TESTING OF, AND ENHANCEMENTS TO, TWO-LANE HIGHWAY MODELING IN CORSIM

By

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To The University of Florida Steel Bridge Team

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Two-lane highways make up a large part of the roadway network in the United States and are important for transporting people and goods across long distances. When two-lane highways begin to operate poorly, it is important that the conditions are improved, but improvements can be costly as two-lane highways span a long distance. Therefore, it is important to have accurate tools available for analyzing two-lane highways in order to make appropriate improvements. Recently, a two-lane highway modeling capability has been implemented into the simulation program, CORSIM. CORSIM is now the only U.S.-based simulation program that is capable of modeling two-lane highways while being compatible with modern computers. The main analytical tool that has been used in the U.S. for two-lane highway analysis is the Highway Capacity Manual (HCM), but it is not yet known how the results from these two tools compare.

This research provides an extensive comparison of Percent Time-Spent-Following (*PTSF)* and Average Travel Speed (*ATS*), the two primary performance measures used in the HCM analysis methodology, as estimated from the HCM and CORSIM, including the speed-flow relationship and the *PTSF*-flow relationship. Guidance is provided for

setting up corresponding networks between CORSIM and the HCM. CORSIM is also used to estimate two-lane highway directional capacity and the effects of passing lanes are tested and discussed. Other performance measures that are not included in the HCM are critiqued and ranked based on a variety of categories. Finally, recommendations are made for improvements and enhancements to CORSIM and the HCM as well as areas for future two-lane highway research.

CHAPTER 1
INTRODUCTION

Background

Two-lane highways are an important part of the roadway system in the United States and in many other countries. They serve as major connectors between areas of high activity and interest and provide routes for commuters and recreational use. Two-lane highways provide cost effective, reliable access to areas of low population. They usually carry low volumes and tend to have few interruptions from traffic signals (*1*). Two-lane highways may also have occasional passing lanes, which are intended to allow faster vehicles to safely pass slower vehicles.

The defining characteristic of two-lane highways is that they generally allow drivers to pass slower vehicles by going into the lane of oncoming traffic if there is a large enough gap to permit this maneuver and if the sight distance is adequate. As traffic volume increases, more vehicles are likely to want to pass. However, higher traffic volume can mean fewer gaps, which means there are fewer opportunities to pass. This leads to higher vehicle delays due to faster vehicles being stuck in platoons behind slower vehicles and causes the two-lane highway to operate poorly before it is even near capacity(*1*).

Problem Statement

Although two-lane highways are a very important element to roadway systems, there are few tools available to model two-lane highway traffic operations and also provide estimates of the performance measures appropriate for the basis of level of service (LOS) classification. The HCM is used as the standard analysis tool in the United States, but its analysis methodology for two-lane highways has been the subject of much debate and criticism in recent years. Many researchers believe that significant revisions to the HCM’s models and performance measures are necessary.

One of the greatest challenges of two-lane highway research is field data collection. The behavior and measures of interest for two-lane highways take place over significant distances and spans of time. Thus, field data collection for two-lane highways tends to be very expensive and time-consuming, often to the point of being impractical. Consequently, the research community often must rely on simulation. However, the primary simulation tool used in past research (and in the development of the HCM analysis methodology), is based on software technology that no longer functions on modern computers. In order to facilitate improvements and enhancements to the HCM’s analysis procedure, a new simulation tool is required. Such a tool has recently been developed (*2*). More specifically, this tool was created by incorporating two-lane highway modeling into the CORSIM microsimulation program (*3*).

CORSIM is one of the most commonly used simulation programs in the United States due to its low cost and reliable results. While the two-lane modeling capability underwent preliminary testing as part of the implementation project, more comprehensive testing is still required. Additionally, it is necessary to consider some of the additional performance measures that have been proposed in the literature for possible implementation in CORSIM.

Research Objectives and Tasks

The objectives of this study are to:

- Perform comprehensive testing of two-lane highway modeling in CORSIM to verify consistency with traffic flow theory.
- Make recommendations for revisions, as necessary, to the two-lane highway modeling methodology in CORSIM to improve its accuracy and usability.

- Use CORSIM to assess the validity of the HCM speed-flow and percent time-spent-following-flow relationships.
- Use CORSIM to develop more guidance on capacity values of two-lane highways than currently provided in the HCM.
- Use CORSIM to evaluate the effects of passing lanes on performance measures and capacity.
- Identify other performance measures that should undergo further consideration for use in assessing two-lane highway LOS.

The following tasks were completed in order to accomplish the objectives of this research:

- Completed a literature review on the HCM two-lane highway analysis, criticisms of the HCM methodology, other proposed performance measures, effects of passing lanes on capacity and performance measures, and simulation tools used for two-lane highway analysis.
- Developed an experimental design for testing *PTSF* and *ATS* in the HCM and CORSIM.
- Developed an experimental design for testing capacity in CORSIM.
- Compared current two-lane highway methodology in CORSIM with the 2010 HCM methodology for *PTSF* and *ATS* for two-lane highways with and without passing lanes.
- Analyzed the effects of passing lanes on capacity and performance measures.
- Evaluated the appropriateness of different performance measures for analyzing two-lane highways.

Document Organization

Chapter 2 presents a literature review on current two-lane highway methodologies and tools, performance measures that have been proposed for determining two-lane highway LOS, and how passing lanes affect two-lane highway operations. Chapter 3 explains the procedures and test scenarios used to compare different methodologies and performance measures and how to estimate capacity using CORSIM. Chapter 4 presents the results and findings of the research and provides explanations for trends and differences. Chapter 5 presents conclusions and recommendations for further research for two-lane highways and CORSIM improvements.

CHAPTER 2
LITERATURE REVIEW

Overview

This chapter describes the HCM two-lane highway analysis methodology (the primary analytical method currently used in the United States) and criticisms of the HCM methodology. It also discusses other performance measures that have been proposed for use in evaluating the operations of two-lane highways and methods for determining the effects of passing lanes on two-lane highways. This chapter also describes methods for determining two-lane highway capacity and simulation tools capable of modeling two-lane highways.

2000 HCM and 2010 HCM

The 2010 HCM two-lane highway methodology is very similar to the 2000 HCM version, but there are a few minor revisions. One change between the 2000 HCM and the 2010 HCM is that, in the 2000 edition, there are two separate procedures for finding the performance measures for a two-way analysis and for a directional analysis and the 2010 edition only has a methodology for a directional analysis. The 2010 HCM can be used for a two-way analysis by analyzing each direction separately. Since the 2010 HCM is the most recent edition, this section does not go into detail describing the 2000 HCM two-way analysis procedure (*1*, *4*).

There are slight changes in the values for certain adjustment factors such as the grade adjustment factor (f_g) and the heavy vehicle adjustment factor (f_{HV}) between the 2000 HCM and the 2010 HCM. The 2010 HCM displays more precise values for these adjustment factors because they are based on smaller increments of input values instead of having one adjustment factor for a broad range of input values. For example, in the 2000 HCM, the grade adjustment factor for *ATS* on rolling terrain is 0.71 for a directional flow rate between 0 and 300 pc/h whereas the 2010 HCM gives different grade adjustment factors for directional demand flow rates in increments of 100 (0.67 for a directional demand flow rate less than or equal to 100, 0.75 for a directional demand flow rate equal to 200) (*1*, *4*).

Another change is that the 2000 edition has only two highway classes while the 2010 edition has three. Both editions use *ATS* and *PTSF* as the performance measures to determine the LOS of class I highways and only *PTSF* for class II highways. The LOS of class III highways is determined by Percent Free-Flow Speed (*PFFS)* (*1*, *4*).

The first step in the 2010 HCM methodology is collecting accurate input information and making the necessary adjustments, beginning with speed. If the speed is measured from the field, then the average speed of the field data can be used to approximate the free-flow speed (*FFS*) as long as the two-way flow rate is no more than 200 pc/h. If the two-way flow rate exceeds 200 pc/h, then Equation 2-1 can be used to approximate the *FFS*:

$$FFS = S_{FM} + .00776 \cdot \frac{v_f}{f_{HV,ATS}} \tag{2-1}$$

where,

FFS = estimated free-flow speed (mi/h)

S_{FM} = average field measured speed (mi/h)

v_f = flow rate observed in both directions during data collection period (veh/h)

$f_{HV,ATS}$ = heavy vehicle adjustment factor

If field data is not available, then the *FFS* can be determined by estimating a base free-flow speed (*BFFS*) and making adjustments according to Equation 2-2. The *BFFS* is often estimated to be 10 mi/h higher than the posted speed limit.

$$FFS = BFFS - f_{LS} - f_A \tag{2-2}$$

where,

FFS = estimated free-flow speed (mi/h)

BFFS = base free-flow speed (mi/h)

f_{LS} = lane and shoulder width adjustment factor

f_A = access point adjustment factor

The second step in the 2010 HCM methodology is to determine the passenger car equivalent demand flow rate based on adjustments to the hourly demand volume. This can be accomplished by using Equation 2-3. Once the *FFS* and demand volume are adjusted, the average travel speed can be found using Equation 2-4:

$$v_{i,ATS} = \frac{V_i}{PHF \cdot f_{g,ATS} \cdot f_{HV,ATS}} \tag{2-3}$$

where,

i = "*d*" for analysis direction and "*o*" for opposing direction

$v_{i,ATS}$ = demand flow rate for i (pc/h)

V_i = peak hour demand volume for i (veh/h)

PHF = peak hour factor

$f_{g,ATS}$ = grade adjustment factor

$f_{HV,ATS}$ = heavy vehicle adjustment factor

$$ATS_d = FFS - .00776(v_{d,ATS} + v_{o,ATS}) - f_{np,ATS} \tag{2-4}$$

where,

ATS_d = average travel speed in analysis direction (mi/h)

FFS = free-flow speed (mi/h)

$v_{d,ATS}$ = demand flow rate in analysis direction (pc/h)

$v_{o,ATS}$ = demand flow rate in opposing direction (pc/h)

$f_{np,ATS}$ = percentage of no-passing zones adjustment factor

ATS is not used to find the LOS of class II highways. *PTSF*, which refers to the amount of time a vehicle spends in a following state because of a slower-moving lead vehicle, is found in a similar way to average travel speed, but uses different adjustment factors. Class III highways do not use *PTSF* as a performance measure. Equation 2-5 and Equation 2-6 are used to find *PTSF*.

$$BPTSF_d = 100[1 - e^{(a \cdot v_{d,PTSF}{}^{b})}] \tag{2-5}$$

where,

$BPTSF_d$ = base percent time-spent-following in analysis direction (%)

$v_{d,PTSF}$ = demand flow rate in analysis direction (pc/h)

a = constant from HCM Exhibit 15-20

b = constant from HCM Exhibit 15-20

$$PTSF_d = BPTSF_d + f_{np,PTSF}\left(\frac{v_{d,PTSF}}{v_{d,PTSF} + v_{o,PTSF}}\right) \tag{2-6}$$

where,

$PTSF_d$ = percent time-spent-following (%)

$f_{np,PTSF}$ = percentage of no-passing zones adjustment factor

$v_{o,PTSF}$ = demand flow rate in opposing direction (pc/h)

PTSF is the percentage of time that each vehicle is in a following state for its total time on the facility. The *PTSF* for the facility is taken as the average *PTSF* of all the vehicles on the facility. This performance measure cannot be accurately measured in the field because it is impossible to track every vehicle's following state at every moment. Therefore, a simulation tool is required to measure the true *PTSF*. Since *PTSF* is impossible to measure directly in the field, the HCM considers a vehicle to be following if it has a headway of three seconds or less at a chosen point along the highway. The new performance measure used in the 2010 HCM for class III highways is percent free-flow speed and can be found using Equation 2-7.

$$PFFS = 100\frac{ATS_d}{FFS} \tag{2-7}$$

where,

PFFS = percent free-flow speed (%)

ATS_d = average travel speed in analysis direction (mi/h)

FFS = free-flow speed (mi/h)

ATS, *PTSF*, and *PFFS* are the performance measures used to determine the LOS of different classes of highways. Table 2-1 shows the LOS thresholds for each highway class. The effects of passing lanes on two-lane highway performance are discussed in a later section.

Criticisms of the HCM Methodology

The HCM two-lane highway methodology has been a topic of much criticism over the years. Researchers have uncovered inconsistencies between the HCM and field data, which make the results of the HCM analysis procedures less reliable. These problems could be leading to results that do not reflect the true state of the facility being analyzed. The criticisms and limitations of the HCM are discussed in this section.

Overestimation of *PTSF*

Luttinen (*5*) found that the 2000 HCM method for *PTSF* overestimated the *PTSF* for a study done in Finland. Figure 4 in Luttinen's (*6*) study shows how the 2000 HCM method compares with the results of the Finnish study and with a negative exponential headway distribution is discussed in more detail. The differences in *PTSF* between the 2000 HCM and the Finnish model are 10% or more when the flow rate is between 1500 and 2500 pc/h.

Poor Method for Estimating *BFFS*

The 2010 HCM method for estimating *BFFS* is assuming that it is 10 mi/h higher than the posted speed limit if the analyst does not have speed data for a similar facility to use as a guide. The posted speed is used as a rough starting point because *FFS* is based mainly on the roadway geometry. Grade drastically affects traffic flow on highways and the HCM does not address those effects very well (*7*). The adjustment factors for grade only give a rough estimation of the geometric conditions. *ATS* calculations are drastically affected by the *BFFS*.

Speed-Flow Relationship

The current relationship between speed and flow shown in the HCM is not consistent with the findings of a study done in Finland. Luttinen (*5*) conducted a field study in Finland and found that the overall shape of the speed-flow relationship matched well with a curve shape that initially has a fairly steep negative slope for low flow rates and then the curve slope decreases to the point where it is fairly flat over the moderate to high flow rates. There was a steeper decrease in speed at lower flow rates and the effect of the opposing flow rate on speed was much smaller than the analysis flow rate's effect, which suggests that the directional split should be accounted for when determining *ATS*. The HCM speed-flow curves show a linear relationship that did not match up as well as the decreasing model to the field data. Figure 7 in Luttinen's (*5*) study shows the comparison of the speed-flow relationship between the Finnish field data and the HCM prediction.

Brilon and Weiser (*8*) used field data and simulation to estimate a speed-flow model. They found that the speed-flow relationship follows a curve shape that initially has a fairly steep negative slope for low flow rates and then the curve slope decreases to the point where it is fairly flat over the moderate to high flow rates. Equation 2-8 fits the field data of the Brilon and Weiser (*8)* study well.

$$v_{T(car)} = a + b\sqrt{q} \tag{2-8}$$

$V_{T(car)}$ = average passenger car travel speed (mi/h)

q = two-way traffic volume (veh/h)

a = model parameter

b = model parameter

Deterministic Method for Identifying Follower Status

For purposes of measuring *PTSF* in the field, the HCM uses a constant value of 3 seconds for the headway threshold. That is, if the headway between successive vehicles is 3 seconds or less at a chosen point along the highway facility, the trailing vehicle is considered to be in a following state. This method does not account for drivers having different desired following headways. A stochastic approach for the determination of follower status has been proposed by Catabagan and Nakamura (*9)* and is discussed in a later section.

Other Performance Measures More Applicable for LOS Determination

Several researchers such as Luttinen (*5*, *6*, *7*), Catabagan and Nakamura (*9*), Al-Kaisy and Freedman (*10*), Van As (*11*), Polus and Cohen (*12*), and Morrall and Werner (*13*) have suggested that the HCM two-lane highway analysis methodology is a very rough and potentially inaccurate standard for LOS assessment and that *PTSF* and *ATS* are not necessarily the most appropriate performance measures to use for assessing two-lane highway performance. *PTSF* has not been used in Germany as a primary two-lane highway performance measure because it mainly indicates the drivers' discomfort level rather than how efficiently the highway is operating. The main performance measure used to evaluate two-lane highway operations should indicate problems with safety, system operations, or the environment (*8*).

The *ATS* of passenger cars, as opposed to the *ATS* of all vehicles, has been used in Germany and Finland as the main performance measure for two-lane highways because it gives a better indication of how increased volumes affect traffic operations (*8*, *14*). Trucks speeds are not very sensitive to increases in traffic volume, but traffic volume is the main factor affecting the *ATS* of passenger cars (*8*).

Although *ATS* is easy to measure in the field, it is not very informative about the efficiency of the highway. Since the analysis section of a two-lane highway facility is usually several miles long, there could be many changing conditions such as posted speed. This makes *ATS* somewhat meaningless for determining how the highway is operating (*14*).

PFFS is meant to account for the limitations of *ATS.* It measures the speed reduction due to increased traffic volume, which makes it possible to compare the current conditions to the ideal conditions (*14*). Volumes in the analysis direction and opposing direction were found to be statistically significant in the *PFFS* models developed by Al-Kaisy and Freedman (*10*). One of the limitations of *PFFS* is that it is almost completely unaffected by the addition of a passing lane, which indicates that it is not a useful performance measure for capturing the delay caused by platooning (*10*). The 2010 HCM only uses *PFFS* for determining the LOS of Class III highways, which do not include passing lanes by definition.

The *PFFS* of passenger cars, as opposed to the *PFFS* of all vehicles, has been analyzed as a possible performance measure. Since cars are more sensitive to increased traffic volumes than trucks, the *PFFS* of passenger cars gives a better indication of how traffic operations are affected by changes in traffic volume (*14*). Al-Kaisy and Karjala (*14*) found that speed-related performance measures showed a higher correlation to opposing flow rate than other performance measures. The relationship between *ATS* and *PFFS* of passenger cars and platooning variables did not prove to have a higher correlation than *ATS* and *PFFS*. *PFFS* would be sufficient for capturing changes in platooning variables for a two-lane highway facility. Other performance measures that have been proposed to replace or supplement the 2010 HCM performance measures are discussed in a later section.

Poor Method for Indicating Necessary Improvements

PTSF is not a good performance measure for indicating if improvements should be made to a highway that has low volumes with a high percentage of heavy vehicles and few passing sections. In this case, *PTSF* would be high and suggest that additional lanes or passing sections need to be added even though the volumes are low. Another performance measure, known as follower density, has been proposed to account for this shortcoming of *PTSF* and is discussed in a later section (*11*).

Overestimation of Performance Measure Improvements Due to Passing Lanes

The results obtained from the inclusion of a passing lane lead to unrealistic improvements to the performance measures and, consequently, the level of service. *PTSF* and *ATS* are very sensitive to changes in volume and passing lane adjustments result in large reductions to both *PTSF* and *ATS.* When solving for a service volume, which is the volume corresponding to a given LOS, based on *PTSF* and *ATS* for a facility with a passing lane, the calculated volume is unreasonably higher than the volume for the facility with no passing lane.

These results are misleading because, realistically, the number of vehicles before and after a passing lane section should be approximately the same. A small percentage of the vehicles may change positions, but it does not drastically change the number of vehicles in the traffic stream. This means a passing lane should not show major increases to the traffic-carrying capability of the highway section. This issue is demonstrated in Chapter 4.[1]

Limitations During Saturated Conditions and Near Signalized Intersections

PTSF is limited in that it is not useful in saturated conditions. This is because as the traffic volume increases, spacing becomes a more important factor than time headways and *PTSF* does not incorporate spacing (*6*).

[1] Washburn, S. S. Meeting Discussion. University of Florida, Gainesville, Florida, May 19, 2010.

The HCM methodology cannot be used to accurately describe conditions for two-lane highways with signalized intersections (*1*). Yu and Washburn (*15*) have proposed a method to address this situation by using a performance measure that describes the LOS of an entire highway facility instead of breaking the highway up into smaller segments. Long highway facilities usually have disruptions such as two-way stop controlled intersections, driveways, and signals and the HCM does not have a methodology that describes the overall facility operations. The approach taken by Yu and Washburn (*15*) was to divide the facility into sections where conditions changed. Intersections were regarded as a segment of the highway rather than a point location and the effective influence area upstream and downstream of the signal was determined.

Percent delay (*PD*) was chosen as the two-lane highway facility performance measure because it can be applied to all possible situations encountered on a two-lane highway facility. *PD* is the ratio of delay to free-flowing travel time which gives more information about the operational conditions than total delay alone because it compares unfavorable time spent traveling to favorable time spent traveling. Equation 2-9 gives the formula for *PD* and Table 2-2 shows the threshold values for two-lane highway facility LOS.

$$PD = \frac{\sum_{H,S}(D_H + D_S)}{\sum_{H,S}\left(\frac{L_H}{FFS_H} + \frac{L_S}{FFS_S}\right)} \cdot 100 \tag{2-9}$$

where,

PD = average percent delay per vehicle through the entire facility (%)

D_H = average delay per vehicle for a two-lane highway segment (s/veh)

D_S = average delay per vehicle for a signalized intersection influence area (s/veh)

FFS_H = *FFS* for a two-lane highway segment (ft/s)

FFS_S = *FFS* for a signalized intersection influence area (ft/s)

L_H = length of a two-lane highway segment (ft)

L_S = length of a signalized intersection influence area (ft)

Additional Performance Measures

Performance measures should indicate how drivers feel about the traffic level, be useful for congested and uncongested conditions, be compatible with performance measures of other facilities, and be easy to measure in the field and estimate when it is not feasible to gather all field data (*6*). Different methods are used to determine performance measures for two-lane highways and they each give different results. There are several performance measures that are described in the literature, but not included in the 2010 HCM methodology, that could be useful for assessing two-lane highway operations.

Percent Impeded

Al-Kaisy and Freedman (*10*) have proposed the ‘percent impeded’ (*PI*) measure to determine the operational status of two-lane highways. Speed and headway are the two main parameters used to develop two-lane highway performance measures and *PI* encompasses both of these aspects. *PI* considers only vehicles that are unable to pass when assessing LOS. Equation 2-10 is used to calculate *PI*.

$$PI = P_p \cdot P_i \tag{2-10}$$

where,

PI = percent impeded

P_p = probability that a vehicle is part of a platoon

P_i = probability that a vehicle is impeded

P_p accounts for the headway component and P_i accounts for the speed component of this performance measure. P_p can be estimated using a deterministic approach similar to the 2010 HCM *PTSF* method, which is to collect time headway data and choose a headway threshold to determine if a vehicle is in a platoon or unrestricted. P_i can be estimated by collecting speed data for slow moving vehicles and for vehicles that are not part of a platoon or vehicles that lead a platoon. Then the data can be used to find the percentage of vehicles with a higher desired speed than the average speed of slow moving vehicles. Figure 1 in Al-Kaisy and Freedman's (*10*) study shows P_i based on the desired speed distribution.

PI consistently shows the greatest percent change due to the addition of a passing lane compared to percent followers, follower density, and *PFFS*. The Al-Kaisy and Freedman study (*10*) also showed that volumes in the analysis direction and opposing direction were not statistically significant in *PI* models and percent follower models. This means an additional performance measure would need to be used, such as the volume to capacity ratio (*v/c*), to report the appropriate LOS. However, *PI* showed a strong correlation to other performance measures and most platooning variables and was consistent with the expected effects of the passing lane. Also, *PI* was the only performance measure that found the percentage of trucks in the traffic stream to be significant in the model (*10*).

Probability-Based Follower Identification

A new method has been developed that can better estimate whether or not a driver is following or freely moving. Current procedures identify followers by a chosen headway, but those procedures do not account for driver variability or changes in roadway conditions. Some drivers may feel unrestricted while driving with a headway of three seconds or less, which is what the 2010 HCM uses as a standard for determining follower status, while others may have a headway larger than three seconds and feel like they are following. Also, a certain driver may have a different desired headway based on weather conditions, pavement conditions, the time of day, and other factors that affect drivers' comfort levels (*9*).

Probability-based follower identification takes a stochastic approach that incorporates both speed and headway into determining when a driver is following. This procedure uses a mixed distribution model of headways known as the Semi-Poisson Model (SPM) in order to separate following and free vehicles based only on the headway portion of this method. As headways increase, the probability that a vehicle is following decreases until a critical headway is reached at which point no vehicles should be considered as followers. Equation 2-11 shows the proportion of vehicles that are following and free.

$$f(t) = \phi \cdot g(t) + (1-\phi) \cdot h(t) \tag{2-11}$$

where,

$f(t)$ = total observed headway distribution

φ = proportion of constrained vehicles

$g(t)$ = constrained headway distribution function

$h(t)$ = unconstrained headway distribution function

Equation 2-11 can be manipulated to give the probability that a vehicle is following as shown in Equation 2-12.

$$P(Foll_{headway}) = \frac{\phi \cdot g(t)}{f(t)} \tag{2-12}$$

where,

$P(Foll_{headway})$ = probability that a vehicle is following given its headway

The speed-based portion of this method is hindered by the difficulty in collecting data on the ever-changing desired speeds of different drivers. This procedure assigns different desired speeds to certain conditions and if a vehicle's speed drops below the assumed desired speed, then it is considered to be in the following state. The unified speed distribution method was used to approximate the desired speeds. Equation 2-13 projects the probability that a vehicle is following based only on desired speeds:

$$P(Foll \mid v_i) = \int_{v_i}^{\infty} f_d(v)dv \tag{2-13}$$

where,

v_i = travel speed of vehicle *i*

$P(Foll \mid v_i)$ = probability that vehicle *i* traveling at speed v is following

$f_d(v)$ = desired speed distribution function

Figure 1 in Catabagan and Nakamura's (*9*) study graphically shows the probability that a vehicle is following based on headway and speed. Equation 2-14 combines the headway and desired speed models into one formula for finding the probability that a vehicle is following.

$$P_i(Foll \mid t, v) = \theta_i(t) \cdot S_i(v) \tag{2-14}$$

where,

i = driving condition

P_i *(Foll | t,v)* = probability that a vehicle is following at condition *i*

$\theta_i(t)$ = following probability at condition i based on headway

$S_i(v)$ = following probability at condition i based on speed

Catabagan and Nakamura (*9)* found that the *PTSF* measure used by the HCM underestimates the number of following vehicles. As the highway approaches capacity, the percent of followers should increase and theoretically reach 100% and the probability-based follower identification method is consistent with that concept.

This study was done in Japan, the results of which may not necessarily transfer directly to conditions in the United States, particularly since Japan does not allow passing on any two-lane highways. Drivers in Japan may behave differently because of the nature of their highways or because of unknown characteristics (*9)*.

Follower Density

Van As (*11*) performed a study in South Africa and found that follower density was a useful performance measure for determining when capacity improvements need to be made. It essentially combines the percentage of followers, traffic flow, and travel speed into one performance measure. Volumes in the analysis direction and opposing direction were found to be statistically significant in the follower density models (*10*).

Follower percentage by itself is limited in that it does not capture the effects of traffic volume. The HCM uses the percentage of followers as a surrogate for estimating *PTSF* from field data. Follower density is calculated by multiplying the percentage of followers by density. It is best suited as a point measurement. While the measurement of follower percentage to be used in the follower density calculation is consistent with the surrogate measure for *PTSF*, it should be noted that the true *PTSF* is intended to reflect continuous measurements of following over both space and time. Al-Kaisy and Karjala (*14*) found that traffic flow affected two-lane highway performance measures more than other platooning variables such as opposing flow, percentage of heavy vehicles, percentage of no-passing zones, and speed differentials. Therefore, it is important that the performance measure used to analyze two-lane highways captures the effects of traffic volume.

One of the advantages of using follower density as a performance measure is that it allows two-lane highway LOS to be compared easily with freeways and multilane highways, which use density as a performance measure. Follower density internally incorporates speed, which means *ATS* would not have to be used as a performance measure (*7*).

The LOS for follower density is based on the worst conditions along the highway unlike the 2010 HCM procedure, which is based on the average conditions. The LOS is based on the segment with the highest follower density. This approach is better than the average-conditions approach because the problem area can be easily identified for improvements.

The 2010 HCM gives the LOS based on the average value of the performance measures per vehicle where follower density gives the LOS based on the value of the performance measure for the traffic stream. The limitation of using the average per vehicle is that the average LOS may be poor, which would indicate that improvements should be made, even when there are low traffic volumes. The traffic stream approach takes traffic density into account, which gives a better indication of when highway improvements should be made. Equation 2-15 gives the calculation for follower density. Table 2-3 shows the proposed follower density LOS thresholds. These threshold values require further verification (*11*).

$$Follower\ Density = \%Followers \cdot Density \tag{2-15}$$

One of the methods for finding follower density in the field is to divide the facility into different segments, making sure that each separate segment has the same characteristics such as passing or no-passing allowed. Then, the percentage of followers could be recorded at the beginning and end of each segment and the worst segment could be easily identified. It would also be possible to find the average percentage of followers along each segment. Follower density can then be easily calculated using Equation 2-15 (*11*).

Freedom of Flow

Polus and Cohen (*12*) did a study and found that freedom of flow was an effective tool for determining the LOS of a two-lane highway. Freedom of flow is similar to *PTSF*, but it gives a better representation of the drivers' opportunities to pass when they are delayed by a slower lead vehicle. The variables that are needed to calculate freedom of flow can be easily estimated from existing traffic data for two-lane highways with similar characteristics to the highway being analyzed.

Traffic intensity is defined as the ratio of the arrival rate to the service rate. The arrival rate is the interarrival times of vehicles to the back of a platoon and the service rate is the time a vehicle has to wait behind an impeding vehicle until it is able to pass. For M/M/1 queuing, $E[T_D]$ represents the average service rate. Freedom of flow represents the ratio of travel times between platoons to the service rate. This performance measure captures the freedom that a vehicle has to move around in the traffic stream. The variables for this performance measure are all dependent on the opposing flow rate. Since freedom of flow internally incorporates the flow in both directions, it is a two-directional analysis tool. Freedom of flow is given by Equation 2-16. Table 2-4 shows the projected LOS thresholds compared to thresholds for other performance measures.

$$\eta = \theta / E[T_D] = N_O / \rho \tag{2-16}$$

where,

η = freedom of flow

h_b = average interarrival times of fast vehicles to the back of a moving platoon (s)

N_O = average number of headways between platoons

ρ = traffic intensity

θ = average travel time between platoons (s) = $N_O \times h_b$

$E[T_D]$ = expected time between the arrival of a fast vehicle into a position behind a slow vehicle and the time when the passing maneuver starts (s) = $h_b \times \rho$

Overtakings

Morrall and Werner (*13*) noticed that the performance measures used by the HCM to determine LOS do not externally show the effects of passing lanes. They proposed that an additional performance measure, called overtakings, could be used to account for this weakness in the HCM. The idea of measuring LOS by overtakings is based on how important passing opportunities are to drivers. It takes into account the effects of passing lanes and the percentage of no-passing zones. This is a useful tool for identifying highways that need improvements. Equation 2-17 is used to determine the overtaking ratio.

$$overtakings = \frac{AO}{DO} \tag{2-17}$$

where,

AO = achieved overtakings

DO = desired overtakings assuming a continuous passing lane section

Although a certain two-lane highway may not have a continuous passing lane section, desired overtakings are the number of overtakings the driver would make for a highway that has a continuous passing lane section and geometry similar to the highway in question. Overtakings measures how many passes a vehicle makes on a highway versus how many passes a vehicle would make if it was unrestricted.

One of the limitations of this performance measure is that it does not give any information about speed or delay, which is very important for determining two-lane highway LOS. Therefore, overtakings cannot be used as the primary measure for LOS. Also, it is unclear how the overtaking ratio corresponds to how drivers feel about the traffic conditions, which makes it difficult to assign specific LOS thresholds to overtaking ratios. Morrall and Werner (*13*) proposed that several graphs should be developed for a variety of road, traffic, and vehicle characteristics in order to find the overtaking ratio without having to do simulation for every highway that needs to be analyzed.

Passing Lanes

Passing lanes are a unique feature of two-lane highways that provide a cost-effective alternative to decreasing delay by helping platoons dissipate and providing passing opportunities when the gaps are inadequate due to high oncoming traffic volumes or when there is insufficient passing sight distance (*PSD*). They also decrease delay at locations where bottlenecks are formed due to slow-moving vehicles on upgrades. However, passing lanes further complicate the effort to accurately analyze a two-lane highway because several more variables need to be accounted for and different roadway conditions can change how effective a passing lane is in decreasing congestion. Typical passing lane lengths are usually between 1000 feet and 3 miles (*16*).

HCM and Passing Lanes

According to the 2010 HCM, the lengths upstream and downstream of the passing lane have a large impact on performance measures. The effects of passing lanes on *PTSF* and *ATS* are shown in Exhibits 15-25 and 15-27 in the 2010 HCM where L_U is the length upstream of the passing lane, L_{pl} is the length of the passing lane, L_{de} is the effective length downstream of the passing lane, and L_d is the non-effective length downstream of the passing lane (*1*).

Passing Lane Location

Passing lanes are often added at locations where bottlenecks are formed along upgrades due to slow-moving vehicles or where general highway operations are inadequate. The optimal passing lane length should be determined by using a base percent time delay. The effective length of a passing lane depends on traffic flow, vehicle composition, passing opportunities downstream of the passing lane, and the length of the passing lane itself. The passing lane is most effective if it is added before speeds decrease below tolerable levels (*16*).

Passing lanes on upgrades, also known as climbing lanes, can also be effective if one short passing segment is placed near the middle of the upgrade or if two passing lane segments are placed at locations one third and two thirds of the way along the length of the upgrade (*17*). When a highway is operating poorly in areas besides upgrade segments, passing lanes should be added periodically to help improve the overall performance (*16*).

Effects on Other Performance Measures

The operational improvements due to the addition of a passing lane depend on the percentage of vehicles traveling in platoons, traffic flow, and passing lane length. Passing lanes have a large positive impact on decreasing the *PTSF* and the percentage of vehicles delayed in platoons, but they do not have a large impact on the *ATS* (*16*). Passing lanes noticeably affect the segment far downstream from the actual passing lane location as shown in Exhibit 15-22 of the HCM.

Passing Procedure

Polus et al. (*18*) did a study on quantifying values for passing maneuvers and concluded that the American Association of State Highway and Transportation Officials (AASHTO) may not be an accurate standard for determining the distances for passing components when a car is passing a truck. A car passing a truck stays in the opposing lane for a longer amount of time than a car passing another car and when the car returns to the original lane, there is a longer time gap between the car and the truck than between the car and another car.

Polus et al. (*18*) found that the reaction time to start a passing maneuver once a gap is available is not dependent on speed. The time between the return of the passing vehicle to the original lane and the next oncoming vehicle is also not dependent on speed. Polus et al. (*18*) also found that the speed differential between overtaking and overtaken vehicles decreases as their travel speeds increase. AASHTO (*19*) assumes that there is no acceleration while the passing vehicle is in the oncoming lane of traffic. However, the results of Polus et al. (*18*) show that the acceleration happens mainly in the opposing lane. AASHTO (*19*) assumes that a vehicle's acceleration is 2.1 ft/s^2 before it begins to move into the opposing lane for a passing maneuver, but Polus et al. (*18*) found that the average acceleration in the oncoming lane during a pass is about 3.0 ft/s^2.

Driver Decision to Pass

There are several factors that motivate a driver to attempt a pass. Platoons caused by slow-moving lead vehicles such as trucks instigate drivers to pass and the number of lane changes varies as the length of the platoon changes. As volume increases, the drivers' desire to pass also increases because it is more likely that a slow-moving vehicle could be in the traffic stream (*20*).

Passing Sight Distance

PSD is an important parameter for deciding if drivers will attempt to pass. Several factors such as passing, impeding, and oncoming vehicle speeds, acceleration and deceleration, and vehicle lengths have an impact on the *PSD* required for a driver to make a safe and successful pass. These factors change depending on roadway conditions, driver type, and vehicle type. However, current design standards do not take their variability into account. Instead, they use a conservative, constant value, which means different passing scenarios cannot be modeled accurately (*21*).

AASHTO (*19*) provides standard *PSD* guidelines for different parts of a pass and the total required *PSD* is calculated based on these component parts. Table 2-5 shows values for distances, speeds, times, and accelerations for each component of a passing maneuver according to AASHTO. Exhibit 3-4 in the AASHTO green book (*19*) illustrates the distance values for each of these components of a passing maneuver. Descriptions of the variables that are used in Table 2-5 are as follows:

- d_1 = initial maneuver - distance traveled from start of passing maneuver until passing vehicle encroaches upon oncoming lane (ft)
- t_1 = time required for initial maneuver (s)
- a = acceleration of passing vehicle when initiating passing maneuver (ft/s/s)
- v = average speed of passing vehicle (mi/h)
- m = difference in speed of passed vehicle and passing vehicle (mi/h)
- d_2 = distance traveled by passing vehicle from the point of encroachment in the oncoming lane to the point of return to the original lane (ft)
- t_2 = time spent traveling in the oncoming lane (s)
- d_3 = shortest desirable distance between the front bumpers of the passing and opposing vehicles when the passing vehicle returns to the original lane (ft)
- d_4 = distance traveled by the opposing vehicle during the time that the passing vehicle travels from the position of being directly abreast of the vehicle being passed to the return to the original lane (ft)

Glennon (*22*) developed a *PSD* equation that was inspired by the concept of a critical point where the sight distance requirements for a vehicle to complete or abort a pass are equal. AASHTO assumed that the passing vehicle would not have a chance to abort, which is an unrealistic assumption. Glennon's (*22*) critical sight distance equation assumes that the opposing vehicle and the passing vehicle are traveling at the design speed and that the impeding vehicle is traveling at some speed below the design speed. Glennon's (*22*) critical sight distance model is given in Equation 2-18.

$$S_c = 2v \cdot \left[2 + \frac{16 - \Delta_c}{m} \right] \tag{2-18}$$

where,

S_c = critical sight distance (ft)

v = design speed (ft/sec)

Δ_c = critical separation between passing and impeding vehicles (ft)

m = difference in speed between passing and impeding vehicles (ft/sec)

El Khoury and Hobeika (*21*) did a study on the risk level associated with different *PSD* that helped reinforce Glennon's (*22*) findings. They found that AASHTO gives a conservative design standard, while the Manual on Uniform Traffic Control Devices (MUTCD) and Glennon's (*22*) equation give reasonable estimates for the necessary *PSD*. AASHTO has a more conservative calculation because it measures *PSD* from the time the passing maneuver begins to the time it ends whereas the MUTCD and Glennon's (*22*) equation measure *PSD* from the time the vehicle is in the critical position to the time it completes the pass. Figure 3 in El Khoury and Hobieka's (*21*) study shows the relationship between the MUTCD design standard and Glennon's (*22*) equation in metric units.

Glennon (*22*) also found that as vehicle length increases, *PSD* requirements increase, but not by a severe amount. Vehicle length may not have a drastic impact on *PSD* because it becomes important only for end-zone passes and also because drivers are able to adapt to the conditions under which they are passing and adjust for inhibiting factors such as longer impeding vehicle lengths (*22*).

Hassan et al. (*23*) built on Glennon's model, incorporating a level of safety for the passing maneuvers that increases as design speed increases. The *PSD* model is given in Equation 2-19.

$$PSD_c = 2V_d(t + h) \tag{2-19}$$

where,

PSD_c = *PSD* required for a vehicle at the critical position to complete or abort the pass (ft)

V_d = design speed (ft/s)

t = time required for a passing vehicle to return to the original lane from the critical position for a completed pass (sec)

h = minimum headway between passing and passed vehicles at the end of a completed or aborted pass and minimum headway between passing and oncoming vehicle at the end of a completed or aborted pass (sec)

This model determines the critical distance based on the positions of the front bumpers of the passing and impeding vehicles. Equation 2-20 gives the calculation for the critical position.

$$\Delta_c = L_p + h(V_d - m) - 1.47mt \qquad (2\text{-}20)$$

where,

Δ_c = relative positions of the front bumpers of the passing and passed vehicles at the critical position with a negative value meaning the passing vehicle is behind the vehicle being passed (ft)

L_p = length of passing vehicle (ft)

V_d = design speed (ft/s)

m = speed differential between passing and passed vehicle (ft/s)

Once the front bumper of the passing vehicle is past the front bumper of the impeding vehicle, it is not likely that the passing vehicle would abort, even if the critical position was not yet reached. To account for this, Hassan et al. (*23*) modified *t* in Equation 2-19 so that it provides adequate sight distance for any passing vehicle to complete the pass as long as its front bumper is side by side with the impeding vehicle's front bumper. The new definition of *t* is the time required to complete a pass when the front bumpers of the passing and passed vehicles are side by side. Figure 16 in Hassan et al. (*23*) shows the comparison between the *PSD* models according to Hassan, Glennon, and the MUTCD.

Capacity

The 2010 HCM states that directional capacity is 1700 pc/h and two-way capacity cannot exceed 3200 pc/h (*1*). Capacity is computed by adjusting the base flow rate of 1700 pc/h for grade and heavy vehicles. Equation 2-21 and Equation 2-22 are used to calculate capacity in veh/h based on *ATS* and *PTSF*, respectively.

$$c_{d,ATS} = 1700 \cdot f_{g,ATS} \cdot f_{HV,ATS} \tag{2-21}$$

$$c_{d,PTSF} = 1700 \cdot f_{g,PTSF} \cdot f_{HV,PTSF} \tag{2-22}$$

Class I capacity is based on the lowest of $c_{d,ATS}$ and $c_{d,PTSF}$, Class II capacity is based only on $c_{d,PTSF}$, and Class III capacity is based only on $c_{d,ATS}$ (*1*).

