to be a stochastic variable generally varying in a range which represents the more aggressive and the more conservative drivers.

Study Sites

Field data from 15 study sites in Montana, Idaho, and Oregon were used in this study. Different criteria were used for choosing the study sites. In the selection of study sites an attempt was made, as much as possible, to include sites with a wide range of traffic conditions. Study sites were selected to represent uninterrupted flow conditions away from the influence of driveways with high volume, intersections, or other access points that may have implications on vehicle speeds and driver behavior. Moreover, the study sites were selected not to be affected by major geometric features such as grades, horizontal and vertical curves. All sites are located in rural areas. Data for these sites were provided by the Departments of Transportation in the respective states. Per vehicle data, including arrival time, spot speed, and vehicle classification, were obtained from automatic traffic recorders. Headways were found using the difference between time stamps for two consecutive vehicles. Data were carefully screened to make sure that any defective data were eliminated from the data sets. Data were collected for both directions of travel, however, only one direction was used for the analysis. A description of the data collected at the 15 study sites is provided in Table 14.

Table 14. Description of Field Data at Study Sites

Site Number	Site Name	Dates	Class ¹	Duration of Data Collection (hours)	Total Vehicle Count (veh)	Annual Average Daily Traffic ² (veh/day)	Speed Limit (mi/h)	Direction of Analysis
1	ATR 43-MT	July 20, 2014- July 26, 2014	I	168	23,676	4776	60	Southbound
2	ATR 8-MT	March 28, 2016- April 11, 2016	I	360	54,449	7,059	70, 60 (trucks)	Southbound
3	ATR 107-MT	July 16, 2014- July 31, 2014	I	372	64,056	6,093	50	Southbound
4	ATR-130 MT	July 9, 2014- July 24, 2014	I	375	38,037	3,372	70, 60 (trucks)	Eastbound
5	ATR 28 -MT	July 16, 2015 – July 30, 2015	II	360	24,311	2939	70, 60(trucks)	Northbound
6	ATR 73 –MT	July 16, 2015 – July 30, 2015	III	360	47,052	3601	60	Northbound
7	ATR 47-ID	June 16, 2015 – June 30, 2015	I	360	62,643	6799	60	Westbound
8	ATR 44-ID	June 15, 2015 – June 30, 2015	I	384	49,737	5206	65	Northbound
9	ATR 32-ID	May 1, 2016- May 7, 2016	I	168	12,406	3,629	65	Southbound
10	ATR 92- ID	May 1, 2016- May 7, 2016	I	168	20,885	5,260	65	Southbound
11	ATR 147-ID	September 12, 2015- September 20, 2015	II	216	8,727	1582	50	Northbound
12	ATR 126-ID	September 12, 2015- September 20, 2015	III	216	33,300	6391	45	Southbound
13	Site 2-OR	July 9, 2015- July 12 2015	I	96	21,932	3900	55	Southbound
14	Site 13-OR	June 4, 2015- June 7, 2015	I	96	12,596	2700	55	Southbound
15	Site 17-OR	June 11 2015- June 14, 2015	I	96	26,757	5100	55	Southbound

¹ Per current classification definitions of the HCM² Data from respective DOT's websites

Study Results

Investigation of following status on two-lane highways was accomplished using three different analyses. In the first analysis, speeds and headways on two-lane highways were examined graphically in an attempt to identify the range of headways where car-following interactions are expected. This analysis is based on the fact that car-following interactions on two-lane highways often involve adjustment of speed of following vehicles.

The second analysis in this investigation involves examination of the minimum safe headway using vehicle speed and headway data. Specifically, it was assumed that at minimum safe headway, the speeds of the lead and following vehicles should be approximately the same. The third analysis in this investigation involves developing a procedure for determining the headway cut-off value used in estimating percent followers; that is, identifying the percentage of vehicles in car-following mode. The proposed procedure is based on the car-following process described earlier and the assumption that the percent followers are directly proportional to the reduction in average speed from that of free-flowing vehicles.

Headway Speed Investigation

As car-following interaction between successive vehicles on the same lane is usually reflected in speed adjustments, speed data were used in examining the car-following parameters on two-lane highways, particularly the critical headway range and boundary values.

Figure 24 shows the average speed for vehicles traveling with different headways at six selected study sites for headway values up to 12 seconds. The general trend exhibited at all study sites affirms that average speed tends to be lower at low headway values (mostly below two seconds, with the exception of site ATR 92 where average speed remains low up to 3 seconds), increases steadily afterwards until headways reach some value that generally fall in the range of 5 to 7 seconds, beyond which average speed would level out reflecting the average speed of free-moving vehicles. However, site-specific trends are

slightly inconsistent and fluctuate at times, something expected given the stochastic nature of speed observations.

To gain a better insight into the relationship between headways and speeds, average speed was calculated for headways equal to or greater than a certain headway (h) and plotted at the same selected sites using the same data for headways up to 12 seconds. The results are shown in Figure 25. This figure shows more consistent patterns that are largely similar at the six study sites. For the majority of the sites, average speed starts to increase when the headway exceeds 2 seconds, then continues to increase steadily until it starts to flatten out when headway reaches a value around 6 seconds (with a couple of exceptions: ATR 32 at 5 seconds and ATR 92 at 7 seconds). The general shape of the relationship is an S curve, which is an expected pattern for this relationship.

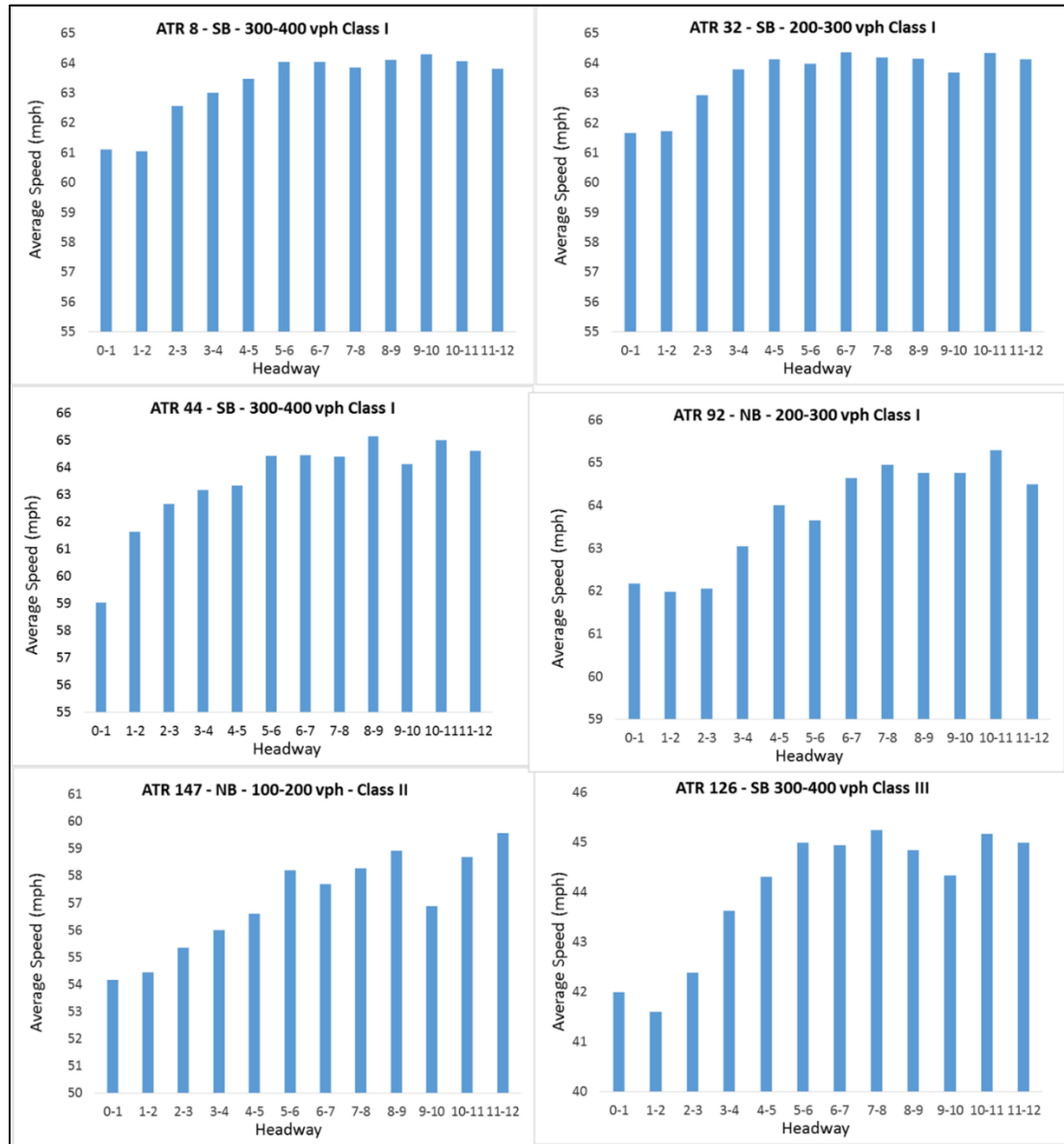


Figure 24. Headway speed relationship at selected study sites

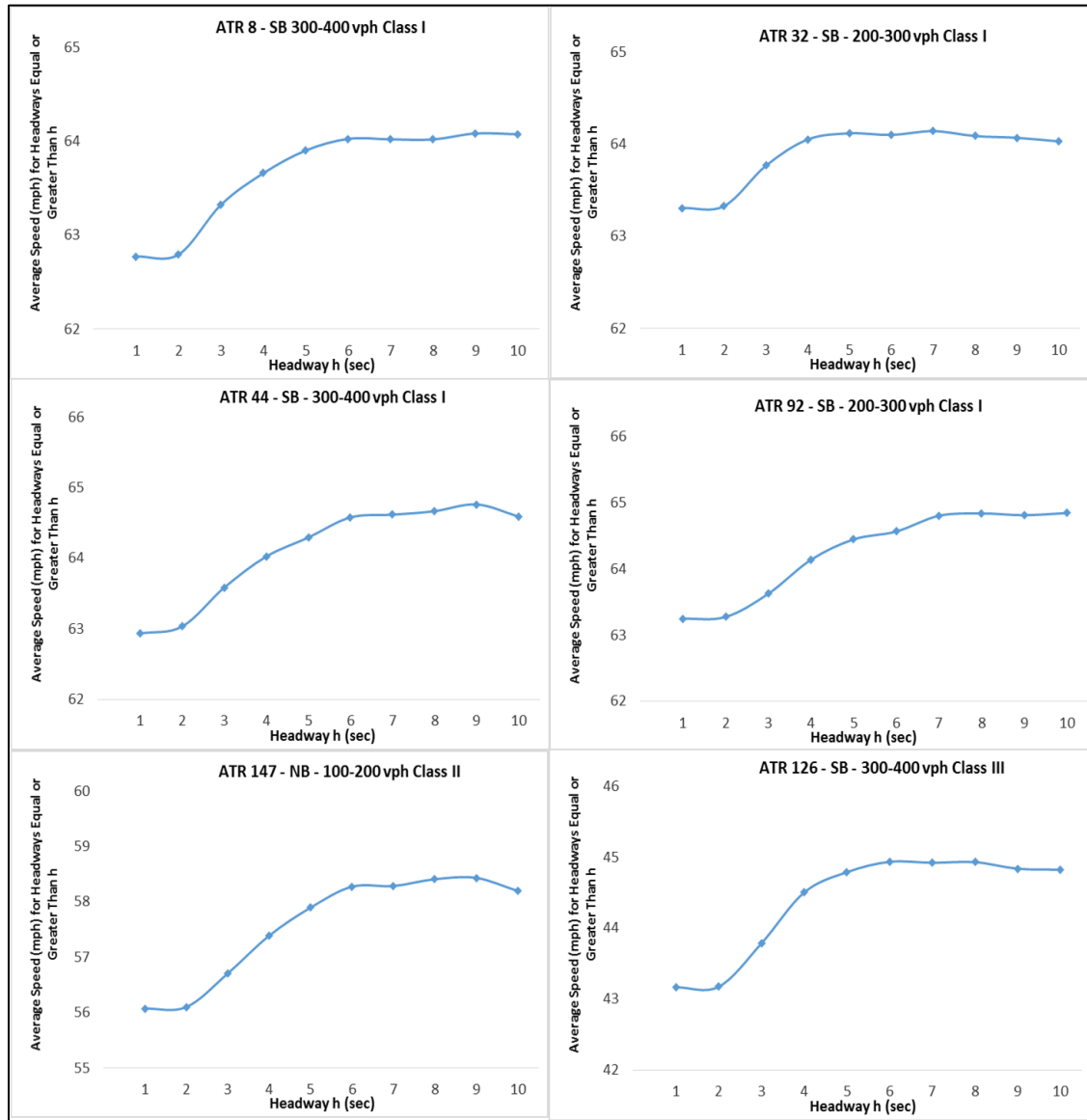


Figure 25. Average speed for headways equal or greater than h at selected study sites

Minimum Safe Headway Investigation

Another important aspect of the speed-headway investigation is to examine the percentage of headways for vehicles traveling at roughly the same speed. This was deemed to be directly related to the percentage of vehicles in following mode that are maintaining perceived minimum safe headways (h_{min}). To perform this investigation, the percentage of

headways with relative speed between the following and lead vehicles of up to ± 1 mi/h was determined for headways up to 12 seconds using 1-second intervals. Results of this analysis at site ATR 8 are shown in Table 15. This table shows a consistent pattern regarding pairs of vehicles traveling at the same speed in the traffic stream. Specifically, the table clearly shows that headways associated with “same speed” vehicles increase as relative speed increases and decrease with the increase in headway value.

Table 15. Percentage of Headways with Relative Speed between the Following and Lead Vehicles of up to ± 1 mi/h for ATR 8

Relative Speed (mph)	Headway (sec)										
	≤ 2	$>2-3$	$>3-4$	$>4-5$	$>5-6$	$>6-7$	$>7-8$	$>8-9$	$>9-10$	$>10-11$	$>11-12$
0	6.3%	3.9%	3.4%	2.8%	2.3%	1.8%	1.7%	2.2%	2.0%	1.9%	1.8%
≤ 0.2	9.3%	6.0%	4.7%	4.1%	3.1%	2.3%	2.2%	2.8%	2.7%	2.4%	2.5%
≤ 0.4	20.5%	14.9%	11.3%	10.2%	8.2%	6.4%	6.3%	7.2%	6.0%	7.2%	6.7%
≤ 0.6	25.6%	18.5%	14.4%	12.2%	9.6%	8.2%	7.5%	8.7%	7.5%	9.1%	8.0%
≤ 0.8	34.5%	25.0%	19.8%	16.9%	14.1%	11.8%	11.0%	12.3%	10.8%	13.2%	12.1%
≤ 1.0	40.6%	29.4%	23.1%	20.0%	16.9%	14.0%	14.1%	13.8%	12.5%	15.4%	14.6%

Accounting for inaccuracies in detector speed measurements and the minimal differences in speeds of following (platooned) vehicles, speeds of up to ± 1 mi/h was considered as “same speed” in this analysis. For headways less than two seconds, the percentage of headways with relative speed of ± 1 mi/h is more than 40%, which is relatively high given that each headway is associated with two vehicles in the traffic stream and therefore the percentage of “same speed” vehicles is expected to be higher than that of “same speed” headways (generally a function of platoon size). Other vehicles in this headway range with relative speeds greater than ± 1 mi/h might be in the process of performing a passing maneuver, have not yet reached the minimum safe headway, or are

simply just outside the cut-off value of ± 1 mi/h. It is important to note that even at headway values where free-flow conditions are believed to exist (e.g., headways greater than 10 seconds), a certain percentage of vehicles still travel at the same speed which is expected given the tendency of speed observations to concentrate around the mean value.

Figure 26 shows the percentage of headways with relative speeds of ± 1 mi/h for different headway values at three two-lane highway sites, ATR 8, ATR 32, and ATR 92. This figure shows a consistent trend in the change in percent of “same speed” headways with the increase in headway at the three study sites.

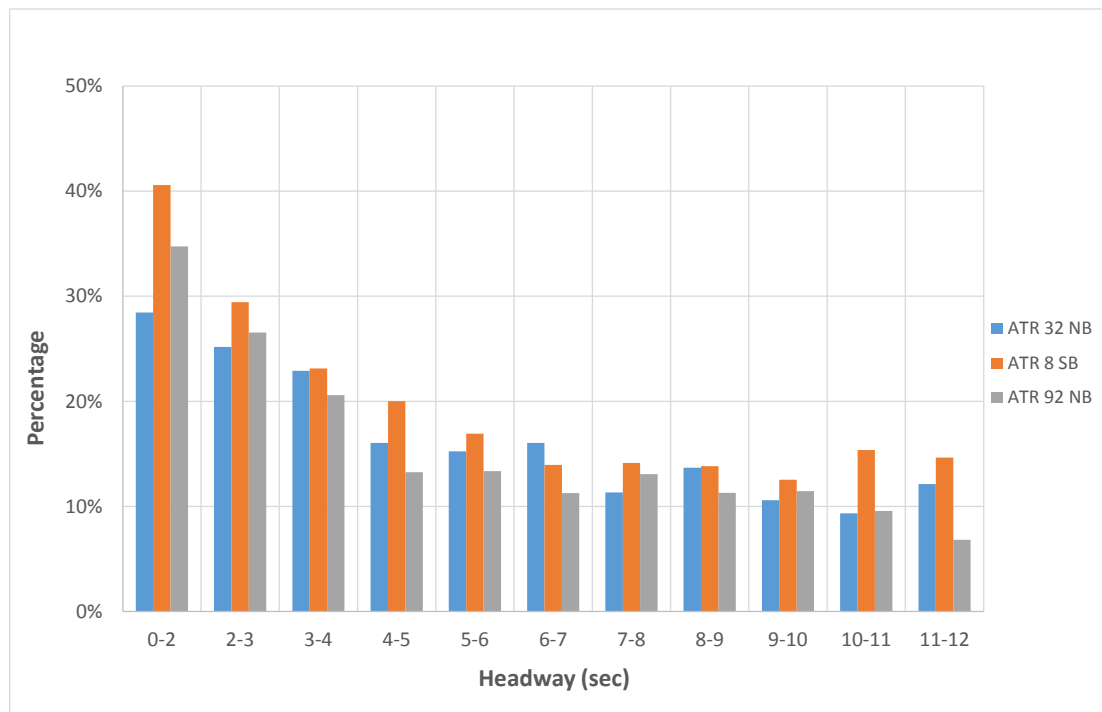


Figure 26. Percentage of headways with relative speeds of ± 1 mi/h for different headway values

Estimating Percent Followers Using Speed Data

In this research, the speed data were further analyzed in an attempt to achieve a better estimation of vehicles that are in car-following mode. This estimation is very important as it has been used in practice in determining percent followers, a surrogate measure for percent-time-spent-following, which is a major performance measure for two-lane highways.

The approach followed in this research is based on the premise that average speed and car following status are directly related. It was shown in the previous section that almost all vehicles with headways less than h_{agg} are in car following mode and almost all vehicles with headways greater than h_{con} are in free-flow mode. In the range between h_{agg} and h_{con} , some vehicles are in car-following mode while others are in free-flow mode. In this range, assuming that the percentage of following (platooned) vehicles is linearly proportional to the difference between average speed of following vehicles and that of the specific headway bin, the proportion of platooned (following vehicles) in each headway bin can be estimated. Knowing the frequency of headways in each bin, the number of followers can be estimated. Using a headway cut-off value for determining percent followers requires the number of following vehicles in the transition range (range between h_{agg} and h_{con}) to be equivalent to the number of all vehicles in the range with headways smaller than the cut-off value (Al-Kaisy et al. 2017).

The above proposed approach was applied to field data collected at the fifteen two-lane study sites. At each site, the speed-headway relationship is established along with the values of h_{agg} , h_{con} , average speed of following vehicles, and average speed of free-moving

vehicles. Using ATR 32 as an example, these values are 2 seconds, 6 seconds, 61.7 mi/h, and 64.1 mi/h, respectively as shown in Figure 27.

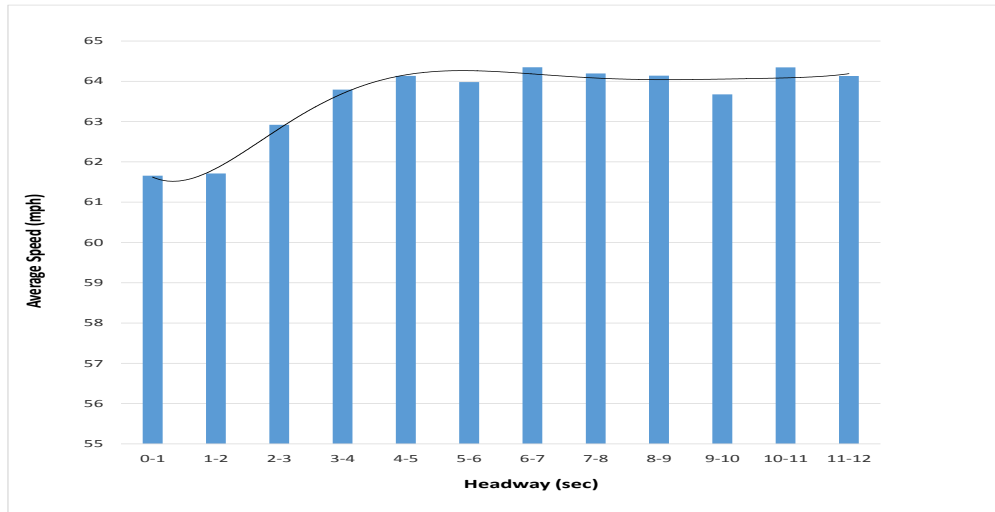


Figure 27. Speed headway curve at ATR 32

Assuming average speed in the transition range is directly proportional to percent followers, the frequencies of followers in this range can be determined, and calculations for ATR 32 are summarized in Table 16.

Table 16. Calculations for Estimating # of Followers in Transition Range at ATR 32

Headway Bin	Frequency	Cumulative Frequency	Cumulative Frequency (Transition Range)	Following Probability	Follower Frequency (Transition Range)
0.0 - 0.5	0	0	-	1.000	-
0.5 - 1.0	28	28	-	1.000	-
1.0 - 1.5	67	95	-	1.000	-
1.5 - 2.0	95	190	-	1.000	-
2.0 - 2.5	70	260	70	0.500	35.000
2.5 - 3.0	58	318	128	0.500	29.000
3.0 - 3.5	38	356	166	0.145	5.510
3.5 - 4.0	25	381	191	0.145	3.625
4.0 - 4.5	22	403	213	0.000	0.000
4.5 - 5.0	16	419	229	0.000	0.000
5.0 - 5.5	14	433	243	0.000	0.000
5.5 - 6.0	13	446	256	0.000	0.000
Total					73.14

Establishing the headway cumulative frequency diagram in the transition range and entering the chart with the total number of followers in transition range found in the last column of Table 16 results in a headway cut-off value for calculating percent followers at this site (see Figure 28 below).

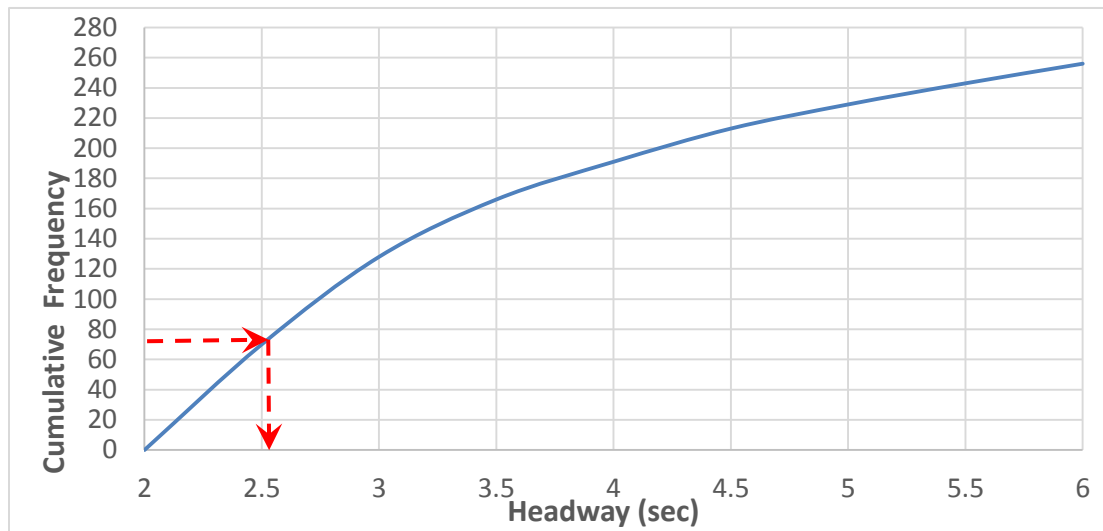


Figure 28. Determining % followers headway cut-off value using cumulative frequency diagram for headways in transition range

The approach described above was applied to all fifteen study sites and the results are summarized in Table 17. For class I highways, the estimated headway cut-off for percent followers varied between 1.8 and 2.8 seconds with the exception of ATR 92 where the cut-off value is much higher (3.845 seconds). Examining the transition range at this site and the relationships shown in Figure 24 reveals that average speed remained insensitive to headway up to 3 seconds, something unexpected and atypical on rural two-lane highways. For class II and class III sites, the cut-off values were all slightly above 3 seconds. Average operating speeds at those sites are generally lower than those at class I

sites, which may be related to car following headway parameters being different from those sites on higher speed class I facilities.

Table 17. Headway Cut-off Value for Calculating Percent Followers

Study Site	Highway Class	Traffic Flow (veh/h)	Transition Range (s)	Headway Cut-Off (s)
ATR 8 - MT	Class I	300-400	2 - 6	2.785
ATR 43 - MT	Class I	300-400	1 - 5	2.748
ATR 107 - MT	Class I	300-400	1 - 7	2.745
ATR 130 - MT	Class I	200-300	1 - 7	2.747
ATR 32 - ID	Class I	200-300	2 - 6	2.527
ATR 44 - ID	Class I	300-400	1 - 6	1.985
ATR 92 - ID	Class I	200-300	3 - 7	3.849
ATR 47 - ID	Class I	400-500	1 - 7	2.195
2A - OR	Class I	200-300	1 - 6	1.829
13A - OR	Class I	100-200	1 - 7	2.103
17A - OR	Class I	400-500	1 - 7	1.873
ATR 28 - MT	Class II	200-300	1 - 7	3.127
ATR 147 - ID	Class II	100-200	1 - 7	3.063
ATR 73 - MT	Class III	300-400	1 - 6	3.114
ATR 126 - ID	Class III	300-400	2 - 6	3.227
Average	-	-	-	2.66

As the results show, the average headway cut-off for all investigated sites is 2.66 seconds which is lower than the 3 seconds value suggested by the HCM (HCM 2016) for finding the percentage of vehicles in the following mode.

CHAPTER SIX

PASSING LANES INVESTIGATION

Contribution of Authors and Co-Authors

Manuscripts in Chapter 6

Author: Amirhossein Jafari

Contributions: Draft manuscript preparation

Co-Author: Ahmed Al-Kaisy

Contributions: Draft manuscript preparation

Co-Author: Scott Washburn

Contributions: Review the draft

Manuscript Information

Amirhossein Jafari, Ahmed Al-Kaisy, Scott Washburn

Status of Manuscript:

☐ Prepared for submission to a peer-reviewed journal

☒ Officially submitted to a peer-reviewed journal

☐ Accepted by a peer-reviewed journal

☐ Published in a peer-reviewed journal

CHAPTER SIX

PASSING LANES INVESTIGATION

Introduction

High volume of traffic on a highway network causes congestion, unpleasant delays to drivers, and contributes to air pollution. As the traffic volume on two-lane highways increases, highway agencies are looking for alternatives to accommodate traffic on such highways. Traditionally, they turn a two-lane highway into a four lane highway when certain criteria are met. For instance, when the peak hour volume on the highway exceeds a predefined amount, some highway agencies expand the two-lane to four lanes to improve the level of service. However, the high costs of road constructions would justify using other alternatives such as the use of turnouts and passing lanes (Harwood and Hoban 1987). A lane is added to one or both directions of travel to increase the passing opportunities. Providing a passing lane on a two-lane highway can improve the operational performance and level of service. Passing lanes on steep upgrades are also referred to as climbing lanes. On a passing lane, the slow moving vehicles will move over letting the vehicles behind pass. Figure 29 shows a typical isolated passing lane.

