ESTIMATING QUALITY OF TRAFFIC FLOW ON TWO-LANE HIGHWAYS

by

Sarah Renee Karjala

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

of

Master of Science

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2008

APPROVAL

of a thesis submitted by

Sarah Renee Karjala

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
Chair of Committee

Approved for the Department of Civil Engineering

Dr. Brett Gunnink
Department Head

Approved for the Division of Graduate Education

Dr. Carl A. Fox
Vice Provost for the Division of Graduate Education

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.

Sarah Renee Karjala

July 2008

ACKNOWLEDGEMENTS

First and foremost, I would like to thank the Western Transportation Institute for funding my research and education. This project has been a great learning experience and it would not have been possible without their support. Secondly, I would like to thank my advisor, Dr. Ahmed Al-Kaisy for guiding the research. He was always able to see the research from a broad prospective and discern the next step to take. Lastly, I would like to thank my family for their continual support and encouragement throughout my education.

TABLE OF CONTENTS

TABLE OF CONTENTS - CONTINUED

LIST OF TABLES

Table Page

LIST OF FIGURES

LIST OF FIGURES - CONTINUED

ABSTRACT

Since the publication of the 2000 *Highway Capacity Manual* (HCM), there have been several studies that indicate that the HCM equations for Percent Time-Spent-Following (PTSF) on two-lane highways do not correspond to field-based measurements. This discrepancy was the motivation for this research project. The purpose of this project was two-fold. First, it aimed to find an alternative performance measure to PTSF that could be measured directly in the field and could adequately describe the quality of traffic flow. Secondly, the project aimed to investigate the inter-vehicular interaction between consecutive vehicles traveling on the same lane of two-lane rural highways. Both studies were empirical in nature and utilized field data gathered from rural two-lane and four-lane highways in the state of Montana.

Six performance measures for two-lane highways were investigated; they were: average travel speed, average travel speed of passenger cars, average travel speed as a percent of free-flow speed, average travel speed of passenger cars as a percent of free-flow speed of passenger cars, percent followers, and follower density. The performance measures were evaluated based on their level of association with major platooning variables. Among all performance measures investigated, follower density and percent followers exhibited the highest correlation to platooning variables, respectively. Overall, follower density was recommended as the best performance measure for two-lane highways. Based on the fact that follower density is a headway-based service measure, the second study aimed to achieve a better understanding of car-following interaction on two-lane rural highways. Car-following interaction was studied by examining headway distributions, speed-headway relationships, and percent followers and flow relationships. The study found that car-following interaction generally ceases when headways exceed a value of approximately six seconds. Also, a significant proportion of drivers choose to maintain relatively short headways while following other vehicles on two-lane highways regardless of passing restrictions.

CHAPTER 1

INTRODUCTION

Two-lane highways constitute the vast majority of the highway system in the United States. A picture of a typical two-lane highway is shown in Figure 1. This chapter provides background information on two-lane highway operation, a summary of the problem and research motive, the objective and scope of the project, the significance of the project, and the organization of this thesis.

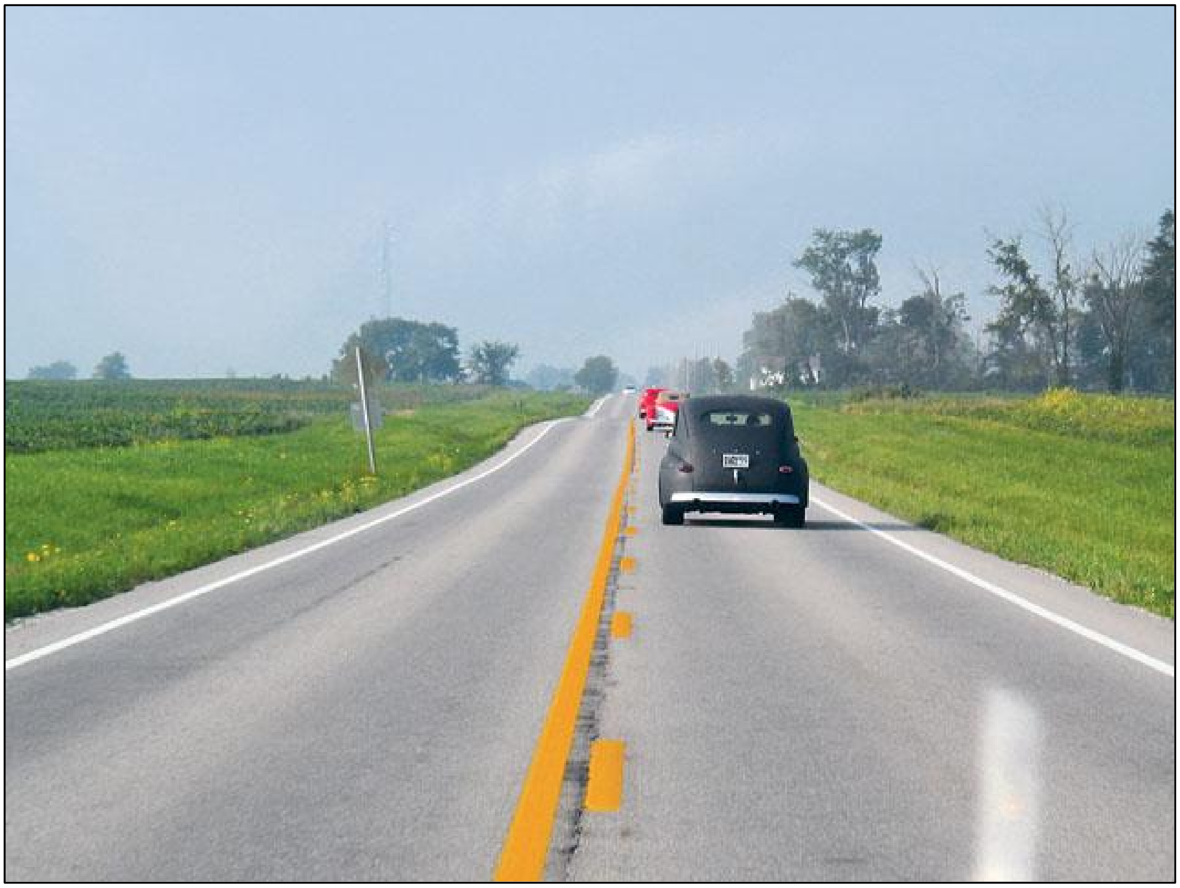


Figure 1 Typical Two-lane Two-way Highway (Street Rodder, 2008)

Background

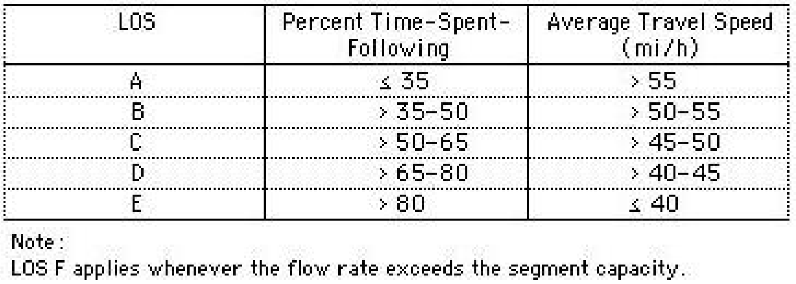
This research is related to two-lane highways in rural areas. A two-lane highway has a single lane in each direction of travel; therefore, passing takes place in the opposing lane, and can occur only if sight distance and gaps in the opposing traffic stream permit. Most rural two-lane highways are uninterrupted flow facilities (i.e., they have little traffic control and very few access points). Therefore, the operational conditions are based mainly on the interaction between vehicles. Logically, as the number of vehicles on the road increases, so does the interaction between vehicles. Variation in travel speed causes faster vehicles to catch up to slower vehicles in the same lane. The demand for passing increases rapidly as traffic volumes increase, while the ability to pass decreases as traffic in the opposing lane increases. Platoons begin to form when the faster vehicles are unable to pass the slower ones. This explains the unique interaction on two-lane highways, and how traffic flow in one direction affects flow in the other direction.

Platoons are a major indicator of performance on two-lane highways because they are associated with delay, inconvenience, and increased safety concerns. Drivers stuck in platoons are delayed because they are unable to pass. Platoons decrease the average travels speed (ATS) and create frustration for drivers. They can affect safety because drivers tend to make hasty passing maneuvers when frustrated or impatient from being stuck in a platoon. The role of traffic engineers is to determine when delay and accidents warrant the addition of a passing lane or widening to four lanes. In the United States, traffic engineers use the *Highway Capacity Manual* (HCM) to decide when upgrading is warranted.

The HCM uses level of service (LOS) to describe the traffic conditions on a road. LOS is a letter scheme ranging from A to F, where LOS A represents the highest quality of service where motorists are able to travel at their desired travel speed, and LOS F represents heavily congested flow where traffic demand exceeds capacity.

The HCM classifies two-lane highways into two classes; class I and class II. Class I two-lane highways typically serve long-distance travel and are roads where drivers expect to travel at high speeds. Class II two-lane highways serve recreational trip purposes, and are usually roads which traverse rugged terrain. For class I two-lane highways, both ATS and percent time-spent-following (PTSF), are used to assign a LOS. PTSF is defined as the average percentage of time vehicles must travel behind slower vehicles due to the inability to pass (TRB 2000); it represents freedom to movement & driver frustration. Average travel speed reflects the mobility on the road, and is measured as a space mean speed (TRB 2000). The criteria used to assign LOS to a class I two-lane highway are shown in Table 1. On class II two-lane highways, mobility is less critical, and therefore only PTSF is used to assign a LOS. The LOS thresholds for class II highways differ slightly from those shown in Table 1.

Table 1 LOS Criteria for Two-Lane Highways in Class I (2000 HCM)



LOS	Percent Time-Spent-Following	Average Travel Speed (mi/h)
A	≤ 35	> 55
B	> 35-50	> 50-55
C	> 50-65	> 45-50
D	> 65-80	> 40-45
E	> 80	≤ 40

Note:
LOS F applies whenever the flow rate exceeds the segment capacity.

Problem Statement and Research Motive

Since the publication of the 2000 HCM, there have been a few studies which suggest that the HCM PTSF equations produce results that are inconsistent with the 3-second rule. The results of these studies are described in this section, as well as an overview of the problem.

The HCM procedures offer two methods to estimate PTSF. The first is via equations derived from the TWOPAS microscopic computer simulation model. TWOPAS is one of the main simulation models for two-lane highways. It was developed in 1978 by the Midwest Research Institute and is used to simulate two-lane highway operation by updating the position, speed, and acceleration of each vehicle every second. Using the TWOPAS model, the PTSF can be calculated directly because the desired speed of each vehicle is known. The HCM equation for directional PTSF and its adjustment factors (Equation 1) were developed based on TWOPAS simulation studies.

$$PTSF_d = 100(1 - e^{a v_d^{\,b}}) + f_{np}$$

Equation 1

where v_d = directional flow rate

a, b = adjustments for opposing flow rate

f_{np} = adjustment for percent no-passing zones

The second method is to calculate PTSF using field measurements. Because PTSF can not be measured in the field, the HCM provides a surrogate measure. That is, the percentage of vehicles with headways less than three seconds. This relationship has been nicknamed the 3-second rule. Figure 2 illustrates the definition of time headway. Like the equation for PTSF, the surrogate measure was derived based on TWOPAS studies. In the TWOPAS model, PTSF was found approximately equal to the percentage of headways less than three seconds.

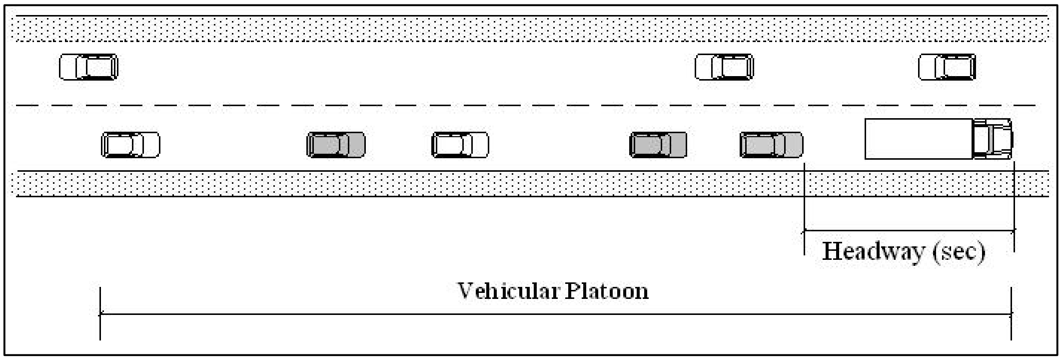


Figure 2 Illustration of Time Headway (Durbin, 2006)

The motivation for this research stems from the fact that, as mentioned earlier, several studies have found that the HCM PTSF equation produces results that are inconsistent with the 3-second rule.

The first study was done by Tapio Luttinen (2001) at the Helsinki University of Technology. Luttinen collected data from 20 two-lane highway sites in Finland. This data was then used to create a model to estimate the percent headways less than 3 seconds (or PTSF) based on flow rates in the observed and opposing directions. A comparison of the 3-second Finnish model, shown in Figure 3, and the HCM PTSF model, shows that the HCM model provides consistently higher values of PTSF than the 3-second rule.

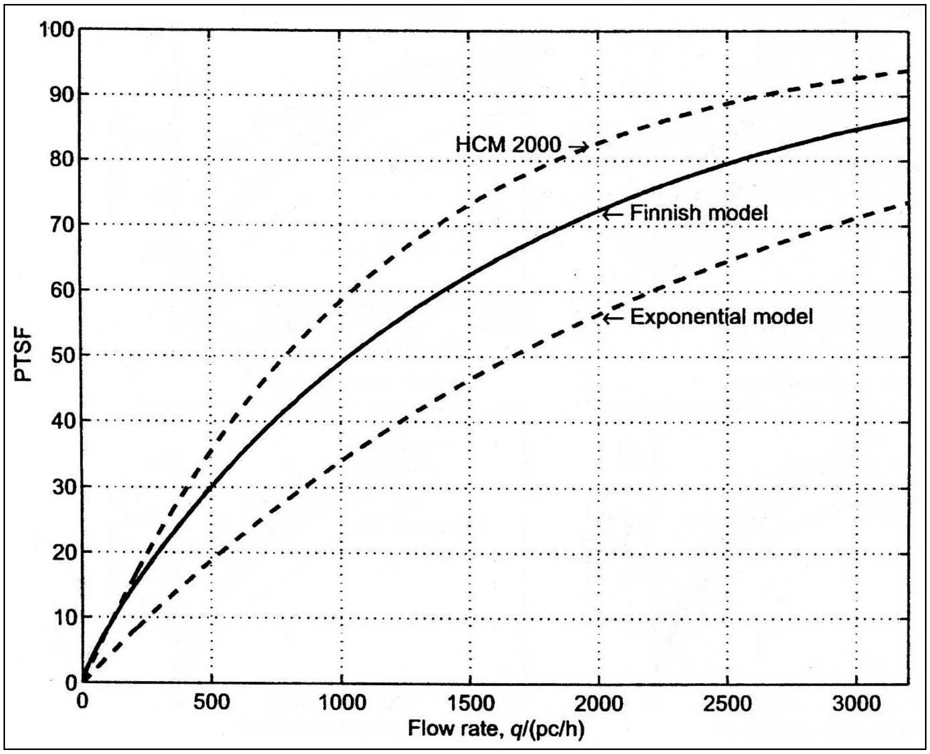


Figure 3 Comparison of HCM PTSF and the 3-Second Rule in Finland (Luttinen, 2001)

The second study was by Michael Dixon (2002) at the University of Idaho. Dixon gathered data at five points along Highway 12 in Idaho. Field observed values of the 3-second rule were compared to PTSF estimates computed using HCM procedures. Dixon found that the HCM procedures gave significantly higher estimates of PTSF than the 3-second rule. Table 2 shows the results of the study. For example, the northbound field percent followers (PF) calculated using the 3-second rule is 15.4 during the first time interval, while the corresponding HCM and TWOPAS PTSF values are 46.0 and 36.2, respectively.

Table 2 Comparison of HCM Directional PTSF and Field Measurements of Percent Followers (PF) (Dixon, 2002)

Time Interval	Field PF		HCM Directional Analysis, PTSF		TWOPAS PTSF	
	NB	SB	NB	SB	NB	SB
10:15-10:30	15.4	11.0	46.0	43.9	36.2	30.2
13:30-13:45	24.1	21.8	52.1	50.7	40.6	40.8
13:45-14:00	19.4	20.8	51.9	53.2	40.0	44.9
15:45-16:00	19.7	28.3	55.4	57.0	43.5	49.1

The third study was done by Christo Van As (2003, 2007) with the South African National Roads Agency. Van As collected data from 25 two-lane highways; a typical plot of his results is shown in Figure 4. He also found that that the HCM PTSF model gave results much higher than the percent followers measured in the field.

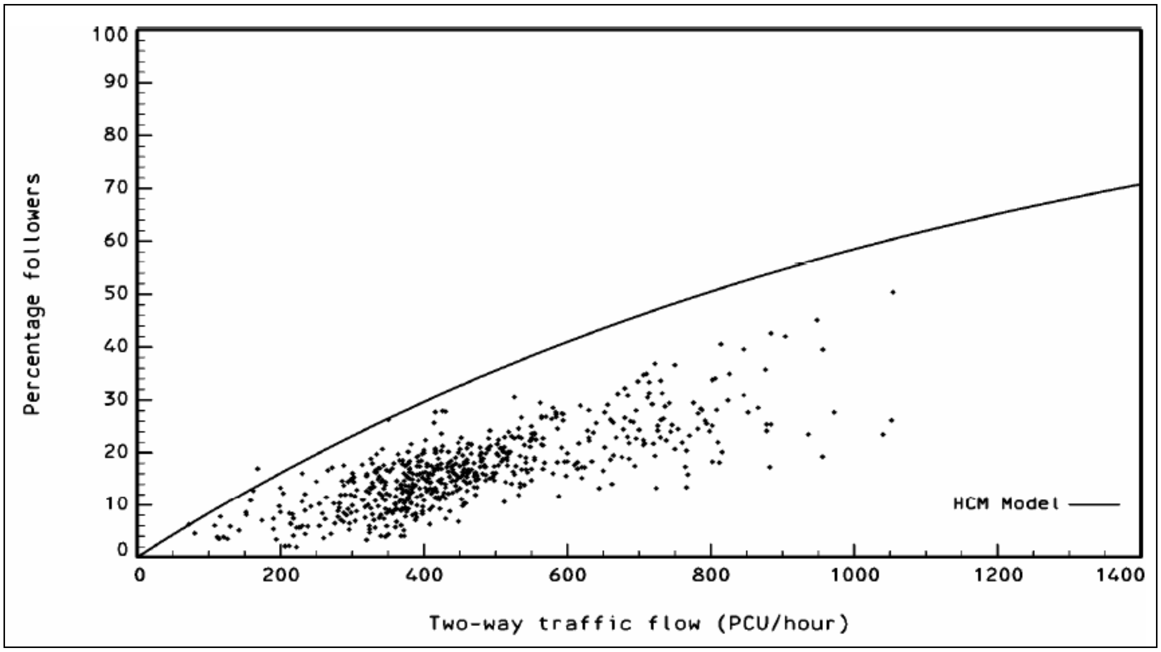


Figure 4 Comparison of HCM PTSF and the 3-Second Rule in South Africa (Van As, 2007)

The fourth and final study was done by Ahmed Al-Kaisy and Casey Durbin (2006) at Montana State University. Al-Kaisy and Durbin collected data from six two-lane highway sites in Montana and compared the field measured percent followers to the PTSF calculated using the HCM directional analysis. The results of their study, shown in Table 3, are in accord with the other results just discussed.

Table 3 Comparison of HCM PTSF and the 3-Second Rule in Montana (Al-Kaisy & Durbin, 2006)

Study Site	HCM 2000 Directional Analysis	HCM 2000 Field Estimation
HWY 287 South - NB	68.4	39.31
HWY 287 South - SB	82.2	32.59
HWY 287 North - NB	72.2	41.33
HWY 287 North - SB	59.9	40.49
Jackrabbit Lane - NB	81.3	34.24
Jackrabbit Lane - SB	90.3	52.32

The results shown above are significant because they show that the TWOPAS simulation software does not accurately represent field conditions. Using an alternative performance measure to PTSF, that does not rely on TWOPAS simulation output, would significantly improve the reliability and accuracy of the HCM procedures for two-lane highways.

Objective/Scope

This research explores other performance measures that could be used as indicators of performance on two-lane highways. Six performance measures were investigated:

1. Average Travel Speed (ATS)
2. Average Travel Speed of Passenger Cars (ATS_{PC})
3. ATS as a percent of free-flow speed (ATS/FFS)
4. ATS_{PC} as a percent of free-flow speed of passenger cars (ATS_{PC}/FFS_{PC})
5. Percent Followers
6. Follower Density

This research also investigates the vehicle interaction between successive vehicles on two-lane highways. Vehicle interaction is strongly related to headway; therefore it is important in the context of the service measure research, especially if headway-based service measures are being used to assign a LOS to two-lane highways. Vehicle interaction was investigated to develop a better understanding of the follow-by-choice phenomenon on two-lane rural highways and the conditions where vehicles are considered free-moving in the traffic stream.

Significance

This research is significant because the reliability and accuracy of the HCM procedures is very important. The HCM performance measures should accurately portray the amount of platooning on a road. If the performance measure overestimates or underestimates the severity of platooning, this may lead to highways being upgraded when not needed or exacerbation of problems related to severe platooning, respectively. The first outcome is relevant because the upgrading of a two-lane highway, especially from two-lane to four-lane, is a very expensive endeavor. The second outcome is relevant because it affects the comfort of road users and the safety of the road.

Thesis Organization

This thesis consists of seven chapters. The following chapter, chapter two, provides the results of the literature search that was conducted in the course of this research. The third chapter presents an overview of the research methods used in this research. The fourth chapter provides information on the selection and location of study sites, the data collection method, the type and amount of data collected, and the processing of field data. The fifth and sixth chapters present the results of the examination of performance measures and the examination of free-moving vehicles in the traffic stream, respectively. Finally, the seventh chapter provides a summary of the conclusions and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter provides the results of the literature search that was conducted in the course of this research. In general, it included the two main aspects presented in this thesis; the performance measures for two-lane two-way highways and vehicle interaction among successive vehicles in the same travel lane.

