

ANALYZING THE EFFECT OF PASSING-LANES ON RURAL TWO-LANE
HIGHWAY OPERATIONS

by

Zachary Sebastian Freedman

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

of

Master of Science

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

November 2009

©COPYRIGHT

by

Zachary Freedman

2009

All Rights Reserved

APPROVAL

of a thesis submitted by

Zachary Sebastian Freedman

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency and is ready for submission to the Division of Graduate Education.

Dr. Ahmed Al-Kaisy

Approved for the Department of Civil Engineering

Dr. Brett Gunninck

Approved for the Division of Graduate Education

Dr. Carl A. Fox

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Zachary Sebastian Freedman

November 2009

ACKNOWLEDGEMENTS

This thesis was made possible by a number of people and organizations. I would first like to thank my research advisor, Dr. Ahmed Al-Kaisy. Dr. Al-Kaisy provided appropriate insight to all stages of my thesis, from the data collection to the thesis organization. He was also extremely helpful in providing technical writing tips throughout the composition of the thesis. This work would not have been possible without his oversight. Next I would like to thank the Western Transportation Institute for funding my project. The financial support I received provided me with all the resources necessary in completing the thesis, such as the equipment for data collection and the computers and software required for analysis. I also want to thank Mr. Scott Keller of the Montana Department of Transportation Design Unit for providing all the as-built drawings and passing-lane video data that allowed me to screen my data-collection sites. Lastly, I want to thank my family for providing their support and encouragement of my continuing education.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
Background.....	1
Problem Statement.....	3
Research Objective.....	4
Scope.....	5
Research Importance.....	5
Thesis Organization.....	5
2. LITERATURE REVIEW.....	7
Two-Lane Highways.....	7
Performance on Two-Lane Highways.....	9
Passing-lanes.....	12
Passing-Lane Effective Length.....	13
Passing-Lane Length.....	21
3. STUDY SITES AND DATA COLLECTION.....	25
Study Sites.....	25
Site Selection.....	25
Description of Study Sites	28
Data Collection.....	29
Technique.....	30
Counter Layout-Site I.....	31
Counter Layout-Site II.....	31
Counter Layout-Site III.....	31
Data Processing.....	32
Data Limitations.....	34
Difficulties Encountered.....	35
4. SELECTING PERFORMANCE MEASURES.....	37
Study Approach.....	37
Percent Followers.....	38
Follower Density.....	38
Average-Travel-Speed.....	38
Average-Travel-Speed _{passenger-cars}	39
Average-Travel-Speed divided by Free-Flow Speed.....	39
Percent Impeded.....	39
Results.....	42
Preliminary Examination.....	42

TABLE OF CONTENTS-CONTINUED

Before-After Examination.....	46
Correlation Examination.....	48
Statistical Regression Analysis.....	50
Investigation Findings.....	51
5. DOWNSTREAM EFFECTIVE LENGTH OF PASSING-LANE.....	53
Study Approach.....	53
Results.....	56
Preliminary Examination.....	56
Headway Analysis.....	61
Statistical Analysis.....	62
Investigation Findings.....	66
6. LANE USE AND PERFORMANCE WITHIN A PASSING-LANE.....	68
Study Approach.....	68
Results.....	70
Performance Measure Analysis.....	70
Interpretation and Validation.....	76
Investigation Findings.....	79
7. CONCLUSIONS AND RECOMMENDATIONS.....	80
Thesis Conclusions.....	80
Future Research.....	82
REFERENCES.....	83
APPENDICES.....	86
APPENDIX A: FHWA 13-Category Vehicle Classification System.....	86

LIST OF TABLES

Table	Page
1 Comparison of Two PTSF Methods.....	9
2 Downstream Length of Roadway Affected by Passing-Lanes.....	14
3 Effective Lengths of Passing-lane Based on Performance Measure Used.....	20
4 Optimal Lengths of Passing-lanes.....	21
5 Total Data Collected at Each Site.....	31
6 Before-After Results for US-287.....	46
7 Before-After Results for US 191.....	47
8 Correlation Analysis Results.....	49
9 Results from Multivariate Linear Regression.....	51
10 Change in Performance Measure for (a) HWY US 287 and (b) HWY US 191..	56
11 Correlation Coefficients between Performance Measures and Platooning Variables at Same Traffic Level.....	62
12 Regression Analysis at Study Site US 287.....	64
13 Regression Analysis with Distance as the Only Predictor Variable.....	65

LIST OF FIGURES

Figure	Page
1 A Passing-lane on a Rural Two-Lane Road.....	2
2 A Vehicular Platoon as Defined by the Three-second Headway Cutoff Value.....	7
3 A Typical Passing-Lane Set-up.....	12
4 Operational Effect of a Passing-lane.....	13
5 Station Setup (a) and Results from Simulation (b).....	16
6 A 2+1 Passing-lane Configuration.....	22
7 Passing-lane Configurations.....	24
8 Study Site Locations.....	29
9 Automatic Traffic Counter Set-up.....	30
10 Counter setup (a) Site I (US 287),(b) Site II (US 191), and (c) Site III (US 287).....	32
11 Distribution of Two-Lane Highway AADT's in Montana.....	35
12 General Shape of Performance in the Vicinity of a Passing-Lane.....	41
13 Performance Measures as a Function of Distance Downstream of Passing-Lane On US 287.....	43
14 Performance Measures as a Function of Distance Downstream of Passing-Lane On US 191.....	44
15 Curve Depicting the Change in PTSF in the Proximity of a Passing-Lane.....	54
16 Percentage Change in Platooning Variables on US 287.....	58
17 Percentage Change in Platooning Variables on US 191.....	60
18 Headway Distributions at Each Site.....	61

LIST OF FIGURES-CONTINUED

Figure		Page
19	Percent Followers as a Function of Distance at All Traffic Levels.....	71
20	Percent Impeded as a Function of Distance at All Traffic Levels.....	73
21	Follower Density as a Function of Distance at All Traffic Levels.....	74
22	Average-Travel-Speed.....	76
23	Traffic Split at Each Station for the Passing-Lane and the Normal Lane.....	78

LIST OF EQUATIONS

Equation	Page
1.....	8
2.....	14
3.....	19
4.....	33
5.....	39
6.....	50

ABSTRACT

Two-lane highways make up 80% of roads in this country. Rural two-lane highways are unique in they are typically characterized by high-speeds and low volumes. Level-of-service is associated with the proportion of vehicles stuck in platoons, or the percentage of vehicles impeded by a slow-moving vehicle. The Highway Capacity Manual 2000 (HCM 2000) recommends determining the percentage of vehicles stuck in a platoon using a performance measure called Percent Time Spent Following (PTSF). Because PTSF is nearly impossible to measure in the field, the HCM has proposed two methods for estimating its value. However, there are inconsistencies between the two methods. This limitation has led researchers to seek more appropriate performance measures for two-lane highways.

When performance on these highways deteriorates to the point of needing an upgrade, the addition of a passing-lane is considered. A passing-lane is an extra lane in one or both directions of travel. The current design standards for passing-lanes (length and frequency) are based on simulation research conducted more than 20 years ago. The purpose of this thesis is to analyze traffic stream characteristics within and around a passing-lane as to improve design standards. Three appropriate performance measures were used to analyze data from two passing-lane sites in Montana. The purpose of this analysis was to determine passing lane *effective length*. The results showed this value may be greater than 6.6 miles.

Lane use within a passing-lane section was also investigated. Traffic counters were placed at pre-determined locations within a passing-lane and data were recorded. Analysis of the data showed that aggressive drivers in the left lane are able to drive at 10 miles-per-hour faster than they were traveling as they entered the three-lane section. Further analysis showed that nearly all passing maneuvers of slower vehicles were conducted in the first ½-mile of the passing-lane.

This thesis found the most appropriate performance measures for investigating passing-lanes are Percent Followers, Percent Impeded, and Follower Density. Also, the required spacing of passing-lanes on a two-lane highway may be farther than the current standards recommend. Lastly, for the site investigated a ¾-mile long passing-lane would have been adequate.

CHAPTER 1

INTRODUCTION

Background

Two-lane highways make up the vast majority of the highway system in this country, by length. Nationwide, they constitute 82% of all Federal highways (Federal Highway Administration [FHWA], 2006). In rural states such as Montana and Nebraska, two-lane highways make up over 90% of all Federal roads. They are critical in transporting farm products to and from remote regions in the US and because of this their safety and operational vitality are essential to this nation's transportation infrastructure. When the level of service on a rural two-lane highway deteriorates to the point of needing an upgrade there are a few common options available for highway agencies.

The cheapest and simplest of these upgrades are turnouts. Turnouts are locations on the highway with a widened shoulder. These upgrades are typically constructed in areas with difficult or steep terrain such as on mountains in canyons where there is very limited space for a full additional lane. They are not usually built on high-speed facilities due to the fact that drivers may not have enough distance to decelerate and enter an 18-30 foot-long area. They are intended for slower-moving vehicles to pull into as to allow following vehicles, with higher desired speeds, to pass. Turnouts are relatively inexpensive and easy to construct. The second option is passing-lanes. Passing-lanes are sections of highway in which an additional lane has been added to be used by slower-moving vehicles thus allowing other vehicles to travel at higher speeds on the normal

lane. They are usually constructed at regular intervals along long stretches of two-lane two-way highways. Passing-lanes are considerably costlier than turnouts and their construction may interrupt the normal flow of traffic on a particular roadway. The next possible upgrade is a Super 2+1 lane, a type of passing-lane. This configuration has a center lane that alternates use for each direction every so often (usually 1.0 – 2.0 miles). Super 2+1 is far more expensive than a traditional passing-lane that can be installed where and when needed, at specific locations along the highway. The fourth, and most expensive, option is upgrading the highway from two lanes to four lanes. This involves adding a second lane for each direction of traffic. A four-lane highway upgrade should only be used as a last resort measure due to its high cost.

This research is limited to the study of passing-lanes. Passing-lanes are more effective than turnouts, yet considerably cheaper than four-lane upgrades. There will be no discussion of turnouts or four-lane upgrades in this thesis.

Figure 1 shows a passing-lane on a rural two-lane highway in Washington.



Figure 1: A passing-lane on a rural two-lane road [westcoast.roads.com 2006]

Problem Statement

Rural two-lane highways generally have a low volume-to-capacity ratio thus their level of service (LOS) cannot be measured by any appreciable congestion. Different performance measures must be employed in order to determine a reasonable LOS. Some accepted measures are average-travel-speed, density, free-flow-speed, and speed ratio (average speed divided by free flow speed). However, previous studies have shown these measures are relatively insensitive to performance on two-lane highways. Currently there is no single accepted performance measure for these highways that is both measureable and sensitive to traffic operations.

Passing opportunities on two-lane roadways are typically offered on the opposing travel lane when sight distance and time gaps are adequate for a safe maneuver. As volumes increase, these passing opportunities become more limited. This in turn causes drivers to become frustrated and accept smaller gaps in oncoming traffic than they normally would. This creates an unsafe environment for all road users. Thus, operational deterioration can become a real safety hazard.

One solution to this hazard is a passing-lane. Passing-lanes reduce platooning (percent followers) and alleviate drivers' frustrations by allowing trapped vehicles to pass slower-moving vehicle.

Passing-lanes are proven method for improving operations on two-lane highways. The problem, however, is that there are no set guidelines for state Departments of Transportation (DOT's) as far as the planning, design, and location of these lanes.

Passing-lanes are being used more and more because they are deemed the most appropriate upgrade for relieving platoons.

Currently there is a limited amount of research in the area of passing-lanes that addresses design considerations. Almost all the research that has been conducted in the area has involved simulation software. The most common simulation package for research of two-lane highway is Two-Way Operational Passing-lane Analysis Software (TWOPAS). TWOPAS was developed in the 1980's and although it was commonly used in research, it was never widely used by government agencies such as DOTs for design purposes. This software was used to develop the Highway Capacity Manual's (HCM) guidelines for passing-lane design.

Research Objective

The objective of this research is to develop a more in-depth understanding of the effect of passing-lanes on two-lane highway operations and performance. Such an understanding requires a good knowledge of performance both within and downstream of the passing-lanes. This will eventually help in answering some of the critical lane design assessment questions such as the appropriate length of passing-lanes and the frequency at which they should be provided along a particular highway.

Scope

This research is concerned only with the function of passing-lanes, their operations on two-lane highways, and platooning performance measures. It will not discuss any other class of highway, including two-way highways in general.

Also, safety and cost analysis are beyond the scope of this work.

Research Importance

Passing-lanes are costly to design and build for any highway agency. Some estimates say they cost an average of \$1 million per mile to construct. Because DOTs' budgets are under intense scrutiny, it is important that passing-lanes are constructed only as often as they are needed and only for the optimal length. By knowing the optimal length and spacing of these lanes, highway agencies can better make decisions regarding highway upgrades. Currently decisions are made loosely and are largely based on the HCM capacity analysis procedures.

Thesis Organization

This thesis is organized into eight chapters. Chapter 2, the literature review, will discuss the previous research that has been conducted in this area as well the HCM guidelines and guidelines from Policy on the Geometric Design of Highways and Streets (AASHTO 2004), known as the Green Book.

The third chapter explains how the data was collected, processed, and screened. Also, the considerations that were taken into account as far as site selection are discussed as well.

The fourth chapter will discuss the results from Investigation I. It will also explain which performance measures will be used for the rest of the thesis.

Chapter 5 will detail the results of Investigation II and discuss passing-lane design recommendations.

The sixth chapter will explain the results of Investigation III.

Lastly, Chapter 7 will include conclusions and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter first discusses two-lane highways and current procedures for evaluating performance on these highways. Next, some of the recently proposed performance measures on two-lane highways are presented. Finally, the analytical procedures of passing-lanes and the previous research in this area are discussed.

Two-Lane Highways

Rural two-lane highways are characterized by high-speeds and low traffic volumes. Typically the volume-to-capacity ratio on these highways is too low to be used as a performance measure. Because of these characteristics, different performance measures must be chosen to quantify operations. An appropriate measure for two-lane highways should consider the proportion of vehicles in platoons along a stretch of highway. A platoon is a group of successive vehicles with relatively short headways on the same travel lane. Figure 2 depicts a vehicular platoon.

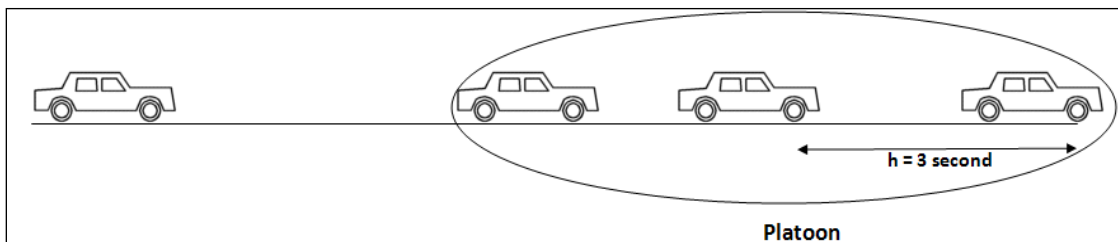


Figure 2: A vehicular platoon as defined by the three-second headway cutoff value

The Highway Capacity Manual 2000 (HCM 2000) suggests two performance measures for evaluating two-lane highways: average-travel-speed and percent-time-

spent-following (PTSF). The advantage of using average-travel-speed as an indicator of performance is that it is easy to measure in the field and it directly impacts drivers' perception of operations. The drawback of average-travel-speed is the inability to compare two different highways or segments of the same highway using this measure. Percent-time-spent-following is equal to the average percent of time drivers spend impeded by slower vehicles. In concept this is a sound measure because when driving on two-lane roads, motorists care about how much of the time they are not able to drive at their desired speed. Like average-travel-speed, percent-time-spent-following is easily perceived by drivers. The drawback of percent-time-spent-following is that it is nearly impossible to measure on a highway. In light of this drawback the HCM has proposed two methods for determining PTSF: an equation and the three-second rule, as known as percent followers. The HCM equation for estimating PTSF is:

$$PTSF = 100(1 - e^{-0.000879 * V_p}) * f_{d/np} \quad \text{Eq. 1}$$

Where,

V_p = Traffic volume, as a passenger-car-equivalent (pc/hr)

$F_{d/np}$ = Percentage no-passing zones (%)

The three-second rule is the percentage of vehicles with headways of three seconds or less. This is similar to the platoon definition above.

For a given traffic stream and a given highway, the equation and the three-second rule do not produce equal PTSF values. A study published in 2006 by Al-Kaisy and Durbin compared the two methods for estimating PTSF using six two-lane highway sites in Montana. After converting the PTSF values to a Level-of-Service (LOS) the researchers found dramatic differences in the two methods. Table 2.1 shows these differences.

Table 1: Comparison of Two PTSF Methods [Al-Kaisy & Durbin 2006]

Study Site	HCM Equation	LOS	HCM 3-second Rule	LOS
287 (NB)	68.4	D	39.3	B
287 (SB)	82.2	E	32.6	A
287/12 (NB)	72.2	D	41.3	B
287/12 (SB)	59.9	C	40.5	B
JR (NB)	81.3	E	34.2	A
JR (SB)	90.3	E	52.3	C

Using the three-second rule, the LOS is significantly better than the LOS determined by using the equation, at all sites. Similar findings were noticed in other studies as well.

Performance on Two-lane Highways: Proposed Measures

The limitations with the two performance measures suggested by the HCM and the inconsistency between the two methods for determining PTSF have lead researchers to look for new performance measures of two-lane highways.

Al-Kaisy and Karjala (2007) investigated other performance indicators believed to be related to platooning. Data was collected from four, Class I two-lane highway sites in Montana. Five alternative measures were analyzed (ATS, $ATS_{\text{passenger-cars}}$, ATS/FFS , $ATS_{\text{passenger-cars}} / FFS_{\text{passenger-cars}}$, and follower density) to determine which had the highest correlation to level of platooning. $ATS_{\text{passenger-cars}}$ and $ATS_{\text{passenger-cars}} / FFS_{\text{passenger-cars}}$ were used because passenger cars are believed to be more sensitive to the effect of platoons than heavy vehicles. However the data showed that by limiting the ATS and ATS/FFS to just passenger-cars there was no higher correlation to platooning than average speed and

speed ratio for all vehicles. The results showed that follower density had the highest correlation to platooning of all the measures investigated, even higher than percent-followers. The R^2 values for follower density and percent-followers regression models were 0.96 and 0.62, respectively. This shows that HCM's percent-followers is not as closely related to platooning as follower density.