Luttinen (*5*) did a study in Finland and found that capacity was reached at higher speeds and lower densities than the 2000 HCM method projected, but the 2000 HCM capacity estimate matched the field data capacity estimate well. Differences could be due to conditions that were not totally congested and factors that were not ideal. The field data showed that capacity was reached at flow rates of 1550 veh/h and 1600 veh/h, which is close to the 2000 HCM prediction of 1700 pc/h. The 2000 HCM estimates the capacity to occur when the density is about 32 pc/h while the field study showed that capacity was reached when the density was about 29 veh/mi. The results of the Luttinen (*5*) study suggest a linear relationship between opposing flow rate and directional capacity.

Rozic (*24*) did a study showing that capacity depends on how the traffic flow is divided and how it is measured. The ideal two-way capacity was found by dividing traffic flow from a car-following aspect. Ideal capacity assumes the entire traffic stream is made up of passenger cars only that are in one long platoon with 1.8 second headways between each successive vehicle, which is approximately the smallest realistic headway. The ideal two-lane two-way highway capacity was found to be 4000 pc/h, which occurred when the traffic flow was made up of two platoons that consisted of passenger cars only. The realistic capacity accounts for trucks in the traffic stream and vehicles breaking up into several smaller platoons instead of staying in one long platoon. The realistic two-lane two-way highway capacity was estimated to be about 2700 veh/h.

Kim (*25*) created a simulation program called TWOSIM, which was specifically designed to estimate two-lane highway capacity under different conditions. The first program, known as TWOSIM I, was used to estimate the capacity of a 2-mile two-lane highway with all passenger cars, 100% commuters, level terrain with no curves, low opposing flow rate, and 100% no-passing zones. For this two-lane highway, Kim (*25*) found the directional capacity to be about 1850 pc/h for and average *FFS* of 40 mi/h, 2000 pc/h for an average *FFS* of 50 mi/h, and 2100 pc/h for an average *FFS* between 60 and 70 mi/h.

TWOSIM II was designed to analyze a two-lane highway with the same base conditions as the highway analyzed in TWOSIM I, but with a 20% no-passing zone. There were two no-passing zones of 0.2 mi at each end. TWOSIM II estimated capacity for this two-lane highway configuration to be 2100 pc/h, which is the same as the TWOSIM I capacity estimate for high *FFS*. This means that passing zones did not affect capacity.

TWOSIM III was designed to estimate capacity for two-lane highways with horizontal curves (radius less than 500 ft), driveways, upgrades, and trucks in the traffic stream. With no trucks in the traffic stream, TWOSIM III estimated capacity reductions to be between 10% and 12% for two-lane highways with a driveway, between 3% and 17% for two-lane highways with a horizontal curve, and between 11% and 30% for two-lane highways with an upgrade between 4% and 8%.

For an increasing proportion of trucks in the traffic stream (10%-20%), TWOSIM III estimated capacity reductions to be between 10% and 23% for two-lane highways with a driveway, between 3% and 26% for two-lane highways with a horizontal curve, and between 11% and 40% for two-lane highways with an upgrade between 4% and 8%. TWOSIM III showed that capacity increased with an increasing radius of horizontal curvature when there was a constant percentage of trucks in the traffic stream. TWOSIM III also showed that, for 10% trucks in the traffic stream, capacity decreased as the length of the upgrade increased. Kim (*25*) found that the capacity for both directions could be calculated as twice the capacity of the analysis direction since the directional capacity was not sensitive to the opposing flow rate, which is in conflict with Luttinen’s (*5*) findings. However, since both directions rarely, if ever, reach capacity at the same time, capacity should only be reported for the analysis direction.

Brilon and Weiser (*8*) used a German simulation model, known as LASI, to estimate two-lane highway capacity. The two-way capacity was estimated to be 2500 veh/h for straight two-lane highways with level terrain. The directional capacity was estimated to be between 1200 veh/h and 1450 veh/h. When a two-lane highway is at capacity, there are still gaps in the traffic stream, but they cannot be filled because of speed differences and few passing opportunities.

Simulation Tools

There are few simulation tools that have been developed specifically for analyzing two-lane highways. TWOSIM, which was designed to estimate two-lane highway capacity, is described in the capacity section of this chapter. The main software programs that were created to simulate two-lane highways and to evaluate their performance are discussed in this section.

TWOPAS

TWOPAS is a microscopic, stochastic traffic flow simulation model that was originally created by the Midwest Research Institute (*26*). This model incorporates formulas for roadway geometry, passing zones, driver type, vehicle type, and the direction of traffic. It uses thirteen different types of vehicles including five passenger cars, four RVs, and four trucks. This program was written in the FORTRAN language and the user interface, which is known as UCBRURAL, was developed at the University of California Berkeley (UCB) (*27*). The 1985 HCM was developed largely based on adjustment factors, calculations, and outputs from TWOPAS (*26*). The 2000 HCM two-lane highway methodology is still very similar to the 1985 HCM methodology and reflects refinements largely based on TWOPAS simulation results.

Allen et al. (*28*) suggested that TWOPAS should include more vehicle types or that truck characteristics should have more variability to allow for better modeling of truck speeds on steep upgrades and downgrades. TWOPAS is limited in that it cannot internally evaluate downgrades for different truck types to determine which ones are at crawl speed (*28*).

TRARR

The Australian Road Research Board developed a microscopic, stochastic simulation program, known as TRARR, to analyze two-lane two-way highways. TWOPAS is recommended for use in the United States because many of the parameters in TRARR, such as driver and vehicle characteristics, are based on Australian conditions, which causes the outputs to be considerably different from field data in the United States (*26*).

CORSIM

CORSIM is a microscopic, stochastic simulation program that is maintained by Mc*Trans* at the University of Florida (*3*). It uses FRESIM links to model freeways, and NETSIM links to model urban streets. FRESIM, NETSIM, or both models are used to simulate traffic on freeways, interchanges, roundabouts, arterials, and other roadway facilities. CORSIM can also model incidents, preemption, and left-sided driving.

Washburn and Li (*2*) developed the logic and algorithms for two-lane highway modeling within CORSIM. Mc*Trans* implemented the logic and algorithms in the CORSIM code. This two-lane highway modeling capability is available in TSIS 6.2. It is capable of handling passing in one or both directions and can model a two-lane highway with a passing lane. These tasks were accomplished using FRESIM links. Washburn and Li (*2*) made it possible to simulate signalized intersections along two-lane highways based on recommendations from the Yu and Washburn (*15*) study. This was done by connecting FRESIM and NETSIM links.

Several new inputs and outputs were added in CORSIM to allow the user to change different factors specific to affecting the performance of two-lane highways. The new inputs include passing zones, follower headway, minimum and maximum clearance distance between the passing vehicle and passed vehicle, impatience value, passing acceleration, and several others. *PTSF*, *ATS*, follower density, and several passing-related measures were added to the measures of effectiveness (MOE) screen for the user to select as reported simulation outputs. Most of these new outputs require further testing and validation.

The two-lane highway car-following model used in CORSIM is the Pitt car following model and the default *PSD* models used are based on AASHTO values, but can be changed to *PSD* models based on the MUTCD values. Passing maneuvers are restrained by the distance needed to travel in the oncoming lane, the *PSD*, and the required clearance. CORSIM uses many different checks and equations to calculate those restraints and generate successful and aborted passes in a stochastic manner.

For vehicles passing in a section that has a passing lane, CORSIM considers a vehicle’s willingness to move over (WTMO) to the non-passing lane. The WTMO is then adjusted by the driver type if the vehicle’s length is less than 40 feet, which results in trucks longer than a single unit having a higher WTMO. There are also lane-changing models for determining when a vehicle will return to the original lane.

Washburn and Li (*2*) tested many different combinations of inputs for both no-passing allowed and 100% passing allowed scenarios and compared the *ATS*, *PTSF*, and follower density for three different volume splits, 50/50, 60/40, and 70/30, in the analysis and opposing direction. Scenarios with passing allowed had a positive impact on the major direction, which is the direction with the highest volume, for *ATS* and *PTSF*, but had a negative effect on the minor direction as a result of fewer passing opportunities than the major direction. Scenarios with passing lanes added showed improvements for *ATS* and *PTSF*. The results for follower density are slightly lower for 100% passing allowed compared to 100% no-passing allowed.

Table 2-1. Level of service thresholds as a function of highway class

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

Adapted from Highway Capacity Manual. TRB, National Research Council, Washington, D.C., 2010, (Page 15-7, Exhibit 15-3).

Table 2-2. Threshold values for two-lane highway facility LOS

LOS	Percent delay (%)
A	≤ 7.5
B	> 7.5-15.0
C	> 15.0-25.0
D	> 25.0-35.0
E	> 35.0-45.0
F	> 45.0

Adapted from Yu, Q., and S. S. Washburn. Operational Performance Assessment for Two-Lane Highway Facilities. Journal of Transportation Engineering, ASCE, Vol. 135, No. 4, April 2009, pp. 197-205, (Page 202, Table 1).

Table 2-3. LOS thresholds for follower density

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

Adapted from Van As, C. 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, Pretoria, 2003, (Page 18).

Table 2-4. LOS thresholds for freedom of flow compared to *PTSF* and two-way flow

LOS	PTSF (%)	Two-way flow (pc/h)	Freedom of flow
A	0-15	0-300	≥ 16.5
B	15-30	300-700	7.1-16.5
C	30-45	700-1200	4.1-7.1
D	45-60	1200-1800	2.8-4.1
E	60-75	1800-2700	1.8-2.8
F	75-100	≥ 2700	≤ 1.8

Adapted from Polus, A., and M Cohen. Theoretical and Empirical Relationships for the Quality of Flow and for a New Level of Service on Two-Lane Highways. Journal of Transportation Engineering, ASCE, Vol. 135, No. 6, June 2009, pp. 380-385, (Page 384, Table 2).

Table 2-5. AASHTO components and values of passing sight distance

Component of passing maneuver	Speed range (mi/h)			
	30-40	40-50	50-60	60-70
	Average passing speed (mi/h)			
	34.9	43.8	52.6	62.0
Initial Maneuver				
a	1.40	1.43	1.47	1.50
t_1	3.6	4.0	4.3	4.5
d_1	$1.467t_1\left(v - m + \frac{at_1}{2}\right)$			
Occupation of left lane				
t_2	9.3	10.0	10.7	11.3
d_2	$1.467vt_2$			
Clearance length				
d_3	100	180	250	300
Opposing vehicle				
d_4	$0.667d_2$			
Minimum PSD	$d_1 + d_2 + d_3 + d_4$			

Adapted from A Policy on Geometric Design of Highways and Streets. AASHTO, Washington, D.C., 2004, (Pages 120-122, Exhibit 3-5, Equations 3-6 and 3-7).

CHAPTER 3
RESEARCH APPROACH

This chapter describes the research approach used to accomplish the objectives of this study. It describes the preliminary testing procedure and the process for comparing CORSIM outputs to the 2010 HCM outputs and gives detailed information about the files used in the testing procedure. This chapter also describes the criteria used to evaluate the usefulness of different performance measures for the assessment of two-lane highway LOS. It also discusses the procedure used for estimating capacity using CORSIM.

CORSIM and 2010 HCM Comparison

In order to compare the results between the 2010 HCM and CORSIM, it is important to have a comparable set of inputs. Table 3-1 shows an example of common inputs for the HCM and CORSIM and also shows which inputs are not applicable for each method. The inputs in Table 3-1 must have the same values where applicable in CORSIM and the HCM in order to ensure that the conditions are as similar as possible for each of the corresponding HCM and CORSIM testing scenarios.

There are several factors that are inputs in CORSIM, but not in the HCM, that could cause majors differences in the results. These factors include existing upstream conditions, truck type distribution, and passing zone configuration. A facility with a changing grade configuration could also have major effects on the results as the HCM does not have an input for specifying where the grade changes. However, all testing scenarios in this chapter have a constant grade along the entire facility, which eliminates uncertainties with changing grades. Several preliminary tests were run to see which CORSIM inputs for these factors should be used to give similar results to the HCM. These testing procedures are described in the next section.

Preliminary Experimental Designs

There are several inputs required for the HCM that are not applicable in CORSIM and conversely as shown in Table 3-1. The inputs that are not applicable in CORSIM are programmed internally in the algorithms. There are certain factors that have an impact on CORSIM results that are not mentioned in the HCM such as existing conditions upstream of the facility, truck type distribution, and passing zone configurations. Before any major comparison between CORSIM and the HCM was made, preliminary tests for existing conditions upstream of the facility, truck type distribution, and passing lane configuration were performed. Also, a preliminary test was done that compared the speed vs. flow rate relationship and *PTSF* vs. flow rate between CORSIM and the HCM. The results of these tests were used as guidance for matching the CORSIM inputs as closely as possible to the HCM inputs.

Existing upstream conditions

When analyzing a facility in the HCM, there are preexisting conditions upstream of the facility such as platoon structure on some unknown length of roadway. The HCM was based on TWOPAS simulation where one of the inputs was percentage of traffic flow entering as platoons. This established the incoming traffic conditions for the analysis facility. In CORSIM, vehicles are generated from an entry node and no upstream conditions have been established. This has a large impact on the entering platoon structure, especially for short facilities with low traffic volumes because the vehicles are spaced out when they are generated and can possibly move through the entire facility before coming near other vehicles. This could lead to an unrealistically low

PTSF. In order to have accurate results, there needs to be a lead up length to the facility that allows platoons to form and incites vehicles to interact prior to the section of roadway for which data will be collected. There should also be a follow up length that is identical in distance to the lead up length in an effort to have similar traffic conditions coming from both the eastbound and westbound directions. The results of the analysis for any facility should then only be extracted from the links that make up the analysis facility and not from the lead up or follow up segments.

Three different facility lengths were tested with varying lead up lengths in order to determine what the lead up length should be and how the performance measures were affected. The facilities have lengths of three, five, and ten miles. Each facility was tested with different lead up lengths ranging from one to six miles. The three facilities were tested with passing allowed and passing not allowed. Table 3-2 shows the general input values used in CORSIM and a sample schematic for the three-mile long facility is shown in Figure 3-1.

Truck type

The HCM has an input for the percentage of trucks, but does not allow the analyst to specify what types of trucks make up that percentage. CORSIM has an input for the percentage of trucks and also allows the analyst to specify which types of trucks make up that percentage. The truck types range from 3 to 6. Type 3 indicates single unit trucks that are 35 ft long. Type 4 trucks have a medium-sized load and are 53 ft in length. Type 5 trucks are fully-loaded with a length of 53 ft, and type 6 trucks are 64 ft long double-bottom trailers (*3*).

Trucks in the traffic stream have a large impact on *ATS*. Several different truck type distributions were tested in CORSIM in order to see how the performance measures are affected. Table 3-3 shows the general input values used for this test and Table 3-4 shows the truck type distributions that were tested. Figure 3-2 shows the no-passing zone configuration for this test. These tests were each performed with a lead up length based on the results of the lead up length test. Also, there was a follow up length with a length based on the results of the upstream segment length test. The results of this truck type test were only extracted from the links that made up the analysis facility and not from the lead up or follow up segments.

Passing zone configuration

The HCM allows the user to specify that the facility has some percentage of no-passing zones. However, CORSIM specifies passing zones on a link by link basis. In CORSIM, the user can select exactly where the no-passing zones are located. The HCM does not allow the user to select where the no-passing zones are along the facility. Therefore, even when both methods have the same percentage of no-passing zones, the configuration is ambiguous. This problem could potentially lead to differences in the performance measure results.

Three different no-passing zone configurations were tested in CORSIM for a 10-mile long facility with 50% no-passing zones as shown in Table 3-5. These configurations were all tested against a variety of traffic flow rates ranging from 100 to 4000 veh/h, each with a 50/50 directional split, in order to see how the performance measures were affected. Table 3-6 shows the general inputs for this test.

Speed vs. flow rate relationship and *PTSF* vs. flow rate

There have been claims (*5*, *8*) that the HCM speed vs. flow rate relationship does not accurately reflect what is happening in the field. Also, Luttinen's (*6*) study shows that the HCM overestimates *PTSF*. Before doing the major comparison between the HCM and CORSIM, the speed vs. flow rate and *PTSF* vs. flow rate relationships between the HCM and CORSIM were tested under the conditions shown in Table 3-7, for both passing allowed and passing not allowed. The speed vs. flow rate and *PTSF* vs. flow rate relationships for a 50% no-passing zone were tested in the passing zone configuration test.

CORSIM/HCM Experimental Design

The procedure that was chosen for comparing the 2010 HCM to CORSIM was to use the same inputs for both tools, to the extent possible, and compare the outputs. A wide range of inputs was used to analyze how these two methods compared to each other for a variety of situations. A variety of combinations was used to see if there was a certain scenario that showed drastically different results from the other scenarios. This experiment involves variations of the directional volumes, heavy vehicle percentages, grades, no-passing zone percentages, and the presence or absence of a passing lane. The input values that were selected for the comparison are described in this section.

Flow rates and splits

Six different two-way flow rates were used in this experiment in order to capture possible differences with low, medium, and high volumes. The values used were 200, 700, 1200, 1700, 2200, and 3200 veh/h. These six volumes were each analyzed under three different splits, 50/50, 60/40, and 70/30. The base conditions were 0% heavy vehicles, 0% no-passing zones, and 0% grade.

Percent heavy vehicles

Two different percentages of heavy vehicles were used in this experiment in order to analyze the changes in performance measures due to heavy vehicles and to analyze the effects of heavy vehicles on attempted passes. The heavy vehicle percentages that were used were 0% and 10%. These values were chosen because the performance measures are expected to show a noticeable change for an increase from no trucks to 10% trucks in the traffic stream. All heavy vehicles are assumed to be trucks and not recreational vehicles. The base conditions were modified to incorporate the increased truck percentage in the traffic stream. The truck type distribution is based on the results of the preliminary truck type distribution test.

Grades

Two different grades were used in this experiment because upgrades can have a large impact on truck speeds and this variation in grade is expected to have a large effect on the number of platoons, attempted passes, and following vehicles. The values that were chosen for grade were 0% and 6%. The slope of 6% was added as a test variable by building on the previous cases, which included the base conditions and the cases that incorporated the percentage of heavy vehicles.

Percent no-passing zones

The percentage of no-passing zones is another variable that affects two-lane highway performance measures. The 2010 HCM and CORSIM have different methods for inputting the percentage of no-passing zones. The differences between these two tools make it impossible to ensure that the two-lane highway analyzed in the 2010 HCM is the same as the two-lane highway created in CORSIM.

In the 2010 HCM, the percentage of no-passing zones is accounted for in the percent no-passing zone adjustment factor, f_{np}, which is different for *ATS* and *PTSF* calculations. However, the 2010 HCM does not specify which section of the highway is a no-passing zone. It only specifies that, somewhere along the highway, a certain percentage is a no-passing zone.

CORSIM does not include a direct input for the percentage of no-passing zones. Instead, the user specifies what the center-line striping condition is for each link (passing allowed in one-direction, passing allowed in both directions, or passing not allowed in either direction). For example, to specify a 50% no-passing zone on a ten-mile long highway segment with ten one-mile links, the user could select no passing allowed on the first five links and passing allowed on the last five links. The user could choose any five links to allow no passing and it would still be a 50% no-passing zone. The advantage in CORSIM is that the user can chose the passing zone configuration or where the passing zone section is located along the highway. The preliminary test for passing configuration was also used to compare the two tools' sensitivity to this factor.

The other passing zone scenarios that were tested in this experiment, besides 0%, were 50% and 100% no-passing zones. These changes were made in the existing files of the previously-tested cases, which all consisted of 0% no-passing zones. In CORSIM, the segments that were changed from 0% no-passing zones were the ones closest to the eastbound entry node. For example, the 50% no-passing zone case would have five miles of no-passing allowed closest to the eastbound entry node and would continue with five miles of passing allowed. Links with passing allowed in one direction were not tested in this study.

Passing lanes

This experiment also tested the effects of passing lanes on two-lane highway performance measures. All the scenarios described previously had no passing lanes. Changes were made to those scenarios to incorporate a passing lane with a length of 5280 feet.

There are 432 different trials based on all of the different combinations of four volumes, three directional splits, three percentages of heavy vehicles, three percentages of no-passing zones, two grades, and two passing lane length scenarios. Table 3-8 shows a summary of all the variable combinations being used for this study.

The 2010 HCM methodology was programmed into a numerical calculations worksheet and every scenario was analyzed. The numerical calculations worksheet allowed quick and easy changes to be made to the inputs for each testing scenario.

CORSIM Testing Facility

The CORSIM two-lane highway testing facility used in this experiment is ten miles long. The peak hour demand volume for the analysis direction is generated from node 8100 and travels eastbound. The opposing demand volume is generated from node 8200 and travels westbound. The passing lane scenarios have one passing lane that is one mile in length. The passing lane runs along the eastbound direction of the highway and is the fifth link away from node 8100. There are four one-mile upstream links and five one-mile downstream links. Figure 3-3 shows the CORSIM two-lane highway schematic. Ten runs were executed in CORSIM for each testing scenario and the average *PTSF* and *ATS* for the ten runs was recorded.

Capacity

CORSIM was used to estimate the capacity of two-lane highways, for combinations of the following variables:

- *FFS* of 55, 60 and 65 mi/h
- Heavy vehicle percentages of 0% and 10%
- Splits of 50/50, 60/40, and 70/30
- No passing lanes passing lanes

The general approach for each of these conditions was to specify an input volume that clearly exceeded capacity. Then, the throughput was measured at the end of the facility. The highest average throughput from ten runs in CORSIM that was measured was taken as the facility capacity. All test scenarios had 0% no-passing zones and the minimum entry headway was specified as 1.6 seconds.

The two-way capacity may not necessarily be equal to twice the directional capacity. For two-way capacity, there are few passing opportunities, if any, because of the high traffic volumes in both directions. For directional capacity, the volume in the opposing direction could be close to zero, which means there will be plenty of opportunities for vehicles to pass and reconfigure themselves into new platoons as long as there are appropriate gaps for the passing vehicles to move back into in the original lane. With a low volume in the opposing direction, one-way capacity could be higher than half of the two-way capacity because impeded vehicles can potentially join faster platoons, which increases the throughput.

Performance Measures

Another task of this study was to determine if other performance measures, as proposed in the literature, could reasonably be used to evaluate the LOS of two-lane highways. A conceptual evaluation of different performance measures that have been proposed in the literature was conducted. The performance measures included in the qualitative analysis were *PTSF* (with a deterministic and probability-based method for follower identification), *ATS*, *PI*, follower density, freedom of flow, and overtakings. The procedure for this qualitative analysis was to compare advantages and disadvantages for each performance measure as discussed in the literature. The ease of calculation and field measurement for each performance measure were ranked along with other categories. The highest-ranked performance measure was analyzed quantitatively.

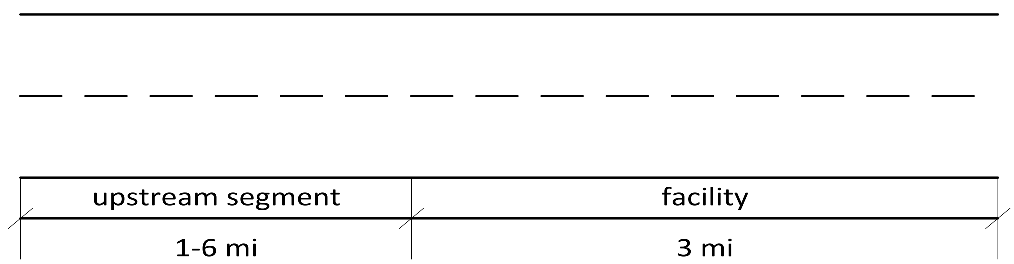

Figure 3-1. Schematic of CORSIM lead up length test for three-mile facility

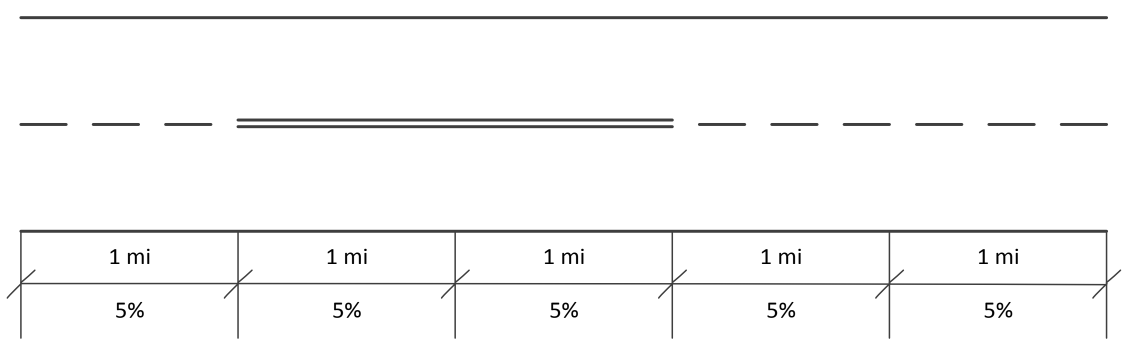

Figure 3-2. Schematic of CORSIM truck type distribution test facility

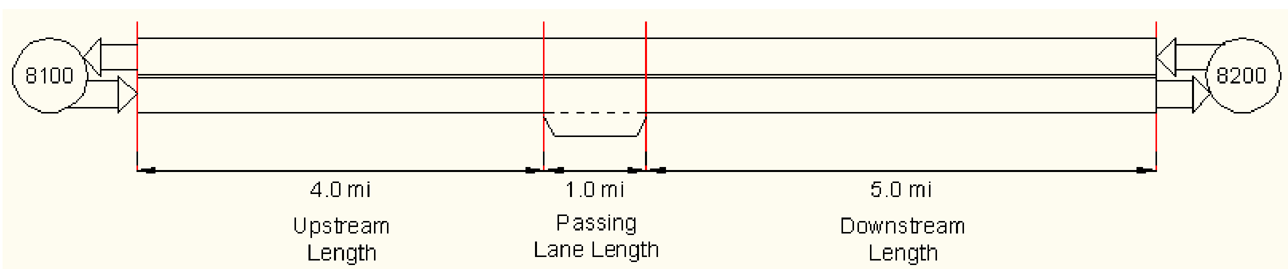

Figure 3-3. Two-lane highway facility in CORSIM with passing lane

Table 3-1. Example inputs for HCM and CORSIM

Inputs	HCM	CORSIM
Geometric data		
facility length (mi)	10	10
lane width (ft)	12	N/A
shoulder width (ft)	6	N/A
access point density (points/mi)	0	N/A
grade (%)	0	0
radius of curvature (ft)	N/A	0
superelevation (%)	N/A	0
percentage of no-passing zones (%)	0	N/A
passing lane length (ft) (if applicable)	5280	5280
highway class	1	N/A
Demand data		
length of analysis period (h)	1	1
PHF	1	N/A
base FFS (mi/h)	60	N/A
FFS (mi/h)	65	65
heavy vehicle percentage (%)	0	0
directional split	50/50	N/A
two-way flow rate (veh/h)	1200	N/A
eastbound flow rate (veh/h)	N/A	600
westbound flow rate (veh/h)	N/A	600

Adapted from Transportation Research Board (TRB). Highway Capacity Manual. TRB, National Research Council, Washington D.C. 2010.

Table 3-2. General CORSIM inputs for lead up length tests

Inputs	Values
grade (%)	0
radius of curvature (ft)	0
FFS (mi/h)	60
heavy vehicle percentage (%)	0
eastbound flow rate(veh/h)	600
westbound flow rate(veh/h)	600

Table 3-3. General CORSIM inputs for truck type distribution tests

Inputs	Values	Values
Geometric data		
facility length (mi)	10	10
grade (%)	0	0
number of links with passing allowed (mi)	0	10
percentage of no-passing zones (%)	100	0
Demand data		
percentage of passenger cars (%)	90	90
percentage of trucks (%)	10	10
FFS (mi/h)	65	65

Table 3-4. Scenarios for CORSIM truck type distribution test

Test	% Type 3	% Type 4	% Type 5	% Type 6
1	50	50	0	0
2	50	0	50	0
3	50	0	0	50
4	25	25	25	25
5	100	0	0	0
6	0	0	0	100
7	50	25	25	0

Table 3-5. Scenarios for CORSIM no-passing zone configuration test

Facility A		Facility B		Facility C	
Link length (mi)	Passing allowed	Link length (mi)	Passing allowed	Link length (mi)	Passing allowed
5	N	2.5	N	1	N
5	Y	2.5	Y	1	Y
		2.5	N	1	N
		2.5	Y	1	Y
				1	N
				1	Y
				1	N
				1	Y
				1	N
				1	Y

Table 3-6. General CORSIM inputs for no-passing zone configuration test

Inputs	Values
Geometric data	
facility length (mi)	10
number of links	20
link length (mi)	0.5
grade (%)	0
percentage of no-passing zones (%)	50
Demand data	
percentage of passenger cars (%)	100
percentage of trucks (%)	0
FFS (mi/h)	60

Table 3-7. General input for speed-flow relationship and PTSF vs. flow rate test

Inputs	HCM	CORSIM
Geometric data		
facility length (mi)	5	5
lane width (ft)	12	N/A
shoulder width (ft)	6	N/A
access point density (points/mi)	0	N/A
grade (%)	0	0
radius of curvature (ft)	N/A	0
superelevation (%)	N/A	0
Demand data		
PHF	1	N/A
FFS (mi/h)	65	65
directional split	50/50	N/A
heavy vehicle percentage (%)	0	0

Table 3-8. Variables used in HCM and CORSIM testing

Flow rates (veh/h)	Splits	% HV	% NPZ	% Grade	Passing lane length (ft)
200	50/50	0	0	0	0
700	60/40	10	50	6	5280
1200	70/30	-	100	-	-
1700	-	-	-	-	-
2200	-	-	-	-	-
3200	-	-	-	-	-

CHAPTER 4
RESULTS

Preliminary CORSIM Test Results

Three main preliminary tests were done in CORSIM for guidance on how to properly compare the 2010 HCM with CORSIM. The CORSIM values that best reflected what the HCM most likely assumes were chosen as the inputs for the main CORSIM and HCM comparison after analyzing the results of these tests. This section discusses the results of each preliminary test.

Existing Upstream Conditions

For the case with a lead up length that allows passing and a follow up length that does not allow passing, the analysis direction showed a significantly higher number of total passes on the lead up segment and along the whole facility. Most of the passes were happening on the lead up segment. Although the opposing direction had many platoons by the time the vehicles reached the lead up segment, the analysis direction vehicles were generated with spacing that led to inadequate passing gaps for the opposing direction vehicles. Therefore, the opposing direction traffic could not pass even though most of them were in platoons.

The analysis direction vehicles were generally not in long platoons on the lead up segment because they had just been generated from the eastbound node. However, even when one vehicle was following for a short amount of time, the vehicle was quickly able to pass because of the long gaps between the westbound platoons. Figure 4-1 shows a screenshot of this phenomenon. In order to prevent lopsided passing, both the lead up and follow up segments were specified as no-passing zones. The performance measures were almost the same between the two directions for both the lead up and follow up segments being specified as no-passing zones as shown in Table 4-1.

The *PTSF* results were almost the same for all three facilities for lead up lengths between two and five miles long for passing allowed as shown in Figure 4-2. For no-passing allowed, the plots of *PTSF* for each facility follow the same general pattern, but the *PTSF* increased as facility length increased for all of the lead up lengths that were tested as shown in Figure 4-3. However, the difference in *PTSF* between the three facilities decreased as the lead up length increased.

ATS was unaffected by whether or not there was a lead up segment as shown in Figure 4-4 and Figure 4-5. A lead up length of five miles was chosen because it led to a small difference in the *PTSF* results for both passing allowed and passing not allowed. This allowed the five-mile lead up segment to be used for all passing zone scenarios. Five miles was also chosen as the follow up segment length in order to maintain symmetry in the facility.

It is necessary to have a lead up segment in CORSIM because existing traffic conditions need to be established prior to the data collection section. Figure 4-6 shows the difference in *PTSF* for facilities with a five-mile lead up segment and facilities with no lead up length when passing is allowed and Figure 4-7 shows the results for facilities where passing is not allowed. The short facilities are affected more than the long facilities by the presence or absence of a lead up segment for both passing zone scenarios.

Truck Type Distribution

Seven different truck type splits were tested and each scenario that had some percentage of type 6 trucks had results that were considerably different from the scenarios with no type 6 trucks. These scenarios included test 3, 4, and 6. The type 6 trucks cause the *PTSF* to be high and *ATS* to be low compared to the HCM results. Tests 1, 2, 5, and 7 matched up closely to the HCM results for *PTSF* for both passing allowed and passing not allowed as shown in Figure 4-8 and Figure 4-9.

All seven tests either underestimated or overestimated the HCM results for speed. The HCM shows a linear relationship between speed and flow while the CORSIM truck type tests all showed a curve shape that initially has a fairly steep negative slope for low flow rates and then the curve slope decreases to the point where it is fairly flat over the moderate to high flow rates, which supports Luttinen's (*5*) and Brilon and Weiser's (*8*) findings about the speed-flow relationship on two-lane highways. Tests 1, 2, 5, and 7 showed *ATS* results that were higher than the HCM estimates and tests 3, 4, and 6 showed results that were lower than the HCM estimates for both passing allowed and passing not allowed as shown in Figure 4-10 and Figure 4-11. The test 1 and test 5 values are very close to the test 2 and test 7 values. Therefore, the test 1 and test 5 curves are somewhat overlapped in the figures by the test 2 and test 7 curves. Ultimately, the test 7 truck percentage split was chosen to be used for the major comparison of the HCM and CORSIM because it has the most realistic distribution of truck types and matched better than the other tests for all four of the figures shown.

Passing Zone Configuration

The average *PTSF* for all three facilities matched up well with the HCM estimates as shown in Figure 4-12. This contradicts Luttinen's (*6*) findings, which showed that the HCM overestimated *PTSF*. As the flow rate increases, the *PTSF* increases rapidly for the lower flow rates, but then levels off to a gentler slope for the higher flow rates. The average *ATS* was similar between all three facilities, but did not match up well with the

HCM estimate for *ATS*. The HCM shows that the *ATS* follows a linear decreasing line, while all three facilities showed that the *ATS* followed a curve shape that initially has a fairly steep negative slope for low flow rates and then the curve slope decreases to the point where it is fairly flat over the moderate to high flow rates as shown in Figure 4-13. The curves began to level off after the flow rate reached 1200 veh/h. Figure 4-13 is consistent with other sources (*5*, *8*) where the speed-flow curve was found to decrease sharply at first, then level off to a gentler slope rather than follow a linear trend as the HCM predicts.

Since the results for *PTSF* and *ATS* were similar between all three facilities, facility A was chosen as the 50% no-passing zone configuration for the major HCM and CORSIM comparison. Facility A was chosen because it is the simplest of the three facilities with the first five miles being specified as a no-passing zone and the last five miles being specified as a passing zone. Any of the facilities would have been adequate for the major comparison since the passing zone configuration does not have an impact on the average of the performance measure results.

Speed vs. Flow Rate and *PTSF* vs. Flow Rate Relationship

The HCM and CORSIM show similar results for *PTSF* vs. flow rate for their respective passing zone specifications as shown in Figure 4-14. The HCM does not consistently overestimate *PTSF* for either passing zone configuration. The results are inconsistent with Luttinen's (*6*) claim. The speed vs. flow relationship between the HCM and CORSIM is drastically different as shown in Figure 4-15. The HCM shows that *ATS* decreases in a linear fashion as flow rate increases while CORSIM shows that *ATS* has a curve shape that initially has a fairly steep negative slope for low flow rates and then the curve slope decreases to the point where it is fairly flat over the moderate to high flow rates. These results are consistent with Luttinen's (*5*) findings and Brilon and Weiser's (*8*) findings.

2010 HCM and CORSIM Comparison Results

Each combination of variables described in Table 3-8 were tested in CORSIM and the 2010 HCM. The *PTSF* and *ATS* were plotted against two-way flow rate for the three different splits to allow for easy comparison of the HCM and CORSIM. This process was repeated for all three passing-zone cases, both grade cases, and both percentages of heavy vehicles for scenarios with no passing lane. For the cases with passing lanes, performance measures were plotted against facility length for the 60/40 split only. The results of this test are discussed in this section.

0% No-Passing Zone with 0% Grade

The 2010 HCM and CORSIM followed the same increasing trend for the *PTSF* plots for both 0% and 10% heavy vehicles as shown in Figure 4-16 and Figure 4-17. When the two-way flow rate reached 3200 veh/h, the HCM showed a *PTSF* estimate of 98.6% for the 70/30 split while CORSIM showed a *PTSF* estimate of 91.1%. It is unrealistic that the *PTSF* would be nearly 100% because the traffic stream always breaks up into several platoons due to slow trucks. Figure 4-18 shows the platoon structure for a two-way flow rate of 3200 veh/h under a 70/30 directional split. Although the directional flow rate is 2240 veh/h, there are still some gaps between vehicles.

The *ATS* plots are consistent with the preliminary speed-flow tests. The HCM has a linear decreasing trend and CORSIM has a curve shape that initially has a fairly steep negative slope for low flow rates and then the curve slope decreases to the point where it is fairly flat over the moderate to high flow rates for both 0% and 10% heavy vehicles. The *ATS* values are similar between 0% and 10% heavy vehicles. The ATS plots are shown in Figure 4-19 and Figure 4-20. The plots show that flow rate may not have such a large effect on speed as the HCM shows.

0% No-Passing Zone with 6% Grade

For 0% heavy vehicles, CORSIM showed higher *PTSF* results than the HCM for flow rates lower than 1700 veh/hr. For flow rates higher than 1700 veh/h, the HCM showed higher values for *PTSF* than CORSIM. The trend for *PTSF* is similar between the two tools. For 10% heavy vehicles, the HCM shows the same general trend, but the values for *PTSF* are higher because grade has a large effect on truck speeds and slow-moving trucks cause platoons to form. The HCM *PTSF* value at 3200 veh/h for the 70/30 split is 99.9%, which is unrealistic. The reason may be that the HCM equations are not valid for two-lane highways after breakdown.

In CORSIM, the *PTSF* results at 200 veh/h are about 50% higher than the HCM results for a 50/50 directional split and about 60% higher than the HCM results for the 60/40 and 70/30 directional splits for 10% heavy vehicles. For flow rates higher than 700 veh/h, the *PTSF* is consistently near 95% for the CORSIM curve while the HCM trend is similar to the 0% heavy vehicle case. The values given by CORSIM seem unreasonably high, especially for the lower flow rates. The *PTSF* values are high because long platoons form on the upgrade and the vehicles travel at high speeds on the opposing-direction downgrade. Therefore, there are few gaps for passing opportunities because the opposing vehicles arrive frequently. The *PTSF* plots are shown in Figure 4-21 and Figure 4-22.

For 0% heavy vehicles, CORSIM and the HCM had the same trends and values for *ATS* as with the 0% grade. For 10% heavy vehicles, the HCM *ATS* values generally followed a linear decreasing path. The directional splits showed slight differences in

ATS for values before the flow rate of 1700 veh/h. At a flow rate of 3200 veh/h, the speed drops to an unreasonably low value of 4.7 mi/h. The *ATS* plots are shown in Figure 4-23 and Figure 4-24.

The CORSIM results for *ATS* for 10% heavy vehicles followed the same trend as the 0% grade scenario, but the values for *ATS* were much lower. These low *ATS* values are caused by slow-moving trucks in the traffic stream due to the grade. Even for low traffic volumes, there are few opportunities to pass because the vehicles in the opposing direction are on a 6% downgrade. They are traveling at high speeds so vehicles cannot be in the opposing lane very long before the oncoming vehicle approaches and, as a result, vehicles in the major direction have inadequate time to pass. For a flow rate of 200 veh/h, the CORSIM *ATS* for a 50/50 split was higher than the CORSIM *ATS* for a 60/40 split and a 70/30 split. In order to further investigate the CORSIM *PTSF* and *ATS* results for 10% heavy vehicles on a 6% grade, two additional splits, 40/60 and 30/70, were analyzed. The results are shown in Figure 4-25 and Figure 4-26.

There was a greater difference between the splits for the flow rates of 200 and 700 veh/h. Then, the curves for all splits converged to about 96% for *PTSF* and about 23 mi/h for *ATS*. The performance measures are more sensitive to splits for lower flow rates because the number of vehicles in the traffic stream is major factor for vehicle interactions, which affects platooning. Vehicles are generated more frequently for a 70/30 split than for a 30/70 split. One slow truck in the 70/30 split traffic stream impedes all subsequent vehicles. There are fewer total vehicles to be affected by a slow truck in the 30/70 split.

