Mobility And Safety Evaluation Of Integrated Dynamic Merge And Speed Control Strategies In Work Zones

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MOBILITY AND SAFETY EVALUATION OF INTEGRATED DYNAMIC MERGE AND SPEED CONTROL STRATEGIES IN WORK ZONES

by

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ABSTRACT

In recent years, there has been a considerable increase in the amount of construction work on the U.S. national highways. Most of the work undertaken is the reconstruction and rehabilitation of the existing transportation networks. Work zones in the United States are likely to increase in number, duration and length due to emphasis on repair and highway reconstruction as a significant portion of all federal-aid highway funds are now geared toward highway rehabilitation. The challenge of mobility is particularly acute in work zone areas as road repair and construction intensifies traffic issues and concentrates them in specific locations and at specific times. Due to the capacity drop, which is the result of lane closure in work zone area, congestion will occur with a high traffic demand. The congestion increases number and severity of traffic conflicts which raise the potential for accidents; furthermore traffic operational properties of roadway in work zone area become worse.

Intelligent Transportation System (ITS) technologies have been developed and are being deployed to improve the safety and mobility of traffic in and around work zones. In several states in the US, the use of Dynamic Merge Controls also known as Dynamic Lane Merge (DLM) system has been initiated to enhance traffic safety and to improve traffic flow in work zone areas. The DLM usually takes two forms; dynamic

early merge and dynamic late merge. The use of variable speed limit (VSL) systems at work zones is also one of those measures. VSL systems improve safety by helping the driver in determining the maximum speed that drivers should travel. Besides adding improvement to safety, they are also expected to improve mobility at the work zones.

The main goal of this study is to evaluate the safety and operational effectiveness of the dynamic merge systems i.e. the dynamic early lane merge and dynamic late lane merge, in the presence of VSL system. More specifically, the VISSIM model is utilized to simulate a two-to-one lane configuration when one out of the two lanes in the work zone is closed for traffic. Six different scenarios were adopted to assess the effectiveness of these scenarios under different traffic demand volumes and different drivers' compliance rates to the messages displayed by the systems. These scenarios are;

- Work Zone without VSL and without SDLMS or the current Motorist Awareness System (MAS)
- Work Zone with VSL and without SDLMS
- Work Zone with VSL and Early SDLMS
- Work Zone with VSL and Late SDLMS
- Work Zone with early SDLMS and without VSL
- Work Zone with late SDLMS and without VSL

An already calibrated and validated VISSIM model for Simplified Dynamic Lane Merge System (SDLMS) in accordance with the real life work zone was modified with a VSL through Vehicle Actuated Programming (VAP) code. Three different logics were coded each for VSL alone, early SDLMS+VSL and late SDLMS+VSL. All these logics were fine tuned with several test runs before finalizing it for the final simulation. It is found through the simulation of above mentioned scenarios that for low and medium volume levels (V0500, V1000 and V1500), there is no significant difference between the Maintenance of Traffic (MOT) plans for mean throughputs. However, for higher volume levels (V2000 and V2500), late SDLMS with and without VSL produced higher mean throughputs for all compliance rates and truck percentages except when the demand volume was 2,500 vph and compliance of 60%, where it produces the significantly lower mean throughputs.

In terms of travel time through the work zone, results indicated that there is no significant difference between MOT types for demand levels of V0500 and V1000 when compliance is 40% or less but for compliance of 60% and more, only demand volume level that is not significantly different from other MOT types is V0500. This study revealed that VSL increases travel time through the work zone. This might be due to non-compliant vehicles that follow the compliant vehicle ahead unless they find a sufficient gap in adjacent lane to pass the compliant vehicle. It is also found out that VSL makes the system safer at higher volumes (2,000 vph and 2,500 vph). This was observed through safety surrogate measures selected for this study.

Another outcome of this study is that the addition of VSL to the dynamic merge systems helps in improving the overall safety of the system by lowering speed variances and deceleration means of the vehicles travelling through the work zone. The passage of traffic through the work zone is made safer when a speed control is integrated to a dynamic merge system. It can be inferred from the simulation results that integrated SDLMS and VSL systems have better performance in terms of traffic mobility and safety than existing individual controls and also show that the integrated SDLMS and VSL system has more potential than each individual systems.

TO MY PARENTS
for making me what I am today

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CHAPTER 1
INTRODUCTION

In recent years, there has been a considerable increase in the amount of construction work on the U.S. national highways. Most of the work undertaken is the reconstruction and rehabilitation of the existing transportation networks. This may be due to the policies of various states to emphasis on the maintenance of existing facilities rather than on building new ones. Work zones around the globe are vulnerable and prone to crashes which are either fatal or at least causing property damage. Work zones in the United States have approximately 700 traffic-related fatalities, 24,000 injury crashes, and 52,000 non-injury crashes every year. Work zones in the United States are likely to increase in number, duration and length due to emphasis on repair and highway reconstruction as a significant portion of all federal-aid highway funds are now geared toward highway rehabilitation (Khattak et al., 2002)

1.1 Work Zone Issues

The challenge of safety and mobility is particularly acute in work zone areas as road repair and construction intensifies traffic issues and concentrates them in specific locations and at specific times. A stretch of a highway, either in urban or rural areas, that is normally safe and relatively free of congestion can experience severe congestion when construction work is taking place. Safety is also affected by the presence of work zones. Statistics show that in the United States, approximately 2.5 percent of all accidents that occur on the highway system occur in or around work zones (Bushman et al., 2003).

According to the Fatality Analysis Reporting System (FARS), Florida fatal work-zone crashes have risen 34% since 1999, ranking Florida the second highest state in fatal work-zone crashes in 2004 after the state of Texas (FARS 2006). In terms of total highway miles traveled this is a disproportionately high number and reflects the concentration of safety issues at construction sites. Likewise, Traffic safety and efficiency of roadway work zones have been considered to be one of the major concerns in highway traffic operations in Florida. Due to the capacity drop, which is the result of lane closure in work zone area, congestion will occur with a high traffic demand. The congestion increases number and severity of traffic conflicts which raise the potential for accidents; furthermore traffic operational properties of roadway in work zone area become worse.

1.2 Work Zone Lane Management Schemes

Intelligent Transportation System (ITS) technology has been developed and is being deployed to improve the safety and mobility of traffic in and around work zones. In several states, use of Dynamic Lane Merge (DLM) system has been initiated to enhance traffic safety and smooth traffic operations in work zone areas. The DLM usually takes two forms; dynamic early merge and dynamic late merge. The dynamic feature of the DLM systems responds to real-time traffic changes via traffic sensors. The purpose of the dynamic early merge is to make a dynamic "NO-PASSING" zone, so that the drivers merge into the open lane before reaching the taper instead of using the closed lane to pass vehicles in the queue and merge into the open lane ahead of them (Tarko and Venugopal, 2001). A typical early merge DLM system consists of queue detectors and “DO NOT PASS WHEN FLASHING” signs that would be triggered by the queue detectors as shown in Figure 2.2.1. A no-passing zone is created when the queue is detected next to a sign and the flashing strobes of the near most sign upstream are activated (Tarko et al., 1998).

The thought behind late merge is to make more efficient use of roadway capacity by permitting drivers to use all available traffic lanes to the merge point. At the merge point, the drivers in each lane take turns to pass through the work zone (McCoy and Pesti, 2001). Usually a dynamic late merge system consists of several Portable Changeable Message Signs (PCMSs) that are activated under certain traffic conditions to display “USE BOTH LANES TO MERGE POINT” and a PCMS at the taper advises drivers to “TAKE TURNS / MERGE HERE” as shown in Figure 2.2.2. In comparison to the static lane merging, the dynamic lane merging systems respond to instantaneous traffic changes passing through traffic sensors. The instantaneous or real-time traffic data obtained by the sensors is communicated to a central controller in a time-stamped manner. Suitable algorithms then determine whether to activate real-time lane merging or not.

1.3 Work Zones and Variable Speed Limits

Many measures have been taken across the country to raise the level of safety in work zones. The use of VSL systems at work zones is one of those measures. It is anticipated that the VSL systems improve safety by helping the driver in determining the maximum speed that he or she should travel. Besides adding improvement to safety, they are also expected to improve mobility at work zones. One very important apprehension in using a VSL system is the reliability of the posted speed limit and the degree to which the drivers show compliance to those posted speeds (Yadlapati and Park, 2004).

It has been observed that static speed reduction signs are often ignored by drivers because they are deemed as irrelevant, both because traffic volumes are low and traffic is flowing freely or because there is no construction activity occurring at the site. According to a survey conducted in Oregon, the foremost driver complaint that was related to the work zones was “SIGNS UP AND NOBODY HOME” validating the need for appropriate road signage. When drivers acquire this habit of ignoring advanced signing, the transition from high speed free flow traffic conditions to slowed or stopped traffic can be a potentially dangerous situation (Bushman et. al., 2003). For this very reason, it is important to study the effectiveness of VSL's in the work zones for both safety and operational point of view.

1.4 Thesis Research Goals and Objectives

The main objective of this research is to evaluate the safety and operational effectiveness of the proposed SDLMS systems i.e. the Dynamic Early Lane Merge and Dynamic Late Lane Merge, in the presence of VSL system. The tasks of this research can be summarized as:

i. Document previous studies' findings related to the application of DLM and VSL.
ii. Review the collected field data from previous findings and select the simulation model to conduct the analysis.
iii. Simulate a two-to-one lane configuration, when one out of the two lanes in the work zone is closed for traffic, for the following six scenarios in VISSIM and generalize the effectiveness of these recommendations to various traffic demands and motorists’ adherence level;

- Work Zone without VSL and without SDLMS
- Work Zone with VSL and without SDLMS
- Work Zone with VSL and Early SDLMS
- Work Zone with VSL and Late SDLMS
- Work Zone with early SDLMS and without VSL
- Work Zone with late SDLMS and without VSL

iv. Propose guidelines for a feasible integrated dynamic merge and VSL control system for a work zone and evaluate safety and mobility effects at the work zone.

CHAPTER 2
LITERATURE REVIEW

This section has a brief literature review that presents a summary of work zones safety aspects including crash rates, crash severity, contributing factors, crash types, and traditional safety countermeasures deployed in work zones. The second section explores previous dynamic lane management in work zones. Third section provides the review of use of VSL on freeways, their role in safety and more importantly in work zones.

2.1 Work Zone in General

The basic challenge faced by the traffic engineers is to maintain the safety and mobility in the best possible way. So much work has been done addressing safety and operational issues. Some of which are illustrated in the following section.

2.1.1 Safety Concerns at Work Zones

Traffic safety may be affected by a number of factors. Alcohol, road geometrics, weather, distraction, headways, speed limits and vehicle speeds can be among those factors. Inclement weather tends to decrease stability, reduces control and sometimes worsens visibility. Distraction during driving is another major factor. It can be of both internal and external. Internal distraction includes actions like driving while talking, using cell phones, eating, smoking and drinking. External factors like looking for directions, activities occurring by the side of the road, etc. might distract the driver and may possibly lead to a crash (Ulfarsson G. F. et. al. 2002). But the factors that affect the work zone safety significantly are roadway geometrics, weather, age, gender, roadway illumination, daily commute through the work zone and influence of drugs or alcohol (Harb et al., 2008).

Work zones have a propensity to originate risky conditions for drivers and construction workers. Existing traffic conditions worsen when lane closures in work zones create conflicts between construction activities and the traffic. This deficiency of work zones need to be addressed and effort should be made to curb it. A traffic engineer must be equipped with sufficient knowledge of work zone crash characteristics that may help to determine appropriate measures to curtail work zone hazards. A study by Garber and Zhao (2002) investigated the characteristics of work zone crashes that occurred in Virginia from 1996 through 1999, obtained from police crash records. Figure 2.1.1 shows that they divided a work zone in five sections namely; advance warning, transition, longitudinal buffer, activity and termination. All the crashes that were reported were found in one of this section. The results showed that the activity area is the primary location of work-zone crashes regardless of highway type, and rear-end crashes are the major crash type. It was also found out that the percentage of sideswipe crashes in the transition area was considerably higher than that in the advance warning area (Garber and Zhao, 2002).