Al-Kaisy and Durbin (2006) explored the use of a new performance measure for two-lane highways. This measurement, referred to as Percent Impeded (PI), is based on segregating the impeded vehicles in a platoon from the “happy to follow” vehicles. “Happy to follow” refers to vehicles that are in platoon yet are driving at their desired speed; they do not wish to be driving faster. Mathematically, PI is the product of the probability of a vehicle being stuck in a platoon (using a headway method) and the probability of a vehicle being trapped in a platoon (unable to pass). The data, collected from three study sites in Montana, showed that PI had a significantly higher regression model R^2 value (0.975) than did HCM percent-followers (0.733).

Gattis et. al (1997) were interested in what headway value between successive vehicles constitutes impedance. In other words, at what headway spacing are vehicles actually impeded (desiring, yet unable to pass) as opposed to ‘happy-to-follow’. Field studies were conducted at three locations where passing-lanes were located. Two of the sites had passing-lanes of 1400 ft and one had a passing-lane of 2500 ft. The authors defined a platooned vehicle as one that a) entered the passing-lane section with headway of 5 sec or less, or b) passed other vehicles in the passing-lane section. Vehicle behavior was recorded with a video camera. The objective of the platooning analysis was to

determine the number of platoons and the number of vehicles in a platoon as a function of traffic volume. The data indicates the number of vehicles in a platoon increases with volume. A passing-attempt analysis showed that passing success began to decline with headways greater than 2 sec. When headways were greater than three seconds or when the platoon speeds were greater than 50 mph, 85% of drivers did not desire to pass. This high proportion of vehicles (85%) unwilling to pass indicates that HCM's three-second is an overestimation of the percent of vehicles that are actually impeded.

A research project in South Africa investigated the use of other measures of performance on two-lane highways as part of developing new analytical procedures and a simulation model for two-lane highways (8). The research project found follower density (number of vehicles with short headways per unit length) a promising measure of performance on two-lane highways. Among other performance measures considered by the same project are follower flow (number of vehicles with short headways per hour), percent followers (percentage of vehicles with short headways), and percent speed reduction due to traffic, total queuing delay, and traffic density.

May and Emoto (1988) compared the use of percent time delayed, currently called the PTSF, as a performance measure versus average speed. A field study was conducted in California on a site with the following criteria: 1. rural, level highway with passing-lanes, 2. high volume, and 3. within driving distance of the Bay area. The site that was finally selected was located in Sonoma County; it had four alternating passing-lanes and was 9.4 mi long. Counters were placed at mile posts 1.69, 4.9, 6, and 6.4. The counters operated for six hours on Friday and six hours on Sunday.

The researchers also used a simulation package to model the road with no passing-lane. The model results showed that percent-following would increase between 20 and 50 % based on the location in the section if there was no passing-lane. The researchers concluded that percent time delayed is a better measure of operations than speed.

Passing-lanes

When performance on two-lane highways deteriorates to the point of needing an upgrade, passing-lanes are considered. Passing-lanes are additional lanes in one or both directions of travel intended for slower vehicles to use and allow faster vehicles to pass on the left. Figure 3 depicts a typical passing-lane setup.

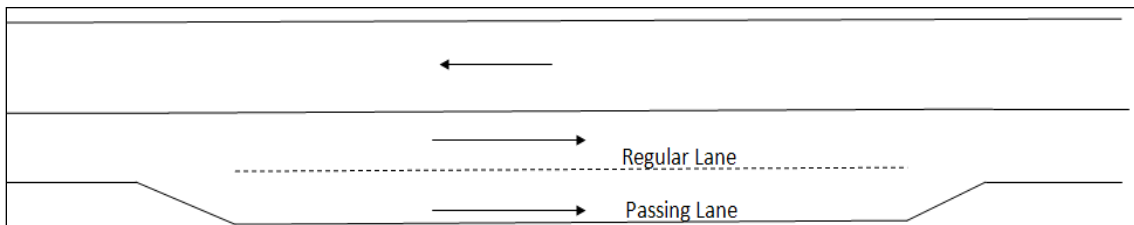


Figure 3: A typical passing-lane set-up

Passing-lanes are intended to relieve platooning for a certain distance downstream of the closing taper, until platoons regroup. The distance required for the level of platooning to return to its pre-passing-lane value plus the length of the passing-lane is known as the passing-lane *effective length*. The next section discusses current standards for determining this length and the previous related studies.

Passing-Lane Effective Length

The HCM 2000 procedures adopted the hypothetical relationship between percent-time-spent-following and location relative to the passing-lane theorized by Harwood and Hoban (1985). The curve is shown in Figure 4 below.

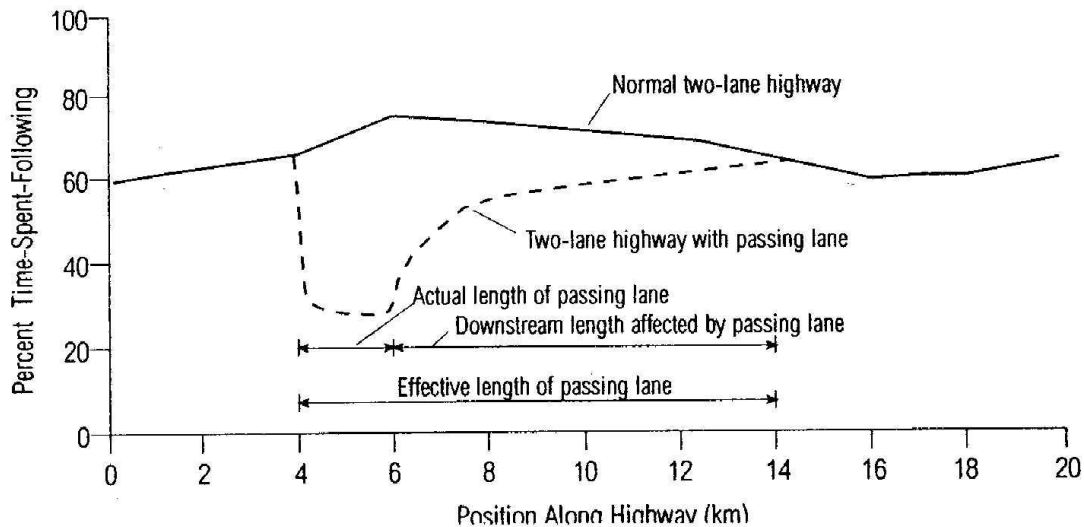


Figure 4: Operational effect of a passing-lane [Harwood & Hoban 1985]

In determining the analysis length of a passing-lane, the HCM 2000 procedures divide the segment into four sections.

1. The distance upstream of the passing-lane
2. The passing-lane itself
3. The distance downstream of the passing-lane (within its effective length) and
4. The distance beyond the effective length of the passing-lane.

The effective passing-lane length, as shown in Figure 4, is equal to the length of the passing-lane plus the downstream distance required for the performance measure to return to its pre-passing-lane value.

L_{pl} , the length of the passing-lane, should include all tapers of either the existing or planned passing-lane. L_{de} , the downstream segment within the effective length, is determined from Table 2, below.

Table 2: Downstream Length of Roadway Affected by Passing-Lanes [HCM 2000]

Directional Flow Rate (pc/h)	Downstream Length of Roadway Affected, L_{de} (mi)	
	Percent Time-Spent-Following	Average Travel Speed
≤ 200	13	1.7
400	8.1	1.7
700	5.7	1.7
≥ 1000	3.6	1.7

Logically, the total length of the analysis segment is the sum of section 1-4 listed above:

$$L_t = L_d + (L_u + L_{pl} + L_{de}) \quad \text{Eq. 2}$$

Where,

L_t = Total length of analysis segment

L_d = Length of two-lane highway downstream of passing-lane and outside effective length

L_u = Length of two-lane highway upstream of passing-lane

L_{pl} = Length of passing-lane including both tapers

L_{de} = Downstream length of highway within passing-lane effective length

Table 2.2 shows that depending on the flow rate, the PTSF benefit persists for 2.6 to 13 miles downstream of the passing-lane. The ATS benefit is apparently independent of flow rate and persists for 1.7 miles downstream of the passing-lane.

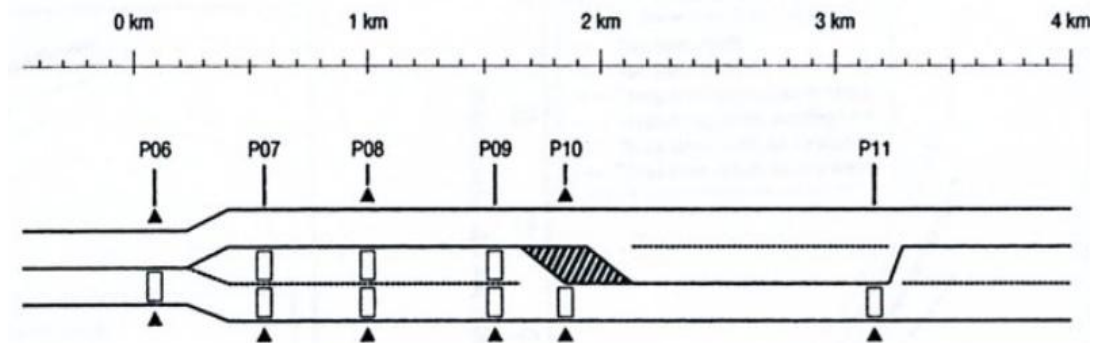
There have been a number of studies trying to determine the effective length of passing-lanes. Most of these studies used a simulation package such as TWOPAS and yielded varying results.

In a relatively recent paper, Woolridge, Messer, and Heard (2002) used a simulation package to determine the optimal spacing of passing-lanes. The spacing of passing-lanes is equivalent to the *effective length*. A generic two-lane highway with

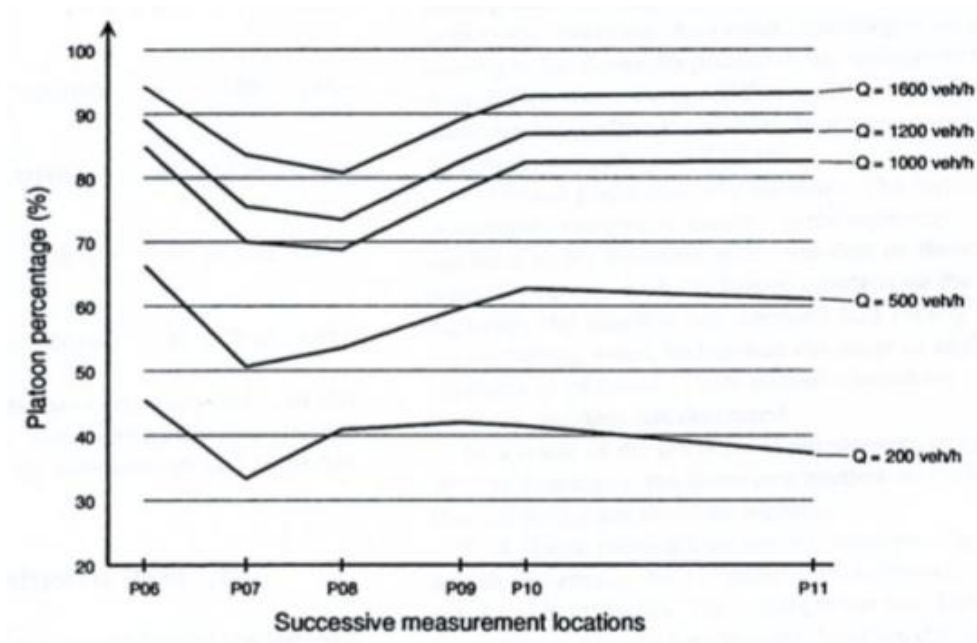
varying lengths of passing-lanes was tested. The spacing between passing-lane sections was varied between 1 to 8 mi at 1 mi intervals and the length of passing-lane was varied between 0.25 and 2 mi at 0.25 mi intervals. There was an additional 1 mi of two-lane roadway included upstream and downstream of the passing sections. The results of the simulation showed that the percent time delay decreased as the passing-lane percentage increased. Based on the volumes, the optimal length of passing-lane varied from 0.8-2 mi and the optimal spacing varied from 11 miles to 3.5 miles. These values were determined based on minimizing percent time delay.

Enburg and Pursula (1995) studied a 12.4 mile section of a three-lane (one lane in each direction with a center alternating passing-lane) rural highway in Finland. The passing-lane segments varied from 0.65 miles to 1.05 miles in length. Data was collected with video cameras for 252 hours. The average travel speed and the average number of passes were determined for each segment. The hourly flows varied from 200 to 1,600 vehicles per hour (vph). The data were used to calibrate a simulation model that was then used to evaluate different designs of the three-lane passing segment and compare it to the two-lane segment. The researchers were interested in the change in average speed and the change in level of platooning as a result of the three-lane segment. For the speed analysis, a linear-regression analysis was performed. The results showed no significant increase in vehicle speeds after the passing-lane. For the platoon analysis, a 5-second headway cutoff value was used to determine if a vehicle was in platoon. The simulation results showed that at all traffic levels, the percentage of vehicles in a platoon was slightly higher before the passing-lane than after, and that 0.62 miles after the passing-lane the platooning level

was the same as the upstream level. Figure 2.4 shows the results from the simulation at each station along the study area.



(a)



(b)

Figure 5: Station setup (a) and results from simulation (b) [Enburg & Pursula]

Taylor and Jain (1991) studied two passing-lane sites in Michigan: one on US-37 in Lake County and one on M-115 in Clare County. Each site had one passing-lane in each direction; all four passing-lanes were examined. Traffic counters were installed 0.5

miles upstream, 0.5 miles downstream, and 1.5 miles downstream of each passing-lane. The upstream stations collected speed, headway, and vehicle classification and the downstream station collected speed and headway data. The data collected were used to calibrate a simulation model. The calibration was done by adjusting the sensitivity factor until the percentage of vehicles in a platoon (the researchers defined a platoon as a group of two or more vehicles with headways of 5 seconds or less) from the field equaled the value reported by the simulation. The traffic volumes at these sites ranged from 175 vph to 470 vph. The simulation results showed that at site 1 (Lake County) the greatest benefit of the passing-lane was a decrease of percent-platooned from 65 % to 63 % between the upstream and the downstream stations. That was at a traffic volume of 470 vph; at lower volumes (175 vph) the upstream-downstream improvement was from 40 % platooned to 38 %. At site 2 (Clare County) the greatest improvement was experienced with a traffic volume of 430 vph, from 63 % platooned to 57 %. The percent platooned value at the third station (1.5 miles downstream) was only available at site 2. The data show that for the eastbound direction the percent platooned has not returned to its pre-passing-lane value at the 1.5 mile station (for all traffic volumes). In the westbound direction, with traffic volumes between 225 vph and 245 vph, the percent platooned at station 3 is equal to or higher than the pre-passing-lane value. These results show that the benefits of the passing-lane extend beyond 1.5 miles from the end of the closing taper, at volumes above 250 vph.

May (1991) collected data on five passing-lanes in Northern California. The volumes on these five sites ranged from 150 to 300 vph. At one passing-lane, a ½ mile

long site, May found percent of vehicles with headways of two-seconds or less increased from 20% to 23%, before and after the passing-lane respectively. At another site, also a ½ mile lane, the Percent Followers decreased from 26 % to 19 % as a result of the passing-lane. The third site had an hourly volume of 150 vehicles with 1 % heavy-trucks. The Percent Followers before the passing-lane was 20 % and after, 15%. The last two sites had passing-lane lengths of 0.9 and 1.5 miles and volumes of 100 and 150 vph, respectively. The Percent Followers fell from 10 % to 4 % at the 0.9 mile long site and from 18 % to 8% at the 1.5 mile-long site. These results show the longer the passing-lane, the greater the improvements, as measured by Percent Followers. May also used a simulation model to conduct a sensitivity analysis. By varying the input lengths of passing-lanes he attempted to answer the question: At what distance downstream from the passing-lane do the operational benefits no longer persist? With a 0.5 mile long passing-lane, the percent time delay returns to its original value after 2 miles. For a 2 mile long passing-lane, the percent time delay returns to its original value after 2.1 miles. For a passing-lane of 0.75 mi or longer, the data showed that benefits tended to diminish after 2 miles. Generally, these results indicate that benefits cease to exist after about 2 miles from the end of the passing-lane.

Harwood and Hoban (1987) conducted an experiment to determine how long benefits persisted after a passing-lane. A simulation modeling software was used to analyze passing-lanes. The results showed that for a flow rate of 400 vph the benefits persisted for at least 7 miles from the beginning of the passing-lane, based on the length of the passing-lane itself. For a flow rate of 700 vph nearly all the benefits diminished

after 5 miles. For a 1.0 mile long passing-lane, the percent of vehicles in a platoon returned to their pre-passing-lane value 5 miles downstream of the passing-lane.

In an earlier study Harwood and St. John (1985) attempted to develop an accurate regression model to predict the operational improvements as a result of the passing-lane.

They collected data at 12 passing-lane sites in six states. At each site, six counters were used. The traffic counters recorded vehicle classification, speed, headway, and acceleration. Three observers were also employed to count the number of passing maneuvers that occurred within the passing-lane section. The six counters were located at: 500' upstream of the entrance taper, 100' downstream of the entrance taper, in the middle of the passing-lane, 300' from the beginning of the exit taper, 500' downstream of the exit taper, and 1 mi downstream of the exit taper. Each vehicle was classified as a free moving vehicle, a platoon member, or a platoon leader. A vehicle was considered to be in platoon if the headway between it and the subsequent vehicle was four seconds or less.

The results showed that the number of vehicles in a platoon decreased from 35.4 % directly upstream of the passing-lane to 20% within the passing-lane. Just downstream of the passing-lane the percentage increased to 29%. One mile downstream of the passing-lane the number of vehicles in a platoon was 3.5% lower than just before the passing-lane. A regression model was developed to predict the change in platooned vehicles as a result of the passing-lane.

$$\%PL = 3.81 + 0.10 * UPL + 3.99 * LEN \quad \text{Eq. 3}$$

Where,

PL = Difference in percent of vehicles platooned between upstream and downstream of passing-lane,

UPL = Percent of vehicles platooned upstream of passing-lane, and

LEN = Length of passing-lane (miles)

The traffic speed analysis showed that mean speeds only increased by 2.2 mph within the passing-lane and were only 0.9 mph faster than downstream of the passing-lane than upstream of the passing-lane. This means percent platooned is a more sensitive variable than mean speed when it comes to measuring effective length and spacing of passing-lanes.