50% No-Passing Zone with 0% Grade

The 2010 HCM and CORSIM followed the same trend for 50% no-passing zones as for the corresponding 0% no-passing zone plots for *PTSF* for both 0% and 10% heavy vehicles as shown in Figure 4-27 and Figure 4-28. However, the HCM 70/30 split has more separation from the other splits for CORSIM and the HCM than in the 0% no-passing zone case. This is especially true at the flow rate of 2200 veh/h. The HCM and CORSIM followed the same trend for 50% no-passing zones as for the corresponding 0% no-passing zone plots for *ATS* for both 0% and 10% heavy vehicles as shown in Figure 4-29 and Figure 4-30.

50% No-Passing Zone with 6% Grade

The HCM and CORSIM *PTSF* curves have a more similar slope for 0% heavy vehicles than for the 0% no-passing zone case. The HCM curve for the 70/30 directional split shows the greatest values for *PTSF* and is slightly separated from the other curves. Overall, the *PTSF* values are higher for 50% no-passing zones than the *PTSF* values for 0% no-passing zones because there are fewer passing opportunities in the 50% no-passing zone case.

For 10% heavy vehicles, the HCM and CORSIM followed the same trend for 50% no-passing zones as for the corresponding 0% no-passing zone plots. However, the HCM curves have more separation between themselves and the CORSIM 60/40 split is more separated from the CORSIM 70/30 split at the flow rate of 200 veh/h. The CORSIM *PTSF* values for the 50/50 and 70/30 split are higher than for the 0% no-passing zones case and the 60/40 split is lower for the flow rate of 200 veh/h. The *PTSF* plots are shown in Figure 4-31 and Figure 4-32.

The *ATS* plots for 0% and 10% heavy vehicles are similar to the 0% no-passing zones case. For 10% heavy vehicles, the *ATS* value for the CORSIM 60/40 split is about 5 mi/h higher at the flow rate of 200 veh/h than for 0% no-passing zones. The *ATS* plots are shown in Figure 4-33 and Figure 4-34.

100% No-Passing Zone with 0% Grade

The HCM and CORSIM *PTSF* curves are much closer together for 100% no-passing zones for both 0% and 10% heavy vehicles than for the 50% no-passing zone case. The HCM 50/50 split shows the highest separation from the other curves. The HCM curves level off at lower *PTSF* values than the other two no-passing zone scenarios. The highest *PTSF* value reached for both heavy vehicle percentages is near 95% rather than 100%. *PTSF* shows improvement for 100% no-passing zones because the value for the no-passing zone adjustment factor must be extrapolated from Exhibit 15-21 in the 2010 HCM when the two-way flow rate is greater than the highest value in the table. This could potentially lead to a negative no-passing zone adjustment factor, which would cause the *PTSF* to improve. The *PTSF* plots are shown in Figure 4-35 and Figure 4-36. The HCM and CORSIM followed the same trend for 100% no-passing zones as for the 0% and 50% no-passing zone cases for *ATS* for both 0% and 10% heavy vehicles The *ATS* plots are shown in Figure 4-37 and Figure 4-38.

100% No-Passing Zone with 6% Grade

The HCM and CORSIM *PTSF* curves are closer together for the 100% no-passing zone case for 0% heavy vehicles than for the 0% and 50% no-passing zone cases. Overall, the *PTSF* values are higher, but the maximum values reached for any curve are lower than the values reached by curves in the other two no-passing zone cases. The plot is shown in Figure 4-39. For the 10% heavy vehicle case, The HCM 50/50 directional split curve has more separation from the other two HCM curves than in the 0% and 50% no-passing zone cases. Also, the CORSIM 60/40 curve overlaps the CORSIM 70/30 split curve from the flow rate of 200 veh/h to the flow rate of 700 veh/h as in the 0% no-passing zone case. For the lower flow rates, the PTSF values were all slightly higher than the values given for the other two no-passing zone cases. The plot is shown in Figure 4-40.

The *ATS* curves for CORSIM and the HCM have trends and values that are similar to the other no-passing zone cases for both percentages of heavy vehicles. However, the CORSIM 60/40 split overlaps the CORSIM 70/30 split curve from the flow rate of 200 veh/h to the flow rate of 700 veh/h as in the 0% no-passing zone case. The plots are shown in Figure 4-41 and Figure 4-42.

Passing Lanes

The *ATS* average for all passing lane scenarios is slightly higher than the corresponding no passing lane scenarios in both CORSIM and the HCM, but within about one mi/h. The *PTSF* values were affected more than *ATS* by the passing lane in both tools. CORSIM showed improvements as high as 17%, which were higher than the HCM's greatest improvements at 13%. The CORSIM results showed that the total *PTSF* improvements increased as the percentage of no-passing zones increased and that the improvements were greater for lower flow rates.

The performance measures for the passing lane scenarios were analyzed using CORSIM based on the position along the highway in order to evaluate how a passing lane affects *PTSF* and *ATS*. Since the no passing lane scenarios did not show much variation between splits, only the 60/40 split scenarios were plotted. This split was chosen to be plotted because it is the median between the perfectly even distribution of 50/50 and the biased distribution of 70/30.

The *ATS* values decreased at the passing lane link for all no-passing zone cases for the higher volumes. This is counterintuitive, but there is a logical explanation. For the higher volumes such as 2200 veh/h and 3200 veh/h, most of the vehicles are in platoons throughout the entire facility because of a slower truck. Most of the vehicles in the platoons are passenger cars, which are capable of traveling at much higher speeds than trucks, especially when there is a 6% grade. As soon as the platoon reaches the passing lane section, most of the slow trucks move to the outside lane and the cars that have been following are able to travel through at their desired speeds. Eventually, the trucks reach the end of the passing lane section and have to merge back into the original lane. When a truck merges back in from the passing lane and continues onto the next link, the cars are trapped again in a platoon behind the truck as shown in Figure 4-43. The cars are almost at a complete stop and back up onto the passing lane link. The link directly after the passing lane link acts as a bottleneck. The plots for each no-passing zone case are discussed in the following sections.

0% no-passing zones

For 0% grade, the *PTSF* values increased as flow rate increased for both heavy vehicle cases. The separation between the curves decreased as flow rate increased with the 200 veh/h curve having the greatest separation from the others. There was a large *PTSF* drop at the passing lane location. This happens because the slow trucks move into the right-hand lane and the cars are able to travel through at their desired speeds. The effects of the *PTSF* reduction lasted further downstream of the passing lane location for the lower flow rates. Overall, the *PTSF* values were higher for the 10% heavy vehicles case. The plots are shown in Figure 4-44 and Figure 4-45.

The *ATS* curves are bunched close together for 0% grade. The passing lane does not have a large impact on speed. There was a slight increase in the *ATS* values after the passing lane for the flow rate of 700 veh/h. The *ATS* values were basically unchanged after the passing lane for the flow rate of 200 veh/h. All other flow rates had an *ATS* drop at the passing lane location. This happens at the higher flow rates because, when trucks merge back into the original lane, the cars are forced to slow down and become part of a slow-moving platoon again. Since the passenger cars are able to travel fast on the passing lane link, they arrive quickly and frequently at the end of that link, but they get backed up because of the slow-moving trucks at the beginning of the next link. The *ATS* plots are shown in Figure 4-46 and Figure 4-47.

For a 6% grade, the *PTSF* trend is similar to the 0% grade trend. The curves are closer together and the values are slightly higher. The 200 veh/h curve still has the greatest separation from the other curves. The *PTSF* drop is larger for the higher flow rates, but the downstream effects last longer for the lower flow rates. For 10% heavy vehicles, the flow rate curves are all close together except for the 200 veh/h curve. The *PTSF* has a large drop at the passing lane location for the flow rate of 3200 veh/h. The plots are shown in Figure 4-48 and Figure 4-49.

The *ATS* values are slightly lower on the 6% grade for the 0% heavy vehicles scenario compared to the 0% grade scenario. For 10% heavy vehicles, the speeds jump at the passing lane location and decrease again for all flow rates except 2200 veh/h and 3200 veh/h. For the flow rates of 2200 veh/h and 3200 veh/h, the *ATS* jumped at the link before the passing lane link. This is because the slow trucks leading the platoons move to the right-hand lane in the passing lane section, which creates a shockwave upstream. The passenger cars are suddenly free to travel at their desired speeds. Passing lanes are a more effective highway improvement method for low flow rates. The plots are shown in Figure 4-50 and Figure 4-51.

50% no-passing zones

For the 0% grade, the trends are almost the same as for 0% no-passing zones. However, the *PTSF* values increased for the first four links in the 50% no-passing zone case whereas the values decreased in the 0% no-passing zone case until the vehicles reached the passing lane. The values increase because the platoons grow larger as the vehicles move through the facility. In the 0% no-passing zone case, the values decreased before the passing lane because the opposing flow rate was low enough that the following vehicles could make use of the passing zones. For the 50% case, passing was not allowed on the links leading up to the passing lane section. Therefore the *PTSF* values grew larger and larger until the passing lane relieved the following vehicles. There was no major difference between the 0% and 10% heavy vehicles cases as shown in Figure 4-52 and Figure 4-53.

For the 0% grade, the *ATS* values increased more sharply due to the effects of the passing lane for the flow rates of 200 veh/h and 700 veh/h than in the 0% no-passing zone case. This is because the links prior to the passing lane link were specified as no-passing zones. Slow trucks on those links caused all the following vehicles to travel at lower speeds until they were finally able to pass on the passing lane link. All flow rates showed a small improvement after the passing lane section for both heavy vehicle percentages. The plots are shown in Figure 4-54 and Figure 4-55.

For the 6% grade, the curves for the *PTSF* plot for 0% heavy vehicles are spaced out with the spacing between them getting smaller as the flow rate increases as shown in Figure 4-56. The *PTSF* values are much higher just before the passing lane. The 200 veh/h curve reached 36.2%, but in the 0% no-passing zone case it only reached 23.8%. The passing lane effects last longer for this no-passing zone case. The *PTSF* values did not return to the values they were at prior to the passing lane section as quickly. For 10% heavy vehicles, the values are the same as the corresponding 0% no-passing zone case except the 200 veh/h curve only returns to 67.4% by the end of the facility rather than 73% as it did for 0% no-passing zones. The plot is shown in Figure 4-57.

For the 6% grade, the *ATS* plots have the same general trend as in the 0% no-passing zone case for 0% heavy vehicles. The curve for the flow rate of 3200 veh/h drops to a lower value at the passing lane than it did in the 0% no-passing zone case and the 200 veh/h flow curve increases after the passing lane as shown in Figure 4-58. For 10% heavy vehicles, the *ATS* values reached the highest point on the link after the passing lane for the flow rate curve for 200 veh/h. That link is a passing zone and the vehicles that come from the passing section have just gotten away from slow trucks. The combination of these two factors is the cause of the ATS highpoint happening on link 6. For the flow curves for 2200 veh/h and 3200 veh/h, the highest point occurs on link 4, which is the link just before the passing zone section. The traffic is extremely congested prior to the passing lane because of the few trucks in the traffic stream impeding all of the other vehicles. As soon as a slow truck reaches the passing lane, the other vehicles are unimpeded and begin traveling at high speeds. This creates a shockwave that propagates through the links prior to the passing lane and link 4 is affected as shown in Figure 4-59.

100% no-passing zones

For the 0% grade, the *PTSF* plots for both heavy vehicle percentages have the same trends and values as the 50% no-passing zone case until after the passing lane. The flow curves return more quickly to the values they were at prior to the passing lanes for this no-passing zone case as shown in Figure 4-60 and Figure 4-61. The passing lane effects do not carry on to the downstream links when passing is not allowed. The *ATS* trends are also similar to the 50% no-passing zone case for both percentages of heavy vehicles except the values return quickly to the values they were at just before the passing lane. The *ATS* plots are shown in Figure 4-62 and Figure 4-63.

For the 6% grade, the *PTSF* results have the same patterns as the 0% grade for 0% heavy vehicles. The 10% heavy vehicles case has the same trends as the 50% no-passing zone case, but for the 100% no-passing zone scenario, the *PTSF* values after the passing lane for the flow rate of 200 veh/h return quickly to the values they were at before the passing lane section. The plots are shown in Figure 4-64 and Figure 4-65.

For 6% grade, The *ATS* trends and values are about the same as for the 50% no-passing zone case for 0% heavy vehicles. For 10% heavy vehicles, the curve for the flow rate of 200 veh/h decreases more sharply after the passing lane section than it does in the 50% no-passing zone case and it decreases to a lower speed by the end of the facility than in the 50% no-passing zone case. The *ATS* plots are shown in Figure 4-66 and Figure 4-67.

Passing Lane Field Observations

In order to compare the CORSIM passing lane procedure to the true field procedure, observations were made on SR-40, where there are several passing lane sections. CORSIM incorporates a passing lane configuration where the slower vehicles make a lane change so faster vehicles can continue through as shown in Figure 4-68. SR-40 had a different passing lane configuration where slow vehicles continue on the original lane and faster vehicles pass to the left. The original lane merges back in later along the road as shown in Figure 4-69.

The field observations were taken on Tuesday, October 5, 2010 and the traffic volume was low. Typically, there were three vehicles in a group entering the passing lane section, including the observation vehicle. The other vehicles treated the passing lane section as if it were two full lanes. They passed to the right if the slower vehicle was not in the right-most lane. There was a case where the observation vehicle was going about 10 mi/h under the speed limit. The observation vehicles stayed in the right-most lane and two vehicles went by in the left-most lane. Then, the second vehicle to go by changed lanes again and stayed in the slow-vehicle lane until it was time to merge. This vehicle was not going slower than the other vehicle that passed. The reason for this second lane change is most likely because that vehicle wanted to be a free vehicle while it was on the two-lane section. In order for the passing lanes to be used by slow vehicles as they were intended, the speed differential needs to be somewhat high. Otherwise, the faster vehicles do not have enough time to pass before the passing lane ends unless they go well over the speed limit.

Capacity Estimate

CORSIM was also used to estimate the capacity of two-lane highways with and without passing lanes. Capacity on a two-lane highway without a passing lane, according to the HCM, is estimated to be 1700 pc/h in one direction and 1500 pc/h in the opposing direction. CORSIM was used to estimate the directional capacity for three different splits and free-flow speeds and two heavy vehicle percentages. Each case was tested with and without a passing lane. Table 4-2 shows the results of the capacity tests for 0% heavy vehicles and Table 4-3 shows the results for 10% heavy vehicles.

For 0% heavy vehicles, the split had a slight impact on the capacities as well as speed. The passing lane did not change the capacity in any case. The passing lane does not improve capacity because the number of vehicles moving through the system is the same even though the passing lane may change how they interact with each other and allow some platoons to reconfigure themselves. For 10% heavy vehicles, the capacity worsens for all cases. The capacity gets worse in CORSIM when there is a passing lane along with trucks because there is congestion at the merge area when vehicles in the passing lane try to move back over. The passing lane makes capacity worse for 10% heavy vehicles, but the results are the same with or without a passing lane for 0% heavy vehicles. The passing lane link essentially detains some of the vehicles and the downstream throughput is affected. When the same number of vehicles moves through the facility without a passing lane, there is nothing causing the vehicles to slow down as the merge section does. Therefore, when there is no passing lane, the last link in the facility shows a higher throughput than when there is a passing lane.

Performance Measures Analysis

A qualitative analysis was performed in order to evaluate the effectiveness and usefulness of each performance measure that was discussed in the literature review. After being analyzed, they were given a score in several categories with 1 being the best and 5 being the worst score attainable. The points were averaged and the performance measures were ranked with 1 being the best ranking and 5 being the worst ranking. The performance measure with the highest ranking was analyzed quantitatively. The advantages and disadvantages of each performance measure that was discussed in the literature review are summarized in this section.

Percent Impeded

PI shows a high change for the addition of a passing lane. Therefore, it is a useful performance measure for reflecting the effects of highway improvements. Also, *PI* is useful for capturing changes due to heavy vehicles in the traffic stream, which is a major cause of platooning. *PI* showed a strong correlation to most platooning variables. This performance measure is limited in that it shows similar results for the analysis direction volume and the opposing direction volume, regardless of the split. This means an additional performance measure, such as *v/c*, may have to be used to determine the LOS.

PI is relatively easy to measure in the field because P_p can be estimated using a minimum headway threshold value and P_i can be determined by collecting speed data for slow-moving and free vehicles (*10*). These measurements can also be found with a simulation program. The *PI* calculation is simply P_p multiplied by P_i.

Probability-Based Follower Identification

Probability-based follower identification is unique in that it determines follower status in a stochastic manner, which is better for capturing driver variability and changes in roadway conditions. Probability-based follower identification is consistent with the expectation that, when the highway is near capacity, it should approach 100%. This performance measure is limited in that it was tested in Japan, which does not allow passing in the oncoming lane. This method may not be accurate for determining the LOS of two-lane highways in the United States because of differences in driver characteristics and other unknown differences (*9*).

Probability-based follower identification is relatively difficult to measure in the field because there are challenges with finding the proportion of constrained vehicles based on headway without using a deterministic method. It is easier to find the following probability based on headway with theoretical models. Also, it is impossible to collect field data on the desired speeds of drivers because they are constantly changing. Some drivers may want to travel at higher speeds than the *FFS* and some drivers may want to travel at lower speeds than the *FFS*, but there is no way for the analyst to collect this data accurately.

Probability-based follower identification is also somewhat difficult to calculate even with theoretical values obtained from models. The headway portion of this performance measure uses a mixed distribution model, known as the SPM, to differentiate between following and free vehicles. This performance measure uses a critical headway, which is the largest headway that a vehicle can still be considered following, to determine following and free vehicles based on the headway distribution. The desired speeds are estimated by assigning different desired speeds to certain roadway conditions. If a vehicles speed falls below the assumed desired speed, then the vehicle is considered to be in a following state. The unified speed distribution method was used to estimate the desired speeds for this performance measure (*9*). Simulation could be used to track each individual vehicle's speed at every second, which could lead to more accurate results for desired speed.

Follower Density

Follower density is a useful performance measure for determining when capacity improvements need to be made (*11*). Volumes in the analysis direction and opposing direction were found to be statistically significant in the follower density models, which is important because traffic flow affects two-lane highway performance measures more than other platooning variables such as opposing flow, percentage of heavy vehicles, percentage of no-passing zones, and speed differential (*10*, *14*). Follower density allows two-lane highway LOS to be compared easily with freeways and multilane highways, which use density as a performance measure. Follower density internally incorporates speed, which means *ATS* would not have to be used as a performance measure (*7*).

Follower density is based on the worst conditions along the highway rather than the average conditions. This makes it easy to pinpoint where improvements need to be made, which can lead to savings in highway-improvement costs. Follower density gives the LOS based on the value of the performance measure for the traffic stream rather than for individual vehicles. This eliminates having a situation where the average LOS is poor even when there are low traffic volumes, leading to unnecessary highway improvements. The traffic stream approach takes traffic density into account, which gives a better indication of when highway improvements should be made (*11*).

Follower density is relatively easy to measure in the field because it is based on the percentage of followers, which is measured at a point. The percentage of followers can be found at different sections of the facility in a deterministic manner. The density can be found based on speed and flow data. Follower density can be easily calculated by multiplying the percentage of followers by density (*11*).

Freedom of Flow

Freedom of flow gives a good representation of drivers' passing opportunities on two-lane highways. This performance measure is closely related to the risk that drivers are willing to take, which means that it captures information about safety. Freedom of flow is limited in that it is a two-way analysis tool. Therefore, it is not reliable for directional analyses. Freedom of flow factors can be easily estimated from existing traffic data and freedom of flow is easy to calculate. The most difficult part of calculating this performance measure is making correct assumptions about the variables used in the formula.

Overtakings

Overtakings focuses on drivers' passing opportunities, which is important in two-lane highway analysis because passing in the oncoming lane is a major two-lane highway characteristic. Overtakings accounts for the effects of passing lanes and the percentage of no-passing zones. This performance measure is useful for identifying highways that need improvements (*13*). Overtaking is limited in that it is not informative about speed or delay. Since speed and delay are very important components of two-lane highway operations, overtakings should only be used as a secondary performance measure for LOS determination (*13*).

The number of achieved overtakings is easy to count in the field with the appropriate equipment. The number of desired overtakings, assuming a continuous passing lane section, is moderately difficult to determine because it is not possible to gather information about each driver’s desire to pass. Desired overtakings can be estimated with a deterministic approach that consists of choosing a maximum time threshold that a vehicle is following before it should always have a desire to pass. The calculation for overtakings is simple. The challenge of this calculation is assuming reasonable and accurate values for the variables.

Qualitative Analysis Results

Probability-based follower identification was given the worst ranking because it is very cumbersome to measure and calculate. Therefore, it is unlikely that professionals could readily apply this method of follower identification to projects. Also, it is based on a specific distribution of headways, which means if the headways on a two-lane highway do not follow that distribution, then the method may not be applicable to that highway. The Catabagan and Nakamura (*9*) study showed that there were many cases where both follower identification methods led to the same results for follower status. For the results that led to differences between the two methods, there was no way to tell which one was correct. Both methods give rough estimates of how the driver feels. Therefore, the more complicated, stochastic method is not well-justified for follower identification compared to the simple, deterministic method.

Freedom of flow was assigned the second worst ranking mainly because of its difficulty to measure in the field. *PI* and overtakings received fours in the category for usefulness in determining LOS. This is because they are meant to be secondary performance measures and should not be used independently to determine LOS.

Follower density was given the highest ranking because of its ease of field data collection and calculation and also because of its usefulness in indicating when and where capacity improvements need to be made. Also, it can be easily compared to performance measures for freeways and multilane highways. Table 4-4 shows the rankings of each of the performance measures that were analyzed.

Quantitative Analysis Results

Follower density was tested in a quantitative analysis because it was the highest-ranked performance measure in the qualitative analysis. The follower density methodology was programmed into CORSIM and is available in the run properties measure of effectiveness screen. The 432 tests that were used to compare *PTSF* and *ATS* between the 2010 HCM and CORSIM were repeated in CORSIM for follower density. Figure 4-70 shows the general trends for all four combinations of grade and percentage of trucks under a 50/50 directional split for 0% no-passing zones and no passing lane. The curves all follow a linear increasing trend. The results of the follower density tests were somewhat counterintuitive for several scenarios. For 0% grade, the follower density was higher for 0% heavy vehicles than for 10% heavy vehicles, especially for the higher flow rates as shown in Table 4-5 and Table 4-6. There were also some cases where the follower density was higher for 0% heavy vehicles than for 10% heavy vehicles for the lower flow rates. The differences were small for the scenarios that had a higher follower density for 0% heavy vehicles than for 10% heavy vehicles.

One explanation for the results is that it was found that heavy vehicles do not perform much differently than passenger cars when there is a 0% grade. The 6% grade scenarios all showed the follower density being higher for 10% heavy vehicles in the traffic stream than for 0% heavy vehicles. This is because the 6% grade has a large impact on heavy vehicle performance. Another reason for these differences may be attributed to traffic streams with heavy vehicles having a lower density than corresponding traffic streams without trucks. Follower density is directly proportional to density. Unlike the HCM, CORSIM deals only in units of vehicles for the traffic stream, not an equivalent number of passenger cars. Trucks occupy more space than passenger cars. Therefore, for the same flow rate, the density of the traffic stream will be lower (considering units of veh/mi/ln) for a traffic stream with a higher percentage of trucks than for a traffic steam with a lower percentage of trucks. Thus, increases in heavy vehicle percentages (consequently reducing the traffic stream density) may, for the most part, offset increases in follower percentage that the trucks usually create.