Performance Measures for Two-Lane Highways

A service measure is defined as any quantitative measure used to assign a level of service (LOS) to a road. This section provides background information on the qualifications of good service measures, a historical overview of the service measures used for two-lane highways in the *Highway Capacity Manual*, a state-of-the-art review of the service measures used for two-lane highways outside the United States, and an overview of other measures researched and recommended for two-lane highways.

Background

In selecting a service measure, one has to consider both the types of data needed about traffic operation and how the data will be measured. The Transportation Research Board Committee on Highway Capacity and Quality of Service selects service measures based on the following two qualifications (Harwood et al., 2001):

1. The service measure(s) should represent speed and travel time, freedom to maneuver, traffic interruptions, and/or comfort and convenience, as specified in

the definition of LOS, in a manner most appropriate to characterizing quality of service for the particular facility type analyzed;

2. The service measure(s) should be sensitive to traffic flow rates so that the service measure(s) characterize, at least in part, the degree of congestion on the facility.

In other words, it is important to measure both the quality of service and the degree of congestion on the facility. The degree of congestion is an important factor because poor service alone may not adequately warrant capacity upgrading. Generally, poor service must also be accompanied by high traffic volumes.

A recent paper by Luttinen, Dixon, and Washburn (2005) prescribed six additional criteria specific to two-lane highways segments; the six criteria state that service measures should:

1. Reflect the perception of road users on the quality of traffic flow;
2. Be easy to measure and estimate;
3. Correlate to traffic and roadway conditions in a meaningful way;
4. Be compatible with the performance measures of other facilities;
5. Describe both uncongested and congested conditions;
6. Be useful in analyses concerning traffic safety, transport economics, and environmental impacts.

The first criterion is that the service measure should reflect the road users' perceptions of the quality of traffic flow. Generally speaking, road users' perceptions of service quality are based on speed and the freedom to maneuver. One study indicated that drivers generally expect to travel at speeds close to the speed limit and expect to be able to pass slower-moving vehicles in the traffic stream (Romana, 2006). According to a study in Finland, increased density (or short headways) is not the main cause of driver frustration (Romana, 2006). Many drivers are comfortable traveling with short headways as long as they are able to travel at their desired speed. In summary, the best service measures for two-lane highways segments are those that reflect frustration due to a decrease in speed below the speed limit or frustration due to an inability to pass slower-moving vehicles.

The second criterion is that the service measure should be easy to measure and estimate. Performance measures that are solely theoretical in nature and can not be measured directly in the field should be avoided. It is important to be able to directly gauge the service measure because field measurements allow validation of models (i.e., equations used to estimate the service measure when field data is not available). Field measurements also provide an alternative method for establishing LOS.

The third criterion is that the service measure should correlate to traffic and roadway conditions in a meaningful way (i.e., the service measure should have a high correlation to traffic flow). The fourth criterion is that the service measure should be compatible with the performance measures of other facilities. This criterion is important for planning purposes because it allows the existing two-lane highway operation to be compared to the expected operation after an upgrade to a four-lane highway. The fifth criterion is that the service measure should describe both uncongested and congested conditions. In other words, the service measure should correlate to the degree of congestion (or the volume to capacity ratio) on the road. This is important because, as stated before, LOS should be assigned based on both the quality of service and the degree of congestion on the facility (Harwood et al., 2001). Finally, the sixth criterion is that the service measure should be useful in analyses concerning traffic safety, transport economics, and environmental impacts. Meeting this criterion would alert engineers to other problems that are occurring as a result of congestion (e.g., high crash rates, negative impacts on the regional economy, or high vehicle emission rates).

Of course, it would be difficult to find a service measure that meets all the qualifications above, but these criteria can be used to evaluate the suitability of a service measure.

Highway Capacity Manual Service Measures

This section provides information about the service measures used for two-lane highways in the *Highway Capacity Manual* (HCM). It provides a brief description of the evolution of the two-lane highway capacity analysis procedures and highlights the service measures used in the 1950, 1965, 1985, and 2000 editions of the HCM.

The first HCM was published in 1950; it was meant to provide "a practical guide by which the engineer, having determined the essential facts, can design a new highway or revamp an old one with assurance that the resulting actual capacity will be as calculated" (HCM, 1950). The 1950 HCM defined three different capacities: the capacity under ideal conditions, the capacity under prevailing conditions, and the practical capacity (the point at which drivers become "unreasonably restricted").

The congestion at practical capacity was defined using three quantitative performance measures. Table 4 shows the three performance measures and their corresponding index of congestion. The percent of headways less than or equal to nine seconds was used to estimate the percentage of drivers governing their speeds based on the speeds of other vehicles, one of the main effects of reduced vehicle spacings. The passing rate was observed to account for the effects of reduced passing opportunities. The practical capacity was reached when the passing rate ceased to increase as flow increased. Finally, the percentage of time that the desired speed was maintained was measured to account for decreases in operating speeds.

Table 4 Performance Measures used to determine practical capacity in the 1950 HCM

Index of Congestion	Performance Measure
Vehicle spacings	Percent of headways less than or equal to nine seconds
Passing opportunities	Average number of passings per vehicle (per mile per hour)
Operating speeds	Percent of time that a certain desired speed can be maintained

The 1965 HCM introduced the level of service (LOS) concept, in which HCM users were able to classify operations into one of six levels of service (A through F). This was an important advancement because it allowed HCM users to classify operations at low and intermediate conditions; whereas previously, conditions could only be defined as ‘above capacity’ or ‘below capacity.’ LOS was assigned based on two service measures: the operating speed and the volume to capacity ratio (v/c).

The 1985 HCM used three service measures to assign LOS: average travel speed (ATS), percent time delay, and v/c. Percent time delay is defined as the average percent of time that drivers on a particular road section are delayed while traveling in platoons due to the inability to pass. The 1985 HCM stated that percent time delay can be estimated in the field as the percent headways less than five seconds. Percent time delay was added to account for the drivers' freedom to maneuver. Freedom to maneuver was considered an important factor because it measured the drivers' desire to pass and the frustration of being delayed, two concepts that are not accounted for in average travel speed.

The current 2000 HCM uses average travel speed and percent time-spent-following (PTSF) to assign LOS. PTSF is the same as percent time delay; it was renamed simply to clarify its meaning. The 2000 HCM states that PTSF can be estimated in the field as the percentage headways less than three seconds. In addition to ATS and PTSF, the 2000 HCM also provides equations for the v/c ratio, the total travel in vehicle-miles-traveled, and total travel time in vehicle-hours, although these parameters are not used to assign a LOS.

The historical overview of the HCM service measures, provided in this section, is valuable because the HCM procedures are developed with great care and represent the agreement of many experts. Table 5 provides a summary of the service measures used to assign a LOS in the 1950, 1965, 1985, and 2000 editions of the HCM. From this table, it is clear that mobility, freedom to maneuver, and the degree of congestion (represented by ATS, PTSF, and v/c, respectively) are considered the most significant factors when assigning a LOS. These factors were given special consideration when proposing alternative service measures for two-lane highways.

Table 5 HCM Service Measures Used to Assign a LOS to Two-Lane Highways

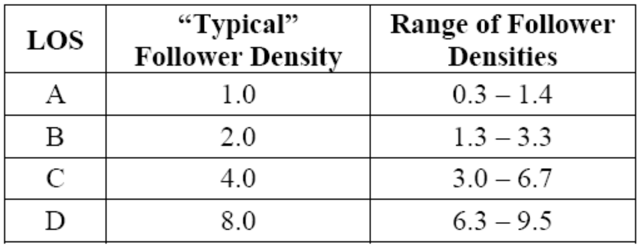
1950 HCM	---
1965 HCM	Operating Speed, v/c
1985 HCM	ATS, Percent Time Delay, v/c
2000 HCM	ATS, Percent Time-Spent-Following

Service Measures Used Outside the United States

Many countries outside the United States use the HCM analysis procedures but adapt the procedures to fit local conditions. However, sometimes the HCM procedures are not used due to perceived deficiencies. This section provides an overview of the service measures used for two-lane highways in South Africa, Germany, and Finland. These countries were chosen because they have recently published papers on the service measures they use and recommend for two-lane highways. This section is important because these countries have intentionally chosen not to use the HCM 2000 service measures due to perceived deficiencies.

South Africa has used follower density as a service measure for two-lane highways since 2006 (Van As, 2007). Follower density is calculated by multiplying the percent followers (defined as the percent of vehicles with headways less than three seconds) by the traffic density. Table 6 shows the follower density for different levels of service. These values have been adopted for the interim in South Africa.

Table 6 Proposed Follower Density Values (Van As, 2003)



LOS	"Typical" Follower Density	Range of Follower Densities
A	1.0	0.3 – 1.4
B	2.0	1.3 – 3.3
C	4.0	3.0 – 6.7
D	8.0	6.3 – 9.5

Follower density was deemed a good service measure because it accounts for both the freedom to maneuver and the degree of congestion, through the percent followers and the density, respectively. In addition, if density is computed via the basic relationship (i.e., traffic flow rate divided by space mean speed), follower density will also account for the speed of traffic, thus making it unnecessary to use speed as a secondary service measure. Lastly, follower density was deemed a good service measure because it allows some degree of correspondence between the analysis of two-lane highways and multi-lane highways, where density is used as a service measure.

Van As (2007) studied the relationship between flow and follower density on a two-lane highway in South Africa using double inductive loops to gather data. He found a quadratic relationship between flow and follower density (see Figure 5).

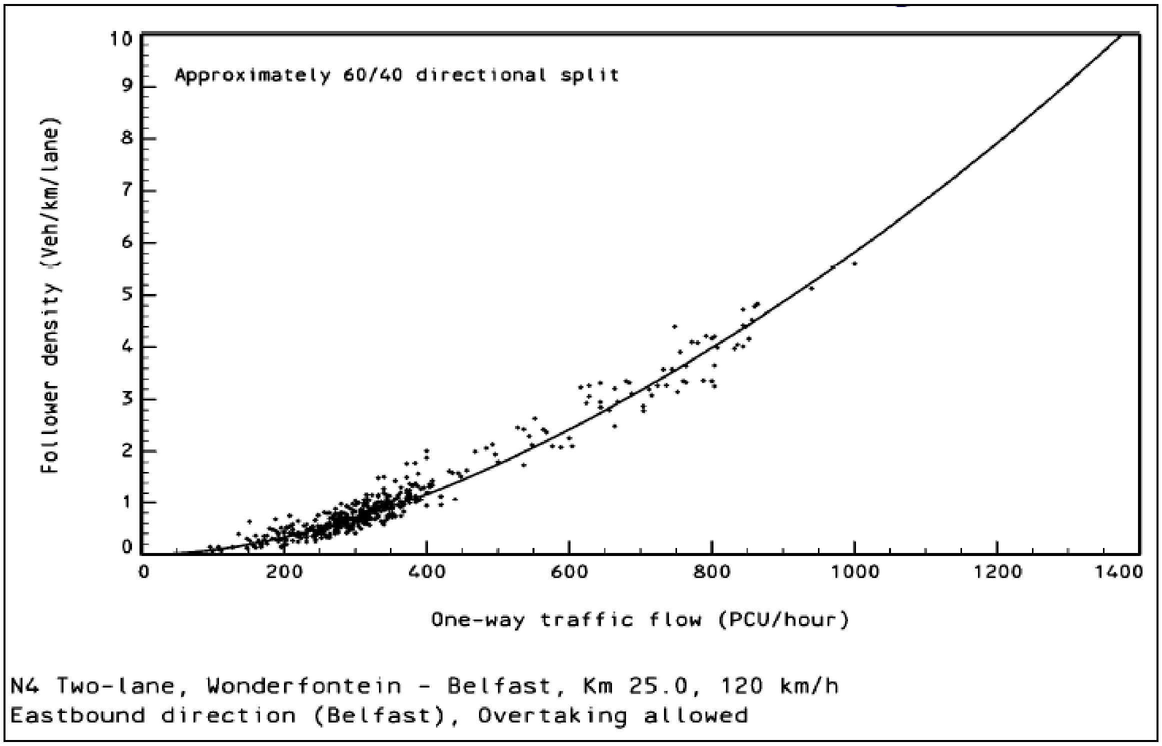


Figure 5 Relationship between follower density and flow on a two-lane highway in South Africa (Van As, 2007)

Van As (2003) also investigated the possibility of using other performance measures for two-lane highways. The measures investigated included:

- Percent followers
- Follower flow (defined as flow multiplied by percent followers)
- Travel speed
- Percent speed reduction due to traffic (as a percentage of free-flow speed)
- Traffic density
- Total queuing delay (vehicle-hours per mile)

Percent followers, travel speed, and percent speed reduction were abandoned because they only account for the experience of the individual road user and do not factor in the degree of congestion. Van As (2003) stated that density was a good service measure, but that it does not fully gauge the impediments experienced by drivers stuck in platoons. Van As considered follower flow a good service measure, but he considered it inferior to follower density because it does not factor in travel speed.

Follower density was also recommended as a performance measure for two-lane expressways in Japan (Catbagan, 2006). Two-lane expressways are slightly different than two-lane highways because they are limited access facilities and they have median barriers which prohibit passing maneuvers. Nevertheless, follower density exhibited a strong relationship with flow rate. Figure 6 shows field measurements of follower density plotted against flow on a two-lane expressway in Japan. For this study, density was calculated as the flow rate divided by the average spot speed at the detector location.

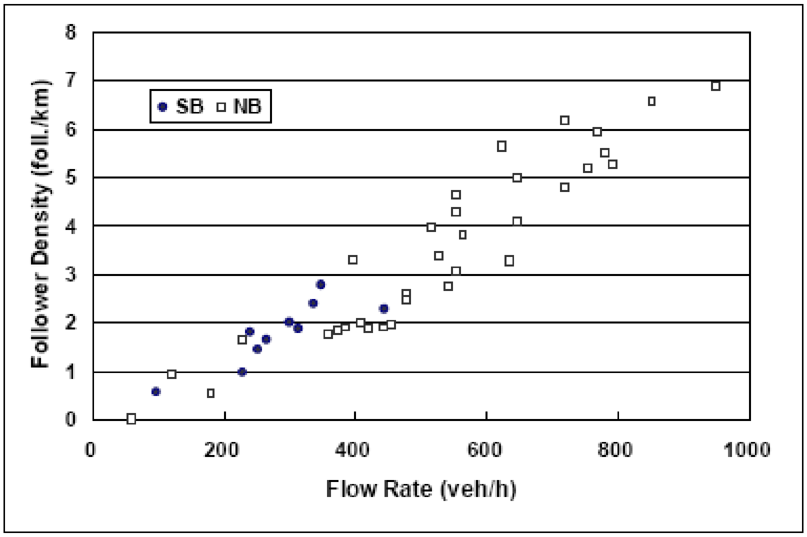


Figure 6 Relationship between follower density and flow on a two-lane expressway in Japan (Catbagan, 2006)

Finland uses two performance measures to assign LOS on two-lane highways: average travel speed of passenger cars (ATS_{PC}) and platoon percentage (the percentage of headways less than three seconds) (Luttinen, 2006). ATS_{PC} was chosen over ATS because passenger car speeds are more sensitive to increases in flow than heavy vehicle speeds. As shown in Figure 7, passenger cars tend to have higher speeds than heavy vehicles, and therefore, the speeds of passenger cars are more sensitive to increases in flow. Finland uses the platoon percentage instead of PTSF because “it was not possible to measure actual PTSFs,” which would be needed to calibrate and validate the PTSF measurements from simulation models (Luttinen, 2006).

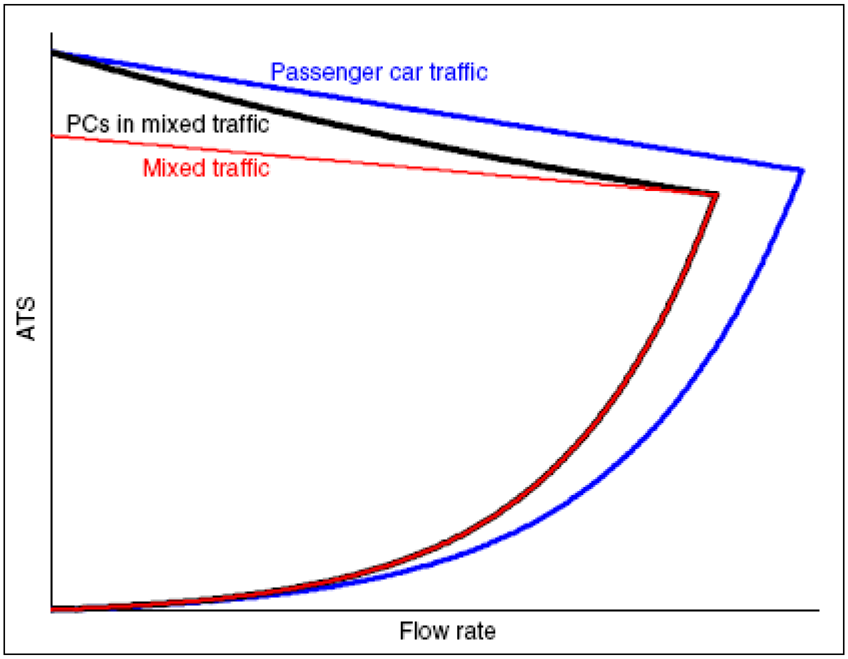


Figure 7 Average travel speed of passenger car traffic, mixed traffic, and passenger cars in mixed traffic (Luttinen, 2006)

The German highway capacity manual uses density as the service measure for two-lane highways, calculated as flow divided by the average travel speed of passenger cars (Brilon, 2006). This performance measure was adopted in 2003; prior to 2003, the average travel speed of passenger cars (ATS_{PC}) was the primary service measure. ATS_{PC} was abandoned because it did not factor in the degree of congestion. For example, using ATS_{PC} alone, a LOS A or B could never be obtained in speed-reducing environments (e.g., upgrades or areas with low speed limits). In these areas, free-flow conditions, not speed, should indicate a high LOS. Using density as service measure solves this discrepancy. Brilon also makes an interesting comment on PTSF (2006). He states that PTSF has never been considered as a substantial performance measure in Germany because PTSF is more an expression of drivers' inconvenience and does not directly express the degree of efficiency of the traffic operation.

In summary, the two-lane highway service measures used by other countries have two trends. The first trend is that ATS_{PC} is recommended over ATS because passenger car speeds are more sensitive to increases in congestion. The second trend is that density-related measures are recommended in order to account for the degree of congestion. The results of the studies provided in this section had a strong influence on the performance measures selected for further investigation in this project.

Other Recommended Service Measures

Several other performance measures have been studied and recommended but have never been used in practice. This section highlights a few of those recommendations.

Normann (1942) stated that the mean difference in speed between successive vehicles was the best index of congestion for two-lane highways. As shown in Figure 8, Normann found a strong linear relationship between field measurements of flow and mean difference in speed between successive vehicles. Normann suggested three other performance measures as well: the proportion of headways less than nine seconds, the ratio of actual passings to desired passings, and the average number of passsings per vehicle (Normann, 1942). These performance measures were eventually used in the determination of practical capacity for the 1950 HCM.

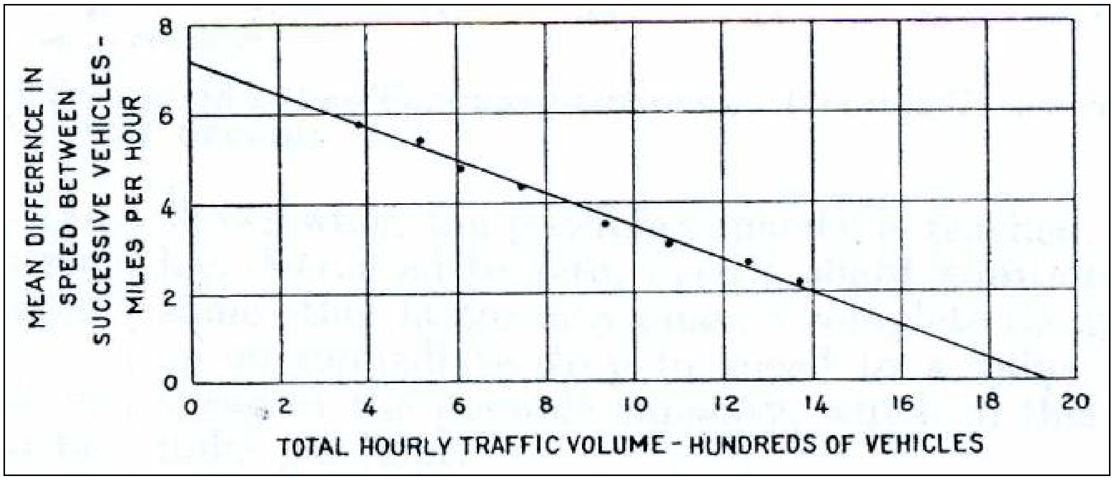


Figure 8 Mean speed and mean difference in speed between successive vehicles for a two-lane level tangent highway section in Illinois (Normann, 1942)

In 1990, Morrall and Werner also suggested using the overtaking ratio (defined as the number actual passing maneuvers divided by the number of desired passing maneuvers) as a performance measure for two-lane highways. The overtaking ratio was evaluated using a simulation model.

Other recommended performance measures for two-lane roads, not mentioned in the previous two sections, include:

- Frequency and amount of speed changes per mile (Greenshields et al., 1961 cited in Luttinen, 2001)
- Acceleration noise (i.e. the standard deviation of accelerations) (Drew, 1968 cited in Luttinen, 2001)
- Delay Rate in seconds per vehicle-mile (Harwood et al., 1999)
- Platoon rate (measured percentage of short headways divided by the percentage of short headways in random flow) (Luttinen, Dixon, & Washburn, 2005)

In summary, this section highlighted various performance measures that have been studied and recommended but have never been used in practice. These performance measures were used to gain insight into other variables that gauge driver frustration. The platoon rate, recommended by Luttinen, Dixon, & Washburn in 2005, has not been studied as of yet, but could be investigated in future research.

Inter-Vehicular Interaction on Two-Lane Highways

Two separate states of car-following interactions are examined in this section. The first is the free-vehicle in the traffic stream. A free vehicle defined as a vehicle that is traveling at its desired travel speed and is not impeded by the presence of the vehicle ahead. This part of this section focuses on studies that have used empirical methods to identify free vehicles. The second part of this section provides a literature review of studies that have aimed to quantity the follow-by-choice phenomenon. This phenomenon is related to vehicles that voluntarily follow the vehicle ahead with a short headway but are not adjusting their speed based on the speed of that vehicle. Therefore, these vehicles are not actually being impeded or inconvenienced. The follow-by-choice phenomenon has important implications on headway-based service measures like percent followers (the percentage of vehicles with headways less a certain cut-off headway value).