Table 3 summarizes the findings of the studies above in regards to the effective length of passing-lane. The values in the table are based on a 1.5 mile passing-lane with an hourly volume of less than 400 vehicles. Most studies used percent followers as the performance measure, yet some used other measures. These are shown across the top of the table.

Table 3: Effective Lengths of a Passing-Lane Based on Performance Measure Used

Researcher	Effective Length (mi)		
	Percent Followers	Average Travel Speed	Percent Time Delay
Highway Capacity Manual	8.1	1.7	-----
May (1991)	2.1	-----	-----
Harwood and Hoban (1987)	7.0	-----	-----
Woolridge & Messer & Heard (2002)	-----	-----	0.8-2.0
Enburg & Pursula (1995)	1.3-1.7	-----	-----
Taylor & Jain (1991)	>1.5	-----	-----

Note: ----- indicates performance measure was not used

All seven of these studies used accepted simulation packages and all showed quite different passing-lane effective lengths. Woolridge, Messer, and Heard found that the level of platooning took between 3.5 and 11 miles to return to its pre-passing-lane values. May concluded that benefits tended to persist no longer than 2 miles downstream of the passing-lane. Harwood and Hoban showed that the benefits may persist for at least 7

miles. Enburg and Pursula's simulation results showed that benefits may only last approximately 1.0 kilometer (0.5 miles).

Passing-lane Length

Current design standards regarding passing-lane length are based on decades-old, simulation-based research. The passing-lanes built today are based on these standards and their lengths rarely reflect what is needed.

The HCM 2000 recommends a passing-lane length based on traffic level as shown in Table 4. The foundation for the values provided in this table is a study that was conducted more than 20 years ago (Harwood 1986).

Table 4: Optimal Lengths of Passing-Lanes [HCM 2000]

Directional Flow Rate (pc/h)	Optimal Passing Lane Length (mi)
100	≤ 0.50
200	$> 0.50-0.75$
400	$> 0.75-1.00$
≥ 700	$> 1.00-2.00$

The Green Book suggests values for passing-lane length that are derived from the current HCM. The absolute minimum length for passing-lane according to the green book is 300 m (1000 ft.) excluding tapers. Also, the optimal length provided in the green book is 0.8-3.2 km (0.5-2.0 miles) which is the same range of values found in the HCM.

Gattis and Bhawe (2006) studied sites with a 2+1 passing-lane configuration (also known as a three-lane configuration or an alternating passing-lane) in Arkansas. This configuration has one lane in each direction (like a normal two-lane highway) and a center lane that acts as a passing-lane alternating in direction. This is demonstrated in Figure 2.5.

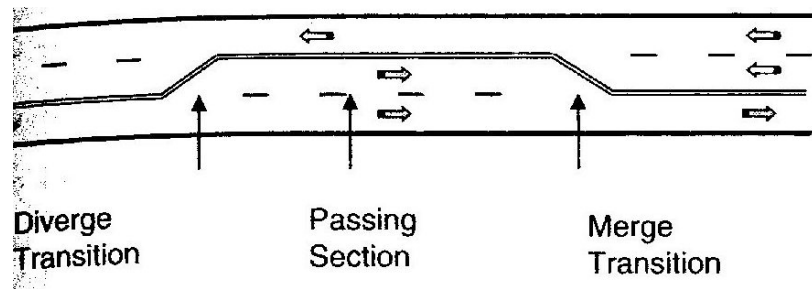


Figure 6: A 2+1 Passing-lane Configuration [Gattis & Bhawe 2006]

A number of criteria were established to determine which site would be selected. First, the site had to be a rural road with a speed limit of 55 mph. Second, the three-lane section must be at least 2.8 miles long. Third, the grade had to be flat or near flat. It had to have a high enough traffic volume. Last of all, it had to have high access control. Four sites were ultimately picked; two on US-70, one on US-65, and one on US-82. At each site data were collected at four stations using pneumatic, road-tube counters. The counters were placed immediately upstream of the passing-lane and at 0.93 mi, 1.86 mi, and 2.79 mi into the three-lane section. Speed, classification, headway, and passing attribute data were gathered. Vehicles were considered to be in a platoon if the headway between them was 3 seconds or less, and, interestingly, even if they were in adjacent lanes. The justification for this was that eventually they would be forced to merge to the same lane. The data analysis results showed that:

1. The greatest reduction in platooning was between Stations 1 and 2. There was even a slight increase in platooning between Stations farther downstream
2. The platooning at the beginning of the three-lane segment was always greater than at the end.

A passing analysis was also conducted. The researchers found that the maximum number of passes occurred between stations 1 and 2. Past station 2 passing leveled off or declined. Passing rates also increased with higher volumes.

In May and Emoto's (1988) report (mentioned above) the researchers conducted a microscopic study to analyze the passing-lane usage. Counters gathered the total number of vehicles in the eastward direction and the number of vehicles in the passing-lane in the east direction. A plot of the total volume versus the passing-lane volume was created. A best fit line was drawn in by hand and the equation of this line was determined: $V_{pl} = 10 + .025(V_t)$. A passing experiment was conducted to determine the number of passes vehicles made per mile of passing-lane. A test vehicle was driven through the section and the number of passes was observed for each alternating passing-lane subsection. The number of passes varied from 1.5 passes / mile to 1.75 passes / mile.

Mutabazi, Russell, and Stokes (1999), researchers at Kansas State University, conducted a simulation study to determine the passing-lane configuration that was best as far as reducing delay. The configurations investigated are shown in Figure 7. Traffic data was gathered from two sites, US-54 and US-50, for calibration of TWOPAS simulation software. Two video cameras, one at each end of the test section, collected data simultaneously at one site and the number of passes within the section was determined by analyzing the sequence of departures and arrivals. The calibrated model was applied to the second site to compare predicted values to actual values. The model was adjusted until the values coincided. TWOPAS simulation was then used to determine the best configuration of passing-lane. The results showed that percent time delay was equivalent

for side-by-side configuration and head-to-head configuration; however percent delay was higher for all other configurations.

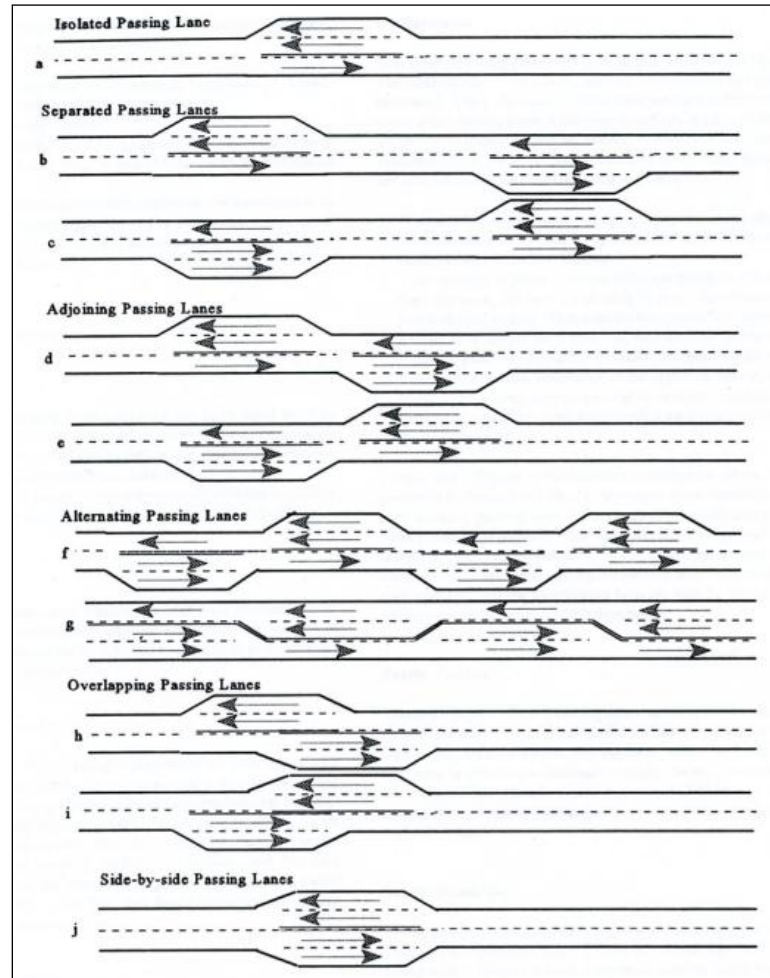


Figure 7: Passing-lane configurations [Mutabazi & Russell & Stokes 1999]

CHAPTER 3

STUDY SITES AND DATA COLLECTION

This chapter is divided into two main parts: study site description and data collection. The study site description part will discuss how the sites were selected and the location and characteristics of each site. The data collection part will explain how the data was collected and how it was processed and uploaded.

Study Sites

This section will discuss the study site characteristics and the criteria for selecting the sites.

Site Selection

The data for this thesis was collected from three passing-lane sites. These three locations were selected after narrowing down a list of potential sites. The criteria, in order of importance, for considering a site for data collection were:

- Presence of minor driveways or intersections within the passing-lane
- Presence of minor driveways or intersections upstream or downstream of passing-lane
- Grade
- Length of passing-lane
- Proximity to Bozeman
- Field Safety

It was important that the passing-lane site did not have any major intersections in it. This is so that platooning-level could be controlled. Analysis will be done to compare the level of platooning before and after the passing-lane. If the intersection is a major ingress or egress point, the benefits seen may not be valid.

Sites had to have a limited number of access points upstream and downstream of the passing-lane to be considered. It was important for the upstream section to be clear of intersections as to prevent artificial platoons from reach the passing-lane. All platoons reaching the passing-lane should be formed by slow vehicles, not be vehicles grouping at a red-light. The downstream section also had to clear of intersections as to allow for an accurate calculation of how far passing-lane benefits persist. Some researchers have found it could take as far as 8 miles for the benefits to diminish.

The grade of the passing-lane was another variable taken into consideration. If the grade of the section is more than 2-3% the passing-lane practically becomes a climbing lane, on two-lane highways. Note, on four-lane highways a climbing lane is intentionally used for trucks and other vehicles with diminished performance on steep grades. The purpose of a climbing lane is slightly different from that of a passing-lane in that passing-lanes are used to break-up platoons and climbing lanes are used because speeds of heavy vehicles are affected more than those of lighter vehicles. If the section is at a grade of 4 or 5% it may not be possible to study platoon dispersal.

The passing-lane had to be of adequate length. If the section is too short, operational benefits may or may not be noticed due a passing-lane. Previous research indicated that there may be no benefits from passing-lanes less than 0.5 miles in length.

Sites with different lengths would be ideal because comparisons could be done to determine the optimal passing-lane length.

Due to the fact that a few trips to study sites may be needed, it was important that sites be within a reasonable driving distance (<1hr) from Bozeman. If the sites are too far away a follow-up visit to insure the tubes are in place may not be possible. Although this was never a major criterion and is of lesser importance, it is a nice convenience.

Lastly, field safety was a concern when selecting a site. Unsafe situations, such as high traffic volumes with short gaps or sites with limited sight distance, did exclude a site from being picked. It was necessary for a site to have gaps in the flow because researchers would be in the middle of the road installing equipment. It was also necessary for a site to have adequate sight distance so that the researcher could have ample time to move off the roadway if a vehicle approached.

Originally six potential data collection sites were examined. These were:

- US 191 MP 70 to 72
- US 287 MP 58 to 61
- US 287 MP 68 to 71
- US 287 MP 94 to 96
- US 287 MP 103 to 106
- US 87 MP 32 to 35

After a close examination of each of the six sites, only 3 met the criteria mentioned above: US 191 MP 70 to 72, US 287 MP 94 to 96, and US 287 MP 58 to 61.

The other three did not meet one or more of the criteria listed above.

US 287 MP 68 to 71 had an intersection within the passing-lane as well as on the north and south approaches.

US 287 MP 103 to 106 did not contain any intersections within and on the approaches, yet it was at a grade of 5 % which classified it as a climbing-lane rather than a true passing-lane.

US 87 MP 32 to 35 was also on a grade of more than 4 %, making it a climbing lane. The other drawback to this site was its location: a four hour drive from Bozeman. This would have prevented any necessary follow-up visits during the study period.

Description of Study Sites

Site I is a passing-lane on US HWY 287 between mileposts 94 and 96. This site is located on the major highway that connects the interstate, Interstate-90, to Helena, the capital city. The study site is 3 miles north of the junction between I-90 and US 287. There is a 1.5 mile-long passing-lane in each direction at the site; only the northbound passing-lane was investigated. This site was chosen because there are no major access points on either approach.

Site II is the passing-lane on US 191. US HWY 191 is the major highway between Yellowstone National Park and Bozeman, Montana. Approximately 50 miles of the highway winds through the narrow Gallatin Canyon and has limited passing opportunities. The passing-lane is located immediately after the canyon (on the North side) and is intended to relieve platoons that were unable to break-up within the canyon. The passing-lane is 0.7 miles long and runs only in the northbound direction. US 191 eventually runs through Bozeman, MT and connects to I-90. This site was chosen

because of its close proximity to Bozeman, MT and it had no access points within the passing-lane.

Site III is another passing-lane on US HWY 287. This particular passing-lane is approximately 5 miles north of Townsend, MT and 10 miles south of Helena, MT. A relatively high number of recreational vehicles are present on this section of US 287 due to its proximity to Canyon Ferry Lake. The passing-lane (located on the southbound direction) is 2.33 miles in length and does have one intersection within it giving access to the lake and residences around the lake.

Figure 8 shows the location of each site on a map of Montana.

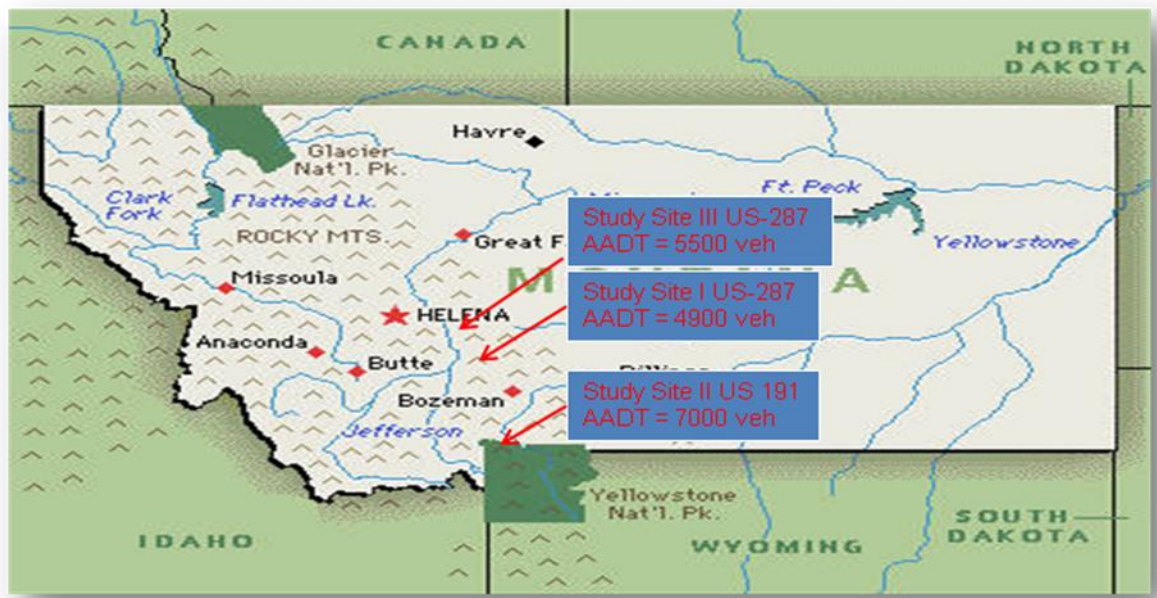


Figure 8: Study site locations [mthomesandland.com 2009]

Data Collection

This section will explain how the data was collected, screened and processed. It will also explain data limitations and difficulties.

Technique

Data was for this thesis collected using automatic traffic counters. The counters were connected to air tubes stretched across the lanes of traffic of interest. The free end is knotted to prevent it from slipping through its strap. They were kept in place with road tape (mastic), nails, and straps (or webbing). The general installation is shown in Figure 9.

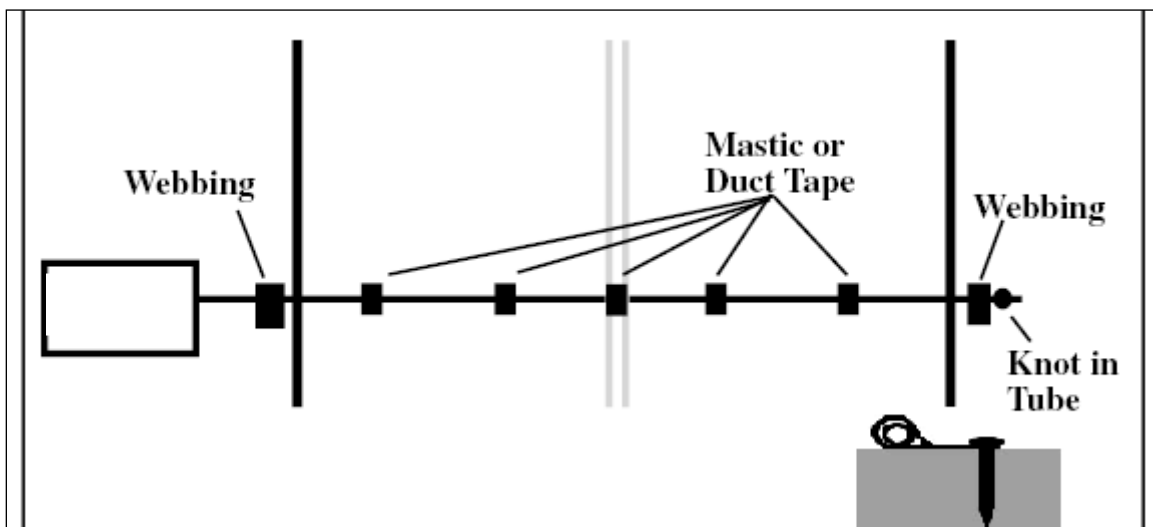


Figure 9: Automatic Traffic Counter set-up [JAMAR 2007]

Data was collected for one week at each site in the summer of 2008. Data was collected from study sites I and II in June 2008 and from site III in August 2008. Table 5 quantifies all the data gathered at each site.