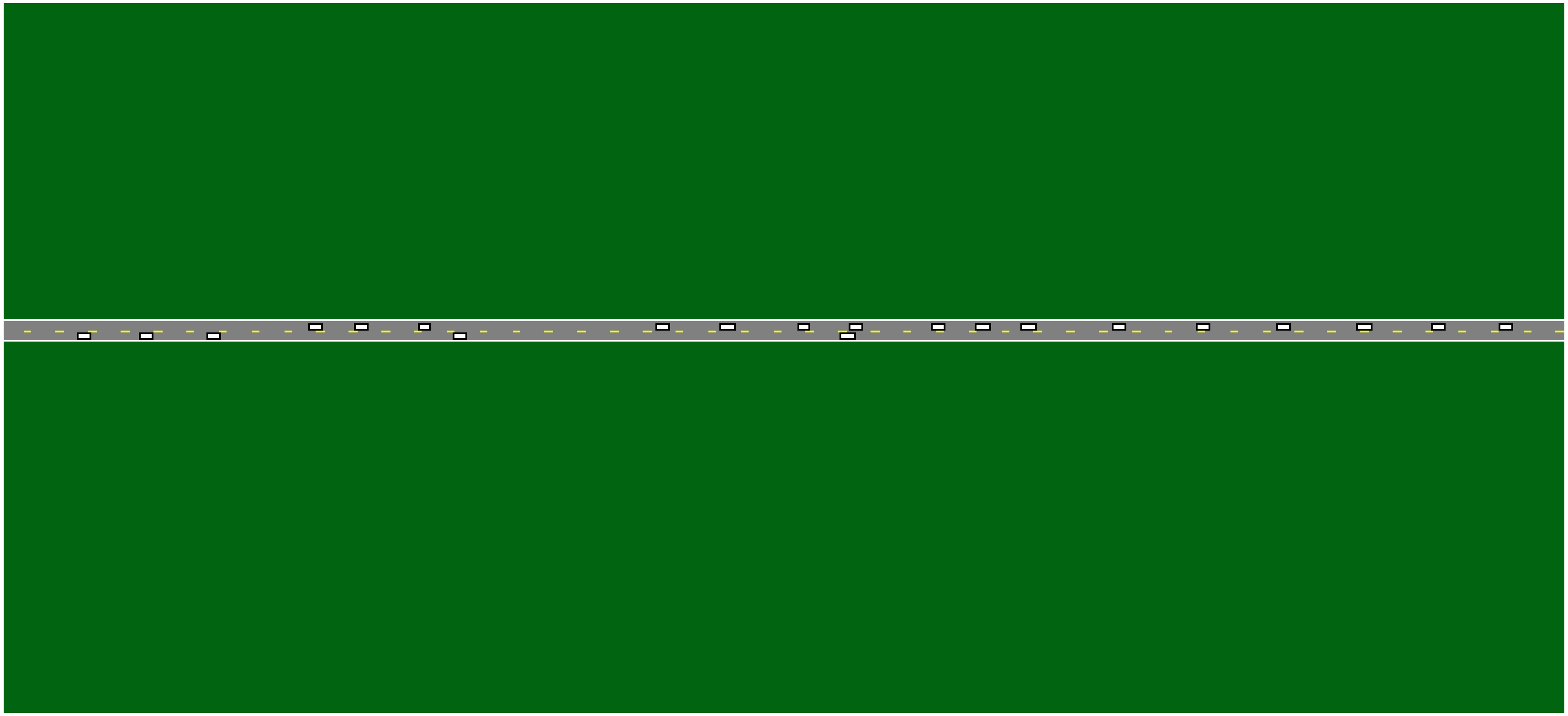

Figure 4-1. CORSIM westbound platoons

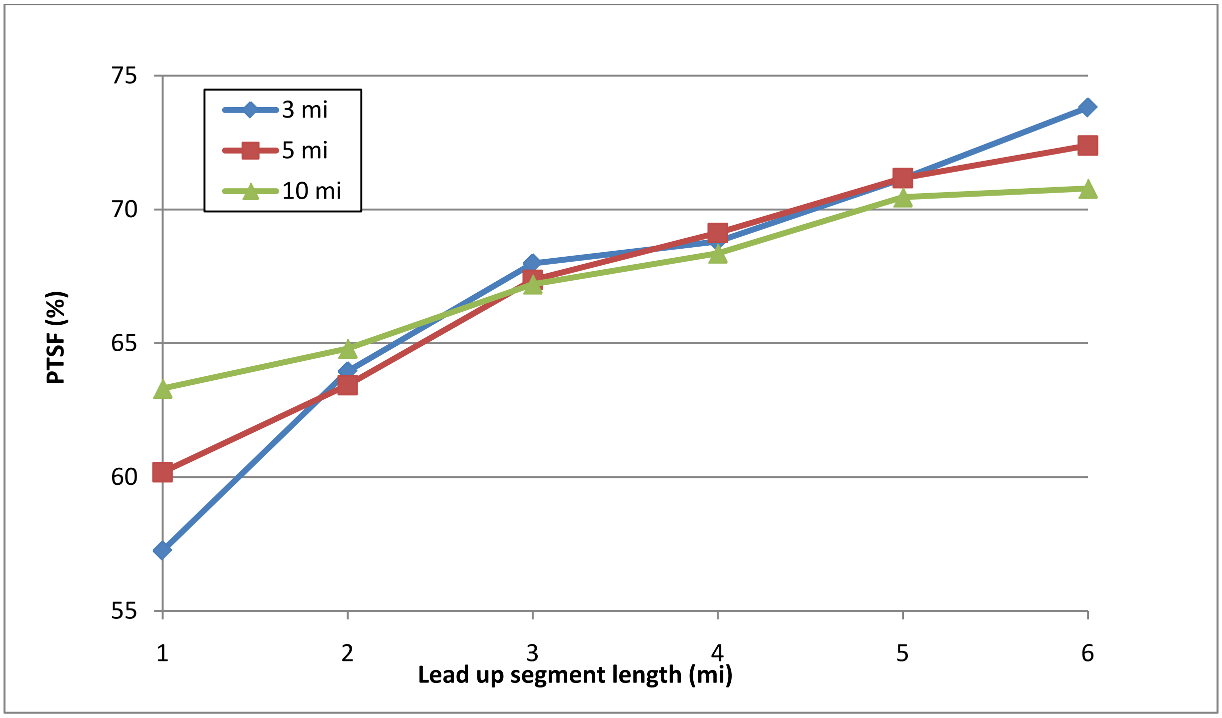

Figure 4-2. Middle segment PTSF for passing allowed

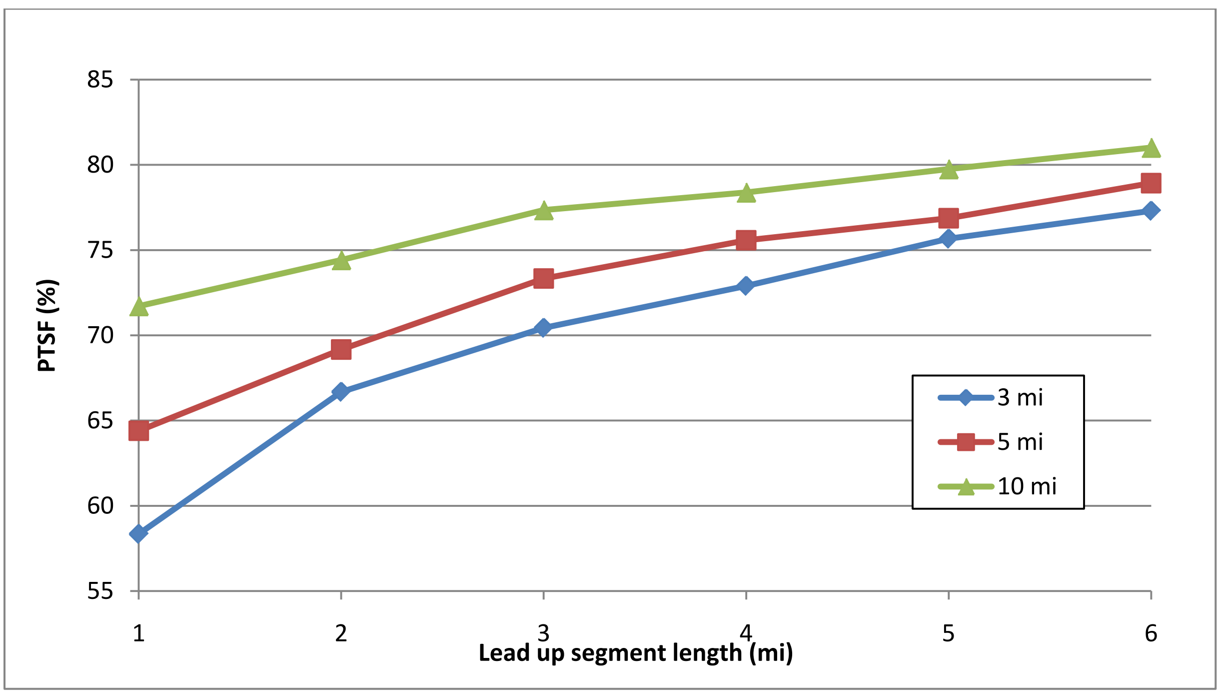

Figure 4-3. Middle segment PTSF for passing not allowed

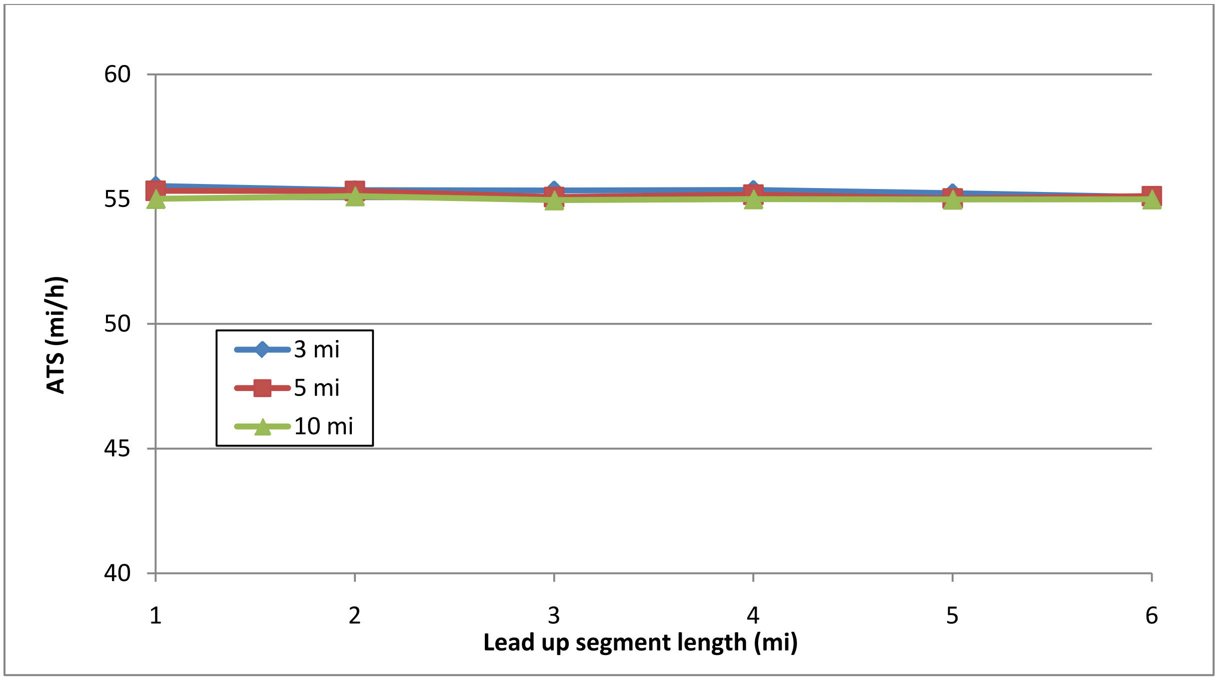

Figure 4-4. Middle segment ATS for passing allowed

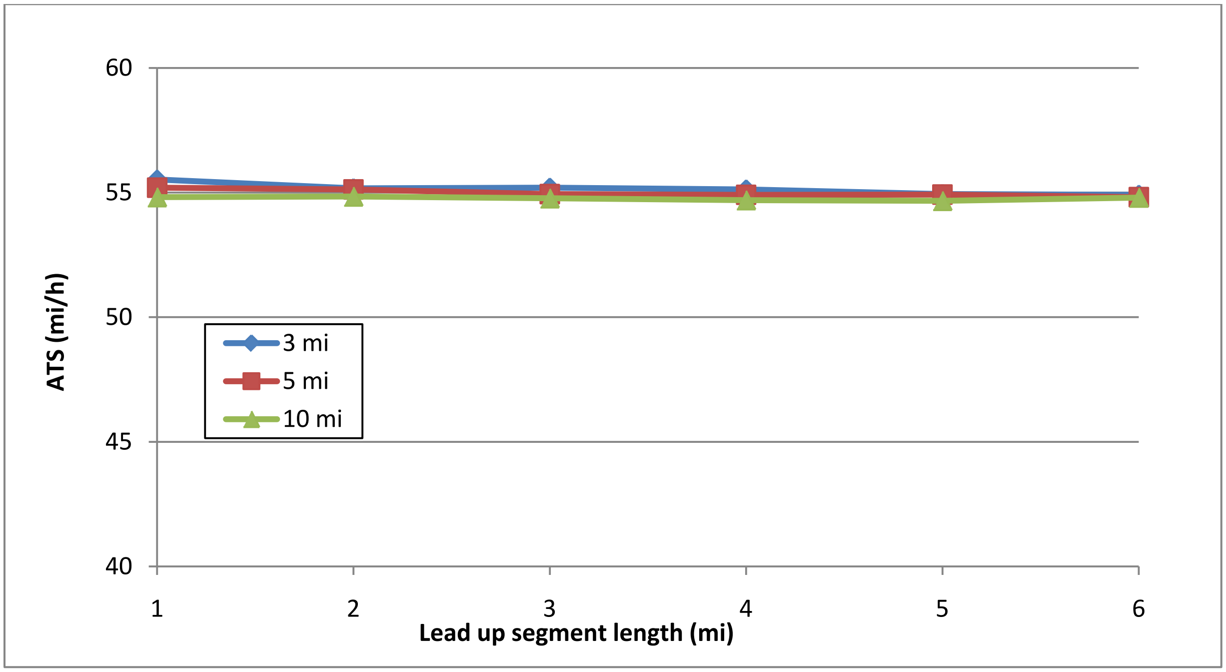

Figure 4-5. Middle segment ATS for passing not allowed

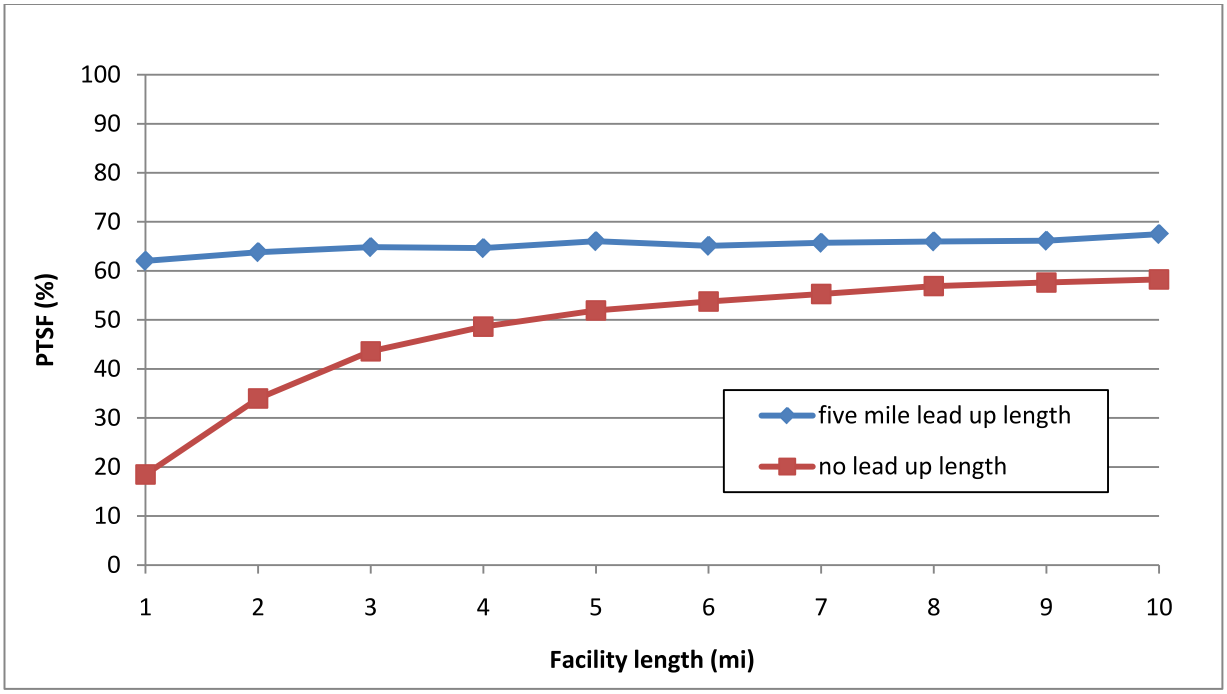

Figure 4-6. PTSF vs. facility length for passing allowed

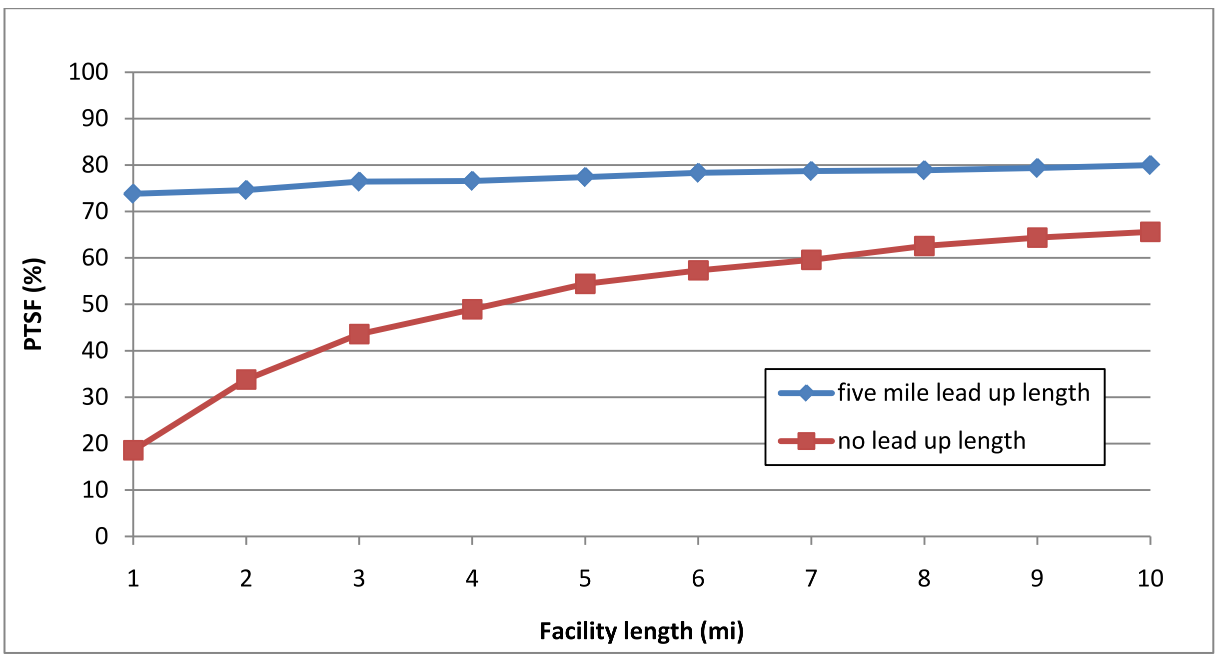

Figure 4-7. PTSF vs. facility length for passing not allowed

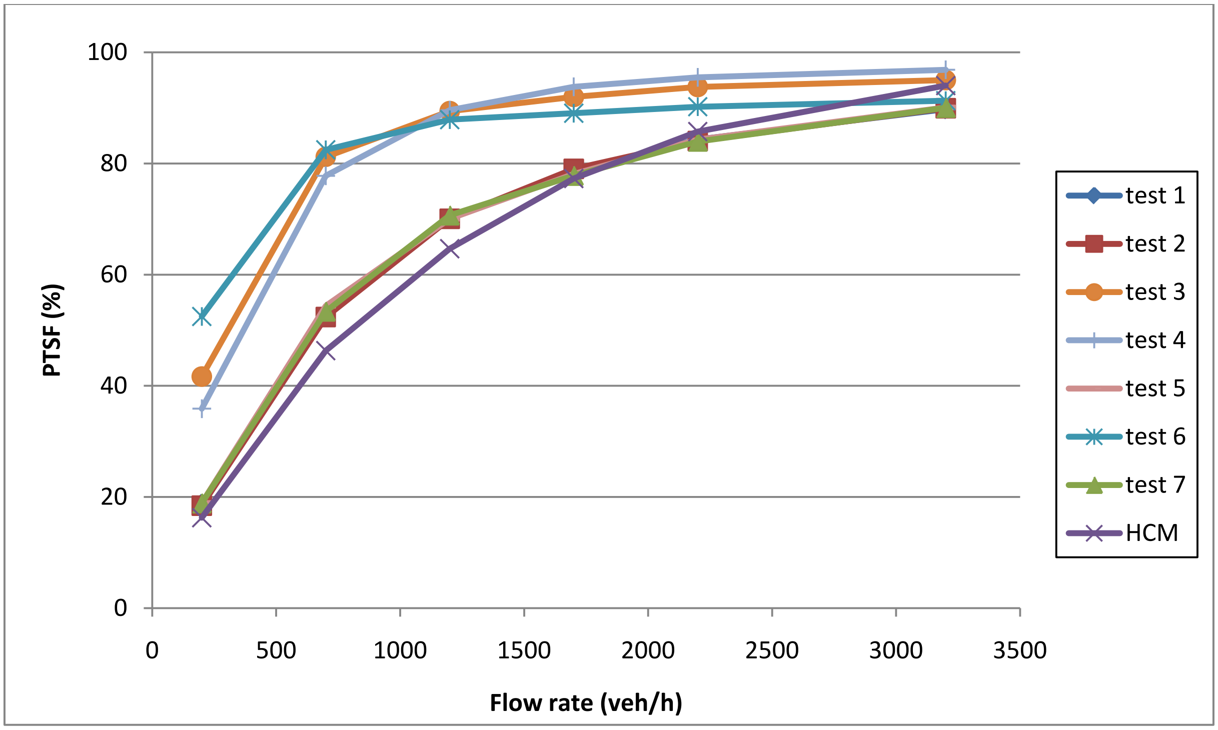

Figure 4-8. Truck type test – PTSF vs. flow rate for passing allowed

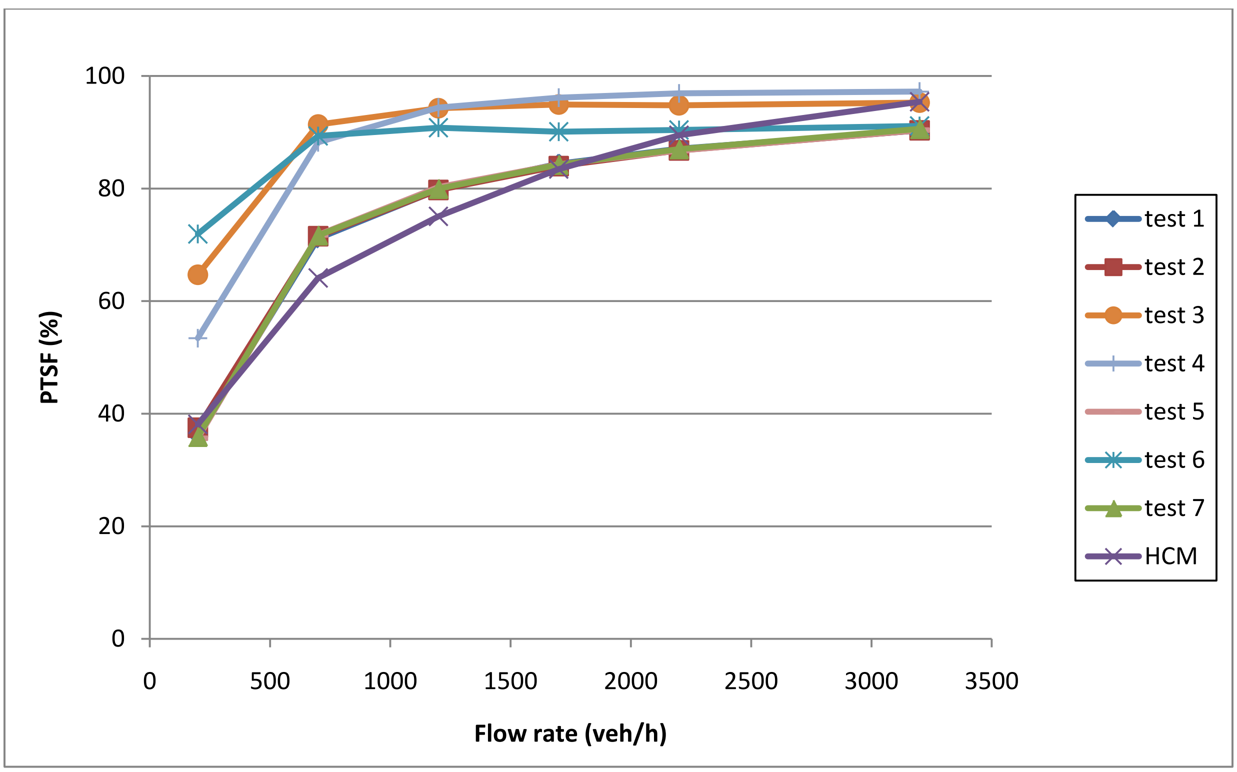

Figure 4-9. Truck type test – PTSF vs. flow rate for passing not allowed

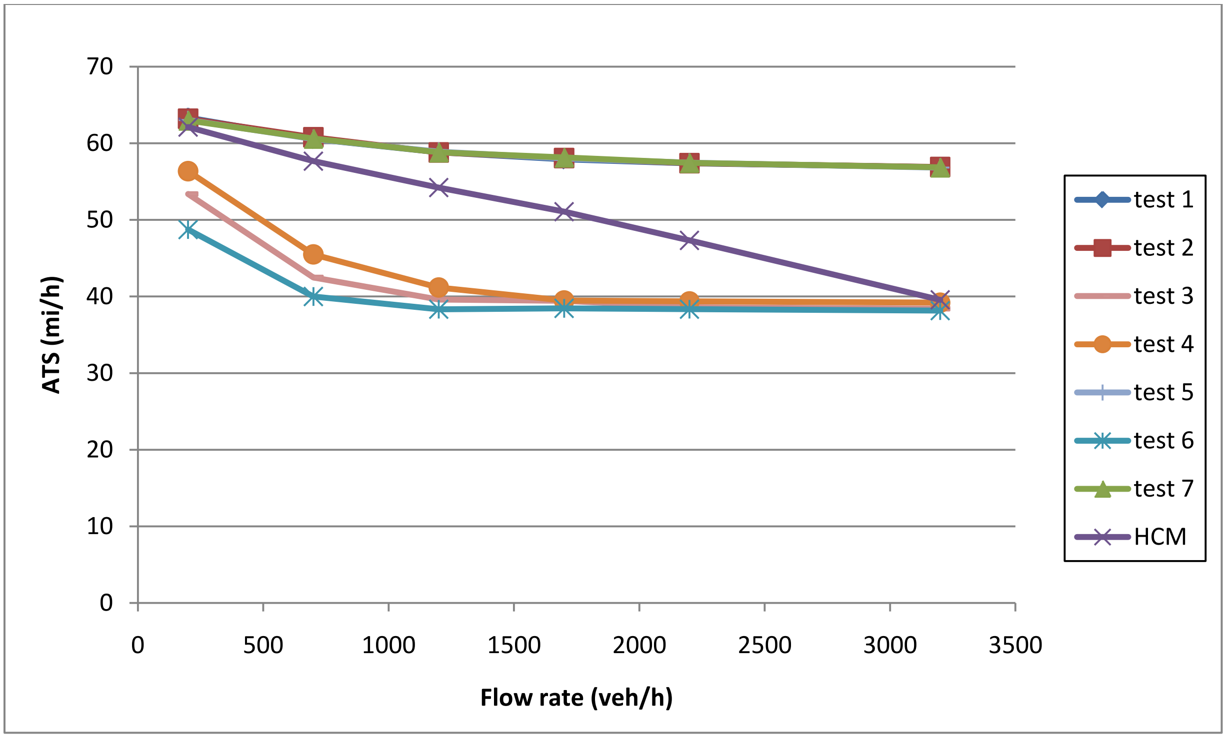

Figure 4-10. Truck type test – ATS vs. flow rate for passing allowed

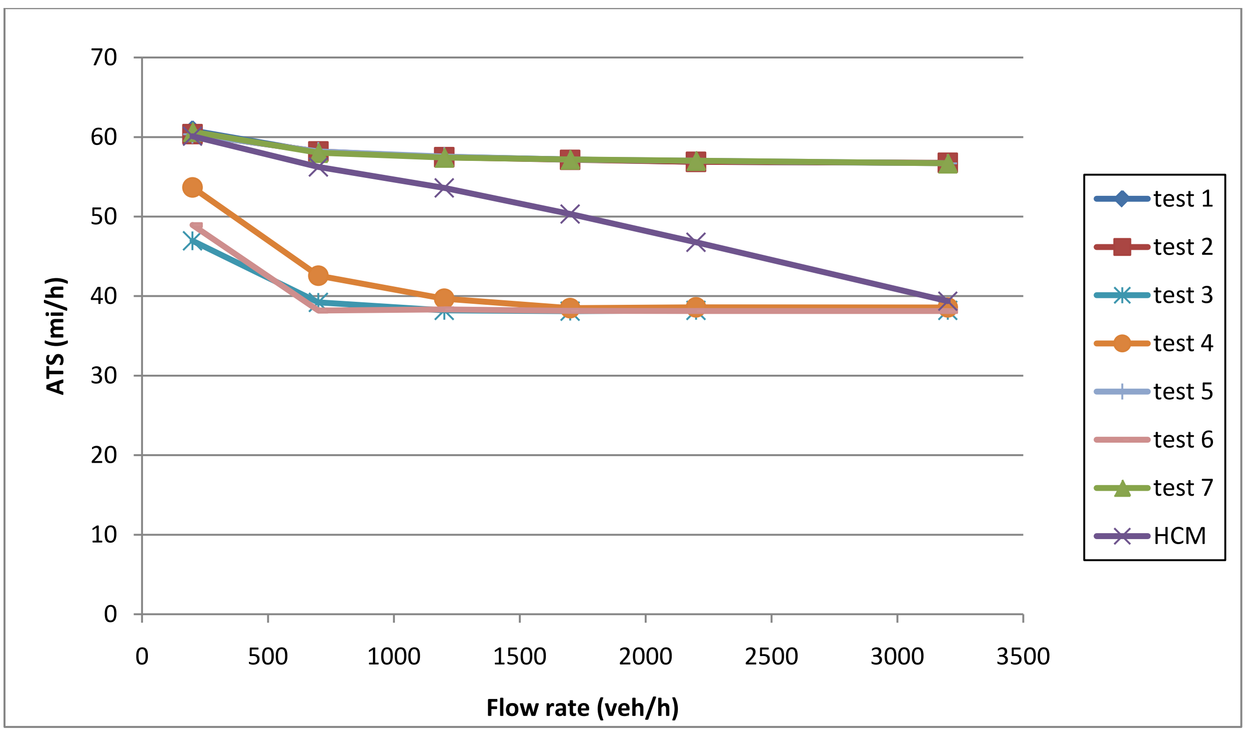

Figure 4-11. Truck type test – ATS vs. flow rate for passing not allowed

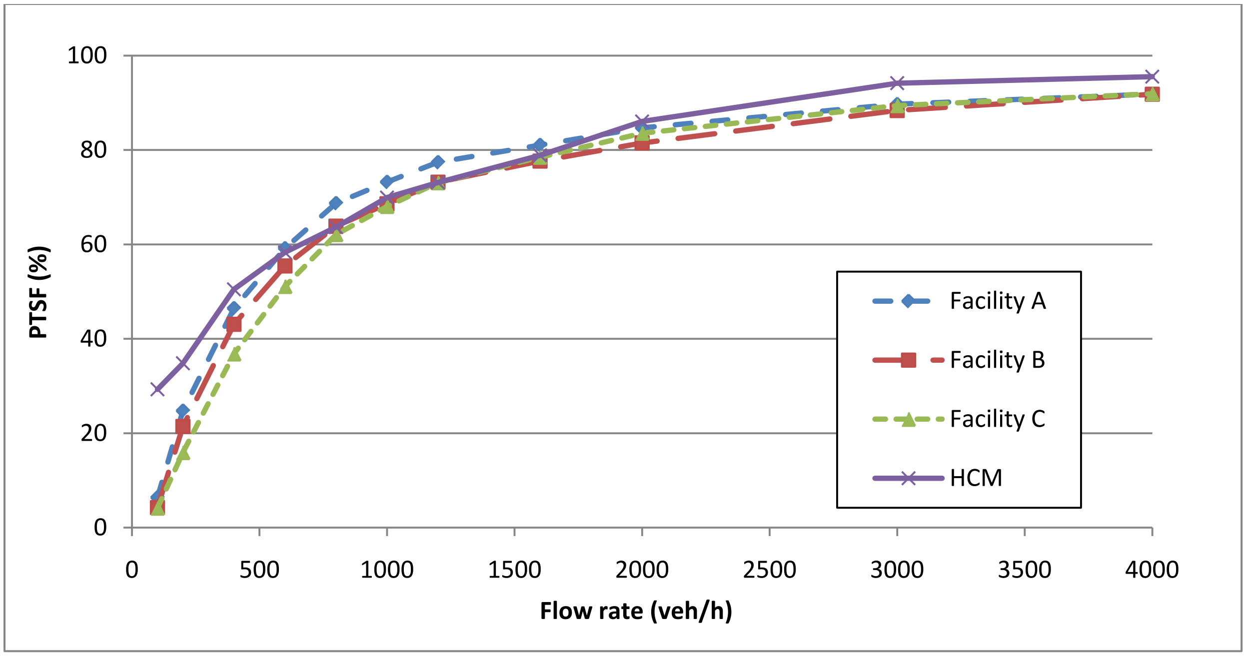

Figure 4-12. Average PTSF vs. flow rate

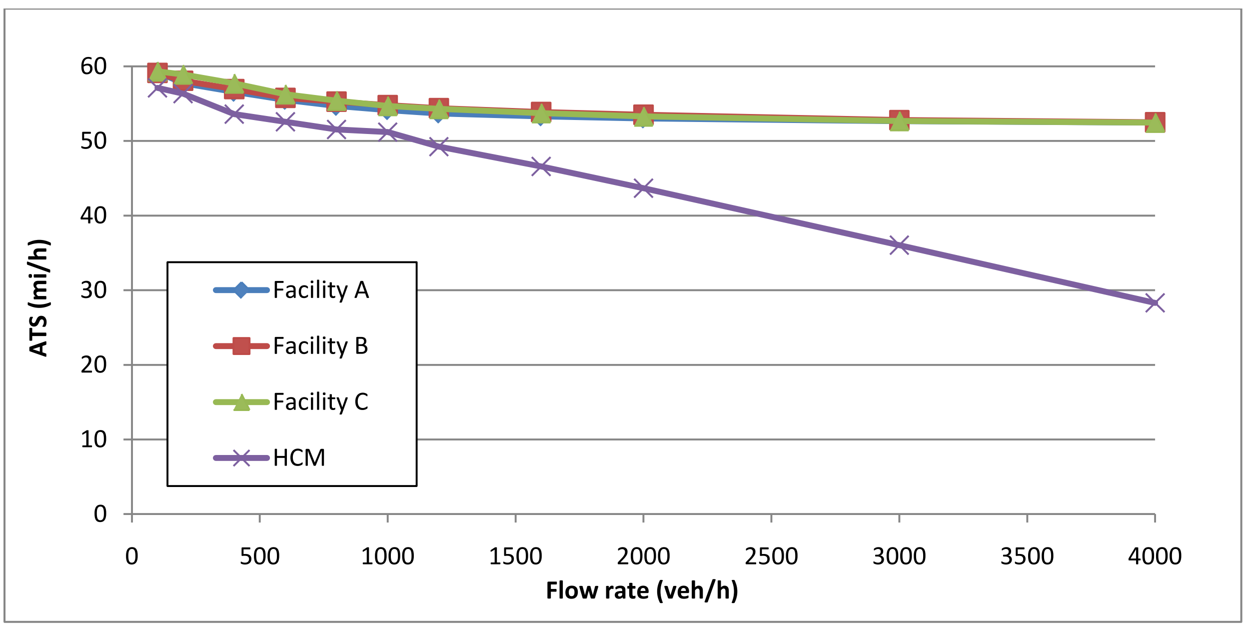

Figure 4-13. Average ATS vs. flow rate

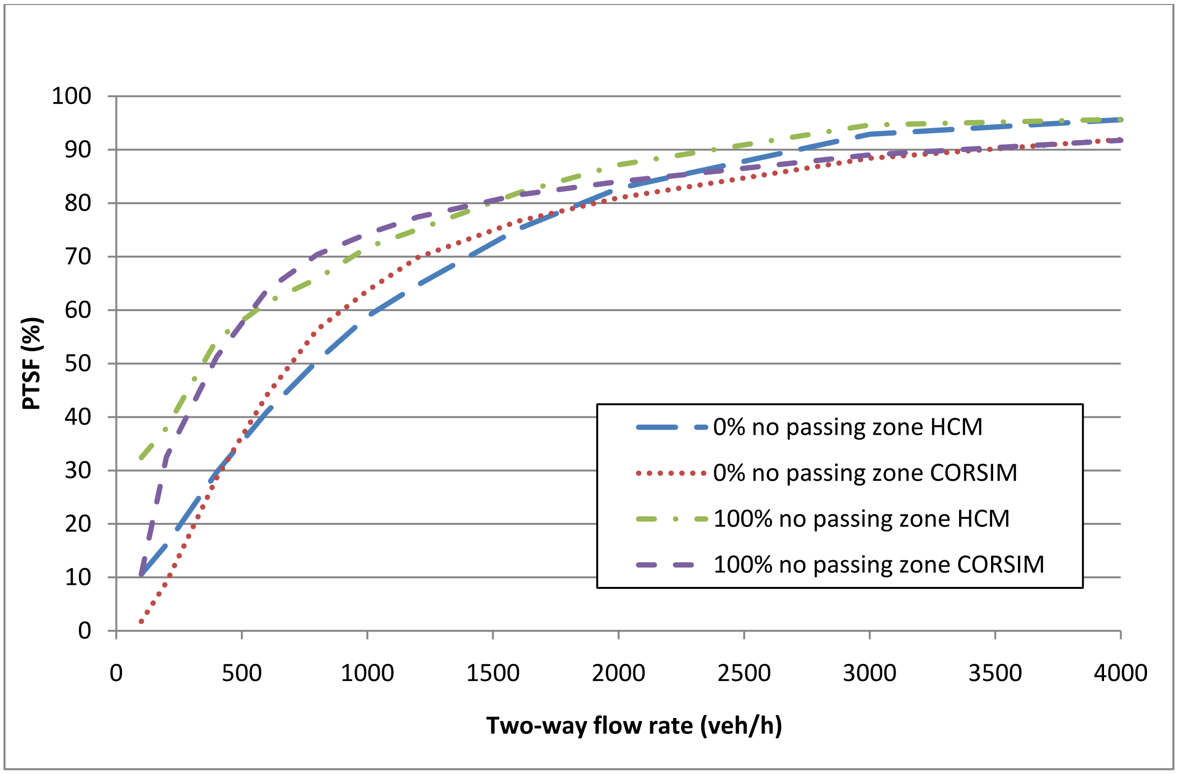

Figure 4-14. PTSF vs. flow rate

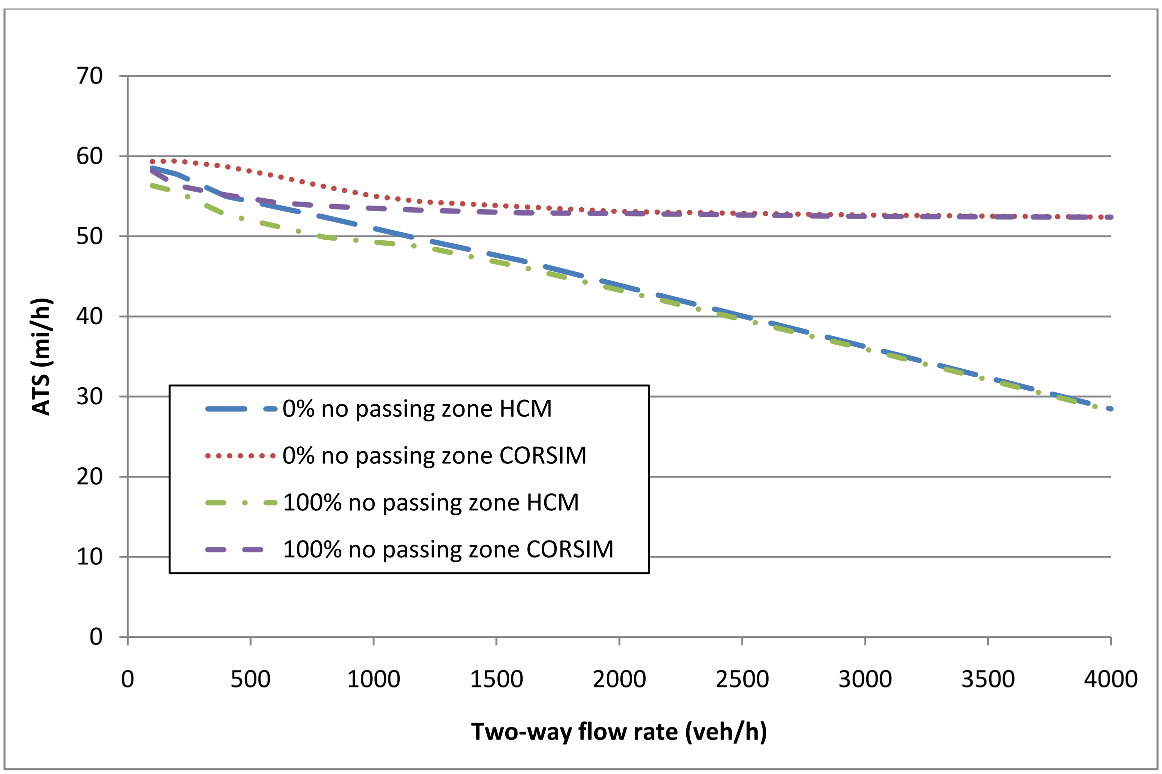

Figure 4-15. ATS vs. flow rate

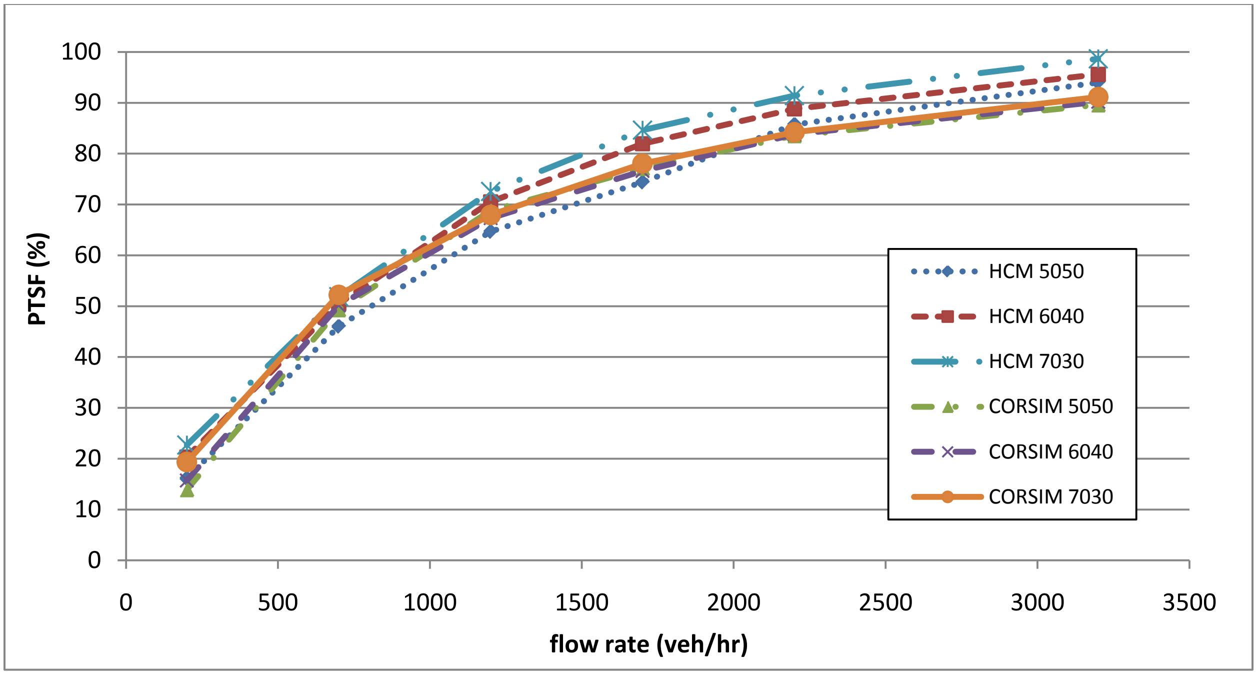

Figure 4-16. PTSF vs. two-way flow rate - 0% grade, 0%NPZ, 0%HV, no passing lane

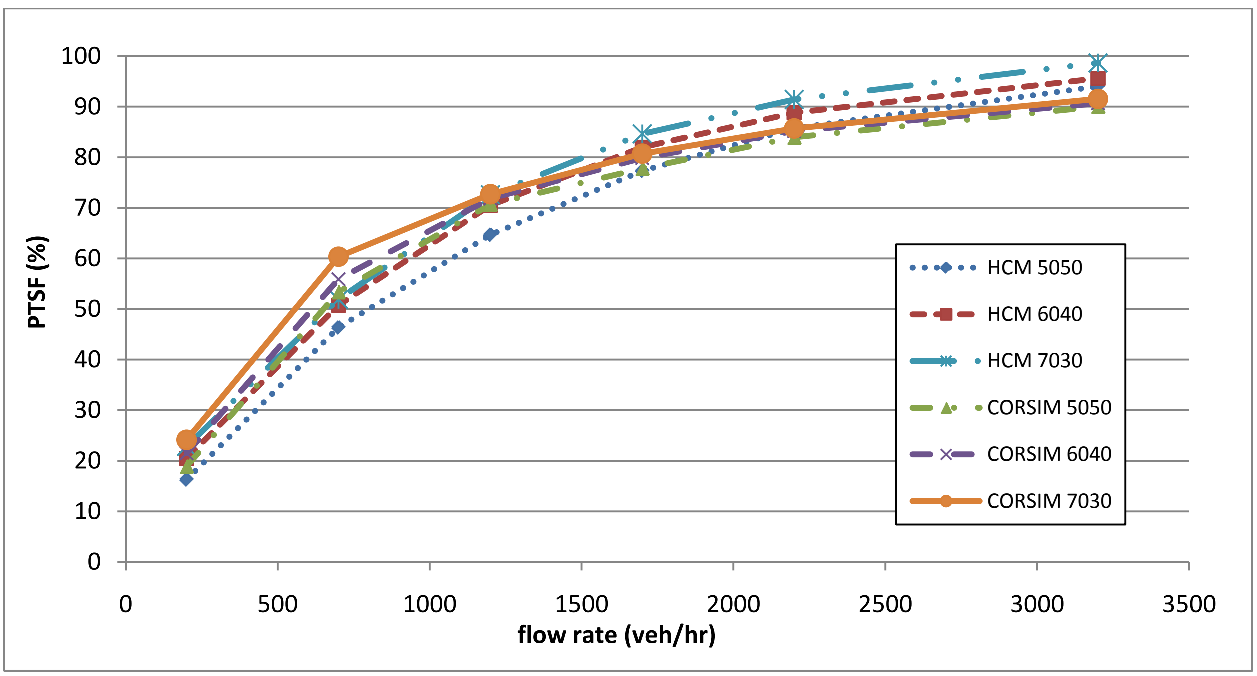

Figure 4-17. PTSF vs. two-way flow rate - 0% grade, 0%NPZ, 10%HV, no passing lane

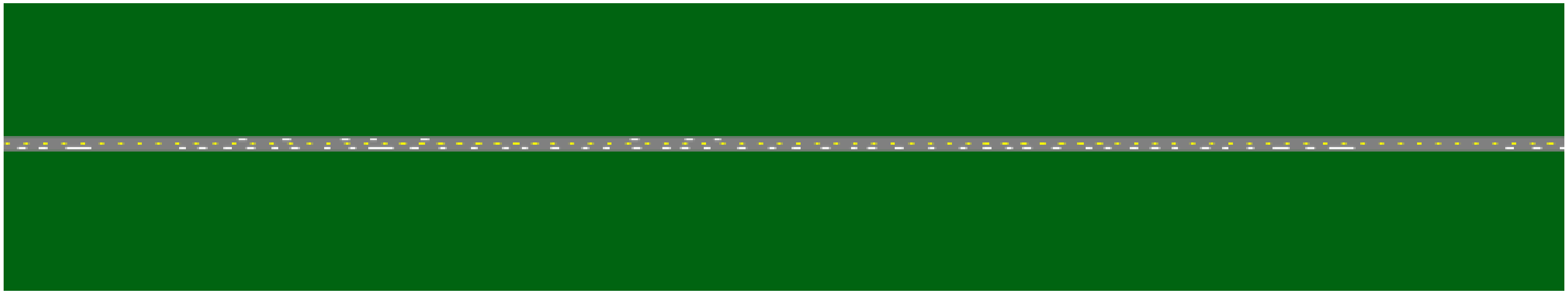

Figure 4-18. Platoon structure for 3200 veh/h flow rate

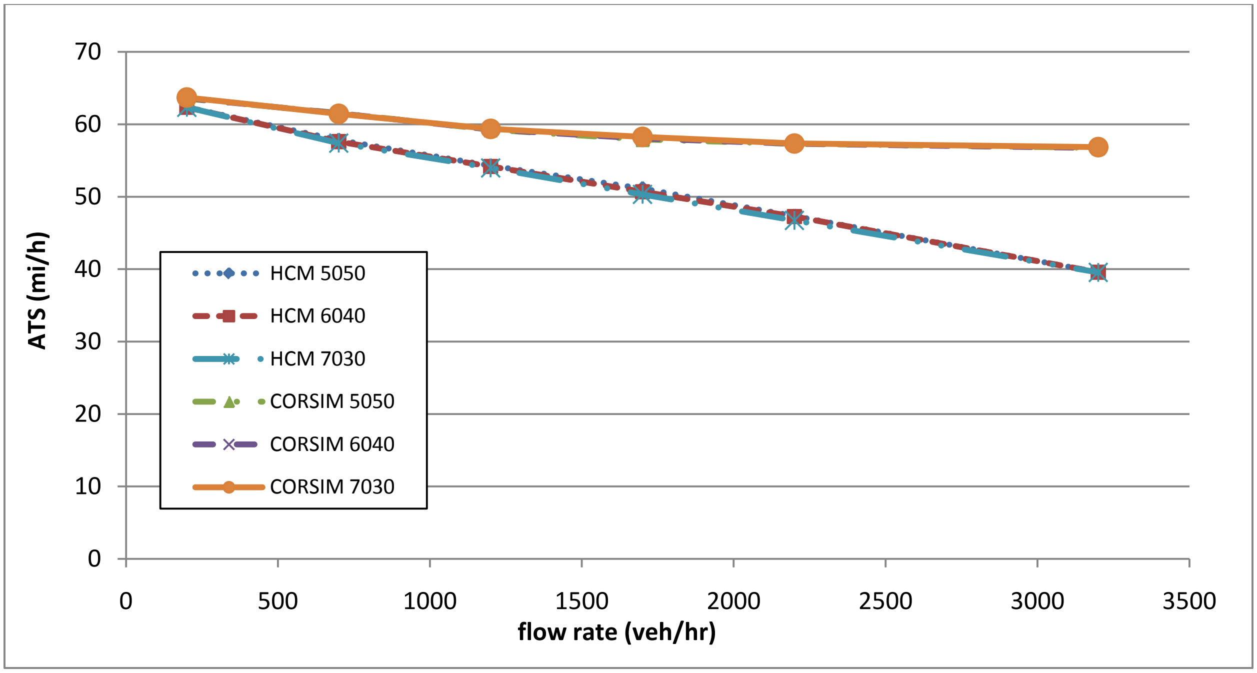

Figure 4-19. ATS vs. two-way flow rate - 0% grade, 0%NPZ, 0%HV, no passing lane

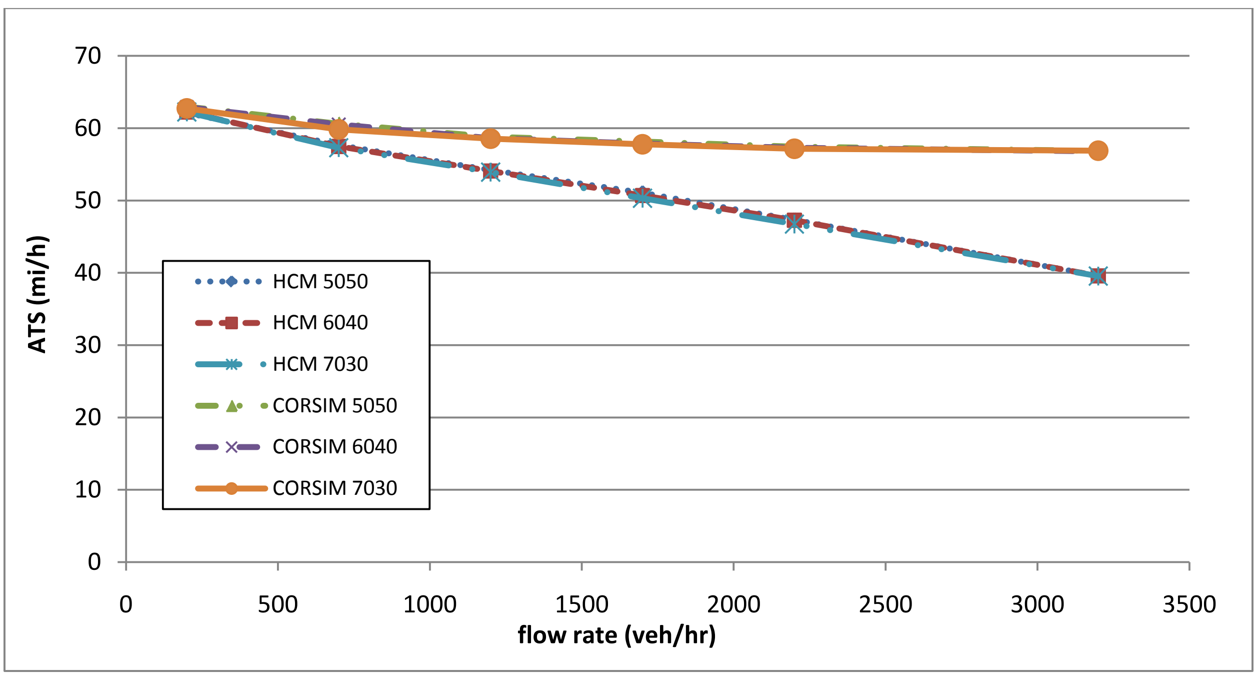

Figure 4-20. ATS vs. two-way flow rate - 0% grade, 0%NPZ, 10%HV, no passing lane

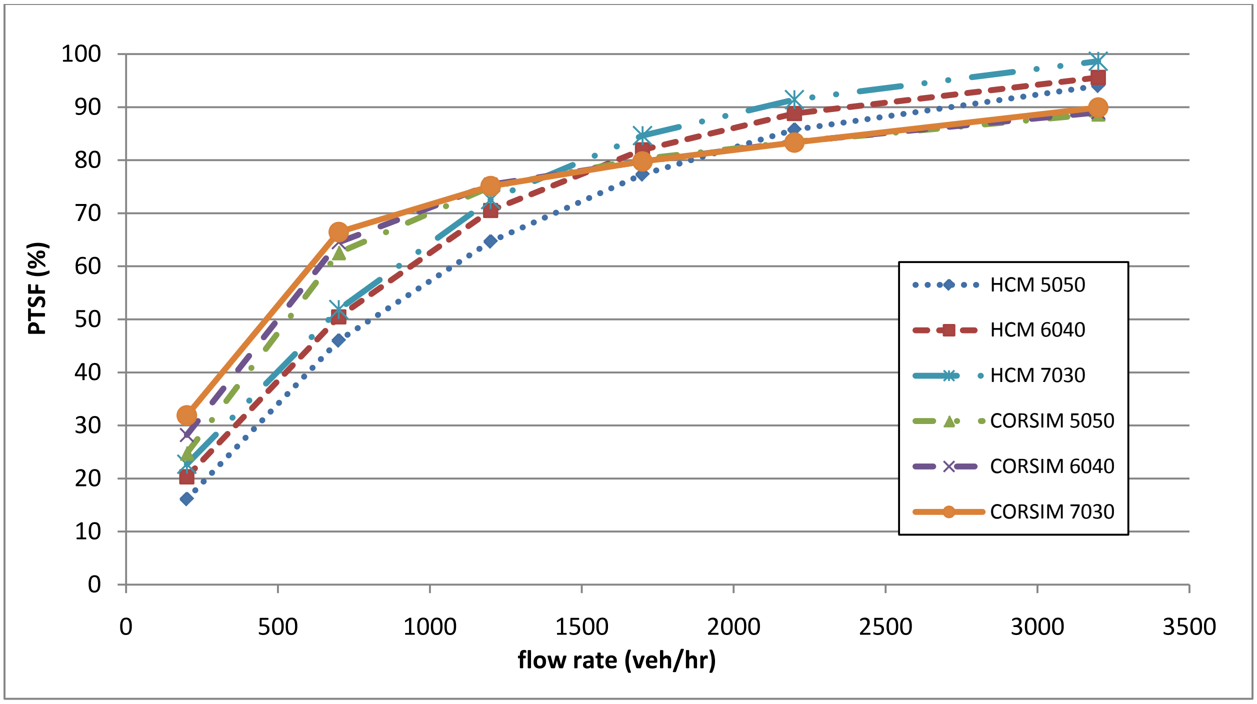

Figure 4-21. PTSF vs. two-way flow rate - 6% grade, 0%NPZ, 0%HV, no passing lane

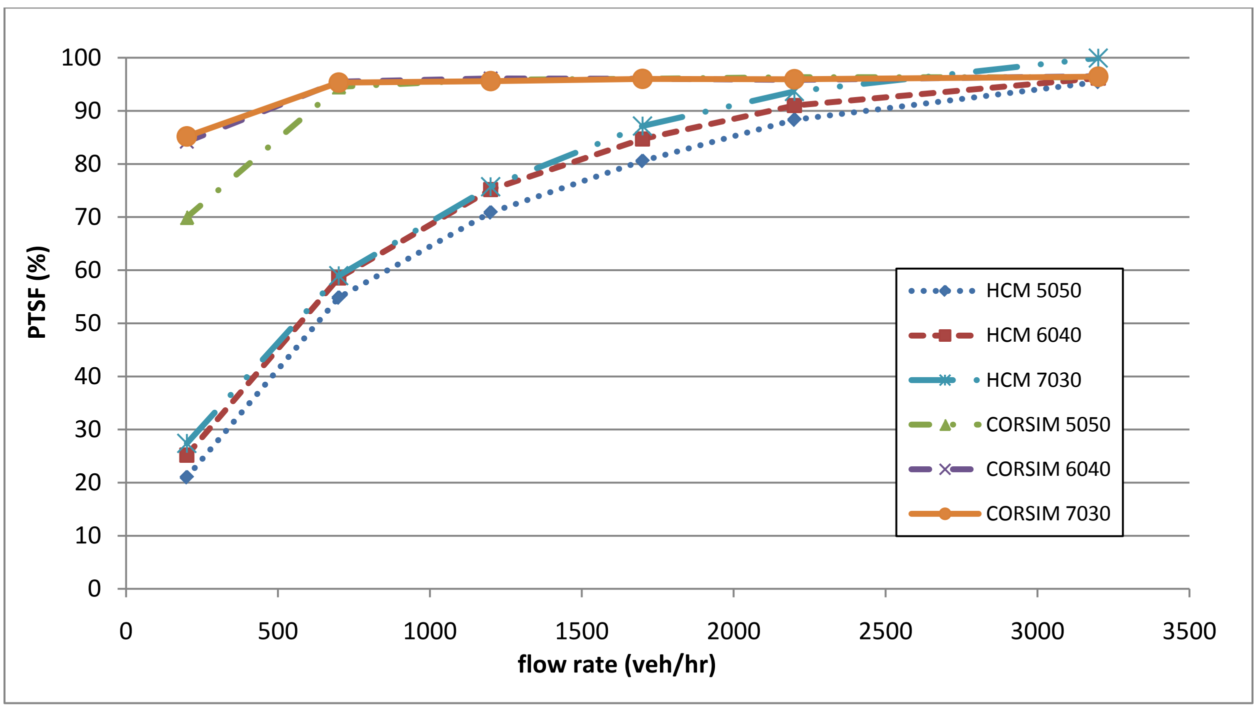

Figure 4-22. PTSF vs. two-way flow rate - 6% grade, 0%NPZ, 10%HV, no passing lane