In addition to the factors mentioned above work zones have other traits like reduction in capacity, reduced speed and conflicts between construction activities and traffic. These make work zones less safe compared to regular roadway sections. Apart from crashes between vehicles, work zones also involve construction workers whose life is in constant danger due to the increased risk of exposure to crashes. Thus crashes at work zones have been one of the primary concerns of researchers. Various studies have already been conducted to improve the safety at work zones. Some of them include the assessment of reduction in speed; evaluations of late merge versus early merge concepts (McCoy and Pesti, 2001a); studies on the location, implementation and message type to be displayed on variable messages signs (McCoy and Pesti, 2001b) and use of Advanced Traveler Information Service, etc (Pesti et al. 2004).

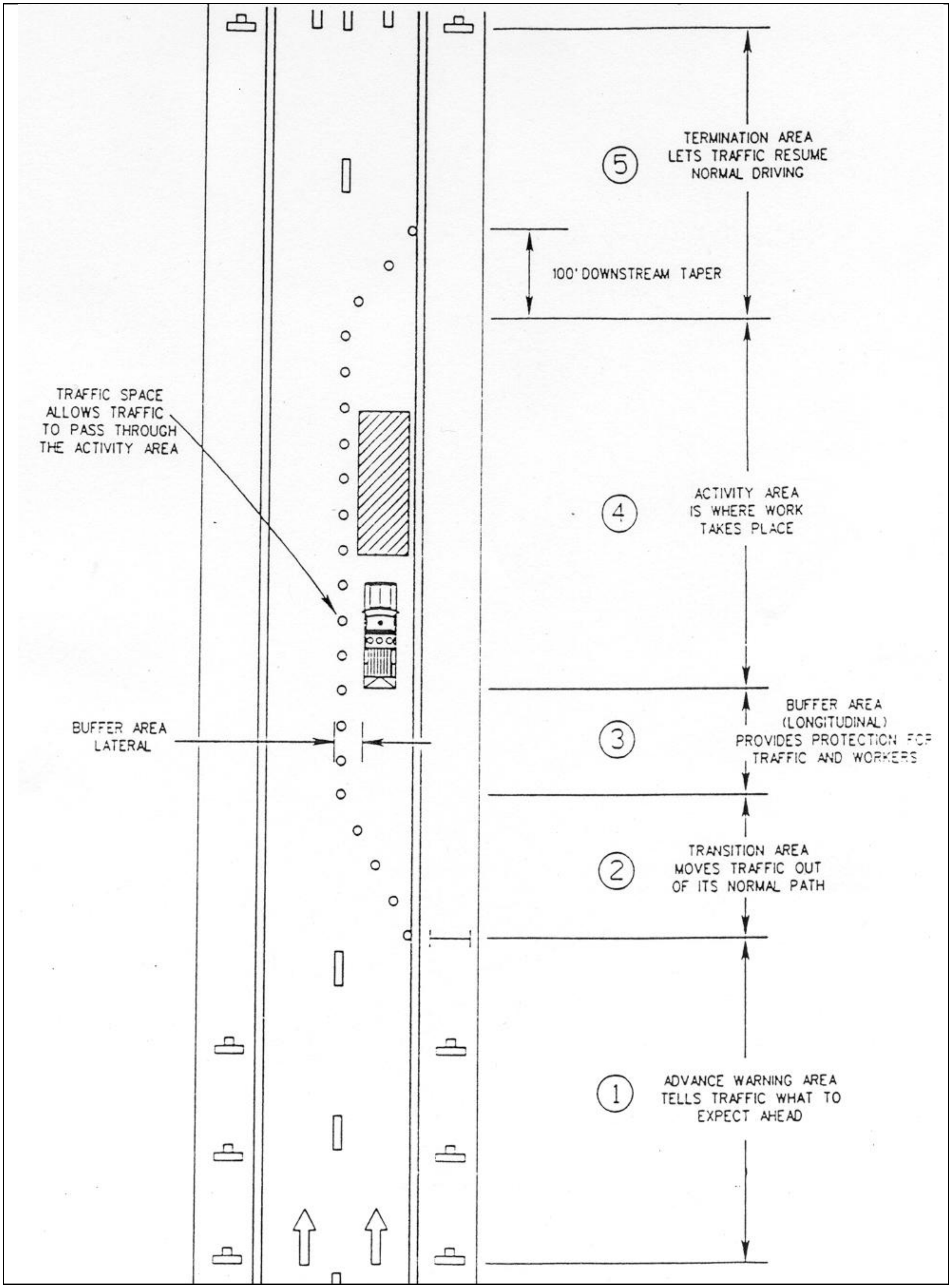

Figure 2.1.1: Typical Work Zone Sections (Source: Garber and Zhao, 2002)

A primary safety concern associated with work zones on Interstate Highways is the increased crash potential when congestion occurs on the approach to the work zone due to the reduction in capacity. Depending on the traffic demand volume and the capacity of the work zone, the queue of slow moving or stopped vehicles caused by the congestion, may extend rapidly to upstream locations creating a long queue. If the incoming traffic is not informed about this development before they reach the end of the queue it may lead to severe rear end crashes. The high speed-differential between the end of the queue and approaching traffic also makes it difficult for the incoming vehicles to safely reduce their speeds and avoid colliding (Yadlapati and Park, 2004).

Benekohal et al. (1995) conducted a survey of truck drivers' concerns about traffic control in work zones in a Illinois Department of Transportation sponsored study. The study also discovered hazardous driving situations and the locations of crashes within a work zone. Researchers conducted an opinion survey of 930 semi-trailer drivers commuting on several highways in Illinois. The survey was comprised of questions about driver and vehicle characteristics, drivers' assessment of work zones and the traffic control devices, their crash and hazardous driving experiences and their suggestions for improving traffic flow and safety in work zones. The analysis of survey results showed that about 90 percent truck drivers considered driving through work zones as more dangerous. Around 50 percent sought for a warning sign 3 to 5 miles ahead of work zones. According to a significant portion of truck drivers, the 55 mph speed limit was too high. Some drivers also called for more signs be added to work zones as the conventional signs were not clear enough. About crash locations, the survey results depicted that there were fewer crashes in the activity area than in the advanced warning area and transition area. It was also identified that crashes were significantly caused by bad driving situations but not other driver/truck characteristics (Benekohal et al., 1995).

Harb et al. (2008) conducted a statistical analysis to expose the freeway work zone crash characteristics and to help develop safety countermeasures. They utilized the Florida Traffic Crash Records Database for years 2002-2004. Three statistical models were developed to analyze single-vehicle and two-vehicle freeway work zone crashes. In the first model, comparison between work-zone and non work-zone single-vehicle crashes was made and results were interpreted on the basis of vehicles/drivers/environment attributes. The second model was to compare two-vehicle work-zone at-fault versus not-at-fault drivers divulging the drivers/vehicles characteristics. The third model compared at-fault work zone versus at-fault non work-zone drivers for two-vehicle crashes and retrieved work-zone environment aspects. After analyzing the model results, researchers found out that trucks are more liable to have a single-vehicle crash in a work zone rather than in a non-work zone freeway segment. Roadways geometric in a work zone also play a considerable role in single vehicle crashes. They found that the poor illumination may also significantly affect the safety within the work zone and is more likely to have single-vehicle crashes as compared to non-work zones. Weather, on the other hand, does not affect the work zone safety when compared to non work zones. It may be due the fact that the drivers are more cautious in driving through the work zones in bad weather than in non work zone freeway sections. Other significant factors that the researchers found were age, gender and driver origin also impact the work zone safety. Harb et al. (2008) recommended well-lit work zone segments to warn the drivers approaching a work zone and to help them avoid both single-vehicle and two-vehicle crashes. They suggested lower speed limits for trucks to help them maneuver easily within the open/closed lanes in a work zone. They also suggested to enforce through police patrol and penalizing the at-fault drivers in the work zones to reduce age, gender, road geometrics etc related violations by the drivers in work zone to enhance safety (Harb et al., 2008).

2.1.2 Operational Concerns in Work Zones

It is evident that the capacity in the work zones decreases due to lane closures that forces reduction in speeds and it then adds to congestion in approaching lanes. According to Oak Ridge National

Laboratory Report (2002), freeway work zones produced an estimated 0.5 billion vehicle-hours (0.8 billion person-hours) of delay in 1999 only. Out of which, almost 90% delay was associated with the transition area of the work zone rather than the activity area.

A study, to investigate various independent factors that contribute to capacity reduction in work zones, was conducted by Kim et al. (2001), to propose a new methodology for estimation of the work zone capacity. In all, 12 work zones with lane closures on four normal lanes in one direction, were selected generally in the off-peak hours both during day and night. They developed a multiple regression model to estimate work zone capacity to create a practical relationship between work zone capacity and several key independent factors such as the number of closed lanes, the proportion of heavy vehicles, grade and the intensity of work activity. The proposed model demonstrated improved performance for all of the validation data when compared to existing scenarios. The only constraint in this model was that this model is not applicable to work zones with 3 and 2 Lane freeway sections (Kim et al., 2001).

Chatterjee et al., (2009) conducted a study with an objective to identify driver behavior parameters that determine the work zone capacities using VISSIM simulation model. Table 2.1.1 has been borrowed from their research that clearly shows that different States within the US have different driving behavior which effects the work zone capacity. A VISSIM simulation model was developed depicting two scenarios, two-to-one lane closure and three-to-two lane closures in a traditional early lane merge system. The input demand volumes were 3000 and 5000 vph for two-to-one lane and three-to-two lane closure scenarios, respectively. The results acquired from their study by varying those parameters produced capacities between 1200 vph and 2100 vph for both scenarios of lane closure with some exceptions. The model produced desired traffic conditions consistent with traffic flow theory (Chatterjee et al., 2009).

Table 2.1.1: Affect of Driving Behavior on Work Zone Capacity (Source: Chatterjee et al., 2009)

State	Two lanes to One	Three lanes to One	Units
Texas	1340	1170	vphpl
North Carolina	1690	1640	vphpl
Connecticut	1500 to 1800	1500 to 1800	vphpl
Missouri	1240	960	vphpl
Nevada	1375 to 1400	1375 to 1400	vphpl
Oregon	1400 to 1600	1400 to 1600	pcphpl
South Carolina	950	950	vphpl
Washington	1350	1350	vphpl
Wisconsin	1600 to 2000	1600 to 2000	pcphpl
Florida	1800	1800	vphpl
Virginia	1300		vphpl
Iowa	1400 to 1600		pcphpl

Maze and Bortle published a report in 2005 sponsored by FHWA with an objective to study the effect of various traffic characteristics, road furniture and environmental variable on the capacity of work zone lane closures. Table 2.1.2 below, that registers variables that effect capacity of lane closures, is reproduced here from the report. According to Maze and Bortle (2005), many variables are outside the control of state transport agencies such as weather and other environmental issues. But some of the variables can be controlled such as location of merge points and work times etc. Overall the table allows the work zone managers an insight of lane restrictions from location to location (Maze and Bortle, 2005).