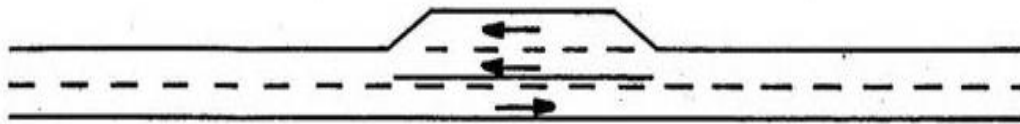


Figure 29. Typical Passing Lane (Isolated)

The current guidelines in the HCM (2016) regarding the optimum and effective length of passing lanes are very limited and based on studies conducted more than three decades ago (Harwood and St. John 1985, 1986). Optimum length has been used to refer to the length that would bring the most operational benefits given the amount of passing lane investments while effective length is defined as the length of two-lane highway over which the effect of a passing lane extends. From a practical perspective, it is critical to know how long and often these passing lanes should be provided to ensure the best use of highway improvement funds. Unfortunately, the HCM provides no guidance on the proper configuration of passing lanes, i.e. the most effective combinations of passing lane length and spacing.

This chapter investigates the optimum and effective length of passing lanes on two-lane highways. Moreover, it examines the operational efficiency of different passing lane design configurations in order to identify the most appropriate length and spacing to be used in the planning and design of passing lanes. The chapter is organized as follows: First, the effective length of passing lanes is discussed. Then, passing lanes optimum length is presented. Finally, different configurations of passing lanes are examined and design guidelines are presented.

Effective Length of Passing Lanes

The Highway Capacity Manual (HCM) (HCM 2016) suggests that the operational improvement of a passing lane typically extends for some distance downstream of the passing lane, and is referred to as the “Effective Length”. Specifically, effective length is

the distance from the start of a passing lane to a point downstream where the performance returns to its original value, i.e. immediately upstream of the start of the passing lane. Figure 30 illustrates conceptually how a passing lane affects operational conditions, in this case with respect to the Percent Time Spent Following (PTSF), the primary performance measure used by the HCM for two-lane highways. The PTSF is defined as the “average percentage of total travel time that vehicles must travel in platoons behind slower vehicles due to the inability to pass” (HCM 2016).

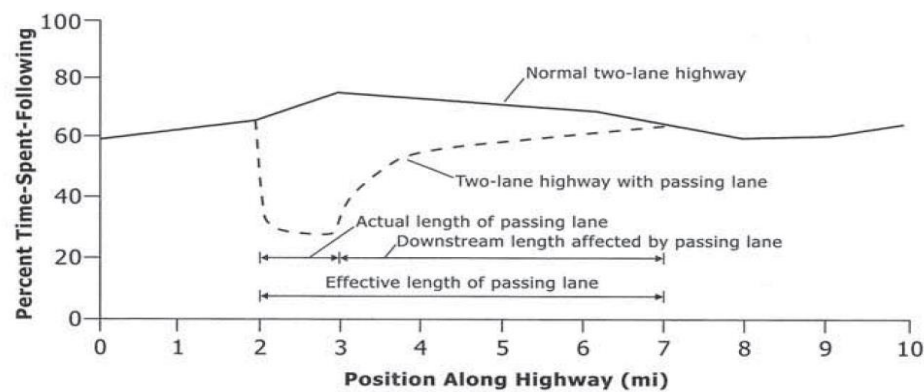


Figure 30. Operational effect of a passing lane on performance (HCM 2016)

As the current HCM guidance on the effective length of passing lanes is based on a study that was conducted more than three decades ago (Harwood and St. John 1985), it was deemed important to develop updated information on this important aspect of passing lane planning and design using recent field data and new analytical tools.

This section aims to investigate the operational effects of passing lanes on two-lane highway performance. The current state of knowledge regarding the effective length of passing lanes (including the HCM guidance) is limited as it involves only a few older

studies that were conducted in the 1980's and 1990's, with the exception of the limited empirical investigation performed by Al-Kaisy and Freedman (2010) and Potts and Harwood (2004). The knowledge gained from this study is valuable for the planning and design of passing lanes on two-lane highways.

Research Approach

Overview. As it was impractical to gather field data from passing lane sites that would cover the desired ranges of traffic and geometric conditions, this study utilized microscopic traffic simulation in developing the passing lane effective length values. However, the current study did utilize field data from two study sites in the state of Oregon as it was deemed vital in calibrating and validating the simulation model. Upon calibrating and validating the simulation model, an experimental design was developed to perform a sensitivity analysis to examine the effect of the two study variables, traffic flow rate and percent no-passing, on the effective length of a passing lane. For each scenario in these experiments, the average performance measure value from 30 simulation runs were used to satisfy the sample size requirements at the 95% confidence level. A constant percent of heavy vehicles (15%) and traffic directional split (55% in analysis direction) were used throughout the analysis. The effective length of a passing lane was found when the platooning level, as defined by follower density, downstream of the passing lane reaches some maximum value beyond which it remains roughly the same. Follower density is defined as the density multiplied by percent followers. Percent followers was found in this research as the percentage of vehicles with headways of 2.5 seconds or less. This headway value was used based on the findings from a study by Al-Kaisy et al. (Al-Kaisy et al. 2017).

In simulation experiments, follower density was measured just upstream of the passing lane as well as at several detector locations downstream of the passing lane placed at periodic intervals. It is important to note that the possible effect of other variables such as grade, vehicle mix, etc. were beyond the scope of the current study.

Swashsim Simulation Program

At the time of this study, very few traffic simulation programs were capable of modeling two-lane highways. This study used a recently developed microscopic simulation software program, called SwashSim that has extensive capabilities for modeling traffic operations on two-lane two-way highways (Washburn 2017). It was developed as part of the NCHRP 17-65 project which aims at developing an improved operational methodology for two-lane two-way highways. There are several steps required to model a two-lane highway network in SwashSim, as follows.

a. Specifying the Roadway Geometry

The first step in modeling the network is creating the roadway geometry. For each link, different inputs including the length, orientation angle, free flow speed and grade are required. Moreover, passing lanes in one or both directions can be modeled. Detectors can be placed on each segment to measure specific items such as speed, headway, and type of vehicles. Figure 31 shows the main network specification screen.

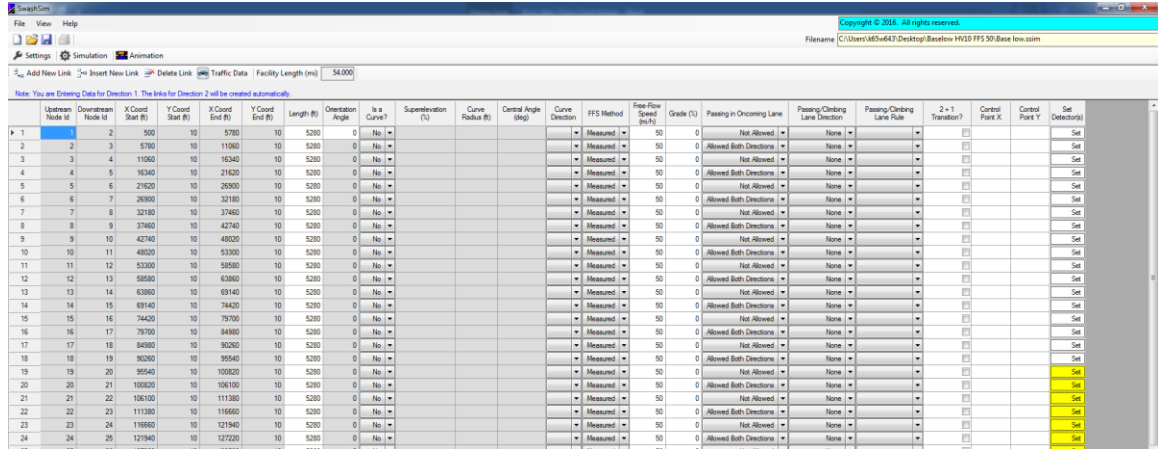


Figure 31. Main network specification screen

b. Traffic Input Variables

Traffic volumes are assigned on the entry link inputs screen. The hourly demand volume along with the percentage of each vehicle type in each direction are assigned in this step. Moreover, there are two types of vehicle arrival distributions, including uniform and random that can be assigned. SwashSim uses 14 types of vehicles to model the traffic stream. Table 18 shows the different types of vehicles modeled in the software as well as their equivalent classification by the FHWA.

Table 18. SwashSim Vehicle Classification

Type of vehicle	SwashSim Classification	FHWA Classification
Passenger Cars	1,2,3,6,8,9,10	2
Pickups, Panels, Vans	4,5,7	3
Single Unit 2-Axle Trucks	11	5
Single Trailer 3- or 4-Axle Trucks	12	8
Single Trailer 5-Axle Trucks	13	9
Multi-Trailer 6-Axle Trucks	14	12

c. Simulation Control Panel

Four random number seeds are used to affect the random numbers in the simulation program. The first number is related to the vehicle generation. The second one is for vehicle type generation. The third one applies to the driver type generation and the last, is related to the other randomly generated inputs. The seed numbers can be generated manually or automatically by the software. There is a warm-up time field which dictates how long the software will run before the outputs are collected. The simulation duration time field is used to identify the simulation time after warm up time. The software is capable of single as well as multiple simulations. The software can provide various output measures, including the detector vehicle records and link performance measure data. The link performance measure output includes the percent followers, follower density, and average speed for each link. This was the primary output used in this study. Figure 32 shows the animation screen of the SwashSim.

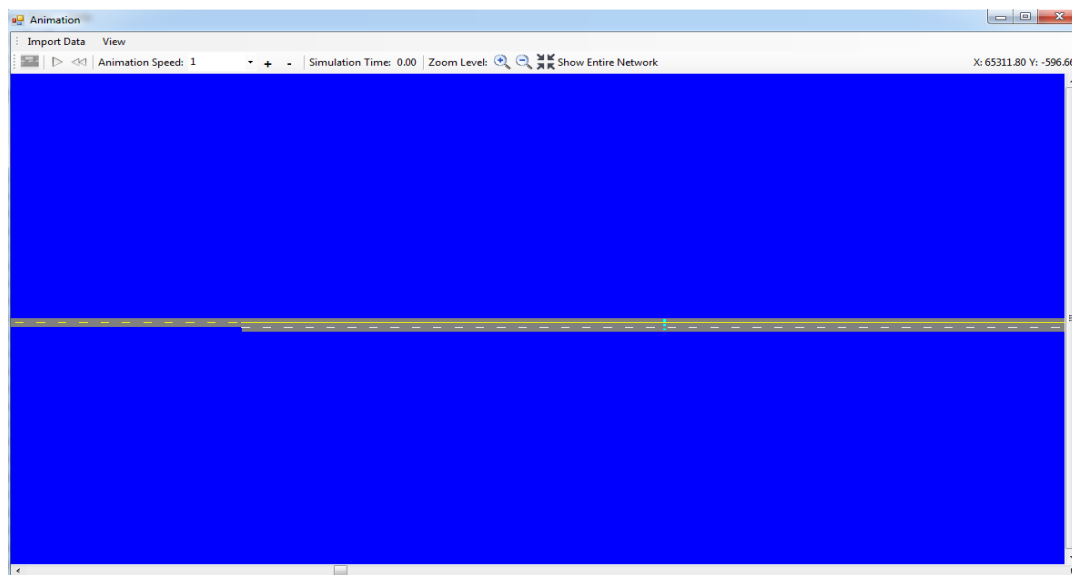


Figure 32. Animation screen of simulated model

Field Data. SwashSim was calibrated and validated using field data from two study sites in the state of Oregon, as listed in Table 19. Data were collected at one detector location upstream, as well as several detector locations downstream, of the passing lane using automatic traffic recorders (ATRs). Traffic volume, area setting, terrain type and number of access points were among the considerations for selecting study sites. The data were collected and provided by the Oregon Department of Transportation (ODOT).

Table 19. Description of Study Sites

Site Number	Site Name	Data Collection Dates	Length of Passing Lane (mi)	Duration of Data Collection (hours)	Annual Average Daily Traffic (2014) (veh/day)	Speed Limit (mi/h)	Direction of Analysis
1	Oregon 2	July 9, 2015-July 12 2015	2.2	96	3900	55	South-bound
2	Oregon 17	June 11 2015-June 14, 2015	1.6	96	4900	55	South-bound

A schematic of study locations is shown in Figure 33.

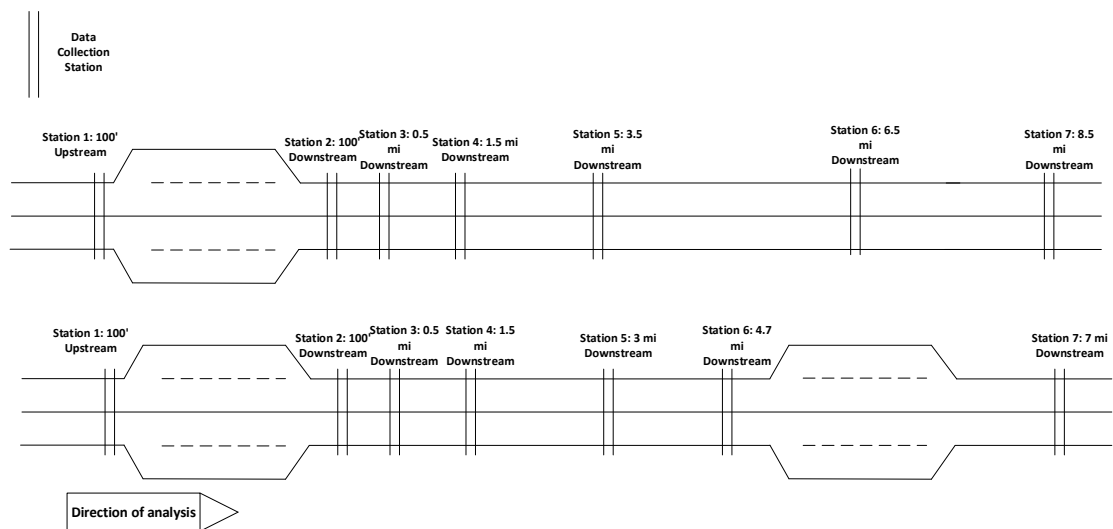


Figure 33. Data collection set up OR 2 (top), OR 17 (bottom)

Simulation Calibration Process and Results. Performance measures were analyzed from the field data for various traffic flow levels (100-150, 150-200, 200-250, and 250-300 veh/h) at different detector locations for each study site. Data were aggregated over a 1-hour period at each detector location and all volumes within each flow range were averaged. Performance measures used in the calibration and validation of SwashSim included:

- Percent Followers (*PF*): Percentage of vehicles with headways ≤ 2.5 seconds.
- Follower Density (*FD*): The number of vehicles with headways ≤ 2.5 seconds per mile per direction of travel. It is calculated as the product of *PF* and traffic density.
- Average Travel Speed (*ATS*): Average speed of all vehicles traveling in one direction.

Figure 34 shows the results of field data analysis for the two sites (OR 2 and OR 17) where percent followers significantly decreases downstream of the passing lane before it starts to increase again with the formation of platoons as traffic progresses further downstream. The trends for follower density look very similar to those of *PF* due to the fact that traffic flow rate observed at successive detector stations does not vary much. *ATS* generally varies in a very narrow range, and unlike headways, can easily be affected by sight distance or cross section elements, and hence the less consistent patterns shown at the two study sites.

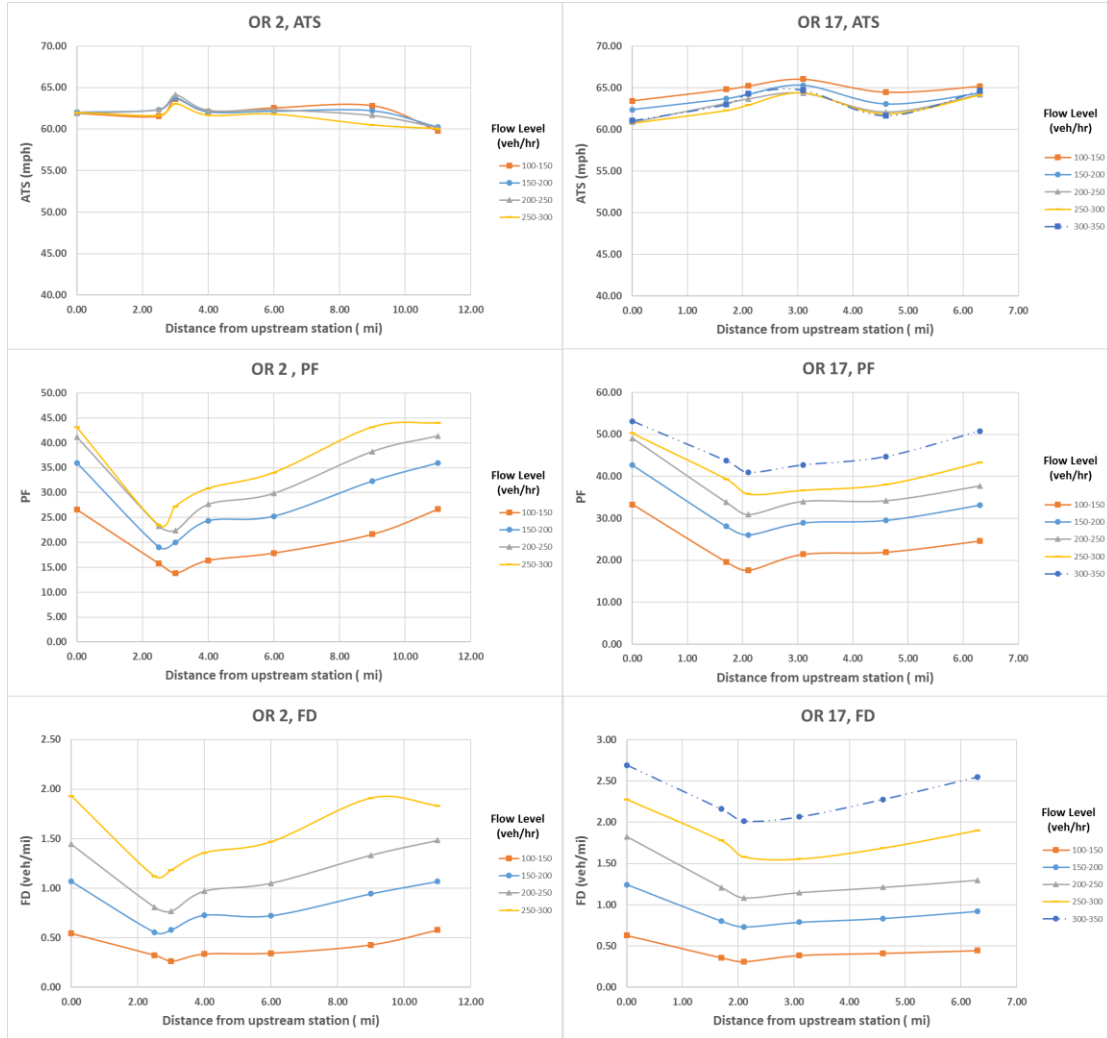


Figure 34. Performance measures along study sites

Table 20 and Table 21 show the results of the calculated performance measures at different detector locations for sites OR 2 & 17, respectively.

Table 20. Performance Measures at Different Study Stations (OR 2)

Station	ATS (mi/h)	PF	FD (veh/mi)
Flow Rate (100-150 veh/h)			
Upstream	61.89	26.64	0.54
Downstream	61.56	15.76	0.32
0.50 mi	63.61	13.81	0.26
1.50 mi	62.09	16.39	0.34
3.50 mi	62.55	17.87	0.34
6.50 mi	62.82	21.65	0.43
8.50 mi	59.78	26.69	0.58
Flow Rate (150-200 veh/h)			
Upstream	62.04	35.95	1.07
Downstream	62.34	19.04	0.56
0.50 mi	63.76	20.00	0.58
1.50 mi	62.10	24.32	0.73
3.50 mi	62.17	25.24	0.72
6.50 mi	62.23	32.28	0.94
8.50 mi	60.25	35.92	1.07
Flow Rate (200-250 veh/h)			
Upstream	61.91	41.17	1.44
Downstream	62.40	23.30	0.81
0.50 mi	64.13	22.39	0.77
1.50 mi	62.28	27.64	0.97
3.50 mi	62.34	29.87	1.05
6.50 mi	61.65	38.25	1.33
8.50 mi	60.19	41.39	1.48
Flow Rate (250-300 veh/h)			
Upstream	62.00	43.08	1.93
Downstream	61.64	23.47	1.12
0.50 mi	63.03	27.24	1.18
1.50 mi	61.65	30.84	1.36
3.50 mi	61.78	34.02	1.47
6.50 mi	60.49	43.14	1.91
8.50 mi	60.03	44.00	1.83

Table 21. Performance Measures at Different Study Stations (OR 17)

Station	ATS (mi/h)	PF	FD (veh/mi)
Flow Rate (100-150 veh/h)			
Upstream	63.44	33.29	0.63
Downstream	64.80	19.63	0.36
0.50 mi	65.21	17.63	0.31
1.50 mi	66.05	21.42	0.39
3.00 mi	64.47	21.93	0.41
4.70 mi	65.18	24.58	0.45
7.00 mi	65.37	19.01	0.36
Flow Rate (150-200 veh/h)			
Upstream	62.35	42.70	1.24
Downstream	63.69	28.07	0.81
0.50 mi	64.20	26.02	0.74
1.50 mi	65.31	28.90	0.79
3.00 mi	63.04	29.50	0.84
4.70 mi	64.36	33.13	0.92
7.00 mi	65.15	23.85	0.63
Flow Rate (200-250 veh/h)			
Upstream	60.85	49.06	1.83
Downstream	63.13	33.80	1.21
0.50 mi	63.65	30.86	1.08
1.50 mi	64.34	34.01	1.15
3.00 mi	62.08	34.17	1.21
4.70 mi	64.17	37.69	1.30
7.00 mi	64.45	29.27	1.01
Flow Rate (250-300 veh/h)			
Upstream	60.74	50.27	2.28
Downstream	62.27	39.37	1.78
0.50 mi	62.92	35.77	1.58
1.50 mi	64.40	36.69	1.56
3.00 mi	61.87	38.07	1.69
4.70 mi	64.14	43.30	1.90
7.00 mi	63.93	33.12	1.43
Flow Rate (300-350 veh/h)			
Upstream	61.05	53.12	2.69
Downstream	62.98	43.71	2.16
0.50 mi	64.28	40.96	2.02
1.50 mi	64.70	42.75	2.07
3.00 mi	61.66	44.73	2.28
4.70 mi	64.66	50.82	2.55
7.00 mi	64.46	38.53	1.85

For the calibration of the simulation tool, several outputs from the SwashSim were compared to the field data counterparts. Those outputs include: percent followers, follower density, and average travel speed.

SwashSim defines 10 types of drivers. Type 1 corresponds to the most conservative driver, while type 10 corresponds to the most aggressive driver. Thus, the level of aggressiveness will increase by the driver type index. The calibration process was conducted by changing the driver parameters summarized below.

- Headway Multiplier: This value is used to calculate the driver's desired headway. The desired headway is the product of this value and a base desired headway defined in the software.
- Desired Speed Multiplier: This value is used to calculate the driver's desired speed. The desired speed is the product of this value and link free-flow speed.
- Percentage of each driver type: The default condition is that the percentage of driver types in the traffic stream is approximately normally distributed.

Satellite imagery and GIS data were used to code the roadway network in SwashSim. Flow rates between 200-250, 250-300, and 300-350 veh/h were used in calibrating the simulation model. Specifically, two flow rate levels, 200-250 veh/h and 250-300 veh/h, were used for site OR 2 and three flow rate levels, 200-250 veh/h, 250-300 veh/h, and 300-350 veh/h were used for site OR 17. It was not possible to use higher flow rates as traffic levels at the two study sites were relatively low. In order to perform the calibration, the calibration parameters in SwashSim were repeatedly revised in a systematic way with the objective of minimizing the discrepancy between the simulation output and

field observations. Percent followers was the primary performance measure used for this purpose as it closely corresponds to headway distribution and platooning levels. While follower density is highly correlated to percent followers, it is also influenced by traffic flow rate which could be slightly different in simulation compared to field data. Table 22 shows the simulation outputs for the calibrated model along with percentage difference between simulation and field measurements. Percentage values higher than 10 are marked in red. As can be seen, while the percent difference in PF at any particular station may exceed 16%, the average discrepancy at all detector stations for various traffic levels at the two study sites are well below 10%. Results for other performance measures are also provided in this Table for comparison purposes. Overall, the average discrepancy for other performance measures is as favorable if not better than that of PF.

The calibrated model was validated using other sets of field data to make sure that the model is capable of reasonably replicating field performance at the two study sites. Field data corresponding to flow levels 100-150 veh/h and 150-200 veh/h were used for this purpose. Table 23 presents validation results which include simulation outputs as well as the percent discrepancy from field measurements. In regards to the primary performance measure, *PF*, the highest discrepancy at any individual detector station is around 14%, while the average discrepancy for all detector stations at each study site and traffic level reached 11.5% at only one site and traffic level. Overall, the discrepancies of *PF* and other performance measures from field measurements are very comparable to those exhibited during the calibration process.