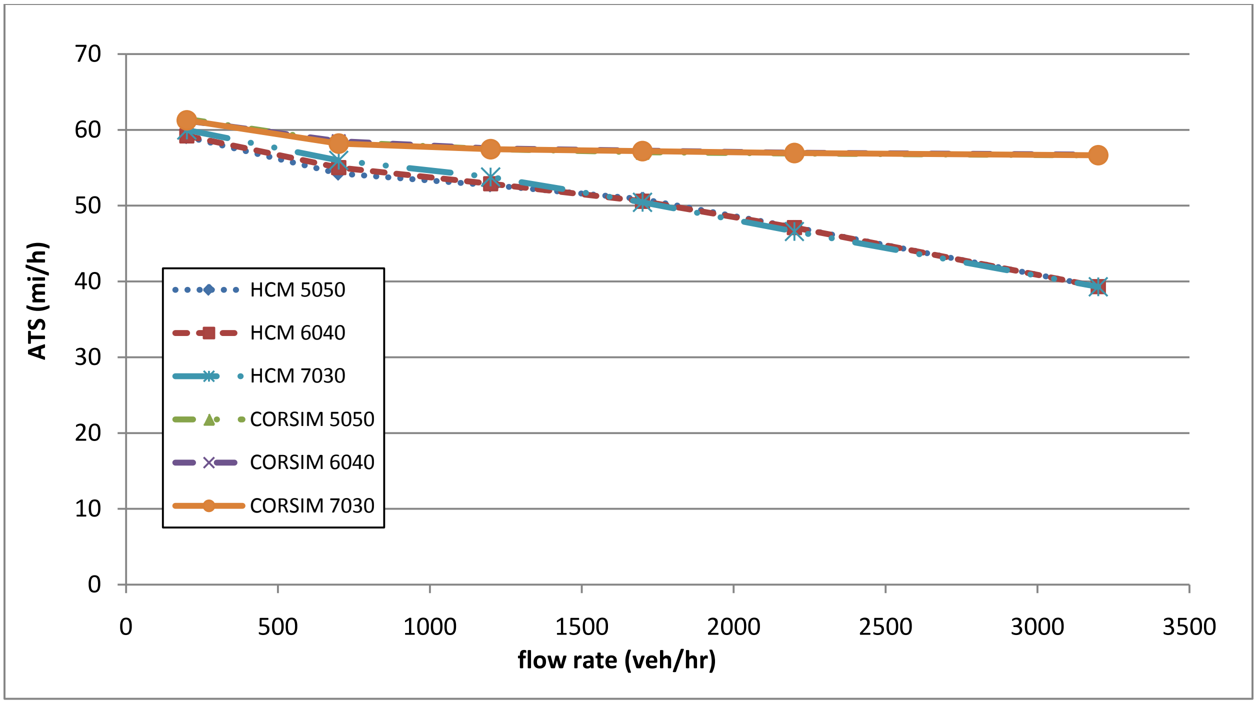

Figure 4-23. ATS vs. two-way flow rate - 6% grade, 0%NPZ, 0%HV, no passing lane

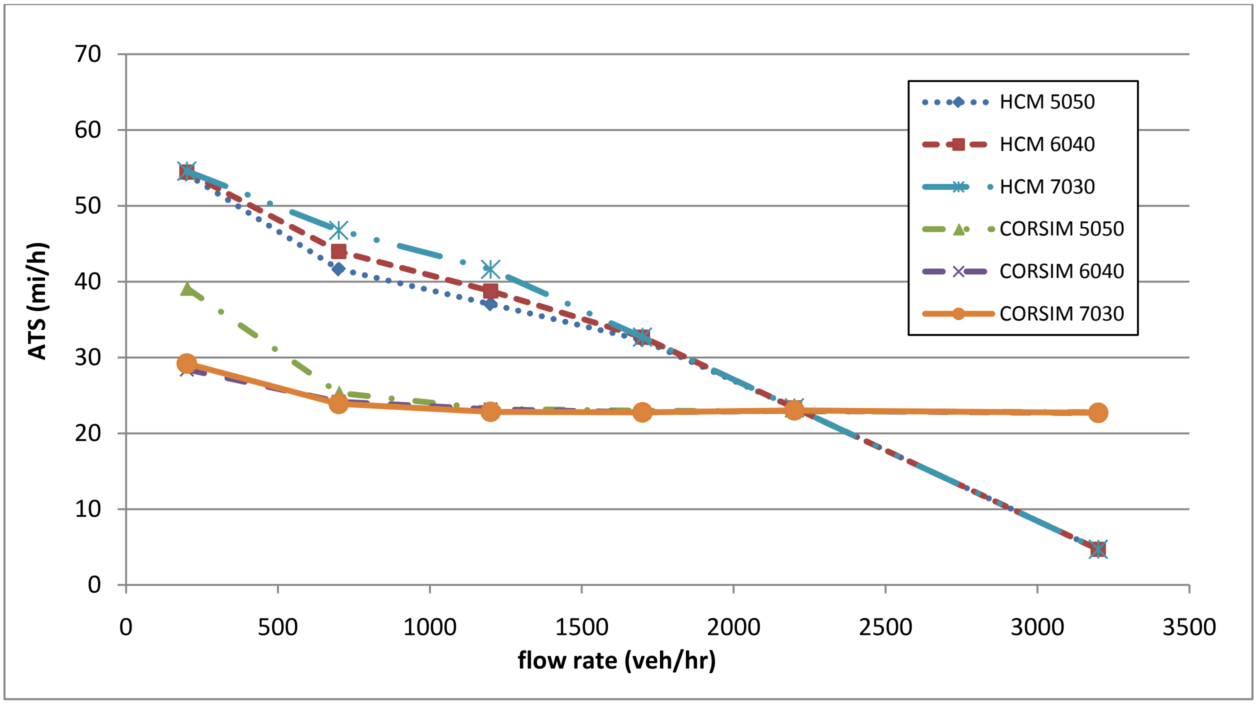

Figure 4-24. ATS vs. two-way flow rate - 6% grade, 0%NPZ, 10%HV, no passing lane

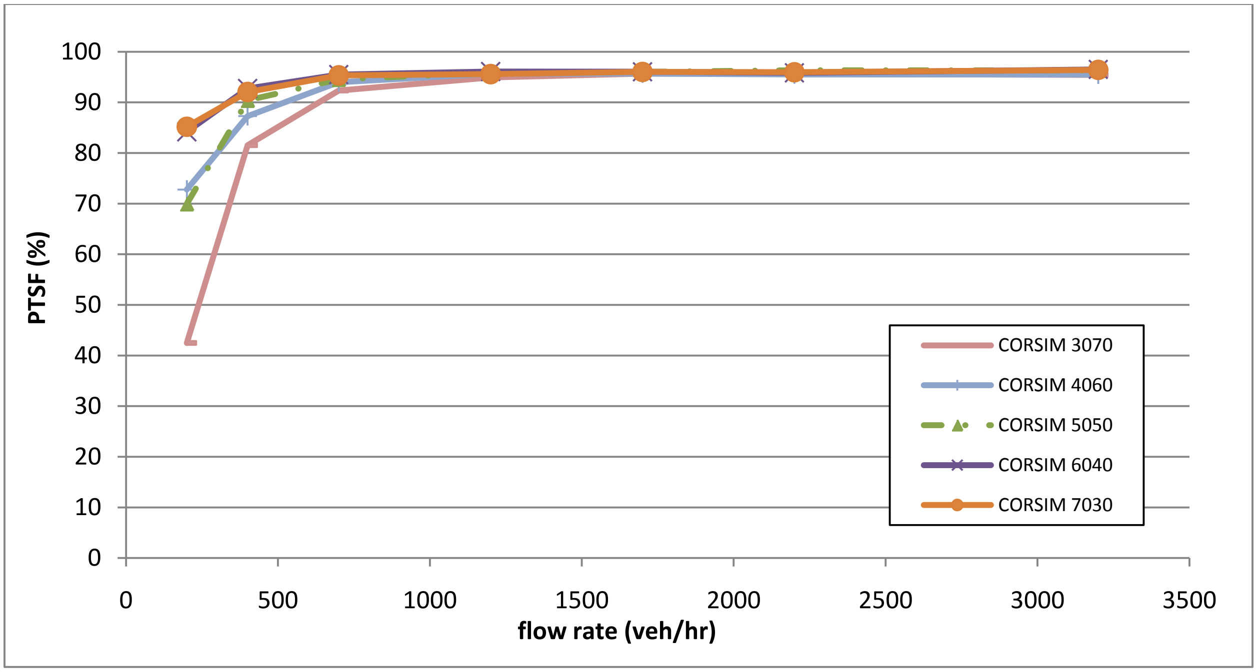

Figure 4-25. PTSF vs. two-way flow rate - 6% grade, 0%NPZ, 10%HV, no passing lane

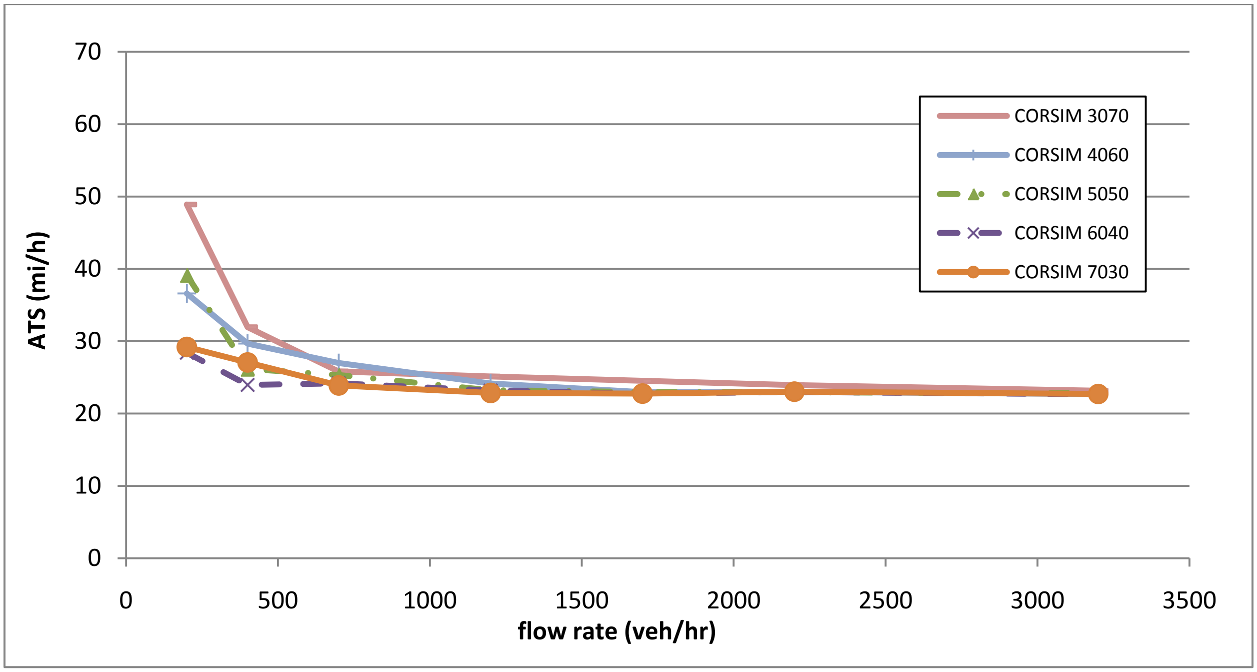

Figure 4-26. ATS vs. two-way flow rate - 6% grade, 0%NPZ, 10%HV, no passing lane

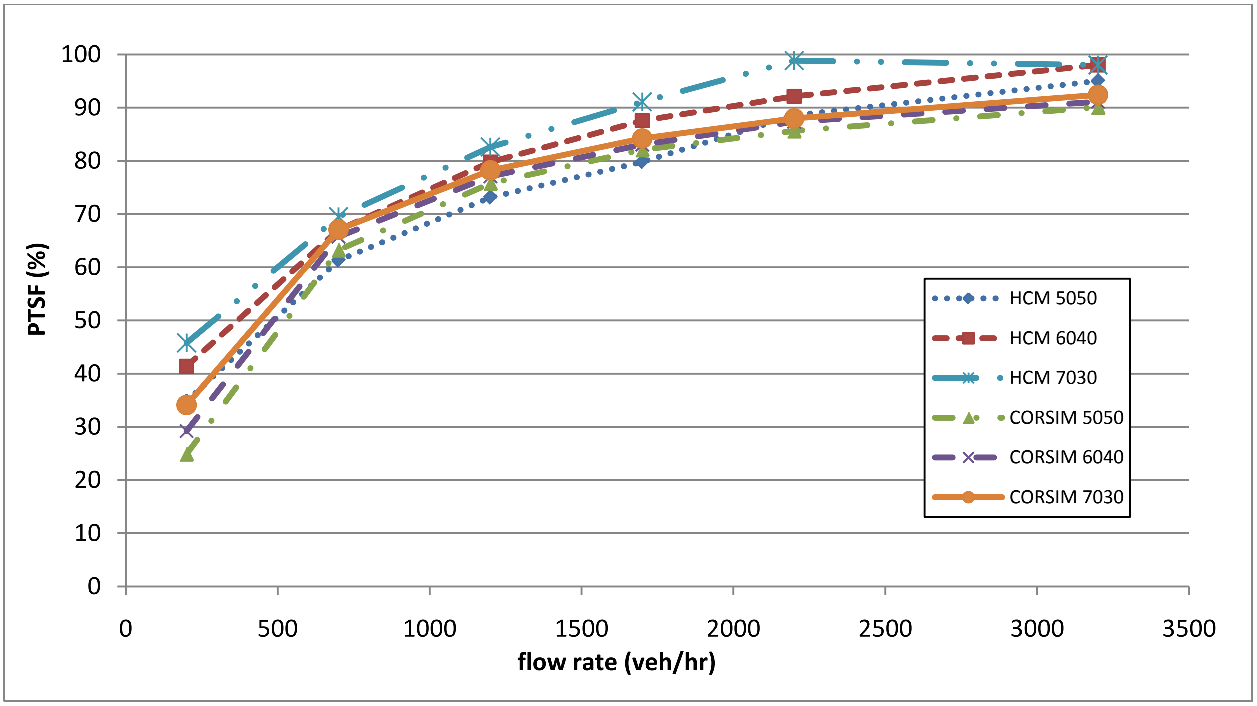

Figure 4-27. PTSF vs. two-way flow rate - 0% grade, 50%NPZ, 0%HV, no passing lane

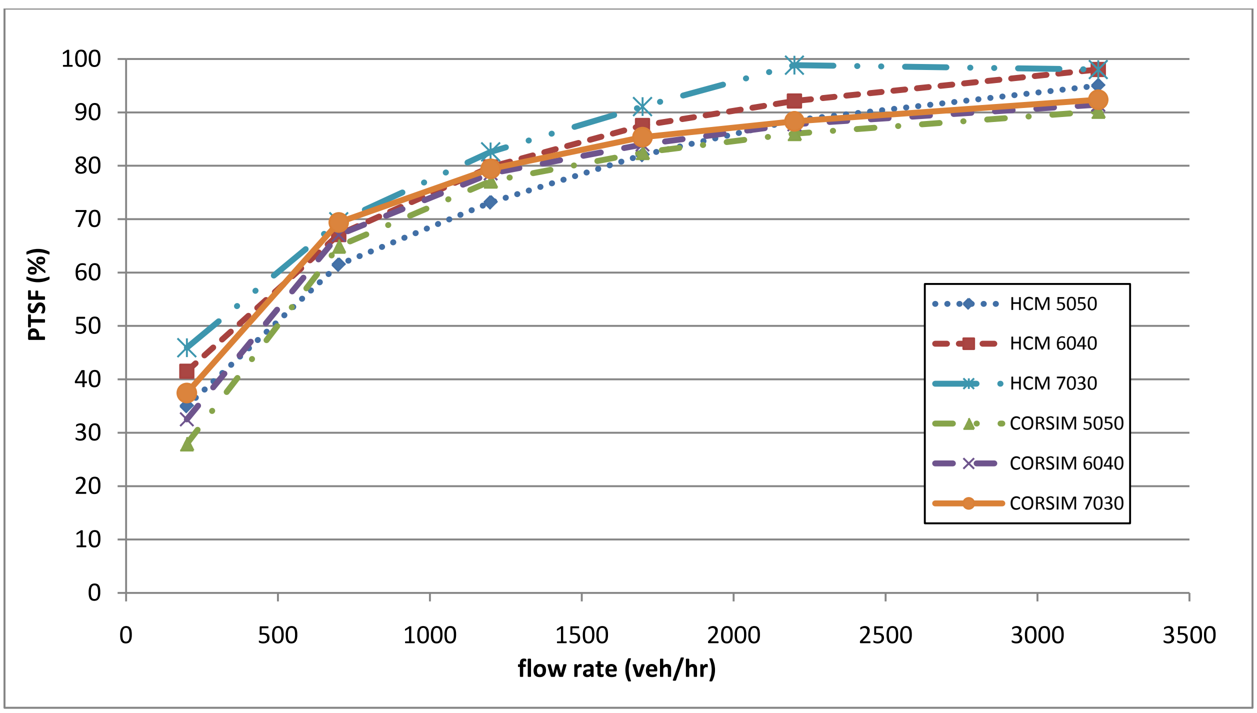

Figure 4-28. PTSF vs. two-way flow rate - 0% grade, 50%NPZ, 10%HV, no passing lane

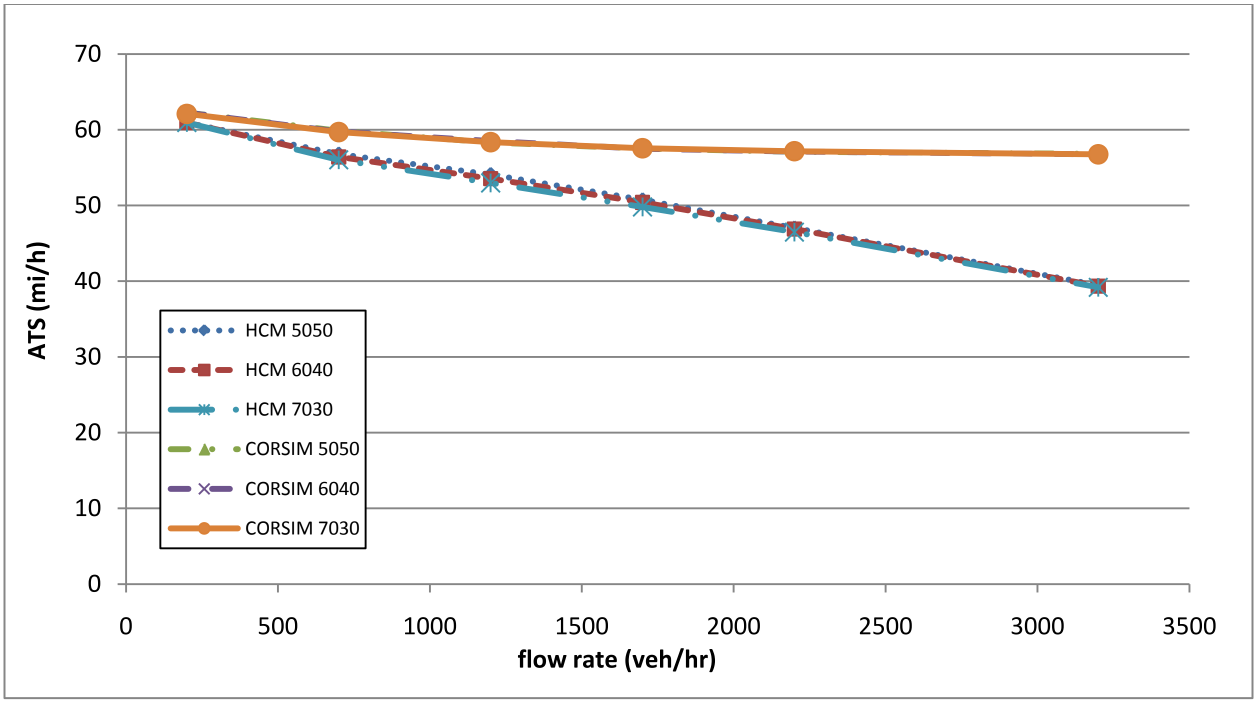

Figure 4-29. ATS vs. two-way flow rate - 0% grade, 50%NPZ, 0%HV, no passing lane

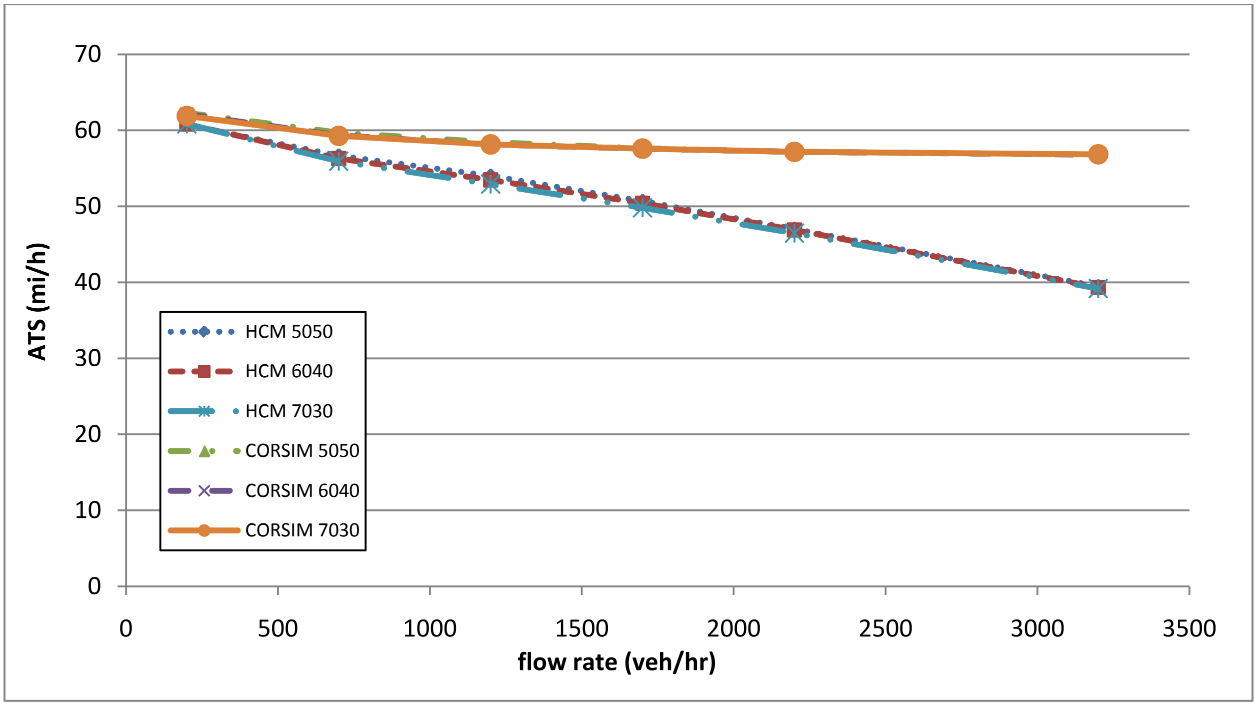

Figure 4-30. ATS vs. two-way flow rate - 0% grade, 50%NPZ, 10%HV, no passing lane

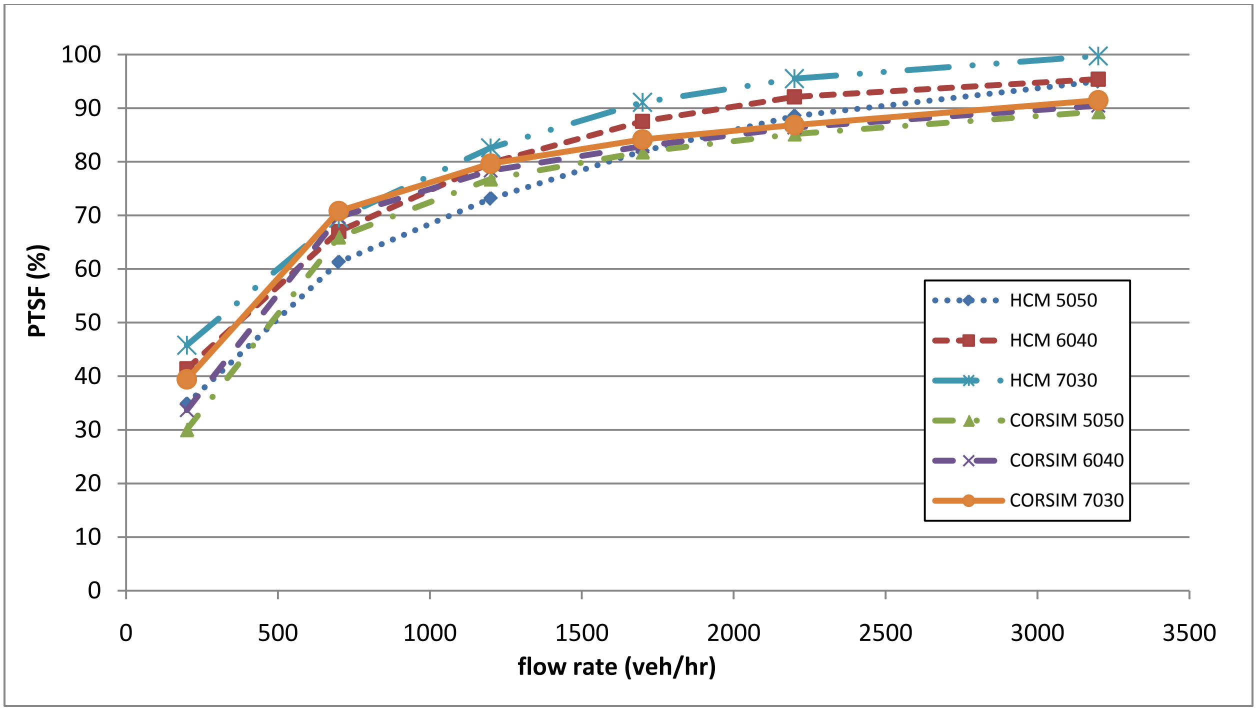

Figure 4-31. PTSF vs. two-way flow rate - 6% grade, 50%NPZ, 0%HV, no passing lane

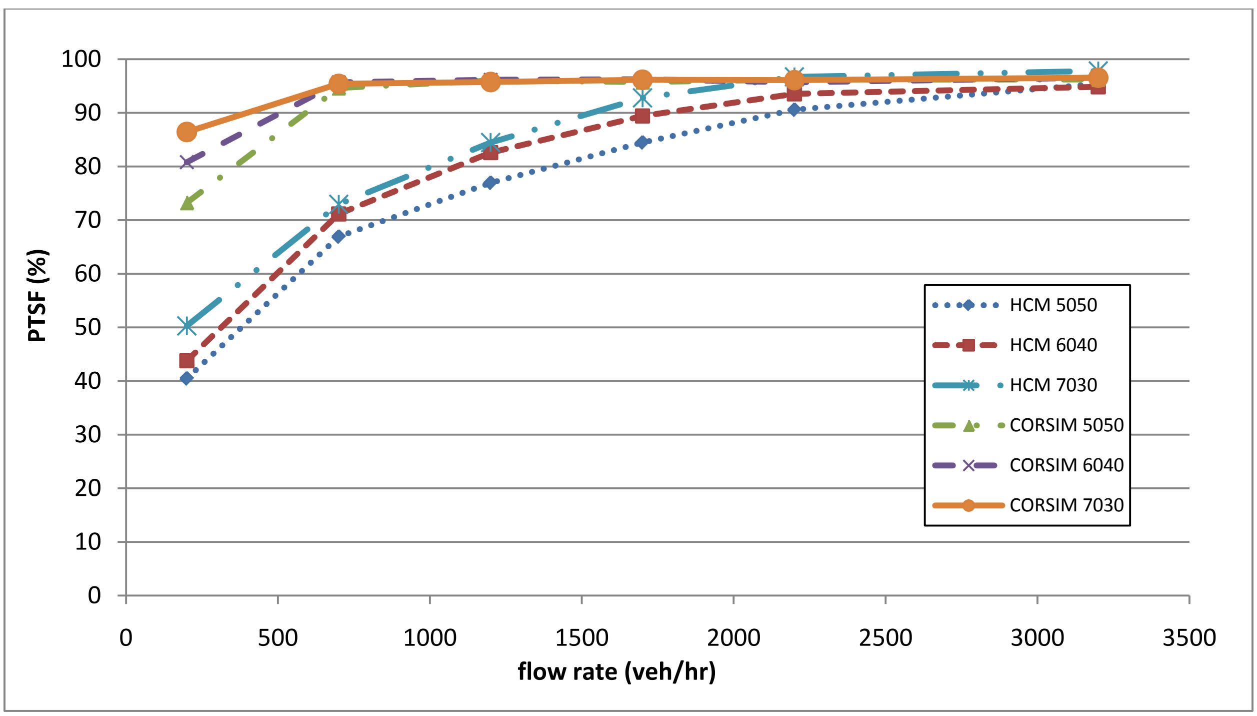

Figure 4-32. PTSF vs. two-way flow rate - 6% grade, 50%NPZ, 10%HV, no passing lane

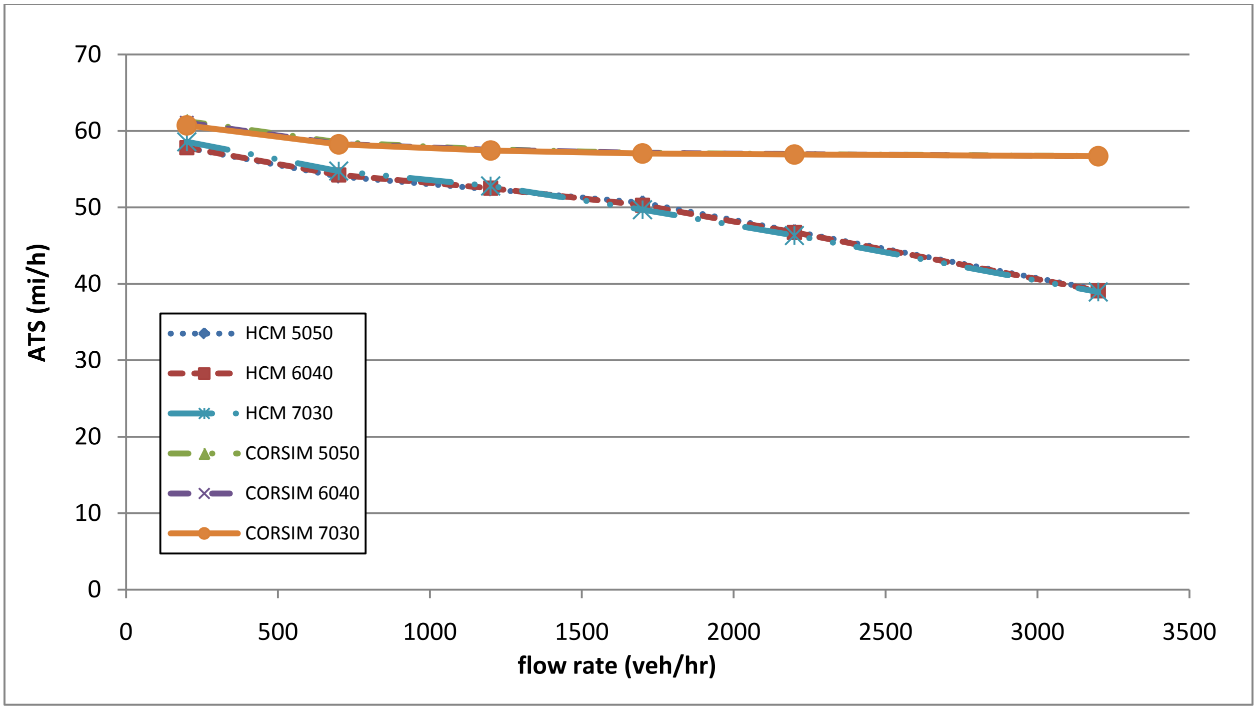

Figure 4-33. ATS vs. two-way flow rate - 6% grade, 50%NPZ, 0%HV, no passing lane

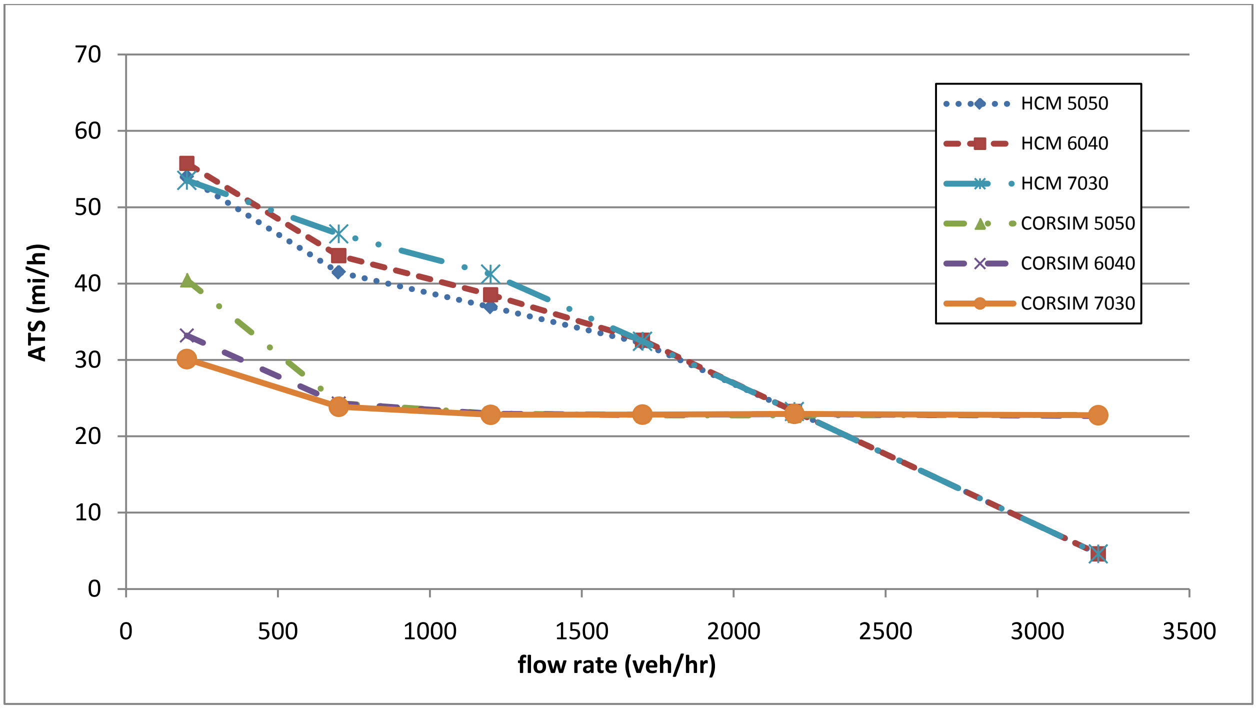

Figure 4-34. ATS vs. two-way flow rate - 6% grade, 50%NPZ, 10%HV, no passing lane

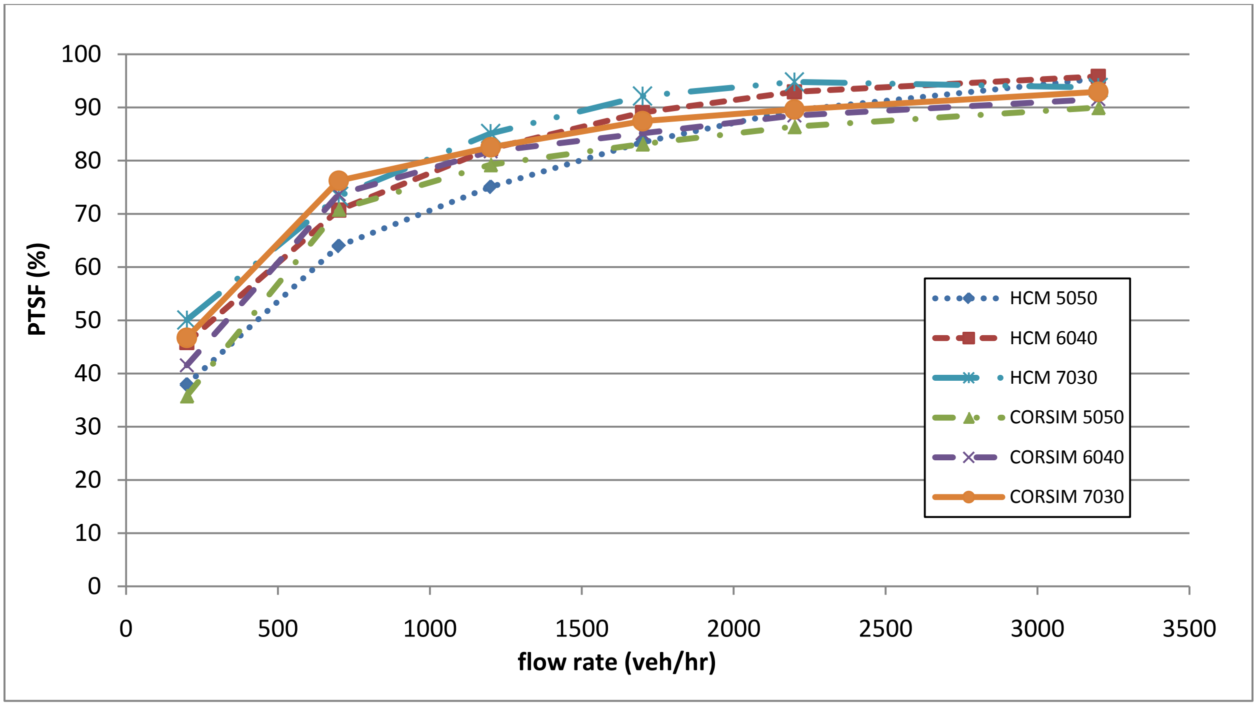

Figure 4-35. PTSF vs. two-way flow rate - 0% grade, 100%NPZ, 0%HV, no passing lane