Table 2.1.2: Variables Affecting Work Zone Capacity (Source: Maze and Bortle, 2005)

Variable impacting capacity	Attributes associated with variable	Known characteristics
Work zone lane closure configuration	The capacity of a lane closure is dependent on the number of lanes left open and closed and the location of the lane or lanes closed.	When one or more lanes are closed, the remaining open lane(s) have less capacity than normal through lanes. For example, when one lane of a two-lane segment is closed, the open lane has less capacity than one normal lane due to merging. Also, right lane closures result in lower capacity than left lane closures because the right lane generally carries more traffic, resulting in more vehicles merging into the open lane.
Intensity and location of work	The capacity of the open lane will be impacted by visible construction work in proximity to the open lane(s).	Even when there is a concrete barrier between the driver and the construction activity, drivers will slow when the work is in close proximity to the open lane. Intensity and location of work have been found to negatively impact capacity by 1.85%–12.5%.
Percentage of heavy vehicles	Due to their poor speed change performance, high percentages of heavy vehicles will reduce capacity of the through lanes.	Because of poor speed change performance, trucks have a greater impact on capacity after queuing than during free flow. On level terrain and in work zone merge areas, trucks equal 2.4 passenger cars and buses equal 1.5 passenger cars.
Driver characteristics	Drivers that have experience with the work zone are likely to select shorter headway, and capacity will increase.	Commuters making routine trips are familiar with the work zone and are more likely to reduce headways through the work zone. During off-peak hours, capacity reduces by approximately 7% and, during the weekends, by 16%.
Entrance ramp locations and volumes	Ramps in the area of the work zone are likely to create more turbulence in the traffic flow and reduce capacity.	The capacity of the open lanes should be reduced by at least the volume of the ramp within or downstream of the taper.
Grade of lane closure	Positive grades will diminish the capacity of open lanes, particularly where there is a high proportion of heavy vehicles.	At only a 3% grade, passenger car equivalent factors for trucks increased from 2.4 to the range of 2.7–3.2. Positive grades are likely to have the greatest impact if they are located at the lane closure merger point.
Duration of work	As the work zone duration increases, drivers are more likely to be familiar with the work zone and reduce their headways, thus increasing the capacity of the work zone with time.	See comments above for driver characteristics.
Weather conditions	The *Highway Capacity Manual 2000* contains reductions in maximum volumes due to weather.	During trace rainfalls, urban freeway capacity is reduced by 1%–3%; in rainfalls of 0.01–0.25 inches per hour, capacity is reduced by 5%–10%; and for rainfalls above 0.25 inches per hour, capacity is reduced by 10%–17%.
Work time	When work is scheduled at night to avoid peak travel times, traffic control presents significant challenges. Drivers are more frequently impaired by drugs or fatigue and generally behave differently due to lower visibility and glare caused by roadway lighting.	Significant differences in traffic flow exist for nighttime work zones and for daytime work zones.
Location of merge point and enforcement	Merging upstream from the taper point of a lane closure increases capacity more than late merging. However, when using early merge, drivers not following expected merge discipline skip to the head of the queue and force themselves into it, creating a crash risk and turbulence, thus diminishing any efficiency gained through an early merge.	Very little is known about the benefits of enforcement, and most studies of enforcement focus on safety benefits, as opposed to traffic flow efficiency benefits. It is believed that using enforcement personnel to support smooth behavior improves traffic flow.

2.2 ITS Work Zones

In order to improve safety and mobility at work zones, several states in the U.S, deployed ITS technologies in work zones which are generally referred as Smart Work Zones. The primary objective of the Smart Work Zone system is to improve safety and mobility for motorists by providing them with real-time information regarding traffic conditions and alternate route options. The smart work zone system measures current traffic conditions at strategic points to advise drivers of expected delays ahead and direct them to alternate routes using portable changeable message signs and may provide current delay information on a website. Under periods of heavy delay the system will encourage drivers to use specified detour routes, reducing traffic demands at the work zone. Other types of smart work zones may be designed to address concerns with speed management and lane merging conflicts in work zones. Several factors are associated with the success of these systems such as age, gender, trip purpose, network familiarity, education, and trust in the messages content. According to Peeta et al. (2000) the responsiveness of the drivers to these messages increased when at least two pieces of information are provided together.

A survey was conducted of local residents in North Carolina to determine their perceptions and acceptance of the Smart Work Zones in North Carolina at several highway construction projects on Interstate 95.

Results indicated that overall, motorists were aware that the system was providing more up-to-date information than at other work zone sites and perceived the information as always accurate or sometimes accurate in over 95 percent of cases. Over 95 percent of motorists supported the future use of these types of systems in North Carolina (Bushman and Berthelot, 2005). Following is the brief literature review of the DLM systems and VSL devices in use.

2.2.1 Dynamic Lane Merge (DLM) Schemes

When traffic demand surpasses the capacity of a work zone, queues get bigger and go beyond the advance warning signs, which may surprise the approaching vehicles and consequently increases the crash potential. To address this concern, a variety of merge control schemes for work zones have been studied in the past. Several studies have evaluated operational effectiveness of the conventional lane merge strategies along with some unconventional merge configurations such as static early merge (McCoy and Pesti, 2001 and Bernhardt et al., 2001), static late merge (McCoy et al, 1999 and Walter et al., 2001), dynamic early merge (Tarko, 1998) and dynamic late merge (Beacher et al., 2004 and Grillo et al., 2008). This following section provides a brief review of research studies that examined the effectiveness of most commonly used dynamic lane merge schemes.

2.2.1.1 Dynamic Early Lane Merge Schemes

A dynamic early merge (DEM) scheme consists of dynamic early merge signs (e.g. DO NOT PASS or MERGE HERE), flashing strobes, upstream traffic sensors and static early merge signs. McCoy and Pesti (2001) studied the dynamic early merge strategy with Indiana lane merge system shown in Figure 2.2.1.

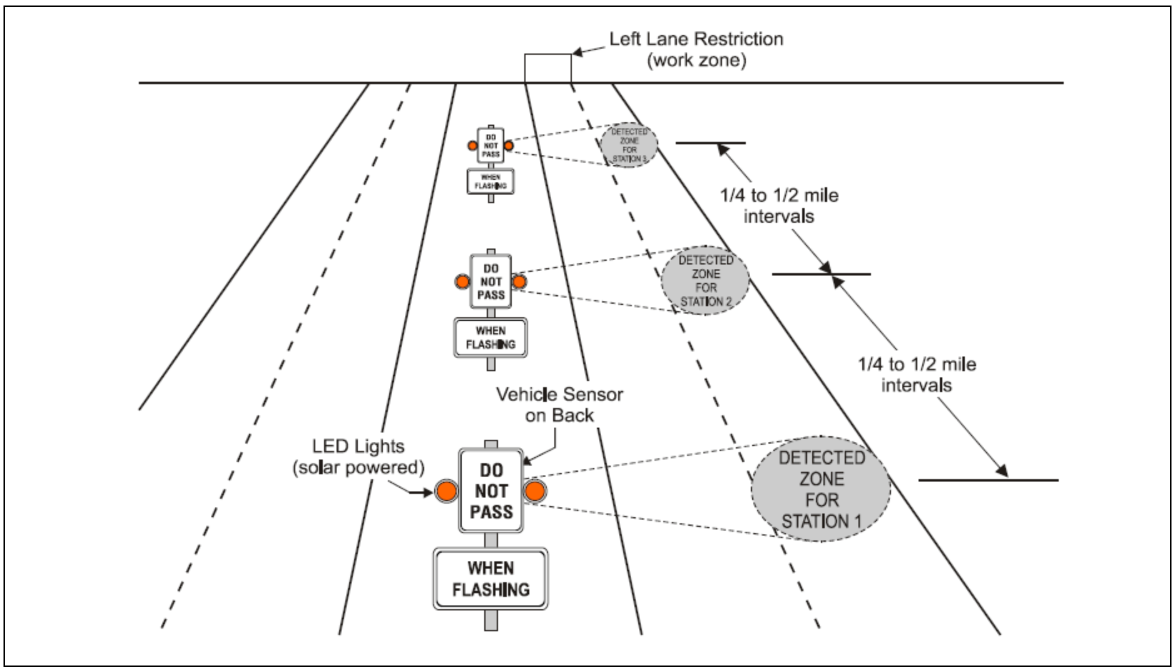

Figure 2.2.1: Dynamic Early Lane Merge (Source: Beacher et al., 2004)

When stopped vehicles are detected in the open lane next to a sign, a signal is transmitted to the controller to turn on the flashing strobes on the next upstream sign. The signs are installed adjacent to the closed lane at 1/4 to 1/2 mile intervals for up to 2 miles or more in advance of the lane closure. When vehicles are moving again, the strobes are turned off. By doing so, the length of the NO PASSING zone is adapted to the length of congestion.

This DEM scheme was tested in the field in 1997 by the Indiana Department of Transportation. Its performance (See Figure 3.2.1) based on the results of field execution (McCoy et al. 1999, and McCoy and Pesti 2001) is stated below:

- DEM can smooth the merging maneuvers in advance of a lane closure,
- Lesser rear-end accidents due to consistency in traffic flows in the open lane,
- Spacing of the signs should be designed in a logarithmic instead of the uniform format in order to account for the speed reduction incurred when traffic approaches the lane closure.
- A simulation study conducted by Purdue University indicated DEM actually increases the travel time through the work zones and there is no improvement in the throughput.

As a comparison of Nebraska Department of Roads (NDOR) Merge system and Indiana Lane Merge System (ILMS), a study was conducted on right lane closures. It was found out that, in ILMS vehicles moved into the open lane earlier than that of NDOR merge. Also, merging maneuvers in ILMS were uniform for a longer distance than NDOR merge. There were much lesser forced merges experienced in the study (McCoy and Pesti, 2001).

2.2.1.2 Dynamic Late Lane Merge Schemes

Late lane merge is used where full use of open lanes is intended till the taper has reached. McCoy and Pesti (2001) suggested a dynamic late lane merge scheme should be used at times when work zone experiences the high density throughputs to control the amount of confusion that is faced by drivers at the merge point. While comparing the late lane merge with early lane merge schemes, McCoy and Pesti (2001) found that late merge can reduce congestions and delays. A typical late lane merge scheme employed in Minnesota is shown in the figure 2.2.2 below.

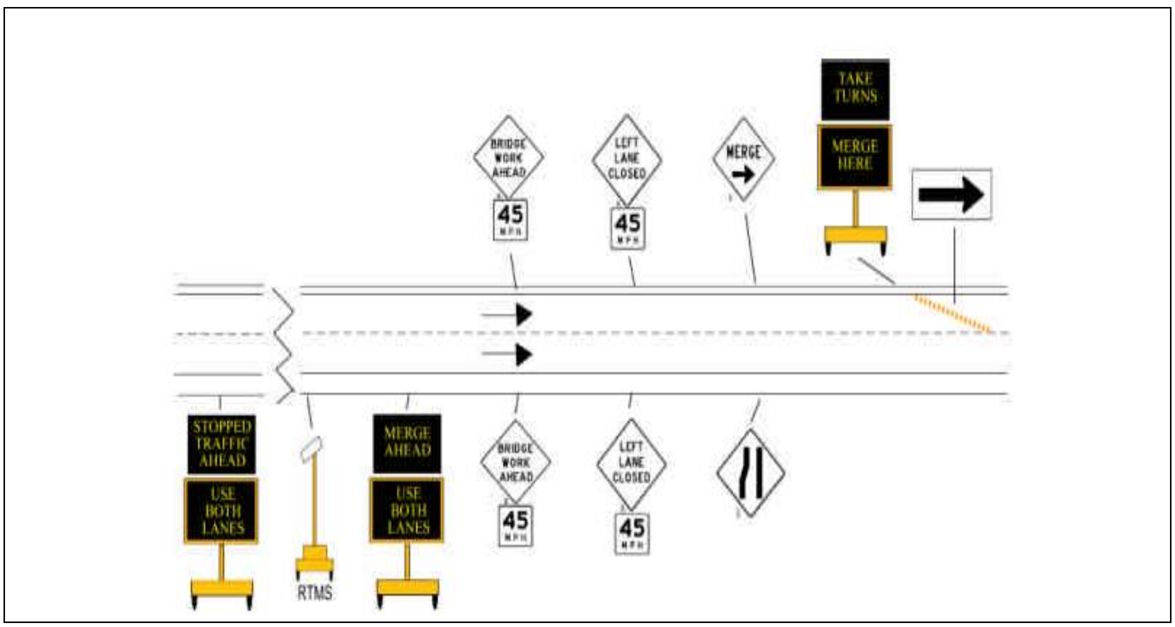

Figure 2.2.2: Dynamic Late Lane Merge (Source: McCoy and Pesti, 2001)

The afore-mentioned dynamic late lane merge system was evaluated by Tavoola et al., (2004) by the Minnesota Department of Transportation (MnDOT). The system was composed of three Changeable Message Signs (CMS), a Remote Traffic Microwave Sensor (RTMS) detector and conventional warning signs. When congestion appears, the signs trigger to instruct drivers approaching the closed lane. The first CMS (with respect to the direction of traffic) displays the message "STOPPED TRAFFIC AHEAD/USE BOTH LANES". The next CMS sign says "USE BOTH LANES/MERGE AHEAD". The last sign located at the start of the taper shows alternating messages of "TAKE TURNS/MERGE HERE". As soon as the congestion dispels, dispels, the signs turn off and the system returns to the conventional static work zone traffic control that encourages early merging. Tavoola et al., (2004) came up with the following results;

- Use of the closed lane increased dramatically when the CMS were activated. During congestion, the closed lane use percentage increased to almost 60% at locations approximately half-mile from the construction taper.