Table 5: Total Data Collected at Each Site

	Site		
	I	II	III
Hours of Data	956	577	800
Total Vehicles	127,410	99,678	95,625

Counter Layout-Site I. For the purpose of assessing the operational benefits of the passing-lane, one counter was placed 250' upstream of the passing-lane and one placed 250' downstream of the passing-lane. The distances mentioned are measured from the end of the taper.

The second analysis to be performed was to determine for how far those benefits persisted after the end of the passing-lane. This required placing counters at specified distances downstream of the passing-lane to understand how the benefits diminished. These counters were placed at 0.5 miles, 1.5 miles, 3.0 miles, 5.0 miles, and 6.6 miles after the taper.

Counter Layout-Site II. The counter layout at this site was similar to that of the US 287 site. One counter was located 250' upstream of the taper and one located 250' downstream of the taper. Two more counters were located downstream: at 0.5 miles and 1.5 miles. Counters locations did not extend as far at this site as they did on US 287 because there was not as much 'clean' distance downstream (i.e. intersections, grades, etc.).

Counter Layout-Site III. For the purpose of understanding how platoons split up and how traffic distributed itself within a passing-lane, one counter was placed upstream and four counters were located inside the passing-lane.

The first counter (upstream) was located 250' before the widening taper. The stations inside the passing-lane were placed 0.25 miles, 0.5 miles, 1.0 mile, and 1.5 miles

past the end of the taper. Figure 10 illustrates the schematic of the counter layout for each site.

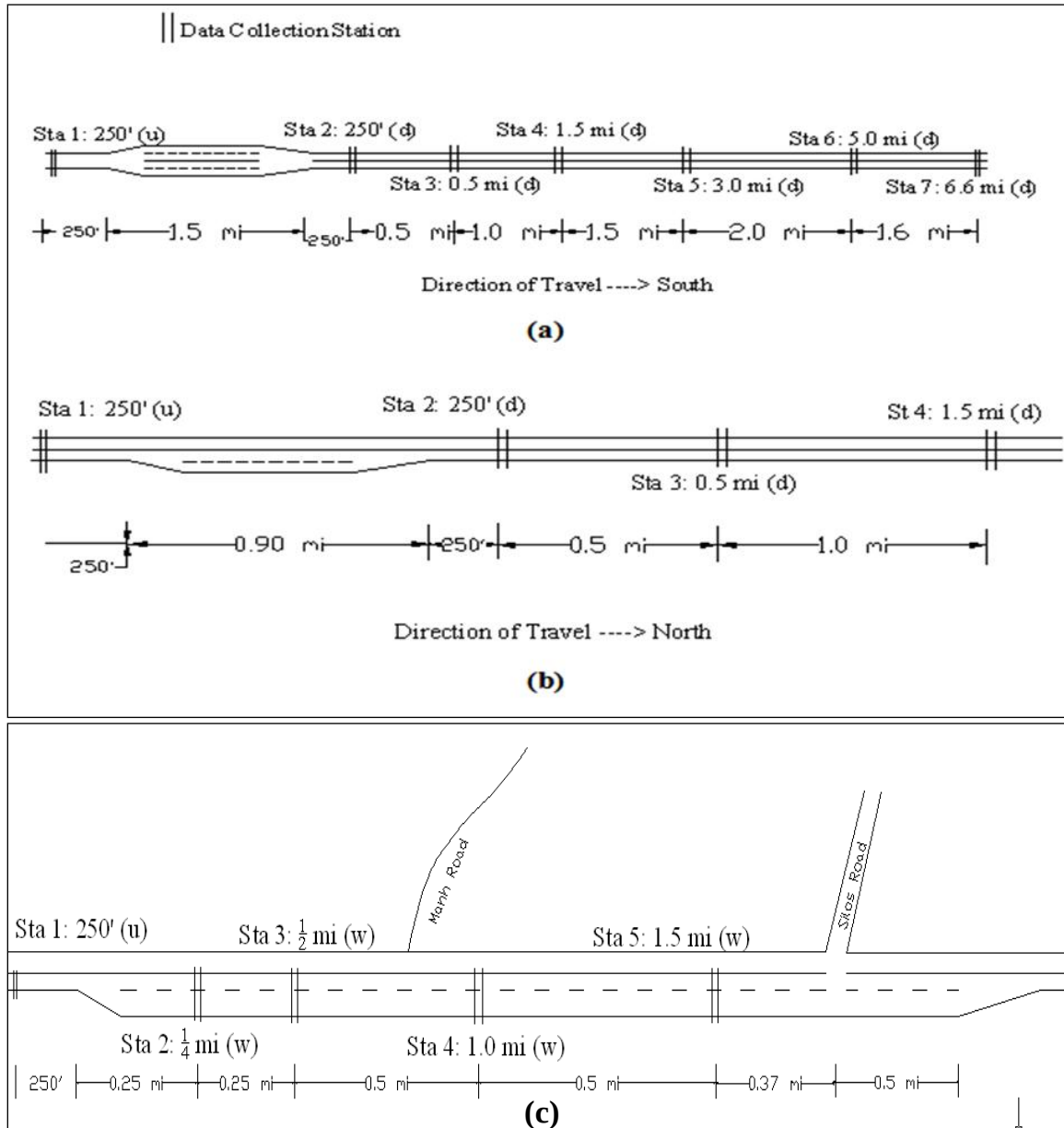


Figure 10: Counter setup at (a) Site I (US 287), (b) Site II (US 191), and (c) Site III (US 287)

Data Processing

After the counters were brought back to the lab from the field, the data was uploaded to the computer using the counters' proprietary software. The software tabulated the raw data into Microsoft Excel from which it was 'cleaned'.

All counters collected a time stamp, speed, gap, and vehicle classification. The gap is equal to the amount of time that passes between the rear axle of the lead vehicle hitting the tubes and the front axle of the following vehicle hitting the tubes. To be consistent with HCM 2000 procedures, this time gap had to be converted to a headway value. Headway is the amount of time between the front axle of the lead vehicle and the front axle of the rear vehicle. The difference between gap and headway is the time it takes the lead vehicle to travel a distance equal to its length.

$$\text{Headway} = \text{Gap} + (\text{Vehicle Length} / \text{Speed}) \quad \text{Eq. 4}$$

Vehicles were grouped into one of fourteen classes according to the FHWA vehicle classification scheme:

Class 1. Motorcycles

Class 2. Passenger Cars

Class 3. Pickups and Vans

Class 4. Buses

Class 5. Two axle, six-tire trucks

Class 6. Three-axle trucks

Class 7. Four or more axle trucks

Class 8. Four or less trailer trucks

Class 9. Five-axle trailer trucks

Class 10. Six or more axle trailer trucks

Class 11. Five or less multi-trailer trucks

Class 12. Six-axle multi-trailer trucks

Class 13. Seven or more axle multi-trailer trucks

Class 14. Unclassified

Being able to segregate heavy vehicles from the rest of the traffic is important for certain performance measures.

Each vehicle was classified as either a platoon leader, a member of a platoon, or a free-moving vehicle (outside of a platoon). A vehicle was considered a platoon leader if it had a least one vehicle behind it following with a headway of three seconds or less.

Platoon members were vehicles with headways of three seconds or less (between itself and the vehicle in front of it). Free-moving vehicles were vehicles that had headways of eight seconds or greater.

The data was screened thoroughly before including it in any analysis. Vehicles with erroneous data were thrown out of the analysis. The remaining data was then grouped into 15 minute intervals and hourly rates were determined.

Data Limitations

The range of volumes collected for the analysis was typical of rural two-lane highways. Yet higher traffic volumes at the three sites would have been desirable. The saturation flow rate for two-lane highways is 1,700 vehicles-per-hour-per-lane (vphpl). The maximum volumes measured for this thesis are roughly one-fifth this value (~350 vphpl).

However, the volumes measured represent 80-90 percent of the two-lane highways in Montana. This distribution is shown in Figure 11.

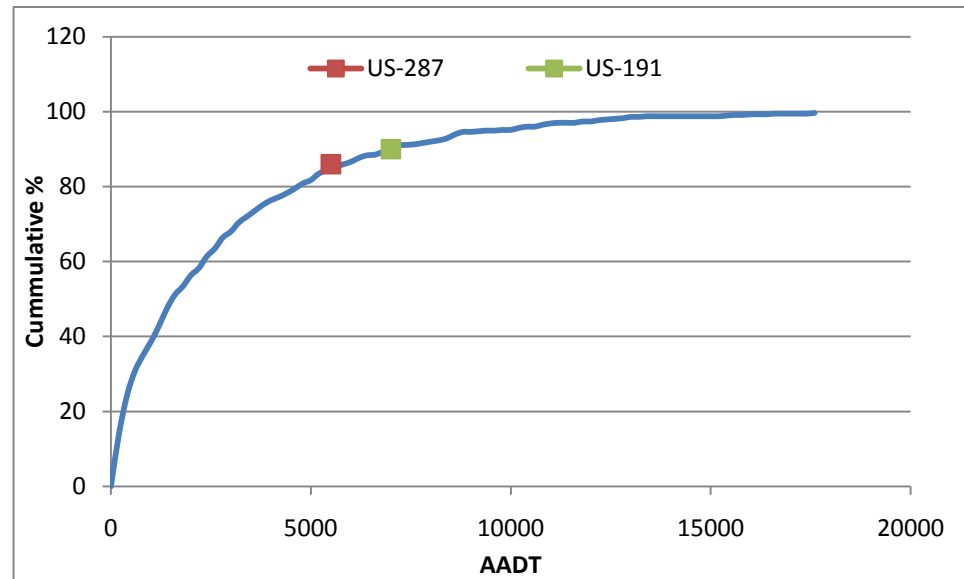


Figure 11: Distribution of two-lane highway AADT's in Montana
[Montana Department of Transportation 2007]

Difficulties Encountered

Not all the counters installed functioned properly. After uploading the data from the counter at the Site I upstream location, it could be seen that the file was corrupt. Data from this location could not be used. The counter at the three mile downstream location at the same site also had a problem: the battery had died after counting for just four hours. Because a before-after analysis of the passing-lane was to be conducted, new counters were placed at the upstream and downstream locations (at Site I) at a later date. There was slightly higher traffic and a slight increase in percentage of heavy vehicles at the later date. Very little of the data at the three mile downstream location could be used and this station was left out of most analyses.

Three of the five counters at Site III used for data collection malfunctioned in some way that resulted in ‘bad’ data points. Roughly twenty-percent of the vehicles at the quarter-mile station were unclassified and had reported speeds of 0 mph. Almost forty-percent of the vehicles from the half-mile station, in the passing-lane, showed the same problem. The counter at the one-mile station failed to collect data for lane 1 (the inside lane). Although the missing data could be used when doing volume comparisons between the two lanes and headway analyses, it was not used for speed or classification analyses.

CHAPTER 4

SELECTING PERFORMANCE MEASURES

This chapter discusses the results from the investigation that aimed at examining and selecting the most appropriate performance measure(s) to be used in the passing-lanes investigations. The chapter is broken into two main parts: the first part discusses the methodology that was used in performing the examination, while the second part presents the results of the investigation along with the major findings that are related to study objective.

Study Approach

The approach utilized in this investigation is to use traffic data from the vicinity of a passing-lane to examine the appropriateness of a number of performance measures in assessing performance on two-lane highways. Passing-lane-data is used because the current research is concerned with examining performance at passing-lane locations. It is worth mentioning that only empirical data was used in this investigation (and other investigations presented in this thesis). This is important because previous research has largely used simulation in one regard or another to analyze performance at two-lane highways.

Six measures of performance were used in the current investigation. These include measures that are being used in the current practice in the U.S. and other measures that were suggested in the literature or reported as being used in other countries. These measures are Percent Followers, Follower Density, Average-Travel-Speed (ATS), Average-Travel-Speed of Passenger Cars (ATS_{pc}), Average-Travel-Speed

divided by Free-Flow-Speed (ATS / FFS), Average-Travel-Speed of Passenger Cars divided by Free-Flow-Speed of Passenger Cars (ATS_{pc} / FFS_{pc}), and Percent Impeded (PI). These measures are discussed individually below.

Percent Followers

Percent Followers represents the percentage of vehicles with short headways in the traffic stream. This performance indicator can easily be measured in the field and as such is used by the HCM as a surrogate measure for PTSF field estimation. The headway cut-off value used by the current HCM is 3 seconds, which is the same value used in this study.

Follower Density

Follower density is the number of followers in a directional traffic stream over a unit length. The argument behind using this performance indicator is that a road with low average daily traffic (ADT) and high PTSF should have a lower LOS than the same road with a higher ADT and equal PTSF. This is particularly true in the context of highway improvement decision making.

Average-Travel-Speed

Average-Travel-Speed is the average speed of all the vehicles in the traffic stream. Logically, as performance improves on a two-lane highway the average speed of vehicles should increase. The drawback of this measure is that average speed cannot be used to compare two highways because design standards govern speed.

Average-Travel-Speed_{passenger-cars}

This performance measure quantifies the average speed of passenger cars. It may be more appropriate than the general average speed because passenger-car speeds are known to be more sensitive to platooning than heavy-vehicles. However, it has the same limitation as ATS.

Average-Travel-Speed divided by Free-Flow-Speed

This measure is an indicator of the amount of speed reduction due to traffic. In the context of this research, if the percentage is high, then the interaction among successive vehicles in the traffic stream is small, and a low platooning level is expected. By the same token, a lower percentage indicates a higher level of platooning.

Percent Impeded

Al-kaisy and Durbin (2006) introduced this performance measure in their paper *Estimating Percent Time Spent Following on Two Lane Highways: Field Evaluation of New Methodologies*.

This surrogate, referred to as PI, is based on a probabilistic approach. It is based on the probability of a vehicle being in platoon and of being a *trapped vehicle* in that platoon. Mathematically, PI is equal the probability of a vehicle being a platoon *times* the probability of a vehicle being trapped (impeded).

$$PI = P_p \times P_t \quad \text{Eq. 5}$$

Where,

P_i = Probability of a vehicle being part of a vehicular platoon using a time headway
platoon definition

P_t = Probability of a vehicle being trapped in a platoon unable to pass the lead vehicle

P_i is determined the same way percent-followers is: measuring headways of all vehicles and determining what percent values fall within a certain cut-off value (usually 3-seconds).

The changes of various performance measures in the proximity of passing-lanes were examined using the general performance curve shown in Figure 12. This performance curve is consistent with the general understanding of passing-lane effect as outlined in the Highway Capacity Manual procedures (HCM, 2000). The premise of the approach is that the suitability of any performance measure should be assessed using the extent to which that particular measure is sensitive to platooning level changes on two lane highways.

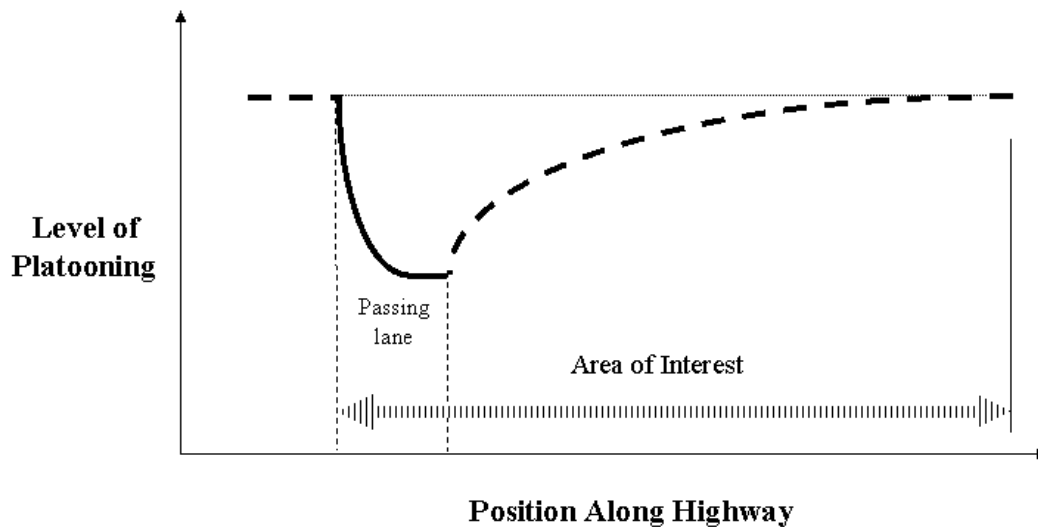


Figure 12: The general shape of performance in the vicinity of a passing-lane

Two study sites were used in this investigation, HWY US 287 and HWY US 191.

Automatic traffic counters were placed upstream and at various distances downstream of the passing-lane at each site. The counters were brought back to the lab and the data were uploaded onto spreadsheet files. The data were then analyzed and processed. The speed, classification, and gap of every vehicle were collected at each station.

For the purpose of this investigation, four analyses were conducted:

1. Visual Analysis
2. Before-and-After Analysis
3. Correlation Analysis
4. Linear Regression Analysis

A visual analysis was conducted by plotting each of the six performance measures vs. distance downstream of the passing-lane. Each plot was compared to the hypothesis curve in Figure 3.1. More appropriate performance measures will closely resemble the hypothesis curve and less appropriate measures may take another shape.

A before-and-after examination was conducted to determine how each measure changed as a result of the passing-lane.

Third, a correlation analysis was conducted to assess which measure related highest to known factors that affect platooning on two-lane highways. These factors may be percent-trucks in the traffic stream, highway grade, or traffic volume. A good performance measure will correlate highly to the variables mentioned.

Fourth, a multivariate regression analysis was conducted. Each performance measure was expressed as function of the variables used in the correlation analysis. The R-squared

value was determined for each relationship and the measures with the highest such value will be deemed most appropriate.

Results

The main interest of this study is to choose an appropriate performance for use on two lane highways using empirical data collected from passing-lanes in Central Montana.

Preliminary Examination

The first step in the preliminary examination was to assess how platooning changed as the traffic flow moved downstream from the passing-lane using the six measures of performance, namely: Percent Followers, Follower Density, Average Speed, Speed Ratio, and Average Speed of Passenger Cars . The six measures were plotted as a function of downstream distance at each site. These relationships are shown for US 287 and US 191 on Figures 13 and 14, respectively. Note that because of the higher ADT on US 191, three traffic levels were examined at that site as opposed to two on site I.