Table 22. Traffic Simulation Output and Deviations from Field Measurements (Calibration)

Site OR 2								
Station	Flow Rate	ATS	PF	FD	% difference Flow Rate	% difference ATS	% difference PF	% difference FD
Flow Rate (200-250 veh/h)								
Upstream	215.73	62.81	36.54	1.26	-0.50%	1.50%	-11.30%*	-12.70%
Downstream	215.33	63.64	21.38	0.73	-0.10%	2.00%	-8.30%	-9.90%
0.5	212.70	64.10	22.55	0.75	-3.00%	0.00%	0.70%	-2.00%
1.5	213.70	63.84	25.64	0.86	-2.30%	2.50%	-7.20%	-11.20%
3.5	214.93	63.45	30.75	1.04	-1.80%	1.80%	2.90%	-0.50%
6.5	215.07	62.84	36.80	1.26	0.30%	1.90%	-3.80%	-5.30%
8.5	216.00	62.51	40.08	1.39	0.30%	3.90%	-3.20%	-6.40%
Average					1.17%	1.94%	5.34%	6.88%
Flow Rate (250-300 veh/h)								
Upstream	267.60	62.39	43.57	1.88	-2.90%	0.60%	1.10%	-2.70%
Downstream	267.37	63.37	25.60	1.08	-9.10%	2.80%	9.10%	-3.20%
0.5	262.73	63.97	26.71	1.10	-4.30%	1.50%	-1.90%	-6.90%
1.5	263.90	63.75	29.91	1.25	-2.70%	3.40%	-3.00%	-8.30%
3.5	264.90	63.06	36.24	1.53	-0.80%	2.10%	6.50%	4.10%
6.5	264.83	62.41	42.99	1.83	-0.50%	3.20%	-0.30%	-4.10%
8.5	263.07	62.03	46.47	1.98	5.20%	3.30%	5.60%	7.90%
Average					3.66%	2.42%	3.95%	5.31%
Site OR 17								
Flow Rate (200-250 veh/h)								
Upstream	221.50	61.97	50.62	1.81	-1.90%	1.80%	3.20%	-0.70%
Downstream	220.90	62.40	31.61	1.12	-2.30%	-1.20%	-6.50%	-7.10%
0.5	218.73	63.24	32.30	1.12	-2.40%	-0.70%	4.60%	3.60%
1.5	219.13	62.99	34.54	1.21	1.60%	-2.10%	1.60%	5.20%
3.0	220.10	62.67	38.40	1.35	0.50%	0.90%	12.40%	11.70%
4.7	220.80	62.03	44.03	1.57	0.20%	-3.30%	16.80%	21.20%
7.0	218.90	63.17	29.84	1.04	-0.80%	-2.00%	2.00%	3.30%
Average					1.36%	1.72%	6.71%	7.54%
Flow Rate (250-300 veh/h)								
Upstream	269.67	61.62	55.87	2.45	-1.50%	1.50%	11.10%	7.50%
Downstream	270.27	61.96	35.54	1.55	-3.60%	-0.50%	-9.70%	-12.80%
0.5	268.43	62.87	36.80	1.57	-3.60%	-0.10%	2.90%	-0.60%
1.5	268.83	62.62	39.66	1.70	-1.10%	-2.80%	8.10%	9.40%
3.0	271.97	62.17	43.79	1.92	-0.10%	0.50%	15.00%	13.60%
4.7	269.60	61.52	48.94	2.15	-3.90%	-4.10%	13.00%	12.90%
7.0	269.03	62.86	32.89	1.41	-1.40%	-1.70%	-0.70%	-1.00%
Average					2.17%	1.58%	8.66%	8.29%
Flow Rate (300-350 veh/h)								
Upstream	309.30	61.49	57.63	2.90	0.00%	0.70%	8.50%	7.70%
Downstream	308.77	61.62	37.00	1.86	-0.60%	-2.20%	-15.40%	-13.90%
0.5	304.57	62.70	38.10	1.86	-3.70%	-2.50%	-7.00%	-8.00%
1.5	307.47	62.43	40.78	2.02	-1.50%	-3.50%	-4.60%	-2.50%
3.0	310.33	61.94	45.21	2.27	-0.90%	0.50%	1.10%	-0.20%
4.7	309.23	61.34	50.26	2.54	-4.60%	-5.10%	-1.10%	-0.40%
7.0	306.67	62.64	34.66	1.70	-1.00%	-2.80%	-10.10%	-8.20%
Average					1.75%	2.47%	6.81%	5.85%

Table 23. Traffic Simulation Output and Deviations from Field Measurements (Validation)

Site OR 2								
Station	Flow Rate	ATS	PF	FD	% difference Flow Rate	% difference ATS	% difference PF	% difference FD
Flow Rate (100-150 veh/h)								
Upstream	124.77	63.94	23.87	0.47	-0.6%	3.3%	-10.4%	-13.4%
Downstream	125.57	64.35	13.54	0.27	0.5%	4.5%	-14.1%	-17.5%
0.5	125.07	64.59	13.82	0.27	4.0%	1.6%	0.1%	2.1%
1.5	125.53	64.46	16.07	0.31	0.1%	3.8%	-1.9%	-6.3%
3.5	124.97	64.26	19.05	0.37	4.8%	2.7%	6.6%	8.2%
6.5	123.97	64.03	22.66	0.44	1.7%	1.9%	4.7%	2.6%
8.5	123.43	63.82	25.43	0.49	-3.6%	6.8%	-4.7%	-14.5%
Average					2.19 %	3.52%	6.07%	9.22%
Flow Rate (150-200 veh/h)								
Upstream	178.1	63.06	31.69	0.90	-2.3%	1.7%	-11.9%	-15.7%
Downstream	177.93	63.80	16.96	0.48	-1.5%	2.3%	-10.9%	-14.1%
0.5	176.33	64.19	17.88	0.49	-3.8%	0.7%	-10.6%	-14.6%
1.5	177.53	64.00	20.84	0.58	-3.3%	3.1%	-14.3%	-19.9%
3.5	177	63.57	25.61	0.72	0.2%	2.2%	1.5%	-0.7%
6.5	178.3	63.15	30.80	0.87	-1.6%	1.5%	-4.6%	-7.6%
8.5	177.33	62.77	34.37	0.98	-1.4%	4.2%	-4.3%	-8.4%
Average					2.24%	8.30%	11.57%	10.35%
Site OR 17								
Station	Flow Rate	ATS	PF	FD	% difference Flow Rate	% difference ATS	% difference PF	% difference FD
Flow Rate (100-150 veh/h)								
Upstream	118.87	63.35	30.95	0.59	-0.6%	-0.1%	-7.0%	-6.8%
Downstream	119.1	63.93	18.03	0.34	0.6%	-1.3%	-8.2%	-6.1%
0.5	117.67	64.18	18.13	0.34	2.6%	-1.6%	2.9%	7.1%
1.5	118.4	64.05	19.32	0.36	0.3%	-3.0%	-9.8%	-7.4%
3.0	118.7	63.92	21.66	0.41	-1.7%	-0.8%	-1.2%	-1.9%
4.7	117.27	63.39	27.64	0.52	0.0%	-2.7%	12.4%	15.1%
7.0	117.4	64.10	18.72	0.35	-3.5%	-1.9%	-1.5%	-3.2%
Average					1.32 %	1.66%	6.15%	6.81%
Flow Rate (150-200 veh/h)								
Upstream	179.1	62.49	45.36	1.30	-0.4%	0.2%	6.2%	4.8%
Downstream	179.63	63.11	27.48	0.79	-1.1%	-0.9%	-2.1%	-2.3%
0.5	177.4	63.72	27.89	0.78	-1.0%	-0.7%	7.2%	6.0%
1.5	178.7	63.48	30.56	0.86	0.7%	-2.8%	5.8%	9.2%
3.0	179.5	63.10	34.43	0.98	0.5%	0.1%	16.7%	17.4%
4.7	180.23	62.60	39.26	1.13	1.2%	-2.7%	18.5%	22.7%
7.0	179.07	63.66	26.21	0.74	3.8%	-2.3%	9.9%	16.6%
Average					1.23%	1.40%	9.48%	11.29%

Simulation Experimental Design. In order to assess the impact of varying geometric and traffic conditions on passing lane effective length using simulation, it was necessary to perform a sensitivity analysis which incorporates the variables of interest. Two variables of interest were used in this analysis: traffic flow rate and percent no-passing. Traffic volume is directly related to platooning on two-lane highways and is believed to affect the effective length of passing lane. The rate of platoon formation is also affected by the Percent No-Passing (%NP), which is defined as the percentage of no-passing zones along a given length of highway. The fewer passing opportunities upstream of the passing lane, the higher the level of platooning entering the passing lane. Likewise, the fewer the passing opportunities downstream of the passing lane, the sooner the platooning level will return to its original level just prior to the start of the passing lane. For each variable, appropriate ranges and levels were selected considering typical ranges for directional traffic volumes and %NP in practice. Table 24 shows the ranges and levels selected for each variable. A default traffic directional split of 55/45 for the analysis direction and opposing direction, respectively, was used for all scenarios. Moreover, a fixed percentage of heavy vehicles (15%) was used in all scenarios. Due to the stochastic nature of simulations in SwashSim, 30 simulation runs with different random seed values were used for each scenario.

Table 24. Ranges and Levels for Study Variables

	Analysis Direction Flow Rate (veh/h)	Opposing Direction Flow Rate (veh/h)	Percent No-passing
Levels	200	164	0, 20, 40, 50, 60, 80, 100
	300	245	
	400	327	
	500	409	
	600	491	
	700	573	

	800	655	
	1100	900	
	1400	1145	
Ranges	200-1400	164-655	0-100

A straight, level segment of two-lane highway, including a passing lane of 1.5 miles was created in SwashSim. This length was chosen to represent a typical passing lane in practice. A combination of passing and no-passing segments with a length of 0.5 miles per segment were used. For a %NP of 0, passing is allowed along the entire length of the facility, while for a %NP of 100, passing is not allowed in any part. For a %NP of 20, passing is allowed in 4 out of 5 consecutive segments, and so on. The detectors were located in the middle of the segments. One detector was located upstream of the passing lane and multiple detectors were located downstream of the passing lane at 1-mile increments. For lower traffic flow levels, a longer network is required to reach steady state in the platooning level downstream of the passing lane. Here, steady state refers to the condition where the performance measure becomes nearly constant. Therefore, for low traffic flow levels, detectors were installed for a distance of approximately 32 miles downstream of the passing lane, while for higher traffic flow levels, detectors were installed for a distance of approximately 23 miles downstream of the passing lane. The performance measure selected for determining the effective length is follower density, as it accounts for both the percentage of short headways and traffic level. The outputs from the multiple runs were averaged at each detector location.

Passing Lane Effective Length Results

Figure 35 shows follower density as it changes along the passing lane network described earlier for the 50% no-passing scenario. The general trend exhibited in this Figure is that follower density decreases significantly just downstream of the start of the passing lane before it starts to increase again as traffic progresses along farther downstream of the start of the passing lane. The latter increase in *FD* is most significant beyond the third detector station (approximately a mile from the end of the passing lane) and then *FD* increases slightly the farther traffic moves away from the passing lane until it eventually becomes more or less constant. Per the study approach, the point at which follower density becomes essentially constant designates the end of passing lane effective length.

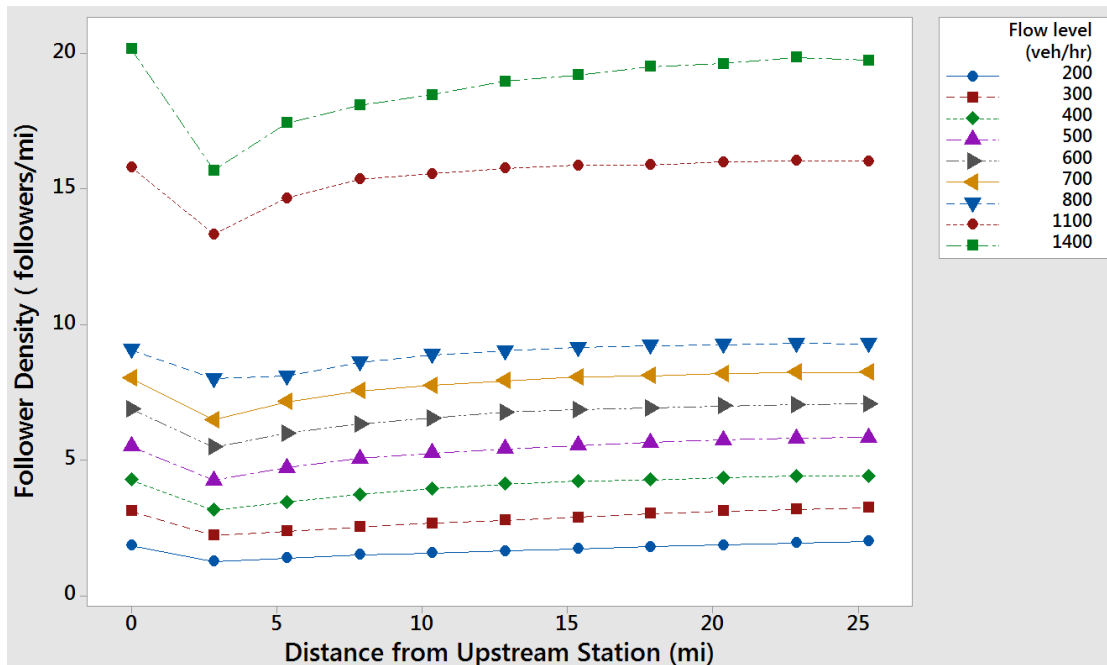


Figure 35. Follower density along the highway (%NP = 50)

To account for the stochastic nature of the simulation outputs and to address changes in values that are too small to have a meaningful effect on performance, the following method was used in this study to determine the start of the flat portion of the curve; that is, the end of the passing lane effective length:

- the percentage difference in FD between successive detector locations was found,
- a 5-point moving average (average of the point of interest, two points upstream and two points downstream) of the percentage difference was used to dampen the fluctuations due to randomness in the simulation process (see Figure 36),
- the 5-point moving average curve for each flow level was fitted using an exponential function, which was found to best represent the trends shown in Figure 36, and
- a cut-off value was selected for demarking the end of the passing lane effective length.

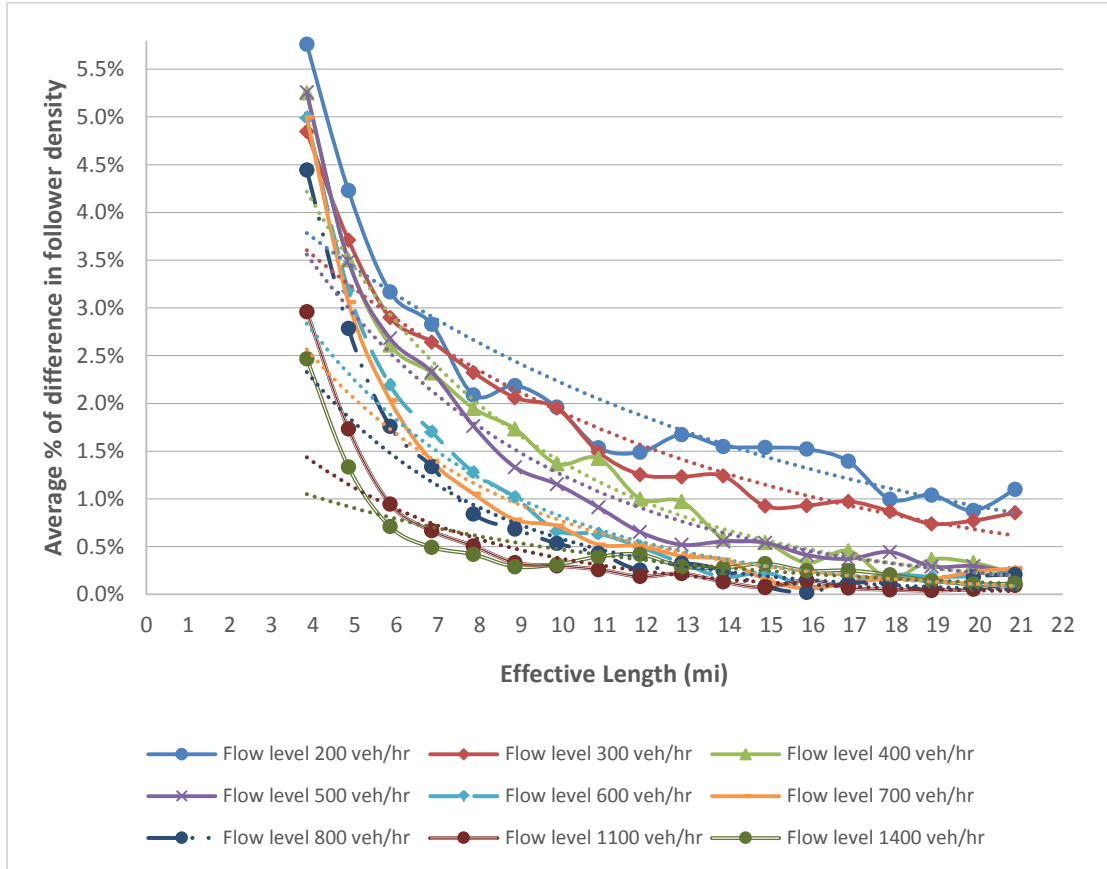


Figure 36. Effective length calculation using empirical method (% NP = 50)

Using the aforementioned method, the effective length for various traffic flow levels, percent no-passing, and three different cut-off values (i.e. 1, 1.5, and 2 %) was identified and the results are summarized in Table 25.

Table 25. Effective Length of Passing Lane Using Empirical Method (miles)

Percent No-Passing (%NP)	Directional Demand Flow Rate (veh/h)								
	200	300	400	500	600	700	800	1100	1400
Cut-off value=1%									
0	27.5	20.1	16.2	14.8	11.9	11.1	9.7	4.8	4.6
20	29.8	19.9	15.9	14.3	12.1	10.6	9.5	4.5	4.1
40	25.1	16.5	14.8	13.6	11.3	10.4	9.6	4.8	4.5
50	24.1	18.3	14.4	13.7	11.5	10.6	9.7	4.5	4.3
60	23.2	15.9	13.8	13.1	11.1	10.1	9.4	4.4	3.9
80	22.2	15.4	13.3	13.0	10.4	9.5	8.6	4.3	4.2
100	18.4	14.5	11.8	11.3	9.0	8.6	7.6	4.1	3.8
Cut-off value=1.5%									
0	19.8	14.5	12.5	11.2	9.2	8.5	7.8	3.8	3.4
20	20.1	14.7	12.4	11	9.2	8.3	7.9	3.7	2.8
40	17.6	12.9	11.6	10.3	8.5	8.1	7.7	3.5	3.5
50	17.7	13.9	11.4	10.5	8.9	8.1	7.6	3.4	3.4
60	16.4	11.7	10.8	10.1	8.3	7.7	7	3.6	2.9
80	15.3	11.2	10.4	9.6	7.6	7	6.4	3.5	3.2
100	14.2	11.9	9.5	8.9	7	6.6	5.8	3.3	2.7
Cut-off value=2%									
0	14.3	10.5	9.8	8.6	7.3	6.8	6.4	3	2.6
20	13.3	11	10	8.7	7.2	6.7	6.6	3.2	2.8
40	12.3	10.3	9.4	8	6.5	6.4	6.4	2.7	2.5
50	13.2	10.8	9.3	8.3	7.1	6.4	6.1	2.8	2.6
60	11.7	8.7	8.7	7.9	6.3	6	5.2	3.1	2.6
80	10.4	8.3	8.4	7.2	5.7	5.3	4.7	2.9	2.5
100	11.2	9.9	8	7.2	5.6	5.1	4.5	2.7	2.1

To further investigate the effect of various cut-off values on effective length, the relationship between the effective length, traffic flow, and percent no-passing was also investigated using regression analysis. Best-fit regression models were developed for each cut-off value. All models were found statistically significant at the 95% confidence level, and overall, have high R^2 values as shown in Table 25.

The model with 1.5% cut-off value was deemed most appropriate as it was associated with the highest coefficient of determination (0.99) and an extremely small

standard error of estimate (0.96) compared to those for other cut-off values used in this investigation. This model is presented below.

$$\text{Effective Length} = 22.53 * \exp(-0.0014 * \text{Flow Rate}) - 0.023 * \% \text{ NP} \quad (1)$$

As shown in Table 26, using this cut-off value, the effective length would vary between 19.8 miles for flow rate of 200 veh/h and 0% no-passing and 2.7 miles for a flow rate of 1400 veh/h and 100% no-passing zones.

Table 26. Regression Results for Effective Length

Model	Regression Model		Coefficients and P-value from t-test	
	R-squared	SE	Exp (-0.0014 Flow)	% NP
1 % cut-off value	0.98	1.7	30.5 0.00	-0.04 0.00
1.5 % cut-off value	0.99	0.96	22.53 0.00	-0.023 0.00
2 % cut-off value	0.98	0.66	16.85 0.00	-0.01 0.00

Optimum Length of Passing Lanes

Optimum length has been used to refer to the length that would bring most operational benefits given the amount of passing lane investments. This section aims to investigate the operational effects of passing lane length on two-lane highway performance. The current guidelines of the HCM regarding the optimum length of passing lanes are very limited and based on studies conducted more than three decades ago

(Harwood and St. John 1985, 1986). Therefore, this study uses recent field data and up-to-date simulation tools to investigate the optimum length of passing lanes.

Study Approach

As it was deemed impractical to gather field data from passing lane sites that would cover the full range of geometric and traffic conditions of interest, the use of traffic simulation was critical to this investigation. Field data from a limited number of study sites was used in the calibration and validation of the simulation tool. To examine the effect of traffic level and passing lane length on performance, a sensitivity analysis was developed for simulation experiments. For each scenario in these experiments, the average performance measure from 30 simulation runs was used, which more than satisfied the sample size requirements at the 95% confidence level.

The two major analysis variables are traffic level and passing lane length. Other variables were held constant at their default values. Specifically, a constant percent of heavy vehicles (15%), percent no-passing (50%) and traffic directional split (55% in analysis direction) were used throughout the analysis. The percent followers (percentage of vehicles with headway ≤ 2.5 seconds) at a detector location just upstream of the passing lane and at two detector locations downstream of the passing lane were measured. This headway value was used based on the findings from a study by Al-Kaisy et al. (Al-Kaisy et al. 2017). The optimum length of a passing lane was found as a function of percent reduction in level of platooning introduced due to the presence of passing lane and passing lanes total length. The percent followers was selected as the performance measure in this analysis, as it is not affected by small discrepancies in traffic flow between detector

locations upstream and downstream of the passing lane. The optimum length is believed to be a function of traffic level as reported in the HCM and other studies (HCM 2016, Harwood and St. John 1985). It is expected that an increase in flow rate is associated with an increase in the optimum length of the passing lane.

Study Sites and Field Data

Field data from two sites in Oregon were used in this study. Information on field data and study sites is provided in Table 19. Data from one detector location upstream as well as two locations downstream of the passing lane were used.

The first study site is located on Highway US 97 near Chiloquin, Oregon. The total length of the study site is 2.7 miles, including the length of the passing lane and a total of 3 detectors. The second study site is located on Highway US 26 about 15.8 miles north of Warm Springs, Oregon. Data from one location immediately upstream of the passing lanes, and other detectors located downstream at 100 feet , and 0.5 miles, beyond the end of the passing lanes were used for both study sites. A schematic of the study locations is shown in Figure 37.

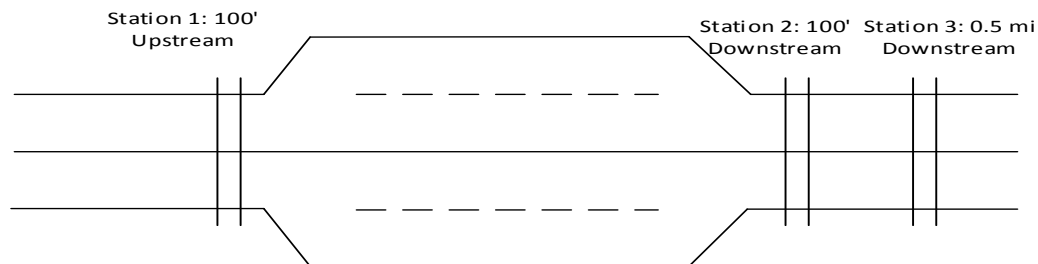


Figure 37. Data collection setup, OR 2 and OR 17

Calibration and Validation of Simulation Program

The simulation program, SwashSim, was calibrated and validated using field data from the two study sites described earlier. Traffic flow levels between 100-150, 150-200, and 200-250 veh/h were analyzed at different detector locations of each study site. Data were aggregated over a 1-hour period at each detector location. All volumes within those flow ranges were averaged and used in the analysis. Performance measures used in the calibration and validation of simulation model include:

- Percent Followers (PF): Percentage of vehicles with headways ≤ 2.5 seconds.
- Follower Density (FD): The number of vehicles with headways ≤ 2.5 seconds per mile per direction of travel. It is calculated as the product of PF and traffic density.
- Average Travel Speed (ATS): Average speed of all vehicles traveling in one direction.

Calibration of Swashsim. For simulation model calibration, the outputs from the software were compared to the field data counterparts. The outputs include:

- Percentage of followers
- Follower density
- Average travel speed

Satellite imagery data and GIS data were used to code the roadway network in SwashSim. Flow rates between 150-200, and 200-250 veh/h were used in calibrating the software. These field sites generally had low flow rates. In order to perform the calibration, the calibration parameters in SwashSim were repeatedly revised in a systematic way with the objective of minimizing the discrepancy between the simulation output and field

observations. Percent followers was the primary performance measure used in calibration as it closely corresponds to headway distribution and platooning levels, and unlike followers density, it is not affected by the small discrepancies in flow rates. Table 27 shows the simulation outputs for the calibrated model along with the percentage difference between simulation and field measurements. As can be seen, while the percent difference in PF at any particular station may exceed 11%, the average discrepancy at all detector stations for various traffic levels at the two study sites are well below 7%. Results for other performance measures are also provided in this Table for comparison purposes. Overall, the average discrepancy for other performance measures is as favorable if not better than that of PF. The lowest discrepancies are observed for flow rate and average travel speed.

Table 27. Traffic Simulation Output and Deviations from Field Measurements (Calibration)

Detector location	Field Measurements				Simulation Results				Deviations from Field Measurements			
	Flow Rate (veh/h)	ATS (mi/h)	PF	FD (veh/mi)	Flow Rate (veh/h)	ATS (mi/h)	PF	FD (veh/mi)	% difference Flow	% difference ATS	% difference PF	% difference FD
Site OR 2, Flow Rate (150-200 veh/h)												
Upstream	182.29	62.04	35.95	1.07	178.33	63.21	34.90	0.99	2.17%	1.89%	2.91%	7.60%
Downstream	180.63	62.34	19.04	0.56	178.53	64.30	19.01	0.53	1.16%	3.14%	0.15%	4.79%
0.50 mi downstream	183.29	63.76	20.00	0.58	177.07	64.43	19.50	0.54	3.40%	1.06%	2.47%	7.45%
	Average								1.66%	2.51%	1.53%	6.19%
Site OR 2, Flow Rate (200-250 veh/h)												
Upstream	216.82	61.91	41.17	1.44	215.67	62.69	41.36	1.43	0.53%	1.26%	0.46%	1.14%
Downstream	215.50	62.40	23.30	0.81	215.60	64.03	23.42	0.79	0.05%	2.62%	0.50%	1.97%
0.50 mi downstream	219.23	64.13	22.39	0.77	212.93	64.26	23.59	0.78	2.87%	0.19%	5.33%	2.30%
	Average								1.15%	1.36%	2.10%	1.80%

Site OR 17, Flow Rate (150-200 veh/h)												
Upstream	179.87	62.35	42.70	1.24	178.70	62.57	46.30	1.33	1.43%	0.34%	8.43%	6.59%
Downstream	181.64	63.69	28.07	0.81	176.77	63.43	28.16	0.79	2.68%	0.41%	0.34%	1.97%
0.50 mi downstream	179.13	64.20	26.02	0.74	176.57	63.86	28.94	0.80	1.43%	0.53%	11.22%	9.39%
	Average								1.85%	0.43%	6.66%	5.98%
Site OR 17, Flow Rate (200-250 veh/h)												
Upstream	225.82	60.85	49.06	1.83	224.70	61.99	52.77	1.92	1.86%	1.86%	7.55%	5.03%
Downstream	226.00	63.13	33.80	1.21	222.40	62.67	33.53	1.19	0.72%	0.72%	0.81%	1.44%
0.50 mi downstream	224.00	63.65	30.86	1.08	221.83	63.43	33.93	1.19	0.35%	0.35%	9.94%	9.75%
	Average								1.18%	0.98%	6.10%	5.41%

* Percentage values higher than 10 are highlighted.

Validation of Swashsim. In order to validate the calibrated model, field data from the same study sites using a different flow level (i.e., 100-150 veh/h) was used for this purpose. Table 28 presents the output results from SwashSim. In regards to the primary performance measure, PF, the highest discrepancy at any individual detector station is around 10%, while the average discrepancy for all detector stations reached 6% at site OR 17 and was only 2.43% at site OR 2. Overall, the discrepancies of PF and other performance measures from field measurements are very comparable to those exhibited during the calibration process.

Table 28. Traffic Simulation Output and Deviations from Field Measurements (Validation)

Detector location	Field Measurements				Simulation Results				Deviations from Field Measurements			
	Flow Rate (veh/h)	ATS (mi/h)	PF	FD (veh/mi)	Flow Rate (veh/h)	ATS (mi/h)	PF	FD (veh/mi)	% difference Flow	% difference ATS	% difference PF	% difference FD
Site OR 2, Flow Rate (100-150 veh/h)												
Upstream	125.54	61.89	26.64	0.54	123.77	63.92	26.53	0.52	1.41%	3.27%	0.41%	5.00%
Downstream	125.00	61.56	15.76	0.32	123.67	64.71	14.61	0.28	2.83%	1.74%	5.82%	7.16%
0.50 mi downstream	120.27	63.61	13.81	0.26	124.30	64.60	16.56	0.32	0.84%	4.05%	1.06%	4.59%
	Average								1.69%	3.02%	2.43%	5.58%
Site OR 17, Flow Rate (100-150 veh/h)												
Upstream	119.56	63.44	33.29	0.63	117.27	63.61	32.66	0.61	4.25%	0.28%	1.89%	3.74%
Downstream	118.36	64.80	19.63	0.36	116.80	64.10	18.45	0.34	1.32%	1.08%	6.05%	6.03%
0.50 mi downstream	114.69	65.21	17.63	0.31	116.73	64.35	19.40	0.36	1.78%	1.32%	10.07%	13.61%
	Average								2.45%	0.89%	6.00%	7.79%

* Percentage values higher than 10 are highlighted.

Simulation Experimental Design.