- Comparatively smaller Queue lengths were experienced. It was also seen that some drivers opted wait in a long single queue rather than using the closed lane.

- Overall driving conditions were enhanced upstream of lane closures.

- Maximum volume throughput within the single lane closure at deployment locations was nearly the same.

Beacher et al. (2004) studied the dynamic late merge system in Tappahannock, Virginia, sponsored by Virginia DOT to investigate the advantages of the system as compared to already installed MUTCD controls. Results showed that there was a considerable increase in the percentage of vehicles in the closed lane. Comparison of the late merge and MUTCD schemes showed the increase in percentage of vehicles from 33.7 to 38.8 percent but no significant difference was found between the throughput volumes. Similarly, wait time in the queue was also not much different among the two schemes which might be due to the fairly low percentage of heavy vehicles. Beacher et al. (2004) proposed some guidelines for the application of the dynamic late merge system, which are;

- **Two-to-one lane closure:** the late merge should be considered for 2-to-1 lane closure configurations to improve throughput when large numbers of heavy vehicles are present (>20%) for the majority of the time and congestion and queuing are often present.

- **Three-to-one lane configuration:** While the simulation results showed that the late merge significantly improved throughput for all situations, there are no documented evaluations of the deployment of the late merge in this configuration. Further research is needed to determine how the late merge could be deployed in this type of configuration to ensure driver understanding of the signs.

- **Three-to-two lane configuration:** The late merge should be considered in the 3-to-2 configuration as a possible means to improve flow when heavy vehicles represent more than 20 percent of the traffic stream and congestion and queuing are frequent.

2.2.1.3 Combined Dynamic Early and Late Lane Merge Schemes

Dynamic early and lane merge can also be used in a combination in such a way that early or late merge is triggered depending upon the congestion build up and reduction in average speed in the work zones. This system was designed and tested in the field (I-95 in Malabar, FL) by Harb et al., (2009) as a modification of the conventional systems used by Florida Department of Transportation. The system was named as Simplified Dynamic Lane Merge System (SDLMS). The SDLMS function (Figure 2.2.3) is based on instantaneous speed data obtained from the traffic detection zones with each data sample for every 2-minutes to display the current message. The RTMS collects the average speed of the vehicles passing through the detection zones over 2-minute time intervals. The SDLMS works under two modes;

- **Passive Mode:** This is the inactivated mode. In this mode PCMS displays a flashing and the "CAUTION/CAUTION" message for both the early and late SDLMS.

- **Active Mode:** This is the activated mode. In this mode, the PCMS displays "DO NOT PASS" followed by "MERGE HERE" alternately for the early SDLMS and "STAY IN YOUR LANE' followed by "MERGE AHEAD" alternately for the late SDLMS.

The early and late SDLMS were activated once the average speed over any 2-minute time interval drops below 50mph. The SDLMS was deactivated (passive mode) once the average speed over the next time stamp goes over 55 mph. It should also be noted that the minimum activation time of the PCMS was set for 5 minutes.

Statistical analysis suggested that the early simplified dynamic lane merge systems had significant positive effects on the capacity of the work zone when compared to the conventional systems and also that some drivers are complying with the messages displayed by the system (Harb et al., 2009).

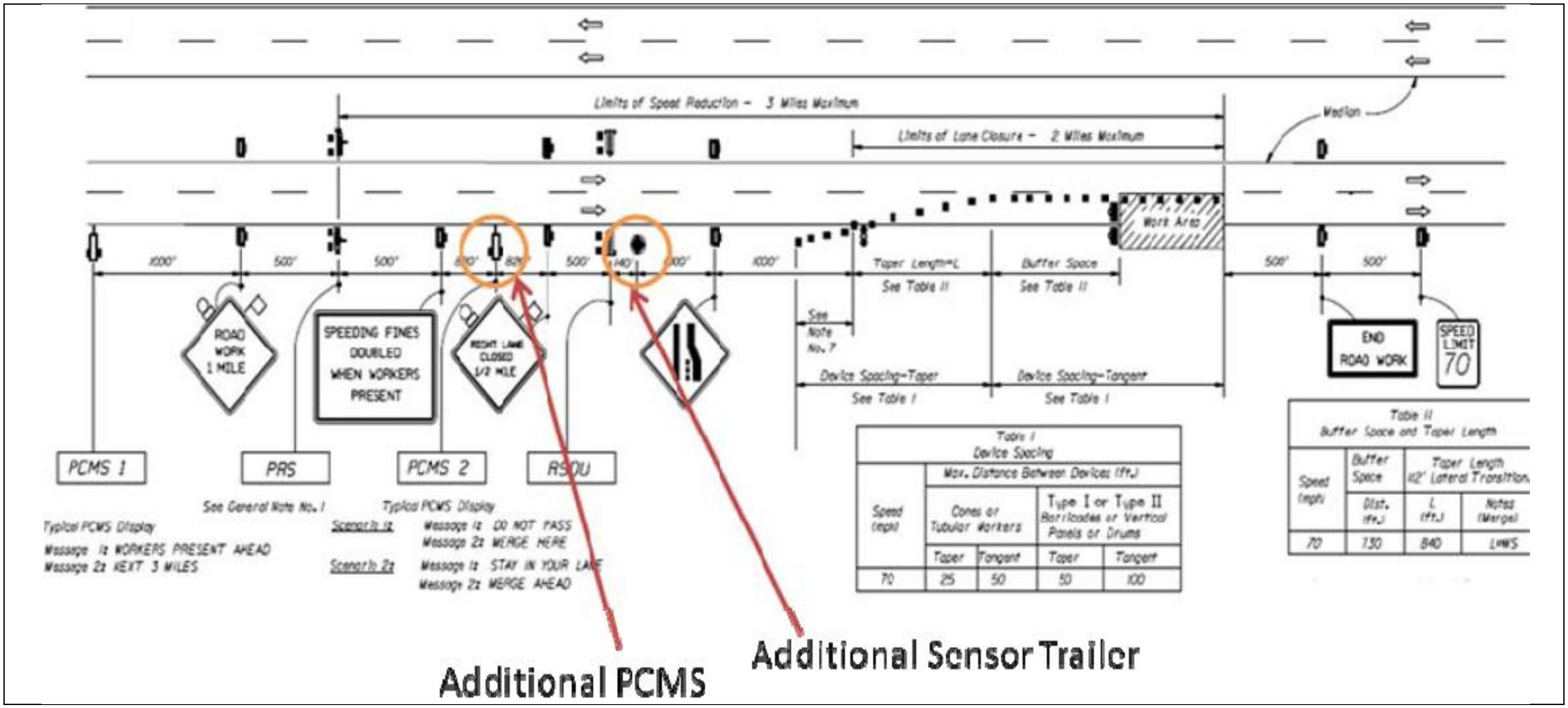

Figure 2.2.3: Simplified Dynamic Lane Merge System (Source: Harb et al., 2009)

2.2.2 Variable Speed Limit (VSL) Systems

VSL systems are a type of intelligent transportation systems technology that involves the setting of maximum and or minimum speed limits. They display speed limits based on observed real time traffic and or weather roadway conditions. The VSL uses overhead or roadside variable message signs (VMS) to inform drivers about the speed limits on the roadway section. The speed limits can be advisory or regulatory and are generally implemented in increments of 5 miles per hour (mph) or 10 mph (Yadlapati and Park, 2004).

The basic principle of VSL is that in some situations the regulatory speed limit should vary dynamically with conditions encountered on the roadway such as inclement weather, work zones, and congestion. Moreover, speed limits that are perceived to be unreasonably low can lead to low speed-limit compliance rates, and high variance in vehicle speeds. With VSL, the hypothesis is that motorists will respond better to realistic speed limits, resulting in higher compliance, and lower speed variance (Lyles et. al. 2004)

The speeds displayed on the VMS of a VSL system can be set either manually or automatically. Manual setting of speeds usually involves the observation of real time traffic and/or weather conditions by an operator. The operator, then, chooses the appropriate speed limit based on pen plots of freeway speed or other decisive factors. Control logics are used to set the speed automatically. Most of the VSL systems that use algorithms have the provision for manual overriding for the speed displayed by the algorithms, to account for unforeseen circumstances (Robinson, 2000).

2.2.2.1 VSL on Freeways

VSL systems have been around for the last 30 years and currently are successfully being used and/or tested in parts of Europe and Australia. VSL systems are already being used in several states and could be implemented in appropriate areas across the United States to improve mobility by potentially reducing driver error and speeds, and enhancing the safety of our roadways through the use of innovative technology (Yadlapati and Park, 2004).

In New Jersey, US, one of the oldest VMS/VSL systems was installed in 1960 at the New Jersey Turnpike to provide early warning to motorists of slow traffic or hazardous road conditions. According to the USDOT report, the New Jersey Turnpike Authority (NJTA) feels that the system is effective. The system provides motorists with information on unusual roadway conditions, which dictate the need for speed reduction (Robinson, 2000). It was also found out in Virginia through a simulation study on various congestion mitigation techniques including VSL that the use of VSL system proved to be the most efficient at smoothing the traffic flow, which was indicated by the more consistent overall average speeds, increased overall average occupancy, and increase in the overall average flow. The VSL systems work well before the onset of congestion at the bottleneck and help in delay of its occurrence. (Mazzenga and Demetsky, 2009). Figure 2.2.4 below shows a typical layout of a VSL System.

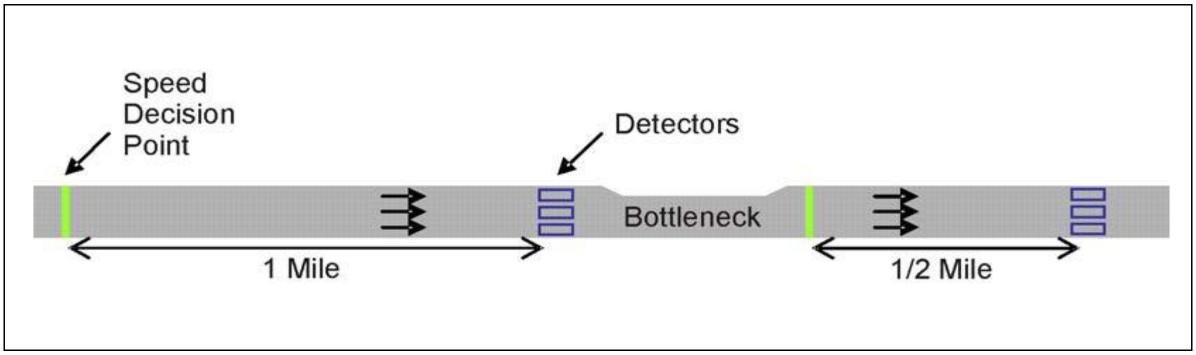

Figure 2.2.4: Typical Layout of VSL System (Source: Mazzenga et al., 2009)

2.2.2.2 VSL and Safety

Safety is one of the most important factor for the freeway operations. Several countries around the world use ITS technologies to improve safety and VSL is one of them. Lee et al. (2004) studied the safety benefits of VSL controls on a simple freeway segment. The objective of their study was to suggest a method of evaluating the effectiveness of VSL in reducing freeway crash potential. They used a real-time crash prediction model that was developed in earlier studies to estimate crash potential for different control strategies of VSL. In order to replicate realistic responses of drivers to changes in speed limits, they used a microscopic traffic simulation model, PARAMICS. Their simulation results indicated that total crash potential over the entire freeway segment can be significantly reduced under VSL control with a minimal increase in travel time compared to the fixed speed limit (Lee et al., 2004). Another simulation based study by Abdel-Aty et al. (2006) also reported that a VSL control on I-4 in Florida reduced both crash likelihood and travel times.