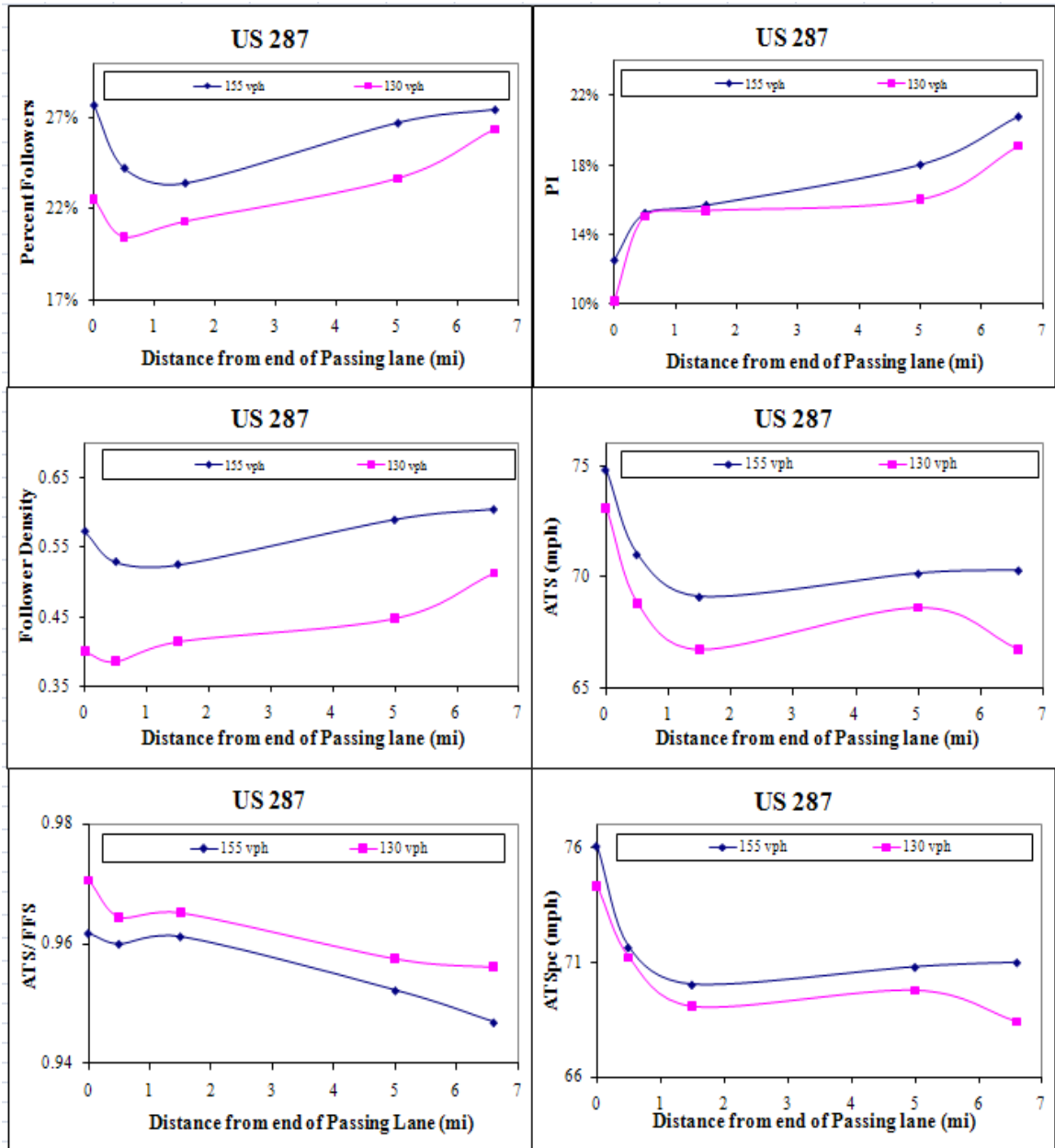


Figure 13: Performance measures as a function of distance downstream of passing-lane on US 287

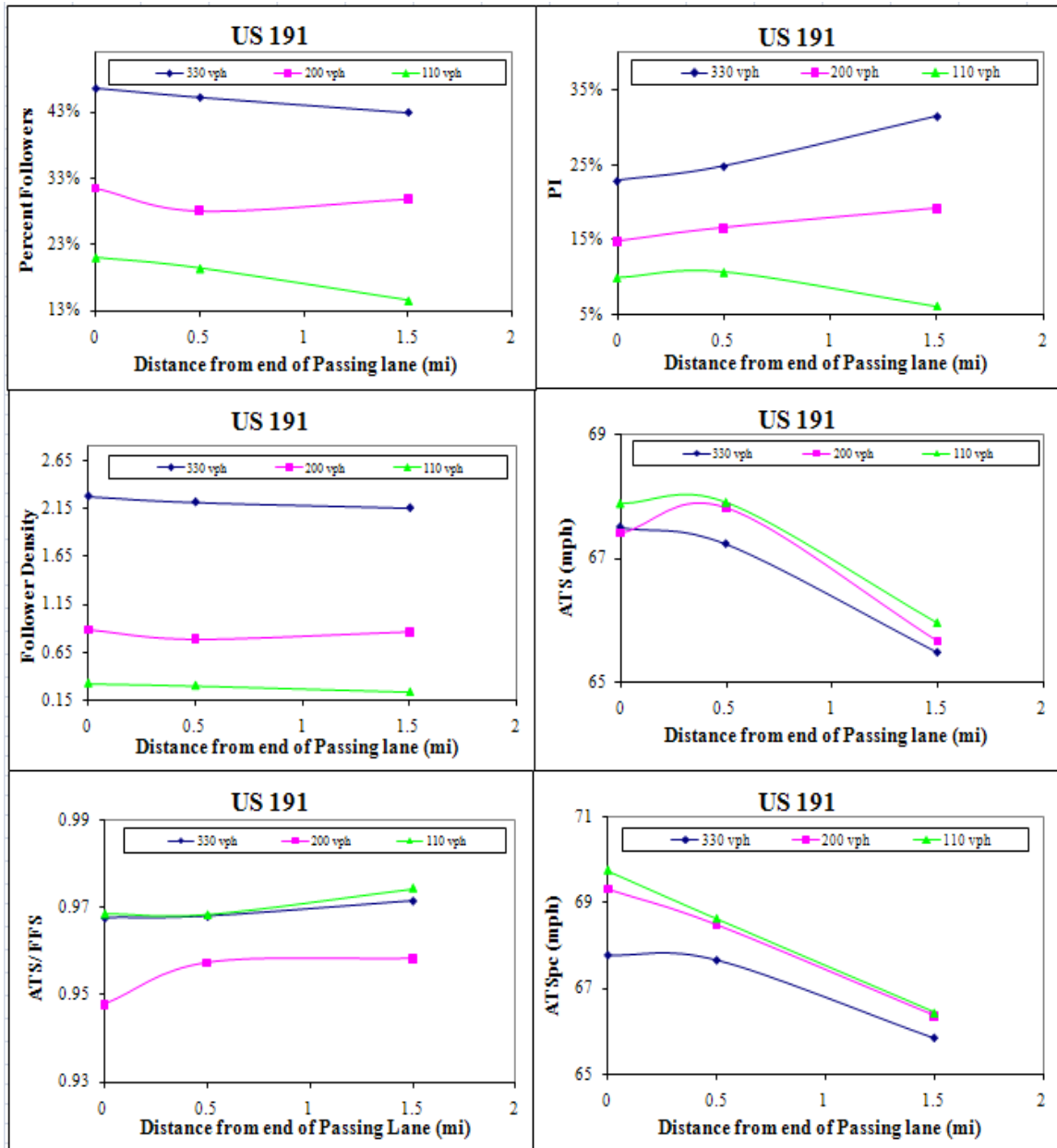


Figure 14: Performance measures as a function of distance downstream of passing-lane on US 191

From the plots above it is evident that Percent Followers is significantly higher than PI at all stations, for both sites. This is understandable if one considers how each performance measure is calculated. Percent Followers is the proportion of vehicles with headways of three seconds or less, with no regard to impedance. P_f is the percent of those

vehicles with three-second headways or less that are actually impeded; not all vehicles with short headways are impeded.

Percent Followers seems to demonstrate a reduction in platooning immediately following the passing-lane, especially on HWY US-287. This trend is slightly noticeable on HWY US-191. This can be explained by a phenomenon called the *merge effect*. As the passing-lane ends, all vehicles (from both lanes) are forced to merge into a single lane. This point causes a high percentage of traffic with relatively short headways at the end of the closing taper. As the platoons move away from the passing-lane they naturally space themselves out driving at more comfortable headways; thus Percent Followers decreases for some distance downstream. Beyond that point, faster vehicles begin to catch up to the slower vehicles and platoons reform; thus causing an increase in Percent Followers. Because Follower Density is based on Percent Followers (Follower Density = [Percent Followers] * [Density]) the two performance measures are expected to exhibit similar trends. Note, density should not change significantly between stations (for a given traffic volume) because speeds will not change drastically.

ATS and ATS_{pc} both show a general decrease in speed in the first 1.5 miles downstream of the passing-lane. It is expected that once drivers leave the passing-lane section their speeds should begin to decrease as platoons start re-forming.

The speed ratio on US 287 decreases beyond the downstream station; this is consistent with the ATS and ATS_{pc} trends. On US 191 the speed ratio does not seem to change significantly as traffic moves away from the passing-lane.

Finally, the performance measures do not seem to follow the exact same patterns on US 191 as they do on US 287. There are two reasons for this. First, the passing-lanes are different lengths: 1.5 miles long on US 287, and 0.7 miles on US 191. Platoons may not have fully broken up within the 0.70-mile passing-lane. Second, note that the distance downstream studied at each site is different, 1.5 miles on US 191 and 6.6 miles on this US 287. The traffic patterns seen downstream on Highway 287 seem to not have evolved in the 1.5 miles downstream on Highway 191.

Before-After Examination

The purpose of passing-lanes is to break-up platoons formed by slow moving vehicles. This analysis was conducted to determine the extent to which the passing-lane dispersed the platoons present at these sites. Table 6 shows these results for site I, US 287. Two traffic levels were considered: 130 and 155 vph.

Table 6: Before-After Results for US-287

130 vph			
Performance Measure	Upstream	Downstream	Percent Change
PI	26.4%	10.6%	-59.67
Percent Followers	36.3%	21.4%	-41.05
Follower Density	0.697	0.400	-42.67
ATS*	67.6	69.7	3.11
ATS/FFS	0.98	0.99	0.81
ATS _{pc} *	68.5	70.9	3.50
155 vph			
Performance Measure	Upstream	Downstream	Percent Change
PI	28.5%	14.11%	-50.58
Percent Followers	40.8%	27.1%	-33.58
Follower Density	0.922	0.564	-38.83
ATS*	68.6	74.8	9.04
ATS/FFS	0.98	0.96	-1.43
ATS _{pc} *	69.1	76.1	10.1

*ATS and ATS_{pc} are expressed in miles-per-hour (mph)

The most noticeable part of Table 6 is how little the speed-related measures changed in comparison to the headway-related measures. This means traffic speed is probably not a good measure of platooning. Next, the improvement for the headway-related measures is considerably greater at the lower traffic volume and speed-related measures are considerably greater at the higher traffic volume. Because the traffic volumes are relatively close, this is an interesting finding. The decrease in platooning as measured by PI is significantly greater than the decrease measured by Percent Followers or Follower Density.

Table 7 shows the before-after results for US 191.

Table 7: Before-After Results for US 191

330 vph			
Performance Measure	Upstream	Downstream	% Change
PI	33.5%	18.8%	-43.9
Percent Followers	48.4%	42.4%	-12.4
Follower Density	2.25	2.10	-6.70
ATS*	71.8	67.5	-5.99
ATS / FFS	0.99	0.96	-3.00
ATS _{pc} *	72.3	67.8	-6.22
190 vph			
Performance Measure	Upstream	Downstream	% Change
PI	23.6%	17.3%	-26.7
Percent Followers	36.3%	28.6%	-21.2
Follower Density	1.00	0.83	-17.0
ATS*	71.1	67.4	-5.20
ATS / FFS	0.98	0.96	-2.00
ATS _{pc} *	71.7	69.3	-3.35
106 vph			
Performance Measure	Upstream	Downstream	% Change
PI	16.6%	5.9%	-64.6
Percent Followers	27.5%	17.4%	-36.7
Follower Density	0.42	0.28	-33.3
ATS*	72.2	67.9	-5.96
ATS / FFS	0.98	0.98	0.0
ATS _{pc} *	72.8	69.8	-4.12

*ATS and ATS_{pc} are expressed in miles-per-hour (mph)

The traffic on US 191 was divided into three levels for this analysis: 106, 190, and 330 vph. Generally the same trends in the data appear at this location as they do for US 287. Again, the percent change of the speed-related measures is minimal compared to the other performance measures. Also, the highest improvements were experienced at the lowest traffic levels for the headway-related measures; there is no discernable trend for the speed measures. PI has a greater percent change as a result of the passing-lane than either Percent Followers or Follower Density. This may be attributed to the *merge effect* discussed earlier. As traffic moves from two-lane to one-lane, there are a high number of short headways that lead to an increase in Percent Followers and Follower Density, but not PI (because the vehicles are not actually impeded).

Correlation Examination

A correlation analysis was conducted to get a brief idea of how the performance measures interrelated and how well they correlated to the platooning variables. Several variables were identified for inclusion in this analysis. These variables are:

1. Volume (in the direction of interest)
2. Percent No-passing Zones
3. Distance Downstream of Passing-lane
4. Merge Effect
5. Percent Heavy Vehicles

The analysis only uses data from US-287, as it covers a much broader range of variables. Each unit of data was one hour of traffic data and 155 hours were used for this analysis as well as for the statistical regression analysis.

Table 8 contains these results. Note ATS and ATS_{pc} were left out of this analysis.

Table 8: Correlation Analysis Results

	<i>PI</i>	<i>Percent Followers</i>	<i>Follower Density</i>	<i>ATS/FFS</i>	<i>% No Passing</i>	<i>Distance</i>	<i>Merge Effect</i>	<i>Volume</i>	<i>% Trucks</i>
PI	1								
Percent Followers	0.58	1							
Follower Density	0.48	0.69	1						
ATS/FFS	-0.96	-0.51	-0.55	1					
% No Passing	0.54	0.08	-0.27	-0.45	1				
Dist	0.95	0.66	0.69	-0.94	0.27	1			
Merge Effect	-0.71	-0.06	0.18	0.74	-0.74	-0.52	1		
Volume	0.08	0.34	0.04	0.09	0.07	-0.01	-0.09	1	
% Trucks	-0.48	0.09	0.22	[0.62]	-0.52	-0.34	0.87	-0.07	1

The first four shaded cells going across the top of the table (as well as the first four cells going down the left-hand column) are the performance measures; the non-shaded cells in the top row and left column are the platooning variables. The lightly-shaded cells in the table represent significant correlations: a correlation value greater than 0.60. The darkly-shaded cells (with white text) represent the relationships that are counterintuitive. A value in a bracket means it is significant and counterintuitive. The performance measures all correlate to each other in a logical fashion, although they may be below 0.60.

‘Distance’ [downstream of the passing-lane] seems to correlate highly and logically to all the performance measures. Traffic volume appears to have a low correlation to the measures.

To gain a deeper understanding of how the measures are linked to the platooning variables, a linear regression was conducted to attempt to model each of the measures after the variables.

Statistical Regression Analysis

Linear regression was another analytical tool used to explore the relationships between the performance measures and the platooning variables. Regression allowed an assessment of the strength of each measure used in this study. The objective of this analysis is to characterize the relationships between performance / platooning and the six measures investigated in this study including the new measure, percent impeded. The five variables used for the correlation analysis plus one more (volume in opposing direction) were used in this analysis.

Merge effect was included in this analysis as previous results suggested a notable effect on headway distribution immediately after the passing-lane. Again, only data collected on US 287 is used in this analysis. A multivariate linear regression was setup in the form:

$$PM = C + a*X_1 + b*X_2 + c*X_3 + \dots h*X_n \quad \text{Eq. 6}$$

Where,

PM = Performance Measure

C = Constant

a, b, c = Coefficients

X_{1-n} = Variables (Volume, % No-passing, etc.)

The F-ratio, R-squared value, and the Standard error (SE) were determined for each model. These results are presented in Table 9.

Table 9: Results from Multivariate Linear Regression

	Regression Model	SE	Adj. R-squared	P-value of F-test
Percent Impeded	$11.4 + 0.0012*\textcolor{red}{X1} + 0.0015*\textcolor{red}{X2} + 0.016*\%X3 + 0.879*X4 - 0.794*X5 + 0.081*\%X6$	0.33	0.986	2.20E-108
Percent Followers	$\textcolor{red}{13.9} - 0.038*\textcolor{red}{X1} + 0.044*\textcolor{red}{X2} + 0.016*\%X3 + 0.853*X4 + 2.96*X5 + .533*\%X6$	1.21	0.732	1.39E-27
Follower Density	$-0.280 + 0.00582*\textcolor{red}{X1} + 0.00687*\textcolor{red}{X2} + 8.67e-5*\%X3 + 0.0108*X4 + 0.0684*X5 - 2.25e-4*\%X6$	0.09	0.707	2.90E-39
ATS	$68.5 - .0284*\textcolor{red}{X1} - .0425*\textcolor{red}{X2} .0132*\%X3 - .0231*X4 - .0587*X5 - .00365*\%X6$	.06	0.621	1.96E-28
ATS / FFS	$1.03 - 4.30e-4*\textcolor{red}{X1} - 2.61e-4*\textcolor{red}{X2} + 3.42e-6*\%X3 - 0.0016*X4 + 0.00125*\textcolor{red}{X5} - 1.10e-4*\%X6$	0.01	0.650	1.65E-33
ATS_{pc}	$70.2 - .0324*\textcolor{red}{X1} - .0245*\textcolor{red}{X2} .0214*\%X3 - .0314*X4 - .0427*X5 - .00156*\%X6$	.21	0.596	1.34E-15

X_1 = Volume X_2 = Volume in Opposite Direction X_3 = % No Passing
 X_4 = Distance Downstream X_5 = Merge Effect (0 or 1) X_6 = % Trucks

The variables (X_{1-6}) are listed below the table. Variables shown in red in the ‘Regression Model’ column were found insignificant at the 95% confidence interval. Percent Impeded had the highest adjusted R-squared value (0.986) meaning that it correlated to platooning variables among all other measures. The R-squared values for the other models were also high.