Empirical Methods Used to Identify Free-Moving Vehicles

All vehicles can be classified as either interacting or non-interacting. The percentage of interacting vehicles decreases as the headway increases, going from 100 percent at the smallest headway observed to nearly zero percent for headways greater than some threshold value, T seconds. This section focuses on empirical studies that have aimed to find this threshold, T. Four major studies are examined, each with a different method to determine T. The first two studies use graphical analysis to determine T, the third study uses headway and relative speed distributions to determine T, and the last study uses the correlation coefficient between the lead vehicle speed and the following vehicle speed to determine T.

The first study is reported in the 1950 *Highway Capacity Manual* (TRB, 1950). It involved a simple graphical examination of headway versus the mean difference in speed between successive vehicles on a two-lane highway. Figure 9 shows that as the headway decreased, there was little difference in speed between successive vehicles until the headway was reduced to nine seconds. Below nine seconds, the speed of the following vehicle quickly approached the speed of the lead vehicle. Based on this plot, it was concluded that vehicles with headways greater than nine seconds are not affected by the presence of the vehicle ahead (i.e., T = 9 seconds).

The second study was done by Casey Durbin (2006), a graduate student at Montana State University. Durbin plotted the average travel speed (ATS) of vehicles traveling with headways equal to or greater than a given threshold value. Figure 10 shows the speed-headway relationships at six two-lane highway sites in the state of Montana. From examining these plots, Durbin noted that the mean travel speed ceased to increase after the 5- or 6-second threshold. Based on this observation, he concluded that T is in the range of 5 to 6 seconds.

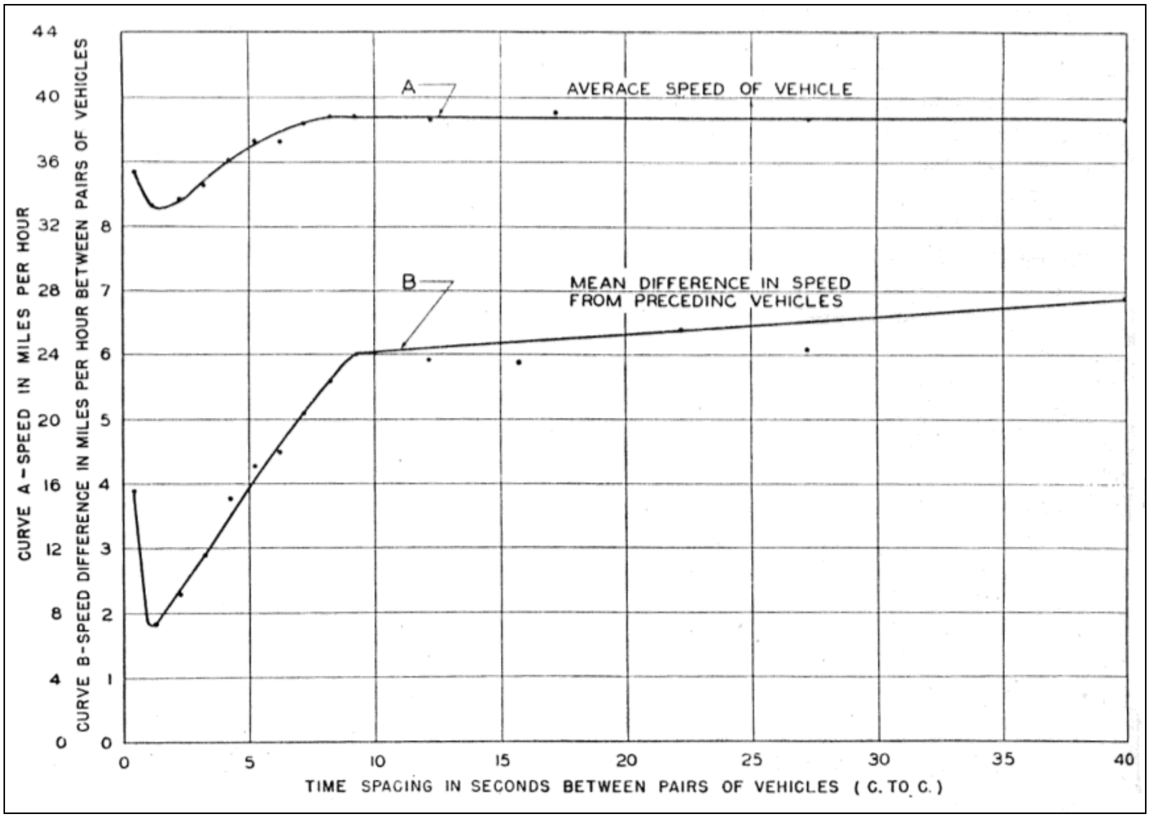
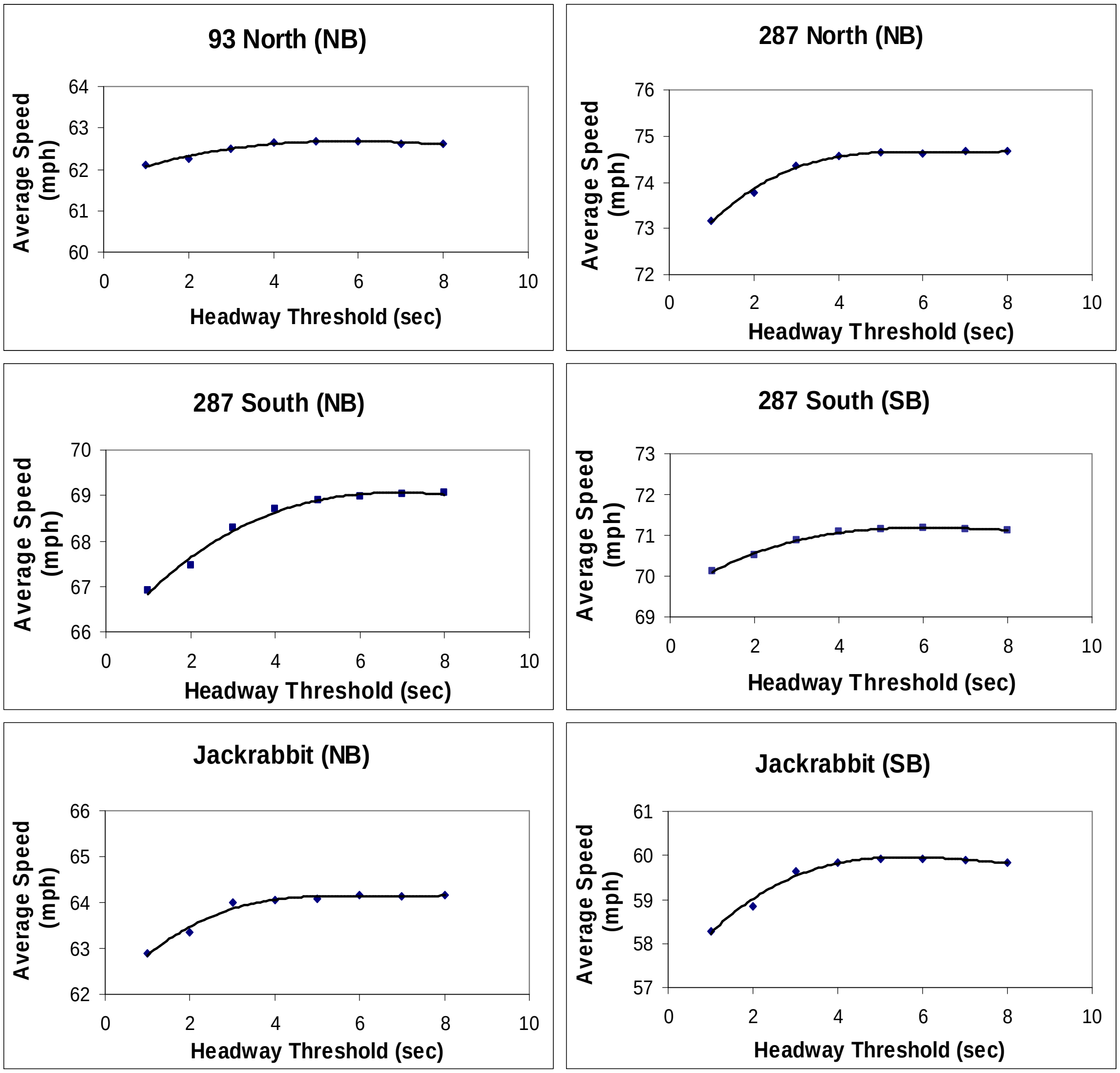


Figure 9 Speed Characteristics of Vehicles versus Headway (HCM 1950)

The third study was done by Alan Miller (1961), a researcher from the United Kingdom. Miller aimed to find a value for T by comparing the observed headway and speed distributions on a two-lane road to the expected distributions under random flow, when all vehicles are traveling at their free-flow (desired) speeds. To start, Miller made two assumptions:

1. free vehicles have a negative exponential distribution of headways, and
2. free vehicles have a normal distribution of relative speeds.


93 North (NB)

287 North (NB)

287 South (NB)

287 South (SB)

Jackrabbit (NB)

Jackrabbit (SB)

Figure 10 Relationship Between Speed and Headways Equal To or Greater Than a Threshold Value at Two-Lane Study Sites (Durbin, 2006)

A plot of the observed headways and the expected headways under random flow conditions is shown in Figure 11. Based on this figure, Miller selected a threshold of T=8 seconds because of the extreme departure from the exponential distribution for headways less than this value.

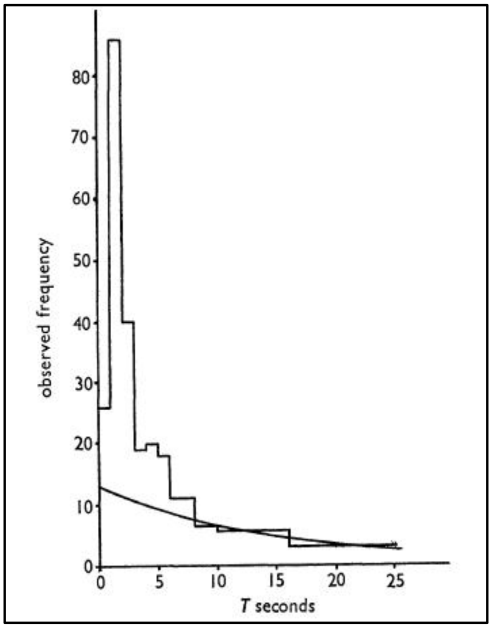


Figure 11 Frequency Distribution of Gaps with Superimposed Negative Exponential Distribution (Miller, 1961)

Miller recognized that, of course, not all vehicles with gaps less than 8 seconds would be in the following mode. Therefore, he added an additional criterion to identify free vehicles with gaps less than 8 seconds. The second criterion was based on relative speed, where a positive relative speed indicated that the second vehicle was faster. A plot of the observed relative speed distribution and the expected distribution of relative speeds under random flow is shown in Figure 12. This figure shows that there are significantly more observed relative speeds in the range of -5 to 10 kilometers per hour (-3 to 6 miles per hour) than predicted. From this, Miller proposed that a vehicle will be in the following mode if it has a relative speed in the range of -5 to 10 km/hr (this is true only if the vehicle also has a headway less than 8 seconds). Vehicles following with relative speeds less than -5 km/hr were considered free, and vehicles following with relative speeds greater than 10 km/hr were assumed to be performing passing maneuvers.

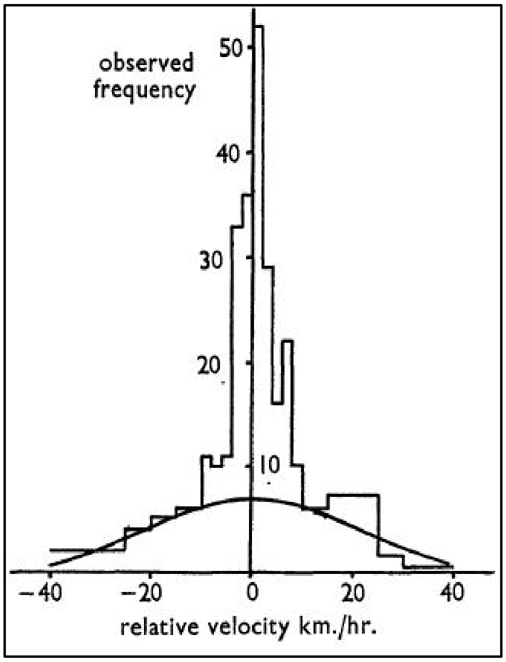


Figure 12 Frequency Distribution of Relative Speeds with Superimposed Normal Distribution (Miller, 1961)

Several studies have followed Miller's approach, by studying headway distributions and relative speed distributions to find a threshold, T. For example, Wasielewski (1979) applied Miller's methodology to headways on a freeway to find T = 2.5 to 3.5 seconds. Similarly, Sands & Pahl (1971) found T = 2.5 to 4.3 seconds on a four-lane divided highway.

The fourth and last method examined is by Vogel (2002). Vogel aimed to find a threshold, T, for free vehicles in an urban area. Data was collected from four legs of an urban intersection, at points downstream from the intersection where vehicles had regained their initial speed. The speed limit at the study site was 50 km/hr (30 mph).

Vogel's work was done under the assumption that a vehicle is considered free when its speed is not influenced by the speed of the vehicle traveling ahead. Correlation coefficients were used to determine the strength of the relationship between successive vehicle speeds at different headways. A correlation coefficient of zero indicates that the speeds are not related at a particular headway. Figure 13 shows a plot of headway versus the correlation coefficient between the lead and following vehicle speeds. This figure shows that the correlation began to level off after a headway of 6 seconds.

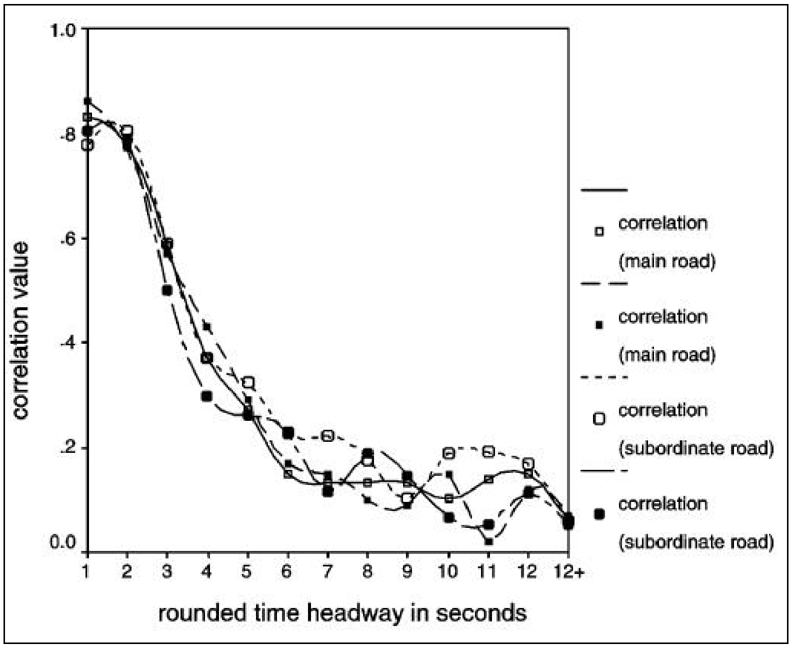


Figure 13 Headway versus the Correlation Coefficient Between Lead and Following Vehicle Speeds (Vogel, 2002)

Vogel also used linear regression to investigate the value of T. Under the assumption that T = 6.5 seconds, two linear regression equations were computed: one for vehicles with headways less than 6.5 seconds and one for vehicles with headways greater than 6.5 seconds. Figure 14 shows the regression lines and R square values. Thresholds of 5.5 and 7.5 seconds were also investigated, but the 6.5 threshold was deemed the most appropriate. In the end, a threshold of T = 6 seconds was selected for simplicity and because the regression lines intersect at six seconds. Using a threshold of 6.5 seconds would have caused an illogical discontinuity in correlation.

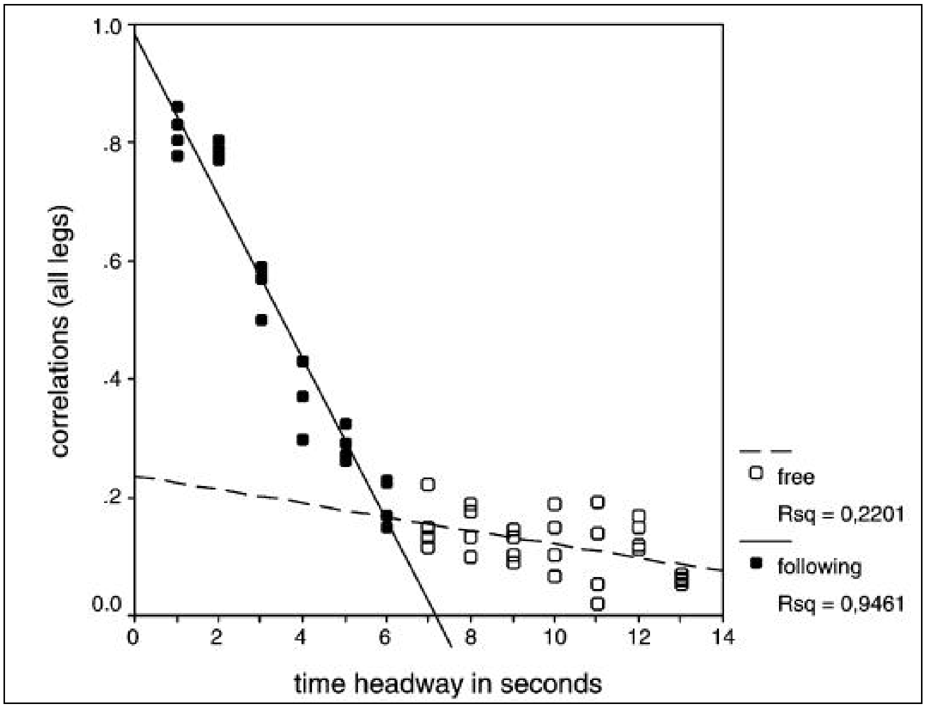


Figure 14 Regression Lines for “Following Vehicles” and “Free Vehicles” Based on a 6.5 Second Threshold (Vogel, 2002)

The studies presented in this section shed light on to the methods that can be used to identify a headway threshold for free-moving vehicles. In addition, the studies highlight the key variables which factor into vehicle interaction (namely, headway, speed, and the difference in speed between successive vehicles). The results of these studies were used to better understand vehicle interaction and to select a method to calculate free-flow speed.

Empirical Methods Used to Quantify the Follow-by-Choice Phenomenon

Durbin (2006) also studied the follow-by-choice phenomenon by examining the headway distribution on the right lane of Interstate 90 near Bozeman, Montana. Durbin examined the headway distributions at both low- and high-flow conditions (v/c ratios of 0.19 and 0.40, respectively). Figure 15 shows the percentage of observed headway counts in three headway intervals: the percent of headways less than three seconds, the percent between three and eight seconds, and the percent greater than eight seconds. During the low-flow period, 27 percent of the headways were less than three seconds. Durbin considered this value abnormally high, considering the low traffic volume and the constant passing opportunities on the interstate. From this, he concluded that many vehicles travel at headways less than three seconds, even when the opportunity to pass is always present.

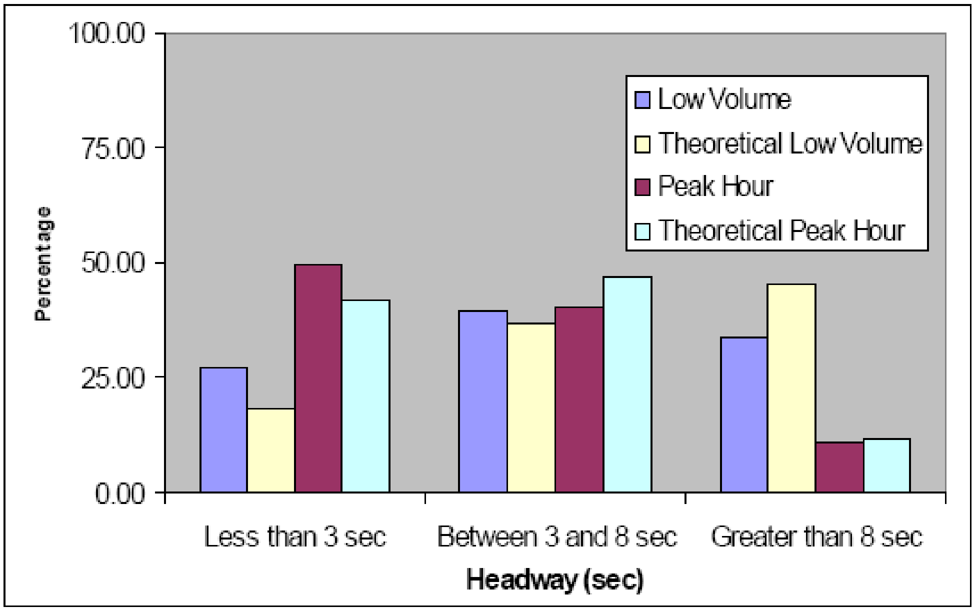


Figure 15 Percentage of Headway Counts Less than Three Seconds on Interstate I-90 During Low and High Flow (Durbin, 2006)

The observed headway percentages were compared to the theoretical percentages under random flow conditions, represented by the negative exponential distribution. This comparison was made to ensure that the presence of on- and off- ramps near the study site did not affect the true proportion of vehicles traveling at less than a three-second headway. Since the actual headways percentages were quite close to the expected headway percentages, Durbin concluded that the data collected on Interstate 90 represented near-random operation.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter presents an overview of the research methods used in this project. This thesis includes two distinct, yet relevant, studies. The first study is an analysis of performance measures for two-lane highways. The purpose of this study was to examine performance measures in regard to their ability to describe performance on two-lane highways. This was done by using graphical and statistical analyses to investigate the level of association between performance measures and major platooning variables.

The second study involves an investigation of vehicle interaction on two-lane highways. The purpose of this study was to develop a better understanding of the follow-by-choice phenomenon on two-lane rural highways and the conditions where vehicles are considered free-moving in the traffic stream. To investigate following-by-choice, headways on two-lane highways were compared to headways on the right lane of a four-lane highway with unlimited passing opportunities. To identify free-moving vehicles in the traffic stream, this study used speed and headway measurements to discern the interaction between successive vehicles. All analyses in this research were conducted using field data from study sites in the state of Montana.