The Dynamic Downhill Truck Speed Warning System Operational Test began in mid 1995 on Interstate 70 in the Eisenhower Tunnel to reduce runaway truck accidents through real-time driver information. The USDOT report says that since the VSL system deployment, truck-related accidents declined on the steep downhill grade sections while the volume of truck traffic increased by an average of 5 percent per year (Robinson, 2000).

2.2.2.3 VSL in Work Zones

Just as ITS technology is being applied in many urban freeway settings to address traffic concerns there are technologies emerging that can be applied specifically to work zone situations. Yadlapati and Park (2004) conducted a study for Centre for Transportation Studies at the University of Virginia to evaluate the performance of various speeds at work zones and to develop VSL control logics that would calculate suitable speeds for different traffic conditions. The research was conducted by simulating a postulated test-bed network and then validating the results by simulating a real world work zone site. The study used a microscopic simulation model - VISSIM. In order to verify the findings from the test network, the speeds were also simulated using the data collected at a real highway work zone near Covington, Virginia.

The study developed a safety surrogate measure, minimum safety distance equation (MSDE), to quantify safety. Travel times were primarily used to quantify mobility. Since most of the existing VSL control logics consider only the traffic advisory speed or average traffic speed, an attempt was made to develop a logic that would consider both safety and mobility in calculating speeds. The results of simulating the postulated network indicated that the performance of VSL varied with traffic demand volumes and compliance rate conditions. In general, an increase in speed decreased safety, but improved travel time. Surprisingly at low volume and low compliance conditions an increase in speed also improved safety. In order to find the speeds that provide optimal measures of safety and mobility a normalization procedure that combines travel time and safety measures is used.

The Federal Highway Administration initiated a project to examine the effectiveness of VSL systems in work zones. In 2002, Michigan DOT and Michigan State University deployed a VSL system on Interstate-96 (I-96) under various work zone configurations to gather data that was being used in the evaluation of the effectiveness of this approach to work zone traffic management. Some of the measures used to determine the effect of the system on traffic flow include speed, speed variance, speed limit violation, and travel time. Initial results indicated that the system may reduce travel time and may reduce the percentage of vehicles exceeding 60 mph and 70 mph (Bushman et. al., 2003).

Lyles et al. (2004) while evaluating the field test of VSL in work zones on the same Michigan DOT project stated that “the VSL system can present far more credible information (realistic speed limits) to the motorist, responding to both day-to-day changes in congestion as well as significant changes in congestion and geometry as motorists go through a given zone”.

Another study was conducted by Pei-Wei Lin et. al. (2004) on the effectiveness of VSL controls at a highway work zone. The study presented two online algorithms for VSL controls at highway work zones that can take full advantage of all dynamic functions and concurrently achieve the objectives of queue reduction or throughput maximization. To evaluate the effectiveness of these algorithms, an extensive experimentation based on simulated highway systems that were calibrated with field data in a simulation environment called CORSIM. Based on the simulation results, researchers concluded that VSL algorithms can yield a substantial increase in both work-zone throughputs and reduction in total vehicle delays. Moreover, traffic flows implementing VSL controls tend to exhibit lower speed variances than other non-controlled traffic scenarios. The speed variance reduction may indirectly contribute to improving the overall traffic safety in work zones.

Kwon et al., (2006) evaluated in the variable advisory speed limit system at one of the I-494 work zones in Minnesota, for a three week period in 2006 and proposed a system that is determined by a two stage speed reduction scheme. It was designed to lower the speed of the upstream traffic approaching the work zone bottleneck to the same level as the current downstream flow. Figure 2.2.5 illustrates the layout of visual advisory speed limit system on I-494 work zone. The data collected from the field indicates 25-35 percent reduction of the average 1-minute maximum speed difference along the work zone area during the morning peak periods after the system was implemented. The reduction in speed difference also resulted in approximately 7% increase of the total throughput volume measured at the downstream work zone boundary during first half of the peak period, while the volume increase during the other half was not significant. The estimation of the driver compliance rate by comparing the speed differences upstream and downstream of the advisory speed limit signs showed 20 to 60% correlation levels during the morning peak periods (Kwon et al., 2006)

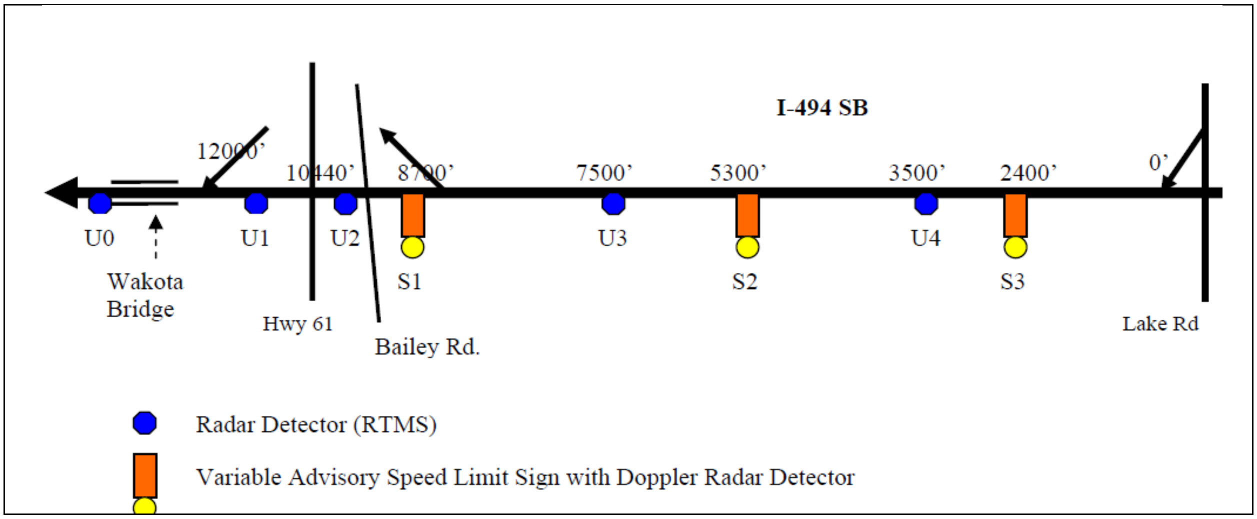

Figure 2.2.5: I-494 Work Zone VASL System Layout (Source: Kwon et al., 2006)

2.2.2.4 Combination of Various ITS Technologies in Work Zones

To improve traffic mobility and safety on highway segments plagued by work zone activities, transportation professionals in recent years have focused on exploring the potentials of using various merge and speed control strategies to regulate traffic flows.

To take advantage of modern developments on the merge and speed limit controls, a study sponsored by Maryland DOT was conducted by Kang et al. (2006) to develop an advanced dynamic late merge and VSL control for work zone applications including an integration of controls for the best use of their strengths in maximizing throughputs and minimizing speed variance in traffic flows (Figure 2.2.6). The researchers compared three models namely; integrated DLM/VSL, DLM only and DLM used by Minnesota DOT. For this purpose, CORSIM was used for simulation. Kang et al., (2006) found that the integrated algorithm of the DLM and VSL controls showed a good response to time-varying traffic conditions and produced more work zone throughputs than the DLM control without VSL. They also found out that the integrated control resulted in an increase in the average speed and a decrease in the speed variation (Kang et al. 2006).

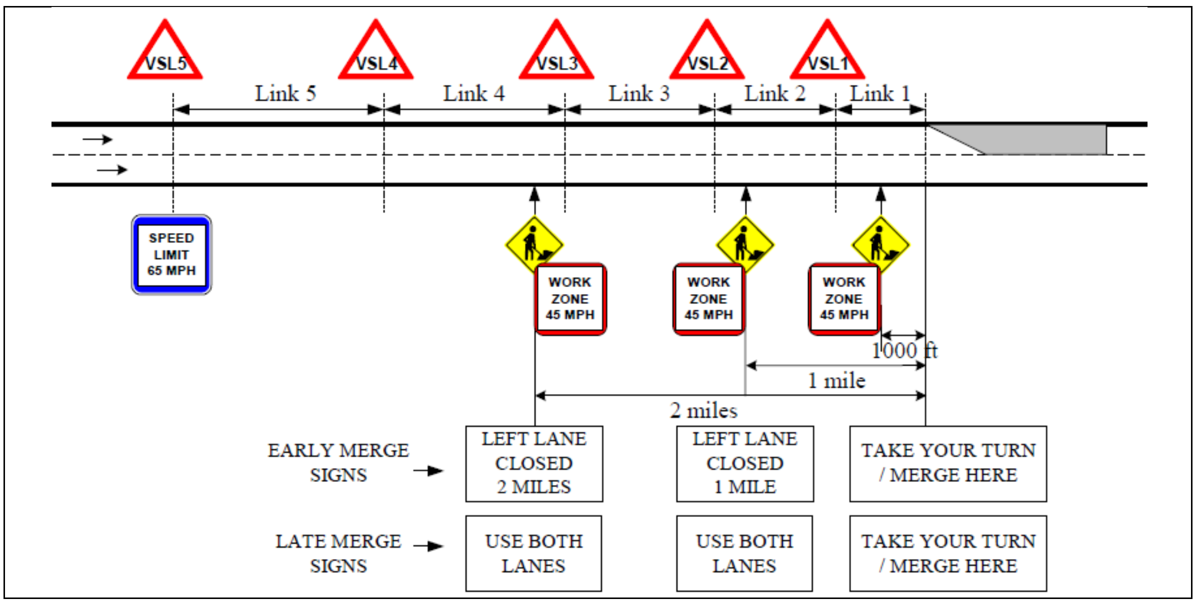

Figure 2.2.6: Integrated DLM/VSL System (Source: Kang et al., 2006)

2.3 Simulation of Work Zones

As mentioned earlier, most of the research studies involving dynamic lane merge schemes and VSL systems in work zones, is being done through simulations. Various microscopic simulation models are available for evaluating these systems but CORSIM, PARAMICS and

VISSIM are the most widely used microscopic traffic simulation models. Following is the comparison of VISSIM versus CORSIM and PARAMICS.

CORSIM was developed under Federal Highway Administration (FHWA) sponsorship (CORSIM Training Manual, 2004) whereas VISSIM is microscopic multi-modal traffic flow simulation software. It is developed by Planung Transport Verkehr AG (PTV) in University of Karlsruhe, Germany. VISSIM was started in 1992 and is the global market leader today (VISSIM User manual, 2007).

CORSIM and VISSIM can be adapted to simulate traffic operations around a work zone on the arterials in urban areas, suburbs and in towns. This is done by assuming that a lane closure for a work zone results in the same type of impact on traffic carrying capacity as a lane blockage caused by an incident. CORSIM is capable of simulating work zones through a prolonged incident blockage. This does not accurately depict traffic behavior in the approach to a work zone. When modeling a lane blockage in CORSIM, the program assumes that drivers have no knowledge of the approaching blockage and there is no taper (CORSIM Training Manual, 2004). VISSIM, on the other hand, does a better job of capturing an appropriate lane-changing behavior at work zones. It even allows introducing VMS (Raju, 2008). VISSIM also enables us of creating specific scenarios via vehicle actuated programming (VAP). A program reflecting the algorithm of dynamic lane merging (to be used for this study) has been written in Visual Basic to communicate with VISSIM in real-time (Harb, 2009).

PARAMICS is a full-featured microscopic simulation model with the ability to obtain detailed state variable information on each vehicle on time scales with better than second-by-second accuracy. A significant disadvantage of the PARAMICS model is the use and dependence on origin-destination matrices to derive traffic volumes. PARAMICS supports most of the modeling features required for obtaining surrogate measures at a reasonable level of fidelity, although some modeling elements are described only at a functional level (Gettman and Head, 2003).

VISSIM is a microscopic and time-step based simulation and it uses a psycho-physical driver behavior model developed by Weidemann (VISSIM User manual, 2007). According to VISSIM User Manual, this model is based on the concept that the driver of a fast moving vehicle following a slow moving vehicle, starts to decelerate as he reaches the individual perception threshold. The speed of his vehicle falls below the speed of the lead vehicle due to his inability to determine the exact speed of the lead vehicle. This speed reduction is followed by acceleration after the driver reaches another perception threshold. The process of deceleration and acceleration continues throughout the traffic stream iteratively. Assigning speed and spacing thresholds to individual drivers stochastically incorporates different drivers' behavior characteristics.