Investigation Findings

This investigation used data gathered from two passing-lane sites in Montana to choose an appropriate performance measure for two-lane highways. The results showed PI demonstrated an improvement of 50-60% at site I and 27-65% at site II (depending on traffic level) as a result of the passing-lane. Other headway-related performance measures showed less of an improvement: 33-43% at site I and 7-37% at site II. Also, based on the

correlation analysis, PI had stronger correlations with other performance measures as well as with the platooning variables.

Based on the results of the linear regression, PI, Percent Followers, and Follower Density were chosen as the most appropriate performance measures for two-lane highways. The speed-related measures will be dropped from the rest of the thesis because they did not perform as well as the other measures.

CHAPTER 5

DOWNSTREAM EFFECTIVE LENGTH OF PASSING-LANE INVESTIGATION

This chapter is broken into two main parts: Investigation Methodology and Investigation Results. The methodology explains the approach followed in conducting the current investigation while the results attempt to identify the effect of passing-lane as a function of distance downstream of passing-lane location.

Study Approach

The aim of this investigation was to determine how far downstream of the passing-lane the operational benefits persist and the magnitude of those benefits.

Automatic Traffic Counters were placed at predetermined locations upstream and downstream of the passing-lanes. The upstream counter was placed immediately before the opening taper; this location was chosen for the purpose of capturing the traffic stream just before it enters the passing-lane section. Downstream the counters were placed immediately after the closing taper and 0.50, 1.5, 3.0 5.0, and 6.6 miles after the passing-lane at site I and 0.50 and 1.5 miles after the passing-lane at site II. The last counter was placed at the farthest distance after the passing-lane before an intersection or driveway. This was done to determine the effective length of the passing-lane. The effective length is the length of the passing-lane plus the distance downstream for which operational benefits persist.

The three performance measures that showed the highest correlation to platooning from the previous investigation were used in this investigation. They are Percent

Followers, Percent Impeded (PI), and Follower Density. The three speed-related measures, ATS, ATS_{pc} , and ATS / FFS , were dropped based on the results of the previous investigation presented in chapter 4.

Using the above three performance measures, this research validated the effective length of passing-lanes as known in the current practice.

The HCM hypothesizes that PTSF, a measure of platooning on two-lane highways, changes in the vicinity of a passing-lane according to Figure 15. This analysis will explain how closely each performance measure reflects the theoretical curve below using the empirical data collected in this study.

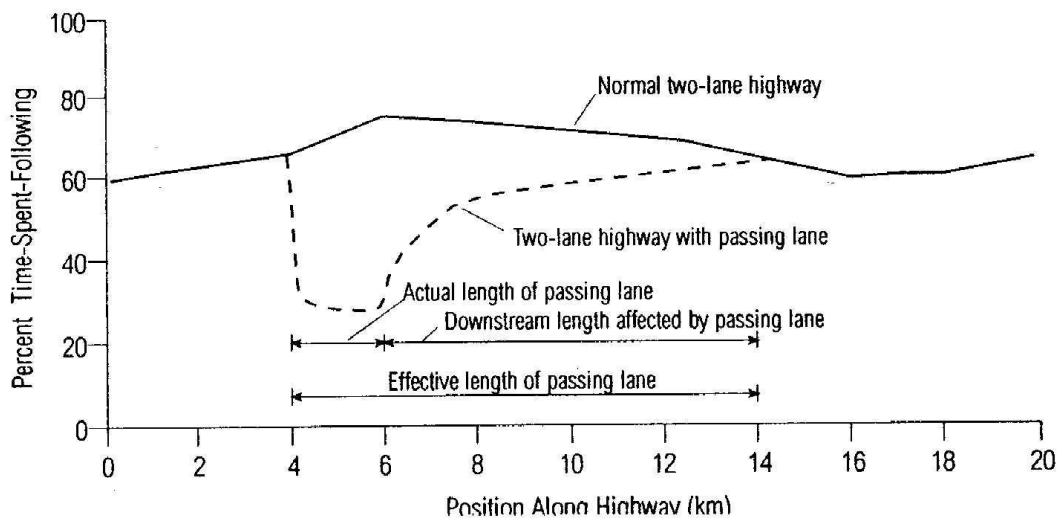


Figure 15: Curve depicting the change in PTSF in the proximity of a passing-lane [HCM 2000]

The curve shows changes in platooning before, within, and after the passing-lane. As traffic approaches the passing-lane section, it is expected to have a high percentage of vehicles with short headways due to the lack of passing opportunities. Traffic entering the three-lane section will split into two groups: one group, usually slower, impeding traffic, will take the right lane while the other group, usually faster, once-impeded traffic, will

take the left lane. The overall level of platooning will drop quite dramatically within the passing-lane section. Once the passing-lane ends the vehicles will leave in a different order than they arrived. Over a certain (unknown) distance the faster vehicles will catch up to the slower moving vehicles and the level of platooning will steadily rise to its pre-passing-lane value, as shown on the right side of the figure.

Two traffic levels were examined using data from site I (155 vph and 130 vph) and three traffic levels for site II (330 vph, 200 vph, and 110 vph). These values were chosen to represent the relatively high, medium, and low traffic levels at each site as applicable. Because site II experienced a higher AADT than site I, three levels could be considered. Further, it was important to control traffic level while investigating changes in platooning downstream of the passing-lane. The changes in the performance measures were used to determine the effective length of a passing-lane.

Three analyses were conducted as part of this investigation. These are:

1. Preliminary Examination
2. Headway Analysis
3. Statistical Analysis

The preliminary analysis examined how each performance measure changes over distance using the aforementioned performance measures. Percent change was used over the distance from the end of the passing-lane. The purpose of this preliminary examination was to determine how useful the passing-lanes are in breaking up platoons.

The Headway Analysis examined headway distributions at both sites to get a better understanding of the amount of platooning in the traffic stream and how it changes

in relevance to passing-lane. Finally, the correlation and regression statistical analyses were used to more accurately assess the change in platooning with the distance downstream of the passing-lane.

Results

This section will discuss the results from the three analyses.

Preliminary Examination

The first step in the preliminary analysis was to examine the change in platooning (represented by the performance measures) as a function of the distance downstream of the passing-lane. Table 10 shows the change in performance measures for two traffic volumes on US 287 (a) and US 191 (b) study sites.

Table 10: Change in Performance Measure for (a) HWY US 287 and (b) HWY US 191

		Hourly Traffic Volume											
		155						130					
	Downstream Distance (mi)	250'	0.5	1.5	3	5	6.6	250'	0.5	1.5	3	5	6.6
PM	PI	12.5%	15.2%	15.7%	-----	18.0%	20.8%	10.1%	15.0%	15.4%	13.3%	16.0%	19.1%
	Percent Followers	27.7%	24.3%	23.4%	-----	26.7%	27.4%	22.6%	20.5%	21.3%	21.3%	23.7%	26.4%
	Follower Density	0.57	0.53	0.53	-----	0.59	0.60	0.40	0.39	0.42	0.42	0.45	0.51

(a)

		Hourly Traffic Volume								
		330			190			106		
	Downstream Distance (mi)	250'	0.5	1.5	250'	0.5	1.5	250'	0.5	1.5
PM	PI	22.9%	24.8%	31.4%	14.8%	16.6%	19.1%	10.0%	10.7%	6.1%
	Percent Followers	46.6%	45.2%	42.9%	31.5%	28.1%	29.9%	21.0%	19.4%	14.5%
	Follower Density	2.28	2.22	2.16	0.89	0.79	0.87	0.33	0.30	0.23

(b)

There are a few important observations that can be discerned from the values in the tables above.

1. Both percent followers and follower density show a slight improvement immediately downstream of the passing-lane. This trend is prevalent at all traffic levels and at both sites, yet more pronounced at site 1 (US 287) and for higher volumes. Note, more distance downstream was examined at site 1 than at site 2.
2. As traffic moves past the 1.5 mile station, platooning increases steadily; percent followers and follower density increase. This observation is only to site I because there were no counters at site 2 beyond 1.5 miles.
3. The tables show that values for performance measures do not seem to be leveling off within the 6.6 mile section examined, as would occur eventually according to the curve shown in Figures 4.2 and 4.3. The continued steady rise in percent followers and follower density indicates that operational benefits of a passing-lane may continue well beyond the 6.6 miles distance investigated in this study.

The first observation above may be caused by the *merge effect*, as discussed in the previous investigation. As the passing-lane ends, all vehicles (from both lanes) are forced to merge into a single lane. This activity is normal at similar merge situations. Therefore platooning, identified by the short successive headways, becomes relatively high right after the passing-lane. However these platoons are different in nature than the pre-passing-lane platoons. The latter platoons were comprised of a number of vehicles with slow speeds that are impeded by a slower lead vehicle. The platoons formed immediately

after the passing-lane are a result of a group of vehicles with short headways; these vehicle are not necessarily impeded.

The sensitivity of each performance measure was assessed by plotting its percent change as a function of distance downstream of the passing-lane at each site in Figures 16 and 17.

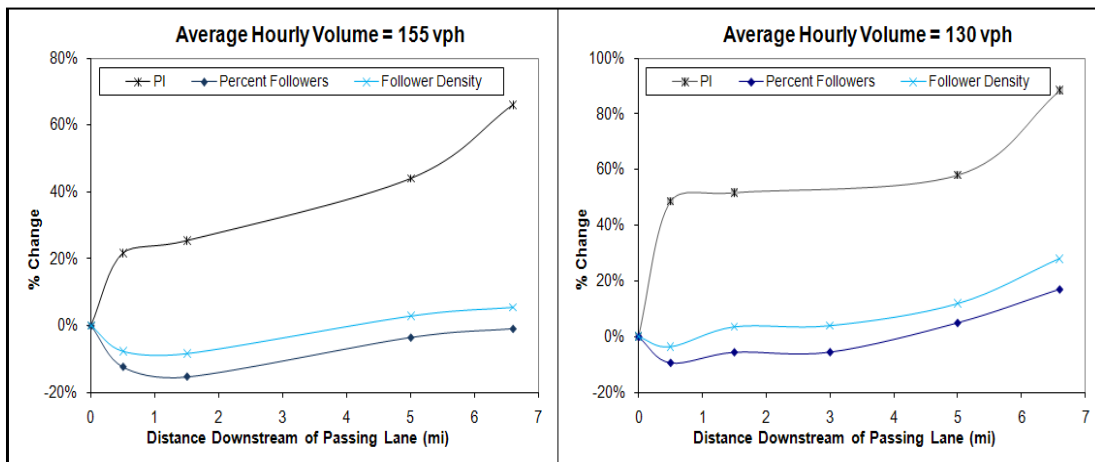


Figure 16: Percent change in platooning variables on US 287

The chart above shows that percent followers and follower density have a greater positive percent change at the lower traffic level and a greater negative percent change at the higher traffic level. This implies that the merge effect is more prevalent when traffic is higher and greater deterioration when traffic is lower. The trend represented by PI brings up some important points. PI is more sensitive to platooning than the other measures. This finding was validated in the previous chapter of this thesis. Also, PI is more sensitive at lower traffic levels. PI is not impacted by the merge effect as percent followers and follower density are. This was explained in Chapter 4. Lastly, PI shows no sign of leveling off even at a downstream distance of 6.6 miles (for either traffic level). This indicates the benefits of a passing-lane may persist far beyond 6.6 miles.

Figure 5.3 shows the percent change of each measure on US 191 for three traffic levels. Except for the medium traffic level, percent followers and follower density seem to have minimal sensitivity to distance when compared to PI. Because the length of the passing-lane at site II is half that of site I, Figure 5.3 does not show percent followers and follower density rebounding after the merge affect at 330 vph and 110 vph traffic levels. PI exhibits the same trend at this site as it does on US 287: it is most sensitive at the lowest traffic level and it shows no sign of leveling off for any traffic level. The second point may be explained by the fact that only 1.5 miles downstream of the passing-lane were examined at this site.

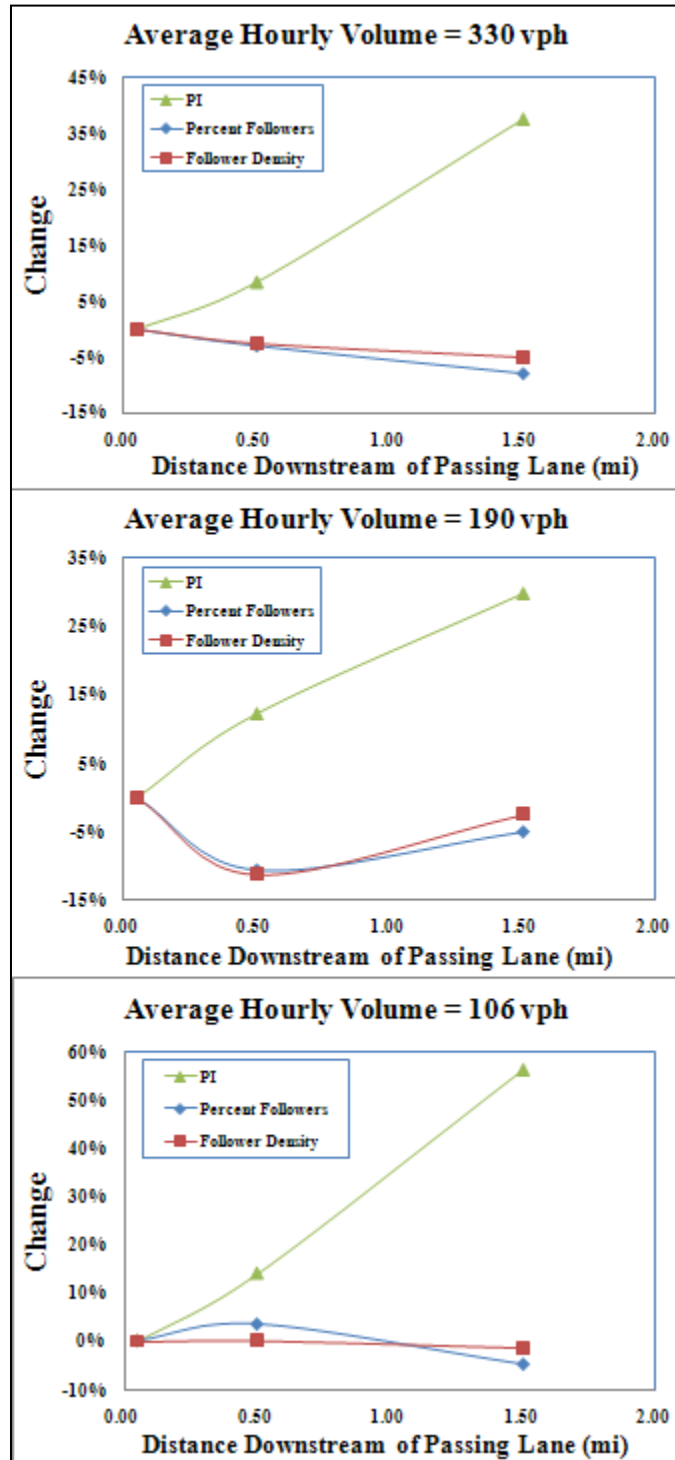


Figure 17: Percent change in platooning variables on US 191

Headway Analysis

Because headways are central to the degree of platooning, a headway distribution was plotted to determine how the headway intervals changed as the vehicles moved through and past the passing-lane. The three headway intervals chosen were 0-3 seconds (percent followers definition), 3-9 seconds, and greater than 9 seconds. Vehicles with headways greater than 9 seconds are assumed to have no interaction with one another. Figure 18 illustrates the distributions at each site.

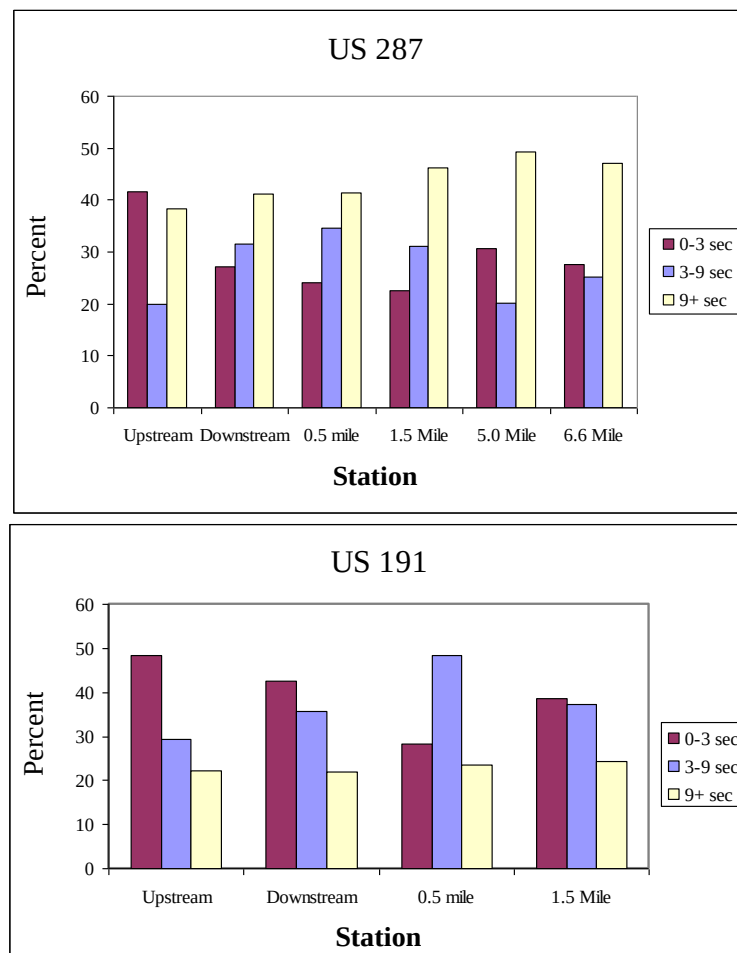


Figure 18: Headway distributions at each site

It is clear from the plots above that the number of short headways decreased as a result of the passing-lane. While this can be seen at both sites, it is more prevalent at site

I. The number of short headways continues to decrease until the 1.5 mile station and the 0.5 mile station at site I and site II, respectively. This pattern can be attributed to the merge effect discussed previously. The proportion of headways greater than 9 seconds seems to increase until the 5.0 mile station at site I. This may be due to the free flow vehicles (faster moving vehicles) separating themselves from the platoons. The percentage of short headways starting to increase again at the 5.0 mile station is indicative of platoon reformation.