In order to assess the impact of varying geometric and traffic conditions on the optimum length of passing lanes using simulation, it was necessary to design and implement a sensitivity analysis which incorporates the variables of interest. Two variables of interest were used in this analysis: traffic volume and passing lane length. Traffic volume is directly related to platooning on two-lane highways and is believed to affect the optimum

length of passing lanes. Higher traffic volume and shorter passing lanes are believed to contribute to higher platooning level. To identify the optimum length of a passing lane, performance improvement was examined while changing the length of passing lane under different traffic levels. For each variable, appropriate ranges and levels were selected considering typical ranges for directional traffic volume and passing lane length in practice. Traffic flow rates from 200 to 800 veh/h with increments of 100 veh/h, and passing lane lengths between 0.5 miles and 3 miles using 0.1-mi increments up to 2.0 miles in length and 0.25-mi increments thereafter, were used in this study. A default traffic directional split of 55/45 for the analysis direction and opposing direction respectively and a fixed percentage of heavy vehicles (15%) were used for all scenarios in this study. Further, 50% no-passing zones were used consistently in all simulation runs, i.e., passing is allowed in 1 out of 2 consecutive segments. Due to the stochastic nature of simulations in SwashSim, 30 simulation runs with different random seed values were performed for each scenario.

A straight, level segment of a two-lane highway including a passing lane was created in SwashSim. Two warm-up segments with a length of 10 to 20 miles depending on the traffic volume (20 miles for traffic volumes of 200 and 300 veh/hr and 10 miles for 400-800 veh/hr) were added at each end of the evaluation segment. These segments were used to ensure stable traffic conditions upon reaching the evaluation segment. A combination of passing and no-passing segments with a length of 0.5 miles per segment were used for the two-lane highway section outside of the passing lane. Additionally, one detector was installed just upstream of the passing lane (250 ft upstream of taper) and three detectors were installed at 0.5, 0.75 and 1.25 miles downstream of the passing lane. The

average outputs from these three detectors were used to estimate performance downstream of passing lane. Performance immediately downstream of the passing lane was not used in estimating the “downstream” performance, as short headways are expected to be overrepresented due to the merge activity towards the end of passing lane, irrespective of platooning level.

Passing Lane Optimum Length Results

In this investigation, three different approaches were attempted with the objective of identifying a passing lane optimum length. The three approaches along with corresponding results are presented in the following sections.

Traffic Split Within Passing Lane Section. Upon entering the passing lane, many slower vehicles move to the right lane either at the taper location or at some other distance downstream. This lane changing behavior is largely dependent on traffic level and the possibility of faster vehicles closely following slower vehicles while in the passing lane section. While it would be difficult to observe lane changing patterns in the field, it was deemed useful to investigate traffic split as it changes within the passing lane as this split is largely related to the lane changing activity within the passing lane. Traffic split shows the proportion of directional traffic volume that is using either lane within the passing lane section. It is expected that lane changes diminish after a certain distance into the passing lane, a point beyond which traffic split becomes steady. This point may be viewed as a good location for the end of an optimum length of the passing lane.

In this investigation, field data was divided into data sets for various traffic levels and traffic split was established at detector locations within the passing lanes at the two

study sites. Figure 38 and Figure 39 show the results of this analysis at sites OR 2 & OR 17, respectively.

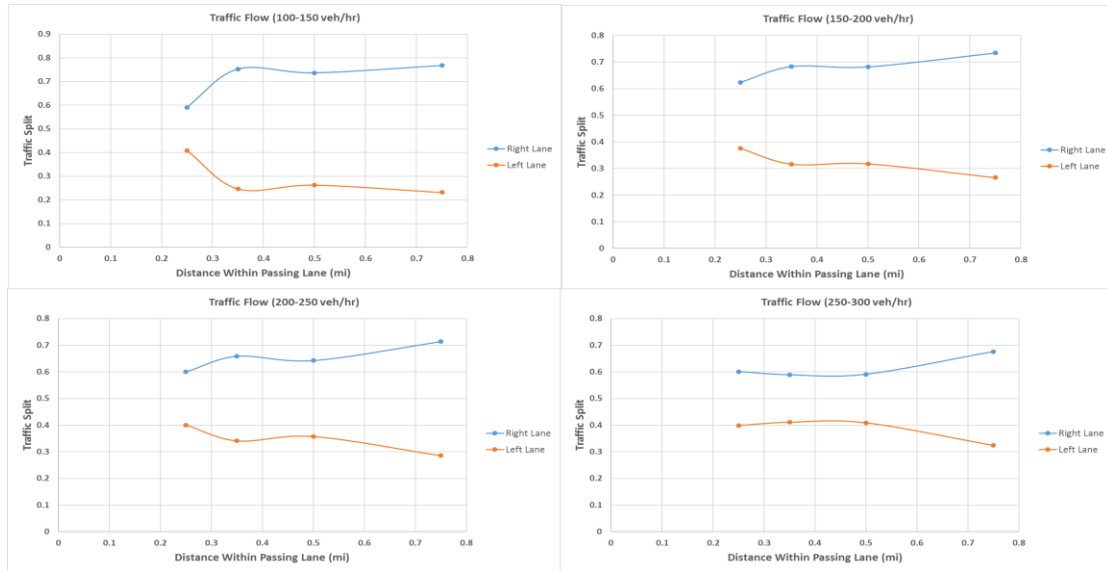


Figure 38. Traffic split within passing lane (OR 2)

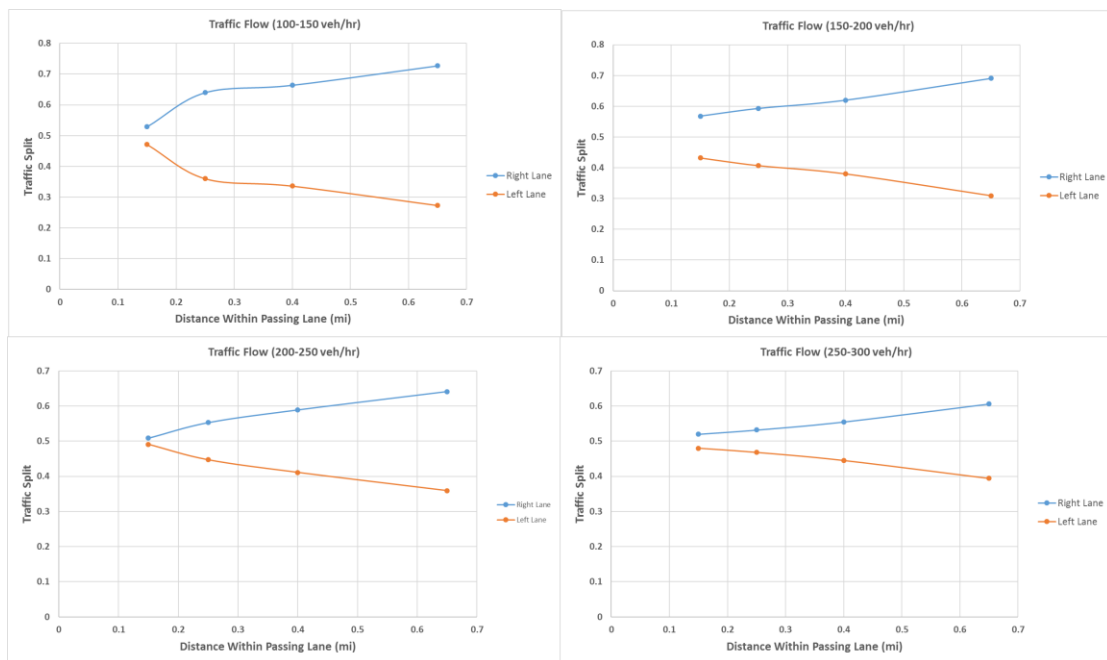


Figure 39. Traffic split within passing lane (OR 17)

Table 29 shows the traffic split within passing lanes for different traffic levels at sites OR 2 and OR 17. As the results show, the right lane traffic split increases, while the left lane split decreases as traffic moves further into the passing lane. Moreover, the left lane traffic split increases with the increase in traffic flow. This shows that more vehicles use the left lane at higher traffic levels. However, the distance into the passing lane investigated at the two study sites is relatively limited (0.75 miles at OR 2 and 0.65 miles at OR17) and therefore, it is not known whether the continuously increasing traffic split in the right lane at the two study sites is due to the distance being too short to reveal the hypothesized pattern, or if the theoretical pattern based on the underlying relationship between lane changes and traffic split is simply not true.

To examine the theoretical pattern of traffic split (a surrogate for lane changing) using traffic simulation, detectors were installed within a 2.5 mi passing lane using 0.1 mi increments. Traffic split from field data was used in calibrating and validating the simulation model Swashsim. Consequently, traffic split in the right lane was measured at different detector locations using the calibrated simulation model and the results are shown in Figure 40. Traffic split in right lane of the simulated highway exhibits a decreasing trend over the whole length of passing lane which is different from the trend stipulated at the onset of this investigation. The trends shown in Figure 40 suggest that the majority of slower moving vehicles take the passing (right) lane at the start of passing lane section, thus the highest traffic split at the first and second detector locations. Thereafter, some of the slower vehicles start to return to the left lane especially when already passed by faster

vehicles following them closely upon arriving at the passing lane section. As such it was deemed impractical to use this approach in identifying passing lane optimum length.

Table 29. Traffic Split within Passing Lane

Site OR 2			Site OR 17		
	Traffic Split (Right Lane)	Traffic Split (Left Lane)		Traffic Split (Right Lane)	Traffic Split (Left Lane)
Traffic Flow (100-150 veh/hr)			Traffic Flow (100-150 veh/hr)		
Detector location 0.25 mi	0.591	0.409	Detector location 0.15 mi	0.529	0.471
Detector location 0.35 mi	0.753	0.247	Detector location 0.25 mi	0.64	0.36
Detector location 0.5 mi	0.737	0.263	Detector location 0.4 mi	0.664	0.336
Detector location 0.75 mi	0.768	0.232	Detector location 0.65 mi	0.727	0.273
Traffic Flow (150-200 veh/hr)			Traffic Flow (150-200 veh/hr)		
Detector location 0.25 mi	0.624	0.376	Detector location 0.15 mi	0.568	0.432
Detector location 0.35 mi	0.683	0.317	Detector location 0.25 mi	0.593	0.407
Detector location 0.5 mi	0.682	0.318	Detector location 0.4 mi	0.62	0.38
Detector location 0.75 mi	0.734	0.266	Detector location 0.65 mi	0.691	0.309
Traffic Flow (200-250 veh/hr)			Traffic Flow (200-250 veh/hr)		
Detector location 0.25 mi	0.6	0.4	Detector location 0.15 mi	0.509	0.491
Detector location 0.35 mi	0.659	0.341	Detector location 0.25 mi	0.553	0.447
Detector location 0.5 mi	0.643	0.357	Detector location 0.4 mi	0.589	0.411
Detector location 0.75 mi	0.714	0.286	Detector location 0.65 mi	0.641	0.359
Traffic Flow (250-300 veh/hr)			Traffic Flow (250-300 veh/hr)		
Detector location 0.25 mi	0.601	0.399	Detector location 0.15 mi	0.52	0.48
Detector location 0.35 mi	0.589	0.411	Detector location 0.25 mi	0.532	0.468
Detector location 0.5 mi	0.591	0.409	Detector location 0.4 mi	0.555	0.445
Detector location 0.75 mi	0.676	0.324	Detector location 0.65 mi	0.606	0.394

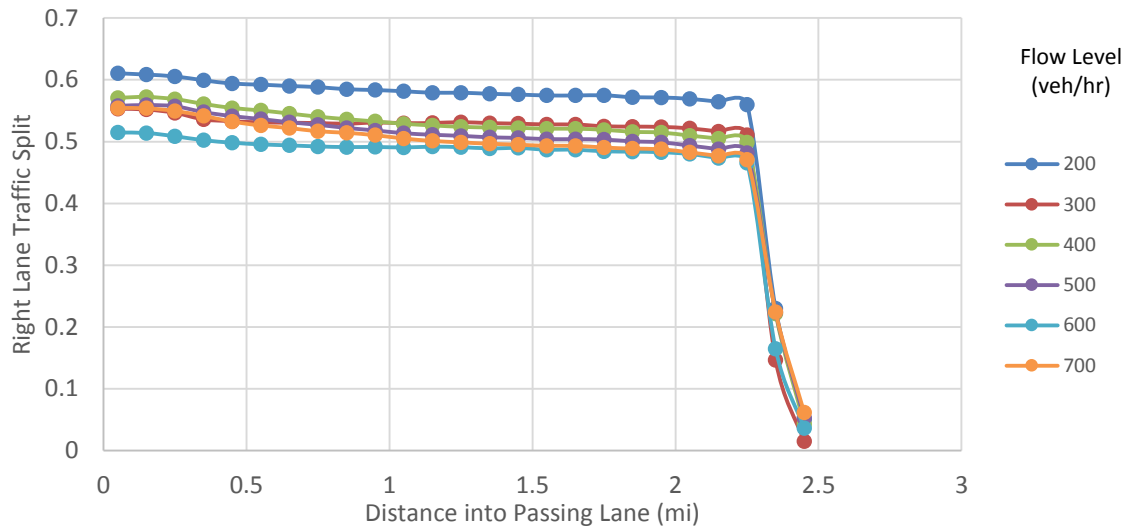


Figure 40. Right lane traffic split within the passing lane

Maximum Rate of Improvement Over Length Approach. This approach was used by Harwood et al. (Harwood and St. John 1986) to find the optimum length of passing lanes. The percent reduction in platooning, using the surrogate measure percent time delay, due to the presence of passing lane was determined. In this study, the percentage of vehicles with headways less than 4 seconds was used to estimate percent time delay. The percentage of short headways in the traffic stream was referred to in later studies (Dixon et al. 2002, Catbagan & Nakamura, 2006; Van As & Van Niekerk 2004) as percent followers (PF).

In this investigation, PF was used as an indicator of performance and is defined as the percentage of vehicles with headways less than 2.5 seconds. To apply the aforementioned approach in this study, percent reduction in PF was divided by the length of the passing lane while changing the length of passing lane systematically using 0.1-mi increments. The rate of performance improvement by length is then plotted to identify the length which corresponds to the highest rate of performance improvement. The results of

this investigation are shown in Figure 41. This Figure shows that the rate of performance improvement over length increases as the length of passing lane increases until it reaches its peak. Then, it starts to decrease with the increase in passing lane length. To more closely examine these results, the rate of performance improvement over length is also provided in Table 30, and the maximum rates of improvement for different traffic levels are identified as shown in the shaded cells. Two important observations can be made here. First, the maximum rate of improvement by length varies in a very narrow range (0.8 to 1.1 miles); second, these maximum values do not seem to be adequately sensitive to traffic level, which is unexpected. Those maximum values are further summarized in Table 31. These results are inconsistent with the expectations of this study as well as the current practice in estimating optimum length (HCM 2016).

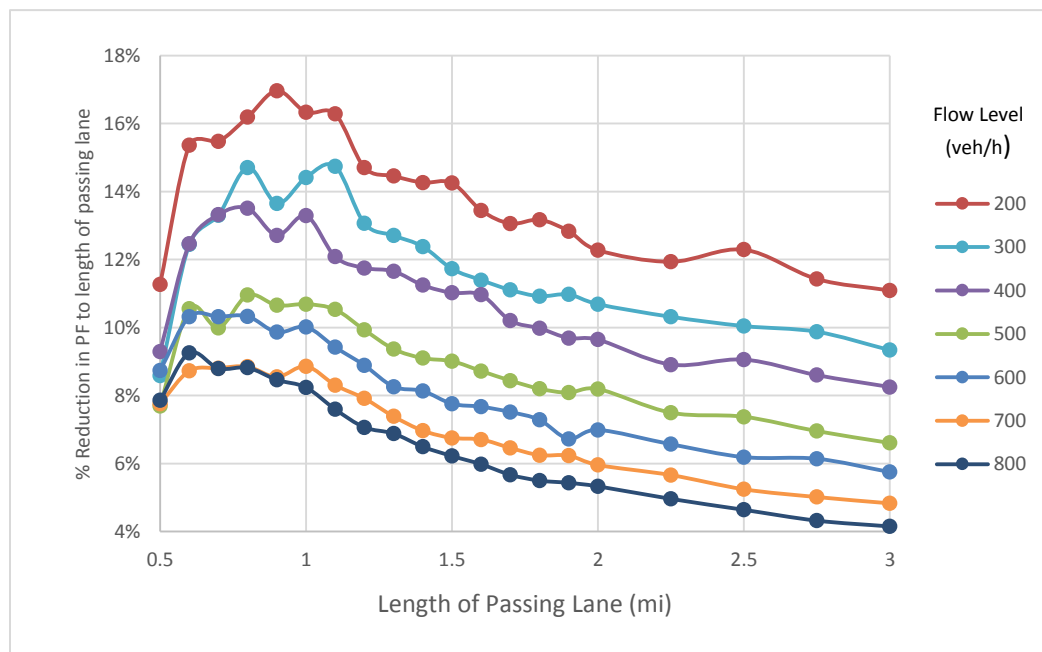


Figure 41. Percent reduction in PF to length of passing lane (Harwood approach)

Table 30. Percent Reduction in PF to Length of Passing Lane (Harwood Approach)

Traffic Flow (veh/hr) Length of passing lane (mi)	200	300	400	500	600	700	800
0.5	11.27	8.73	9.30	7.70	8.73	7.76	7.86
0.6	15.36	12.44	12.46	10.55	10.32	8.72	9.25
0.7	15.48	13.30	13.32	9.99	10.32	8.81	8.80
0.8	16.19	14.70	13.51	10.95	10.33	8.85	8.81
0.9	16.97	13.65	12.71	10.65	9.86	8.55	8.46
1	16.33	14.42	13.29	10.69	10.02	8.86	8.24
1.1	16.28	14.74	12.08	10.53	9.42	8.31	7.59
1.2	14.71	13.06	11.75	9.93	8.89	7.91	7.07
1.3	14.46	12.71	11.66	9.37	8.26	7.39	6.88
1.4	14.26	12.38	11.25	9.10	8.14	6.97	6.49
1.5	14.25	11.73	11.02	9.01	7.76	6.76	6.22
1.6	13.45	11.40	10.96	8.72	7.67	6.71	5.98
1.7	13.06	11.11	10.20	8.44	7.52	6.46	5.67
1.8	13.17	10.92	9.98	8.20	7.28	6.25	5.50
1.9	12.84	10.97	9.69	8.09	6.72	6.24	5.43
2	12.27	10.69	9.65	8.20	6.99	5.96	5.33
2.25	11.94	10.32	8.91	7.50	6.57	5.66	4.96
2.5	12.29	10.04	9.06	7.38	6.19	5.24	4.64
2.75	11.43	9.88	8.60	6.96	6.14	5.02	4.32
3	11.09	9.34	8.25	6.61	5.75	4.83	4.15

Table 31. Optimum Length of Passing Lane (Harwood)

Traffic Flow (veh/hr)	200	300	400	500	600	700	800
Length of Passing Lane (mi)	0.9	1.1	0.8	0.8	0.8	0.8	0.8

Proposed New Approach. Due to the inconsistent results found using the maximum rate approach described in the previous section, a new approach was proposed and attempted in this investigation. In this approach, the optimum length of a passing lane is derived using the rate of change in performance as passing lane length is increased gradually using small fixed increments. It is hypothesized that the rate of performance improvement will be highest as passing lane length increases from some minimum value (0.5 miles in this investigation), and as length increases further, this rate will decrease until it eventually diminishes or reaches some constant value. To verify the hypothesis, the percent change in PF at passing lane lengths between 0.5 miles and 3 mi using 0.1-mi increments up to 2.0 miles length and 0.25-mi increments thereafter was calculated using the calibrated simulation program. The results from this analysis are shown in Figure 42. The general pattern exhibited in this Figure is that increasing passing lane length beyond the 0.5 miles results in a performance improvement that would decrease steadily with the increase in passing lane length. The reduction in PF is greater at shorter passing lane lengths, resulting in an upward convex curvilinear shape (decreasing slope) which gradually becomes linear (constant slope) with the increase in passing lane length. This general pattern is common to all traffic levels. The length at which this change in shape takes place appears to be a function of traffic level; that is, this length is soon reached at lower traffic levels, while it happens at longer lengths for higher traffic levels.

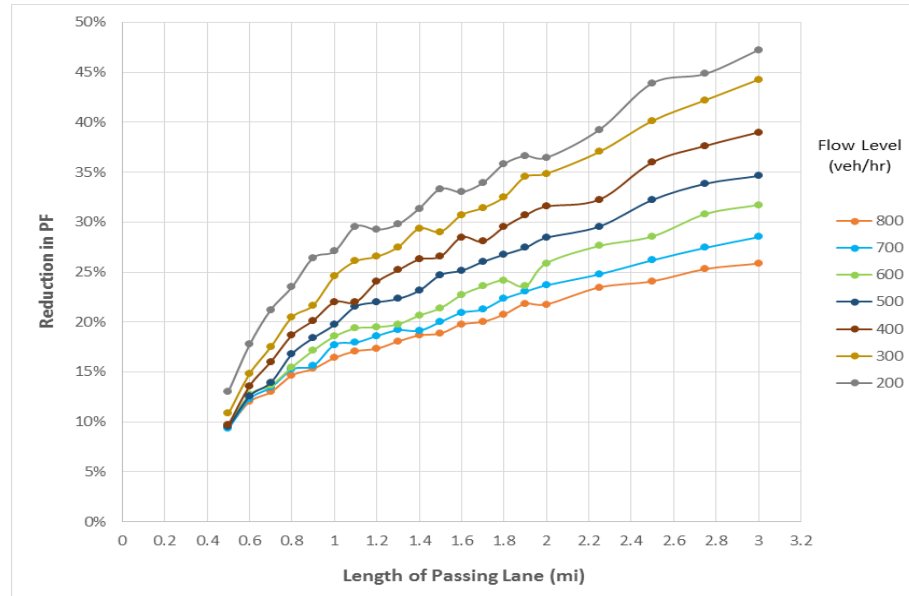


Figure 42. Percent reduction in PF vs length of passing lane

To identify the point at which the rate of performance improvement becomes constant (start of linear segment), the best fit linear relationship was found while varying the length of the linear portion of the curve and the length with the best fit (highest R^2) was selected. Specifically, a linear relationship was fitted to all points in each graph (i.e., from 0.5 to 3 miles) and then points are dropped one by one from the left side of the curve (corresponding to shorter passing lane lengths). The linear relationship was fitted in each step and the goodness of fit using R^2 was recorded. The point resulting in the highest R^2 was found, which demarks the start of the linear segment of the curve. This process was done for all traffic levels and the results are superimposed on the observations as illustrated in Figure 43. It is evident that the point at which the rate becomes constant (linear portion of the curve) moves to the right (i.e., longer passing lanes) as traffic level increases. The remaining points on the curve can best be represented using a nonlinear function.

Specifically, an upward convex declining slope function was found to fit the shorter lengths of passing lane. These results are also summarized in Table 32, where the linear portion of the curves are shown as shaded cells. The results show that the optimum passing lane lengths, derived using the proposed approach, fall in the range of 0.9 to 2.0 miles for different traffic levels.

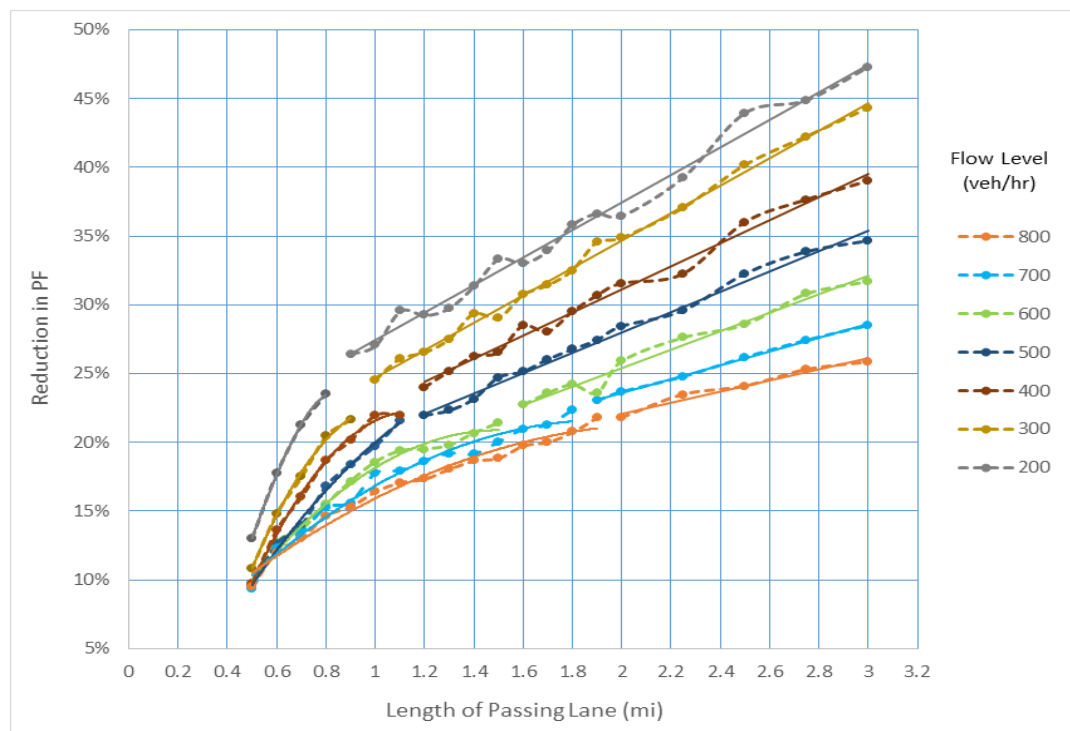


Figure 43. Percent reduction in PF vs length of passing lane with fitted curves

A careful examination of Figure 43 also reveals that the interface between the linear and non-linear segments for the curves shown all correspond to percent reductions in PF that are generally between 22% and 26% depending on traffic level. This is a relatively narrow range, and therefore, it would be interesting to examine passing lane lengths that correspond to a specific rate of performance improvement (i.e., reduction in PF) and see

how they compare to the lengths found using the proposed approach. Table 33 shows the length of passing lane corresponding to percent improvement in performance of 20%, 22.5%, and 25% along with the passing lane length found using the proposed approach. In this Table, it is evident that the passing lane lengths derived using the proposed approach correspond closely to the lengths provided by 22.5% and 25% reductions in PF. This finding is further illustrated in Figure 44.