In addition to these technical advantages of VISSIM over CORSIM and PARAMICS, VISSIM simulation model was selected on the following grounds;

- Not only VISSIM Simulation Model is available in the CECE, UCF labs but the researchers at the Center of Advanced Traffic Systems Simulation (CATSS) have developed their expertise in VISSIM modeling.

- A two-to-one work zone configuration has already been simulated as a part of previous research here at UCF (Harb, 2009).

2.4 Conclusion

This section reviewed two main categories of work zone safety and operational strategies: VSL and DLM. Following conclusions from the literature review are summarized;

It demonstrated that work zones indeed deteriorate safety and operations of roadways. From the safety aspect, work zones produce significantly higher crash rates and result in higher crash severity under certain conditions. From the operations aspect, work zones reduce roadway capacity drastically. The magnitude of the capacity reduction varies under different drivers' characteristics, vehicles' characteristics, and environmental characteristics. It also summarizes the role of both

DLM and VSL in improving safety and operations of a freeway section in their individual capacity.

Since the VSL control has the potential to be effective under a wide range of traffic volume, one can view it as a supplementary control component for any work-zone operation. Thus, to smooth the merging maneuvers and minimize potential collisions during the DLM operations, it is essential to study a process that can integrate the VSL with the DLM so as to maximize the system effectiveness.

Through the literature review of advantages and disadvantages of the various simulation models used in work zones, it was concluded that VISSIM carries the most features that will help in modeling the desired work zone with integrated DLM and VSL systems.

CHAPTER 3
METHODOLGY

The study tasks are explained in this chapter**.** First of all, appropriate measures of effectiveness were selected for the analysis later on. Secondly, identification of various work zone segments followed by the planning for location of the road furniture required for a field study. Then field study has to be conducted for calibration and validation of the simulation model (as this study was performed on an already calibrated and validated simulation model, this step was skipped). Second to last step for this study was to develop the logics for VSL and its integration with SDLMS in VISSIM. These logics were tested and refined through various simulation runs. Simulation models for each scenario were then developed. Through these simulation models, data was collected for analyses of all these MOT types on the basis of MOEs selected in the first step. Finally, recommendations were made based on the analyses.

Following is the brief illustration of only few of these tasks. A detailed description of the whole simulation process has been included in the next chapter. Detailed analyses and reporting of all the results is also provided in chapter 5.

<u>3.1 Measures of Effectiveness (MOE)</u>

Various measures of effectiveness can be used to quantify mobility of the vehicles and the safety of a system as a whole. For the sake of this study, following operational and safety measures of effectiveness have been selected.

3.1.1 Operational Measures of Effectiveness:

The throughput at a work zone is often affected due to the reduced speed and reduction in the number of lanes at a work zone. Throughput remains almost the identical as traffic demand volume for under saturated conditions. Due to merging operations, reduction in throughput is expected in the congested conditions (Harb et al., 2009). Use of VSL also smoothes the flow of traffic and studies show it delays the occurrence of congestion at the bottleneck of a highway section (Mazzenga and Demetsky, 2009). Reason being, the throughput is taken as one of the operational MOE.

Studies illustrate that average speed in a work zone is usually decreased due to lane closures and increased throughput. Decrease in average speed then increases the travel time further. Stop and go conditions may also result due to this decrease in average speed and thus develop a queue (Yadlapati and Park, 2004). As travel time is a function of the speed and lower speed values result in increase in travel time and vice versa (Mitra and Pant, 2005). Travel time, for that matter, is also considered as an operational MOE.

3.1.2 Safety Measures of Effectiveness:

Since crashes are rarely observed in the field, surrogate measures such as speed variance and speed difference between lead and following vehicles are often used to quantify safety. In this study, a surrogate speed variance and deceleration are taken as measures of safety.

As already discussed in literature review, speed variance reduction indirectly contributes in improving overall traffic safety in work zones (Pei-Wei Lin et al., 2004), Kang et al. (2006) also used speed variance as safety MOE in their simulation study. On the other hand, sudden deceleration leads to higher prospects of rear-end crashes (Yan et al., 2007). Gettman and Head (2003) also reported speed variance and deceleration rates in their study as safety surrogate measures. Thus, for improvements in these two surrogate measures indicate improvement in safety in a work zone.

3.2 Identification of Work Zone Segments

Work zones may have different configurations depending upon their location, duration of work and the number of lane closures. For freeway, any kind of work zone has at least three segments, advance or early warning area, taper or transition area and the activity are or actual work zone segment (MUTCD, 2009). Work zone for this thesis is also divided in the three segments. Average speed of the vehicles is measured in the advance or early warning area instead of the vehicles travelling in the transition area or activity area. Reason behind selecting advance warning area for measuring average speed over the others is because of the channelized vehicle movement in the activity area (Yadlapati and Park, 2004).

3.3 Location of SDLMS and VSL Trailers

Manual of Uniform Traffic Control Devices (MUTCD) delineates the lengths of various work zone segments. According to MUTCD, minimum length of a taper required for the freeways more than 45 mph regulatory speeds, is given by the relation given below;

$$L = W * S \qquad \text{(Equation 1)}$$

Where, W is the width of each lane and S is the speed limit used in that area.

For a speed of 70mph and lane width of 12ft, the minimum length of transition area "L" is 840 ft and the same was provided for the subject work zone. The MUTCD also specifies minimum distance required between the message signs on a rural freeway in the advanced warning area. It should not be less than 500 ft. Harb et al., (2009) used, Portable Changeable Message Sign (PCMS) at a distance of 3,460 ft from the start of the taper and a Portable Regulatory Sign (PRS) was placed at 1,320 feet from this PCMS, at a work zone site located on I-95 in Malabar, Florida. For this thesis, PRS is replaced by a VSL at the same location and the sensor is placed in the advance warning area of each lane of the work zone before start of the taper in a simulation environment to measure the average speed of the approaching vehicles. Figure 3.3.1 shows the pictorial representation of further modified MAS plans already developed by Harb et al., (2009).

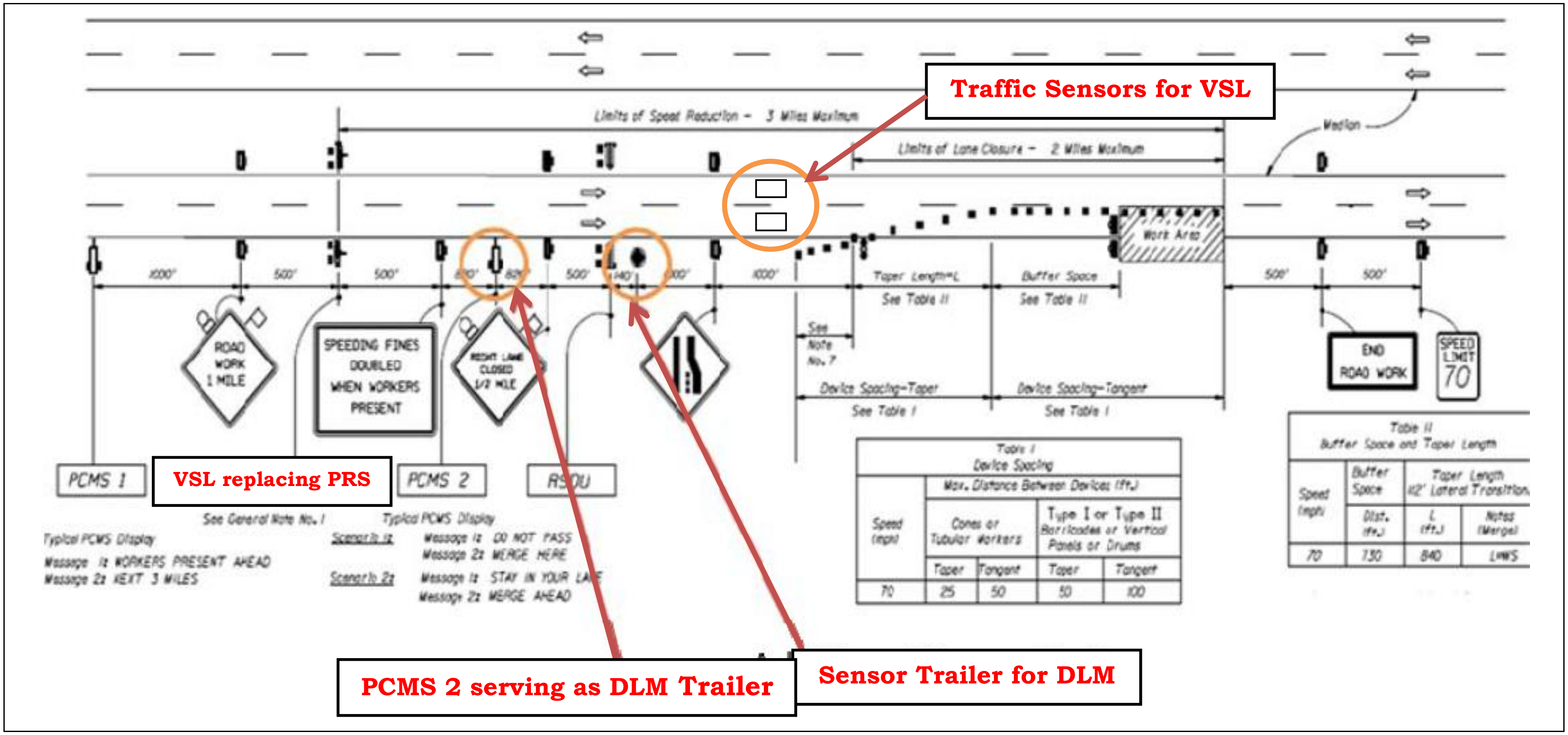

Figure 3.3.1: Modified Motorist Awareness System with Both VSL and SDLMS

CHAPTER 4
SIMULATION OF A 2-TO-1 LANE WORK ZONE IN VISSIM

As it has already been established that one of the tasks of this research is to propose guidelines for a feasible integrated dynamic merge and VSL control system for a work zone and evaluate safety and mobility effects at the work zone. For that matter, a VISSIM simulation study is conducted to determine the operational and safety effectiveness of the VSL in combination of early SDLMS and late SDLMS under different traffic demand volumes and different drivers' compliance rates to the messages displayed by the systems.

4.1 Simulation Tools in Use to Evaluate Operational and Safety Measures of Effectiveness

As discussed in literature review, evaluation of performance measures in a work zone through different simulation models is widely used and there are many tools available for this task. Appropriate simulation model is selected on the basis of available data and the flexibility of that model to adapt to the real environment.

The HCM 2000 presents a methodology for estimating the capacity of work zones. This methodology suggests using a base capacity value and applying adjustment factors for intensity of work activity, effect of heavy vehicles, and presence of ramps in the vicinity of the work area. The proposed base capacity is 1,600 pcphpl which is obtained from Texas work zone studies. HCM 2000 does not provide any approach for estimating queue lengths in work zones.

Queue and User Cost Evaluation of Work Zones (QUEWZ) is a DOS-based tool developed by the Texas Transportation Institute. It uses HCM 2000 for calculation of capacity and HCM 1994 for queue length in the work zone (Krammes et al, 1993).

QuickZone, developed by Mitretrek for FHWA, is an analytical tool used for approximation of traffic impact in a work zones. It is an open-source that facilitates DOT to tailor the impacts applicable in their particular work zones. For example, MDQuickZone is the QuickZone customized for Maryland's work zones (QuickZone, 2001).

DELAY Enhanced 1.2 was developed by FHWA for prompt approximation of the traffic impacts of incidents. The user friendly graphical interface of this application enables its users in visualizing the queue length through data input. This application can also be useful for short term work zone lane closures (FHWA).

Most of the research studies involving dynamic lane merge schemes and VSL systems in work zones, is being done through various microscopic simulation models. CORSIM, PARAMICS and VISSIM are the most widely used microscopic traffic simulation models. Following is the comparison of VISSIM versus CORSIM and PARAMICS.