Statistical Analysis

To examine the effect of distance downstream of the passing-lane on platooning and performance, data from study site I was further analyzed to get a better feel of their association. It was deemed appropriate to control the effect of volume in the analysis. The new data set only involves hourly volumes that are in the range 125 vph to 135 vph which constitute the majority of the observations. At this traffic level, the correlation coefficients were calculated between performance measures and all other platooning variables as shown in Table 11.

Table 11: Correlation Coefficients between Performance Measures and Platooning Variables at Same Traffic Level

US 287					
Performance Indicator	% No Passing	Distance	Merge Effect	Grade	% Trucks
Percent Followers	-----	0.732	-----	0.338	0.189
PI	-----	.693	.105	.212	.171
Follower Density	(-0.233)	0.735	0.139	0.21	0.197

*Note: Cells marked with "-----" refer to coefficient of correlation less than 0
Values in brackets are those that exhibited illogical relationships*

The merge effect included in this analysis is a binary variable that takes care of the merge activity effect on platooning at the downstream station. While the study site is

generally located in level terrain, the exact percentage grade from as-built drawings at various data collection stations was used in the analysis. Percent no passing in this study refers to the percentage of length of highway where passing is prohibited within one mile upstream of the data collection station.

The results show that traffic volume has the highest correlation with performance measures (all coefficients are above 0.74). The results also suggest a weak correlation between the performance measures and other platooning variables including the distance downstream of the passing-lane. Overall, the percent-no-passing showed the lowest correlations with the three performance measures. All correlation coefficients exhibited logical relationships. The distance downstream of the passing-lane showed relatively high correlations with performance measures as shown in the table (all coefficients are above 0.73). All distance coefficients exhibited logical relationships with performance measures.

It is also of interest to bring back the results of the multi-variate linear regression from Chapter 4 to explore the functional relationships between performance indicators and platooning variables with special emphasis on the distance downstream of the passing-lane. Both correlation analysis and multivariate linear regression are valuable tools in exploring linear relationships and associations.

Table 12: Regression Analysis at Study Site US 287

US 287									
Performance Indicator	Regression Model			P-value from t-test ^{2,3}					
	F-test ¹	R-squared	SE	Volume	% No Passing	% Trucks	Dist	Merge Effect	Grade
Percent Follower	<u>1.25E-41</u>	0.73	1.21	3.93E-43	0.01	(0.09)	1.98E-05	0.00	0.43
PI	<u>2.20-108</u>	0.98	0.33	2.36E-33	0.03	(0.06)	1.34E-06	0.01	.32
Follower Density	<u>2.54E-38</u>	0.71	0.09	5.99E-42	0.76	0.92	0.02	(0.08)	0.76

¹ Values underlined in italic refer to models that were found significant using the F-test

² Values in bold are for coefficients that were found significant using the t-test

³ Values in brackets are those that passed significance testing at the 90% confidence level only

Table 12 summarizes the results of the regression analysis which show the relationship between the response variable (performance indicators) and predictor (platooning) variables. Upon examining this table, the following observations can be made:

1. All three models are significant at the 95% confidence level as affirmed by the F-test results.
2. The coefficients of determination (R-square) are relatively high which shows that much of the variation in the performance measures is explained by the respective models.
3. Traffic volume and distance downstream of the passing-lane were found significant in all regression models. This indicates that distance beyond the end of the passing-lane has significant effect on all performance measures investigated in this study. Merge effect and percentage trucks are only significant in the model for estimating percent followers.

4. Grade was found insignificant in all regression models, which shows that it had no tangible effect on any of the performance measures. This is mainly due to the fact that the study site is located in generally level terrain and the amount of changes in grade among data collection stations was minimal.

To further examine the effect of distance on performance measures, another regression analysis was conducted where all variables that were found less important were dropped from further analysis. This has narrowed down the list of variables to traffic volume and distance downstream of passing-lane. To control for the effect of volume, only field data that roughly represents the same traffic level was used in the regression; therefore volume could be dropped from the regression leaving distance as the only predictor variable. Traffic volumes in the range of 125 vph to 135 vph were considered in this analysis as most field observations fall in this volume range. This allowed dropping volume from the regression analysis leaving distance as the only predictor variable.

The objective is to answer the question: for a given traffic volume, what is the effect of distance on traffic performance and platooning? The results are presented in Table 13.

Table 13: Regression Analysis with Distance as the Only Predictor Variable

Performance Indicator	Regression Model			P-value from t-test
	F-test	R-squared	SE	Distance
Percent Follower	1.04E-18	0.536	1.598	1.04E-18
PI	4.25E-14	0.624	0.952	4.25E-14
Follower Density	6.62E-19	0.540	0.023	6.62E-19

Upon examining the F-test and t-test results, it is evident that the three models are significant at the 95% confidence level. Also, the only predictor variable, distance downstream of the passing-lane, was found significant in all three models. The R-square values suggest that distance explained around 54% of the variation in percent followers and follower density and around 62% of the variation in the Percent Impeded. These results are generally consistent with those from the correlation analysis.

Investigation Findings

This Investigation explained the impact of passing-lanes on platooning on two-lane highways. Three performance measures (PI, Percent Followers, and Follower Density) were used to quantify performance on two such highways in Montana.

The data showed that platooning measured by two performance measures decreases for a short distance following the passing-lane, and then increases again throughout the entire study site. This immediate drop in platooning is explained by the *merge effect*, the phenomenon that occurs when both lanes of traffic converge to one lane. The passing-lane cause a significant decrease in the level of platooning as exhibited by the comparison of performance measures upstream and downstream of the passing-lane section. This improvement ranged from 33 to 43 % at site I and 7 to 19 % at site II (using the headway-related performance measures).

The level of platooning at the most downstream station (at both sites) is less than the platooning the pre-passing-lane platooning level. This residual benefit indicates that the benefits of the passing-lane persist for longer than 6.6 miles (from site I). While the

results from previous studies in the literature may not be consistent with this, it is closer to the HCM values.

CHAPTER 6

INVESTIGATION OF LANE USE AND PERFORMANCE
WITHIN A PASSING-LANEStudy Approach

The previous investigations were concerned with identifying appropriate performance measures and assessing the effectiveness of passing-lanes in improving performance on two-lane highways. The investigation presented in this chapter focuses on the dynamics of platoon break-up within a passing-lane with the objective of having a better understanding of the required design length of these lanes.

This investigation used empirical data at a single passing-lane location on HWY 287 two miles north of Townsend, Montana. Five counter stations were used to gather data both upstream and within the passing-lane. The first counter was located 250' upstream of the passing-lane; the other four counters were located 0.25 mile, 0.5 mile, 1.0 mile, and 1.5 miles downstream of the lane addition taper into the passing-lane. The speed, gap, and classification of vehicles using any of the available lanes were recorded at all stations. Because there is a stop-controlled driveway at the other side of the roadway approximately 1.6 miles into the passing-lane, no counter was located beyond that location.

Vehicles entering the passing-lane section have the choice of taking either the right or left lane. It is theorized that most vehicles will take the normal (left) lane, leaving only the slow passenger cars and the heavy vehicles in the right lane. The average speed of the vehicles in the left lane is expected to be higher than the average speed of the

vehicles in the right lane. The percent of vehicles with short headways should logically decrease upon entering the passing-lane section, especially in the left lane. Platooning in the right lane should stay steady or even increase to a level higher than before the passing-lane.

The first step in data processing involved separating the normal lane and the passing-lane into different spreadsheets to be analyzed independently. The data were divided into 15-minute time intervals for the purpose of determining peak periods. Once the peak periods were determined, performance measures were calculated for each. For this investigation Percent Followers, Percent Impeded, and Follower Density were the only performance measures used. A lane by lane comparison was conducted by plotting each measure (as a function of distance into the passing-lane) for three traffic levels: 75 vph, 175 vph, and 275 vph, representing low, moderate, and high volumes, respectively.

Next a plot of the average travel speed in each lane was developed to better understand how traffic was reacting to the passing-lane.

Finally a plot showing the lane split (the percentage of traffic that took each lane) as traffic moved farther into the three-lane section was constructed. This plot, in conjunction with the speed plots, gave a better understanding as to how far it takes traffic to break-up upon entering the passing-lane.

The distance that is required for the impeded vehicles to pass the slower vehicles will be considered the optimal passing-lane length. A passing-lane shorter than this

distance does not serve the purpose of splitting up platoons, and a longer one involves a waste of resources.

Results

This section will explain the results and interpretation of the results for this investigation.

Performance Measure Analysis

Plots of each performance measure were created as a function of distance into the passing-lane. Assessing how each measure (Percent Followers, PI, and Follower Density) changed from station to station was the first part of the examination.

Figure 19 shows the Percent Followers graph at each traffic level.

Three interesting observations can be discerned from these graphs.

1. The percentage of vehicles with three-seconds or less rises significantly in the first $\frac{1}{4}$ - mile on the normal (left) lane. Percent Followers then drops between $\frac{1}{4}$ - mile and $\frac{1}{2}$ -mile on that same lane and finally levels off.
2. The right lane exhibits a slightly different pattern: Percent Followers remains relatively steady in the first $\frac{1}{4}$ -mile, drops minimally between $\frac{1}{4}$ - and $\frac{1}{2}$ mile, and eventually levels off.
3. These trends are prevalent at all three traffic levels, yet are more pronounced at lower volumes.

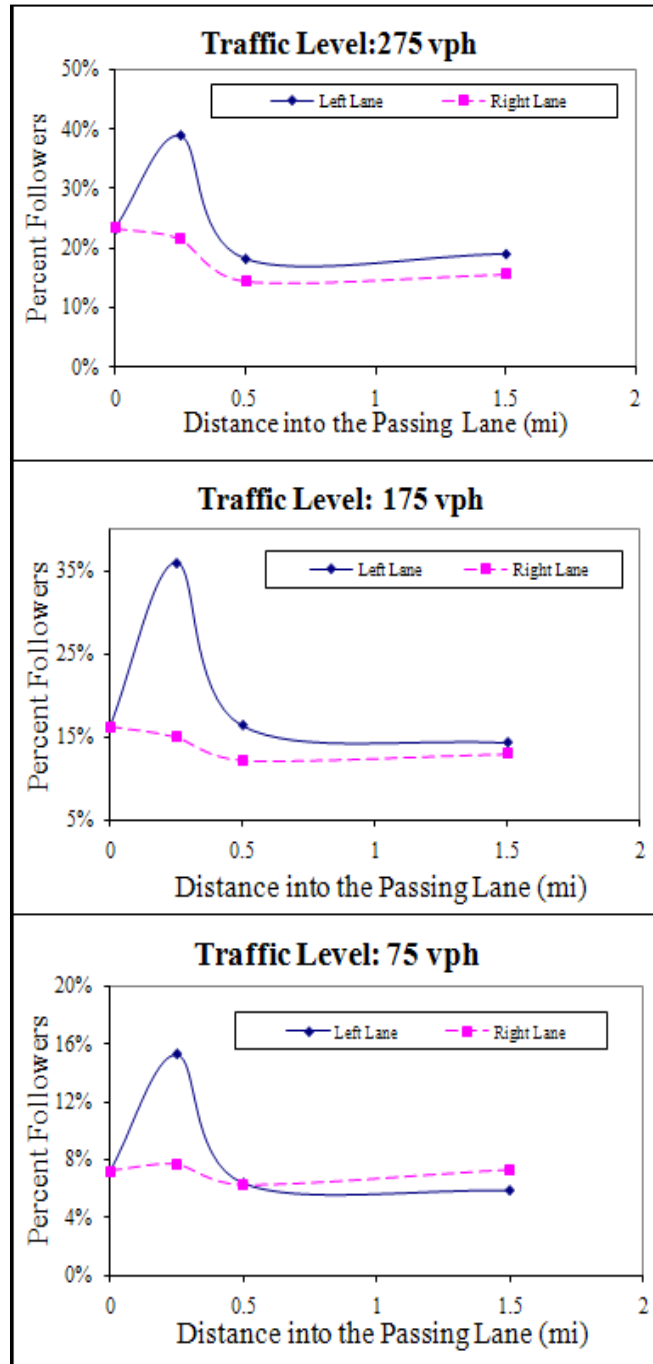


Figure 19: Percent Followers as a function of distance at all traffic levels

Figure 20 illustrates the Percent Impeded as it changes on the normal and passing-lanes at the data collection stations. A number of important observations can be made about this figure.

1. PI exhibits a trend similar to that of Percent Followers: impedance on the left lane rises nearly 80 % in the first $\frac{1}{4}$ -mile, drops to its original value, or lower, in the next $\frac{1}{4}$ -mile, and remains steady throughout the passing-lane.
2. At lower traffic levels percent impeded rises slightly after the half-mile point in the right lane.
3. The values of impedance are nearly the same for the top two traffic levels.

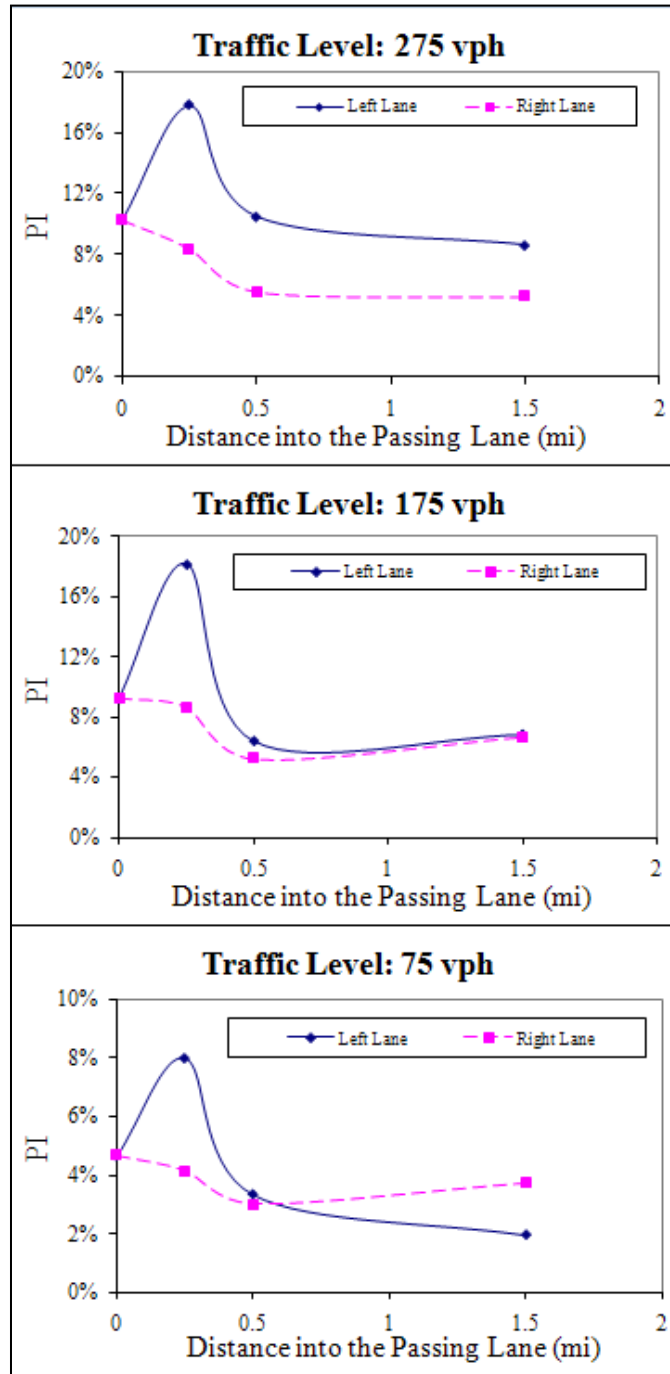


Figure 20: Percent Impeded as a function of distance at all traffic levels

The follower density on the available lanes at various data collection station is shown in Figure 21. Follower Density in each lane drops from the pre-passing-lane value in the first ¼ -mile, in spite of the rise in Percent Followers. This is due to the fact that

the traffic volume is splitting: a major component of Follower Density. Between $\frac{1}{4}$ - and $\frac{1}{2}$ -mile the Follower Density rises slightly in the right lane, for all traffic levels. This measure is, of course, higher at higher volumes.

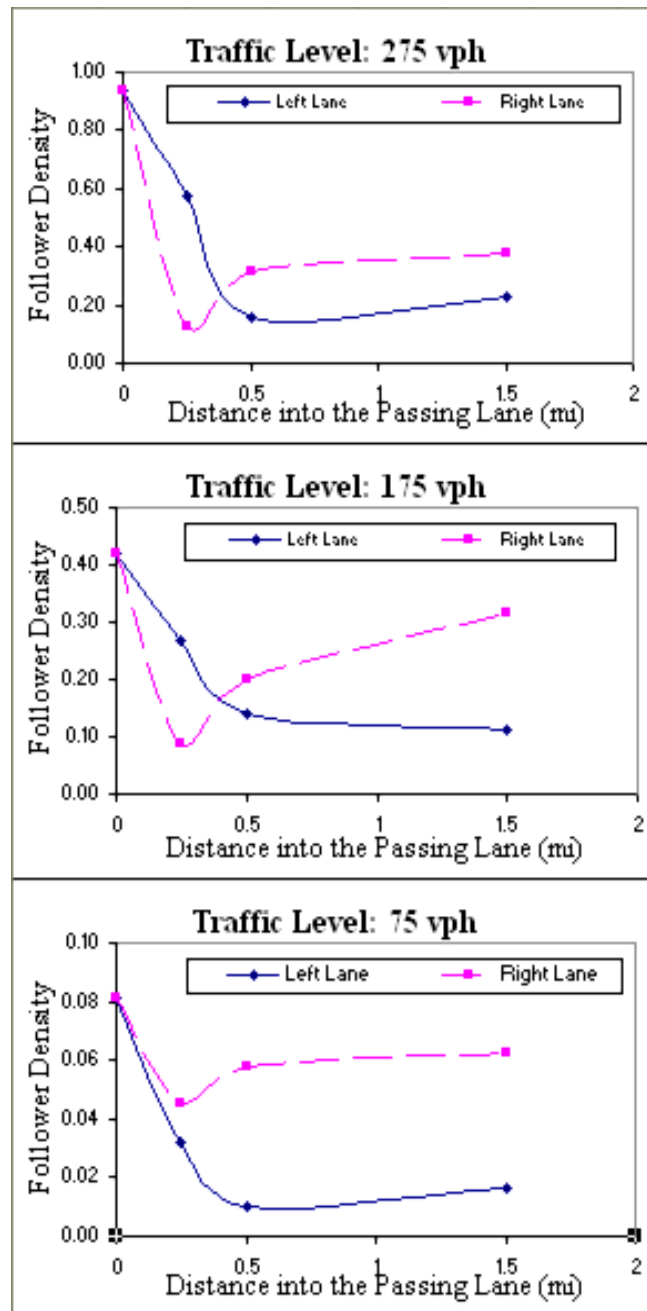


Figure 21: Follower Density as a function of distance at all traffic levels

After the three performance measures were examined a speed analysis was conducted to determine how the average speeds changed in each lane through the passing-lane section. Figure 22 shows the speeds at each traffic level.