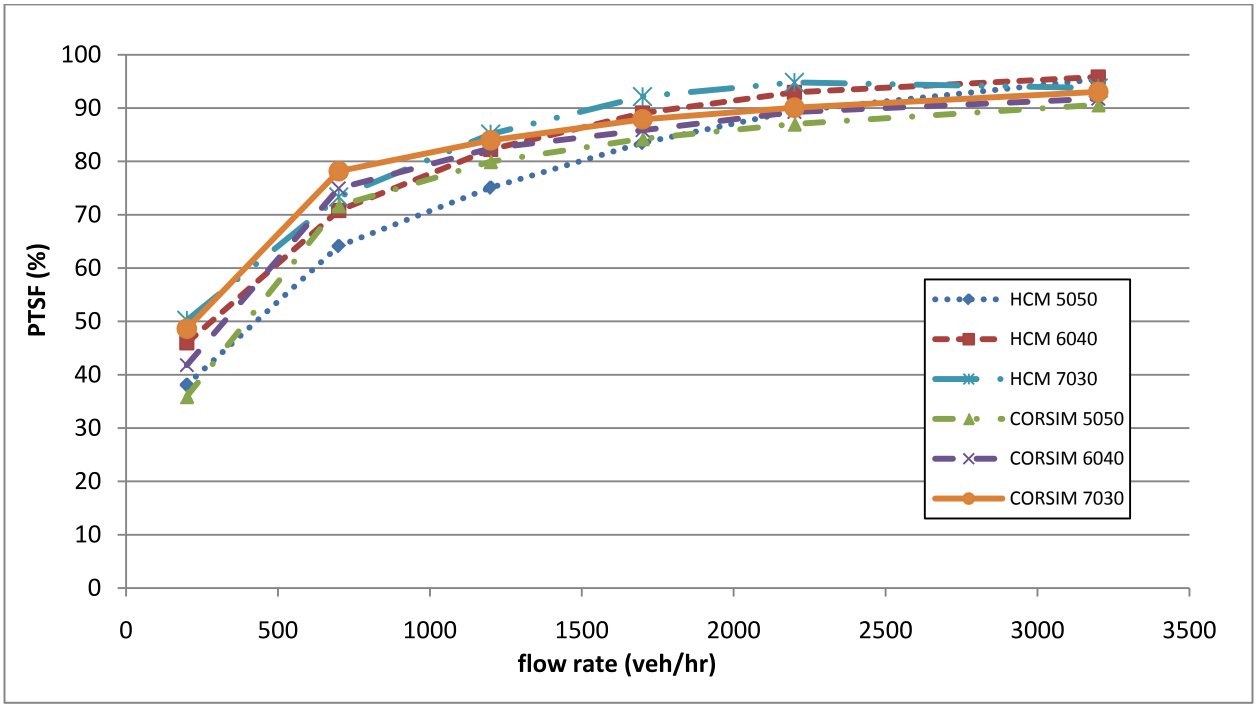

Figure 4-36. PTSF vs. two-way flow rate - 0% grade, 100%NPZ, 10%HV, no passing lane

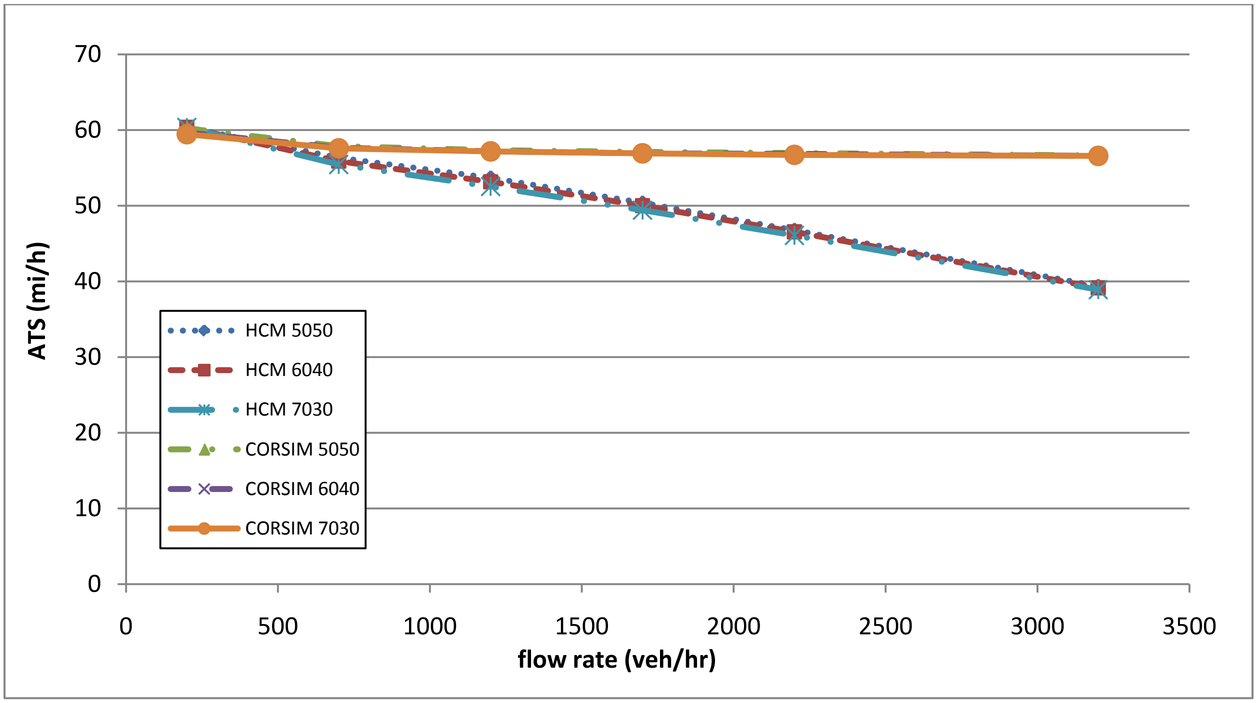

Figure 4-37. ATS vs. two-way flow rate - 0% grade, 100%NPZ, 0%HV, no passing lane

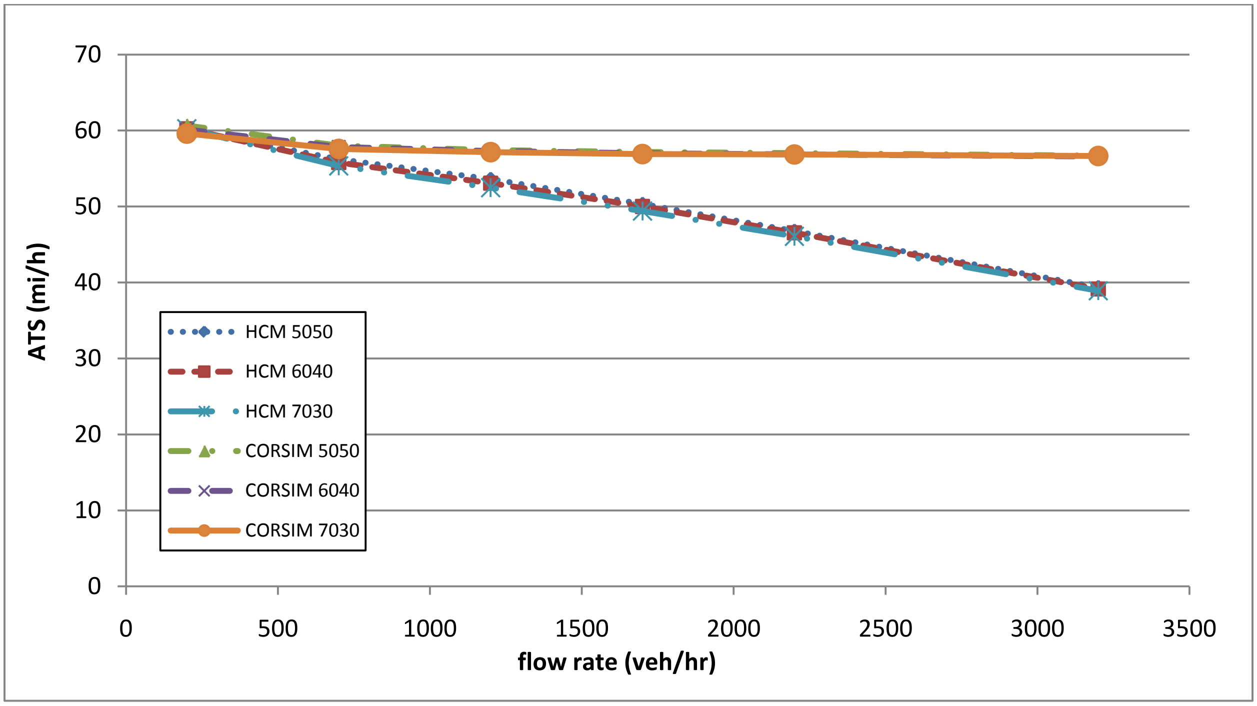

Figure 4-38. ATS vs. two-way flow rate - 0% grade, 100%NPZ, 10%HV, no passing lane

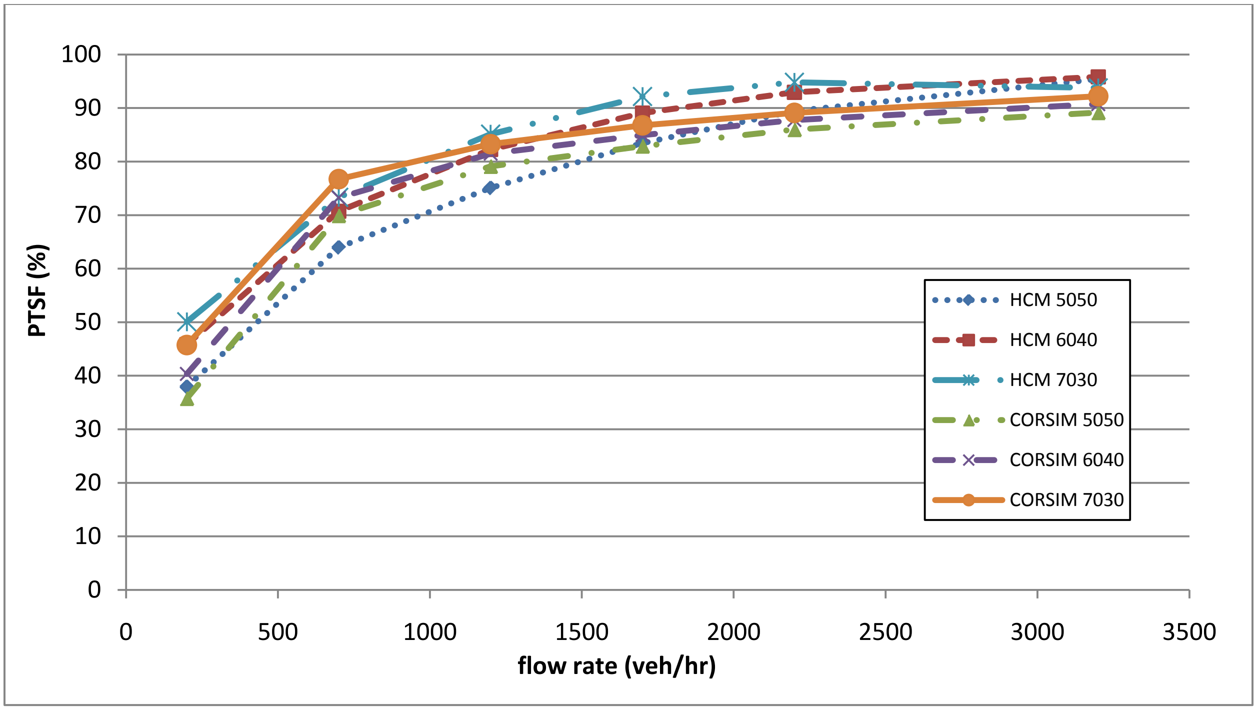

Figure 4-39. PTSF vs. two-way flow rate - 6% grade, 100%NPZ, 0%HV, no passing lane

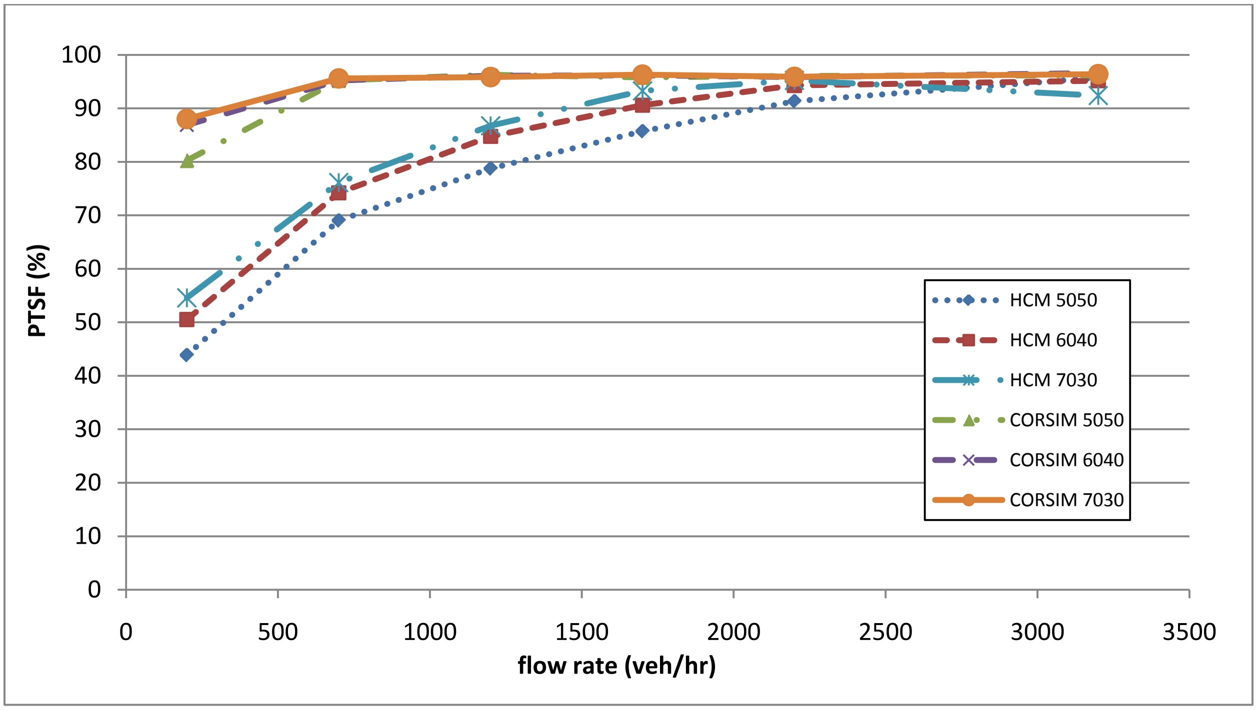

Figure 4-40. PTSF vs. two-way flow rate - 6% grade, 100%NPZ, 10%HV, no passing lane

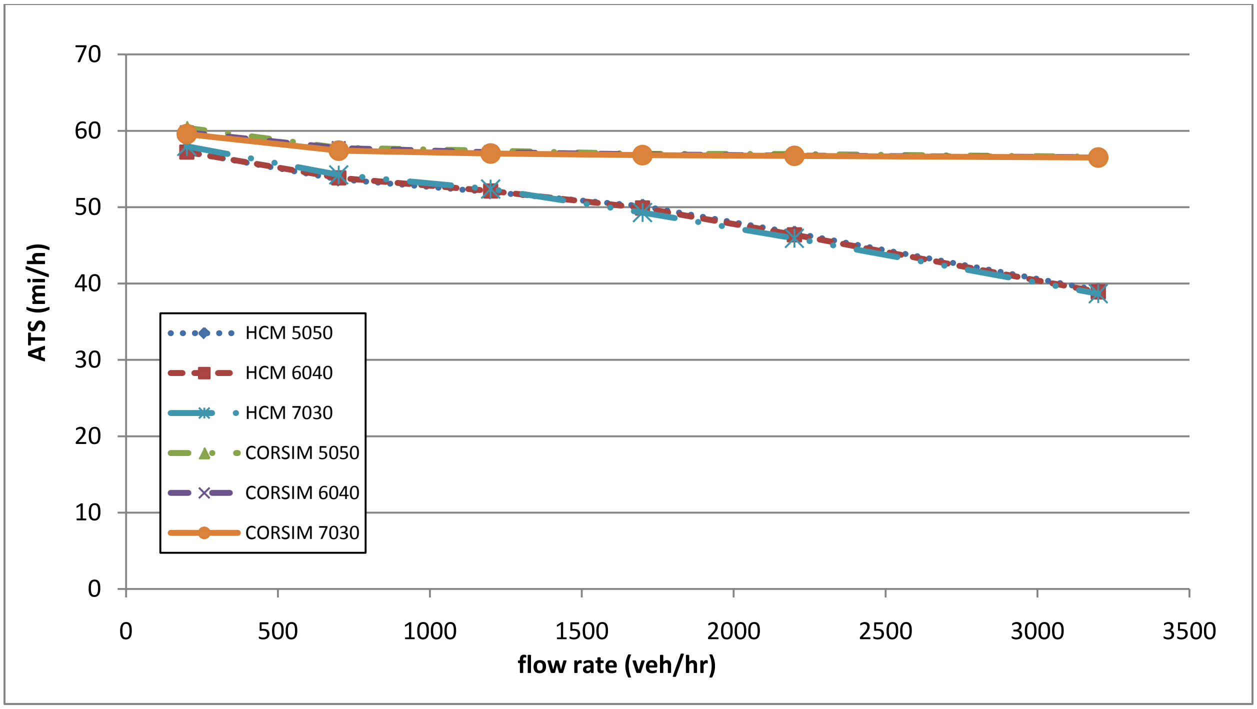

Figure 4-41. ATS vs. two-way flow rate - 6% grade, 100%NPZ, 0%HV, no passing lane

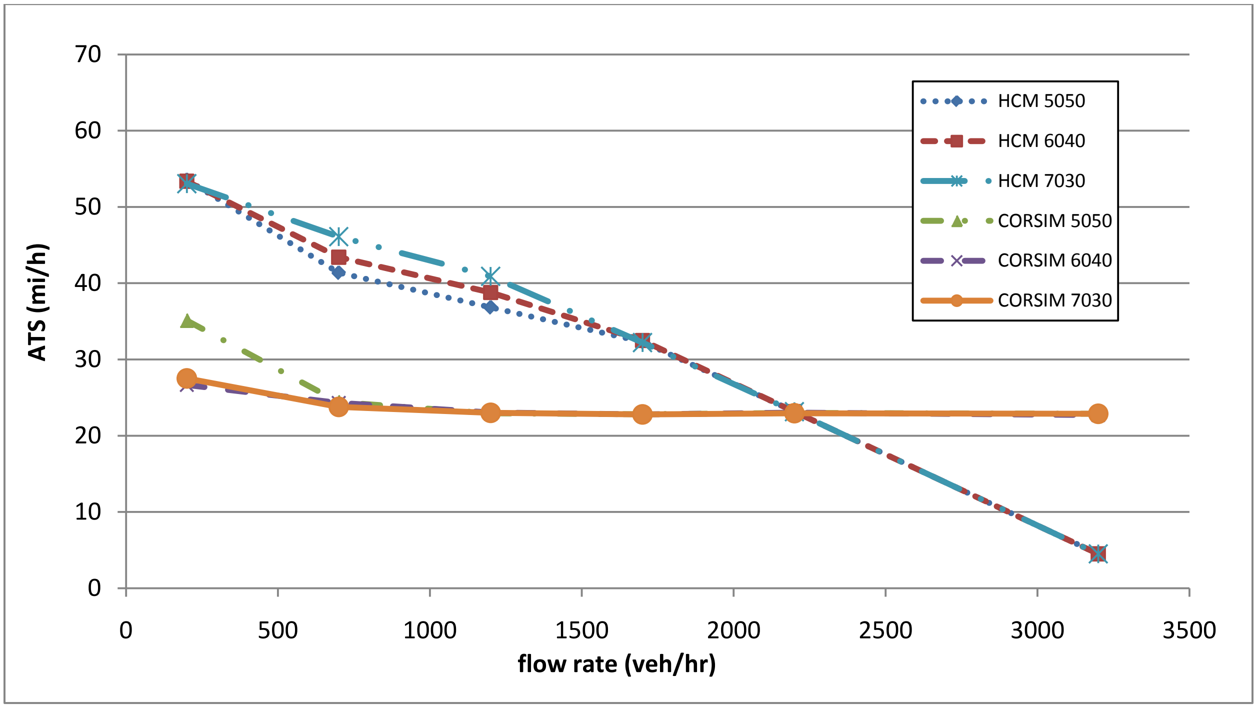

Figure 4-42. ATS vs. two-way flow rate - 6% grade, 100%NPZ, 10%HV, no passing lane