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- A two-to-one work zone configuration has already been simulated as a part of previous research at UCF (Harb, 2009).

4.2 Understanding of a VISSIM Simulation Model

VISSIM is a microscopic and time-step based simulation and it uses a psycho-physical driver behavior model developed by Weidemann (VISSIM User manual, 2009). According to VISSIM User Manual, this model is based on the concept that the driver of a fast moving vehicle following a slow moving vehicle, starts to decelerate as he reaches the individual perception threshold. The speed of his vehicle falls below the speed of the lead vehicle due to his inability to determine the exact speed of the lead vehicle. This speed reduction is followed by acceleration after the driver reaches another perception threshold. The process of deceleration and acceleration continues throughout the traffic stream iteratively. Assigning speed and spacing thresholds to individual drivers stochastically incorporates different drivers' behavior characteristics. Figure 4.2.1 shows the reaction of drivers to changes in 'front to rear distance' and to 'difference in velocities'.

The traffic model in VISSIM is discrete and stochastic using driver-vehicle-units as single entities. The attributes of the driver-vehicle-units are unique and are governed by the characteristics of the vehicle, the behavior of the driver and the interdependence of the driver-vehicle-unit. The psycho-physical car following model is used for longitudinal vehicle movement and a rule-based algorithm is used for lateral movements (VISSIM User Manual, 2009).

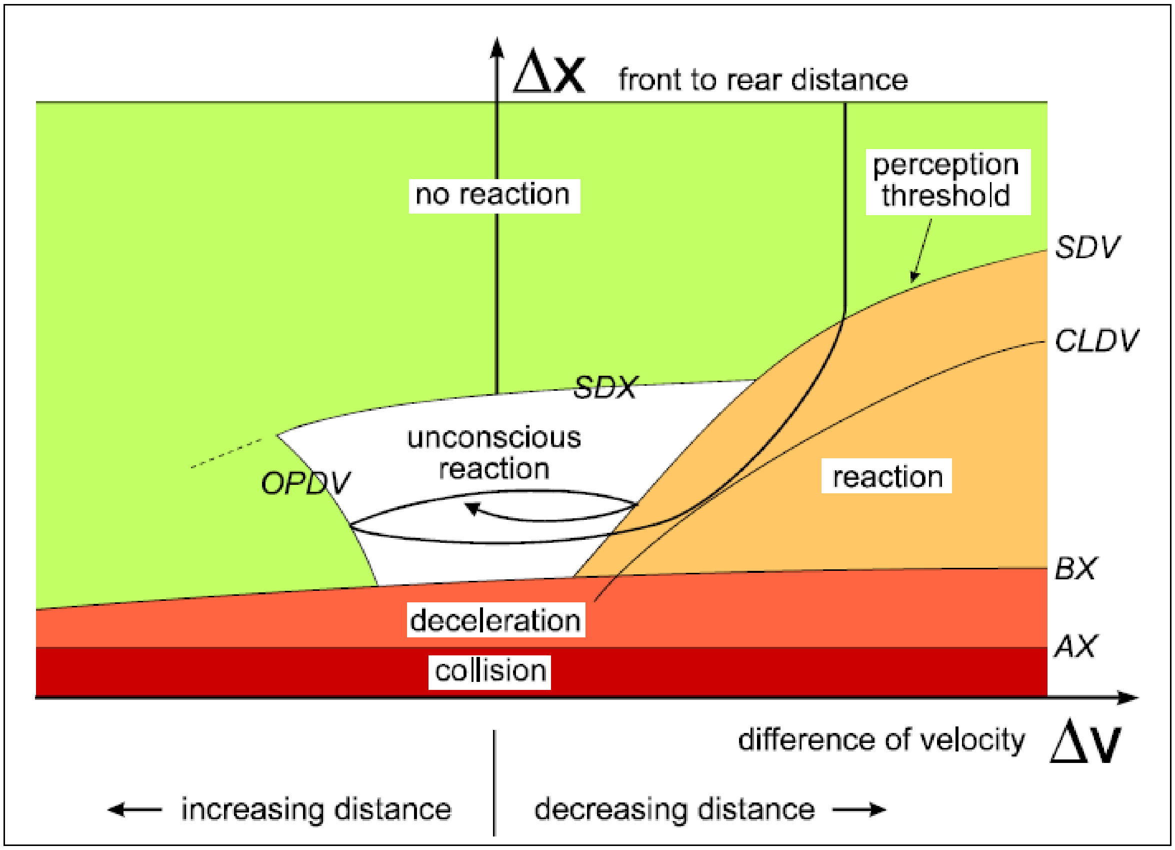


Figure 4.2.1: Car following in VISSIM (VISSIM User Manual, 2009)

VISSIM replicates the traffic flow by moving "driver-vehicle-units" through a network. Each driver with his particular behavioral makeup is allocated to a certain vehicle type. Corollary, the driving behavior corresponds to the technical capabilities of his vehicle. These features characterizing each driver-vehicle-unit can be categorized as:

- ➢ Technical specifications of the vehicle
    - Length
    - Maximum speed
    - Potential acceleration

  - Actual position in the network
  - Actual speed and acceleration
- Behavior of driver-vehicle-unit
  - Psycho-physical sensitivity thresholds of the driver (also known as their ability to estimate thresholds and level of aggressiveness)
  - Memory of driver
  - Acceleration based on current speed and driver's desired speed
- Interdependence of driver-vehicle-units
  - Reference to leading and following vehicles on own and adjacent travel lanes
  - Reference to current link and next intersection

4.3 Development of a VISSIM Model

The procedure of coding VISSIM consists of a logical series of programming methods that must be addressed to replicate an actual traffic situation. This process was divided into three categories; system design of the work zone, vehicle characteristics and driver behaviors. The model features for all designs and vehicles were fixed whereas driver behavior characteristics were kept as the parameters for model calibration.

4.3.1 System Design

The work zone with a two-to-one lane closure configuration can be build in VISSIM through a series of links, connectors, routing decisions and lane closures to represent the actual geometry of the work zone. Figure 4.3.1 shows the Modified MOT plans for the 2-to-1 lane closure and the corresponding resulting nodes and roadway segments in VISSIM. The roadway is drawn on top of the image with links and connectors. Figure 4.3.1 shows 6 links and 5 nodes. The first node of the Figure represents the first work zone PCMS. The second node represents the location of the VSL whereas Node 3 shows the location of additional PCMS where merging information is provided to drivers. Node 4 represents the lane closure start (one open lane). Node 5 represents the lane closure end (two lanes open).

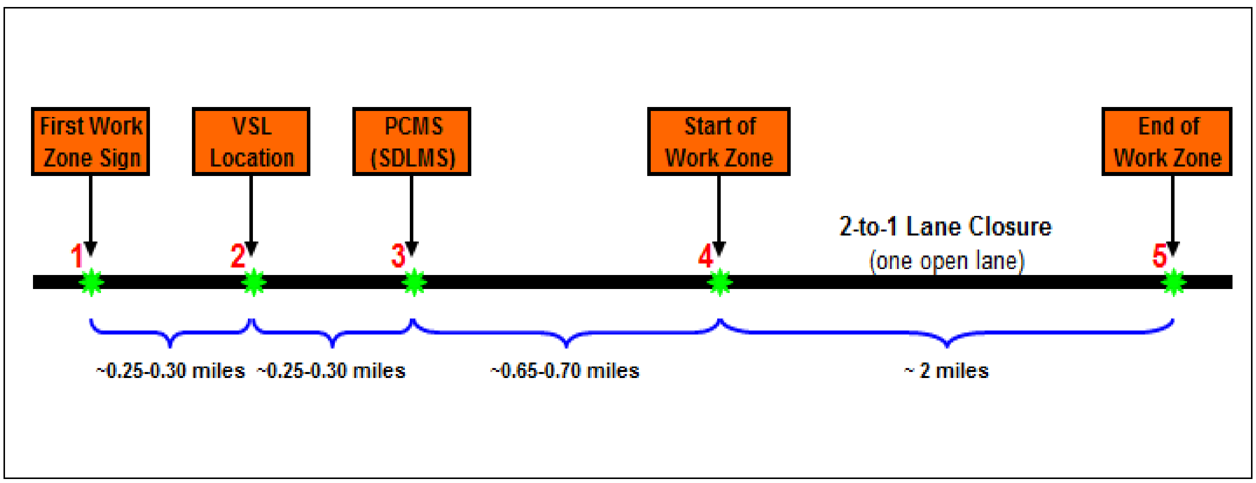


Figure 4.3.1: Modified MOT Plan (with VSL) Replication in VISSIM

4.3.2 VISSIM Model for Simplified Dynamic Lane Merging System

The SDLMS algorithm used for this study was developed by CATSS (UCF) for the Florida DOT. Salient features of that model are as under;

- In the field, average speed of each vehicle is measured every 2-minutes through RTMS and the algorithm verifies that either the lower speed threshold of 50 mph is met or not. If met, the PCMS displays the required message unless the upper speed threshold of 55 mph is reached.
- In VISSIM, loop detectors were placed at the RTMS location to record average speed of each vehicle.
- For Early and Late SDLMS, merging in open lane or waiting till the taper is designated to the drivers respectively through dynamic decision routing. In the normal operation of traffic, random merging was assigned.
- Loop detectors in VISSIM cannot communicate with the routing decisions so Vehicle Actuated Programming (VAP) was used. Algorithm shown in Figure 4.3.3 was coded in VAP and the control logic alternates between partial routes for either early or late merging.
- To simulate the MAS in VISSIM, static routing is specified as all the vehicles entering the network must exit the work zone. In this case the entering node is 1 and the exiting node is 5 (Figure 4.3.2)