The average speed in the left lane appears to rise at a steep slope in the first 0.5-mile: increasing from 68 miles-per-hour (mph) to 78 mph. After the 0.5-mile station the speed in the normal lane falls off at more gradual fashion. In the right lane the average speed remains relatively constant in the first 0.25-mile and takes a small jump between 0.5-mile and 0.5-mile points. After the 0.5-mile station, the average speed in the passing-lane remains constant.

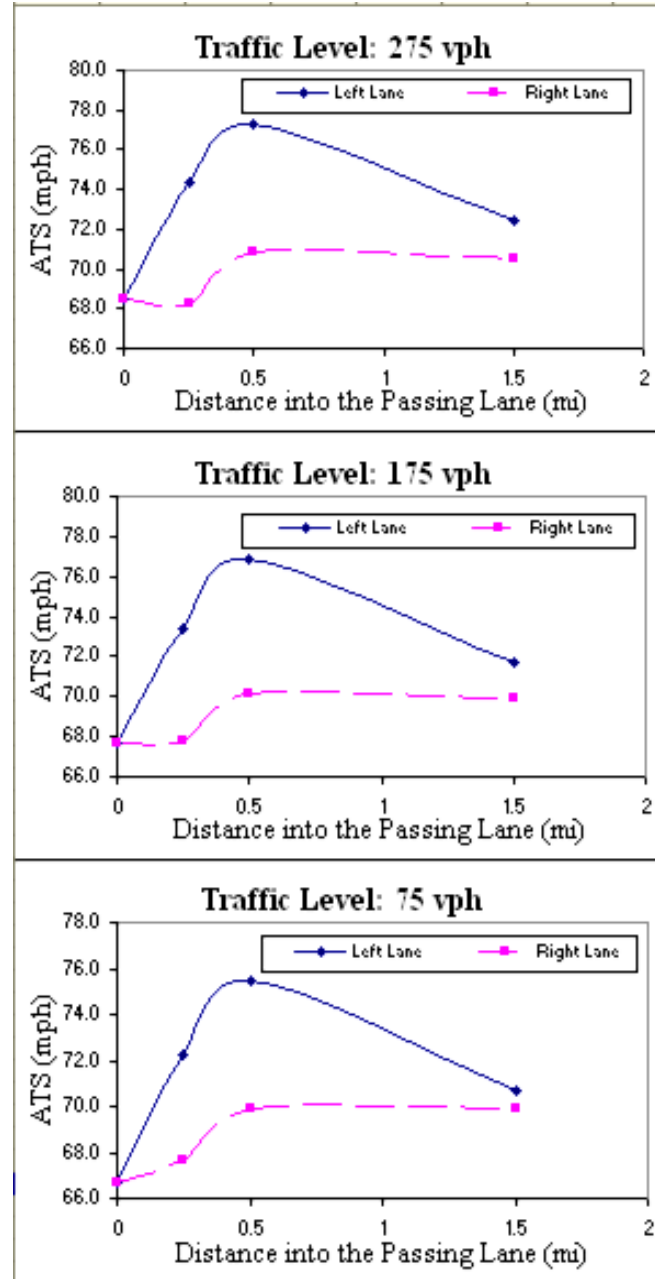


Figure 22: Average-Travel-Speed

Interpretation and Validation

The results presented above lead to an understanding of vehicle dynamics within the passing-lane section. As a platoon of vehicles enters the section it splits into two primary groups: aggressive drivers and everyone else. In this scenario the aggressive

drivers remain in the left lane and almost everyone else takes the right lane. Figure 6.1 shows the aggressive drivers in the left lane have a higher percentage of short headways than all the traffic before the passing-lane. More evidence of the aggressiveness of the drivers in the left lane is Figure 22. Not only do these drivers have short headways, they are also impeded by one another; meaning they are willing to drive faster. Figure 22 shows that these drivers have increased their speeds by an average of 10 mph within the first ½-mile.

The right lane dynamics are slightly different from the left lane. To get a good understanding of these dynamics, traffic split in each lane must be considered. Figure 23 shows between 60 % and 80 % (depending on the traffic level) of the traffic stream taking the right (passing) lane initially.

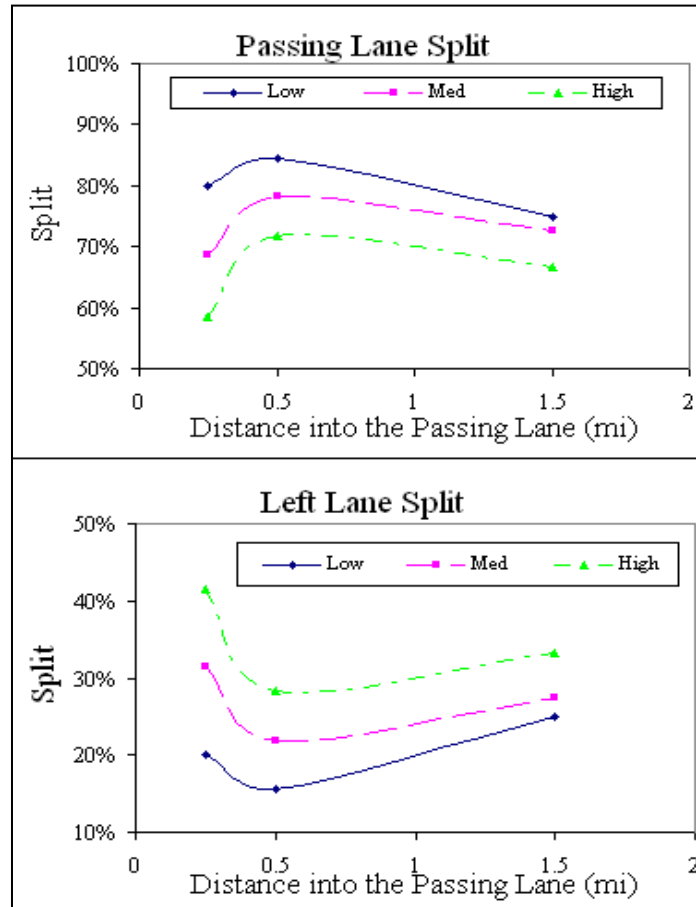


Figure 23: Traffic split at each station for the passing-lane and the normal lane

In the first 0.25-mile, 80 % of the traffic that takes the right lane has the same proportion of Percent Followers as the pre-passing-lane traffic stream and the same level of impedance. Between 0.25- and 0.5-mile something interesting happens in the right lane: impedance decreases slightly while Average Travel Speed (ATS) increases. This can be explained as follows: non-aggressive drivers stuck behind slow moving vehicles are choosing to take the right lane, but only after passing the vehicle they were impeded by. These passing maneuvers may take between a 0.25 and 0.5 mile to complete. This explanation can be verified by the volume split shown in Figure 6.5: the passing-lane split increases roughly 5-10 % between the 0.25-mile and 0.5-mile stations. Furthermore,

the small jump in ATS between these stations indicates it is these moderate drivers may be moving into the right lane.

Investigation Findings

The results discussed above imply that a two-mile passing-lane is unnecessarily long. The percentage of short headways rises steeply in the first 0.25 mile of the normal lane. By the 0.5 mile station the percentage of short headways in that lane has dropped to below the pre-passing-lane value. Meanwhile average travel speed of vehicles in this same lane is continuing to increase (until the 0.5 mile station). Between the upstream point and 0.25 mile point aggressive drivers have chosen the left lane and begun speeding up; the moderate drivers also chose the left lane to pass the slowest vehicles before they take the passing-lane.

Between 0.25 mile and 0.5 mile the moderate drivers are shifting to the right lane after having passed the slow vehicles; this supported by the dramatic drop in percent followers in the left lane. Also Figure 6.5 shows the highest percent of drivers in the passing-lane occurs at the 0.5 mile station. By the time the traffic has reached the 0.5 mile mark the aggressive drivers have been able to pass the moderate (and slowest vehicles) and the moderate drivers have been able to pass the slowest vehicles. Beyond that point drivers begin transitioning back to the normal lane from the passing-lane. This implies that a passing-lane 0.75 mile in length may be adequate for all passing purposes at the site investigated.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the major findings of the research presented in this thesis. It also provides suggested recommendations for future research pertaining to passing-lanes on two-lane highways.

Conclusions

Three investigations were performed to determine the effect of passing-lanes on two-lane highways. Investigation I was a preliminary investigation concerned with selecting appropriate performance measures of two-lane highways. Six performance measures chosen from the literature review were analyzed for appropriateness: Percent Followers, Percent Impeded, Follower Density, Average-Travel-Speed, Average-Travel-Speed as a ratio of Free Flow Speed, and Average-Travel-Speed of Passenger Cars. The notable findings of this investigation were:

1. The most appropriate performance measures for two-lane highways are Percent Followers, Percent Impeded, and Follower Density. This is a distinction from the HCM recommended measures of Average-Travel-Speed and PTSF and from the performance measures found in the literature review.
2. The speed-related measures were found to have the lowest correlation to platooning variables as measured by the R^2 -values. The HCM suggests using Average-Travel-Speed as a measure, yet the R^2 value for this measure was found to be 0.621 compared to the R^2 value of 0.986 for Percent Impeded.

The most important findings of the analysis of the spatial extent of the passing-lane effect were:

1. There is a prevalent merge effect immediately following the passing-lane that results from vehicles merging from two-lanes to one-lane. This merge effect exhibited serious effect on headways and headway distribution.
2. The passing-lane dramatically improves operations on the two-lane highways investigated by reducing platooning by 43 % at one site and 19 % at another site as measured by Percent Impeded.
3. The *effective length* of a passing-lane may extend far beyond 6.6 miles, as demonstrated by the shape of the platooning vs. distance downstream curves. This 6.6-mile effective length is consistent with the HCM 2000 value. However, previous studies have found the effective length to be in the range of 1-2 miles. This range is significantly lower than the value determined by this thesis and the discrepancy may be attributed to limitations of the simulation models that most of the previous studies were based on.

The results of the third investigation explained phenomena of a traffic stream within a passing-lane section. The interesting results of this investigation were:

1. Drivers that choose the left (normal) lane tend to be aggressive in nature while the vehicles that choose the passing-lane tend to be slower. While these vehicles have a high proportion of short headways, they are not believed to be impeded because the average speed of vehicles in the normal lane increases 10-mph within the first 0.5-mile.

2. As the traffic stream nears the end of the passing-lane section Percent Followers increases as drivers try to merge back to the normal lane.
3. For the highway considered, a 0.75-mile long passing-lane would have been sufficient.

Future Research

It is recommended that future research be conducted on the relationship between the posted speed limit and the necessary passing-lane length. Vehicles traveling at higher speeds, say 60-70 mph, should need a shorter passing-lane than those travel at 45-mph. For the passing-lane investigated, the 2-miles provided were deemed as over-design. However if traffic was moving at 45-mph, a 0.75-mile passing-lane, as recommended, may not be adequate.

One variable of interest related to two-lane highways is the difference in speeds between the fastest vehicles and the slowest vehicles. A study that related this speed-difference to passing-lane length and spacing would be of importance.

Another suggestion for future research would to investigate a passing-lane in which a farther distance downstream can be studied, preferably 8 to 10 miles downstream. Also, further research should consider higher traffic levels: volumes greater than 400 vph; or traffic with a greater percentage of heavy vehicles.

Also of interest is the applicability of these results to urban two-lane highways. Future research could try to answer the questions: Does traffic on urban highways exhibit the same characteristics as traffic on rural highways? Does the long duration of rural trips have an effect of drivers and do these effects impact platooning?

REFERENCES CITED

Al-Kaisy, A. & Durbin, C. (2006). Estimating Percent Time Spent Following on Two-Lane Highways: Field Evaluation of New Methodologies. CD-ROM. Proceedings of the Transportation Research Board 86th annual meeting, Washington, D.C., January 21-25, 2007.

Al-Kaisy, A. & Karjala, S. (2007). Indicators of Performance on Two-Lane Rural Highways: An Empirical Investigation. CD-ROM. Proceedings of the Transportation Research Board 87th annual meeting, Washington, D.C., January 13-17, 2008.

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*. 2004, Washington, D. C.

Bureau of Transportation Statistics. (2006). Retrieved 2008 from http://www.bts.gov/data_and_statistics/

Ensberg, A. & Pursula, M. (1995) Traffic Flow Characteristics on a Three-Lane Rural Highway in Finland. *Transportation Research Record* 1572 pp. 33-42

Gattis, J. & Bhawe, R. & Duncan, L. (2006) Alternating Passing-lane Length. *Transportation Research Board* 1961 pp. 16-23

Harwood, D. W. & Hoban, C. J. (1987) *Low Cost Methods of Operational Improvements on Two-Lane Highways*. Midwest Research Institute.

Harwood, D. & St. John, A. (1985) Passing-lanes and Other Operational Improvements on Two-Lane Highway. *OSTO Research and Development*

JAMAR Technologies. Retrieved 2009 from <http://www.jamartech.com/H04000.html>

May, A. (1991) Traffic Performance and Design of Passing-lanes. *Transportation Research Board* 1303 pp. 63-73

May, A. & Emoto, T. (1988) Operational Evaluation of Passing-lanes on Level Terrain: Final Report. *Institute of Transportation Studies* UCB-ITS-RR-88-13 pp. 243

Montana Homes and Land (2009). Retrieved 2009 from <http://www.mthomesandland.com/mapmontana.jpg>

Morrall, J. & Miller, E. & Smith, G. & Feuerstein, J. (1995) Planning and Design of Passing-lanes Using Simulation Model. *Journal of Transportation Engineering* pp. 5062

Mutabazi, M. & Russell, E. & Stokes, R. (1999) Location and Configuration of Passing-lanes. *Transportation Research Record 1658* pp. 25-33

Potts, I. & Harwood, D. (2004) Benefits and Design/Location Criteria for Passing-lanes. *Midwest Research Institute RDT 04-008* pp.100

Taylor, W. & Jain, M. (1991) Warrants for Passing-lanes. *Transportation Research Record 1303* pp. 83-91

Transportation Research Board (2000). *Highway Capacity Manual. Fourth Edition*. TRB, National Research Council, Washington, D.C.

Van As, C. (2003). *The Development of an Analysis Method for the Determination of Level of Service of Two-Lane Undivided Highways in South Africa*. Project Summary. South African National Roads Agency, Limited, 2003.

WestCoastRoads (2005). Retrieved 2009 from
http://www.westcoastroads.com/washington/images500/wa-504_eb_passing_lane.jpg

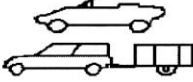
Woolridge, M. & Messer, C. & Heard, B. (2002) Design Criteria for Improved Two-Lane Section (Super 2). *Texas Transportation Institute Project 0-4064*

APPENDIX A

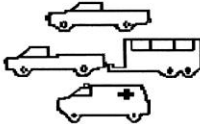
FHWA 13-CATEGORY VEHICLE CLASSIFICATION SYSTEM



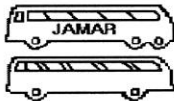
Class 1 - Motorcycles. This class includes all two- or three-wheeled motorized vehicles. These vehicles typically have a saddle-type of seat and are steered by handlebars rather than a steering wheel. This includes motorcycles, motor scooters, mopeds, motor-powered bicycles and three-wheel motorcycles.



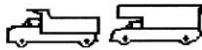
Class 2 - Passenger cars. This class includes all sedans, coupes and station wagons manufactured primarily for the purpose of carrying passengers, including those pulling recreational or other light trailers.



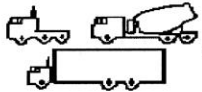
Class 3 - Pickups, Vans and other 2-axle, 4-tire Single Unit Vehicles. This class includes all two-axle, four tire vehicles other than passenger cars, which includes pickups, vans, campers, small motor homes, ambulances, minibuses and carryalls. These types of vehicles which are pulling recreational or other light trailers are included.



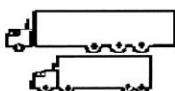
Class 4 - Buses. This class includes all vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This includes only traditional buses, including school and transit buses, functioning as passenger-carrying vehicles. All two-axle, four tire minibuses should be classified as Class 3. Modified buses should be considered to be trucks and classified appropriately.



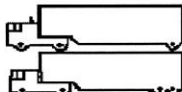
Class 5 - Two-Axle, Six-Tire Single Unit Trucks. This class includes all vehicles on a single frame which have two axles and dual rear tires. This includes trucks, camping and recreation vehicles, motor homes, etc.



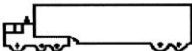
Class 6 - Three-Axle Single Unit Trucks. This class includes all vehicles on a single frame which have three axles. This includes trucks, camping and recreation vehicles, motor homes, etc.



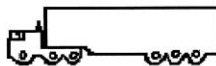
Class 7 - Four or More Axle Single Unit Trucks. This class includes all vehicles on a single frame with four or more axles.



Class 8 - Four or Less Axle Single Trailer Trucks. This class includes all vehicles with four or less axles consisting of two units, in which the pulling unit is a tractor or single unit truck.



Class 9 - Five-Axle Single Trailer Trucks. This class includes all five-axle vehicles consisting of two units in which the pulling unit is a tractor or single unit truck.



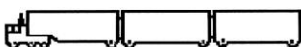
Class 10 - Six or More Axle Single Trailer Trucks. This class includes all vehicles with six or more axles consisting of two units in which the pulling unit is a tractor or single unit truck.



Class 11 - Five or Less Axle Multi-Trailer Trucks. This class includes all vehicles with five or less axles consisting of three or more units in which the pulling unit is a tractor or single unit truck.



Class 12 - Six-Axle Multi-Trailer Trucks. This class includes all six-axle vehicles consisting of three or more units in which the pulling unit is a tractor or single unit truck.



Class 13 - Seven or More Axle Multi-Trailer Trucks. This class includes all vehicles with seven or more axles consisting of three or more units in which the pulling unit is a tractor or single unit truck.