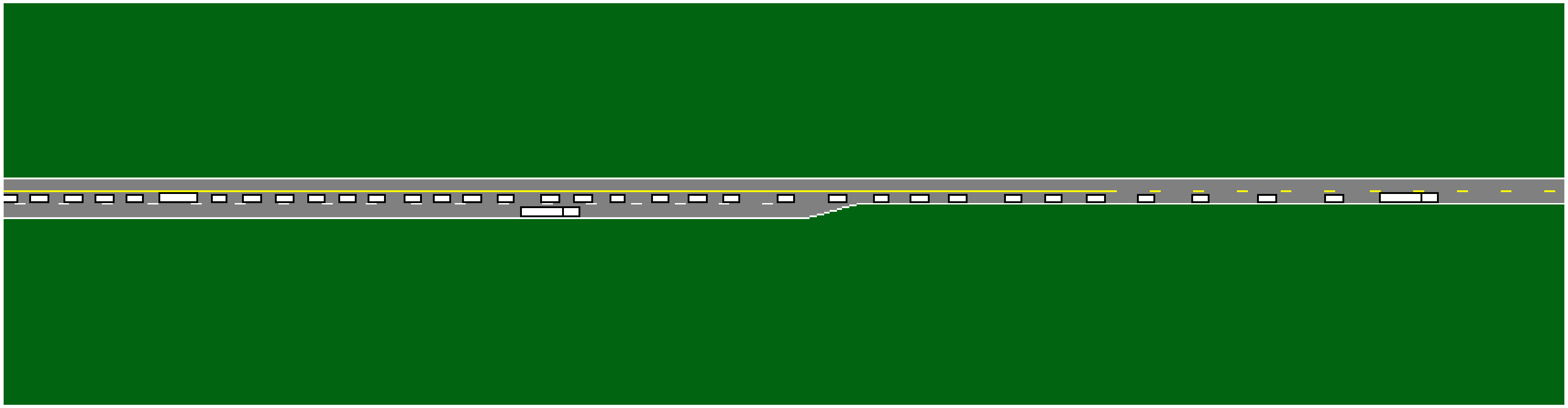

Figure 4-43. Passing lane bottleneck

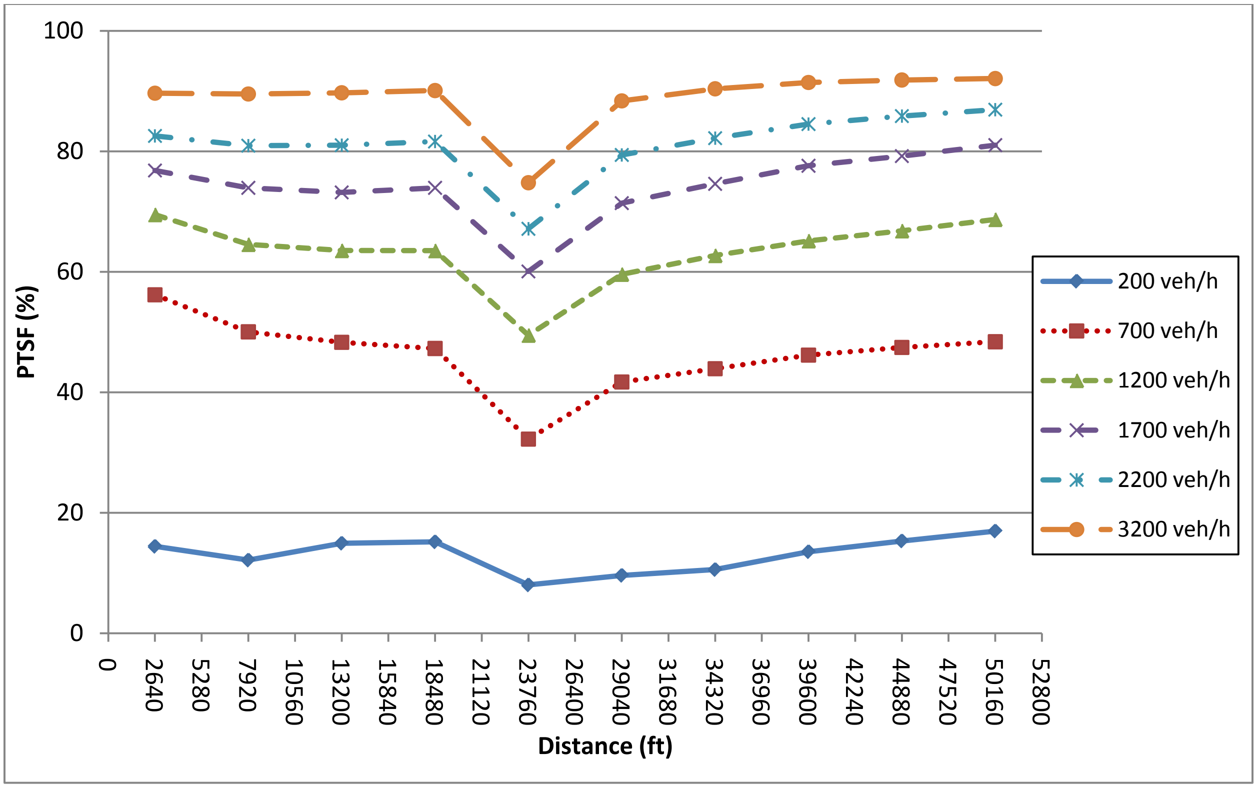

Figure 4-44. PTSF vs. distance - 0% grade, 0%NPZ, 0% HV, passing lane

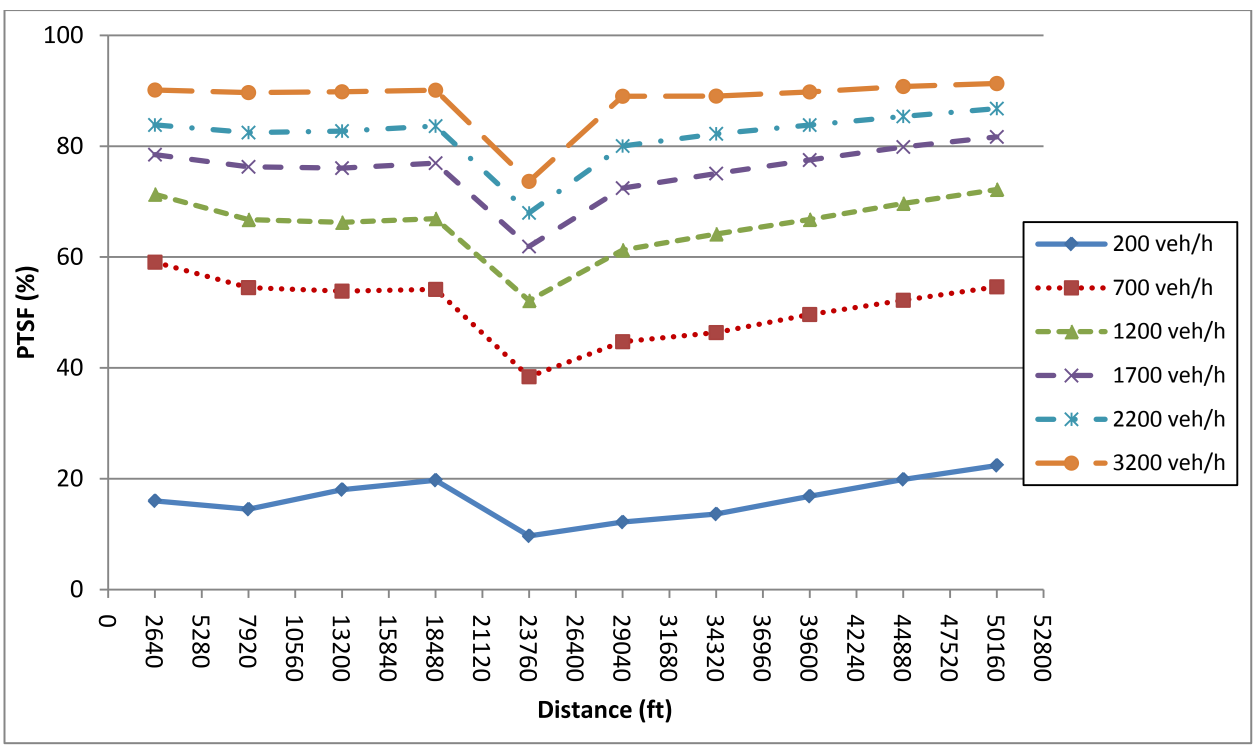

Figure 4-45. PTSF vs. distance - 0% grade, 0%NPZ, 10% HV, passing lane

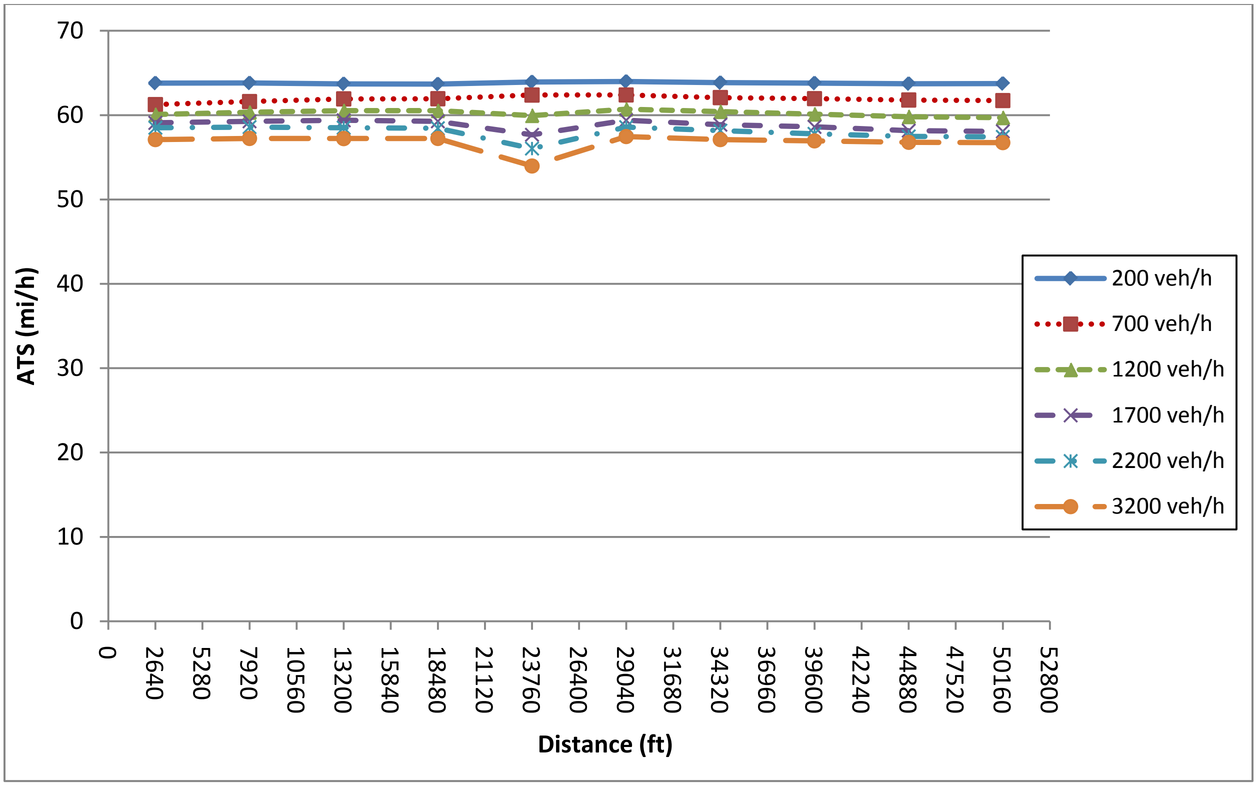

Figure 4-46. ATS vs. distance - 0% grade, 0%NPZ, 0% HV, passing lane

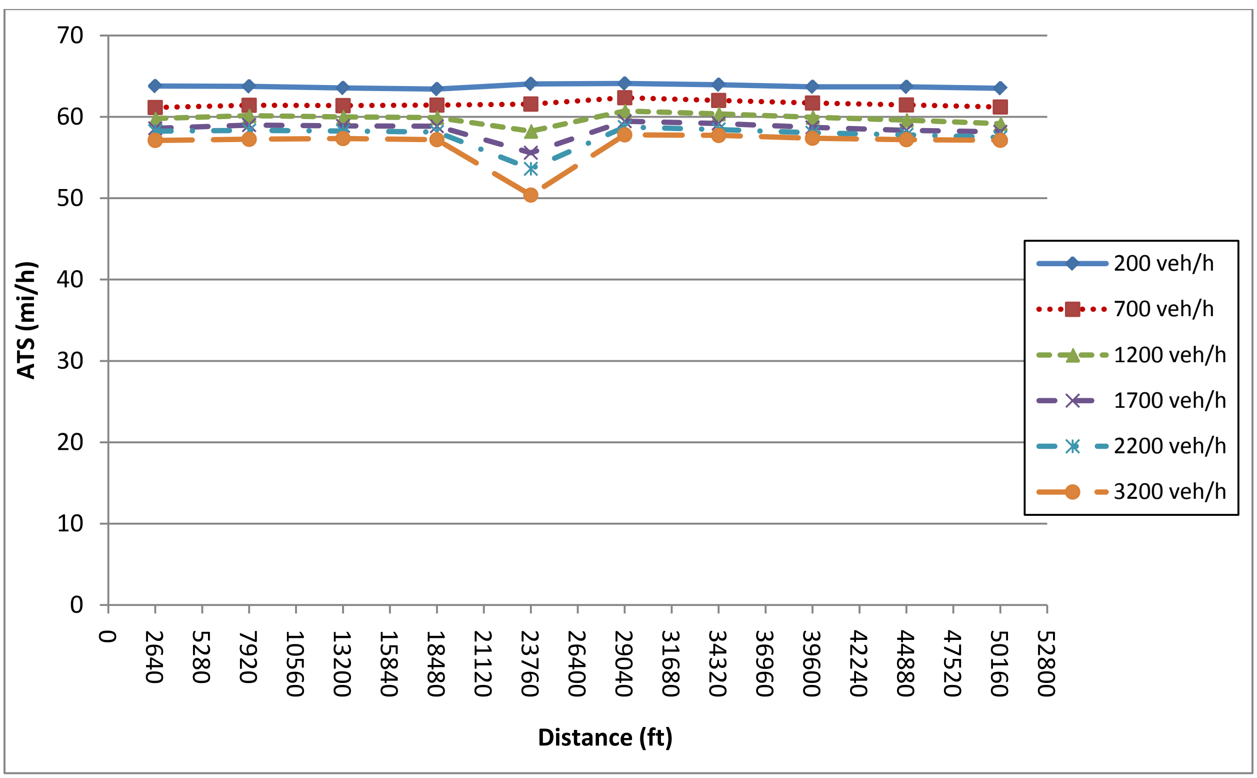

Figure 4-47. ATS vs. distance - 0% grade, 0%NPZ, 10% HV, passing lane

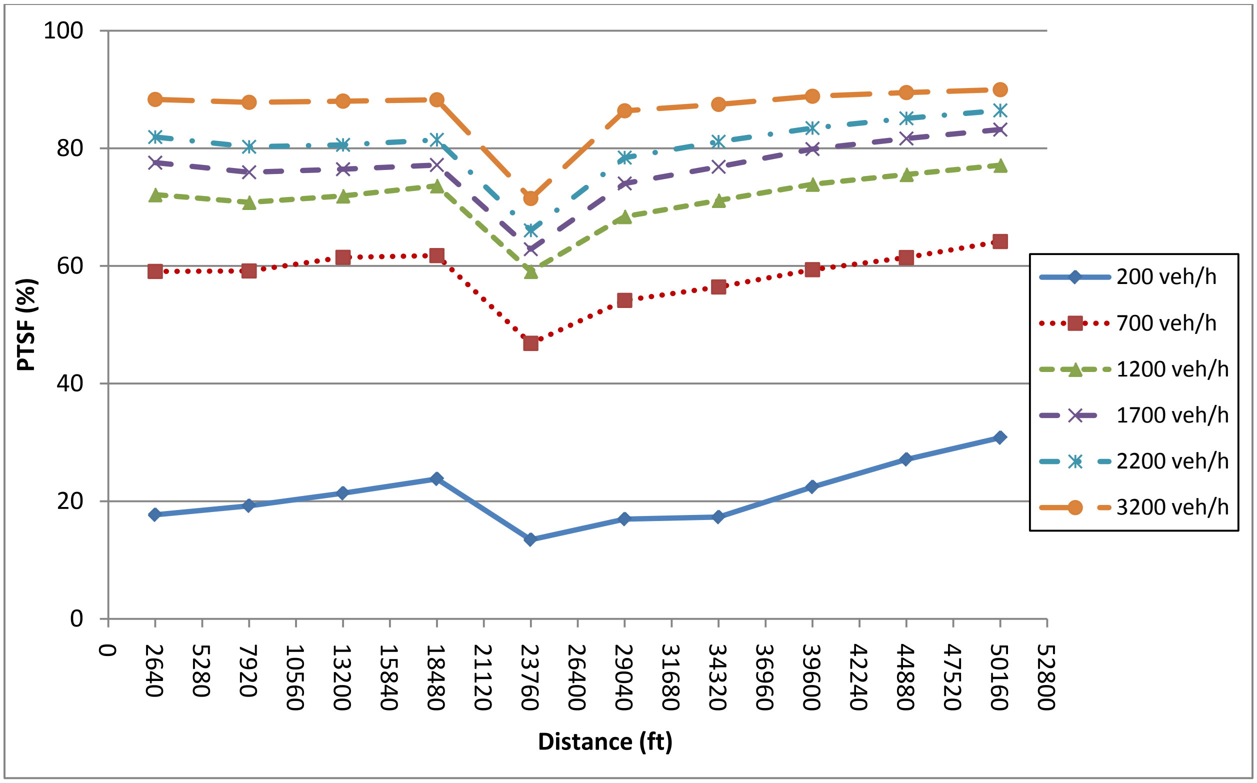

Figure 4-48. PTSF vs. distance - 6% grade, 0%NPZ, 0% HV, passing lane

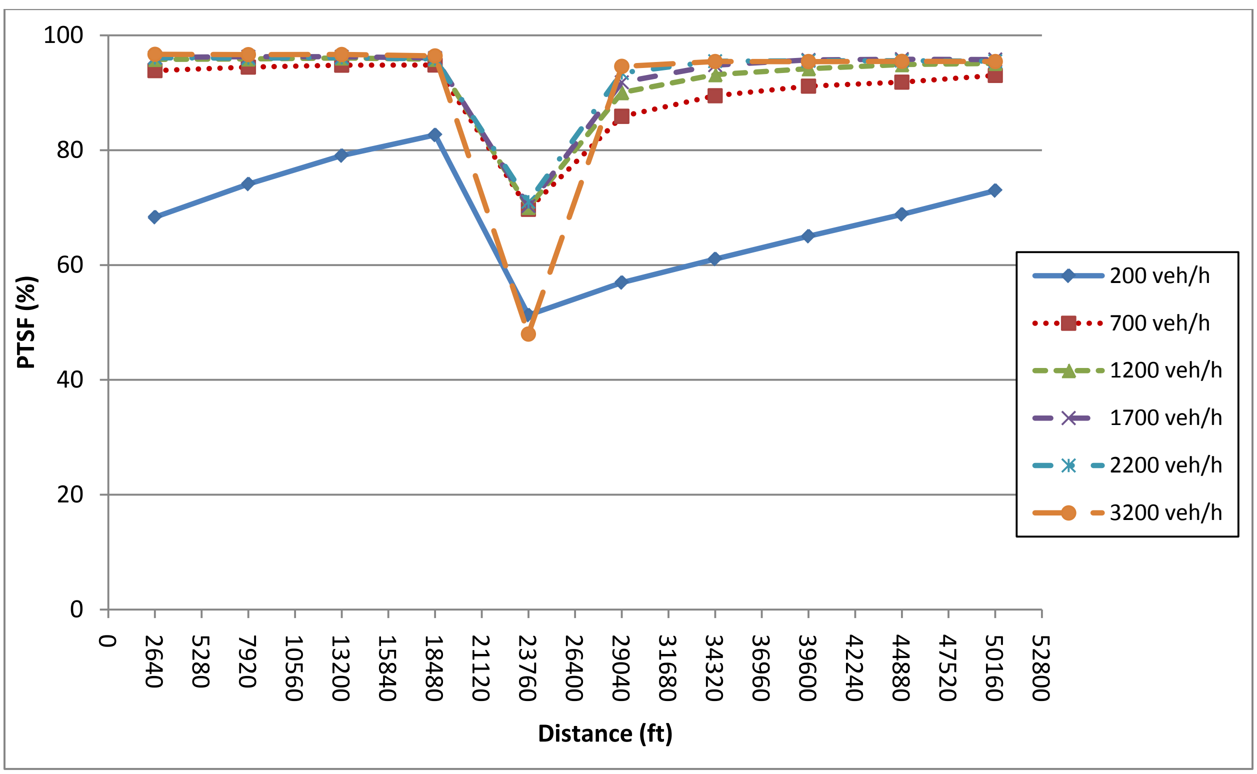

Figure 4-49. PTSF vs. distance - 6% grade, 0%NPZ, 10% HV, passing lane

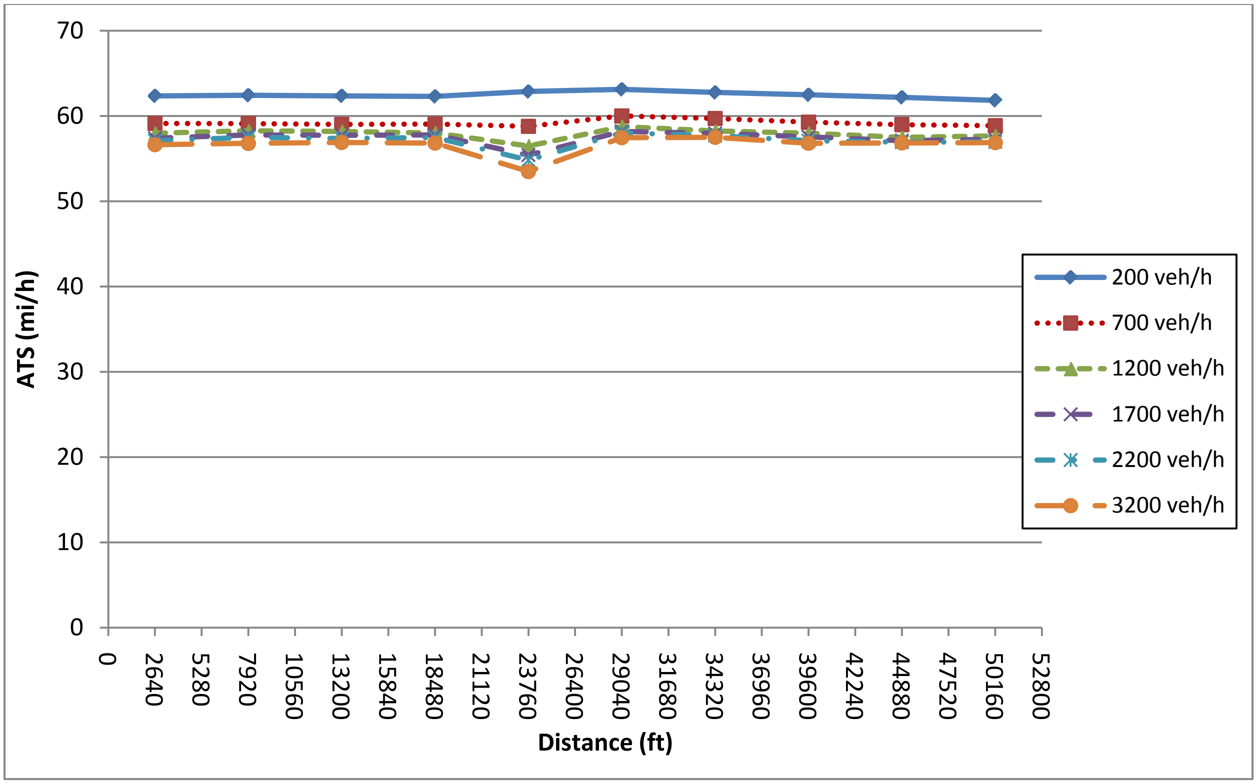

Figure 4-50. ATS vs. distance - 6% grade, 0%NPZ, 0% HV, passing lane

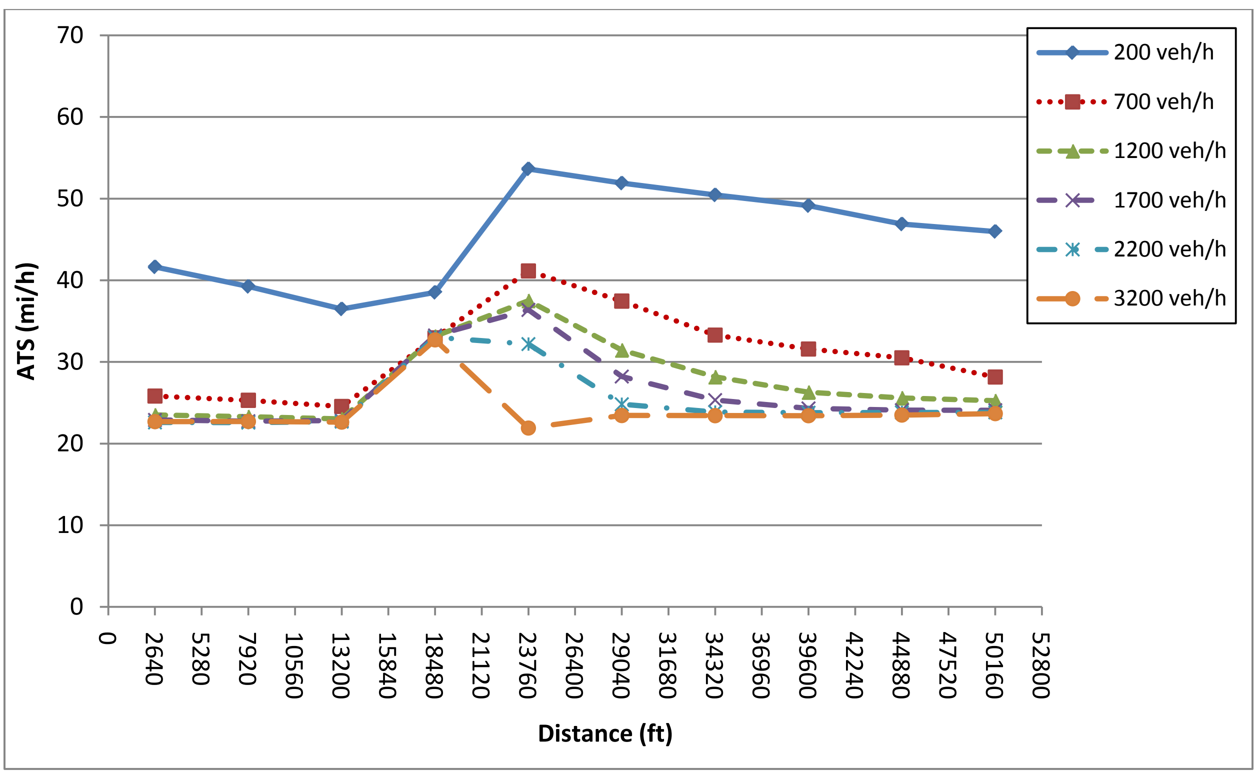

Figure 4-51. ATS vs. distance - 6% grade, 0%NPZ, 10% HV, passing lane

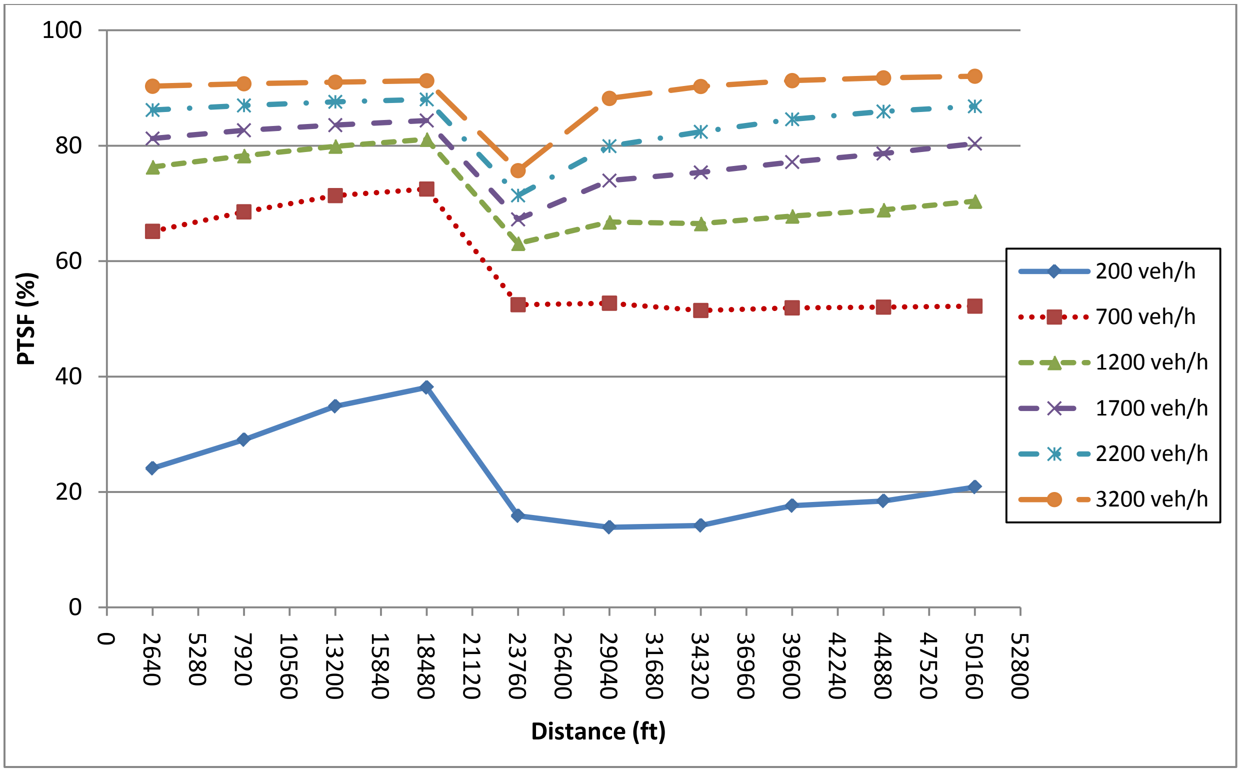

Figure 4-52. PTSF vs. distance - 0% grade, 50%NPZ, 0% HV, passing lane

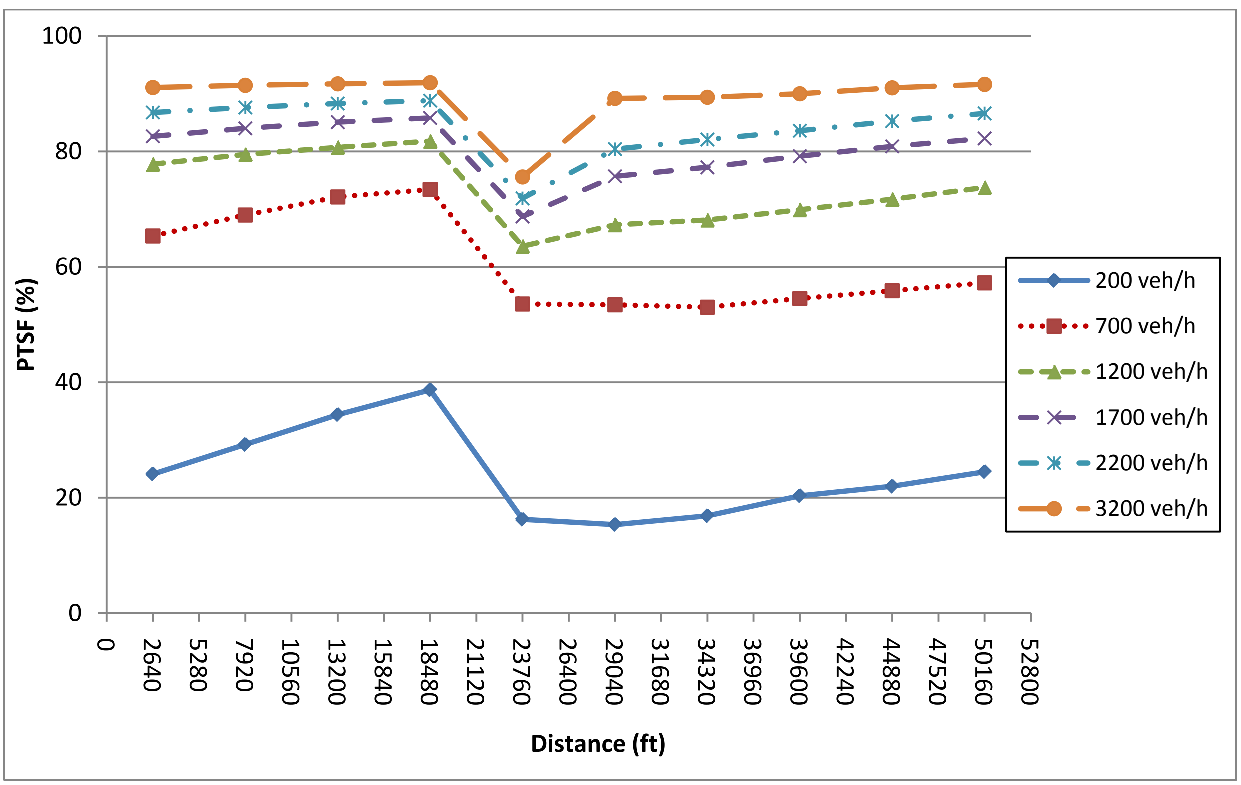

Figure 4-53. PTSF vs. distance - 0% grade, 50%NPZ, 10% HV, passing lane

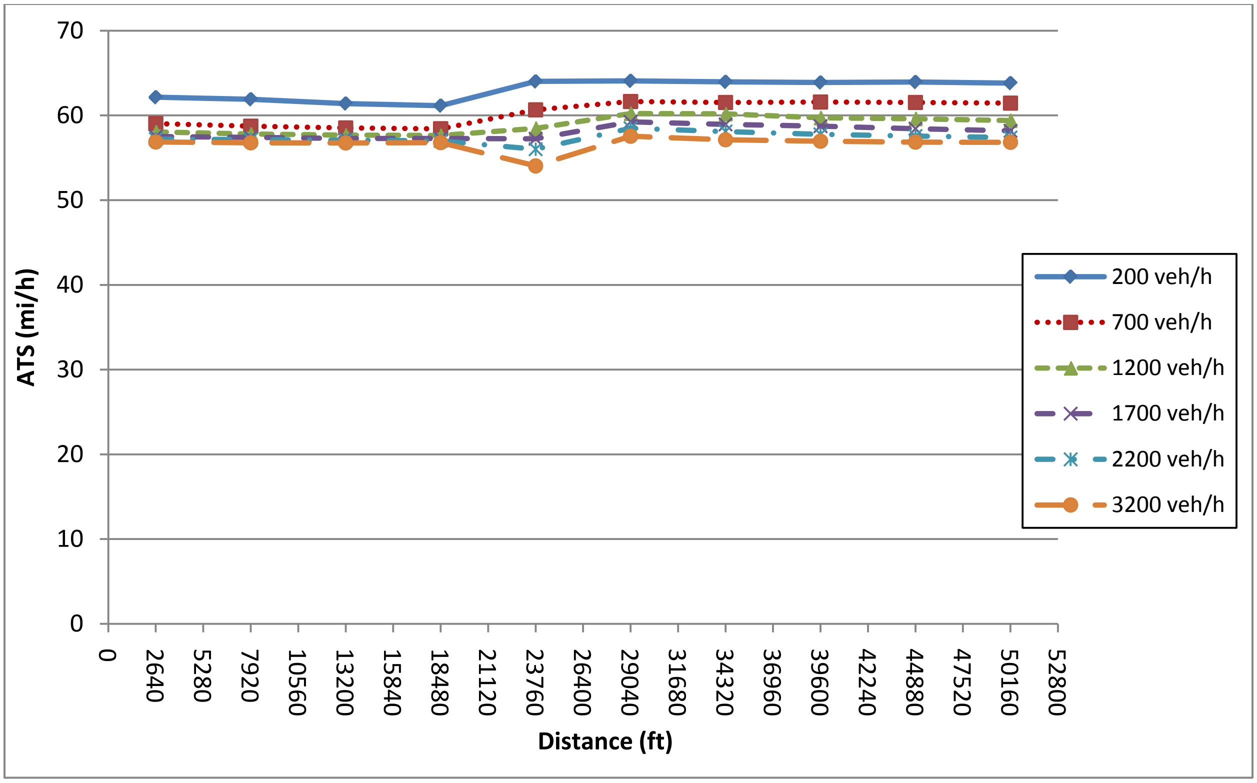

Figure 4-54. ATS vs. distance - 0% grade, 50%NPZ, 0% HV, passing lane

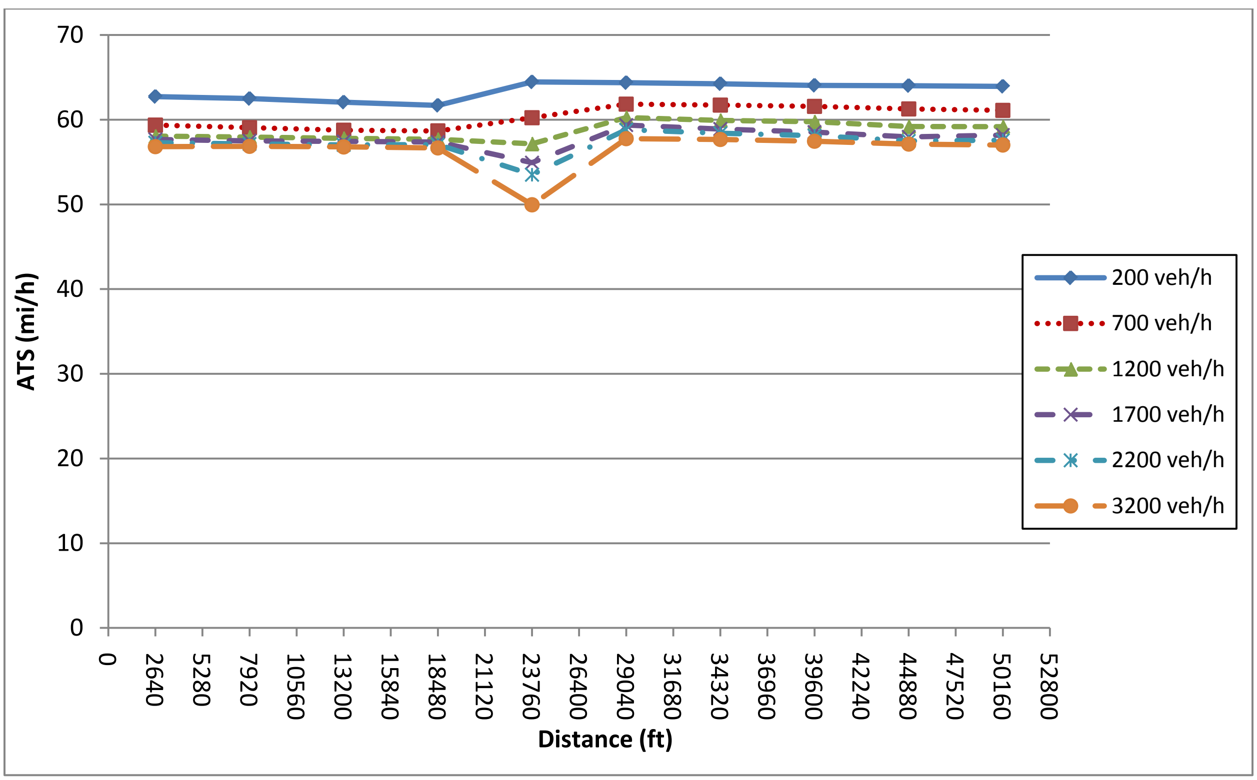

Figure 4-55. ATS vs. distance - 0% grade, 50%NPZ, 10% HV, passing lane

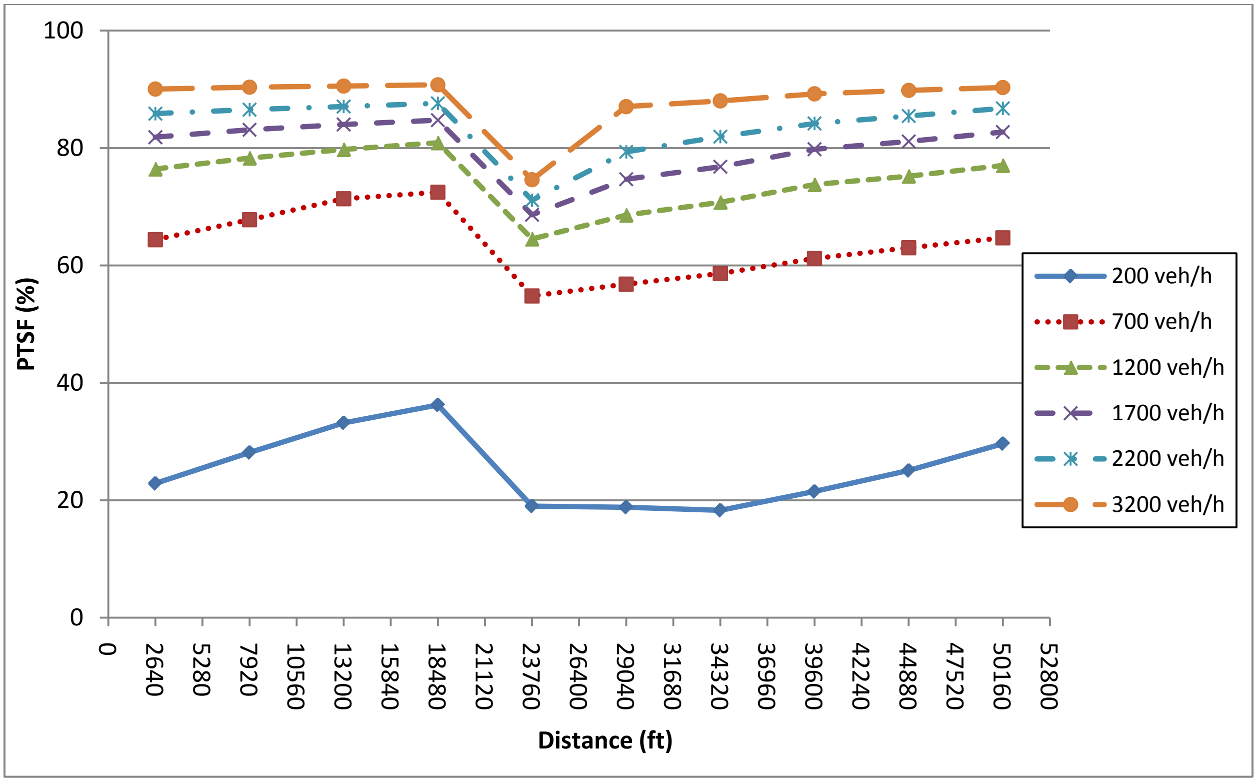

Figure 4-56. PTSF vs. distance - 6% grade, 50%NPZ, 0% HV, passing lane

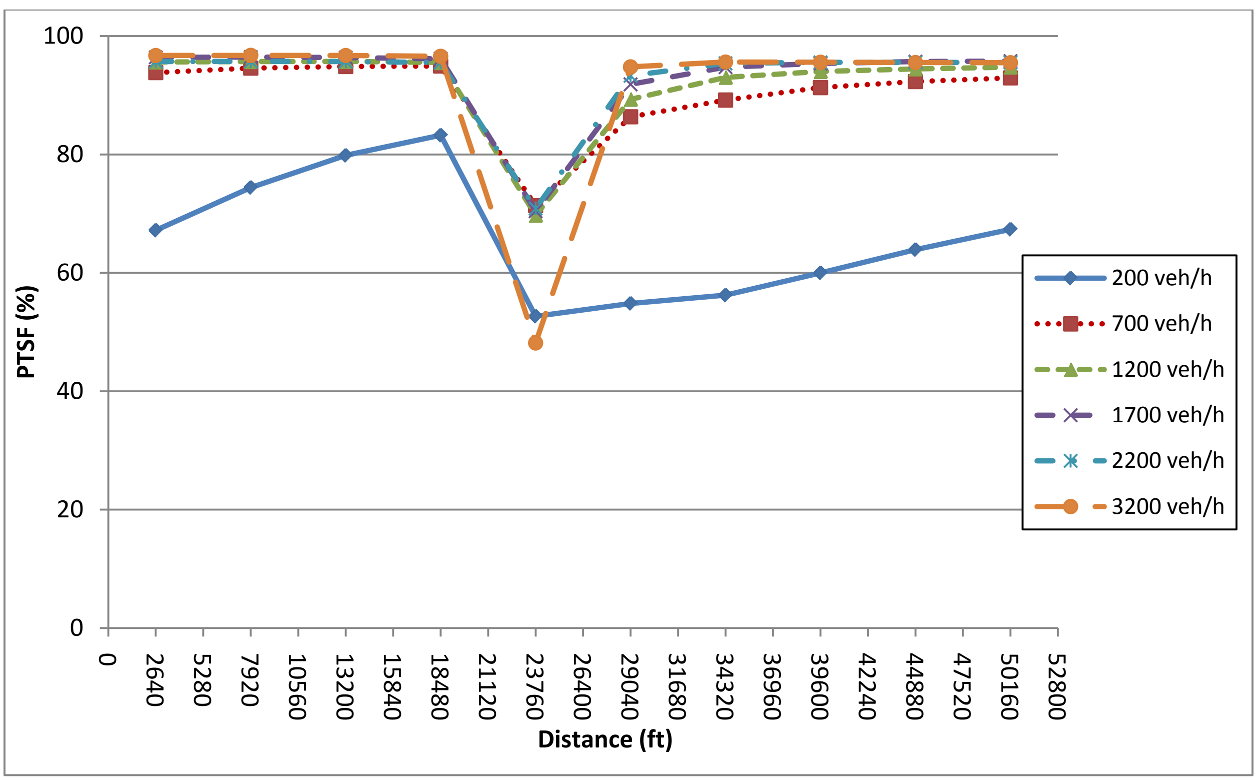

Figure 4-57. PTSF vs. distance - 6% grade, 50%NPZ, 10% HV, passing lane

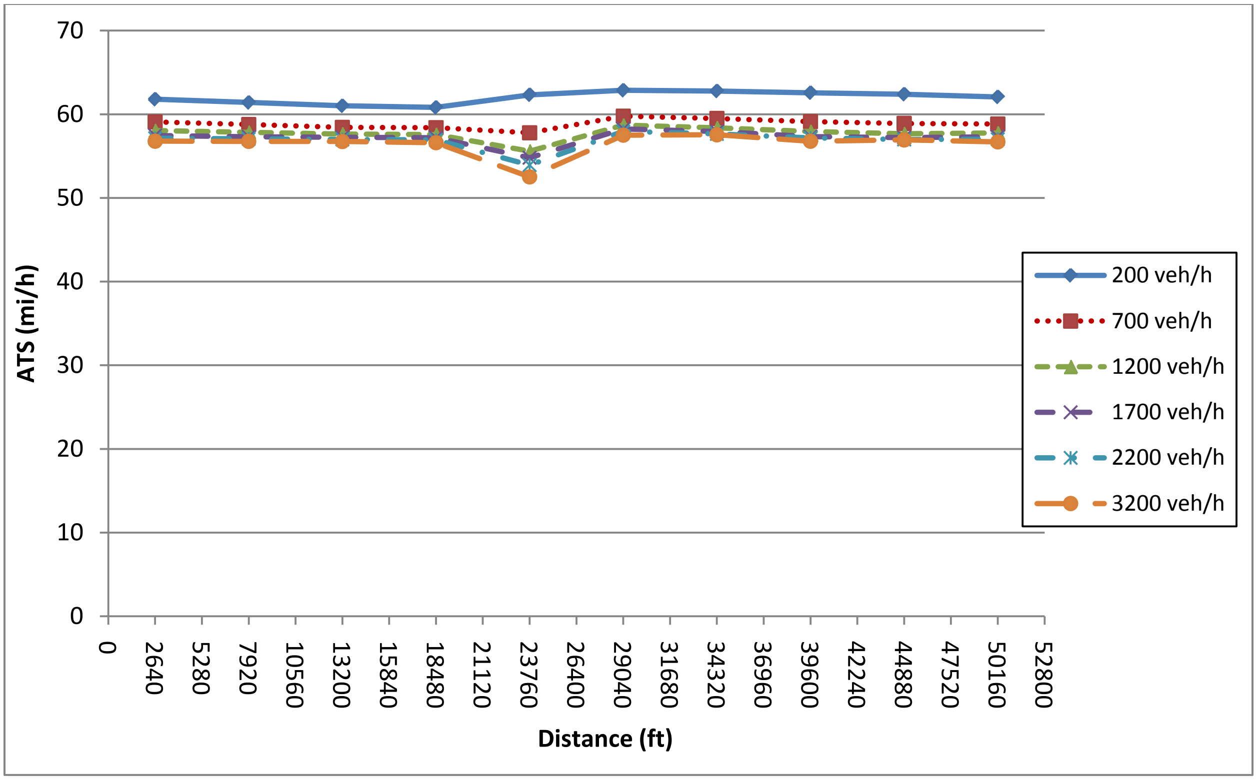

Figure 4-58. ATS vs. distance - 6% grade, 50%NPZ, 0% HV, passing lane

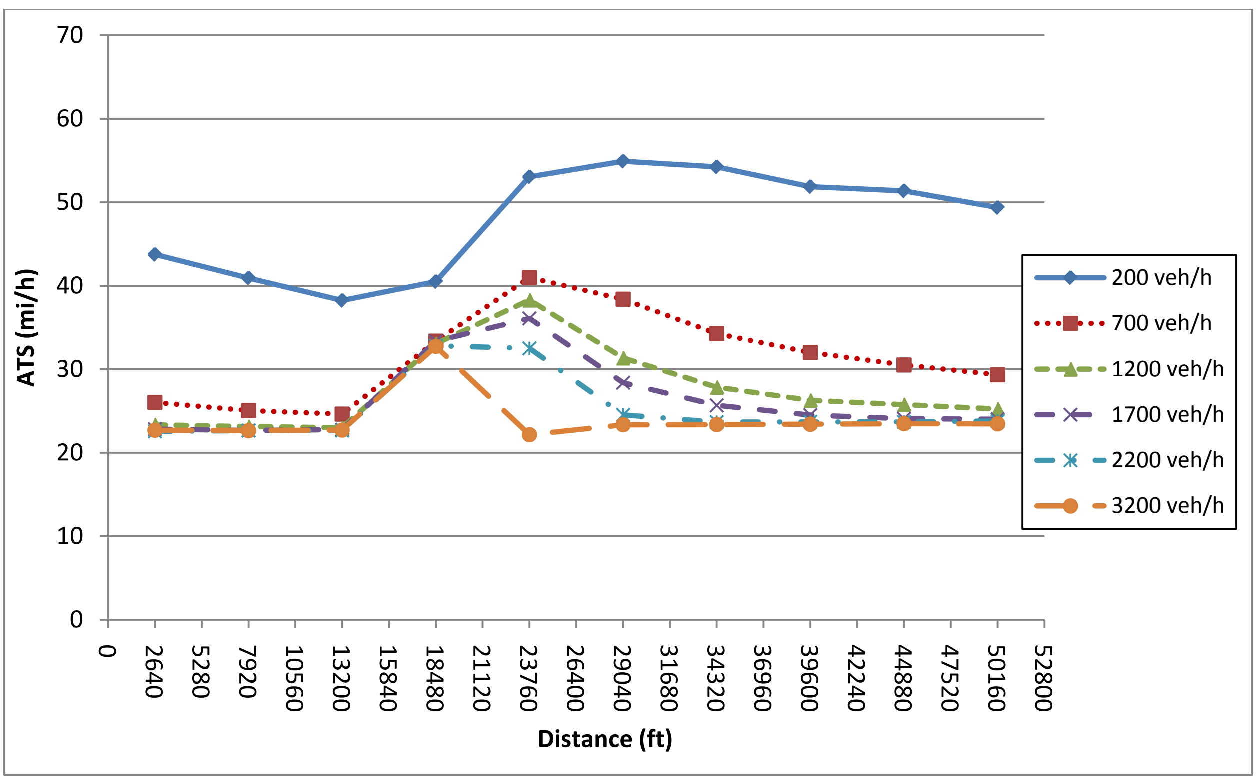

Figure 4-59. ATS vs. distance - 6% grade, 50%NPZ, 10% HV, passing lane

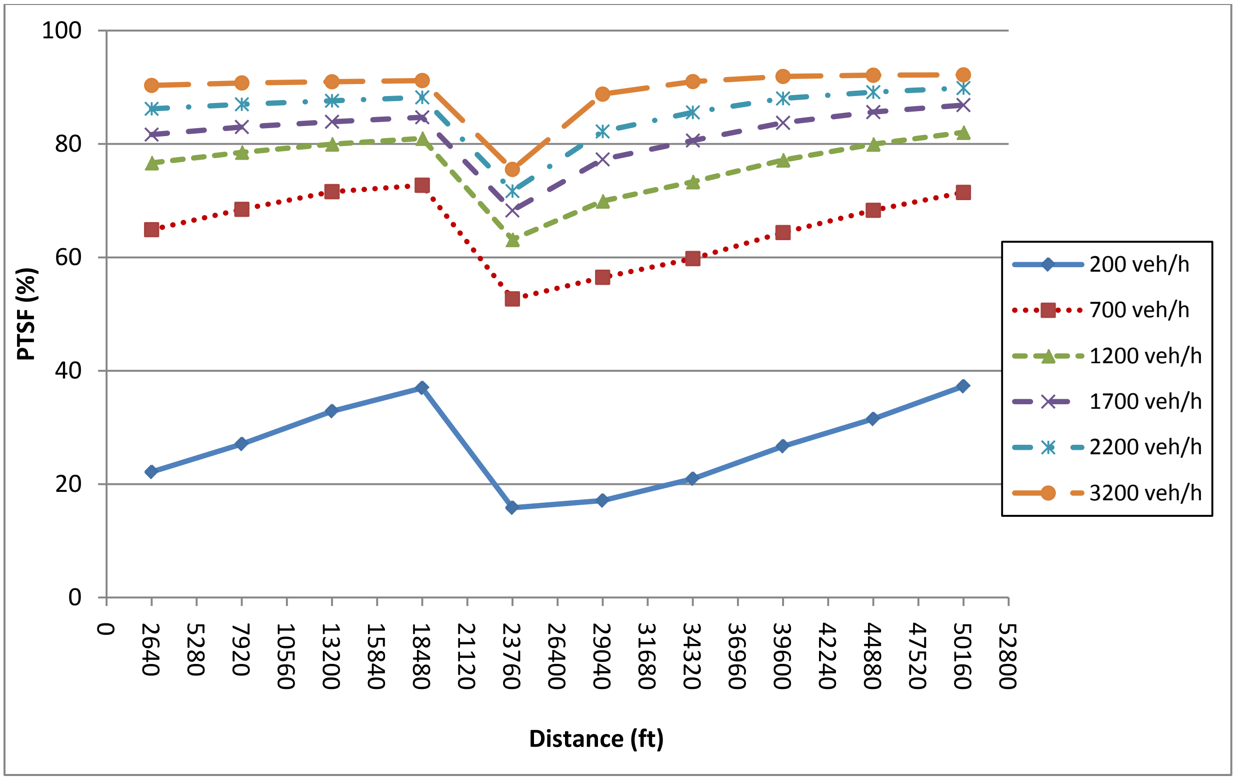

Figure 4-60. PTSF vs. distance - 0% grade, 100%NPZ, 0% HV, passing lane

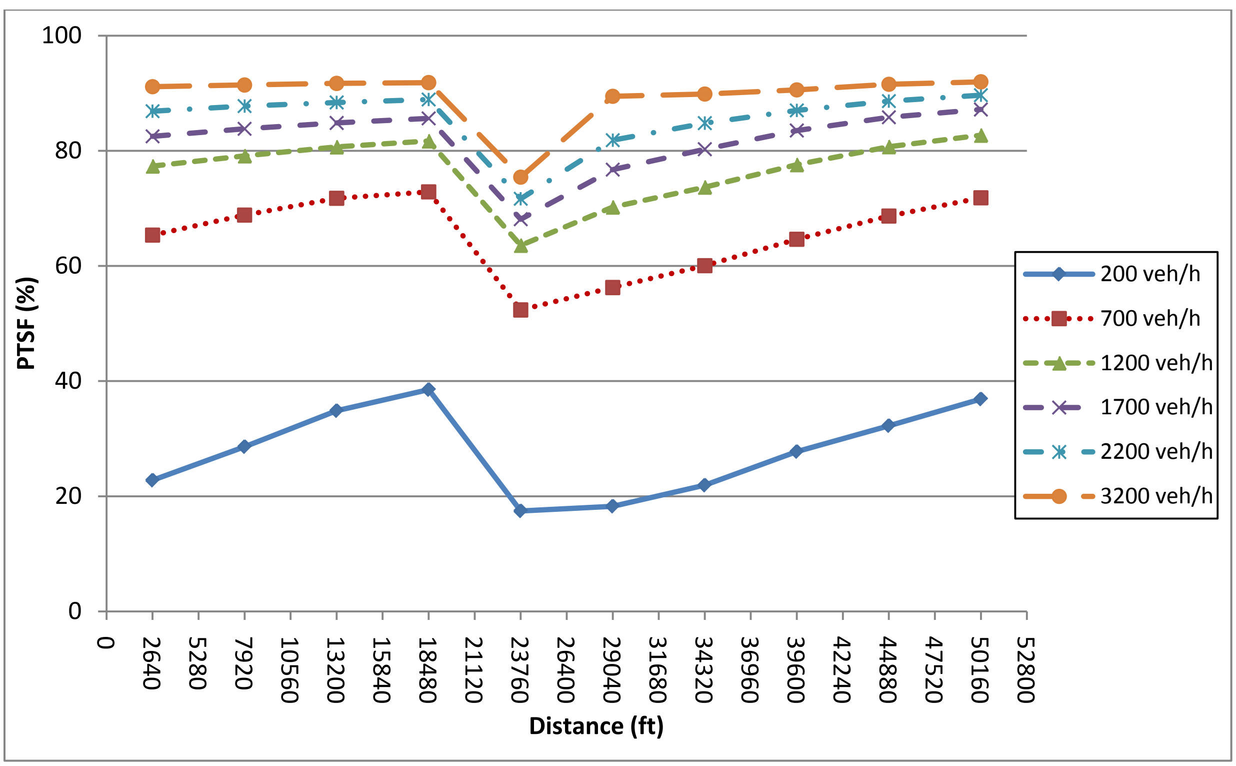

Figure 4-61. PTSF vs. distance - 0% grade, 100%NPZ, 10% HV, passing lane

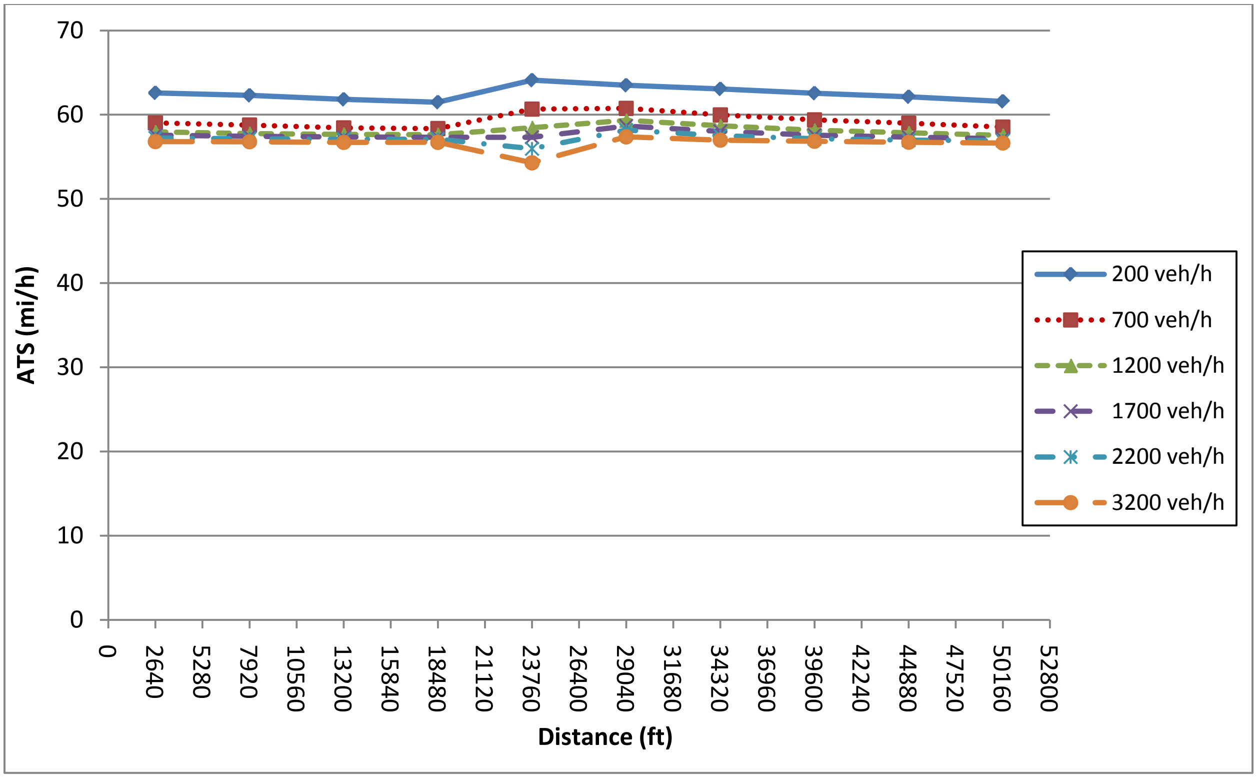

Figure 4-62. ATS vs. distance - 0% grade, 100%NPZ, 0% HV, passing lane

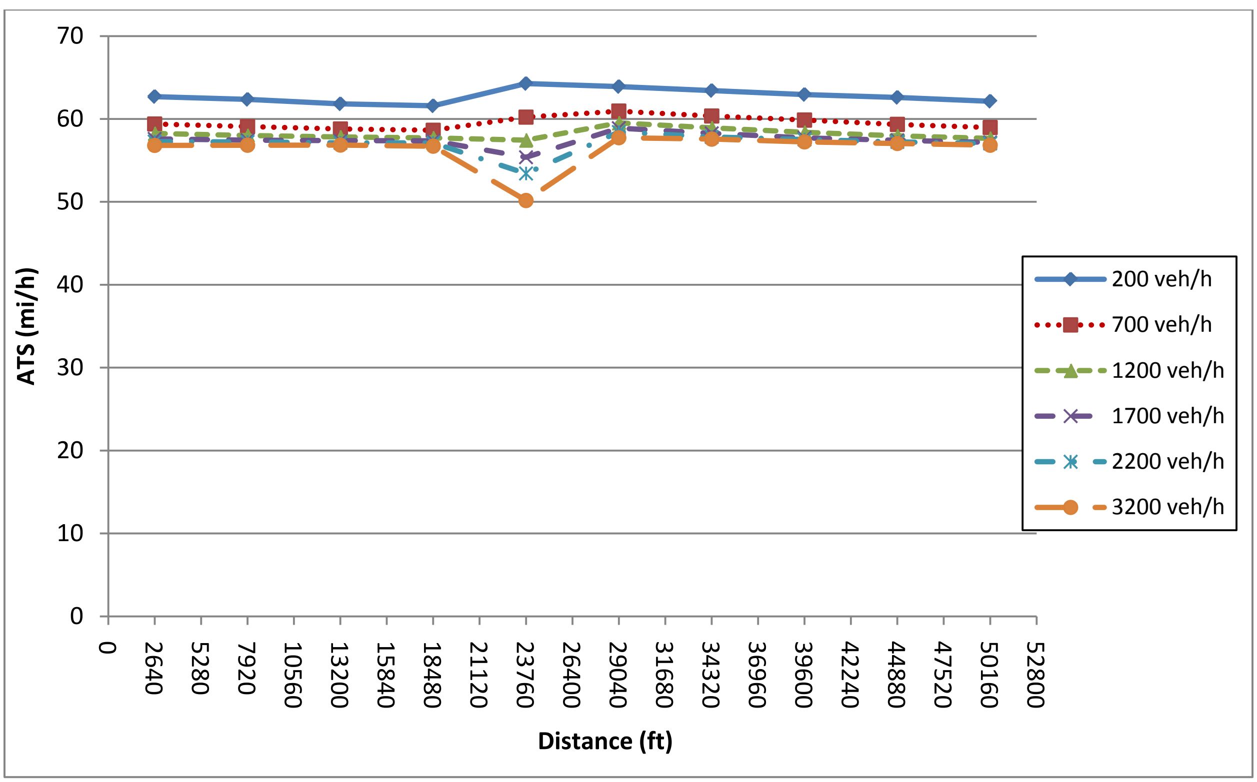

Figure 4-63. ATS vs. distance - 0% grade, 100%NPZ, 10% HV, passing lane

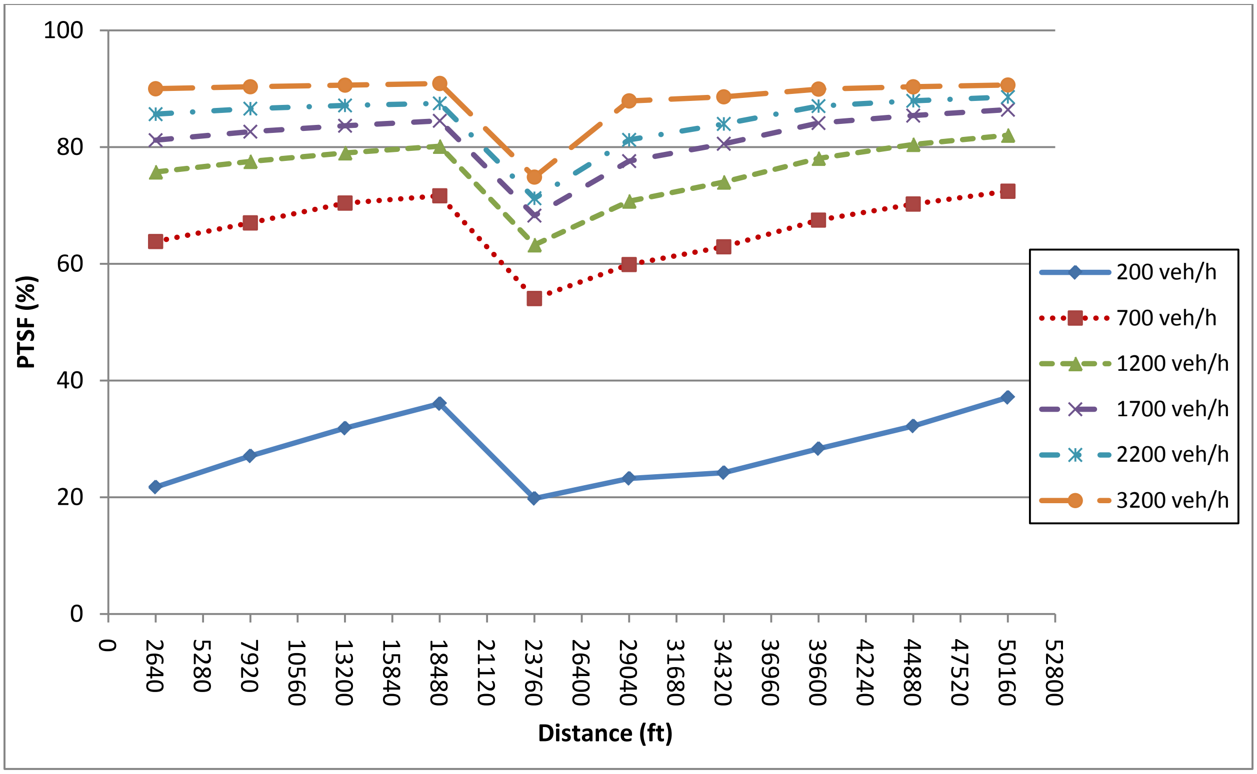

Figure 4-64. PTSF vs. distance - 6% grade, 100%NPZ, 0% HV, passing lane

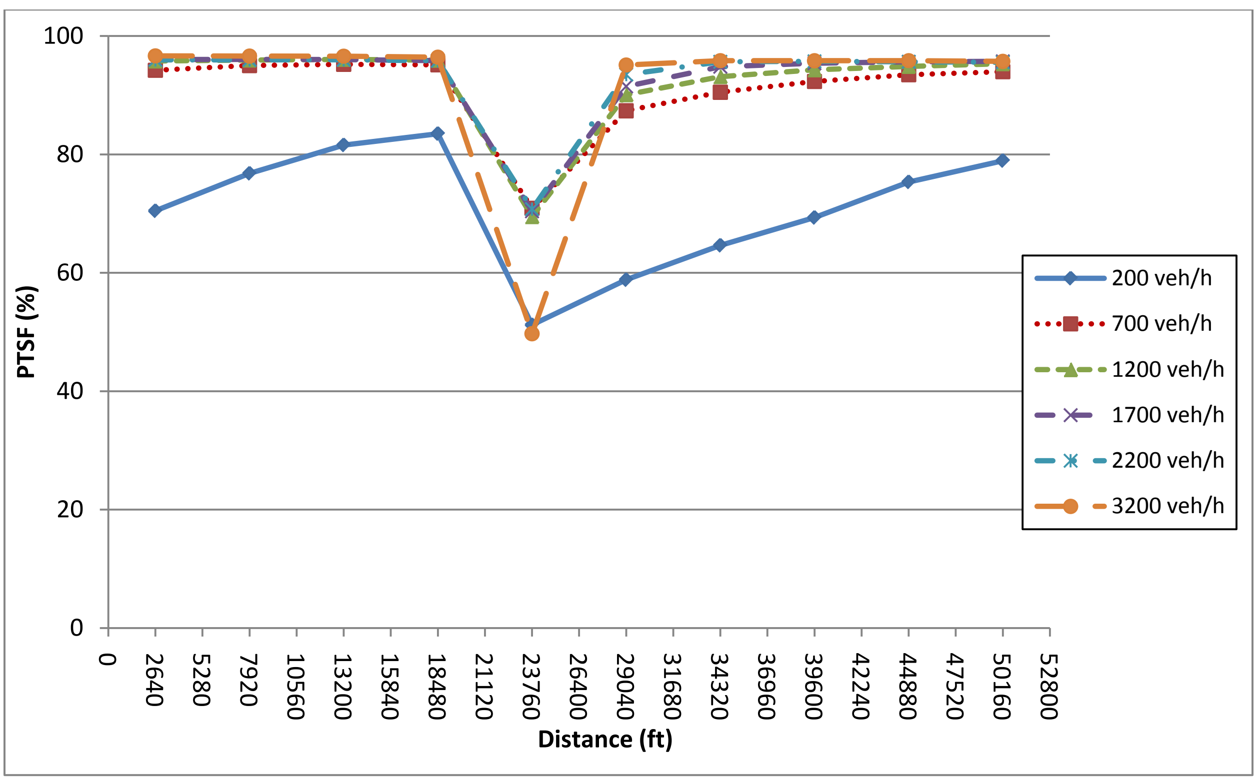

Figure 4-65. PTSF vs. distance - 6% grade, 100%NPZ, 10% HV, passing lane

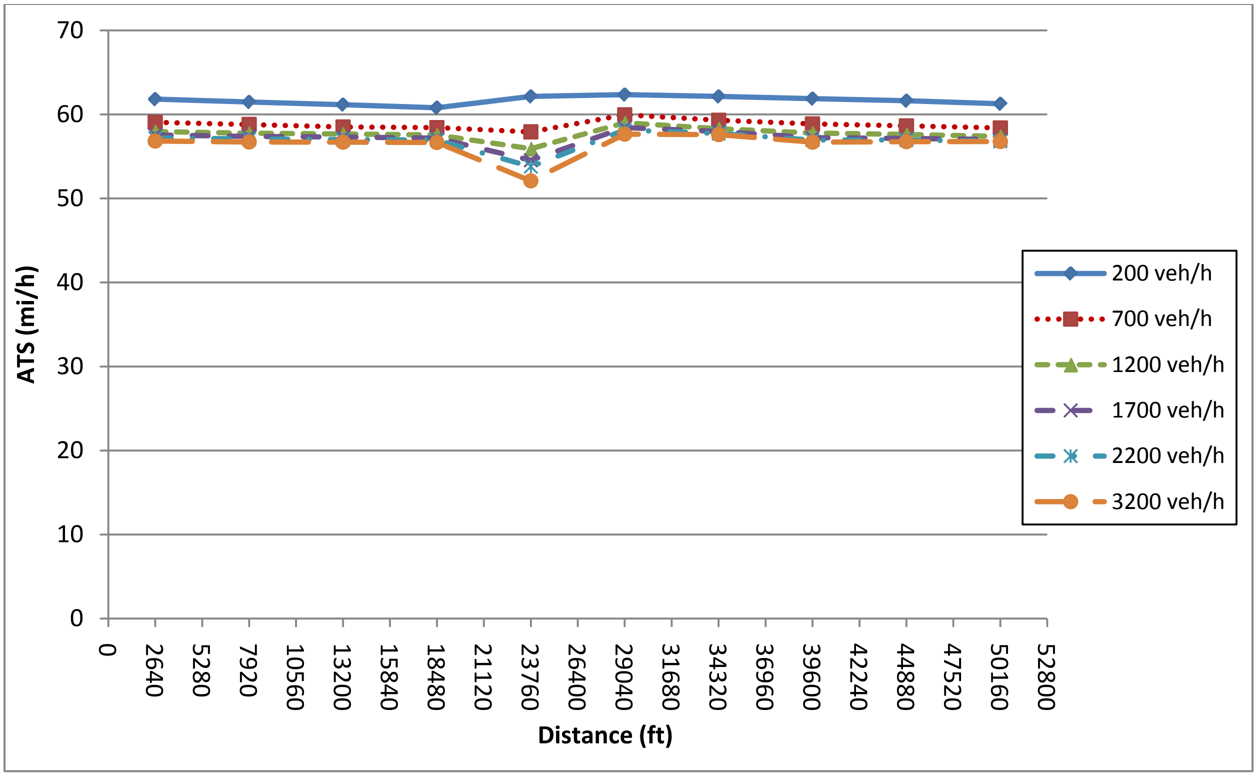

Figure 4-66. ATS vs. distance - 6% grade, 100%NPZ, 0% HV, passing lane

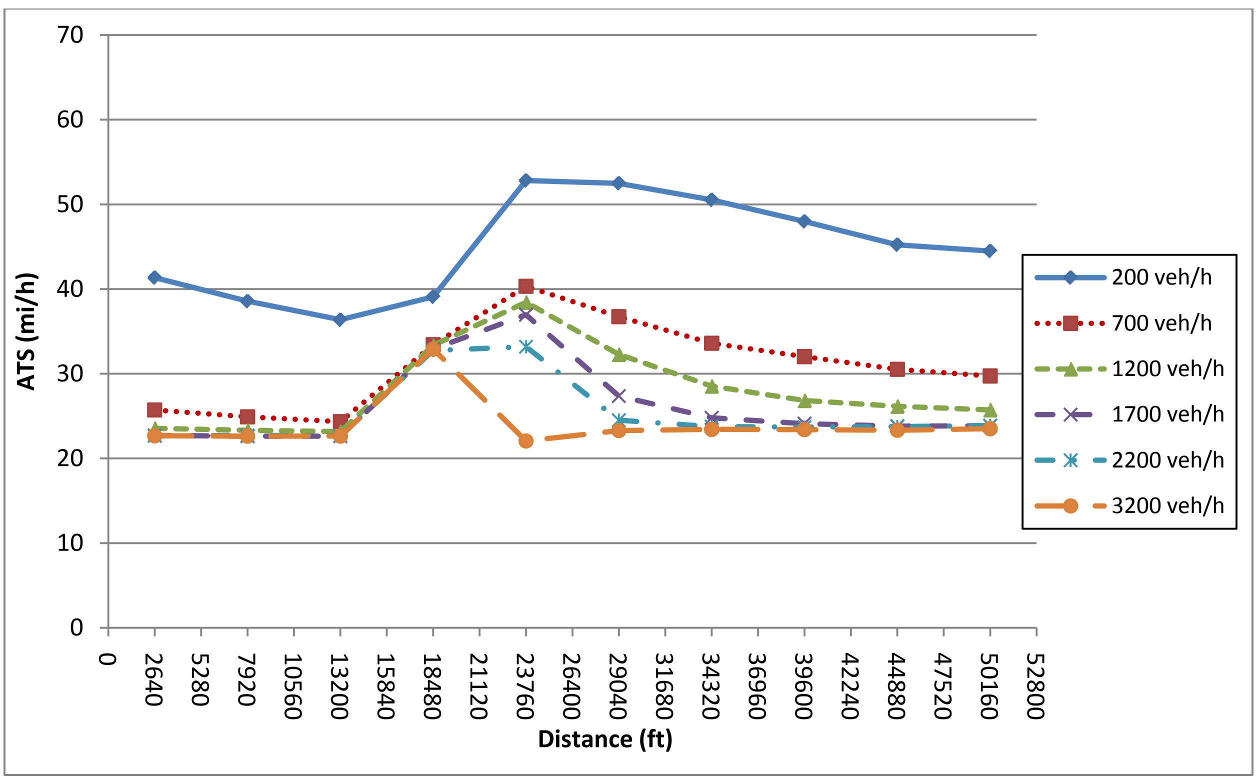

Figure 4-67. ATS vs. distance - 6% grade, 100%NPZ, 10% HV, passing lane

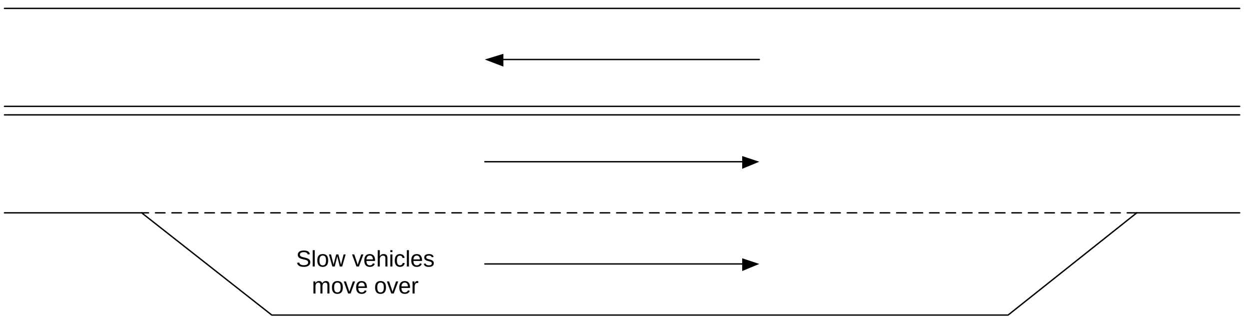

Figure 4-68. CORSIM passing lane configuration

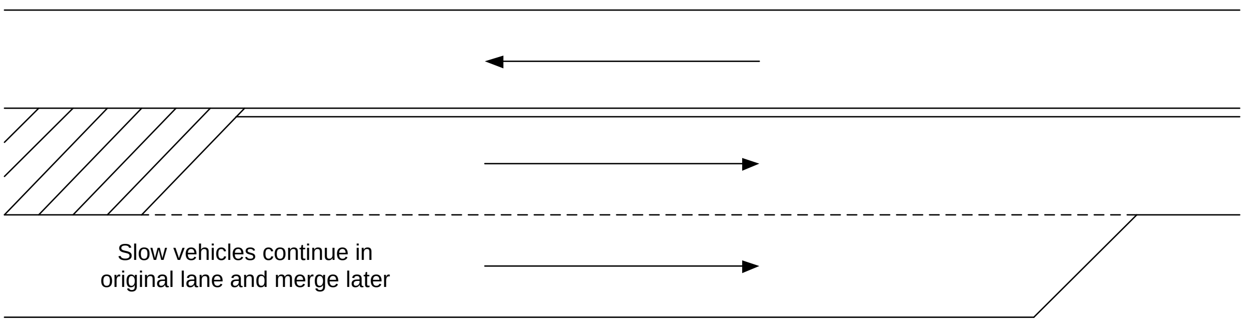

Figure 4-69. SR-40 passing lane configuration

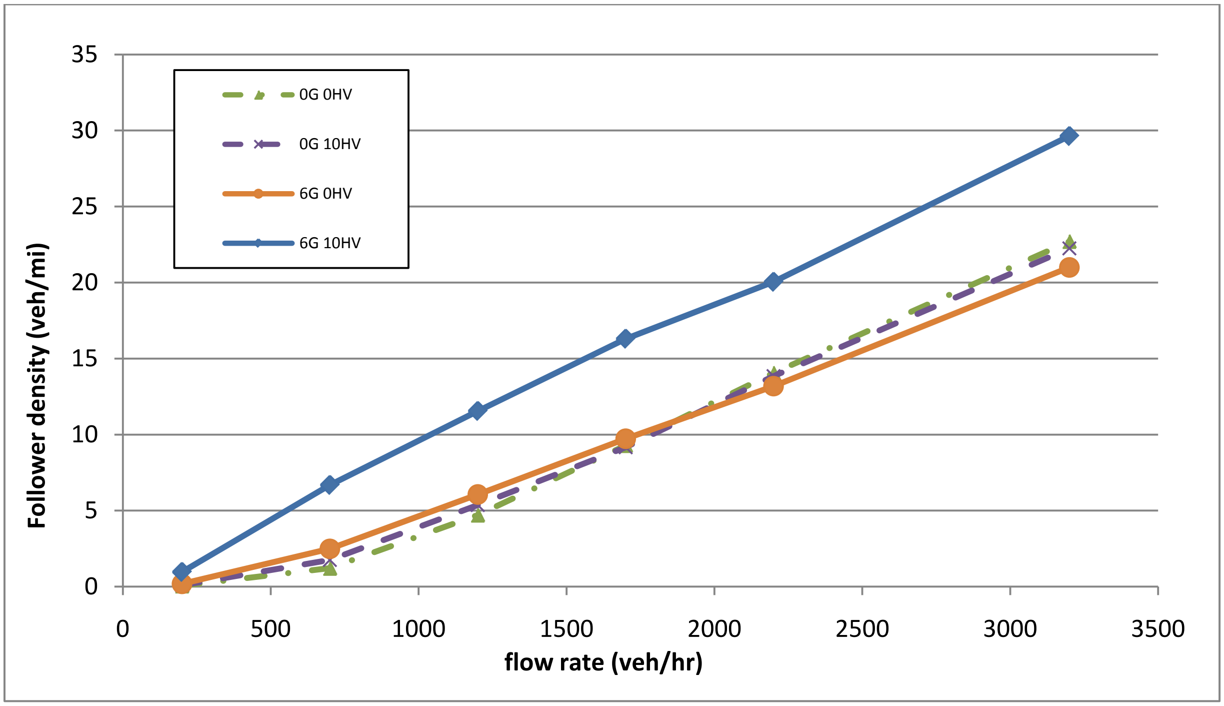

Figure 4-70. Follower density vs. two-way flow rate – 50/50 split, 0%NPZ, no passing lane

Table 4-1. Lead up and follow up passing results

Lead up segment pass allowed	Follow up segment pass allowed	Number of EB passes	Number of WB passes	Difference in number passes	EB PTSF	EB ATS	WB PTSF	WB ATS
N	N	252	291	-39	68.4	54.7	69.0	54.6
Y	Y	471	668	-197	63.5	55.2	65.3	55.0
Y	N	589	201	388	62.0	55.4	70.8	54.3
N	Y	126	692	-566	70.9	54.3	62.8	55.4

Table 4-2. CORSIM capacity estimates 0% heavy vehicles

Speed (mi/h)	50/50 split	60/40 split	70/30 split
65			
Passing lane	2245	2240	2230
No passing lane	2245	2240	2230
60			
Passing lane	2240	2230	2225
No passing lane	2240	2230	2225
55			
Passing lane	2240	2225	2215
No passing lane	2240	2225	2215

Table 4-3. CORSIM capacity estimates 10% heavy vehicles

Speed (mi/h)	50/50 split	60/40 split	70/30 split
65			
Passing lane	2205	2205	2195
No passing lane	2235	2230	2240
60			
Passing lane	2215	2200	2200
No passing lane	2220	2215	2200
55			
Passing lane	2225	2210	2205
No passing lane	2230	2215	2220

Table 4-4. Performance measure rankings

Performance measure*	1	2	3	4	5	6	7
Ease of conceptual understanding	1	3	1	2	1	1	1
Ease of calculation	1	4	1	2	1	2	2
Ease of field measurement	2	5	1	4	3	1	1
Usefulness in identifying improvement needs	3	3	1	3	1	3	3
Usefulness in capturing effects of improvements	1	2	1	3	4	2	3
Ease of adaption to different highway conditions	1	4	2	2	4	2	2
Usefulness in determining LOS	4	1	1	3	4	1	2
Average**	1.9	3.1	1.1	2.7	2.6	1.7	2.0
Final ranking	3	7	1	6	5	2	4

* 1-Percent impeded, 2-Probability-based follower identification *PTSF*, 3-Follower density, 4-Freedom of flow, 5-Overtakings, 6-Deterministic headway *PTSF*, 7-*ATS*.

** 1-best average, 5-worst average

Table 4-5. Follower density difference between 10% and 0% trucks, no passing lane

	0% Grade				6% Grade		
Flow	5050 split	6040 split	7030 split	Flow	5050 split	6040 split	7030 split
0% NPZ				0% NPZ			
200	0.04	0.07	0.07	200	0.78	1.93	1.84
700	0.54	0.72	1.27	700	4.19	5.22	5.71
1200	0.66	1.06	1.30	1200	5.49	6.51	6.84
1700	-0.12	0.60	1.02	1700	6.57	7.12	8.26
2200	-0.21	0.00	0.42	2200	6.86	6.95	8.77
3200	-0.45	-0.17	-0.50	3200	8.64	9.05	7.00
50% NPZ				50% NPZ			
200	0.02	0.04	0.06	200	0.85	1.57	1.65
700	0.17	0.22	0.37	700	4.44	5.60	6.27
1200	0.22	0.42	0.33	1200	6.77	7.90	8.65
1700	-0.07	0.13	0.20	1700	8.23	10.34	10.69
2200	-0.07	0.04	-0.19	2200	9.26	10.87	13.37
3200	-0.18	-0.39	-0.57	3200	12.85	14.39	11.94
100% NPZ				100% NPZ			
200	-0.01	-0.01	0.05	200	0.96	1.94	1.84
700	0.03	0.06	0.20	700	3.32	4.26	4.00
1200	0.11	0.03	0.27	1200	4.86	5.07	4.65
1700	0.04	0.08	-0.15	1700	5.31	6.36	6.92
2200	0.18	0.07	-0.07	2200	6.23	6.69	6.92
3200	-0.07	-0.43	-0.23	3200	7.85	8.19	4.82

Table 4-6. Follower density difference between 10% and 0% trucks, passing lane

	0% Grade				6% Grade		
Flow	5050 split	6040 split	7030 split	Flow	5050 split	6040 split	7030 split
0% NPZ				0% NPZ			
200	0.01	0.02	0.03	200	0.35	0.73	0.77
700	0.15	0.30	0.41	700	4.07	5.23	6.17
1200	0.20	0.33	0.65	1200	7.03	8.58	10.85
1700	0.28	0.27	0.73	1700	9.45	11.75	13.72
2200	-0.17	0.08	0.45	2200	11.71	14.63	17.56
3200	-0.42	-0.81	-0.03	3200	15.33	15.85	12.95
50% NPZ				50% NPZ			
200	0.00	0.01	0.02	200	0.41	0.69	0.98
700	0.06	0.13	0.25	700	3.75	4.72	5.68
1200	0.01	0.24	0.18	1200	6.58	7.64	9.52
1700	0.03	0.38	0.42	1700	9.07	10.67	12.67
2200	-0.22	-0.08	-0.18	2200	10.88	13.00	15.21
3200	-0.36	-0.29	-0.21	3200	15.08	14.89	11.24
100% NPZ				100% NPZ			
200	0.00	0.01	-0.01	200	0.46	0.85	1.25
700	0.04	-0.01	0.18	700	3.77	4.62	5.07
1200	0.04	0.05	-0.01	1200	6.50	7.33	8.29
1700	0.07	-0.06	-0.25	1700	8.99	10.10	11.26
2200	0.07	-0.18	-0.21	2200	10.92	12.41	13.79
3200	-0.22	-0.44	-0.57	3200	14.75	15.31	10.29

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

Overview

The results of this study provide an assessment of the reasonableness of the two-lane highway modeling algorithms used in CORSIM and an assessment of the validity of the two-lane analysis methodology of the HCM. Input differences between the two tools were addressed and the outputs of each tool were compared. This study tested how different values of input variables and the presence of passing lanes affect the performance measures.

The preliminary CORSIM tests provide users with guidance on setting up an analysis network. This study gives insight on two-lane highway capacity under a variety of traffic conditions and also provides an assessment of different performance measures that have been proposed for analyzing two-lane highways. During this study, several potential enhancements and improvements to CORSIM were identified. This chapter presents the main findings of this research and discusses recommendations for CORSIM and HCM improvements as well as areas for future research.

Research Findings

The preliminary tests in CORSIM showed that a lead up length is necessary to establish existing upstream conditions and that type 6 trucks in the traffic stream have a major impact on performance measures. The passing zone configuration test showed that the average of the performance measures was not greatly affected by the passing zone configurations. There were differences at points along the highway between the three facilities, but the average of the performance measures for each facility was similar.

The speed-flow relationship between the HCM and CORSIM did not match up well. Other sources (*5*, *8*) indicate that the speed-flow relationship is not linear, and CORSIM further supports those claims. The HCM and CORSIM comparison showed very different results for the no-passing lane cases with 6% grade and 10% heavy vehicles. CORSIM had much higher values for *PTSF* and much lower values for *ATS* than the HCM for this condition.

The *ATS* for the facility was not greatly affected by the addition of a passing lane, but the *PTSF* showed considerable improvements for lower flow rates. Passing lane effects last further downstream for low flow rates than for high flow rates and they are more effective for upgrades. For high flow rates, the best solution for improving performance measures is adding a full lane because passing lanes only provide a modest improvement at the passing lane location. The effects do not extend downstream after a certain flow rate depending on the other roadway and traffic conditions. The *ATS* graphs for passing lanes show that average speed drops at the passing lane link for higher flow rates due to the congestion at the merge area. Therefore, although the total average speed for the facility increases slightly, by about 1 mi/h, the benefit-to-cost ratio would likely not support building a passing lane.

This research provides capacity estimates for certain geometric and traffic scenarios including with and without a passing lane. CORSIM estimated the capacity to be about 500 veh/h higher than the HCM estimate. The CORSIM capacity estimate matches more closely with Kim's (*25*) estimate than with the HCM estimate. This study also provides a qualitative analysis of several performance measures that could be useful for analyzing two-lane highways. Follower density was ranked as the best performance measure for analyzing two-lane highways because of its ease of field measurement and conceptual understanding as well as its usefulness in determining when improvements should be made. This performance measure was also analyzed in a series of quantitative tests.

CORSIM Findings and Recommendations

There are several areas where CORSIM could be improved. The preliminary tests showed some limitations within CORSIM that should be addressed. The passing procedures and passing lane results also should be improved. This section discusses some of the changes that should be made in CORSIM and describes further testing that should be done in future research.

Preliminary Tests

The preliminary tests exposed some of the user-friendly weaknesses in CORSIM. There should be an easier way for the user to establish existing upstream traffic conditions than by adding a lead up segment. The reason for using a lead up length is to avoid biased results, but there is no guarantee that the lead up length eliminates the possibility of biased results. However, the lead up length is necessary for the vehicles to develop a platoon structure similar to what would be observed in the field before they enter the analysis section. The first recommendation is to add a record type in the CORSIM input file that allows the user to specify a percentage of vehicles entering in platoons. Vehicles would be generated from an entry node as part of a platoon and the user would no longer have to extract data only from the desired links. The percentage of entering platoons was an input used in TWOPAS to establish upstream conditions (*26*). The two main challenges with this recommendation are that the user would have to measure the percentage of vehicles entering as platoons in the field for real-world projects and a new algorithm would have to be developed for vehicle generation in CORSIM.