Table 32. Percent Reduction in PF (Proposed Approach)

Traffic Flow (veh/hr) Length of Passing Lane (mi)	200	300	400	500	600	700	800
0.5	13.03	10.83	9.80	9.65	10.02	10.35	10.50
0.6	17.74	14.70	13.33	12.15	12.08	11.87	11.73
0.7	21.23	17.82	16.27	14.44	13.93	13.28	12.89
0.8	23.51	20.17	18.63	16.51	15.55	14.57	13.98
0.9	26.43	21.77	20.40	18.36	16.97	15.76	14.99
1	27.43	24.75	21.58	20.00	18.16	16.84	15.93
1.1	28.43	25.75	22.17	21.42	19.14	17.81	16.79
1.2	29.43	26.75	24.41	22.12	19.90	18.67	17.58
1.3	30.44	27.74	25.25	22.86	20.44	19.41	18.30
1.4	31.44	28.74	26.09	23.60	20.77	20.05	18.94
1.5	32.44	29.74	26.93	24.34	20.88	20.58	19.51
1.6	33.44	30.74	27.76	25.07	22.72	21.00	20.00
1.7	34.44	31.74	28.60	25.81	23.39	21.31	20.41
1.8	35.45	32.73	29.44	26.55	24.06	21.51	20.76
1.9	36.45	33.73	30.28	27.29	24.73	23.11	21.03
2	37.45	34.73	31.12	28.03	25.40	23.61	22.09
2.25	39.96	37.23	33.22	29.88	27.08	24.86	23.09
2.5	42.46	39.72	35.32	31.73	28.75	26.11	24.09
2.75	44.97	42.22	37.41	33.57	30.43	27.35	25.09
3	47.47	44.71	39.51	35.42	32.10	28.60	26.09

Table 33. Lengths of Passing Lane Derived Using the Proposed Approach and for Various PF Reductions

Directional Demand Flow Rate (veh/h)	200	300	400	500	600	700	800
	PF Reduction=20 %						
	0.65	0.78	0.9	1.02	1.32	1.5	1.7
	PF Reduction=22.5 %						
	0.75	0.93	1.13	1.3	1.57	1.8	2.03
	PF Reduction=25 %						
	0.85	1.02	1.28	1.55	1.95	2.28	2.65
	Proposed Approach						
	0.85	0.95	1.15	1.15	1.55	1.85	1.95

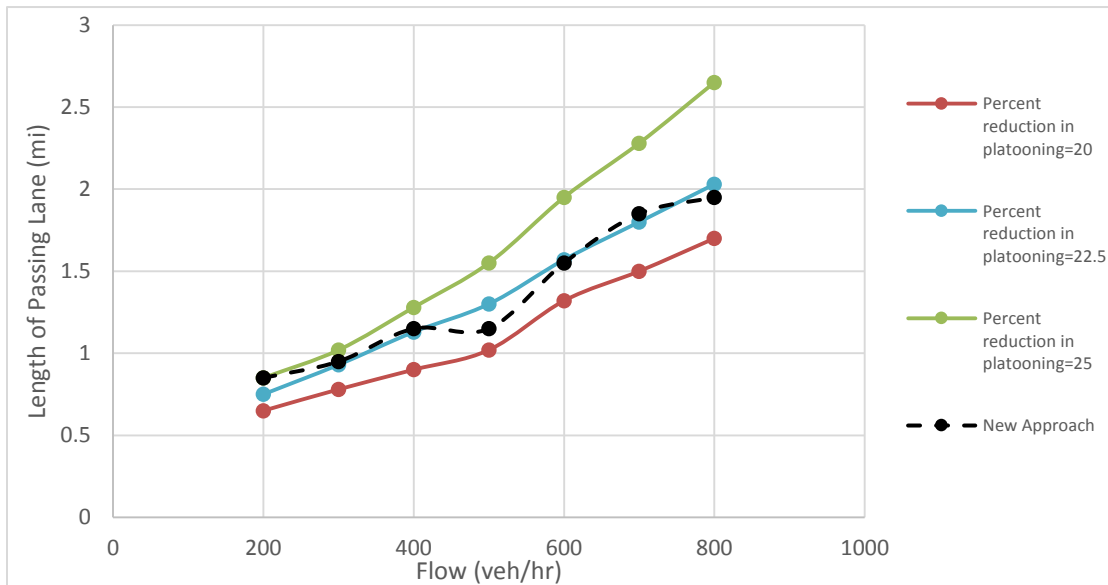


Figure 44. Length of passing lane as a function of percent reduction in platooning

Results from this analysis (shown in Figure 43) were used to model performance improvement (i.e., percent reduction in PF) as a function of passing lane length and traffic levels. A none-linear regression model for percent reduction in PF was developed using traffic flow and passing lane length as explanatory variables as shown in the equation below.

$$\text{Percent Reduction in PF} = 0.290 + .21 * \ln(\text{PassLaneLength}) - 0.0002 * \text{Flow} - 0.0002 * \ln(\text{PassLaneLength}) * \text{Flow} \quad (2)$$

Where Flow equals traffic flow rate in veh/h and PassLaneLength equals the length of the passing lane, in miles. The “ln” shows the natural logarithm of the variables. The goodness-of-fit (R^2) for this model is 0.98. All variables in this model were found statistically significant at the 95% confidence level and all coefficients are consistent with the underlying hypotheses; that is, the lower the traffic level and the longer the passing lane, the greater the reduction in PF.

Evaluation of Passing Lane Design Configuration

The Highway Capacity Manual (HCM) provides some guidance on the optimum length of a passing lane and the distance downstream over which the operational effect of a passing lane persists, also called the passing lane effective length. However, the HCM does not specifically provide guidance on the most effective combination of passing lane design parameters, i.e. passing lane length and spacing, to ensure maximum operational improvements for the resources expended. Such guidance is invaluable for the planning and design of passing lanes along two-lane highway facilities. This section aims at examining the operational efficiency of different passing lane design configurations in order to identify the most appropriate length and spacing to be used in the planning and design of passing lanes.

Study Approach

As it was deemed unfeasible to collect field data from passing lane sites to cover the full spectrum of passing lane length and spacing, it was inevitable to use traffic simulation in this investigation. Field data from two study sites in Oregon were used to calibrate and validate the simulation program, SwashSim, used in this study. A sensitivity analysis was then developed to investigate the effect of length and spacing of passing lanes on operational performance. The average percentage of vehicles with headways equal or less than 2.5 seconds was used in estimating performance. This headway value was used based on the findings from a study by Al-Kaisy et al. (Al-Kaisy et al. 2017). The operational improvement was estimated using a two-lane highway facility without passing lanes as the baseline scenario. The total length of passing lanes along the evaluation facility was used as an indicator of the amount of infrastructure investment in comparing the cost effectiveness of alternative scenarios.

Calibration and Validation of Simulation Model

The calibrated model for effective length investigation was used for this study. The details were already described in Effective Length Investigation section.

Figure 45 presents sample calibration results at the first study site. Blue dots show the results from simulation output and black dots show the field measurements. As can be seen, there is a reasonably good match between the simulation and field values at different traffic levels. Graphs for different stations are provided separately.

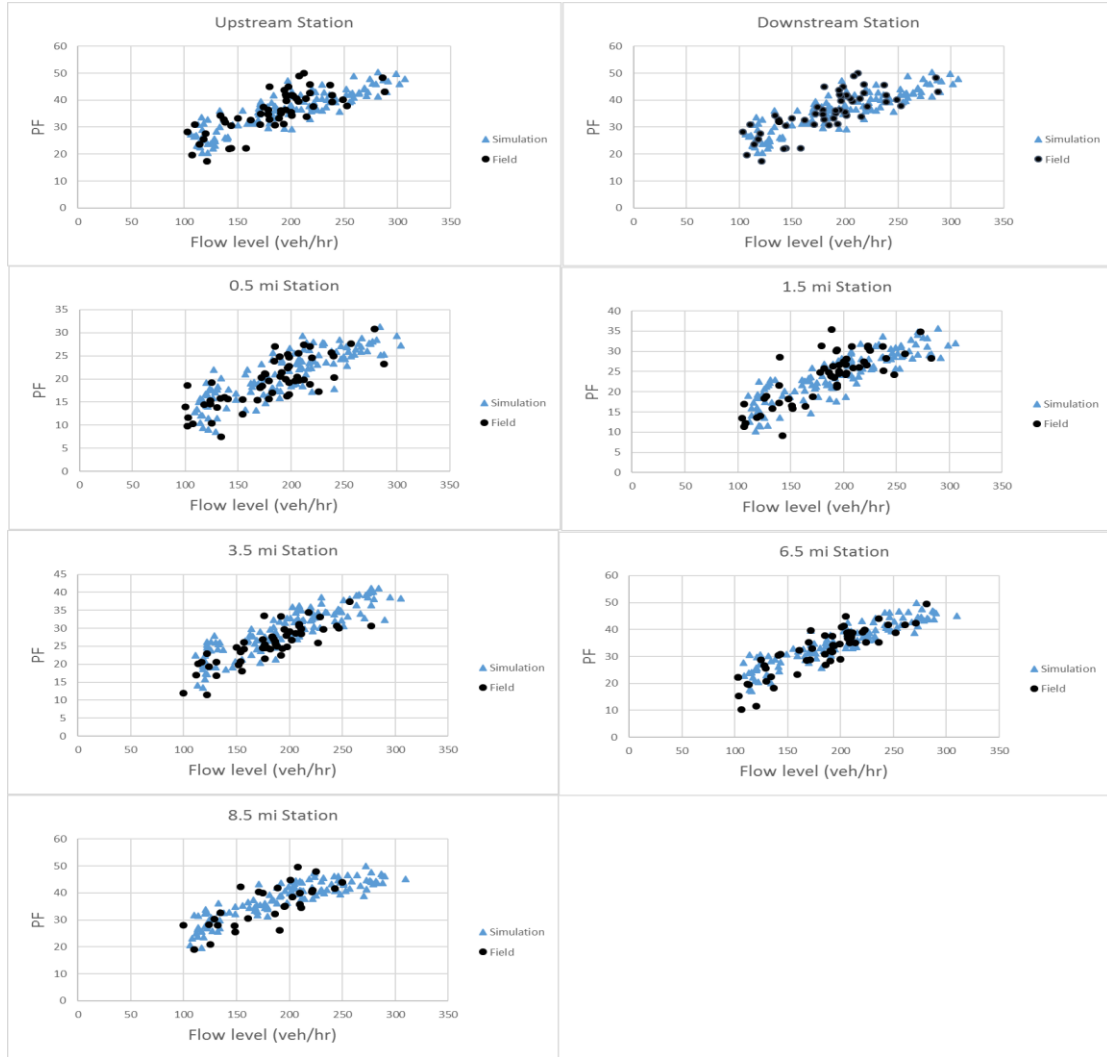


Figure 45. Traffic simulation output and field measurements (study site OR 2)

Experimental Design

To examine the effect of varying geometric and traffic conditions on performance using simulation, it was necessary to design and implement a sensitivity analysis which incorporates the variables of interest. Three variables were used in this analysis: traffic volume, passing lane length and spacing. For each variable, appropriate ranges and levels were selected considering typical ranges used in practice as shown in Table 34. A default

traffic directional split of 55%/45% for the analysis direction and opposing direction respectively and a fixed percentage of heavy vehicles (15%) were used for all scenarios in this study. Further, a 50% no-passing was used consistently in all simulation runs, i.e. passing is allowed in 1 out of 2 consecutive segments. Due to the stochasticity of variables used in simulation, 30 simulation runs with different seed numbers were performed for each scenario.

Table 34. Ranges and Levels for Study Variables

Variables	Analysis Direction Flow Rate (veh/h)	Opposing Direction Flow Rate (veh/h)	Length of Passing Lane (mi)	Passing Lane Spacing (mi)
Levels	200	164	0.5, 0.75, 1, 1.25, 1.5, 2	5.25, 6, 7, 8.4, 10.5, 14, 21
	400	327		
	600	491		
	800	655		
Ranges	200-800	164-655	0.5-2	5.25-21

A straight, level segment of a two-lane highway with a length of 42 miles was created in the calibrated simulation model. Two warm-up segments with a length of 10 to 20 miles depending on the traffic volume (20 miles for traffic volumes of 200 and 400 veh/hr and 10 miles for 600 and 800 veh/hr) were added at each end of the evaluation segment. These segments were used to ensure stable traffic conditions upon reaching the evaluation segment. Figure 46 shows a schematic of a sample experimental set up used in simulation. A total of 2 to 8 equally-spaced passing lanes were used in the evaluation segment. Passing lanes were provided in both directions of travel. Alternating passing and no-passing one-mile segments were used for the two-lane highway section outside of the

passing lane. One detector was installed just upstream of the passing lane (100 ft upstream of taper) and other detectors were installed in the middle of each one-mile segment outside of passing lanes. The average outputs from detectors along the 42-mile evaluation segment were used to estimate performance. The performance measure used in the analysis is percent followers, i.e. the percent of vehicles with headways equal or less than 2.5 seconds measured at a point location. Figure 47 shows how percent followers varies along the evaluation segment for one of the study scenarios. As shown in this Figure, percent followers significantly decreases downstream of the passing lanes before it starts to increase again with the formation of platoons as traffic progresses further downstream.

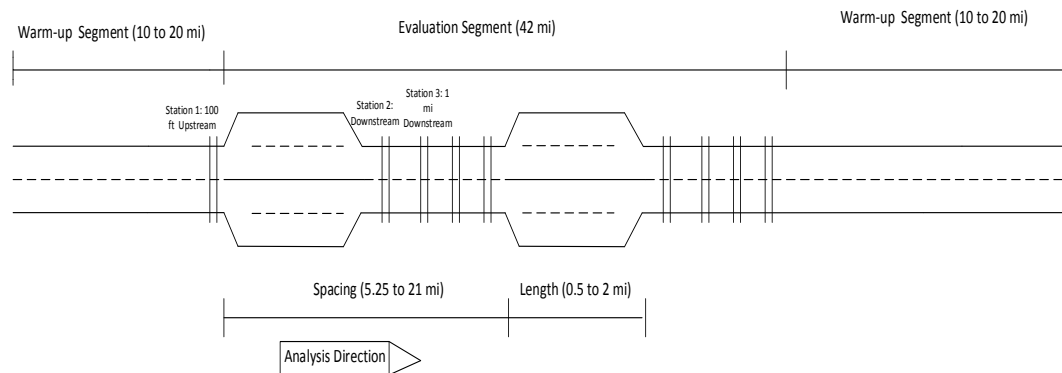


Figure 46. Sample experimental set up (2 Passing lanes, Passing lane spacing=21 mi)

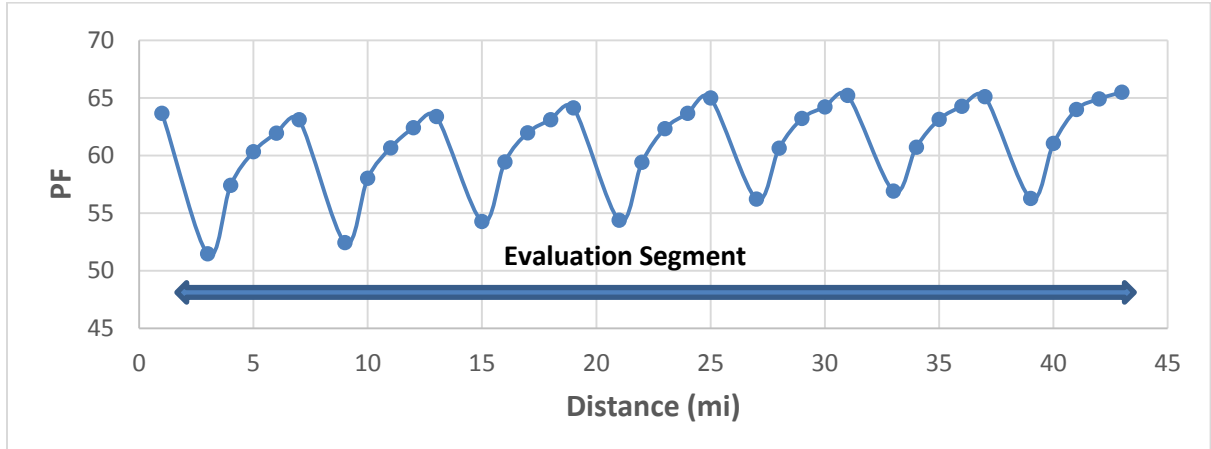


Figure 47. Percent followers along the study site (Flow level=800 veh/hr, Passing lane length=1.5 mi, Passing lane spacing= 6 mi)

Traffic Performance Investigation

This section provides performance results for different passing lane configurations investigated in this study.

Figure 48 presents results showing how PF varies with the increase in length and spacing of passing lanes. Specifically, percent followers consistently decreases with the increase in passing lane length and the decrease in passing lane spacing. Further, an increase in traffic level is associated with higher percent followers, i.e. higher levels of platooning.

Figure 49 shows the improvement in performance (reduction in PF) as a function of the change in passing lane length and spacing using a segment without passing lanes as a baseline. As shown in this figure, longer passing lanes spaced at shorter intervals are associated with greater improvement in performance, i.e. smaller PF and lower platooning level. Moreover, a greater passing lane length is required for a higher traffic volume to achieve the same improvement in performance. As can be seen for all traffic levels, passing

lanes with a length of 0.5 miles have little impact on PF. However, as the length increases above 0.75 miles, the impact on PF substantially increases. Note that the percent improvement in PF is higher for low traffic volumes (i.e. 200 and 400 veh/hr). Specifically, for a traffic flow rate of 200 veh/hr, the improvement is between 10 and 40 percent depending on the configuration used. For flow rate of 400 veh/hr, the improvement is between 8 and 32 %. For flow rates of 600 and 800 veh/hr, the improvement varies in the range from 2 to 20 %.

Figure 50 shows how ATS varies with the change in length and spacing of passing lanes. Longer passing lanes and shorter spacings are generally associated with higher ATS and better performance. While the patterns exhibited in this Figure are logical and consistent with expectations, it is clear that the speed variation was limited to a very narrow range, in the order of 1 to 2 mph. This observation is also consistent with older studies about ATS being insensitive to variation in flow level and road geometry (Al-kaisy et al., 2017; Al-Kaisy & Karjala, 2008).

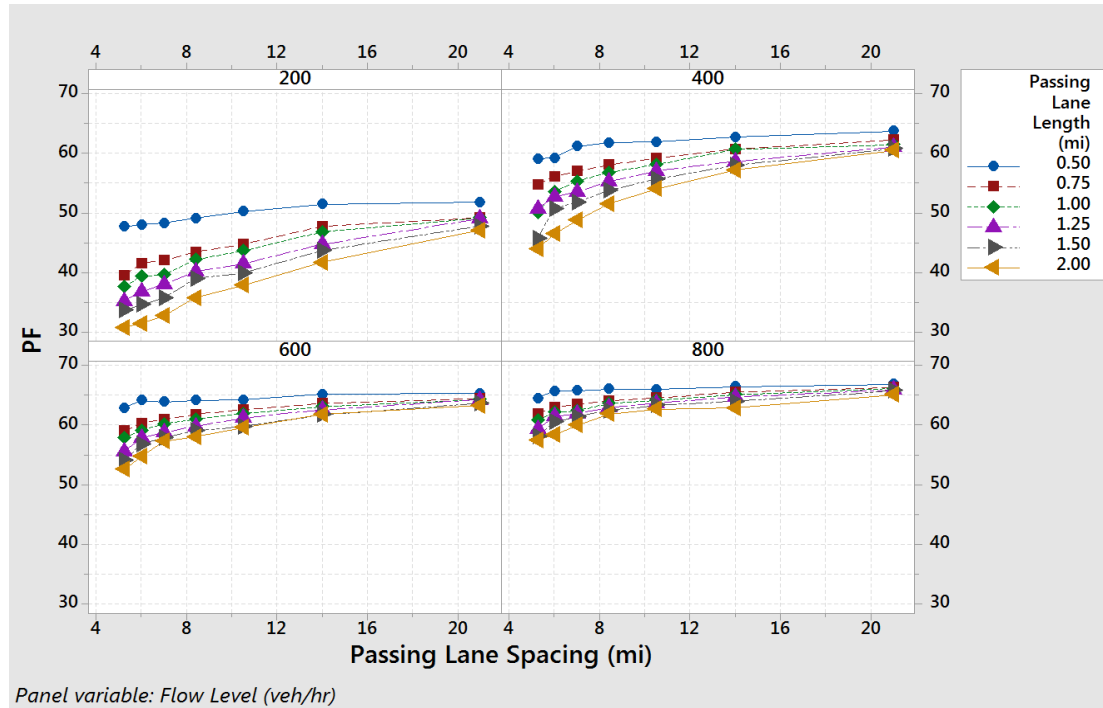


Figure 48. PF for different configurations of passing lanes

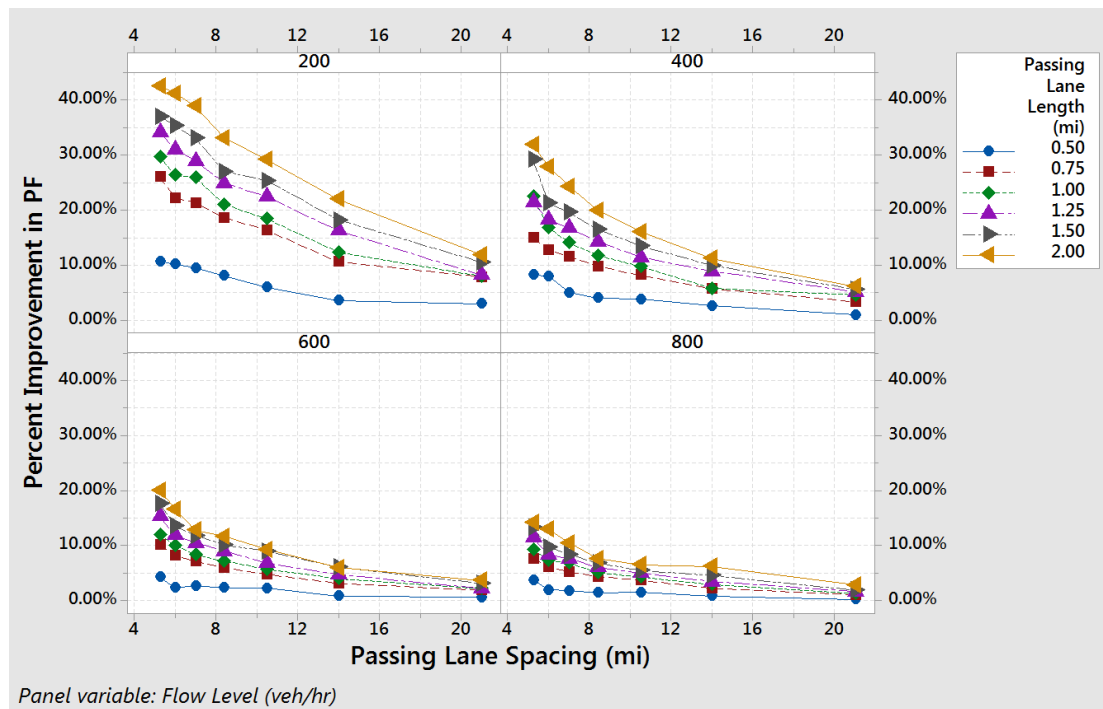


Figure 49. PF improvement for different configurations of passing lanes

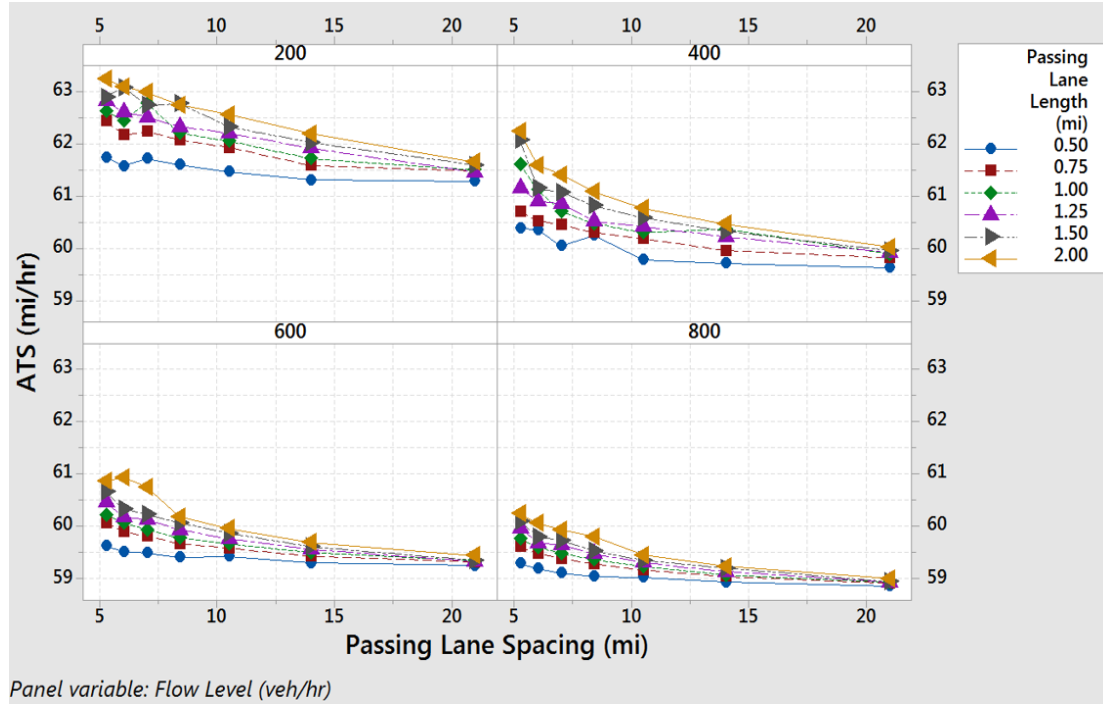


Figure 50. ATS for different configurations of passing lanes

Results from this analysis (shown in Figure 48) were used to model the performance measure PF, a surrogate for the percentage of vehicles in following mode, as a function of traffic level, passing lane length and spacing. A non-linear regression model for PF was developed using traffic flow, passing lane length and spacing as explanatory variables as shown in the equation below:

$$PF = -36.16 + 15.21 \ln \text{Flow} - 5.21 \text{Length} + 0.52 \text{Spacing}, \quad R^2 = 0.92 \quad (3)$$

All variables in this model were found statistically significant at 95% confidence level and all coefficients are consistent with the underlying hypotheses, i.e. the lower the traffic level and passing lane spacing and the longer the passing lane, the lower the PF. The coefficient of determination indicates that more than 92 % of the variability in the response

variable (PF) is explained by the three explanatory variables: traffic level, passing lane length and spacing.

Economic Effectiveness of Passing Lane Configurations

In this investigation, performance improvement was normalized using the total length of passing lanes used along the evaluation segment. To do this, the percent improvement in PF was divided by the total length of passing lanes in the evaluation segment of the study network. This ratio is called “Effectiveness Index” and can be found using equation 4.

$$\text{Effectiveness Index} = \frac{\text{Percent improvement in PF}}{\text{Total length of passing lanes}} \quad (4)$$

This index represents the magnitude of performance improvement along the two-lane highway segment for each mile of passing lanes added. Further, the index should correlate well with the economic effectiveness of adding passing lanes, as the cost of building these lanes (amount of investment) is largely a function of the total length of the proposed passing lanes along the two-lane highway segment. The effectiveness index was calculated for all combinations of passing lane length, spacing and traffic volumes and results are depicted in the contour maps shown in Figure 51. The dark green shows configurations with the highest effectiveness index while dark blue refers to those with the lowest effectiveness index. As can be seen, the most effective length of passing lanes vary in the range between 0.75 and 2 miles. The optimum spacing varies in the range between 5 and 15 miles depending on traffic volume.

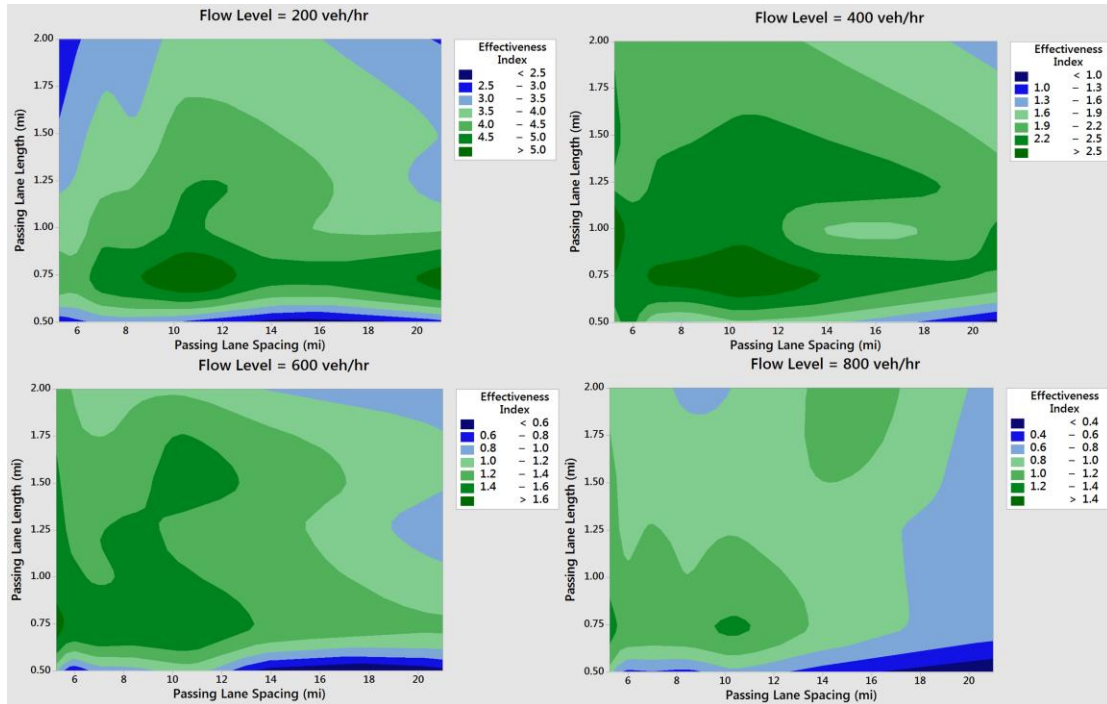


Figure 51. Effectiveness Index for different configurations of passing lanes

Passing Lane Configuration Guidelines

Using the Effectiveness Index, the optimum range for various length and spacing of passing lanes were derived. Table 35 shows the optimum ranges for passing lane length and spacing for each traffic level. As can be seen, passing lane length between 0.75 and 2 miles and spacing between 6 and 15 miles would bring the highest effectiveness depending on traffic level.