Analysis of Performance Measures for Two-Lane Highways

This section presents the six performance measures examined in this study and the methods used to assess them. The performance measures were assessed using both graphical and statistical analyses, which aimed to examine the strength of the relationship between the any of those performance measures and platooning variables.

Performance Measures Examined

This section provides the definition of each service measure, the reason for its selection, and its advantages and limitations. The six performance measures analyzed were:

- Average travel speed (ATS)
- Average speed of passenger cars (ATS_{PC})
- ATS as a percent of free-flow speed (ATS/FFS)
- ATS_{PC} as a percent of free-flow speed of passenger cars (ATS_{PC}/FFS_{PC})
- Percent followers
- Follower density

The first performance measure studied was average travel speed (ATS). Speed has been used as a performance measure for two-lane highways in every version of the Highway Capacity Manual. In the 2000 HCM, ATS is defined as the length of the roadway segment under consideration divided by the average total travel time for all vehicles to traverse that segment during some designated time interval. ATS is a good choice for a performance measure because it relates well to road user perceptions of the quality of traffic flow. As far as drivers are concerned, speed is the most significant indicator of congestion on a two-lane highway (1950 HCM). A study in New Zealand found that road users evaluate a two-lane highway based on their travel speed and that most expect to travel at a speed close to the speed limit (Romana 2006). Speed is also easy to measure in the field, if spot speed measurements are sufficient. However, speed is not a good performance measure when used alone. First, ATS lacks a benchmark for across-site comparison of speeds. This is a problem because two-lane highways have a wide variety of operating speeds due to differences in geometric curvature and speed limits. Therefore, a low speed does not necessarily indicate poor operation or a high degree of congestion. Secondly, ATS does not factor in the degree of congestion. A two-lane highway with a low ATS and low traffic volume should have a higher LOS than a highway with a low ATS and a high traffic volume.

The second performance measure investigated was average travel speed of passenger cars (ATS_{PC}): Average travel speed of passenger cars was investigated because passenger car speeds tend to be more sensitive to increases in congestion than heavy vehicle speeds (Luttinen 2006). ATS_{PC} is currently used as a service measure for two-lane highways in Finland. It was also used as the primary service measure in Germany until 2003; now German planners indirectly use ATS_{PC} as a service measure in calculating density, the current service measure for two-lane highways in Germany (where density is computed as flow divided by ATS_{PC}) (Brilon 2006). ATS_{PC} may have the benefit of being more sensitive to increases in congestion; however it still has the same limitations as ATS, in that it lacks a benchmark for across-site comparisons and does not factor in the degree of congestion.

The third performance measure investigated was average travel speed as percent of free-flow speed (ATS/FFS). This performance measure was investigated because it shows the average speed reduction due to interaction with other vehicles. Therefore, a decrease in vehicle interaction will result in a higher percentage of ATS/FFS and a higher LOS. The main advantage of this performance measure is that it addresses the benchmark issue related to ATS and ATS_{PC}. The free-flow speed can differ greatly from site-to-site, thus using free-flow speed as a benchmark allows fair across-site comparisons. The main limitation of ATS/FFS is that, like the speed-related measures, it does not factor in the degree of congestion.

The fourth performance measure investigated was average travel speed of passenger cars as percent of free-flow speed of passenger cars (ATS_{PC}/FFS_{PC}). This performance measure was investigated because it is likely to be more sensitive to increases in congestion than ATS/FFS. Again, this is because passenger car speeds tend to be more sensitive to increases in congestion than heavy vehicle speeds. Like ATS/FFS, its main advantage is that it provides a benchmark for across-site comparisons and its main disadvantage is that it does not factor in the degree of congestion.

The fifth performance measure investigated was percent followers. Percent followers was measured as the percentage of headways less than three seconds at a spot location. The three second headway was chosen because it corresponds to the HCM surrogate measure for percent time-spent-following (PTSF). Therefore, the percent followers approximately equals the PTSF. The term percent followers is somewhat confusing because the percent headways less than three seconds does not actually reflect the percent vehicles in the following mode. The term percent followers was used in this research because it is widely used by other two-lane highway researchers, and its meaning is well-known. Percent followers, when defined as the surrogate measure for

PTSF, factors in the freedom to maneuver. Freedom to maneuver is an important factor because it reflects driver frustration due to the inability to pass slower-moving vehicles. The main disadvantage of percent followers is that it does not factor in the degree of congestion.

The sixth performance measure investigated was follower density. Follower density is calculated by multiplying the density by the percent followers and is currently used as a service measure for two-lane highways in South Africa (Van As 2007). The major advantages of using follower density are that it factors in traffic level and it is compatible with density (the service measure for multi-lane highways). The main disadvantage of follower density is that density is difficult to measure directly in the field. However, density can easily be estimated at point locations from percent occupancy or from volume and speed measurements.

In reference to the two-lane highway service measure criteria proposed by Luttinen, Dixon, and Washburn (2005), how well do the proposed measures perform? Table 7 shows the evaluation of each proposed service measure. All six measures meet the perception of road users, are easy to measure in the field, and describe both uncongested and congested conditions. The ATS_{PC} and follower density have an advantage over the rest because they correspond to the service measures used for multi-lane highways. The speed-related measures are useful in economic analyses which quantify the lost dollar value due to vehicles delayed in traffic. No service measure meets all six criteria.

Table 7 Evaluation of Proposed Service Measures

	ATS & ATS_{PC}	ATS/FFS & ATS_{PC}/FFS_{PC}	Percent Followers	Follower Density
Reflects perception of road users	✓	✓	✓	✓
Easy to measure and estimate	✓	✓	✓	✓
Correlates to traffic and roadway conditions		✓		✓
Compatible with performance measures of other facilities	✓			✓
Describes both uncongested and congested conditions	✓	✓	✓	✓
Useful in safety, economic, or environmental analyses	✓	✓		

Methods Used to Examine Performance Measures

The main objective of this study was to examine the relationships between the proposed performance measures and platooning variables. The platooning variables used in this study are listed below. Grade was not used as platooning variable because all study sites were located on level terrain.

- Flow
- Opposing flow
- Percent heavy vehicles
- Percent no-passing zones
- Standard deviation of free-flow speed (SD of FFS)

It is hypothesized that increases in these five variables will increase the amount of platooning on a two-lane highway. The relationships were examined in three ways: graphical analysis, analysis using correlation coefficients, and regression analysis.

The first analysis was a graphical examination of the relationship between each service measure and each platooning variable. The purpose of this analysis was to visually inspect general trends between the performance measures and platooning variables. The relationships were plotted using bar charts, with the platooning variable on the x-axis and the performance measure on the y-axis.

For the second analysis, we used correlation coefficients to provide information about the strength of the linear relationship between each performance measure and each platooning variable. Correlation coefficients reflect the noisiness and direction of a linear relationship (see Figure 16). For this study, the correlation was considered significant if the correlation coefficient was greater than 0.5. The correlation coefficients between performance measures and platooning variables were found at individual study sites and across study sites by combining the data from all sites.

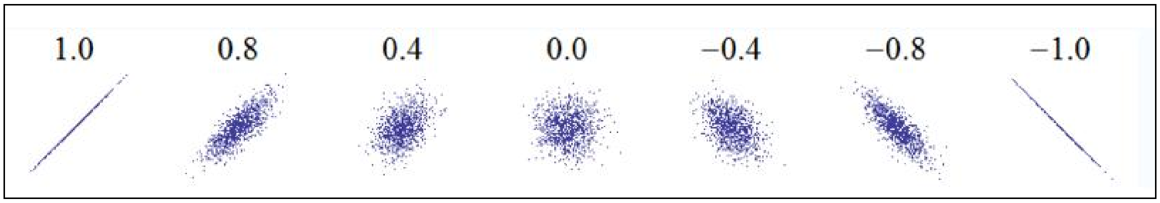


Figure 16 Correlation Coefficients (Wikipedia, 2008)

The third analysis was done using multiple linear regression analysis. The regression analyses were done at individual study sites and across study sites. For the regression model, the platooning variables (the independent variables) were used to predict the performance measure. The general form of the linear regression equation was:

$$Y = \beta_1 + \beta_2(x_1) + \beta_3(x_2) + \beta_4(x_3) + \beta_5(x_4) + \beta_6(x_5)$$

Equation 2

where Y = performance measure
β = coefficients
x_1 = volume in vehicles per hour
x_2 = opposing volume in vehicles per hour
x_3 = percent no-passing zones
x_4 = percent heavy vehicles
x_5 = standard deviation of free-flow speed in miles per hour.

Regression analysis provides a large amount of data. For this study, regression analysis was used to answer the following questions.

- How much of the variability in the performance measure is attributed to the platooning variables? Is this amount significant?
- How high is the standard error (i.e., the typical error of prediction) for the performance measure?
- Which platooning variables are the most significant contributors?

These questions were answered under a 95% confidence level.

Non-linear regression was also investigated because the form of the model was unknown. For the non-linear regression, trial-and-error was used to fit non-linear functions of x to the y-variable. The non-linear functions considered were the inverse function, the log function, the square root function, and the linear function. In the end, the linear regression model was selected for simplicity and because the R Square values were not much improved by using a non-linear model.

Methods Used to Examine Vehicle Interaction

The second investigation included in this thesis involved an examination of vehicle interaction on two-lane highways. The study of vehicle interaction is important in the context of the service measure research discussed earlier, especially if headway-based service measures are being used to assign a LOS to two-lane highways. For example, the percent headways less than three seconds is used to calculate both the percent followers and follower density. What does the percent headways less than three seconds actually represent? In the context of the following-by-choice phenomenon, what percentage of vehicles with headways less than three seconds is actually being impeded by the speed of the vehicle ahead? This part of the study aims to answer such questions.

The next two sections highlight the methods used to identify free vehicles in the traffic stream and the methods used to quantify the follow-by-choice phenomenon on two-lane highways.

Methods Used to Identify a Free-Vehicle in the Traffic Stream

The relationship between speed and time headway was used to identify free-vehicles in the traffic stream. This was done by examining the speed-headway relationships at two-lane highways and comparing them to the speed-headway relationships on the right lane of four-lane highways. The purpose of this analysis was to identify traffic conditions where vehicles can be considered free, this is, where the vehicle’s speed is independent from the speed of the vehicle ahead.

Methods Used to Quantify the Follow-by-Choice Phenomenon

This investigation builds upon the results of a previous study on Interstate 90, referenced in the literature review (Durbin 2006). Using the same methodology, data was collected from the right lane of rural four-lane highways and analyzed in a similar fashion. This was done because traffic flow on rural two-lane highways is more similar to flow on rural four-lane highways than to flow on a freeway. Freeway flow is different because freeways have higher design requirements than rural highways (e.g. wider medians and shoulders, larger clear-zones, and less geometric curvature).

This investigation provided additional information about the following-by-choice phenomenon by directly comparing four-lane operations to two-lane operations. Specifically, the headway distributions at the two-lane highway sites were compared to the headway distributions on the right lane of the four-lane highway sites. A direct comparison of headway distributions was possible on one road, where two-lane and four-lane highway sections were separated by 10 miles (sites 1 and 6 on US 93, referenced in Chapter 4). These study sites had virtually the same roadside environment and driver population.

This same road, where two-lane and four-lane highway sections were separated by 10 miles, was also used to quantify the follow-by-choice phenomenon. This was done by comparing the relationship between the percent followers and flow at the two-lane highway site to that at the right lane of the four-lane highway site. The purpose of this analysis was to compare driver selection of short headways on the different facilities. It was hypothesized that, under low-flow conditions, vehicles on the right lane of the four-lane highway have virtually unlimited passing opportunities, and therefore, vehicles traveling with short headways would represent vehicles following by choice.

CHAPTER 4

DATA COLLECTION AND PROCESSING

Field data from eight study sites in rural Montana were used in this project. Four of the study sites are located on two-lane rural highways and the other four are located on four-lane rural highways. All of the four-lane data and one two-lane highway dataset were collected in November 2006 using automatic traffic recorders. The rest of the two-lane data were borrowed from a previous data collection effort at Montana State University (MSU) that was conducted in July 2005. This section provides information on the selection and location of study sites, the data collection method, the type and amount of data collected, and the processing of field data into formats appropriate for analysis.

Selection of Study Sites

Three criteria were used to select study sites (these criteria were also used to select sites in the 2005 data collection effort). The first criterion was that the study sites should each exhibit a wide range of traffic levels. This way, both high and low traffic conditions could be observed. The second criterion was that the study sites should be outside the influence of major traffic interruptions, i.e., outside the influence of traffic signals and high volume intersections and driveways. Traffic signals were avoided because they cause platooning, which would skew the headway distribution. High volume intersections and driveways were avoided because the speed reduction required to make a turning maneuver would skew the average travel speed. The third criterion for site selection was that the study sites should not be affected by major geometric features such as grades and vertical and horizontal curves (i.e., the study sites should ideally be on straight, flat segments). This was important because it simplified the analysis by reducing the number of platooning variables and made across-site comparisons possible.

Description of Study Sites

Figure 17 shows a map of the data collection. This figure also shows the 2005 annual average daily traffic (AADT) in vehicles per day (vpd) of the segment from which the data was collected. The AADT was obtained from the Montana Department of Transportation. The two-lane highway study sites had a range of AADT from 3,610 to 11,208 vpd, while the four-lane highway study sites had a range of 3,127 to 13,272 vpd.

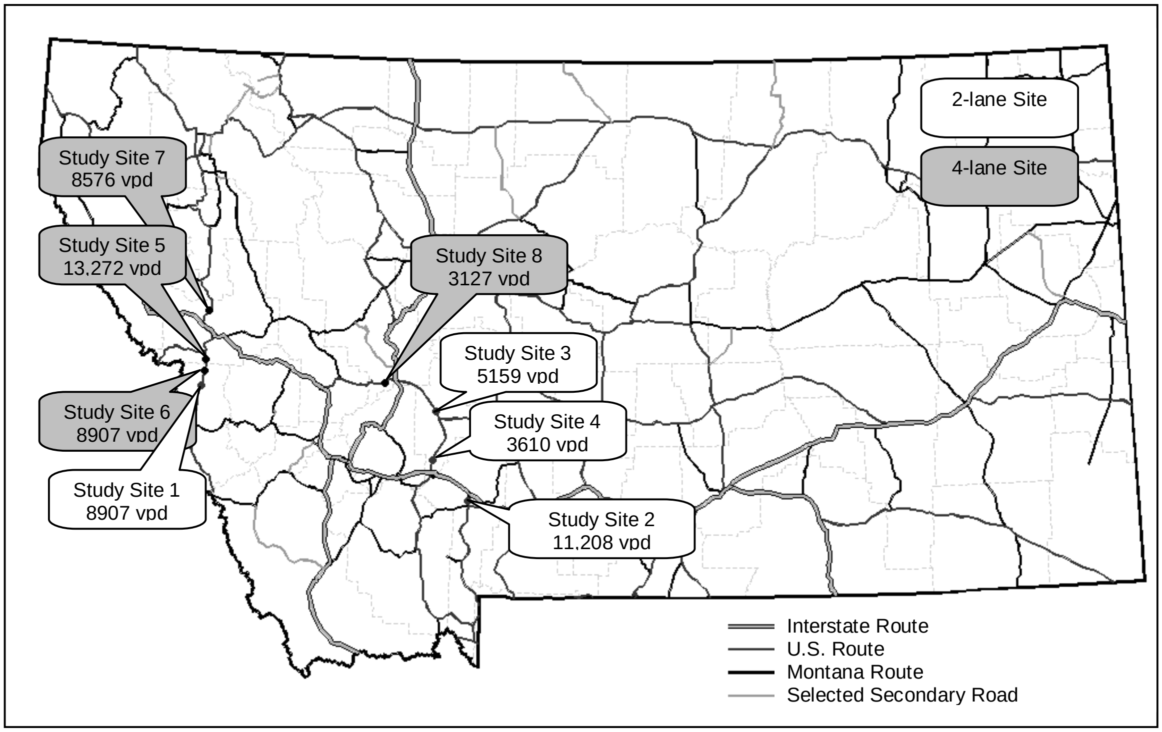


Figure 17 Map of Data Collection Sites with AADT

Data was collected from both lanes of the two-lane highway sites. All two-lane highway study sites were classified as Class I highways (as per the HCM classification), meaning they function as major intercity routes where motorists expect to travel at relatively high speeds. The location of each two-lane highway study site is described in detail below. The data at study sites 2, 3, and 4 were collected in a previous data collection effort in the summer of 2005 (Durbin, 2006). The study site numbers correspond to those shown in Figure 6.

- Study Site 1: Highway US 93 near Florence, MT. This site is located about 12 miles south of Florence on the highway segment which connects Stevensville and Florence, Montana.
- Study Site 2: Jackrabbit Lane near Four Corners, MT. This site is located about 4 miles north of Four Corners on the highway segment between the towns of Four Corners and Belgrade, Montana.
- Study Site 3: Highway 287 North near Townsend, MT. This site is located about 5 miles north of Townsend on the highway segment that connects the towns of Townsend and Helena, Montana.
- Study Site 4: Highway 287 South near Three Forks, MT. This site is located on the segment of Highway 287 between its intersection with I-90, west of Three Forks, and the town of Townsend. Data was collected about 7 miles north of I-90.

Table 8 shows the percent no-passing zones at the two-lane highway sites. This information was obtained from video and tabular highway records provided by the

Montana Department of Transportation (MDT). The percent no-passing zones was used in the across-site regression analysis of performance measures.

Table 8 Percent No-Passing Zones at the Two-Lane Highway Study Sites

Study Site	**Percent No-Passing Zones**
Site 1: US 93 (NB)	17
Site 2: Jackrabbit (NB)	5
Site 2: Jackrabbit (SB)	5
Site 3: Hwy 287 North (NB)	23
Site 4: Hwy 287 South (NB)	33
Site 4: Hwy 287 South (SB)	51

At the four-lane highway study sites, data was only collected from the right travel lane. It was assumed that, under low-flow conditions, the right lane of a four-lane highway would resemble a two-lane highway with unlimited passing opportunities. It was also assumed that the vehicles traveling on the right lane of the four-lane highways during low-flow periods were not substantially different in any way from the total vehicle population.

There were four four-lane highway study sites. The location of each site is described below.

- Study Site 5: Highway US 93 near Lolo, MT. This site is located about 6 miles south of Lolo on the segment connecting Florence and Lolo, Montana. Data was collected for the southbound traffic traveling in the right lane of the four-lane highway.
- Study Site 6: Highway US 93 near Florence, MT: This site is located about 2.5 miles south of Florence. It lies on the highway segment connecting Stevensville

and Florence, Montana. Data was collected for the northbound traffic traveling in the right lane of the four-lane highway.

- Study Site 7: Highway US 93 near Evaro, MT. This site is located about 3.5 miles south of Evaro and about 3 miles north of I-90. It lies on the segment connecting Missoula and Evaro, Montana. Data was collected for the northbound traffic traveling in the right lane of the four-lane highway.
- Study Site 8: Highway 12 near Helena, MT. This site is located about 3 miles west of Helena. It lies on the segment connecting Elliston and Helena, Montana. Data was collected for the westbound traffic traveling in the right lane of the four-lane highway.

Data Collection Techniques

This section describes the equipment used to collect data in the field and the type and amount of data obtained.

Equipment and Setup Procedures

Data was collected using automated traffic recorders. At the two-lane highway sites, the data was collected using TRAX I Plus traffic counters manufactured by JAMAR Technologies, Inc. At the four-lane highway sites, the data was collected using Apollo traffic counters manufactured by Diamond Traffic Products. As far as this research is concerned, the TRAX I Plus and Apollo traffic recorders have basically the same data collection capabilities.

Description of Data Collected

The automated traffic recorders collected per-vehicle data, including arrival time, gap, spot speed, vehicle length, and vehicle class. The automated traffic recorder software classified vehicles using the Federal Highway Administration (FHWA) 13-category classification system. The vehicle classifications are listed in Table 9. A more detailed description of the vehicle classification system is included in Appendix A.

Table 9 FHWA Vehicle Classification System

Class 1	Motorcycles
Class 2	Passenger Cars
Class 3	Pickups, Vans and other 2-axle, 4-tire Single Unit Vehicles
Class 4	Buses
Class 5	Two-Axle, Six-Tire Single Unit Trucks
Class 6	Three-Axle Single Unit Trucks
Class 7	Four or More Axle Single Unit Trucks
Class 8	Four or Less Axle Single Trailer Trucks
Class 9	Five-Axle Single Trailer Trucks
Class 10	Six or More Axle Single Trailer Trucks
Class 11	Five or Less Axle Multi-Trailer Trucks
Class 12	Six-Axle Multi-Trailer Trucks
Class 13	Seven or More Axle Multi-Trailer Trucks

The amount of data collected at each site is shown in Table 10. Data were collected from both directions of travel on the two-lane highways; thus, there are two data sets from each site. Two directional data sets were excluded from the analysis: HWY 287 North Southbound and US 93 Northbound. The data set at HWY 287 North (SB) was excluded because there is a passing lane about two miles north of this site; the data in the southbound direction appeared skewed, likely due to the dissipation of platoons on the passing lane. The data set at US 93 (NB) was excluded because its data also seemed irregular. This site is about 4 miles south of a four-lane segment; therefore it was hypothesized that northbound vehicles were more tolerant to platooning because they knew there would be passing opportunities ahead.

The duration of data collection varied between 14 and 100 hours. Less data was collected at sites 5 and 7 due to snowplow interruption. However, all sites had a substantial number of vehicle counts.

Table 10 Data Collection Durations and Vehicular Counts at Study Sites

Study Site	**Date**	**Duration of Data Collection (hours)**	**Total Vehicle Count (vehicles)**
Two-Lane Sites			
Site 1: US 93 (NB)	November 5-7, 2006	52	8249
Site 2: Jackrabbit (NB)	July 31 - August 1, 2005	16	2128
Site 2: Jackrabbit (SB)	July 1-4, 2005	16	3491
Site 3: Hwy 287 North (NB)	July 1-2, 2005	21	2672
Site 4: Hwy 287 South (NB)	July 1-2, 2005	82	8393
Site 4: Hwy 287 South (SB)	July 1-4, 2005	82	7960
Four-Lane Sites			
Site 5: US 93 South (SB)	November 5-6, 2006	15	1219
Site 6: US 93 South (NB)	November 5-7, 2006	44	8519
Site 7: US 93 North (NB)	November 5-6, 2006	14	1206
Site 8: Hwy 12	November 5-9, 2006	100	7017

Data Processing

This section provides information on how the data was processed. To begin, the vehicle counts were aggregated into 15-minute intervals, and then multiplied by four to convert them into flow rates. The gaps measured by the automatic traffic recorders were converted into headways using the following equation:

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

Equation 3

Free-flow speed was computed as the average travel speed of vehicles with headways greater than 8 seconds. The 8 second threshold was chosen based on the results of a previous research (Durbin, 2006). As mentioned in the literature review, that study found that vehicle interaction diminishes when the time headway exceeds six seconds. Figure 18 shows a sample plot of the study results; it shows the mean travel speed of vehicles traveling with headways that are equal to or greater than a given threshold value. The mean travel speed ceases to increase after the 6-second threshold; therefore, the 8-second threshold was considered conservative in identifying free-moving vehicles.