The truck type distribution test showed that type 6 trucks have a major effect on the performance measures, even when only 2.5% of the traffic consists of type 6 trucks. Type 6 truck speeds should not be extremely different from the other truck type speeds on a 0% grade. The performance characteristics of the type 6 truck, as contained in CORSIM, should be revisited to see if they are still consistent with real-world type 6 trucks.

Passing Procedures

CORSIM is programmed so that a vehicle that is following another vehicle will not pass unless there is a gap ahead of the impeding vehicle. The impeding vehicle may initially have a large enough gap in front of it for a vehicle to pass and move back into the traffic stream. However, it is possible that during the pass, the impeding vehicle reaches the back of another platoon. If the platoon is large enough, then the passing vehicle could be left in the opposing lane with no available gap in the original lane.

There are two ways that CORSIM could be improved to address this shortcoming. The current passing procedure in CORSIM makes a check to see how far ahead the next vehicle is in front of the impeding vehicle before the pass begins. CORSIM could implement this check for every time step during the pass and if the gap in the original lane becomes unacceptable, then the passing vehicle should abort the pass. Another solution could be to implement a methodology for driver cooperation for vehicles in the platoon. If a passing vehicle has no available gap to move back into as it initially had when it began the pass, then one of the vehicles in the platoon should adjust its speed and create a gap for the passing vehicle to fit into.

Currently in CORSIM, vehicles only have a desire to pass when they are in a following mode (i.e., headway ≤ 3 sec). Realistically, when a faster vehicle approaches a slower vehicle, it is possible that the faster vehicle will pass the slower vehicle before it technically becomes a following vehicle. This is referred to as passing on the fly, and the passing algorithm in CORSIM should be modified to allow for this type of passing maneuver.

The tests that compared the HCM to CORSIM showed high *PTSF* results for low flow rates when the grade was 6% with 10% heavy vehicles in the traffic stream. The HCM results were much lower than the CORSIM results for the 6% grade. This large difference in results between the two tools gives another reason for the truck type performance characteristics in CORSIM to be investigated further. Speed data should be collected for different types of trucks on different upgrades so the proper changes can be implemented into CORSIM.

There were instances in CORSIM where vehicles were following behind a slow vehicle and were unable to pass because the gaps in the opposing lane were unacceptable. The desire to pass increases with the time a vehicle spends in a following state, according to the CORSIM algorithm. Eventually, it is likely that vehicles would be willing to go well above the posted speed limit for a short period of time in order to get around a slow vehicle. The slower the lead vehicle goes, the more likely following vehicles are willing to speed in order to get around. This is another reason that a passing on the fly algorithm should be incorporated into CORSIM. Vehicles should accelerate as they approach a vehicle that is going too slow so they can prepare for the pass. If a vehicle accelerates to a high speed before the pass begins, it could potentially spend less time in the opposing lane. This could help increase the number of passes, which would consequently result in more platoon dispersion.

Passing Lanes

There are two types of passing lanes along two-lane highways as shown in Figure 4-68 and Figure 4-69. CORSIM is only capable of modeling the passing lane type shown in Figure 4-68. The passing lane type shown in Figure 4-69 should be implemented into CORSIM so users can model two-lane highways as accurately as possible. The passing lane algorithm should be modified accordingly because slow vehicles are expected to move over in CORSIM's current passing lane algorithm, whereas the slow vehicles continue on the original lane in the other configuration. Heavy vehicles typically take more time to change lanes than passenger cars. Once the other passing lane type is implemented into CORSIM, the two passing lane types should be compared in order to see if they have an impact on the results.

2010 HCM Findings and Recommendations

The *ATS* trends between CORSIM and the HCM were very different. Other sources (*5*, *8*) support the CORSIM trend. Therefore, the HCM methodology should be modified so that the speeds level off as the flow rate increases. Also, the HCM curves show that the *PTSF* reaches values just short of 100% for the 70/30 split in the 0% and 50% no-passing zone cases. Vehicles naturally break up into many smaller platoons. They do not travel in one or two long platoons. The HCM *PTSF* methodology should be investigated further so it reflects accurate results for different conditions. It is possible that the *PTSF* could be near 100% for heavy traffic in both directions. However, the flow rate of 2200 veh/h under a 70/30 split gives the directional flow rate of 1540 veh/h, which is less than the HCM's estimated capacity. For normal conditions where the traffic is not approaching capacity, the *PTSF* should not be 100%.

CORSIM provides a true estimate of *PTSF* in that it records every vehicle's follower status at every time step and finds the percentage of time that each vehicle was in a following state. Then, for the average facility *PTSF*, CORSIM takes the sum of the following time across all vehicles divided by the sum of the time spent in the network by all vehicles. The HCM method uses a regression equation for finding *PTSF* that is based on TWOPAS simulation results. Although the two tools have different procedures for calculating the *PTSF*, the difference between the results was small. The TWOPAS simulation *PTSF* calculation is most likely similar to the one used in CORSIM, which is the reason for small *PTSF* differences between the HCM and CORSIM. The HCM generally provides a good estimate for PTSF and does not consistently overestimate it. This contradicts Luttinen's (*6*) findings.

For grades of 6%, the HCM *ATS* values go as low as 4 mi/h for the flow rate of 3200 for all directional splits when there are 10% heavy vehicles in the traffic stream. The HCM gives the directional capacity to be 1700 pc/h. The flow rate of 3200 veh/h under a 50/50 split has 1600 veh/h in both directions, which means the major direction is operating at a directional flow rate that is less than the capacity according to the HCM. Therefore, the HCM equations should be applicable to this case. The *ATS* calculations and adjustments for grade should be modified to give more reasonable results.

Follower density has been implemented into CORSIM and basic tests were analyzed, but the CORSIM results could not be compared to the HCM as the HCM does not have a calculation methodology for follower density. The qualitative analysis done in this study showed that follower density has several merits as a performance measure for analyzing two-lane highways. Follower density should be given strong consideration for inclusion in the HCM as a performance measure for evaluating LOS for two-lane highways. This would allow for more comprehensive analyses of two-lane highways. CORSIM could be used to develop an analytical procedure for follower density calculation, as well as appropriate LOS thresholds.

Recommendations for Future Research

The passing zone configuration tests showed that the three 50% no-passing zone configurations did not have a large effect on the results even though the two tools have different methods for inputting this variable. Different highway lengths and percentages of no-passing zones should be tested in order to confirm that the passing zone configuration does not have a large effect on the average *PTSF* and *ATS* for any specific facility. There is a similar input difference between the HCM and CORSIM for two-lane highways with a grade change. The HCM does not directly allow the user to specify where there is a grade change along the highway. The user can split the highway into segments depending on where the grade changes and calculate the results based on the weighted averages. In future research, a test that is similar to the passing zone configuration test should be designed to test the difference in results between CORSIM and the HCM for two-lane highways with a grade change. If there are major differences based on this variable, then a procedure should be implemented into the HCM that allows the user to specify where the grades are located along the highway.

The graphs that were created based on the HCM and CORSIM comparison showed several areas where there were major differences between the two tools. The grade effects between CORSIM and the HCM were very different. Field data on two-lane highways with grades should be used to give guidance on how the two tools should be adjusted to better-reflect how vehicles are affected by grade.

In the future, more extensive research should be conducted on how capacity is affected by the placement and frequency of passing lanes along a two-lane highway. This study does not support the concept of capacity being increased because of the presence of a passing lane. The results of this study show that the passing lane hinders capacity when there are heavy vehicles in the traffic stream. This could be due to friction at the merge area, which is plausible in the real world. However, there is not conclusive evidence to support these results. Future research should be done on the merge behavior of vehicles, especially under high flow rates.

Further testing should be done to show whether or not the rearrangement of vehicles into faster-moving platoons on passing lanes affects overall highway capacity. One passing lane may not allow the vehicles enough opportunities to form faster platoons, but multiple passing lanes placed strategically along the highway may increase the capacity. Also, capacity estimates should be tested for different grades, percentages of heavy vehicles, and *FFS* in order to develop an accepted capacity standard for all types of conditions.

Other countries have other techniques besides passing lanes to help platoons disperse. South Africa uses wide shoulders to allow slower vehicles to move over so that faster vehicles can go by in the regular lane. Finland uses wide lanes, (18 ft in each direction, for a total lane cross-section width of 36 ft) in some locations to accommodate passing. Vehicles are able to pass by using the middle of the cross section, as the opposing vehicle and the vehicle being passed are expected to stick close to the right side of their respective lanes. The HCM currently lacks sufficient adjustment factors to account for wide lanes and wide shoulders. CORSIM currently does not account for changes in lane and shoulder width. The user has to make assumptions about what variables are affected by a change in lane or shoulder width and by how much. Then, the user must enter different values for those inputs according to the assumed effects. For example, if a two-lane highway has lanes that are wider than 12 ft, the user may enter the *FFS* at a higher value than for 12 ft lanes. Wide lane and wide shoulder capabilities should be considered for inclusion in CORSIM to make it more usable to the international community.

For future research, methodologies should be developed so that more of the performance measures in Table 4-4 can be quantitatively tested in CORSIM. After CORSIM is capable of generating the results for the proposed performance measures, they can be compared with each other and then additional LOS methodologies could be developed for the HCM as appropriate.

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BIOGRAPHICAL SKETCH

Heather Hammontree grew up in Canton, OH where she graduated from Jackson High School in 2005. She completed her undergraduate studies at the University of Florida and graduated Cum Laude in the fall of 2009 with a Bachelor of Science in civil engineering. At the beginning of 2010, she began graduate studies at the University of Florida and completed a Master of Engineering in transportation engineering in the fall of 2010.