Table 35. Recommended Values of Length and Spacing by Flow Level

Traffic Flow Level (veh/hr)	Recommended Passing Lane Length (mi)	Recommended Distance Between Passing Lanes (mi)
200	0.75-1	11-15
400	0.75-1.25	6-12
600	1-1.5	5-9
800	1.25-2	5-7

Using Figure 49, the spacing corresponding to different percent improvement in PF (i.e. 10, 15, 20, 25 and 30 %) was found. Table 36 shows the results for this investigation. The Effectiveness Index for different configurations is also provided. Values in bold refer to configurations with the highest effectiveness indices. As can be seen, the higher the traffic level, the shorter the passing lane spacing and the lower the effectiveness index. Blank cells in the Table refer to passing lane lengths failing to yield the specific % improvement regardless of the spacing used in the analysis. For instance, to have 10 % improvement for the traffic level of 800 veh/hr, only passing lanes with lengths of 1.25, 1.5 and 2 miles are feasible. The values provided in this Table could be used as a rough guide in selecting the proper configuration of passing lanes along two-lane highways.

Table 36. Passing Lane Spacing and Effectiveness Index for Different PF Reduction

Reduction in PF (%)	Passing Lane Length (mi)					
	0.5	0.75	1	1.25	1.5	2
	Flow Level (200 veh/hr)					
10%	6*	15.2	17.6	19.2	21	-
	2.86**	4.83	4.19	3.66	3.33	-
15%	-	11.2	12.4	15	16.8	18.8
	-	5.33	4.43	4.29	4	3.36
20%	-	7.6	9.2	11.8	13.2	15.2
	-	4.83	4.38	4.5	4.19	3.62
25%	-	5.3	7.2	8.4	10.4	12.4
	-	4.21	4.29	4	4.13	3.69
30%	-	-	5.3	6.4	7.7	10
	-	-	3.79	3.66	3.67	3.57
Flow Level (400 veh/hr)						
10%	-	8.1	10	12.4	13.8	15.4
	-	2.57	2.38	2.36	2.19	1.83
15%	-	5.25	6.6	8	9.4	11.2
	-	2.5	2.36	2.29	2.24	2
20%	-	-	5.6	5.6	6.8	8.4
	-	-	2.67	2.13	2.16	2
25%	-	-	-	-	6	6.8
	-	-	-	-	2.38	2.02
30%	-	-	-	-	-	5.6
	-	-	-	-	-	2
Flow Level (600 veh/hr)						
10%	-	5	6	7.4	8.4	9.8
	-	1.59	1.43	1.41	1.33	1.17
15%	-	-	-	5.4	5.8	6.4
	-	-	-	1.54	1.38	1.14
20%	-	-	-	-	5	5.8
	-	-	-	-	1.59	1.38
25%	-	-	-	-	-	-
	-	-	-	-	-	-
Flow Level (800 veh/hr)						
10%	-	-	-	5.6	6	7.2
	-	-	-	1.07	0.95	0.86
15%	-	-	-	-	-	-
	-	-	-	-	-	-

*Top values are passing lane spacings.

** Bottom values are for “Effectiveness Index”.

CHAPTER SEVEN

2 + 1 HIGHWAYS

Contribution of Authors and Co-Authors

Manuscript in Chapter 7

Author: Amirhossein Jafari

Contributions: Draft manuscript preparation

Co-Author: Ahmed Al-Kaisy

Contributions: Draft manuscript preparation

Co-Author: Scott Washburn

Contributions: Review the draft

Manuscript Information

An Investigation of Operational Performance on 2 + 1 Highways

Amirhossein Jafari, Ahmed Al-Kaisy, Scott Washburn

Status of Manuscript: [Put an x in one of the options below, delete this]

☒ Prepared for submission to a peer-reviewed journal

☐ Officially submitted to a peer-reviewed journal

☐ Accepted by a peer-reviewed journal

☐ Published in a peer-reviewed journal

CHAPTER SEVEN

2 + 1 HIGHWAYS

Overview

There are different alternatives to improve the operational performance of two-lane highways and passing opportunities on these type of facilities such as passing lanes and turn-outs (Harwood and Hoban, 1987). Another alternative is using a specific type of three lane highways called 2 + 1 roads. On these highways, there is one lane per each direction of travel and the middle lane alternates between the two directions. Further, passing vehicles always use the center lane. These facilities are an intermediate option between two-lane highways with or without occasional passing lanes and four lane highways. This configuration may be a suitable treatment for roadways with traffic volumes higher than can be served by isolated passing lanes, but not high enough to justify a four-lane roadway (AASHTO, 2011). The AASHTO Green book reports at least two levels of service improvement for 2 + 1 highways compared to conventional two-lane highways with the same traffic volume. The Green book also recommends using these facilities for flow levels less than 1200 veh/hr and located in level or rolling terrain. These facilities are potentially applicable to locations where environmental or fiscal constraints, or both, make provision of a four lane highway impractical. The economic considerations could be another effective parameter for highway agencies to prefer these highways over four lane highways. Figure 52 shows a schematic of this type of facilities. The striping on the pavement identifies the passing lanes in each direction.

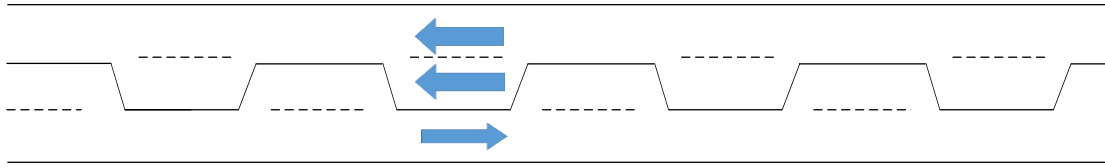


Figure 52. 2 + 1 highway

The Highway Capacity Manual (HCM) is the standard reference used in the US for operational analysis of two-lane highways. The current manual lacks a procedure for 2+1 roads. This type of facilities are common in Europe but very rare in the US. Due to these limitations, this study aims at investigating the operational improvements of 2+1 roads. A simulation software is used to evaluate the effect of different length of passing lanes in each direction on the operational performance of 2+1 roads. Finally, guidelines for identifying the appropriate length of passing lanes in each direction are provided. This information is useful for transportation engineers to use in planning and design of these type of highways.

Study Approach

There are a limited number of two + one roads in the US. As it was deemed impractical to collect field data from sites with different designs of 2+1 roads, traffic simulation was used in this study. Data from two study sites in Oregon were used to calibrate and validate the traffic microsimulation software, SwashSim, as explained on page 110. Then, an experiment was designed to investigate the effect of different variables on the performance of these facilities. The investigated variables include: length of passing lanes, traffic hourly volume, percentage of heavy vehicles and free flow speed of the

highway network. The network overall performance for different scenarios was measured. The network for a base two-lane highway without passing lanes and a percent no-passing of 50 was also simulated and the average performance was measured. The percentage of vehicles with headway less than 2.5 seconds were used to measure the platooning on these facilities. This headway value was used based on the finding of Al-Kaisy et al. (2017). The percent improvement of performance for each scenario compared to the base scenario was also calculated. Finally, some design guidelines for appropriate length of passing lanes on 2+1 roads are provided.

Experimental Design

To examine the effect of varying geometric and traffic conditions on performance using simulation, it was necessary to design and implement a sensitivity analysis which incorporates the variables of interest. Four variables were used in this analysis: traffic volume, free flow speed, passing lane length, and percentage of heavy vehicles. For each variable, appropriate ranges and levels were selected considering typical ranges used in practice as shown in Table 37. A default traffic directional split of 55%/45% for the analysis direction and opposing direction respectively were used for all scenarios in this study. Further, a 50% no-passing was used consistently in all simulation runs, i.e. passing is allowed in 1 out of 2 consecutive segments. Due to the stochasticity of variables used in simulation, 6 simulation runs with different seed numbers were performed for each scenario.

A straight, level segment of a two-lane highway with a length of 16 to 18 miles was created in the calibrated simulation model. Two warm-up segments with a length of 12 and 18 miles depending on the traffic volume (18 miles for traffic volumes of 300 and 600 veh/hr and 12 miles for 900 and 1200 veh/hr) were added at each end of the evaluation segment. These segments were used to ensure stable traffic conditions upon reaching the evaluation segment. Figure 53 shows a schematic of a sample experimental set up used in simulation. A total of 4 to 9 passing lanes were used in each direction of the evaluation segment. A transition segment of 1000 ft was used for the two-lane highway section outside of the passing lanes. Detectors were installed within the passing lanes at distances of 0.25, 0.5, 0.75 miles as shown in Figure 53. The average outputs from the 9 detectors along each study module (i.e. 6 detectors within the passing lane and 3 detectors outside of the passing lane) were used to estimate performance for each module. The performance measure used in the analysis is percent followers, i.e. the percent of vehicles with headways equal or less than 2.5 seconds measured at a point location.

Table 37. Ranges and Levels for Study Variables

Variables	Analysis Direction Flow Rate (veh/h)	Opposing Direction Flow Rate (veh/h)	Free Flow Speed (mi/hr)	Length of Passing Lanes (mi)	Number of Passing lanes in each direction	Percent Heavy Vehicles
Levels	300	246	40, 50, 60	0 (base condition)	4, 5, 6, 7, 9	0, 10, 20, 30
	600	491		0.75,		
	900	737		1, 1.25,		
	1200	982		1.5, 1.75, 2		
Ranges	300-1200	246-982	40-60	0.75-2	4-9	0-30

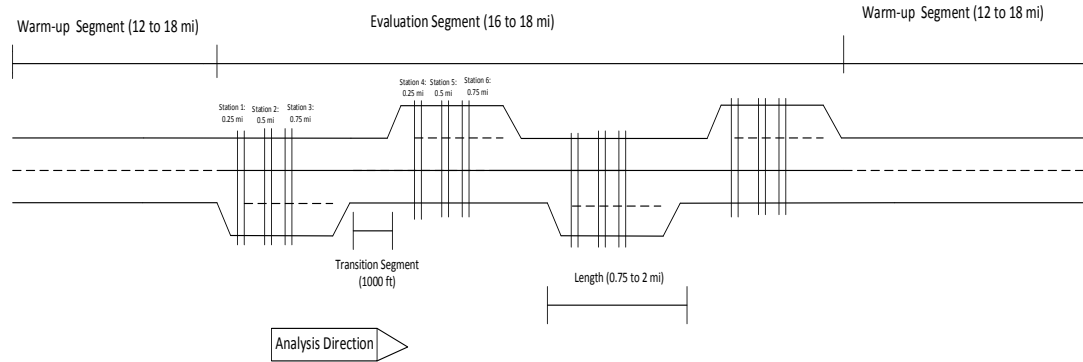


Figure 53. Sample experimental set up

The overall performance of the road network was found using the following equation:

$$PF_{\text{network}} = \frac{PF_1 * Flow_1 + \dots + PF_n * Flow_n}{Flow_1 + \dots + Flow_n}$$

In which PF_{network} shows the weighted average PF for the whole network, PF_n shows the PF at each detector located on a separate lane, and $Flow_n$ shows the traffic volume at the lane where the detector is located. Using this equation, the average performance for each scenario was found.

Study Results

This section provides the results for different simulated scenarios in SwashSim. To have a better understanding of passing lane length effect on platooning, the percent reduction in platooning for each scenario compared to the base scenarios with the same condition, was found. The base scenario is a two-lane highway without any passing lanes and a percent no-passing equal to % 50. The results are shown in Figure 54. As the results

show, for higher flow levels, there is a smaller amount of platoon reduction compared to low flow levels. Moreover, the use of 2+1 roads would reduce the amount of platooning in a range of 35 to 65 percent. A passing lane length of 2 miles has the lowest amount of reduction in platooning for most scenarios, which shows the higher length of passing lane is not necessarily associated with lower platooning on these highways. The panel variables show FFS and percentage of heavy vehicles, respectively.

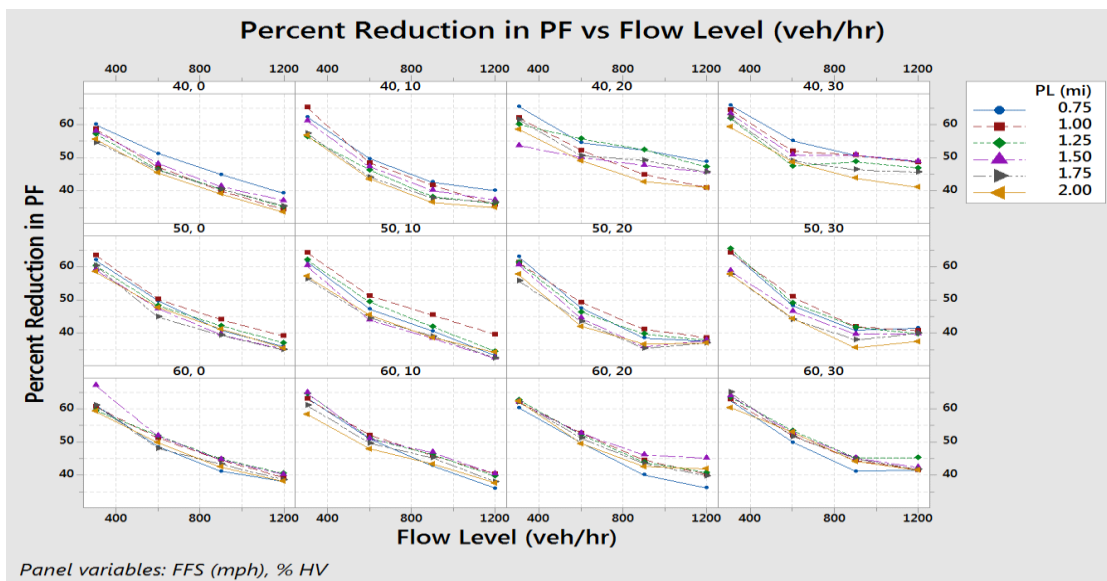


Figure 54. Percent reduction in PF vs Flow Level

Figure 55 shows the trends for average travel speed improvement versus flow level. The trend for ATS is not as clear as PF. It is clear that the speed improvement varies in a very narrow range, in the order of 5 to 10 percent for most scenarios. This observation is also consistent with older studies about ATS being insensitive to variation in flow level and road geometry (Al-Kaisy and Karjala 2008, Al-Kaisy et al. 2017).

Figure 56 shows the graphs for percent improvement in PF versus percentage of heavy vehicles. As the results show, with increase in free flow speed and flow level, sensitivity to percent heavy vehicles decreases. It is clear that the highest improvements are related to low flow levels. The variation in PF improvement is higher for free flow speed of 40 mph.

Figure 57 presents illustrative results showing how PF reduction varies with the increase in free flow speed. There is not a clear pattern for most scenarios.

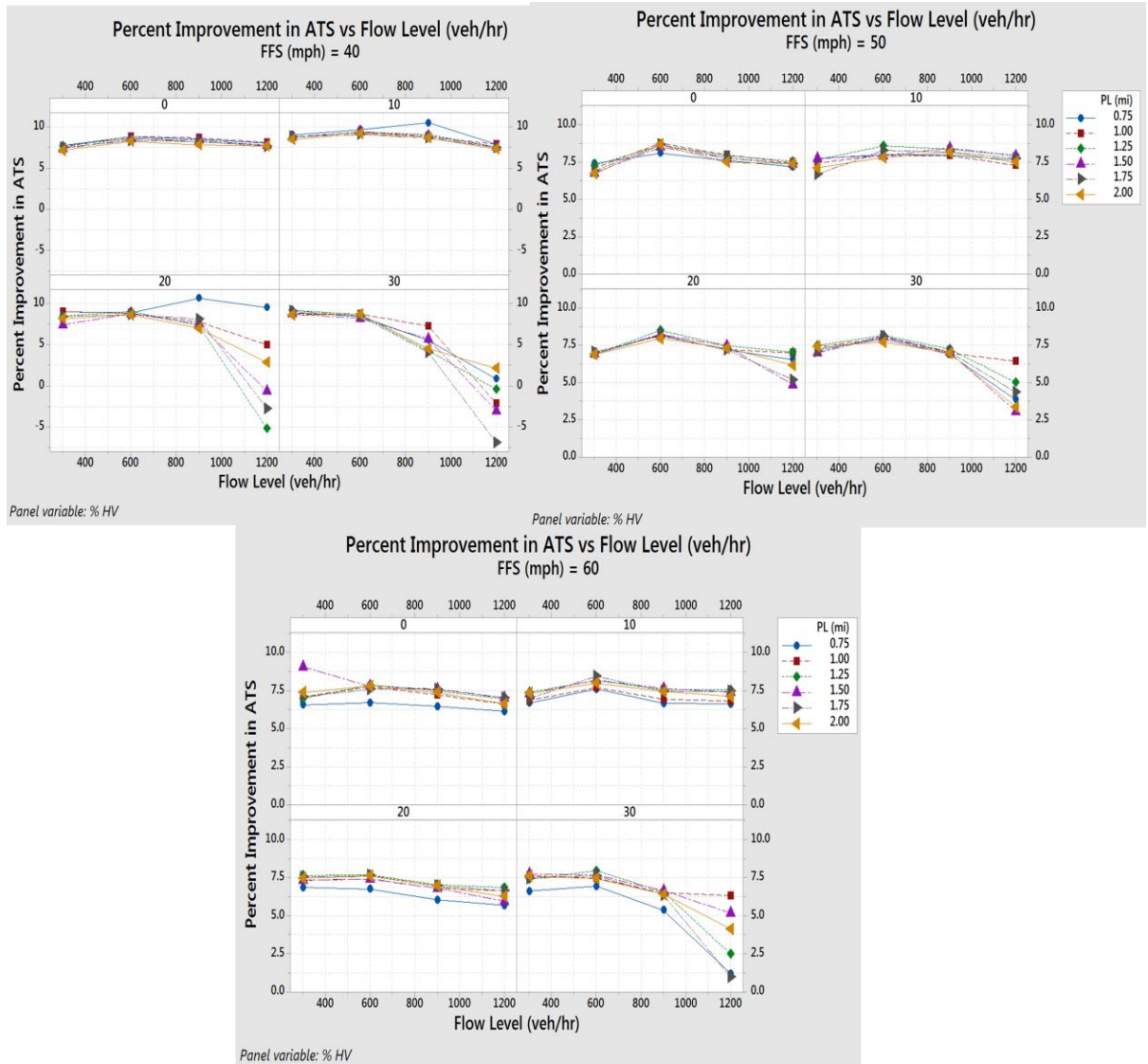


Figure 55. Percent improvement in ATS vs flow level

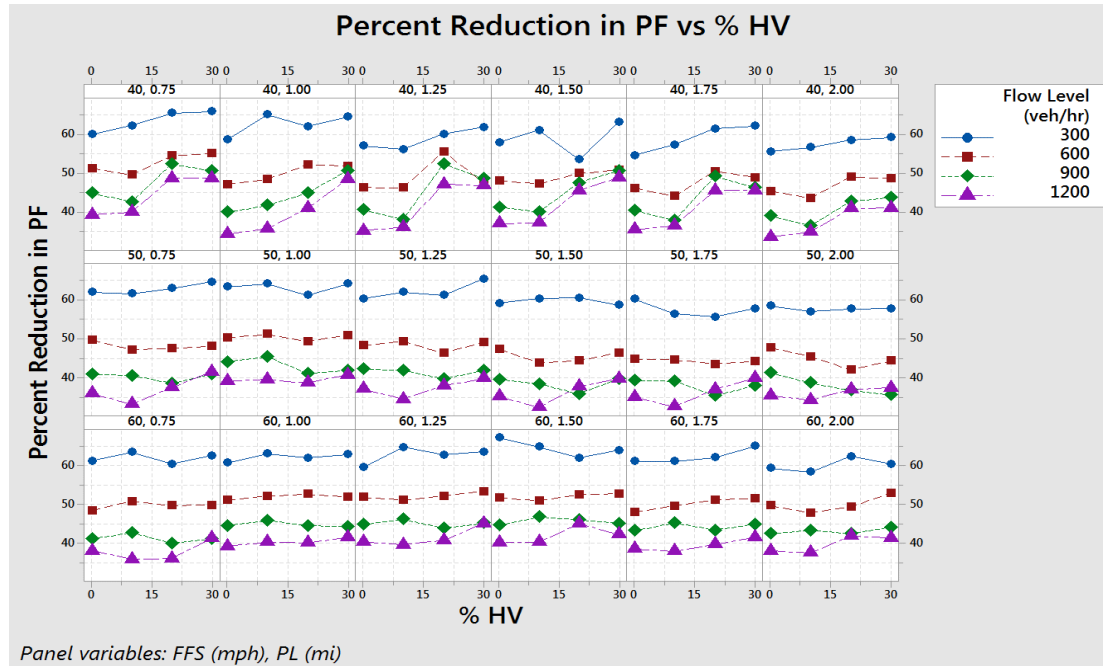


Figure 56. Percent reduction in PF vs % HV

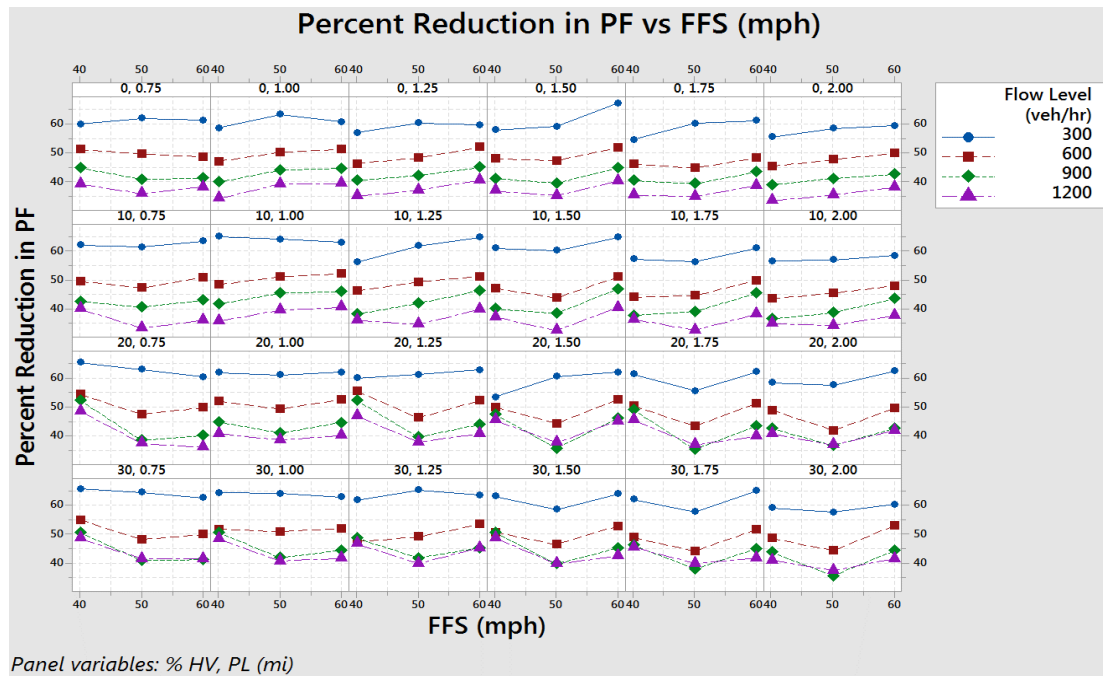


Figure 57. Percent reduction in PF vs FFS

The results from the simulations were used to model the improvement in performance measure (PF) as a function of traffic level, free flow speed, and passing lane length as shown in the equation below:

$$\text{Percent Reduction in PF} = 149.15 - 15.79 * \ln(\text{Flow}) + 0.046 * \text{FFS} - 3.07 * \ln(\text{Passing lane Length})$$

All variables in this model were found statistically significant at 95% confidence level. The coefficient of determination indicates that more than 86 % of the variability in the response variable (Percent reduction in PF) is explained by the three explanatory variables: traffic level, free flow speed, and passing lane length. The percentage heavy vehicles was found to have a minimal effect on platoon reduction. The reason could be related to passing maneuvers happening in the middle lane of 2+1 roads. Most trucks use the right lane of traffic and a change in percentage of them have a minimal effect on platooning.

Optimal Length of Passing Lane Sections on 2 +1 Roads

As mentioned before, six levels of passing lane length (i.e. 0.75, 1, 1.25, 1.5, 1.75 and 2 mi) were used for the experimental design. In this section, the length associated with the highest reduction in PF was found for each scenario. This length is called optimal length of passing section. The results are shown in Table 38.

Table 38. Optimal Length of Passing Lanes (mi) on 2 + 1 Roads

Flow (veh/hr)	FFS (mi/hr)		
	40	50	60
300	1	1	1.5
600	0.75	1	1
900	0.75	1	1.5
1200	0.75	1	1.5

As the results show, an optimum length of 0.75 mi is observed for most scenarios with FFS=40 mph, 1 mi for FFS=50 mph and 1.5 mi for FFS=60 mph. The flow level has a small effect on the optimum length. The optimum length is found to be a function of free flow speed as shown in Figure 58. This could be due to the merge and diverge maneuvers at the transitional zones. At higher speeds, a higher length of passing lane is required for a vehicle to merge back to the original traffic lane.

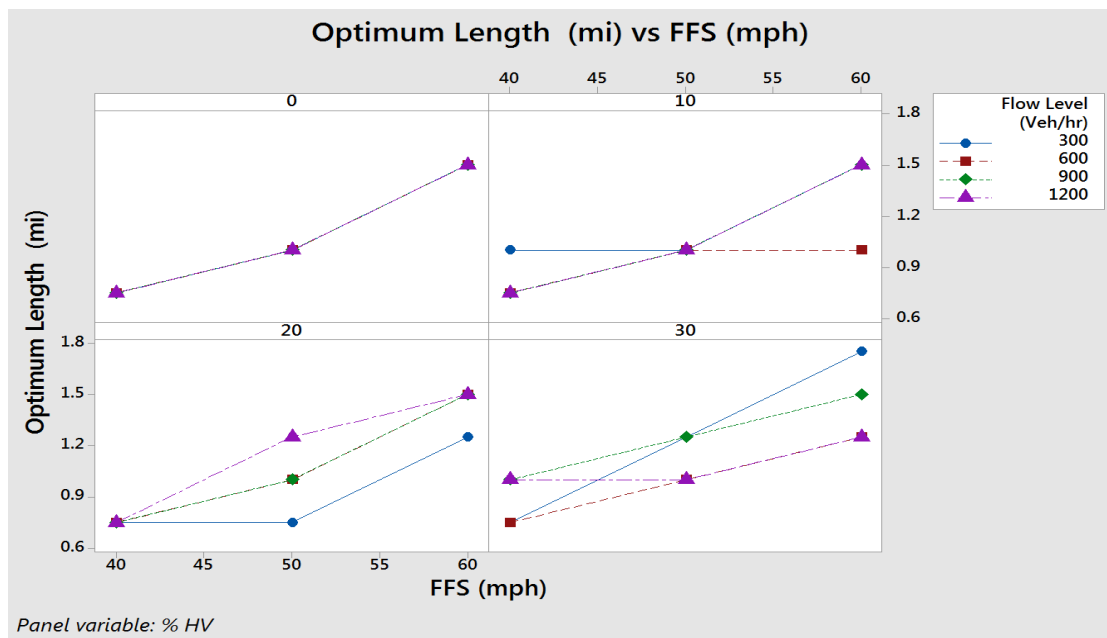


Figure 58. Optimal length of passing sections on 2 + 1 roads

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

Overview

The goal of this study was to examine new performance measures for operational analyses of two-lane highways as well as developing new guidelines for design of passing lanes. Field data from four states including Montana, Idaho, North Carolina and Oregon were used for this purpose. Both field data and simulation analyses using SwashSim software were used.

This chapter summarizes the most important findings of this study under different sections.