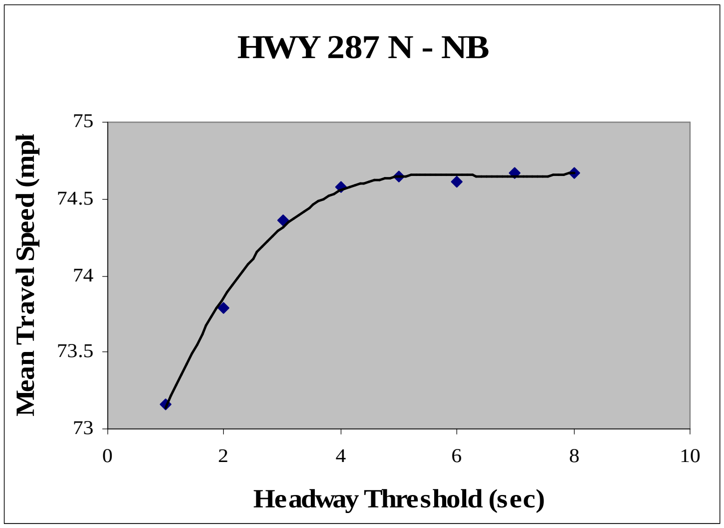
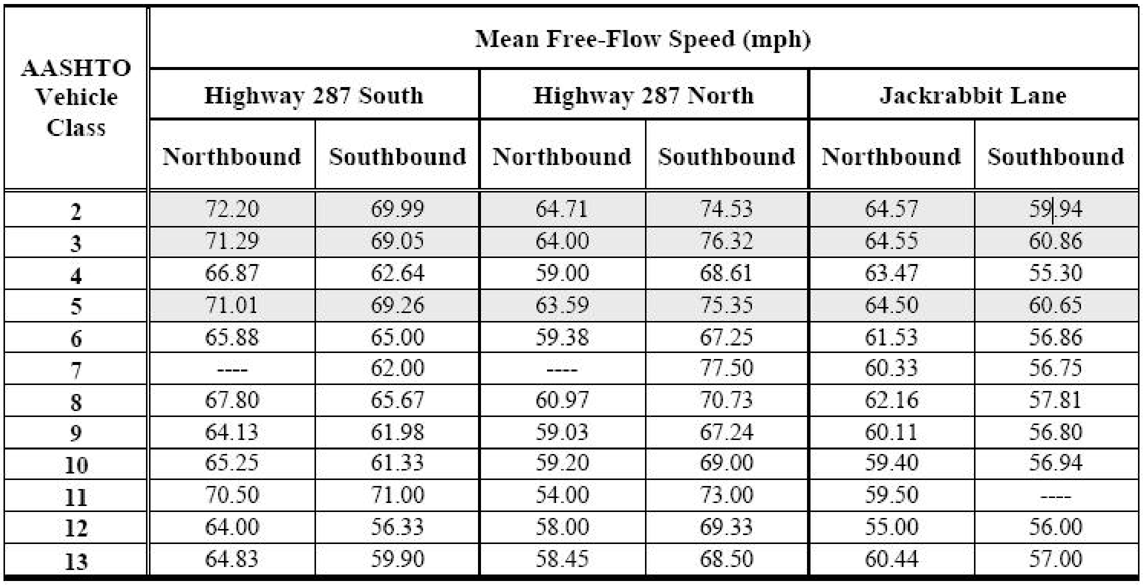


Figure 18 Relationship Between Mean Travel Speed and Time Headway (Durbin, 2006)

Vehicles were classified as passenger cars or heavy vehicles based on their performance and thus their mean free-flow speed. A study by Al-Kaisy and Durbin (2006) found that vehicle classes 2, 3, and 5 had higher free-flow speeds than other vehicle classes. Table 5 shows the data from their study (where mean free-flow speed was calculated using the 8-second threshold). Based on this data, classes 2, 3, and 5 were classified as "passenger cars" or high performance vehicles. Classes 2, 3, and 5 include cars, pickups, vans, campers, small motor homes, ambulances, minibuses, recreation vehicles, and motor homes. All other vehicles (vehicles in class 4 and classes 6 to 13) were considered heavy vehicles. The same vehicle grouping scheme was used when processing the data collected in November 2006.

Table 11 Mean Free-Flow Speed by Vehicle Class (Al-Kaisy & Durbin, 2006)



AASHTO Vehicle Class	Mean Free-Flow Speed (mph)					
	Highway 287 South		Highway 287 North		Jackrabbit Lane	
	Northbound	Southbound	Northbound	Southbound	Northbound	Southbound
2	72.20	69.99	64.71	74.53	64.57	59.94
3	71.29	69.05	64.00	76.32	64.55	60.86
4	66.87	62.64	59.00	68.61	63.47	55.30
5	71.01	69.26	63.59	75.35	64.50	60.65
6	65.88	65.00	59.38	67.25	61.53	56.86
7	----	62.00	----	77.50	60.33	56.75
8	67.80	65.67	60.97	70.73	62.16	57.81
9	64.13	61.98	59.03	67.24	60.11	56.80
10	65.25	61.33	59.20	69.00	59.40	56.94
11	70.50	71.00	54.00	73.00	59.50	----
12	64.00	56.33	58.00	69.33	55.00	56.00
13	64.83	59.90	58.45	68.50	60.44	57.00

CHAPTER 5

PERFORMANCE MEASURES ON TWO-LANE HIGHWAYS

Graphical and statistical analyses were done to examine the relationship between platooning variables and measures of performance. These analyses were only done at the two-lane highway sites. The objective was to examine how variation in each platooning variable impacted the value of the performance measure. Table 12 shows the performance measures and platooning variables used in this study. The results shown in this chapter can also be found in the Proceedings of the Transportation Research Board 87th Annual Meeting (Al-Kaisy & Karjala, 2007A).

Table 12 Performance Measures and Platooning Variables

Performance Measures	Platooning Variables
ATS	Flow
ATS_{PC}	Opposing flow
ATS/FFS	Percent no-passing zones
ATS_{PC}/FFS_{PC}	Percent heavy vehicles
Percent Followers	Standard deviation of free-flow speed
Follower Density	

Graphical Analysis

For the graphical analysis, each performance measure was plotted against each platooning variable. The main objective was to check, by visual inspection, if there are trends between the performance measure and platooning variable. This section first presents the plots of the performance measures plotted against flow.

Figure 19 shows the relationship between the traffic flow in the direction of travel and the speed performance measures ATS and ATS_{PC}. The percent heavy vehicles is superimposed on the graphs to better understand the effects of flow on speed. The general hypothesis was that, as flow increases the average speed will decrease. An examination of the bar plots shows that three out of the six sites exhibited downward trends consistent with the hypothesis; these sites include 287 N (NB), US 93 (NB), and

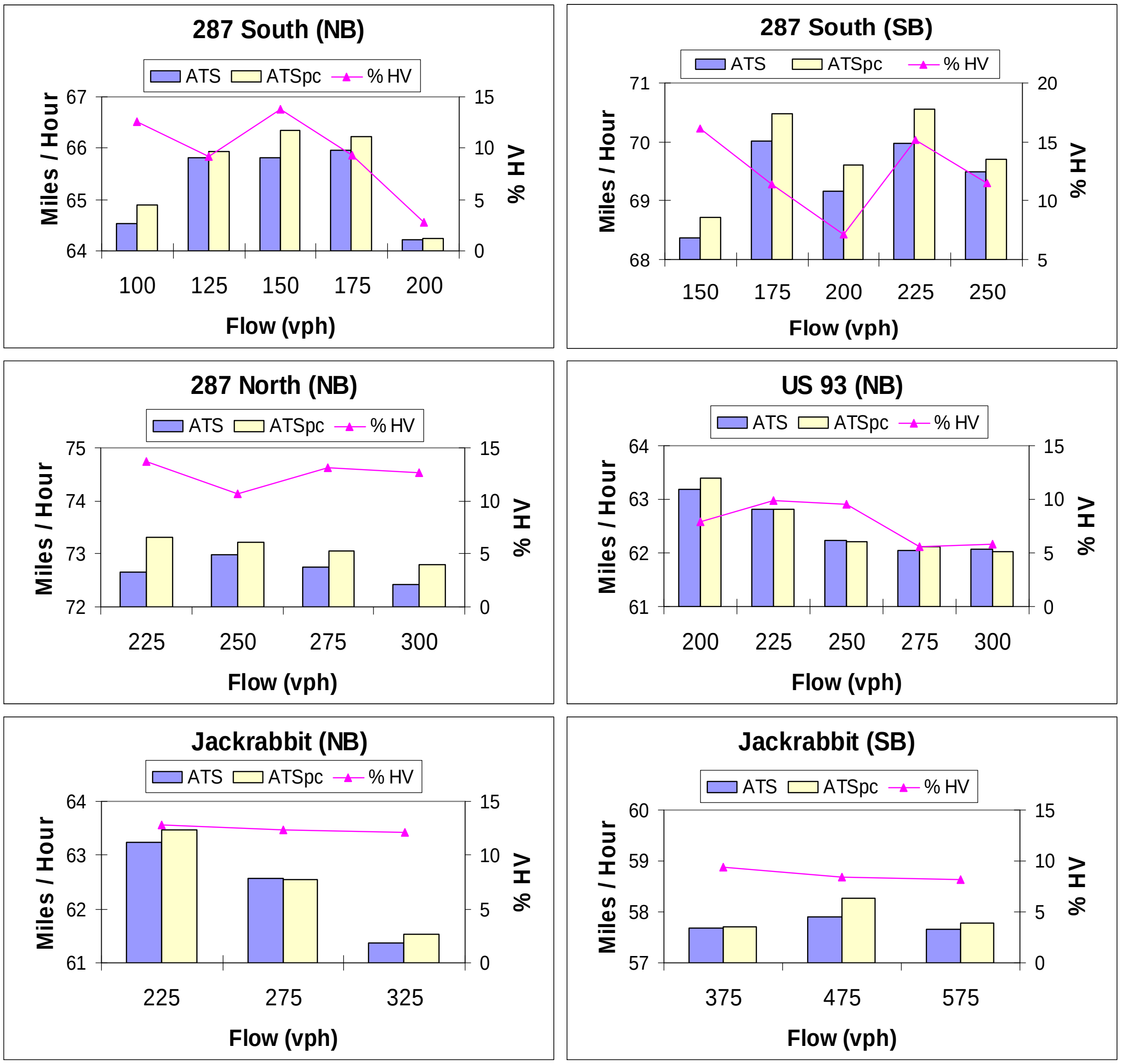


Figure 19 Relationship of ATS and ATSPC with Traffic Flow at Study Sites

Jackrabbit (NB). The rest of the sites exhibited unexpected trends. The ATS$_{PC}$ is relatively more consistent with the hypothesis than ATS.

The second relationship examined is that between flow and the speed ratios ATS/FFS and ATS$_{PC}$/FFS$_{PC}$. The hypothesis was that, as flow increases the speed ratios would decrease. Figure 20 shows that all sites, expect for 287 S (SB), exhibited a clear

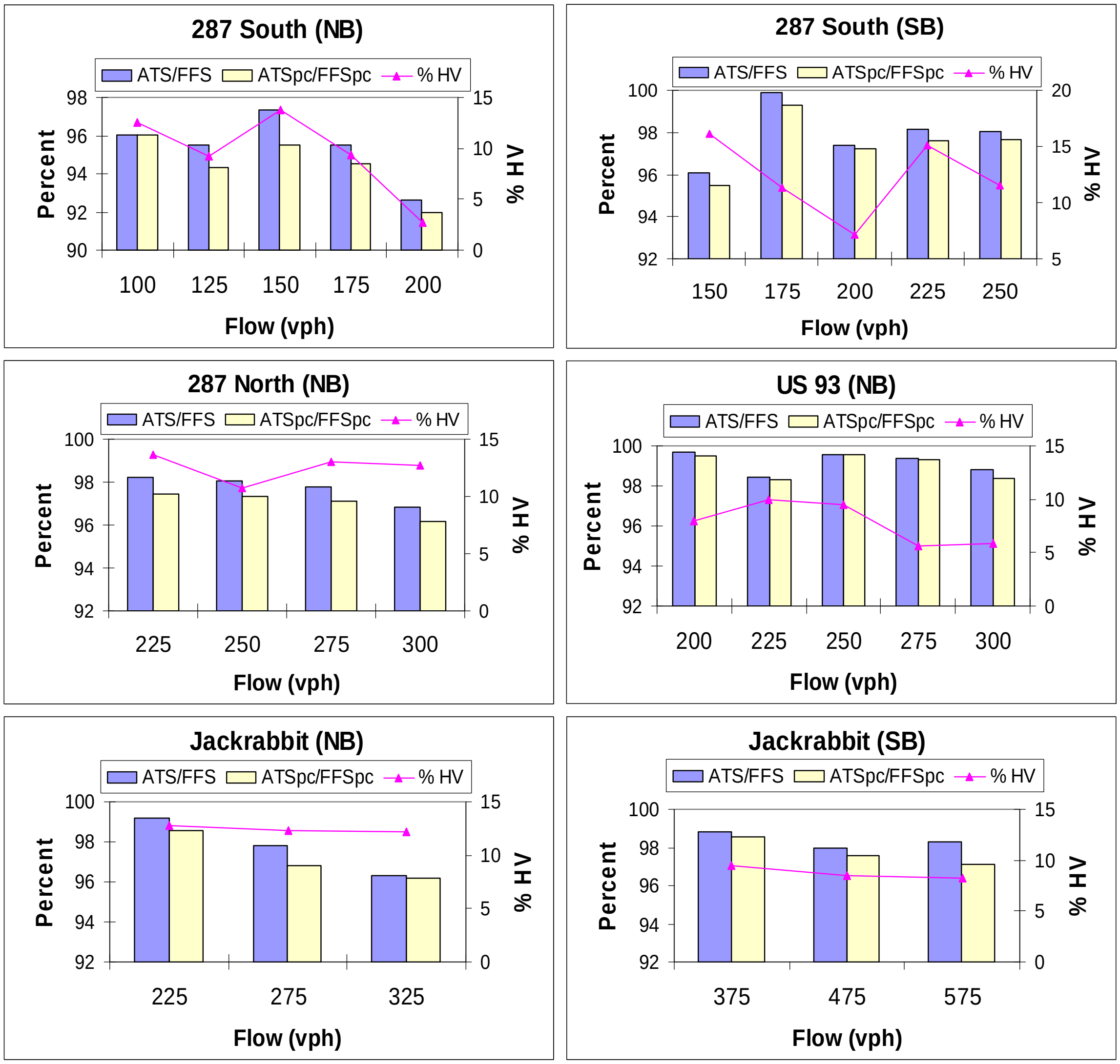


Figure 20 Relationship of ATS/FFS and ATSPC/FFSPC with Traffic Flow at Study Sites

downward trend consistent with the hypothesis. ATS_{PC}/FFS_{PC} was consistently lower than ATS/FFS. This indicates that passenger car speeds are more impacted by platooning than heavy vehicle speeds. This is logical because platoons tend to form behind vehicles with slower desired speeds, and many of these slower vehicles tend to be heavy vehicles with relatively inferior performance.

The third relationship, shown in Figure 21, examined was that between flow and percent followers. The hypothesis was that, as flow increases the percent followers will

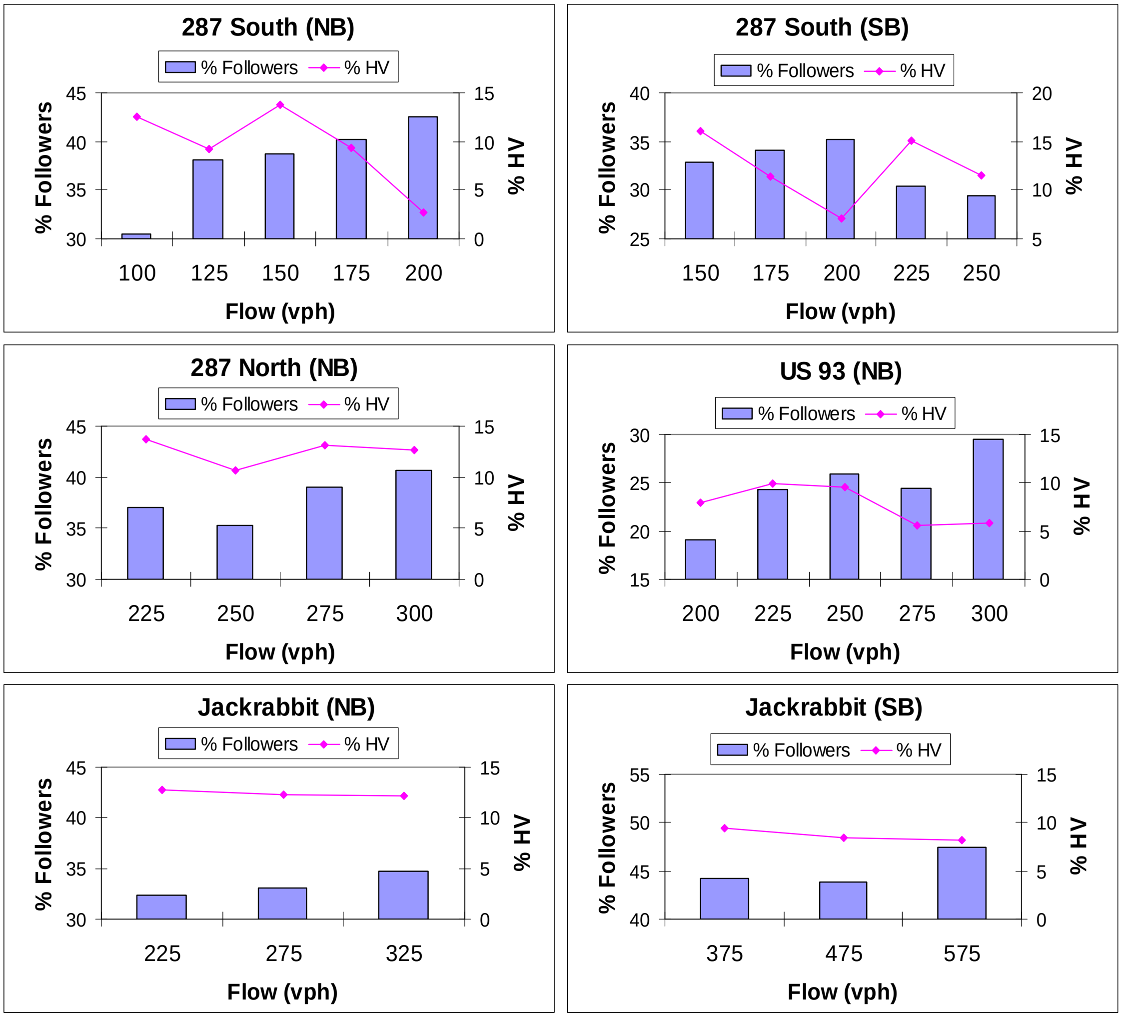


Figure 21 Relationship Between Percent Followers and Traffic Flow at Study Sites

also increase. Figure 21 shows that all sites, except for 287 S (SB), exhibited a positive trend consistent with the hypothesis. The last relationship examined was that between flow and follower density (see Figure 22). The hypothesis was that, as flow increases the follower density will also increase. The trends exhibited in Figure 22 are similar to those exhibited in Figure 21; however, the trends are slightly stronger and more consistent.

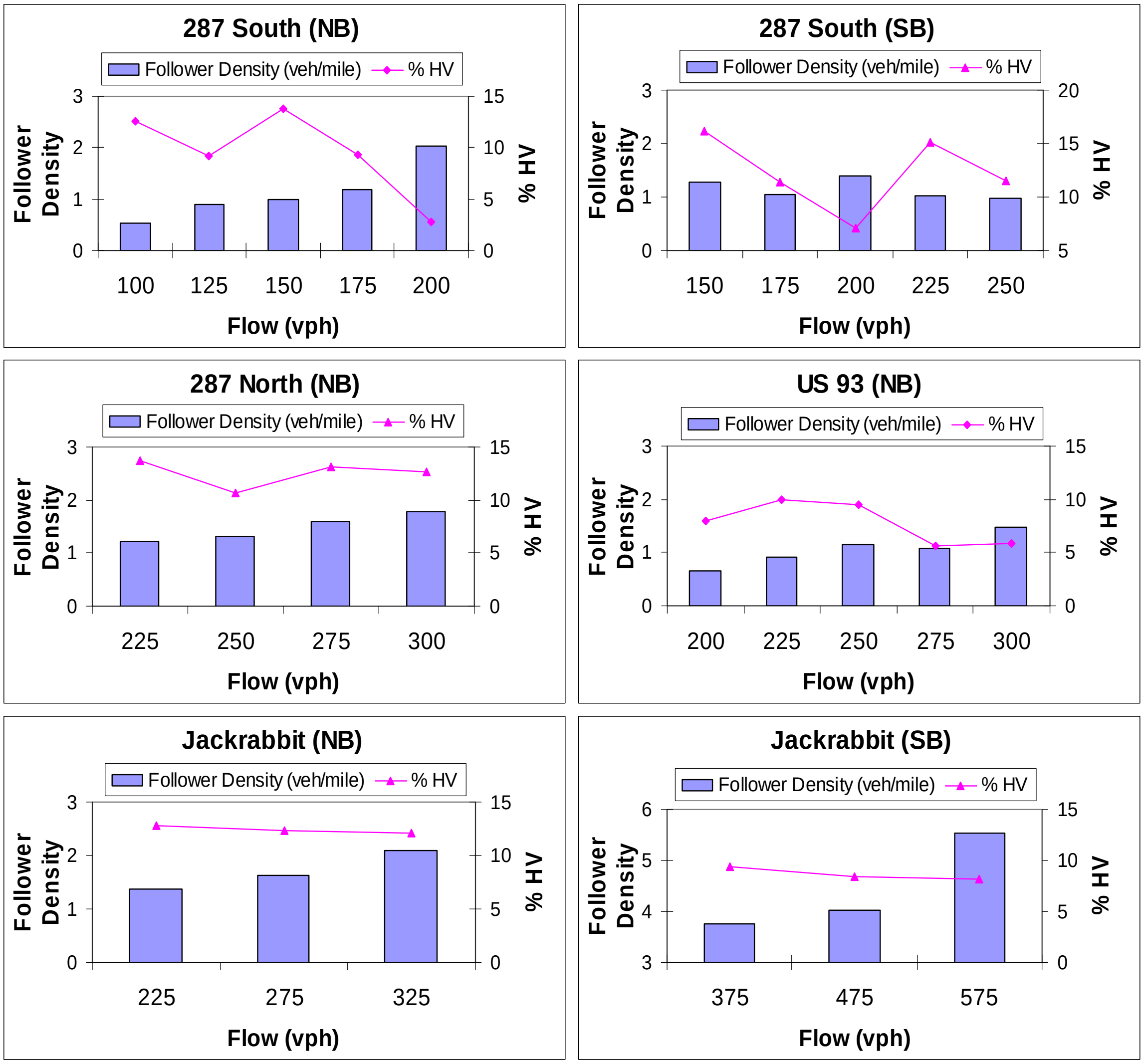


Figure 22 Relationship Between Follower Density and Traffic Flow at Study Sites

The graphical analysis also included an examination of the relationships of the performance measures with opposing flow and the standard deviation of free-flow speed. Figures 23 and 24 show those relationships at one of the study sites, HWY 287 N (NB). This study site was deemed representative of the other sites which showed similar patterns. In Figure 23, ATS and ATS_{PC} exhibited an irregular, yet downward trend. The speed-rates also showed a downward trend, but with only a slight decrease in speed. No trend could be discerned from the plots of percent followers and follower density. In Figure 24, none of the performance measures exhibited clear patterns with respect to the standard deviation of free-flow speed. From this graphical analysis, it is clear that opposing flow and standard deviation of free-flow speed have weaker relationships with the performance measures than flow rate.