Performance Measures Investigation

In an attempt to better understand the transportation agency's perspective with regard to what constitutes a good performance measure for two-lane highways, a questionnaire survey was sent to all state DOTs in the US and the provincial ministries of transport in Canada. The survey also included a few questions about the agency experience with the use of the HCM and proposed changes and revisions to the current analytical procedures. A total of 35 usable responses were received, representing transportation agencies at 25 states and 4 Canadian provinces. The most important findings of the survey on the use of two-lane highway performance measures are summarized below:

- Almost all highway agencies reported the use of the current HCM performance measures on two-lane highways, i.e., average travel speed, percent-time-spent-following, and percent of free flow speed. Among other non-HCM measures used by some agencies were follower density, percent follower for vehicles traveling at headways of less than 2 seconds, traffic flow, delay, v/c ratio and AADT/c ratio.
- While almost all highway agencies in the US and Canada use binned vehicle counts as part of their regular data collection programs on two-lane highways, per vehicle data, which is critical in estimating some performance measures on two-lane highways, is only collected by 17% of the responding agencies. This restricts the ability of those agencies in using many performance measures included in this survey, which require the more detailed per vehicle data.
- The top three criteria that were ranked as being most important characteristics for two-lane highway performance measures are: sensitivity to traffic conditions, sensitivity to road conditions, and relevance to road user perception, respectively.
- Among traffic flow aspects that are most relevant to two-lane highway operations, speed followed by flow were ranked as the most important aspects for all two-lane highway classes.
- With regard to the merit of using individual performance measures within each traffic flow aspect category, the best measures were found to be v/c ratio, average travel speed, PTSF, and overtaking ratio for all two-lane highway classes in the flow, speed, headways and passing maneuvers categories respectively. For the density flow aspect, follower density was found superior on class I and class III

while density was found superior on class II two-lane highways. Percent followers, used by the current HCM as a surrogate measure for PTSF, was associated with much lower average ranking compared with PTSF for all highway classes.

The responses to the practice survey included some of the limitations of the current HCM performance measures from the agencies' perspective, as well as some valuable suggestions and feedback on two-lane highway performance measures that were discussed in the study. This information is expected to help in the selection of the most appropriate performance measure(s) for use in future methodologies of two-lane highway operational analysis.

An empirical investigation of several performance measures for operational analysis on two-lane highways was also conducted. Graphical examination, correlation and regression analyses were conducted to better understand the relationship between performance measures and traffic variables.

- Composite measures showed highest correlations followed by the headway-related measure (percent followers) and speed-related measures respectively. Among all composite measures, follower flow followed by follower density exhibited highest correlations with traffic variables.
- In regards to traffic variables, combined flow exhibited highest correlations with performance measures followed by traffic split which reflects the proportion of traffic in the analysis direction.
- Speed variance and percentage of heavy vehicles exhibited the lowest correlations with performance measures.

- No major differences were observed between different classes of highways, however, the model for ATS/FFS showed higher R^2 compared to other highway classes.

Findings from this study provide valuable information about the merits, or lack thereof, of many performance measures that were either used in practice or proposed in the literature. This information is expected to help in the selection of the most appropriate performance measure(s) for use in future methodologies of two-lane highway operational analysis. It is recommended that further research be conducted on the new performance measures using data from a wide variety of locations with a wide range of traffic conditions.

Car Following Investigation

An empirical investigation into the car-following interaction and the estimation of percent followers on rural two-lane highways was conducted. Field data from 15 study sites in Idaho, Montana and Oregon were used in this investigation. The most important findings of this study are summarized as follows:

- Results from the speed-headway investigation suggest that the critical headway (h_{cr}) varies approximately in the range between a lower limit of 1 to 2 seconds and an upper limit of 6 to 7 seconds, with the majority of sites having a range between 1 and 7 seconds.
- Vehicles traveling at perceived minimum safe headways increase in number as headways get smaller. While pairs of vehicles in free-flow state may still travel at

the same speed, the percentage of these vehicles increases steadily as more vehicles enter into the following state.

- Results from the analysis for determining percent follower headway cut-off value suggest that for class I highway, this value is likely to fall in the range of 1.8 and 2.8 seconds, lower than the current value used by HCM of 3 seconds. For class II and III sites, results suggest values that are slightly higher than 3 seconds.

Further research is needed using data from more study sites, particularly on class II and class III highways, to affirm the findings of this study and gain additional insights into car-following parameters on rural two-lane highways. Moreover, other variables that may have an effect on the car following process such as traffic level and light condition were not investigated in this study.

Passing Lanes Investigation

The focus of this investigation was the determination of the effective and optimum length of passing lanes as well different configurations of passing lanes on rural two-lane highways using empirical data and traffic simulation. Field data from two study sites in Oregon were used to calibrate and validate the traffic simulation program. The calibrated simulation program was then used in evaluating the effective length of passing lane under various traffic levels and percent no-passing zones.

- A method was presented for demarking the end of passing lane effective length, a point where platooning level practically reaches a steady (equilibrium) state.

- Study results showed that both traffic level and percent no-passing have considerable effect on the effective length of passing lane.
- Further, results confirmed that the operational benefits of passing lanes generally last for a significant distance downstream of the passing lane.
- Using the proposed method for demarking the end of effective length, this distance varied approximately between 6 and 20 miles, depending on traffic level and percent no passing zones.
- As expected, higher traffic levels and higher percentages of no-passing zones were found to result in shorter effective lengths. The effective lengths found in this study are relatively longer than the values suggested by the Highway Capacity Manual (HCM).

Three approaches were used in identifying the passing lane optimum length: Traffic split within passing lane section, an approach used by an older study which forms the basis for the current HCM guidance, and a new approach proposed by this study. The older approach yielded results that are inconsistent with the current practice (HCM guidance) and the general understanding of passing lane effectiveness on two-lane highways. Using results from the new proposed approach, the following conclusions can be made:

- The optimum length of passing lane varied roughly in the range between 0.8 mi and 2.0 mi depending on traffic level.
- Higher traffic levels are generally associated with longer passing lane optimum lengths, and vice versa.

- Within the range investigated in this study (0.5 mi to 3.0 mi), traffic performance continued to improve with the increase in passing lane length.
- The passing lane optimum length derived using the new proposed approach corresponds closely to lengths representing a 22.5% performance improvement (reduction in PF).
- The optimum lengths found in this study are relatively longer than the values suggested by the Highway Capacity Manual (HCM).

The above findings along with the rest of the results from this study could be used in refining the current guidelines in determining the optimum length of passing lanes as it is based on more recent field data and a state-of-the-art traffic simulation tool. Future research is needed to address other factors that might affect the optimum length of passing lanes such as grade and heavy vehicle percentage.

An evaluation of different configurations of passing lanes, in terms of passing lane length and spacing, was also conducted in this study. Traffic simulation was used to investigate the effect of different lengths and spacings of passing lanes on highway performance for different traffic levels. Field data from two study sites in Oregon were used to calibrate and validate the traffic simulation program. To account for the economic effectiveness of passing lane configurations, an “Effectiveness Index” was introduced in this study, which refers to the ratio of performance improvement to total length of passing lanes used along the highway segment. The most important findings of this study are:

- Longer passing lanes and shorter spacings are associated with greater reductions in traffic platooning, i.e. greater improvement in performance.

- The improvement in performance is higher for low traffic volumes.
- At lower traffic levels (flow rates of 200 and 400 veh/h in this investigation), passing lane lengths in the range of 0.75 to 1.25 miles and spacings in the range of 6 to 15 miles yielded the most cost-effective configurations.
- At higher traffic levels (flow rates of 600 and 800 veh/h in this investigation), passing lane lengths in the range of 1 to 2 miles and spacings in the range of 5 to 9 miles yielded the most cost-effective configurations.

The findings from this study are valuable for the planning and design of passing lanes on two-lane highways. Further research is needed to investigate the effect of other variables on the performance of two-lane highways with passing lanes such as grades, and terrain type.

Different configurations of 2 + 1 roads were also investigated using traffic simulation. The highway performance under different traffic levels, free flow speed, percentage of heavy vehicles and for different lengths of passing lanes was evaluated using the calibrated traffic simulation model. The most important findings of this study are:

- The improvement in performance is higher for low traffic volumes.
- 2+1 roads reduce the amount of platooning on a two-lane highway in a range of 35 to 65 percent.
- The average travel speed on 2+1 roads is 5 to 10 percent higher compared to conventional two-lane highways with the same volume.
- The optimal length of passing lane was found to be a function of free flow speed. At higher free flow speeds, a higher length of passing lane is needed

REFERENCES CITED

1. AASHTO. A Policy on Geometric Design of Highways and Streets, 6th edition, 2011.
2. A. May. Traffic Performance and Design of Passing Lanes. Transportation Research Record, Journal of the Transportation Research Board, No. 1303, TRB, Washington, D. C., 1991, pp. 63-73.
3. Abdul-Mawjoud A. A., and G. G. Sofia. Development of Models for Predicting Speed on Horizontal Curves for Two-Lane Rural Highways. In Arabian Journal for Science and Engineering, Volume 33, Issue 2 B, 2008.
4. Al-Kaisy, A., and C. Durbin. Platooning on Two-lane Two-way Highways: an Empirical Investigation. In Journal of Advanced Transportation, Volume 43, Issue 1, 2009, pp. 71-88.
5. Al-Kaisy, A., and S. Karjala. Car-Following Interaction and the Definition of Free-Moving Vehicles on Two-Lane Rural Highways. In ASCE Journal of Transportation Engineering, Volume 136, Issue 10, 2010.
6. Al-Kaisy, A., and S. Karjala. Indicators of Performance on Two-Lane Rural Highways: An Empirical Investigation. Transportation Research Record: Journal of the Transportation Research Board, No. 2071, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 87-97.
7. Al-Kaisy, A., and Z. Freedman. Empirical Examination of Passing Lane Operational Benefits on Rural Two-Lane Highways. Journal of Transportation Research Forum, Vol. 49, No. 3, 2010, pp. 53-68.
8. Al-Kaisy, A., and Z. Freedman. Estimating Performance on Two-Lane Highways: Case Study Validation of a New Methodology. Transportation Research Record 2173, Journal of the Transportation Research Board, TRB, National Research Council, Washington, D. C., 2010, pp. 72-79.
9. Al-Kaisy, A., **Jafari, A.**, S. Washburn. Following Status and Percent Followers on Two-Lane Two-Way Highways: Empirical Investigation. Presented at 96th Annual Meeting of the Transportation Research Board, 2017, Washington D.C.
10. Al-Kaisy, A., **Jafari, A.** and S. Washburn. Measuring Performance on Two-Lane Highways: Empirical Investigation. Transportation Research Record, Journal of the Transportation Research Board, No. 2615, 2017. [DOI: 10.3141/2615-08](https://doi.org/10.3141/2615-08).
11. Al-Kaisy, A., **Jafari, A.**, S. Washburn. Measuring Performance on Two-Lane Highways: Empirical Investigation. Presented at 96th Annual Meeting of the Transportation Research Board, 2017, Washington D.C.

12. Al-Kaisy, A., **A. Jafari**, S. Washburn, T. Lutinnen, and R. Dowling. Performance measures on two-lane highways: Survey of practice. *Research in Transportation Economics*, 2018, [DOI: 10.1016/j.retrec.2018.07.001](https://doi.org/10.1016/j.retrec.2018.07.001).
13. Al-Kaisy, A., **Jafari, A.**, S. Washburn, S., Lutinnen, T., and R. Dowling. Performance Measures on Two-Lane Highways: Survey of Practice. Presented at 95th Annual Meeting of the Transportation Research Board, 2016, Washington D.C.
14. Al-Kaisy, A., **Jafari, A.**, S. Washburn, S., Lutinnen, T., and R. Dowling. Traffic Operations on Rural Two-Lane Highways: a Review on Performance Measures and Indicators. Presented at 97th Annual Meeting of the Transportation Research Board, 2018, Washington D.C.
15. Al-Kaisy, A., **A. Jafari**, S. Washburn, T. Lutinnen, and R. Dowling. Traffic Operations on Rural Two-Lane Highways: A Review on Performance Measures and Indicators. *Transportation Research Record, Journal of the Transportation Research Board*, 2018, [DOI:10.1177/0361198118774743](https://doi.org/10.1177/0361198118774743).
16. American Association of State Highway and Transportation Official (AASHTO). *A Policy on Geometric Design of Highways and Streets*, 6th Edition. 2011.
17. Bennett, C.R., and R. C. M. Dunn. Critical Headways on Two-Lane Highways in New Zealand. *Proceedings of the second international symposium on Highway Capacity*, 1994, Volume 1, pp. 91-100.
18. Bergh, T., M. Remgard, A. Carlsson, J. Olstam, and P. Strömgren 2+1-roads Recent Swedish Capacity and Level-of-Service Experience, ISEHP 2016. *International Symposium on Enhancing Highway Performance*, 2016.
19. Bessa, J.E. and J.R. Setti. Deviation of ATS and PTSF Functions for Two-lane, Rural Highways in Brazil. Presented at the 6th International Symposium on Highway Capacity and Quality of Service, 2011.
20. Brewer, M., S. Venglar, and L. Ding. Operational Characteristics of Super 2 Highways in Texas. *Transportation Research Record, Journal of the Transportation Research Board*, No. 2223, TRB, Washington, D. C., 2011, pp. 34-42.
21. Brilon, W., and F. Weiser. Two-Lane Rural Highways: The German Experience. *Transportation Research Record 1988: Journal of the Transportation Research Board*, TRB, National Research Council, Washington, D. C., 2006, pp. 38-47.
22. Cafiso, S., C. D'Agostino, and M., Kiec. Investigating the influence on safety and traffic performance of 2+1 road sections in Poland, 2015.

23. C.J. Hoban. Measuring Quality of Service on Two-lane Rural Roads. Australian Road Research Board Conference Proceedings, 1984, pp. 117-131.
24. Catbagan, J. and Nakamura, H. Evaluation of Performance Measures for Two-Lane Expressways in Japan. Transportation Research Record 1988, Journal of the Transportation Research Board, TRB, National Research Council, Washington, D.C., 2006, pp. 111-118.
25. Catbagan, J. L. and Nakamura, H. An improved follower recognition procedure to estimate follower flow based quality of service measures. In Journal of the Eastern Asia Society for Transportation Studies (EASTS) Vol. 8, 2010, pp. 1822-1837.
26. Chae, C., D.M., Lee, and H., Cho. Evaluation of 2+1 Roads Application to Improve Rural Two-lane Highway in Korea. International Journal of Highway Engineering. Vol. 15 No. 3: 85-92 June 2013, <http://dx.doi.org/10.7855/IJHE.2013.15.3.085>.
27. Choi, J., Y. Kim, T. Bergh, S. Kim, and S. Kim. Sustainable Design of Rural Roads with 2+1 Road Design: Levels of Service and Traffic Flow Performance. KSCE Journal of Civil Engineering. No. 20(3), 2016, pp. 1032-1039, [DOI 10.1007/s12205-016-1696-1](https://doi.org/10.1007/s12205-016-1696-1).
28. Dijkster, T., Bovy, P.H.L., and R. G. M. M. Vermijs. Car-Following Under Congested Conditions Empirical Findings. In Transportation Research Record: Journal of the Transportation Research Board, No. 1644, Transportation Research Board of the National Academies, Washington, D. C., 1998, pp. 20-28.
29. Dixon, M. P., S. S. K. Sarepali, and K. A. Young. Field Evaluation of Highway Capacity Manual 2000 Analysis Procedures for Two-Lane Highways. In Transportation Research Record: Journal of the Transportation Research Board, No. 1802, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 125–132.
30. Enberg, A., and M. Pursula. Traffic Flow Characteristics on a Three-Lane Rural Highway in Finland: Results from Empirical Studies and Simulations. Transportation Research Record, Journal of the Transportation Research Board, No. 1572, TRB, Washington, D. C., 1997, pp. 35-42.
31. Evans, L., and P. Wasielewski. Risky Driving Related to Driver and Vehicle Characteristics. In Journal of Accident Analysis & Prevention, Volume 15, Issue 12, 1983, pp. 121-136.
32. Federal Highway Administration. Manual on Uniform Traffic Control Devices, 2009.

33. Federal Highway Administration, Highway Statistics 2016, FHWA, Office of Highway Policy Information, Retrieved March 04, 2018 from: <https://www.fhwa.dot.gov/policyinformation/statistics/2016/hm55.cfm>
34. Figueroa, A. M., and A. P. Tarko. Speed Factors on Two-lane Rural Highways in Free-flow Conditions. 84th Annual Meeting of the Transportation Research Board, 2005, Washington D.C.
35. Fitzpatrick, K., Miaou, S., Brewer, M., Carlson, P., and M. D. Wooldridge. Exploration of the Relationships between Operating Speed and Roadway Features on Tangent Sections. In ASCE Journal of Transportation Engineering, Volume 131, Issue 4, 2005.
36. Freedman, Z., and A. Al-Kaisy. Investigation of Performance and Lane Utilization within a Passing lane on Two-lane Rural Highway. International Journal for Traffic and Transport Engineering, Vol. 3, issue 3, 2013, pp. 279-290.
37. Gattis, J., R. Bhawe, and L. Duncan. Alternating Passing Lane Length. Transportation Research Record, Journal of the Transportation Research Board, No. 1961, TRB, Washington, D. C., 2006, pp. 16-23.
38. Ghosh, I., Chandra, S. and Boora, A. Operational Performance Measures for Two-Lane Roads: An Assessment of Methodological Alternatives. 2nd Conference of Transportation Research Group of India (2nd CTRG), Agra, India, Procedia - Social and Behavioral Sciences 104, Elsevier, December 12-15, 2013, pp. 440 – 448.
39. Guell, D.L., and M.R. Virkler. Capacity Analysis of Two-lane Highways. In Transportation Research Record: Journal of the Transportation Research Board, No. 1194, Transportation Research Board of the National Academies, Washington, D. C., 1988, pp. 199-203.
40. Handbuch fuer die Bemessung von Strassen (German Highway Capacity Manual). HBS 2001. German Road and Transportation Research Association, Cologne, 2005.
41. Harwood, D. and A. St. John. Operational Effectiveness of Passing Lanes on Two-Lane Highways. Federal Highway Administration, Report No. FHWA-RD-86-195, 1986.
42. Harwood, D. and A. St. John. Passing Lanes and Other Operational Improvements on Two-Lane Highways. Federal Highway Administration, Report No. FHWA-RD-85-028, 1985.
43. Harwood, D., A. St. John, and D. L. Warren. Operational and safety Effectiveness of Passing Lanes Two-Lane Highways. Transportation Research Record, Journal of the Transportation Research Board, No. 1026, TRB, Washington, D. C., 1987, pp. 31-39.

44. Harwood, D., and C.J. Hoban. Low-cost Methods for Improving Traffic Operations on Two-lane Roads: Informational Guide. Midwest Research Institute and Federal Highway Administration. Report No. FHWA/IP-87/2. Contract No. DTFH61-82-C-00070, 1987.
45. Hashim, I. and T.A. Abdel-Wahed. Evaluation of Performance Measures for Rural Two-Lane Roads in Egypt. Alexandria Engineering Journal, No. 50, 2011, pp. 245-255.
46. Hashim, I. H. Analysis of Speed Characteristics for Rural Two-lane Roads: A Field Study from Minoufiya Governorate, Egypt. In Ain Shams Engineering Journal, Volume 2, Issue 1, 2011, pp. 43-52.
47. Highway Capacity Manual: Highway Research Board and Bureau of Public Roads, Washington, D.C., 1950.
48. Hoogendoorn, S.P. Unified Approach to Estimating Free Speed Distributions. In Transportation Research Part B, Volume 39, Issue 8, 2005, pp. 709-727.
49. Ibrahim, M., and O. C. Puan. Measuring Driver's Percent-Time-Spent-Following Using a Moving Video Recording Technique. Journal of Applied Mechanics and Materials, Vol. 567, pp. 736-741.
50. **Jafari, A.**, Al-Kaisy, A., S. Washburn. Investigation of Passing Lane Effective Length on Two-Lane Two-Way Highways. Presented at 97th Annual Meeting of the Transportation Research Board, 2018, Washington D.C.
51. **Jafari, A.**, Al-Kaisy, A., S. Washburn. Evaluation of Passing Lane Design Configurations on Two-Lane Highways. Presented at 97th Annual Meeting of the Transportation Research Board, 2018, Washington D.C.
52. **Jafari, A.**, A. Al-Kaisy, and S. Washburn. Evaluation of the Effective Length of Passing Lanes on Two-Lane Highways. Journal of Transportation Letters, 2019. DOI: [10.1080/19427867.2019.1586329](https://doi.org/10.1080/19427867.2019.1586329).
53. **Jafari, A.**, Al-Kaisy, A., S. Washburn. Investigation of Passing Lane Optimum Length on Two-Lane Highways. Presented at 98th Annual Meeting of the Transportation Research Board, 2019, Washington D.C.
54. **Jafari, A.**, Al-Kaisy, A., S. Washburn. Investigation of Passing Section Optimal Length on 2+1 Highways. Presented at 98th Annual Meeting of the Transportation Research Board, 2019, Washington D.C.

55. **Jafari, A.**, and A. Al-Kaisy. Investigation of side-by-side passing lane length and spacing on two-lane highways. *Journal of Advances in Transportation Studies: an international Journal Section A* 46, 2018. PP 31-42.
56. **Jafari, A.**, A. Al-Kaisy, and S. Washburn. Passing Lane Optimum Length on Two-Lane Highways. *Canadian Journal of Civil Engineering*, 2018. DOI: [10.1139/cjce-2017-0723](https://doi.org/10.1139/cjce-2017-0723).
57. Kirby, P., B. Wilmshurst, and G. Koorey. Operating characteristics and economic evaluation of 2+1 lanes with or without intelligent transport systems assisted merging. NZ Transport Agency research report 549. 102pp.
58. Lay, M.G. *Handbook of Road Technology*, Gordon and Breach, 1986.
59. Lee, D.M. , C. Chae, H.Cho, and S.K. Lee. Estimation of Design Service Traffic Volume for 2+1 Roads Based on Korean Two-Lane Highway Conditions. *Journal of Korean Society of Transportation*. Vol.31, No.2, pp.3-10, April 2013, <http://dx.doi.org/10.7470/jkst.2013.31.2.003>.
60. Li, Jing and Washburn, Scott S. Improved Operational Performance Assessment for Two-Lane Highway Facilities. *Journal of Transportation Engineering*, American Society of Civil Engineers. Reston, VA, Vol. 140, Issue 6, June 2014, pp. 04014017-1/04014017-9.
61. Lobo, A., Jacques, M. A. P., Rodrigues, C. M., and A. Couto. Free-Gap Evaluation for Two-Lane Rural Highways. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2223, Transportation Research Board of the National Academies, Washington, D. C., 2011, pp. 9-17.
62. Luttinen, T. Percent Time-Spent-Following as a Performance Measure for Two-Lane Highways. *Transportation Research Record* 1776, *Journal of the Transportation Research Board*, TRB, National Research Council, Washington, D.C., 2001, pp. 52-59.
63. Luttinen, T., Dixon, M., Washburn, S. (2005). Two-Lane Highway Analysis in HCM2000: Draft White Paper. Retrieved May 24, 2015, from: sites.kittelson.com/hcqs-twolanehwy/Downloads/Download/2546
64. McLean, J. *Two-Lane Highway Traffic operations: Theory and Practice*. *Transportation Studies Volume 11*, Gordon and Breach Science Publishers, 1989.
65. Moreno, A., Llorca, C., Garcia, A., and A. Zuriaga. Operational Effectiveness of Passing Zones Depending on Length and Traffic Volume. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2395, Transportation Research Board of the National Academies, Washington, D. C., 2013, pp. 57-65.

66. Moreno, A., Llorca, C., Sayed, T., and A. Garcia. Field Evaluation of Traffic Performance Measures for Two-Lane Highways in Spain. Presented at 93rd Annual Meeting, Transportation Research Board, Washington, D. C., 2014.
67. Moreno, A., Llorca, C., Lenorzer, A., Casas, J., and A. Garcia. Minimum Passing Zone Length Design Criteria Considering Operational and Safety Impacts. Presented at 94th Annual Meeting, Transportation Research Board, Washington, D. C., 2015.
68. Moreno, A. Effect of Average Passing Zone Length on Spanish Two-Lane Highways Traffic Performance. Presented at 95th Annual Meeting, Transportation Research Board, Washington, D. C., 2016.
69. Morrall, J. F., and A. Werner. Measuring Level of Service of Two-Lane Highways by Overtakings. Transportation Research Record 1287, Journal of the Transportation Research Board, TRB, National Research Council, Washington, D. C., 1990, pp. 62-69.
70. Morrall, J., E. Miller Jr., G. A. Smith, J. Feuerstein and F. Yazdan. Planning and Design of Passing Lanes Using Simulation Model. ASCE Journal of Transportation Engineering, No. 121, 1995, pp. 50-62.
71. Mutabazi, M., E. R. Russell, and R. W. Stokes. Location and Configuration of Passing Lanes. Transportation Research Record, Journal of the Transportation Research Board, No. 1658, TRB, Washington, D. C., 1999, pp. 25-33.
72. Nakamura, H. and Oguchi, T. An Investigation on Performance Measures for Two-Lane Expressways in Japan. Proceedings of the 5th International Symposium on Highway Capacity and Quality of Service. Vol.2: Technical Papers. Tokyo: Japan Society of Traffic Engineers, 2006, pp. 87–104.
73. NCHRP Research Results Digest. Application of European 2+1 Roadway Designs, 2003.
74. Oregon Department of Transportation. Modeling Performance Indicators on Two-Lane Rural Highways: The Oregon Experience. Retrieved December 11, 2014, from <http://www.oregon.gov/odot/td/tp/docs/reports/modelingperf.pdf>
75. Pasanen, E., and H. Salmivaara. Driving Speeds and Pedestrian Safety in the City of Helsinki. In Journal of Traffic Engineering & Control. , Volume 34, Issue 6, 1993, pp. 308-310.
76. Penmetsa, P., Ghosh, I., and S. Chandra. Evaluation of Performance Measures for Two-Lane Intercity Highways under Mixed Traffic Conditions. Journal of Transportation Engineering, Volume 141, issue 10, 2015, pp. 1-7.

77. Polus, A. and M. Cohen. Theoretical and empirical relationships for the quality of flow and for a new level of service on two-lane highways. *Journal of Transportation Engineering*, Vol135, No. 6, 2009, pp. 380-385.
78. Polus, A., Fitzpatrick, K., and D.B. Fambro. Predicting Operating Speeds on Tangent Sections of Two-Lane Rural Highways. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1737, Transportation Research Board of the National Academies, Washington, D. C., 2000, pp. 50-57.
79. Potts, I. B., and D.W. Harwood. Benefits and Design/Location Criteria for Passing Lanes. Missouri Department of Transportation, Report No. RTD-04 -008, 2004.
80. Romana, M. G., and I. Pérez. Measures of Effectiveness for Level-of-Service Assessment of Two-Lane Roads: An Alternative Proposal Using a Threshold Speed. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1988, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 56–62.
81. Rong, J., Guo, J. and Zhou, R. Chinese Highway Capacity Research Studies and Applications. In H.N. & Bang, K.L. (ed.), 6th International Symposium on Highway Capacity and Quality of Service – Country Reports. Stockholm: TRB and KTH, 2011, pp. 52–66.
82. Shiomi, Y., Yoshii, T., and R. Kitamura. Platoon Based Traffic Flow Model for Estimating Breakdown Probability at Single-lane Expressway Bottlenecks. In *Transportation Research Part B*, Volume 45, Issue 9, 2011, pp. 1314-1330.
83. Special Report 209: Highway Capacity Manual, 3rd ed. (1997 update). TRB, National Research Council, Washington, D.C., 1985.
84. Special Report 87: Highway Capacity Manual, 2nd ed. Highway Research Board, Washington, D.C., 1965.
85. Trafikverket (2014). TRVMB Kapacitet och framkomlighetseffekter. TRV 2013:64343.
86. Transportation Research Board. Highway Capacity Manual. Fourth Edition, TRB, National Research Council, Washington, D. C., 2000.
87. Transportation Research Board. Highway Capacity Manual. Fifth Edition, TRB, National Research Council, Washington, D. C., 2010.
88. Transportation Research Board. Highway Capacity Manual. Sixth Edition, TRB, National Research Council, Washington, D. C., 2016.

89. Yu, Qingyong and Washburn, Scott S. Operational Performance Assessment for Two-Lane Highway Facilities. *Journal of Transportation Engineering*, American Society of Civil Engineers, Reston, VA, Vol. 135, Issue 4, April 2009, pp. 197-205.
90. Van As, C. and A. Niekerk. The Operational Analysis of Two-Lane Rural Highways, 23rd Annual Southern African Transport Conference, Pretoria, South Africa, 2004.
91. Van As, C. Technical Reference Manual Highway Traffic Model. South African National Roads Agency, 2014.
92. Van As, C. The Development of an Analysis Method for the Determination of Level of Service on Two-Lane Undivided Highways in South Africa: Project Summary. South African National Roads Agency, Limited, Pretoria, 2003.
93. Vejdirektoratet. Kapacitet og serviceniveau. Vejdirektoratet, Vejregelrådet. – Road Standards for Capacity and Level of Service (in Danish). 2010.
94. Vogel, K. What Characterizes a “Free Vehicle” in an Urban Area? In *Transportation Research Part F*, Volume 5, Issue 1, 2002, pp. 15-29.
95. Washburn, S., McLeod, S. and G.K. Courage. Adaptation of Highway Capacity Manual 2000 for Planning-Level Analysis of Two-Lane and Multi-Lane Highways in Florida, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1802, 2002, pp. 62-68.
96. Washburn, S. SwashSim Traffic Simulation Program, User Guide for the Two-Lane Highway Module. University of Florida, 2017.
97. Washburn, S., A. Al-Kaisy, T. Lutinnen, R. Dowling., D. Watson, **A. Jafari**, B. Zilin, and A. Alias. *NCHRP 17-65 Report: Improved Analysis of Two-Lane Highway Capacity and Operational Performance*. Transportation Research Board, Washington, D.C., 2018. <https://doi.org/10.17226/25179>.
98. Wasielewski, P. Car-Following Headways on Freeways Interpreted by the Semi-Poisson Headway Distribution Model. In *Journal of the Transportation Science*, Volume 13, Issue 1, 1979, pp. 36-55.
99. Wooldridge, M., Messer, C., Heard, B., Raghupathy, S., Parham, A., Brewer, M., and S. Lee. Design Guidelines for Passing Lanes on Two-Lane Roadways. Federal Highway Administration, Report No. FHWA-TX-02-4064, 2001.

LIST OF ACRONYMS

% NP	Percent No-Passing
% HV	Percentage of Heavy Vehicles
ATS	Average Travel Speed
ATS/FFS	Average Travel Speed to Free Flow Speed
ATS _{pc}	Average Travel Speed of Passenger Cars
AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
FD	Follower Density
FF	Follower Flow
FFS _{PC}	Free-Flow Speed of Passenger Cars
FHWA	Federal Highway Administration
h_{min}	Minimum Safe Headway
h_{cr}	Critical Headway
h_{agg}	Aggressive Driver Headways
h_{con}	Conservative Driver Headways
HCM	Highway Capacity Manual
ID	Impeded Density
IF	Impeded Flow
LOS	Level of Service
PF	Percent Followers
PI	Percent Impeded
PFFS	Percent Free Flow Speed
PTD	Percent Time Delay
PTSF	Percent Time Spent Following
v/c	Volume to Capacity Ratio

APPENDICES

APPENDIX A

SURVEY QUESTIONNAIRE

**NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
NCHRP PROJECT 17-65**

**Improved Analysis of Two-Lane Highway Capacity and
Operational Performance**

Two-lane highways account for a very significant portion of the national highway system and serve an essential function for the movement of people and goods. As urban areas continue to see growth further away from the central cities, two-lane highways in previously less developed areas are experiencing increases in traffic demand. Having good and accurate analysis methods for two-lane highways may allow roadway design and traffic engineers to identify ways to make significant improvements to the operational performance on two-lane highways.

The objective of this survey is to identify appropriate performance measures for operational and capacity analyses of two-lane highways to be included in a future edition of the Highway Capacity Manual (HCM). This survey should be completed by those in your agency who are familiar with two-lane highway operational analysis. Participation is voluntary, and you can choose not to answer any question that you do not want to answer, and you can stop at any time. The survey has 17 questions in total and is expected to take 15-20 minutes. Thank you in advance for your participation.

Please respond to the survey by 06/29/2015 and provide any comments or questions to:

**Dr. Ahmed Al-Kaisy
Montana State University, Civil Engineering Department
P.O. Box 173900, Bozeman, MT 59717
aalkaisy@ce.montana.edu**

Contact Information

Name	
Title	
Agency	
Phone	
Email	
Website	

1. Does your agency currently use the 2010 Highway Capacity Manual (HCM) procedures for the operational analysis of two-lane highways?

• Yes ☐ No ☐

2. If no to question 1, what other procedures, methods or guidelines are currently used by your agency?

3. What performance measures are used by your agency in two-lane highway operational analysis? Check all that apply.

- ☐ Average travel speed (ATS)
- ☐ Percent time spent following (PTSF)
- ☐ Average speed as a percent of free-flow speed (PFFS)
- ☐ Percentage of vehicles traveling at headways of less than (____) seconds
- ☐ Follower density
- ☐ Other (please specify)

4. What types of data does your agency collect to estimate performance measures on two-lane highways? Check all that apply.

- ☐ Speed measurements (binned)
- ☐ Vehicle counts (binned)
- ☐ Heavy vehicle counts (binned)
- ☐ Per-vehicle headway data
- ☐ Per-vehicle speed data
- ☐ Individual vehicle classifications

☐ Other (please specify)

5. What criteria are currently considered by your agency in determining when to add a passing or climbing lane?
6. What criteria are currently considered by your agency in determining when to expand a two-lane highway into a continuous three-lane section or a multilane highway?
7. Based on your agency's experience, do the two-lane highway performance measures used by your agency fully satisfy the agency's needs?
 - Yes ☐ No ☐
8. If you answered "No" to the previous question, what specific improvements do you recommend for the HCM 2010 two-lane highway analysis methodology, especially with respect to performance measures that you think would improve your agency's ability to properly analyze two-lane highway operations?

The HCM 2010 currently requires a two-lane highway to be classified into one of three categories for the purpose of identifying the appropriate performance measure(s) for level of service analysis. Those classes are:

- Class 1: High-speed intercity routes and major connectors in rural areas (performance measures: PTSF and ATS)
- Class 2: Medium-speed access and recreational routes in rural areas (performance measure: PTSF)
- Class 3: Medium to low-speed routes in developed areas and/or scenic routes (performance measure: PFFS)

For the next 7 questions, enter your ranking for each item with respect to each HCM two-lane highway classification. If you feel there is another, or different, classification that should be considered, please use the additional column (titled Other) to rank this highway classification, and define the classification in the box below.

9. A good performance measure for two-lane highways should possess certain characteristics. Please rank each of the characteristics in the table below with respect to its importance to a performance measure. Please provide a separate ranking for each highway classification. The characteristic that has the highest importance should be given a ranking of '1'. The next most important characteristic should be given a ranking of '2', etc. Items that are equally important should be given the same ranking number.

Performance Measure Characteristic	Ranking			
	Class 1	Class 2	Class 3	Other
Reflects road user perception				
Easy to measure in the field				
Easy to understand / interpret by analysts				
Sensitive to traffic conditions (e.g. traffic volume, volume-to-capacity ratio, percent heavy vehicles, etc)				
Sensitive to roadway conditions (e.g. horizontal and vertical alignment, lane width, shoulder width, etc.)				
Compatible with performance measures on other facilities				
Describes all flow regimes (congested & uncongested)				
Supports other analyses: including safety, environmental, reliability and economic analyses				
Other (please specify):				

10. Rank each of the following aspects of traffic flow with respect to its usefulness in assessing operations on two-lane highways (*Use 1 for most useful. Items that are equally useful should be given the same ranking number*).

Characteristics	Ranking			
	Class 1	Class 2	Class 3	Other
Flow (e.g., flow rate, volume-to-capacity ratio, etc.)				
Speed (e.g., average travel speed, speed relative to posted speed limit, speed variance, etc.)				
Density				
Platooning / headways				
Delay (e.g., time spent driving at speed less than desired speed)				
Passing maneuvers (e.g., overtaking ratio*, etc.)				
Other (please specify):				

* The number of passes achieved divided by the number of passes desired. The number of passes achieved is the total number of passes for a given two-lane highway, while the desired number of passes is the total number of passes for a two-lane highway with continuous passing lanes with similar vertical and horizontal geometry.

11. If you ranked 'flow' as one of the three most important traffic flow aspects in question 10, please rank each of the following flow measures with respect to its usefulness in describing two-lane highway performance (*Use 1 for most useful. Items that are equally useful should be given the same ranking number*).

Characteristics	Ranking			
	Class 1	Class 2	Class 3	Other
Flow rate				
Volume-to-capacity (v/c) ratio				
Follower flow (FF)*				
Other (please specify):				

* The hourly rate of vehicles in following mode that passes a point along a two-lane highway in the same direction. This measure is calculated as the flow rate multiplied by the percent of vehicles with headways less than a pre-specified threshold value.

12. If you ranked 'speed' as one of the three most important traffic flow aspects in question 10, please rank each of the following speed measures with respect to its usefulness in describing two-lane highway performance (Use 1 for most useful. Items that are equally useful should be given the same ranking number).

Characteristics	Ranking			
	Class 1	Class 2	Class 3	Other
Average Travel Speed (ATS)				
Average Travel Speed as a Percent of Free-Flow Speed (PFFS)				
Average Travel Speed of Passenger Cars (ATS _{PC})				
ATS _{PC} as a Percent of Free-Flow Speed of Passenger Cars (PFFS _{PC})				
Speed Variance*				
Other (please specify):				

* The square of the standard deviation of all vehicle speeds measured at a specific location.

13. If you ranked 'density' as one of the three most important traffic flow aspects in question 10, please rank each of the following density measures with respect to its

usefulness in describing two-lane highway performance (Use 1 for most useful.

Items that are equally useful should be given the same ranking number).

Characteristics	Ranking			
	Class 1	Class 2	Class 3	Other
Traffic density				
Follower density (FD)*				
Other (please specify):				

* The number of vehicles in following mode per mile per lane in one direction of travel. This measure is calculated as the traffic density (in one direction) multiplied by the percent of vehicles with headways less than a pre-specified threshold value.

14. If you ranked 'platooning' as one of the three most important traffic flow aspects in question 10, please rank each of the following platooning measures with respect to its usefulness in describing two-lane highway performance (Use 1 for most useful.
Items that are equally useful should be given the same ranking number).

Characteristics	Ranking			
	Class 1	Class 2	Class 3	Other
Average platoon length (expressed in # of vehicles)				
Percent Time Spent Following (PTSF)*				
Percent Followers (PF)**				
Percent Impeded (PI)***				
Other (please specify):				

* The average percentage of time that vehicles must travel in platoons behind the slower vehicles due to the inability to pass. The HCM 2010 currently suggests that PTSF can be approximated in the field by determining the percentage of vehicles following at a headway of 3 seconds or less at a specific point.

**** Percentage of vehicles in the traffic stream with short headways, i.e. headways less than a certain cut-off value.**

***** Percentage of vehicles impeded by slower-moving vehicles in a directional traffic stream measured at a point. PI is calculated as the probability of desired speeds being greater than the average speed of platoon leaders multiplied by the percent of vehicles with headways less than a pre-specified threshold value.**

15. If you ranked 'passing maneuvers' as one of the three most important traffic flow aspects in question 10, please rank each of the following passing measures with respect to its usefulness in describing two-lane highway performance (Use 1 for most useful. Items that are equally useful should be given the same ranking number).

Characteristics	Ranking			
	Class 1	Class 2	Class 3	Other
Overtaking ratio*				
Average number of passes per vehicle				
Other (please specify):				

* The number of passes achieved divided by the number of passes desired. The number of passes achieved is the total number of passes for a given two-lane highway, while the desired number of passes is the total number of passes for a two-lane highway with continuous passing lanes with similar vertical and horizontal geometry.

16. How well does the current HCM two-lane highway methodology meet your agency's analysis needs in each of the following areas (1 - Not at all, 5 - Very well)?

Aspect of Two-Lane Highway Analysis	Score
Accounting for effect of heavy vehicles	
Accounting for effect of grades	
Accounting for effect of horizontal curvature	

17. In your opinion, what should be the highest priorities for revisions/additions to the HCM two-lane highway analysis methodology?

May we contact you for additional information? Yes ☐ No ☐

Thank you for your participation

APPENDIX B

SITE SPECIFIC REGRESSION RESULTS

Site Specific Regression Results (Class I)

Performance Measure	Regression Model		Intercept	Coefficients and P-value from t-test			
	R squared	SE		Combined Flow	Traffic Split	% Trucks	Speed Variance
	ATR 43 MT						
ATS	0.23	2.4	56.79 0.00	-0.006 0.00	3.26 0.00	- 0.05 0.00	-0.03 0.00
ATS/FFS	0.05	0.027	1.009 0.00	- 0.00003 0.00	---	---	---
% Follower	0.69	10.46	---	0.08 0.00	34.33 0.00	---	---
Follower Flow	0.86	24.81	-123.19 0.00	0.32 0.00	189.76 0.00	---	---
Follower Density	0.85	0.49	-2.26 0.00	0.006 0.00	3.33 0.00	0.007 0.02	---
% Impeded	0.51	9.3	-5.53 0.006	0.05 0.00	22.44 0.00	---	---
Impeded Flow	0.72	22.48	-75.39 0.00	0.19 0.00	110.45 0.00	---	---
Impeded Density	0.70	0.44	-1.39 0.00	0.004 0.00	1.95 0.00	0.005 0.04	---

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 132 MT							
ATS	0.11	3.2	67.6 0.00	0.002 0.007	---	-0.04 0.00	-0.006 0.00
ATS/FFS	0.01	0.02	1 0.00	0.00002 0.01	---	---	---
% Follower	0.50	7.79	-9.62 0.00	0.06 0.00	21.41 0.00	0.08 0.008	---
Follower Flow	0.72	12.25	-44.29 0.00	0.16 0.00	60.22 0.00	0.12 0.01	-0.007 0.003
Follower Density	0.72	0.19	-0.66 0.00	0.002 0.00	0.89 0.00	0.002 0.006	-0.00009 0.01
% Impeded	0.36	6.54	-5.34 0.00	0.04 0.00	11.55 0.00	0.05 0.04	---
Impeded Flow	0.59	10.49	-26.5 0.00	0.10 0.00	35.08 0.00	---	-0.007 0.00
Impeded Density	0.57	0.16	-0.4 0.00	0.002 0.00	0.52 0.00	---	-0.00009 0.005

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 44 ID							
ATS	0.29	1.48	64.43 0.00	-0.002 0.00	1.2 0.003	---	-0.03 0.00
ATS/FFS	0.13	0.01	1.009 0.00	-0.00002 0.00	-0.009 0.007	-0.0001 0.008	-0.00007 0.00
% Follower	0.71	7.14	-10.06 0.00	0.07 0.00	23.05 0.00	---	---
Follower Flow	0.83	15.9	-72.09 0.00	0.22 0.00	100.67 0.00	---	0.04 0.001
Follower Density	0.82	0.26	-1.16 0.00	0.003 0.00	1.6 0.00	---	0.0001 0.00
% Impeded	0.64	5.99	-7.65 0.00	0.05 0.00	14.96 0.00	---	0.02 0.00
Impeded Flow	0.77	12.97	-49.98 0.00	0.15 0.00	67.19 0.00	---	0.06 0.00
Impeded Density	0.76	0.21	-0.81 0.00	0.002 0.00	1.07 0.00	---	0.001 0.00

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 47 ID							
ATS	0.42	1.23	57 0.00	-0.004 0.00	---	0.01 0.03	-0.04 0.00
ATS/FFS	0.02	0.01	1.002 0.00	-0.000007 0.001	---	---	0.00004 0.03
% Follower	0.69	6	-9.81 0.00	0.04 0.00	33.45 0.00	-0.08 0.007	-0.04 0.00
Follower Flow	0.85	18.14	-127.56 0.00	0.2 0.00	198.34 0.00	---	-0.05 0.04
Follower Density	0.85	0.35	-2.43 0.00	0.004 0.00	3.7 0.00	---	---
% Impeded	0.61	4.8	-7.01 0.00	0.03 0.00	20.9 0.00	-0.05 0.04	-0.02 0.00
Impeded Flow	0.80	13.94	-82.17 0.00	0.13 0.00	124.26 0.00	---	---
Impeded Density	0.79	0.27	-1.56 0.00	0.002 0.00	2.32 0.00	---	---

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 2 - OR							
ATS	0.32	2.03	69.44 0.00	-0.006 0.00	-3.88 0.00	-0.06 0.00	-0.02 0.00
ATS/FFS	0.26	0.02	1.009 0.00	-0.00003 0.00	---	---	-0.0001 0.00
% Follower	0.63	9.13	---	0.08 0.00	19.47 0.00	---	---
Follower Flow	0.87	15.37	-65.04 0.00	0.28 0.00	80.15 0.00	---	---
Follower Density	0.86	0.26	-1.1 0.00	0.004 0.00	1.31 0.00	---	---
% Impeded	0.47	8.06	---	0.05 0.00	9.02 0.02	---	0.04 0.00
Impeded Flow	0.76	13.64	-40.07 0.00	0.16 0.00	42.91 0.00	---	0.05 0.009
Impeded Density	0.75	0.23	-0.68 0.00	0.003 0.00	0.71 0.00	---	0.0009 0.001

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 11-OR							
ATS	0.24	1.76	66.63 0.00	-0.005 0.00	-1.94 0.02	---	-0.02 0.00
ATS/FFS	0.12	0.01	1.006 0.00	---	---	---	-0.0001 0.00
% Follower	0.60	8.05	-12.58 0.00	0.07 0.00	33.85 0.00	---	---
Follower Flow	0.75	14.69	-49.27 0.00	0.19 0.00	69.88 0.00	---	---
Follower Density	0.75	0.23	-0.80 0.00	0.003 0.00	1.11 0.00	---	---
% Impeded	0.47	6.47	-8.64 0.00	0.04 0.00	19.6 0.00	---	0.04 0.006
Impeded Flow	0.69	10.22	-29.5 0.00	0.11 0.00	39.03 0.00	---	---
Impeded Density	0.68	0.16	-0.48 0.00	0.002 0.00	0.62 0.00	---	0.0008 0.02

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 13- OR							
ATS	0.44	4.44	63.35 0.00	0.01 0.00	-8.51 0.001	-0.03 0.03	-0.03 0.00
ATS/FFS	0.28	0.06	1.07 0.00	---	---	- 0.0007	-0.0002 0.00
% Follower	0.52	10.49	-18.47 0.00	0.07 0.00	19.92 0.001	0.36 0.00	0.03 0.001
Follower Flow	0.67	11.43	-44.72 0.00	0.17 0.00	44.48 0.00	0.32 0.00	---
Follower Density	0.65	0.23	-0.9 0.00	0.003 0.00	0.9 0.00	0.006 0.00	0.0005 0.008
% Impeded	0.51	7.64	-12.02 0.00	0.05 0.00	11.27 0.007	0.22 0.00	0.03 0.00
Impeded Flow	0.65	8.88	-32.47 0.00	0.12 0.00	30.72 0.00	0.21 0.00	0.02 0.009
Impeded Density	0.65	0.17	-0.65 0.00	0.002 0.00	0.62 0.00	0.004 0.00	0.0005 0.00

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 17- OR							
ATS	0.20	2.01	65.48 0.00	0.001 0.03	---	-0.05 0.00	-0.01 0.002
ATS/FFS	0.47	0.01	1.03 0.00	-0.00004 0.00	-0.03 0.00	- 0.0001	-0.0002 0.00
% Follower	0.74	7.58	-19.2 0.00	0.05 0.00	36.62 0.00	0.13 0.00	---
Follower Flow	0.75	33.62	-123.17 0.00	0.24 0.00	165.6 0.00	0.58 0.00	---
Follower Density	0.75	0.53	-1.95 0.00	0.004 0.00	2.6 0.00	0.009 0.00	---
% Impeded	0.67	5.51	-12.86 0.00	0.03 0.00	20.41 0.00	0.08 0.001	0.03 0.004
Impeded Flow	0.67	25.62	-79.23 0.00	0.15 0.00	97.1 0.00	0.41 0.00	---
Impeded Density	0.66	0.41	-1.26 0.00	0.002 0.00	1.52 0.00	0.007 0.00	---

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 1- NC							
ATS	0.16	1.82	61.59 0.00	-0.001 0.00	---	---	-0.04 0.00
ATS/FFS	0.15	0.01	1.01 0.00	-0.00001 0.00	---	---	-0.0003 0.00
% Follower	0.85	7.45	---	0.05 0.00	19.16 0.00	0.09 0.03	---
Follower Flow	0.92	31.45	-156.23 0.00	0.33 0.00	218 0.00	---	0.26 0.001
Follower Density	0.92	0.54	-2.72 0.00	0.006 0.00	3.7 0.00	---	0.006 0.00
% Impeded	0.7	6.75	---	0.03 0.00	8.2 0.004	0.11 0.002	0.11 0.00
Impeded Flow	0.88	23.93	-94.48 0.00	0.19 0.00	119.9 0.00	---	0.46 0.00
Impeded Density	0.87	0.42	-1.65 0.00	0.003 0.00	2.04 0.00	---	0.009 0.00

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 3- NC							
ATS	0.14	1.56	61.55 0.00	-0.003 0.00	-1.4 0.01	---	---
ATS/FFS	0.18	0.01	1.006 0.00	-0.00002 0.00	-0.01 0.03	---	-0.0002 0.00
% Follower	0.67	12.49	6.71 0.01	0.07 0.00	26 0.00	-0.27 0.00	-0.13 0.00
Follower Flow	0.87	43.6	-294.25 0.00	0.45 0.00	373.3 0.00	---	---
Follower Density	0.77	0.87	-4.35 0.00	0.008 0.00	6.47 0.00	---	---
% Impeded	0.46	10.92	---	0.04 0.00	14.6 0.00	-0.17 0.007	---
Impeded Flow	0.76	36	-142 0.00	0.25 0.00	207.8 0.00	---	0.21 0.04
Impeded Density	0.75	0.65	-2.49 0.00	0.004 0.00	3.62 0.00	---	0.004 0.02

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 4- NC							
ATS	0.34	1.79	61.36 0.00	-0.004 0.00	-4.99 0.00	---	-0.02 0.00
ATS/FFS	0.44	0.01	1.02 0.00	-0.00003 0.00	-0.02 0.00	---	-0.0004 0.00
% Follower	0.84	7.15	-8.98 0.00	0.05 0.00	25.14 0.00	---	---
Follower Flow	0.87	39.96	-193.06 0.00	0.32 0.00	255.8 0.00	---	0.27 0.002
Follower Density	0.85	0.78	-3.74 0.00	0.006 0.00	4.87 0.00	---	0.007 0.00
% Impeded	0.73	6.73	-7.41 0.00	0.04 0.00	15.95 0.00	-0.12 0.001	0.09 0.00
Impeded Flow	0.80	33.56	-133.62 0.00	0.21 0.00	166.3 0.00	-0.35 0.05	0.46 0.00
Impeded Density	0.79	0.65	-2.59 0.00	0.004 0.00	3.18 0.00	---	0.009 0.00

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
Site 7- NC							
ATS	0.19	2.17	62.2 0.00	-0.002 0.00	-2 0.05	-0.02 0.03	-0.05 0.00
ATS/FFS	0.12	0.01	1.007 0.00	-0.000007 0.00	---	---	-0.0002 0.00
% Follower	0.85	7.45	-6.74 0.00	0.05 0.00	29.92 0.00	---	-0.05 0.002
Follower Flow	0.90	30.56	-128.46 0.00	0.28 0.00	203.8 0.00	---	---
Follower Density	0.89	0.55	-2.3 0.00	0.005 0.00	3.53 0.00	---	---
% Impeded	0.69	6.74	-7.46 0.00	0.03 0.00	23.64 0.00	---	---
Impeded Flow	0.83	23.99	-81.4 0.00	0.16 0.00	129 0.00	---	---
Impeded Density	0.83	0.42	-1.46 0.00	0.003 0.00	2.24 0.00	---	0.002 0.01

-Values in bold are inconsistent with the hypothesized logical relationship.

Site Specific Regression Results (Class II)

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 28 MT							
ATS	0.15	2.4	64.3 0.00	0.004 0.00	---	-0.05 0.002	-0.03 0.00
ATS/FFS	0.03	0.01	1.008 0.00	-0.00002 0.002	-0.01 0.00	---	-0.00005 0.003
% Follower	0.26	6.79	-7.2 0.00	0.05 0.00	14.22 0.00	---	---
Follower Flow	0.59	7.1	-23.06 0.00	0.11 0.00	27.1 0.00	---	---
Follower Density	0.58	0.11	-0.36 0.00	0.002 0.00	0.43 0.00	---	---
% Impeded	0.26	5.04	-6.28 0.00	0.04 0.00	10.08 0.00	---	0.01 0.005
Impeded Flow	0.54	5.49	-16.5 0.00	0.07 0.00	18.5 0.00	---	0.01 0.03
Impeded Density	0.53	0.09	-0.26 0.00	0.001 0.00	0.29 0.00	---	0.0002 0.009

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 147 ID							
ATS	0.21	1.65	58.6 0.00	-0.005 0.007	---	---	-0.03 0.00
ATS/FFS	0.08	0.01	1.01 0.00	-0.00006 0.00	-0.02 0.007	-0.0002 0.002	-0.00009 0.005
% Follower	0.37	8.48	-25.32 0.00	0.12 0.00	34.65 0.00	0.19 0.00	---
Follower Flow	0.60	9.08	-55.27 0.00	0.20 0.00	64.79 0.00	0.26 0.00	---
Follower Density	0.60	0.16	-0.99 0.00	0.004 0.00	1.15 0.00	0.005 0.00	---
% Impeded	0.33	6.35	-18.03 0.00	0.09 0.00	22.24 0.00	0.15 0.00	---
Impeded Flow	0.57	6.53	-37.25 0.00	0.14 0.00	41.81 0.00	0.18 0.00	---
Impeded Density	0.56	0.12	-0.67 0.00	0.002 0.00	0.75 0.00	0.003 0.00	---

-Values in bold are inconsistent with the hypothesized logical relationship.

Site Specific Regression Results (Class III)

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 73 MT							
ATS	0.11	2.18	62 0.00	-0.002 0.00	---	---	-0.03 0.00
ATS/FFS	0.16	0.01	1 0.00	-0.00003 0.00	---	---	-0.0002 0.00
% Follower	0.62	6.94	-8.4 0.00	0.05 0.00	20.4 0.00	---	---
Follower Flow	0.78	16.45	-64 0.00	0.17 0.00	0.90 0.00	---	---
Follower Density	0.78	0.28	-1.1 0.00	0.003 0.00	1.5 0.00	---	---
% Impeded	0.55	5.25	-6.08 0.00	0.03 0.00	11.44 0.00	---	---
Impeded Flow	0.73	12.19	-41.1 0.00	0.11 0.00	54.82 0.00	---	---
Impeded Density	0.72	0.21	-0.71 0.00	0.002 0.00	0.92 0.00	---	0.0007 0.03

-Values in bold are inconsistent with the hypothesized logical relationship.

Performance Measure	Regression Model		Coefficients and P-value from t-test				
	R squared	SE	Intercept	Combined Flow	Traffic Split	% Trucks	Speed Variance
ATR 126 ID							
ATS	0.08	1.39	44.75 0.00	---	---	---	-0.03 0.00
ATS/FFS	0.13	0.01	1.02 0.00	-0.00002 0.00	-0.02 0.00	---	-0.0004 0.00
% Follower	0.57	7.42	-12.36 0.00	0.04 0.00	39.41 0.00	-0.19 0.00	---
Follower Flow	0.71	24.34	-109.82 0.00	0.19 0.00	185.36 0.00	-0.67 0.00	---
Follower Density	0.7	0.58	-2.59 0.00	0.004 0.00	4.3 0.00	-0.01 0.00	---
% Impeded	0.44	5.84	-8.33 0.00	0.02 0.00	24.73 0.00	-0.14 0.00	0.05 0.03
Impeded Flow	0.64	17.4	-69.6 0.00	0.11 0.00	116.11 0.00	-0.47 0.00	---
Impeded Density	0.63	0.41	-1.64 0.00	0.003 0.00	2.69 0.00	-0.01 0.00	0.004 0.03

-Values in bold are inconsistent with the hypothesized logical relationship.