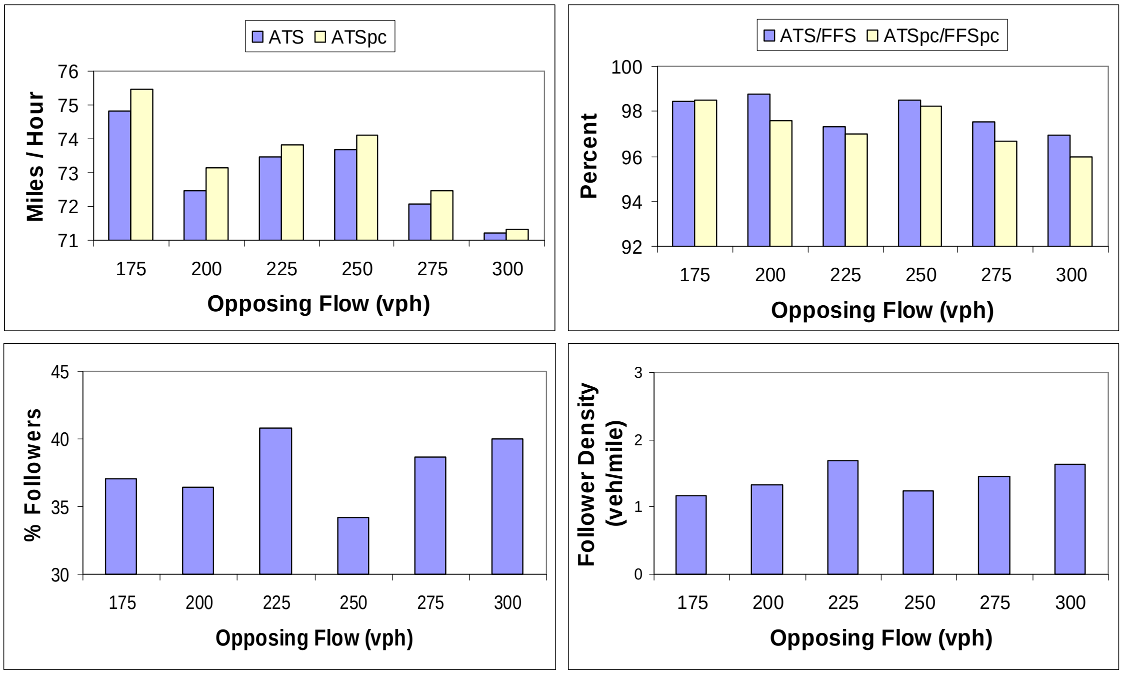


Figure 23 Relationship of Performance Indicators with Opposing Flow Rate at Highway 287 North (NB) Study Site

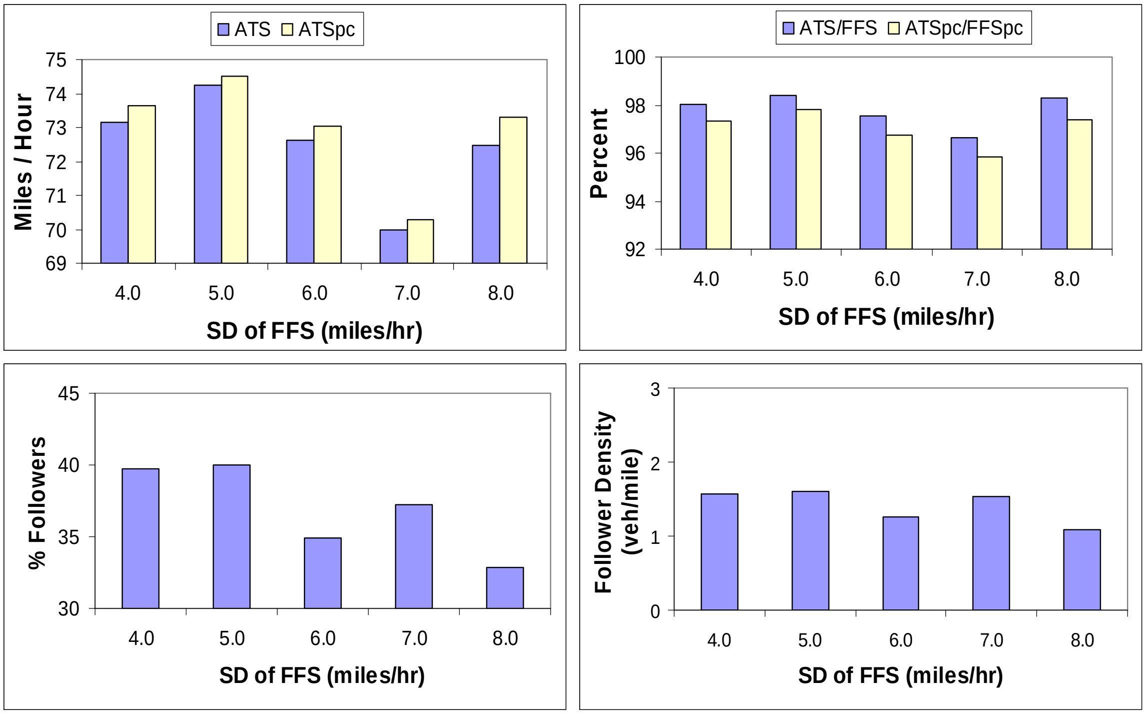


Figure 24 Relationship of Performance Indicators with Standard Deviation of Free-Flow Speed at Highway 287 North (NB) Study Site

In summary, the graphical analysis showed that follower density had the strongest and most apparant relationship to flow rate, followed, in order, by percent followers, the speed-ratios, and the average speeds. Secondly, the graphical analysis showed that performance measures had a significantly stronger relationship with flow rate than with opposing flow rate and standard deviation of free flow speed.

Statistical Analysis

Two statistical analyses were performed to examine the relationships between the performance measures and platooning variables. The first analysis examined the correlation coefficients between each performance measure and each platooning variable. The second analysis utilized multiple linear regression.

Correlation Coefficients

As mentioned earlier, correlation coefficients measure the noisiness and direction of a linear relationship. The correlation coefficient is computed as:

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

Equation 4

Where $\bar{x}$ and $\bar{y}$ are the mean values of the x and y variables.

Table 13 shows the correlation coefficients between the performance measures and platooning variables at the two-lane highway sites. Values in parentheses represent correlations that are inconsistent with the expected logical relationships between platooning variables and performance indicators. The most important observations that can be discerned from Table 13 are:

1. In general, flow rate and the standard deviation of free-flow speed exhibited relatively higher correlations with performance measures than opposing flow and percent heavy vehicles.
2. Follower density, followed by percent followers, had the highest correlations with flow rate. This was somewhat expected given the direct relationship of flow rate with time and distance headways.
3. ATS_{PC} and ATS_{PC}/FFS_{PC} had approximately the same correlation to platooning variables as ATS and ATS/FFS, respectively. This suggests that restricting speed

measurements to passenger cars does not significantly improve the sensitivity to platooning variables.

4. Despite the relatively high correlations of performance indicators with standard deviation of free-flow speed, results are fairly mixed and lack agreement among the sites.
5. All illogical correlations are associated with the Jackrabbit study sites.

Table 13 Coefficient of Correlation Between Performance Measures and Platooning Variables

Performance Indicator	**US 93 (NB)**				**Jackrabbit (SB)**				**Jackrabbit (NB)**			
	Flow	**Opp. Flow**	**%HV**	**SD of FFS**	**Flow**	**Opp. Flow**	**%HV**	**SD of FFS**	**Flow**	**Opp. Flow**	**%HV**	**SD of FFS**
ATS	-0.20	-0.18	-----	-0.53	-0.18	(0.40)	-----	-0.45	-0.37	(0.33)	-0.52	0.10
ATS of PCs	-0.25	-0.18	-----	-0.51	-0.18	(0.34)	-----	-0.45	-0.36	(0.28)	-0.46	-----
ATS/FFS	-----	-0.10	-----	-0.12	(0.21)	(0.41)	-----	(0.29)	-0.53	-0.21	-----	(0.23)
ATS_{pc}/FFS_{pc}	-----	-0.11	-----	-----	(0.17)	(0.42)	-0.10	(0.16)	-0.41	-0.31	(0.24)	(0.23)
% Followers	0.52	-----	-----	0.15	0.59	-0.29	-0.46	0.44	0.19	-----	-----	-0.36
Follower Density	0.77	-----	-0.24	-----	0.91	-0.28	-0.61	0.26	0.65	-0.13	-----	-0.49

Performance Indicator	**287 North (NB)**				**287 South (NB)**				**287 South (SB)**			
	Flow	**Opp. Flow**	**%HV**	**SD of FFS**	**Flow**	**Opp. Flow**	**%HV**	**SD of FFS**	**Flow**	**Opp. Flow**	**%HV**	**SD of FFS**
ATS	-0.25	-0.32	-0.43	-0.28	-0.13	-----	-0.32	-0.70	-----	-0.32	-----	-----
ATS of PCs	-0.29	-0.35	-0.38	-0.27	-0.15	-----	-0.26	-0.70	-----	-0.36	-----	-----
ATS/FFS	-0.33	-0.38	-----	-0.26	-0.29	-0.23	-0.18	-0.52	-0.25	-----	-0.11	-0.38
ATS_{pc}/FFS_{pc}	-0.29	-0.41	-0.16	-0.23	-0.24	-0.27	-0.26	-0.59	-0.25	-----	-0.24	-0.35
% Followers	0.61	0.37	0.23	-0.18	0.43	0.33	0.26	0.46	0.47	-0.25	-----	-----
Follower Density	0.85	0.53	0.28	-0.12	0.77	0.15	-----	0.59	0.76	-0.18	-0.19	-----

Note: Cells marked with "-----" refer to coefficient of correlation less than 0.1

Other performance measures examined in an across-site analysis are listed in Table 14. These performance measures were not analyzed in depth because they were considered less promising than the performance measures discussed prior. However their correlation coefficients are provided here for completeness.

Table 14 Correlation Coefficients for Other Performance Measures

	Flow	Opposing Flow	% Heavy Vehicles	% No-Passing Zones	Standard Deviation of Free-Flow Speed
Density	0.99	0.27	-0.16	-0.60	0.41
ATS/ATS_{PC}	0.54	0.32	-0.41	-0.56	0.28
% Headways < 6 sec	0.87	0.28	-0.05	-0.46	0.55
$ATS_{PC} - ATS_{HV}$	-0.55	-0.30	-0.09	0.43	-0.39
% Headways > 8 sec	-0.90	-0.33	0.04	0.50	-0.54
Follower Flow*	0.98	0.20	-0.16	-0.50	0.44

**Defined as flow multiplied by the percentage of headways less than three seconds*

Regression

Multiple linear regression was also used to assess the relationship between the platooning variables and the performance measures. The regression was done at each individual site separately and across sites by compiling data. This section provides results from both analyses.

To start, the regression assumptions were tested. There are four assumptions in regression analysis. The assumptions are:

1. The form of the model is correct (linear vs. non-linear)
2. The errors are normally distributed with the distribution centered at zero
3. The errors are independent
4. The errors have a constant variance

These assumptions were tested using the across-site data, shown later in this section in Table 16. Residual plots and normal plots of residuals were prepared to test the assumptions. These plots can be found in Appendix B. The linear assumption was verified; therefore the results of the non-linear regression analysis were not used. The error assumptions of normality, independence, and constant variance were met as well.

Table 15 summarizes the results of the regression at each two-lane highway site. Results from the F-test and t-tests for the regression models at the 90 and 95 percent confidence levels are included in Table 15, as explained in the footnotes. Considering the results at the 90 percent confidence level, the following observations can be made:

1. 23 out of the 36 regression runs yielded models that are considered statistically significant with R square values ranging between 0.29 and 0.87.
2. Traffic flow rate, followed by the standard deviation of free-flow speed, percent heavy vehicles, and opposing flow rate, had the most significant contribution to the variation in performance measures. The platooning variables just listed were found to be significant contributors to the regression models in 16, 12, 10, and 2 models, respectively.
3. More than other performance measures, percent followers and follower density have resulted in significant regression models with higher R square values.

To gain more insight into the strengths and limitations of each proposed performance measure, the regression was also done using the across-site data, shown in Table 16. Percent no-passing zones was added as a platooning variable in this analysis. Similar to the site-specific analysis just discussed, the objective was to examine the relationship between the performance measures and the platooning variables. Data from all six two-lane highway sites were used in this analysis (see Table 16). The data in Table 16 represents three one-hour periods of flow from each site observed in the field.

Table 15 Results from Regression Analysis at Individual Study Sites

Performance Measure	US 93 (NB)							287 North (NB)						
	Regression Model			P-Value from t-Test [2, 3,4]				Regression Model			P-Value from t-Test			
	F-test[1,3]	R^2	SE	Flow	Opp. Flow	% HV	SD of FFS	F-Test	R^2	SE	Flow	Opp. Flow	% HV	SD of FFS
ATS	*0.01*	0.45	1.0	**0.04**	0.20	**(0.07)**	**0.00**	*0.04*	0.35	2.2	0.57	0.56	**0.02**	**(0.08)**
ATS$_{PC}$	*0.01*	0.44	1.1	**0.03**	0.22	0.11	**0.00**	*(0.06)*	0.32	2.3	0.50	0.49	**(0.06)**	0.11
ATS/FFS	0.96	0.02	1.0	0.95	0.66	0.86	0.61	0.18	0.23	1.3	0.31	0.38	0.51	0.22
ATS$_{PC}$/FFS$_{PC}$	0.97	0.02	1.2	0.92	0.54	0.68	0.89	0.20	0.22	1.6	0.67	0.22	0.56	0.29
% Followers	*0.04*	0.33	5.8	**0.00**	0.78	0.40	0.21	*0.02*	0.40	5.2	**0.01**	0.92	0.53	0.54
Follower Density	*0.00*	0.60	0.3	**0.00**	0.90	0.74	0.64	*0.00*	0.74	0.2	**0.00**	0.97	**0.00**	0.88

Performance Measure	287 South (NB)							287 South (SB)						
	Regression Model			P-Value from t-Test				Regression Model			P-Value from t-Test			
	F-Test	R^2	SE	Flow	Opp. Flow	% HV	SD of FFS	F-Test	R^2	SE	Flow	Opp. Flow	% HV	SD of FFS
ATS	*0.00*	0.59	2.0	0.78	0.73	**0.03**	**0.00**	0.57	0.11	1.9	0.75	0.12	0.68	0.68
ATS$_{PC}$	*0.00*	0.56	2.0	0.73	0.79	**(0.07)**	**0.00**	0.44	0.15	1.9	0.62	0.07	0.87	0.73
ATS/FFS	*0.02*	0.38	3.0	0.16	0.36	0.17	**0.02**	*(0.09)*	0.29	2.1	**(0.05)**	0.77	0.16	**(0.03)**
ATS$_{PC}$/FFS$_{PC}$	*0.00*	0.48	3.2	0.22	0.23	**(0.05)**	**0.00**	*0.04*	0.34	2.5	**0.02**	0.97	**0.03**	**0.04**
% Followers	*0.00*	0.52	5.5	**0.01**	**(0.05)**	**0.02**	**(0.06)**	*(0.06)*	0.32	8.7	**(0.01)**	0.16	0.23	0.92
Follower Density	*0.00*	0.80	0.2	**0.00**	0.45	0.23	**0.00**	*0.00*	0.63	0.3	**0.00**	0.18	0.21	0.97

Performance Measure	Jackrabbit (NB)							Jackrabbit (SB)						
	Regression Model			P-Value from t-Test				Regression Model			P-Value from t-Test			
	F-Test	R^2	SE	Flow	Opp. Flow	% HV	SD of FFS	F-Test	R^2	SE	Flow	Opp. Flow	% HV	SD of FFS
ATS	*(0.08)*	0.51	1.3	**(0.05)**	0.35	**(0.03)**	0.93	0.31	0.33	1.3	0.92	0.22	0.93	0.13
ATS$_{PC}$	0.15	0.43	1.4	0.07	0.40	0.05	0.88	0.38	0.29	1.4	0.82	0.33	0.97	0.14
ATS/FFS	*(0.07)*	0.51	1.8	**(0.02)**	**(0.04)**	0.14	0.47	0.15	0.43	1.9	0.12	0.03	0.25	0.27
ATS$_{PC}$/FFS$_{PC}$	0.21	0.39	2.1	0.09	0.10	0.48	0.46	0.37	0.30	2.8	0.28	0.07	0.54	0.55
% Followers	0.78	0.14	6.4	0.85	1.00	0.86	0.30	*0.04*	0.56	5.1	0.35	0.29	0.26	**(0.07)**
Follower Density	*(0.07)*	0.51	0.4	**(0.03)**	0.68	0.71	0.19	*0.00*	0.87	0.8	**0.00**	0.34	0.42	0.18

[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 parentheses are those that passed significance testing at the 90% confidence level only

[4] The coefficients for the regression models are provided in Table 18 in Appendix C

Table 16 Various Performance Measures Using Multiple Data Sets from Study Sites

Study Site	Platooning Variables					Performance Measure					
	Volume (vph)	Opp. Flow (vph)	% HV	% No Pass -ing	SD of FFS (mph)	ATS (mph)	ATS$_{PC}$ (mph)	ATS/ FFS (%)	ATS$_{PC}$/ FFS$_{PC}$ (%)	% Follow -ers	Follower Density (veh/mile)
US 93 - NB	298	248	6	17	5	62	62	99	99	28	1.4
	199	278	6	17	5	63	63	98	98	28	0.9
	249	188	9	17	6	62	62	100	100	24	1.0
Jackrabbit Lane - NB	334	396	14	5	6	62	62	98	97	33	1.9
	277	464	15	5	9	62	62	98	98	36	1.7
	307	664	10	5	8	62	63	97	96	36	1.9
Jackrabbit Lane - SB	729	288	6	5	7	57	57	98	97	52	7.1
	396	334	10	5	6	58	58	97	97	42	3.0
	567	292	9	5	8	58	58	98	98	43	4.5
HWY 287 North - NB	295	314	16	23	7	71	72	97	96	40	1.7
	211	171	10	23	5	75	76	99	99	27	0.8
	252	224	9	23	6	75	76	99	99	34	1.2
HWY 287 South - NB	198	219	12	33	6	64	64	93	92	42	1.4
	110	200	7	33	6	68	68	98	97	32	0.5
	155	278	7	33	7	67	67	97	96	38	0.9
HWY 287 South - SB	285	173	9	51	6	70	70	98	97	36	1.5
	172	159	15	51	6	70	71	98	98	26	0.7
	227	175	9	51	5	68	68	97	97	33	1.1

There were six linear regression models (one model for each performance measure). However, only two of the models were found significant using the 95 percent confidence level: the models for follower density and percent followers. The equation, the p-value from the F-test, the R square, and the Multiple R for each model is shown in Table 17. The regression model for follower density had a much higher R square value and a stronger functional relationship with platooning variables than percent followers. Examination of t-test results showed that traffic flow is the major contributor to the follower density and percent followers models. This explains the high R square value for the follower density model, because follower density is largely related to density, which is a function of traffic flow. The t-test results suggest that the contribution of other platooning variables were insignificant. The P-values from the t-Tests are provided in Table 19 in Appendix C.

Table 17 Regression Analysis for Percent Followers and Follower Density

Performance Measure	Linear Regression Model	F-test	R^2	Mult-iple R
ATS	ATS = 65.14866 - 0.01625 (volume in vph) - 0.00953 (opposing volume in vph) + 0.22279 (% heavy vehicles) + 0.09614 (% no-passing zones) + 0.49238 (standard deviation of free flow speed in mph)	0.08	0.53	0.73
ATS_{PC}	ATSpc = 65.35777 - 0.01646 (volume in vph) - 0.00956 (opposing volume in vph) + 0.25400 (% heavy vehicles) + 0.10117 (% no-passing zones) + 0.44034 (standard deviation of free flow speed in mph)	0.07	0.53	0.73
ATS/FFS	ATS/FFS = 100.58875 - 0.00113 (volume in vph) - 0.00583 (opposing volume in vph) - 0.06533 (% heavy vehicles) - 0.04730 (% no-passing zones) + 0.12938 (standard deviation of free flow speed in mph)	0.69	0.20	0.45
ATS_{PC}/FFS_{PC}	ATSpc/FFSpc = 101.73075 - 0.00189 (volume in vph) - 0.00753 (opposing volume in vph) - 0.05035 (% heavy vehicles) - 0.06237 (% no-passing zones) + 0.00119 (standard deviation of free flow speed in mph)	0.66	0.22	0.47
% Followers	% Followers = 9.18177 + 0.03380 (volume in vph) + 0.00607 (opposing volume in vph) - 0.16062 (% heavy vehicles) + 0.10894 (% no-passing zones) + 2.12739 (standard deviation of free flow speed in mph)	0.02	0.62	0.79
Follower Density	Follower Density = -1.67145 + 0.01041 (volume in vph) - 0.00022 (opposing volume in vph) - 0.03057 (% heavy vehicles) + 0.00500 (% no-passing zones) + 0.11670 (standard deviation of free flow speed in mph)	0.00	0.96	0.98

CHAPTER 6

CHARACTERIZATION OF FREE-MOVING VEHICLES IN THE TRAFFIC STREAM

This chapter provides the results from the study of vehicle interaction on two-lane highways. The purpose of this study was to develop a better understanding of the follow-by-choice phenomenon on two-lane rural highways and the conditions where vehicles are considered free-moving in the traffic stream. The results shown in this chapter can also be found in the Proceedings of the Transportation Research Board 87th Annual Meeting (Al-Kaisy & Karjala, 2007B).

Headway Distributions

Headway distributions were analyzed because there is a strong association between car following and time headway. Frequency histograms of the headway distributions at the two-lane highway sites are shown in Figure 25. The traffic level at the sites was relatively low, so all headways data were used to generate the plots. The three-second interval was used for clarity, as largely similar trends were exhibited upon using a one-second interval. In examining Figure 25, one can see a general pattern across study sites: there is a high frequency of short headways, which decreases steadily as the headway increases. There are roughly two regions that can be indentified within these distributions. The first is characterized by a sharp decrease in frequency (evident in the first two to three headway intervals). The second region is characterized by a much smaller and relatively steady decrease in frequency. The cut-off between the two regions occurs between six and eight seconds. This is similar to Miller's threshold (T=8 seconds), discussed in the literature review. The distributions also have a large skew to the right and a remarkable decline between the first and second headway intervals.

Headway distributions at the right lane of the four-lane highway sites are shown in Figure 26. The four-lane highway headway distributions are quite different than those for the two-lane highways. The frequency of short headways (those less than three

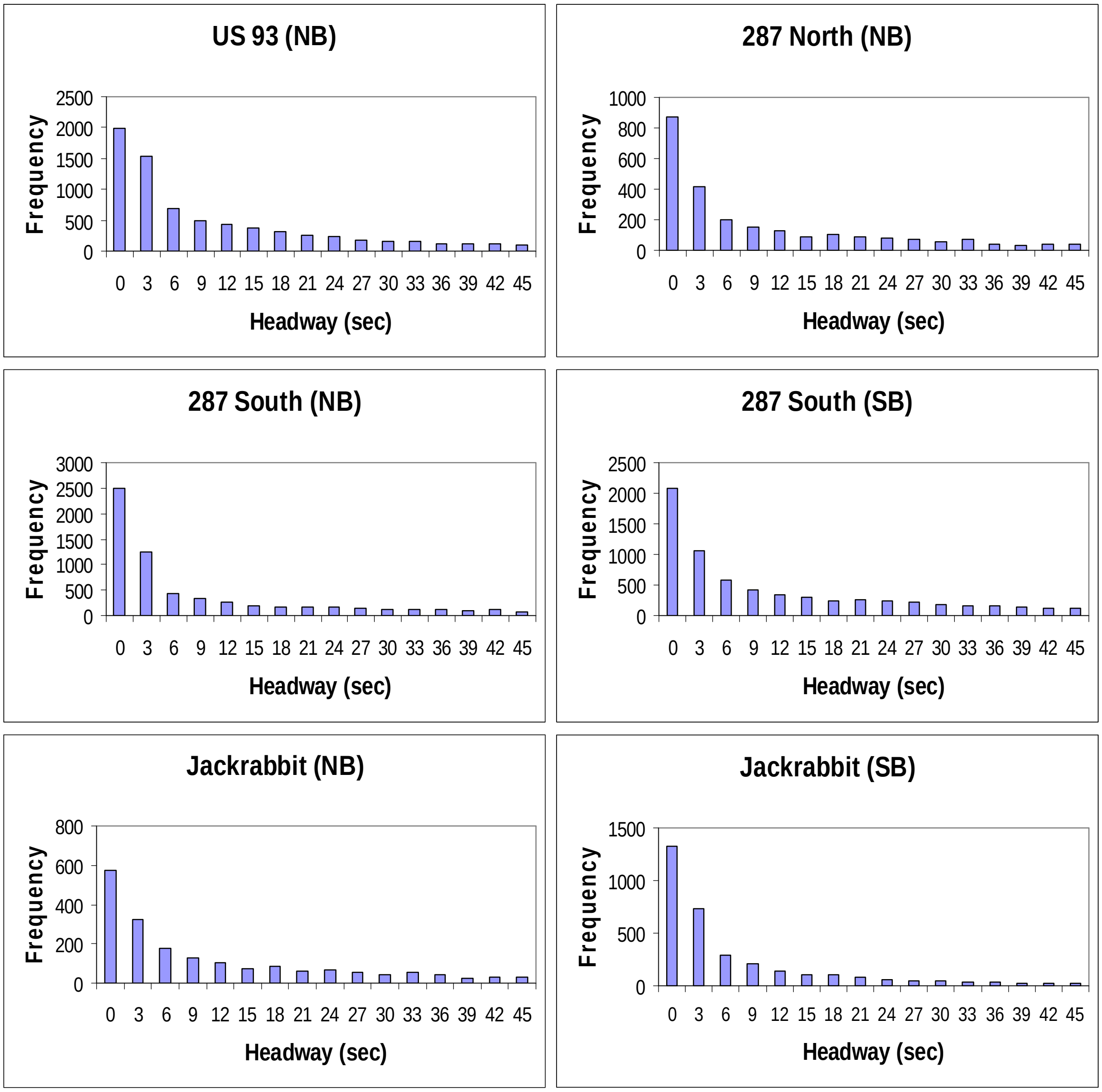


Figure 25 Headway Frequency Histograms for Two-Lane Study Sites

seconds) is about 50-60% of the peak frequency value. The frequency peaks in the three to six second interval at all sites and declines steadily thereafter. The most important observation in Figure 26 is that at almost all study sites, there is still a significant number of drivers traveling at short headways (headways less than three seconds). It is expected that many of those drivers chose to follow the vehicles ahead at short headways, despite the presence of passing opportunities.

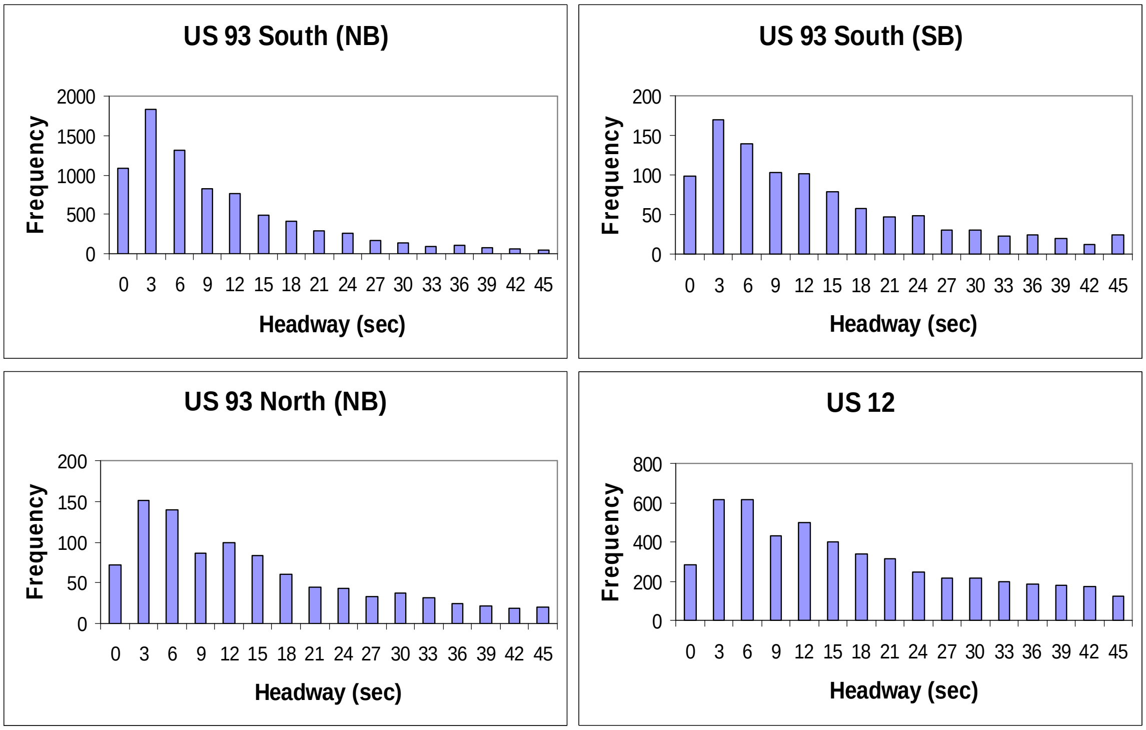


Figure 26 Headway Frequency Histograms for Four-Lane Study Sites

For the sake of comparison, Figure 27 shows headway distributions at the US 93 two-lane study site and the US 93 four-lane study site. These two sites are located on the same highway and separated by about 10 miles. The purpose of using these sites was to control, as much as possible, the variables that affect the headway distribution (besides the number of lanes and cross-section elements). One hour of data was taken from each study site, controlling for daylight conditions and hourly volume. A theoretical random headway distribution is also superimposed on the graph. Again, the three-second headway interval was used for clarity.

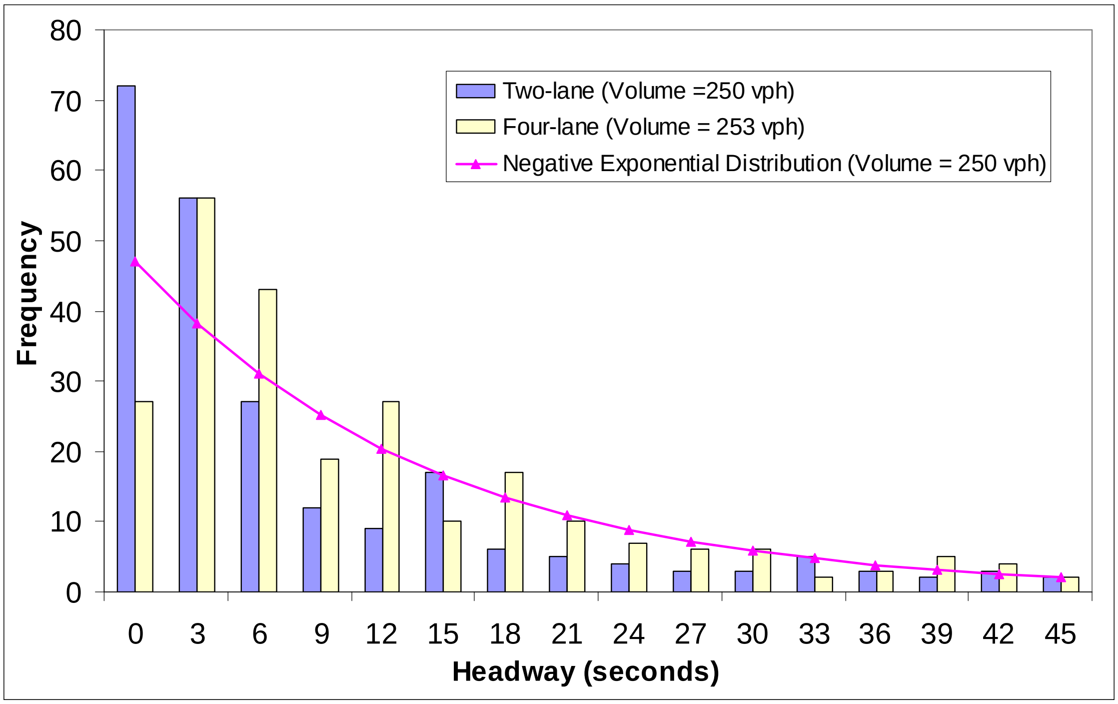


Figure 27 Comparison of Two- and Four-Lane Headway Distributions at US 93 Study Sites near Florence, MT

Examination of Figure 27 shows that the frequency of short headways is overrepresented on the two-lane section; specifically, the frequency of headways from zero to three seconds on the two-lane section is almost twice as large as that at the four-lane section. This is logical, as more vehicles are forced to follow on two-lane highways due to passing restrictions. The frequency of headways between three and six seconds is relatively comparable at the two study sites. In all subsequent intervals, higher frequencies are generally exhibited at the four-lane site. The negative exponential theoretical distribution, used in the literature to model random headways, shows more consistency in shape with the headway distribution from the two-lane study site. However, the two-lane data shows a greater frequency of short headways in the interval from zero to three seconds, which is an indication of a more intense car-following interaction due to passing restrictions. On the other hand, headways in this same interval are underrepresented at the 4-lane study site compared with the random distribution, which indicates that many drivers prefer to maintain longer headways in the presence of passing opportunities.

Speed-Headway Relationships

The relationship between speed and time headway was examined to better understand the car-following interaction. The speed-headway relationships from a previous research (Durbin, 2006) are shown again in Figure 28. As discussed earlier in Chapter 4, the relationship between speed and headway generally diminishes beyond the six-second headway. The plots shown in Figure 28 were compared to the four-lane highway speed-headway relationships, shown in Figure 29. An initial examination of the four-lane highway plots indicates mixed patterns. However, a more careful examination of the figure reveals that the patterns can hardly be meaningful given the magnitudes of changes in average speed. The range of speed change in these graphs generally did not exceed 0.5 percent of the average speed at the study sites. In short, the graphs in Figure 29 demonstrate that car-following interaction is negligible on four-lane highways under low flow conditions.

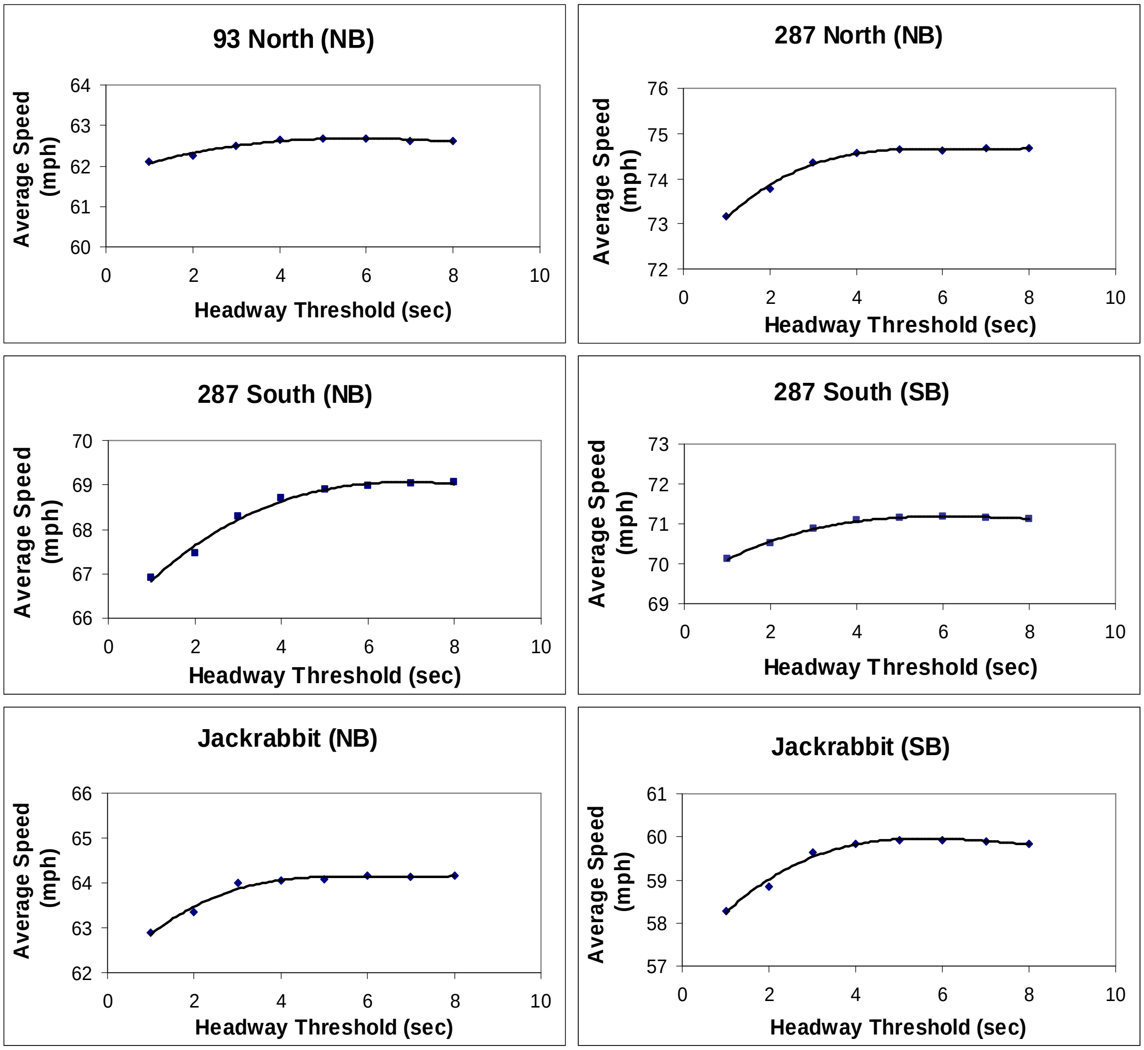


Figure 28 Relationship Between Travel Speed and Headways Equal To or Greater Than a Threshold Value at Two-Lane Study Sites (Durbin, 2006)

Percent Followers and Flow Relationships

Vehicle interaction was also examined through the relationship between percent followers and flow rate. Figure 30 shows the relationships at the two- and four-lane highway sites located on US 93 near Florence, Montana. As mentioned earlier, these

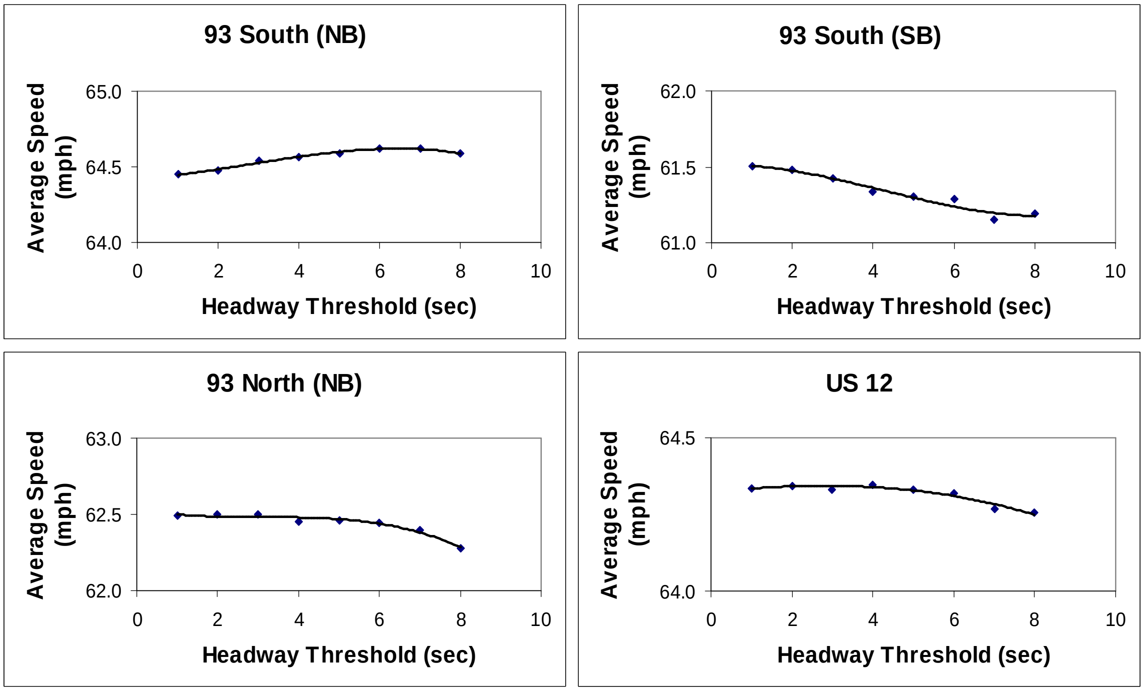


Figure 29 Relationship Between Travel Speed and Headways Equal To or Greater Than a Threshold Value at Four-Lane Study Sites.

sites are separated by only 10 miles and have similar traffic volumes. The observations at the two sites are fitted with a linear relationship that passes through the origin. As expected, the percent followers at the two-lane site is significantly higher than that at the four-lane site. However, the percent followers at the four-lane site is still significant despite the absence of passing restrictions (the v/c did not exceed 0.25 at any time). It is reasonable to say that the curve at the four-lane study site in Figure 30 largely represents the "following by choice" phenomenon where many drivers choose to follow lead vehicles at short headways.

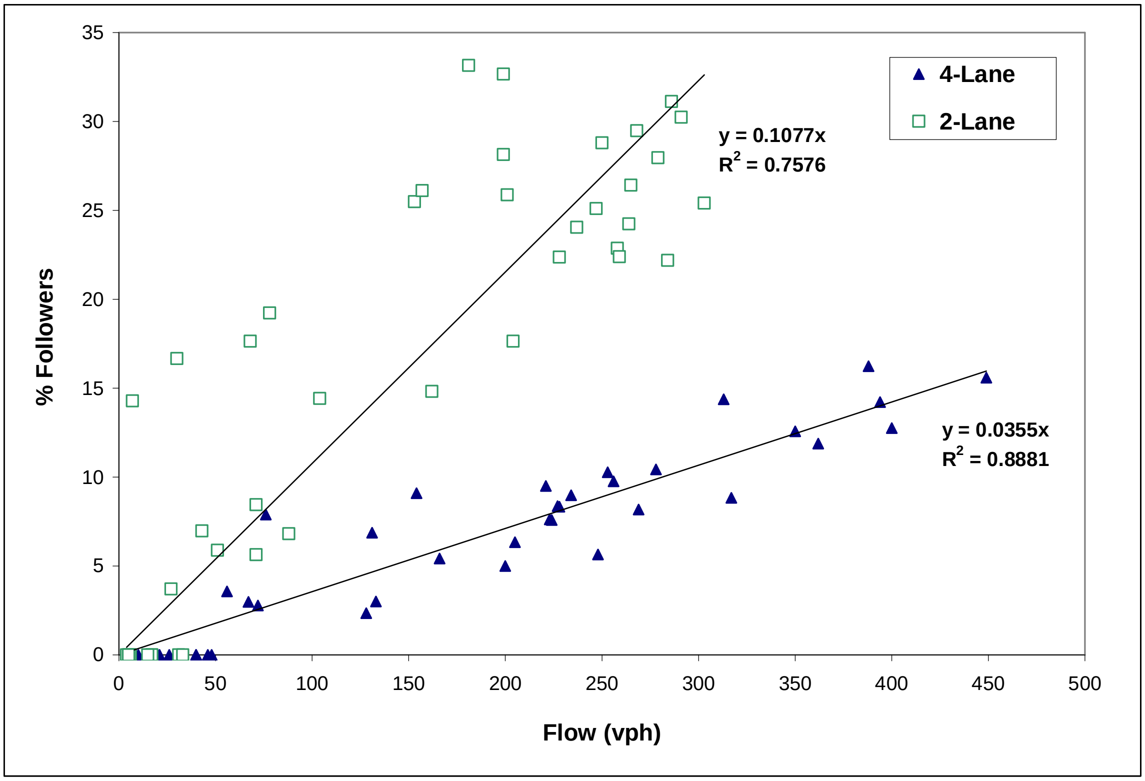


Figure 30 Percent Followers as a Function of Traffic Flow at Two-Lane and Four-Lane Study Sites on US 93 near Florence, MT

CHAPTER 7

CONCLUSIONS & RECOMMENDATIONS

Performance Measures for Two-Lane Highways

Six performance indicators on two-lane rural highways were investigated in this research. The relationships between performance indicators and major platooning variables were examined using graphical screening, correlation, and regression analyses.

Follower density followed by percent followers were shown to have the strongest correlation to platooning variables. An obvious advantage of using follower density is the fact that this performance indicator accounts for traffic level, a major determinant of performance on almost all highway facilities. Unlike follower density, percent followers is primarily a function of time headway distribution and does not relate well to traffic level. Therefore follower density is viewed as the most promising service measure on two-lane highways investigated by this research. This measure has exhibited the highest correlation with platooning variables, accounts for traffic level, and is easier to estimate in the field compared with the current performance measure, the PTSF.

Among all platooning variables investigated, traffic flow in the direction of travel exhibited the highest correlation to performance indicators. This was evident throughout the analyses performed in this study. Further, the analyses provided no evidence that other platooning variables, namely; opposing traffic flow, speed variation, percent heavy vehicles, and percent no-passing zones have any noticeable correlation with performance indicators.

Inter-Vehicular Interaction on Two-Lane Highways

In regard to the analysis of car-following interaction on two-lane rural highways, the most important findings of this research are:

1. Empirical observations suggest that the car-following interactions on two-lane rural highways generally cease beyond a headway value of six seconds.
2. A significant proportion of drivers choose to maintain relatively short headways while following other vehicles in the traffic stream regardless of passing restrictions. This phenomenon exists on two-lane as well as on four-lane rural highways.
3. Passing restrictions on two-lane two-way highways largely affect headway distribution and contribute to formation of platoons. This is evident in the high concentration of short headways compared with the distribution of random headways or the distribution of headways on the right lane of four-lane rural highways.

Recommendations for Future Research

It is recommended that further research be conducted on followers density using data from a wide variety of locations with a wide range of traffic conditions. Similarly, a comprehensive field testing is also recommended in regard to the study of vehicle interaction on two-lane highways; e.g., vehicle interaction should be examined at sites with higher traffic volumes, higher percent trucks, and sites without a speed differential for passenger cars and trucks. And lastly, to better identify free-vehicles in the traffic stream, a field or driving simulator study is recommended to determine when drivers begin to adjust their speed to the vehicle ahead.

REFERENCES

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. (2007A). 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.

Al-Kaisy, A. & Karjala, S. (2007B). Car-Following Interaction and the Definition of Free-Moving Vehicles on Two-Lane Rural Highways. CD-ROM. Proceedings of the Transportation Research Board 87th annual meeting, Washington, D.C., January 13-17, 2008.

Brilon, W. and Weiser, F. (2006). Two-Lane Rural Highways: The German Experience. In *Transportation Research Record 1988,* TRB, National Research Council, Washington, D.C., 2006, pp.38-47.

Catbagan, J., & Nakamura, H. (2006). Performance Measure Evaluation for Japan Two-Lane Expressways. CD-ROM. Proceedings of the Transportation Research Board 85th annual meeting, Washington, D.C., January 22-26, 2006.

Durbin, C. (2006). Traffic Performance on Two-Lane, Two-Way Highways: Examination of New Analytical Approaches. Master's Thesis. Montana State University, 2006.

Harwood, D., May, A., Anderson, I., Leiman, L., & Archilla, R. (1999). *Capacity and Quality of Service of Two-Lane Highways*. Final Report, NCHRP Project 3-55(3). Midwest Research Institute, Nov. 1999.

Harwood, D., Flannery, A., McLeod, D., & Vandehey, M. (2001). *The Case for Retaining the Level-of-Service Concept in the Highway Capacity Manual*. Retrieved May 14, 2008, from https://people.sunyit.edu/~lhmi/ahb40/meetings/2001-07/scout-retaining-LOS.pdf

Committee on Highway Capacity, Department of Traffic and Operations, Highway Research Board. *Highway Capacity Manual: Practical Applications of Research*. Bureau of Public Roads, U.S. Department of Commerce, Washington, D.C., 1950.

Luttinen, T. (2001). Percent Time-Spent-Following as Performance Measure for Two-Lane Highways. In *Transportation Research Record 1776*, TRB, National Research Council, Washington, D.C., 2001, pp. 52-59.

Luttinen, T. (2006). Capacity and Level-of-Service Estimation in Finland. *Fifth International Symposium on Highway Capacity and Quality of Service.* Yokohama, Japan, 2006.

Luttinen, T., Dixon, M., Washburn, S. (2005). *Two-Lane Highway Analysis in HCM2000: Draft White Paper.* Retrieved May 24, 2008, from https://people.sunyit.edu/~lhmi/ahb40/meetings/2005-07/White.pdf

Miller, A.J. (1961). A Queuing Model for Road Traffic Flow. *Journal of the Royal Statistical Society. Series B (Methodological),* Vol. 23, No. 1, pp.64-90.

Morrall, J. and Werner, A. (1990). Measuring Level of Service of Two-Lane Highways by Overtakings. In *Transportation Research Record 1287,* TRB, National Research Council, Washington, D.C., 1990, pp.62-69.

Normann, O.K. (1942). Results of Highway Capacity Studies. *Public Roads,* Vol. 23, No. 4, June 1942, pp. 57-81.

Romana, M., & Pérez, I. (2006). Measures of Effectiveness for Level-of-Service Assessment of Two-Lane Roads. In *Transportation Research Record 1988*, TRB, National Research Council, Washington, D.C., 2006, pp. 56-62.

Sands, T., & Pahl, J. (1971) Vehicle Interaction Criteria from Time Series Measurement. *Transportation Science,* Vol. 5, Issue 4, pp 403-418.

Special Report 87: Highway Capacity Manual 1965. Highway Research Board, National Research Council, Washington, D.C., 1965.

Special Report 209: Highway Capacity Manual 1985. Transportation Research Board, National Research Council, Washington, D.C., 1985.

Street Rodder (2008). Retrieved July 7, 2008, from http://images.streetrodderweb.com/roadtour/2006/0701sr_04_s+2006_road_tour+leg_4.jpg

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.

Van As, C. (2007). *South African Highway Capacity Research.* TRB Workshop Presentation. South African National Roads Agency, Limited, 2007. Retrieved May 12, 2008, from http://www.nra.co.za/content/TRB6.pdf

Vogel, K. (2002). What Characterizes a “Free-Vehicle” in an Urban Area? *Transportation Research Part F,* Elsevier Science Ltd. Vol. 5, No. 1, pp.15-29.

Wasielewski, P. (1979). Car Following Headways on Freeways Interpreted by the Semi-Poisson Headway Distribution Mode. *Transportation Science*, Vol. 13, pp. 36-55.

Wikipedia (2008). *Correlation.* Retrieved May 28, 2008, from http://en.wikipedia.org/wiki/Correlation

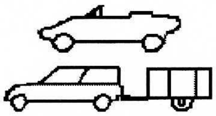
APPENDICES

APPENDIX A:

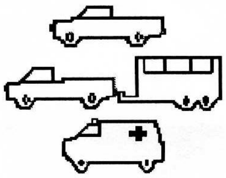
FHWA 13-CATEGORY VEHICLE CLASSIFICATION SYSTEM

Courtesy of JAMAR Technologies, Inc.

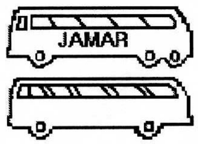
Class 1 - **Motorcycles.** This class includes all two- or three-wheeled motorized vehicles. These vehicles typically have a saddle-type of seat and are steered by handlebars rather than a steering wheel. This includes motorcycles, motor scooters, mopeds, motor-powered bicycles and three-wheel motorcycles.



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.

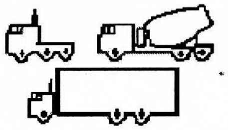


Class 3 - **Pickups, Vans and other 2-axle, 4-tire Single Unit Vehicles.** This class includes all two-axle, four tire vehicles other than passenger cars, which includes pickups, vans, campers, small motor homes, ambulances, minibuses and carryalls. These types of vehicles which are pulling recreational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

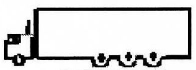


Class 4 - **Buses.** This class includes all vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This includes only traditional buses, including school and transit buses, functioning as passenger-carrying vehicles. All two-axle, four tire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

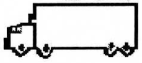
Class 5 - **Two-Axle, Six-Tire Single Unit Trucks.** This class includes all vehicles on a single frame which have two axles and dual rear tires. This includes trucks, camping and recreation vehicles, motor homes, etc.



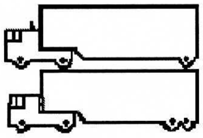
Class 6 - **Three-Axle Single Unit Trucks.** This class includes all vehicles on a single frame which have three axles. This includes trucks, camping and recreation vehicles, motor homes, etc.



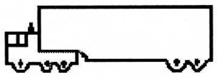
Class 7 - **Four or More Axle Single Unit Trucks.** This class includes all vehicles on a single frame with four or more axles.

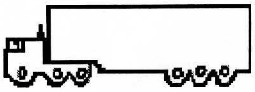


Class 8 - **Four or Less Axle Single Trailer Trucks.** This class includes all vehicles with four or less axles consisting of two units, in which the pulling unit is a tractor or single unit truck.

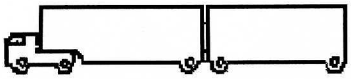


Class 9 - **Five-Axle Single Trailer Trucks**. This class includes all five-axle vehicles consisting of two units in which the pulling unit is a tractor or single unit truck.

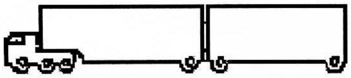




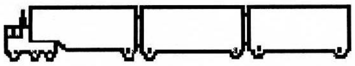
Class 10 - **Six or More Axle Single Trailer Trucks**. This class includes all vehicles with six or more axles consisting of two units in which the pulling unit is a tractor or single unit truck.



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.

<u>APPENDIX B:</u>

TESTING OF REGRESSION ASSUMPTIONS

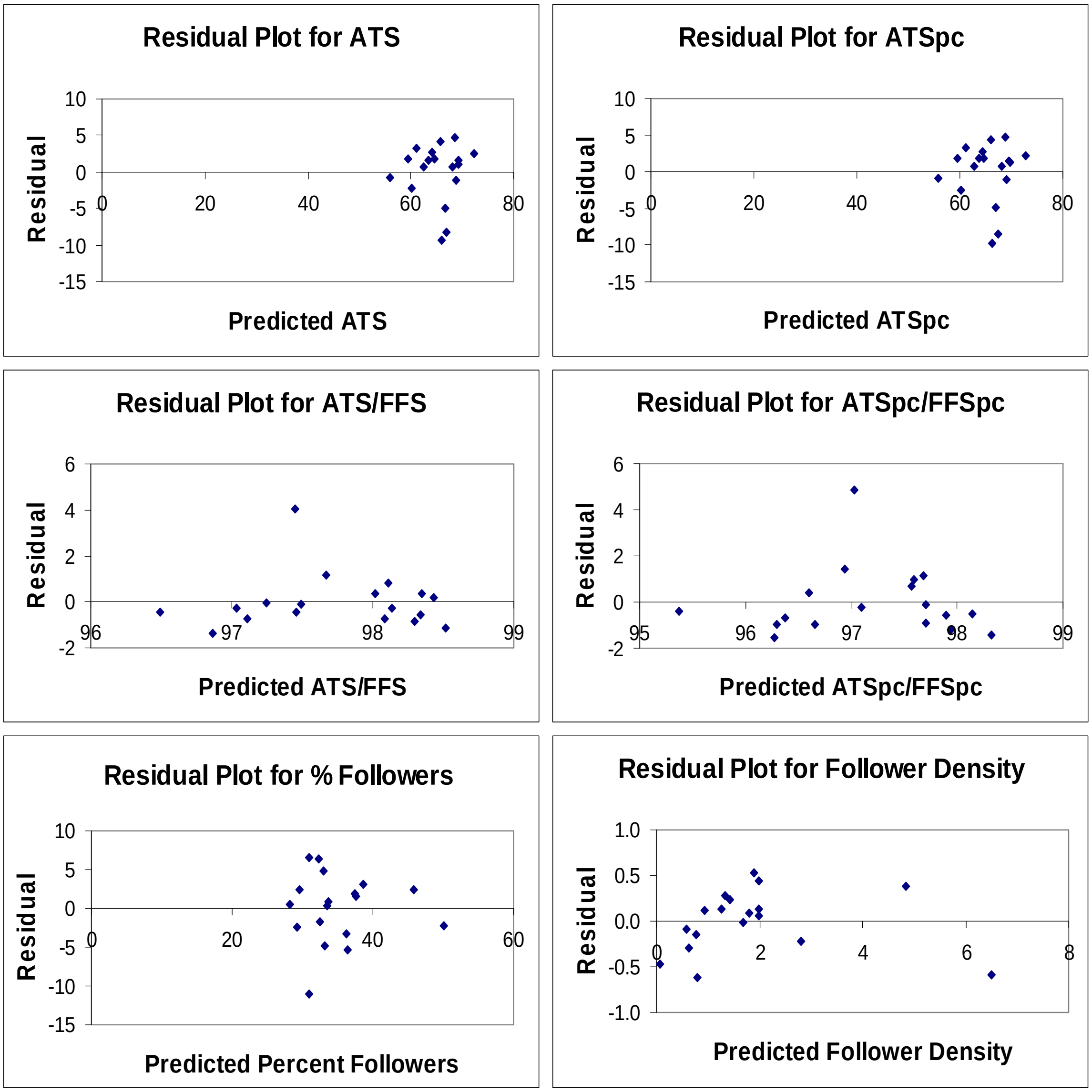


Figure 31 Plots of Residuals versus Predicted Values for Across-Sites Data

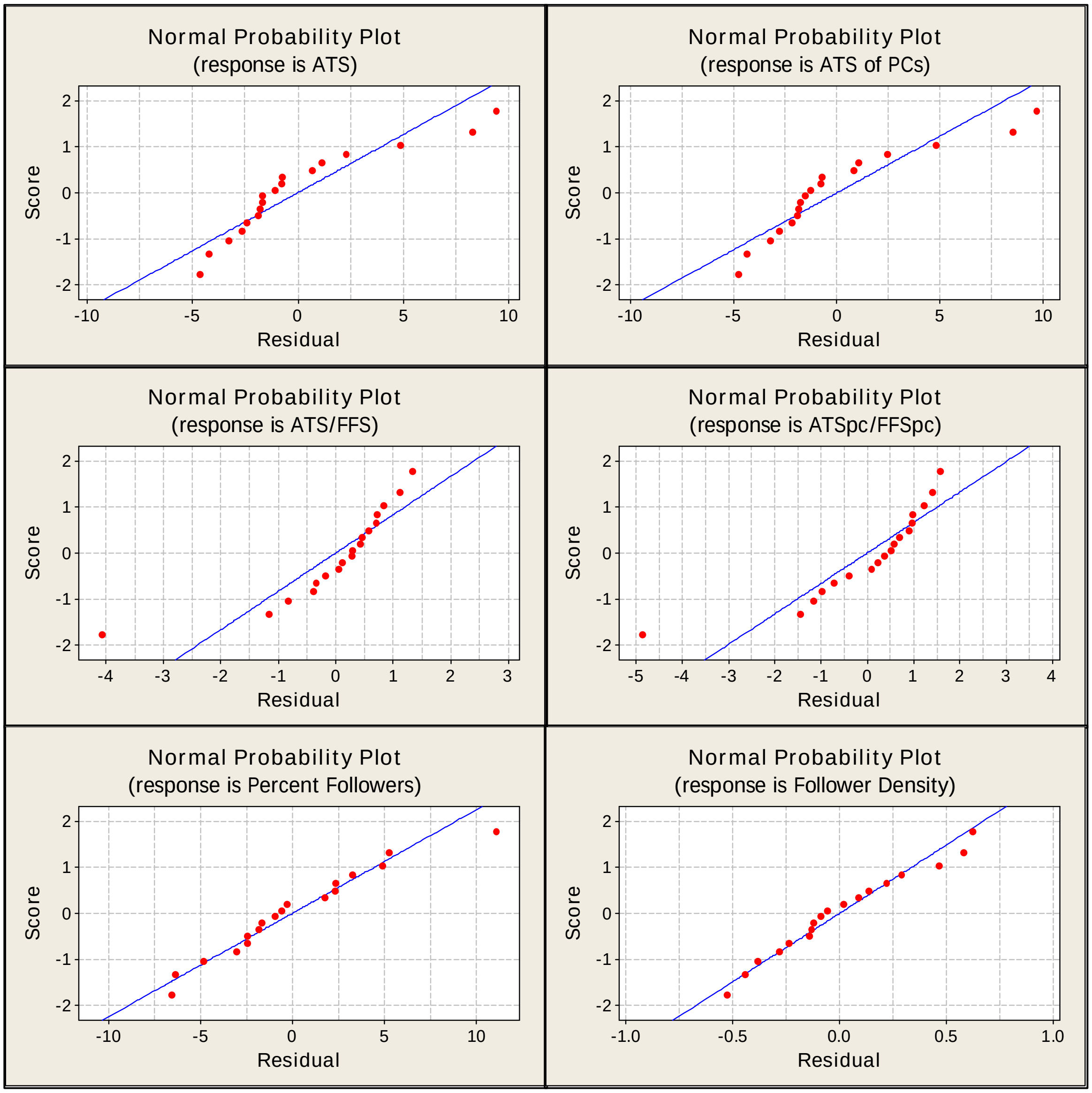


Figure 32 Normal Plots of Residuals for Across-Sites Data

APPENDIX C:

RESULTS FROM REGRESSION ANALYSIS

Table 18 Coefficients from Multiple Linear Regression at Individual Study Sites

	US 93 (NB)					**287 North (NB)**				
MOE	Intercept	Flow	Opp. Flow	%HV	SD of FFS	Intercept	Flow	Opp. Flow	%HV	SD of FFS
ATS	70.95	-0.01	-0.01	-0.11	-0.55	83.60	-0.01	-0.01	-0.24	-0.58
ATS of PCs	71.48	-0.01	-0.01	-0.10	-0.56	84.45	-0.01	-0.01	-0.21	-0.56
ATS/FFS	99.76	0.00	0.00	0.01	-0.07	102.63	-0.01	-0.01	0.04	-0.23
ATS_{pc}/FFS_{pc}	99.98	0.00	0.00	-0.03	0.03	102.84	0.00	-0.01	-0.04	-0.24
% Followers	-7.95	0.10	-0.01	0.29	1.06	10.27	0.10	0.00	0.15	-0.46
Follower Density	-1.15	0.01	0.00	0.01	0.02	-0.96	0.01	0.00	0.01	0.00

	287 South (NB)					**287 South (SB)**				
MOE	Intercept	Flow	Opp. Flow	%HV	SD of FFS	Intercept	Flow	Opp. Flow	%HV	SD of FFS
ATS	72.71	0.00	0.00	-0.20	-0.88	74.47	0.00	-0.02	-0.03	-0.12
ATS of PCs	72.89	0.00	0.00	-0.17	-0.86	75.60	0.00	-0.02	-0.01	-0.10
ATS/FFS	109.17	-0.03	-0.01	-0.19	-0.69	109.17	-0.02	0.00	-0.12	-0.70
ATS_{pc}/FFS_{pc}	111.16	-0.02	-0.02	-0.28	-0.92	111.64	-0.03	0.00	-0.22	-0.79
% Followers	-1.81	0.10	0.05	0.60	0.99	11.37	0.12	-0.08	0.41	0.13
Follower Density	-1.63	0.01	0.00	0.01	0.10	-0.78	0.01	0.00	0.02	0.00

	Jackrabbit (NB)					**Jackrabbit (SB)**				
MOE	Intercept	Flow	Opp. Flow	%HV	SD of FFS	Intercept	Flow	Opp. Flow	%HV	SD of FFS
ATS	74.42	-0.02	0.00	-0.31	0.02	56.19	0.00	0.01	0.02	-0.31
ATS of PCs	74.91	-0.02	0.00	-0.30	-0.04	57.50	0.00	0.01	-0.01	-0.33
ATS/FFS	116.75	-0.04	-0.01	-0.27	0.22	79.20	0.01	0.03	0.28	0.33
ATS_{pc}/FFS_{pc}	111.12	-0.03	-0.01	-0.14	0.27	77.75	0.01	0.04	0.21	0.26
% Followers	40.55	0.01	0.00	-0.11	-1.14	46.77	0.01	-0.04	-0.73	1.49
Follower Density	-0.13	0.01	0.00	0.01	-0.08	0.38	0.01	-0.01	-0.08	0.16

Table 19 P-Values from Across Site Regression Analysis t-Tests

Performance Measure	P-Value from t-Test				
	% No-Passing	Flow	Opp. Flow	% HV	SD of FFS
ATS	0.44	0.18	0.55	0.59	0.78
ATS_{PC}	0.43	0.18	0.56	0.54	0.80
ATS/FFS	0.22	0.75	0.24	0.60	0.81
ATS_{PC}/FFS_{PC}	0.20	0.67	0.23	0.75	1.00
% Followers	0.43	0.02	0.74	0.72	0.28
Follower Density	0.63	0.00	0.87	0.38	0.43