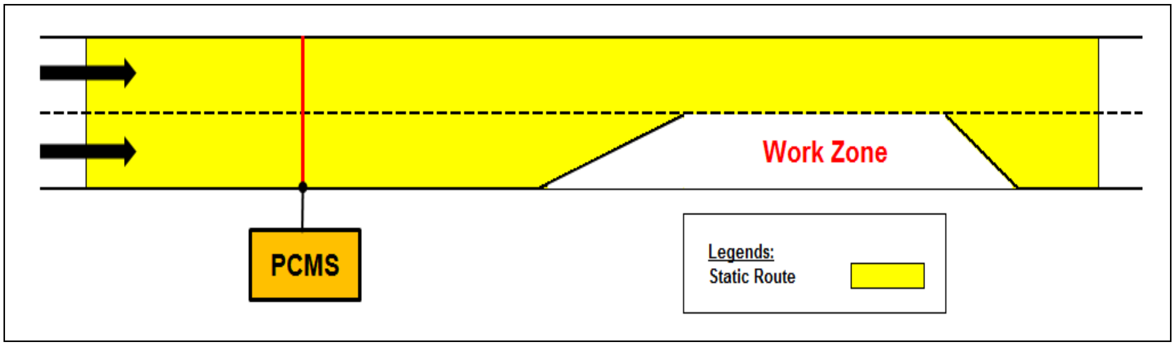


Figure 4.3.2: Static Routing Decision

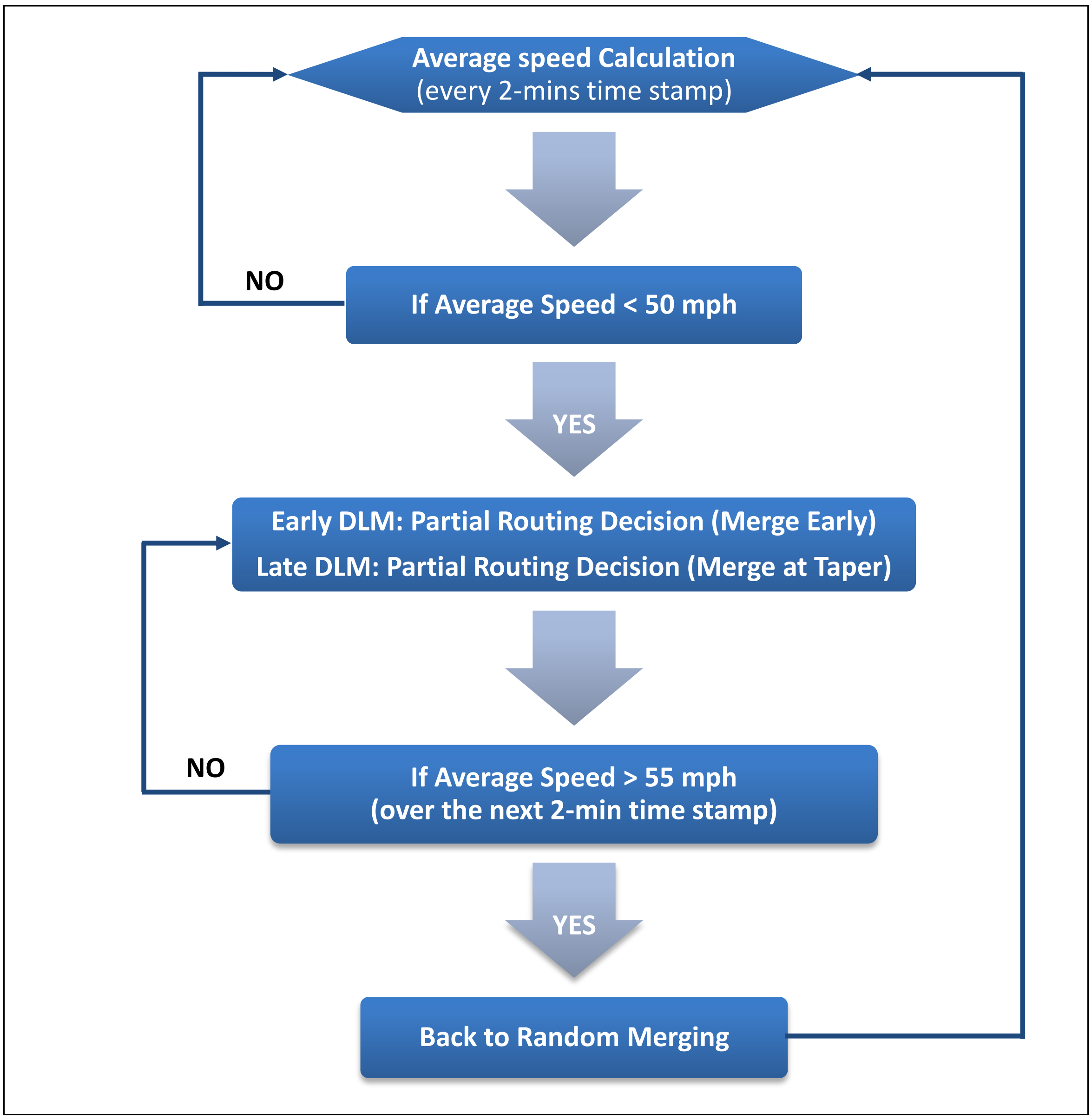


Figure 4.3.3: VAP Logic for SDLMS in VISSIM

4.3.2.1 Early SDLMS

Harb et al. (2009) used partial routing decisions for the creation of early and late lane merge schemes at the work zones. VISSIM describes partial routes as a section of one or more static routes where vehicles should be redistributed to the routes and the percentages defined by the partial routes and after leaving the partial route, vehicles continue to travel on their original route.

One partial routing decision with two routes; route 1 and route 2 were created for the dynamic early merge. In routes 1 and 2, a fraction of vehicles going on each route can be selected. The alternation between route 1 and 2 is based on the speed threshold (50mph as selected in the field). Early SDLMS routing decisions are shown in figure 4.3.4.

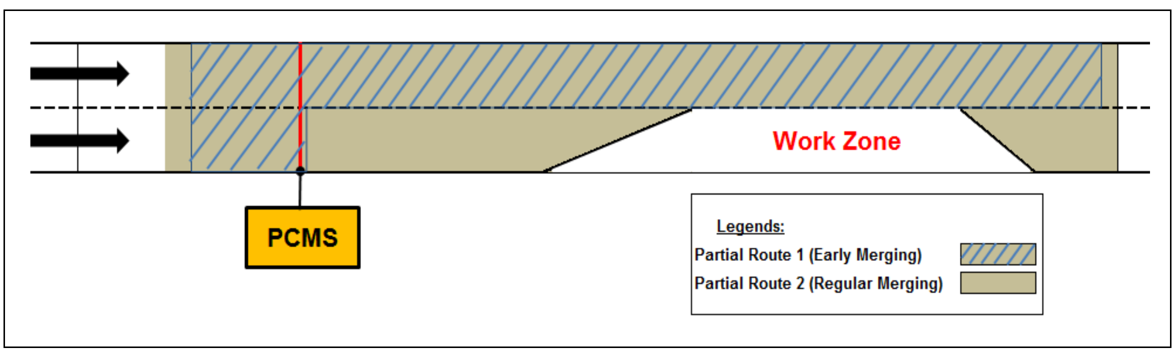


Figure 4.3.4: Early SDLMS Partial Routing Decision

4.3.2.2 Late SDLMS

Similar procedure was adopted for VAP coding of late SDLMS. For late SDLMS, one partial route with three routing decisions was used for late SDLMS. Route 1 was designated for drivers in the open lane, route 2 was designated for drivers in the closed lane and route 3 was designated for all drivers (in both lanes). The illustration in Figure 4.3.5 shows the three different routes.

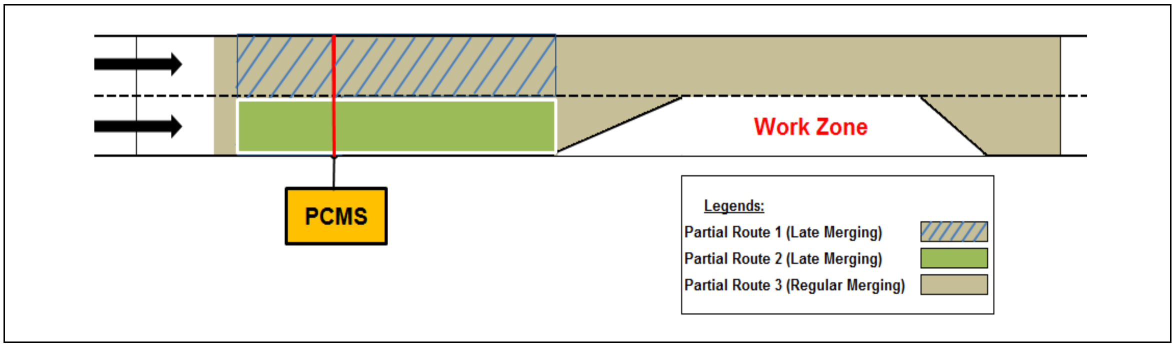


Figure 4.3.5: Late SDLMS Partial Routing Decision

4.3.3 VISSIM Model for Variable Speed Limits System

The VSL algorithm used for this study is shown in figure 4.3.6. Two loop detectors have been introduced in the advance warning area (in the VISSIM model) to calculate the average speed for the VSL. The average speed of vehicles at the advance warning area is calculated during a cycle time of 2 minutes and the corresponding speed distribution is posted at the VSL in the increments of 5 mph. If the average speed drop is more than 5 mph, the VSL will display the reduced speed i.e., 5 miles less than the previously posted speed until the average speed goes beyond the posted speed. Drivers continue to merge randomly in this case with these reduced speeds displayed.

These loop detectors can communicate with signal controllers and can only interact with traffic signals. Since, loop detectors cannot directly communicate with the desired speed decision, VAP is used for this case too. Following algorithm shown in Figure 4.3.7 is coded in VAP.

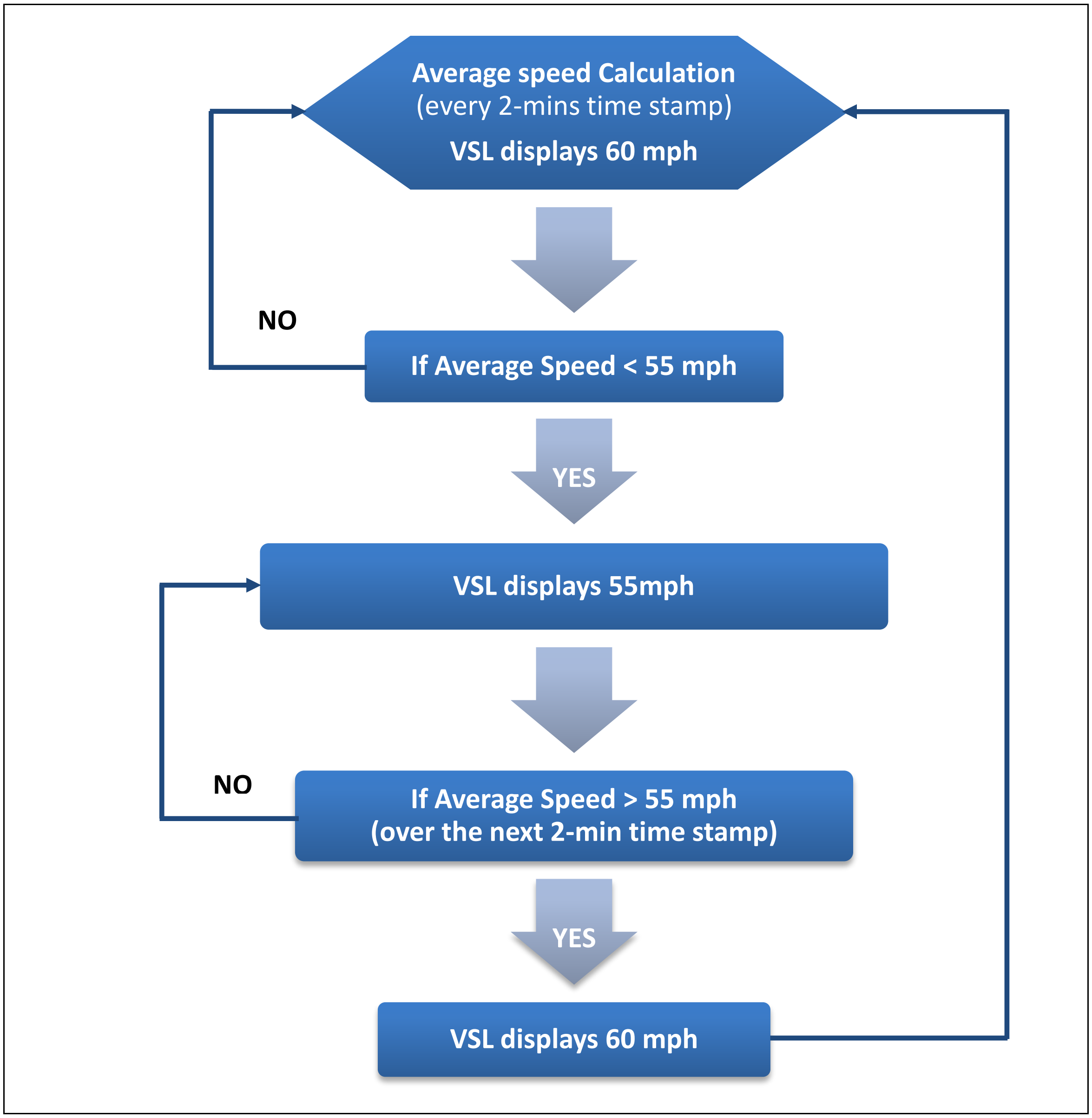


Figure 4.3.6: VAP Logic for VSL in VISSIM

Two desired speed decision points are placed in each lane 4,780 feet (0.9 miles) upstream of the taper. These desired speed decision points served as VSL with their posted speed changes in accordance with the above mentioned VAP logic. These desired speed decision points are placed at the same location where Portable Regulatory Speed sign was placed. The VSL only scenario is similar to MAS with respect to routing decisions but differs only in the exclusive desired speed decision points that act as VSL. Initially sensors for speed detection were placed 1000 ft upstream of the taper but after a few simulation runs, it was found that VSL is not much effective. It was observed that vehicles tend to decrease speed once they reach close to the taper. For that reason, sensors were placed near the start of taper in both lanes. Following (4.3.7) is the illustration of VSL desired speed decision points.

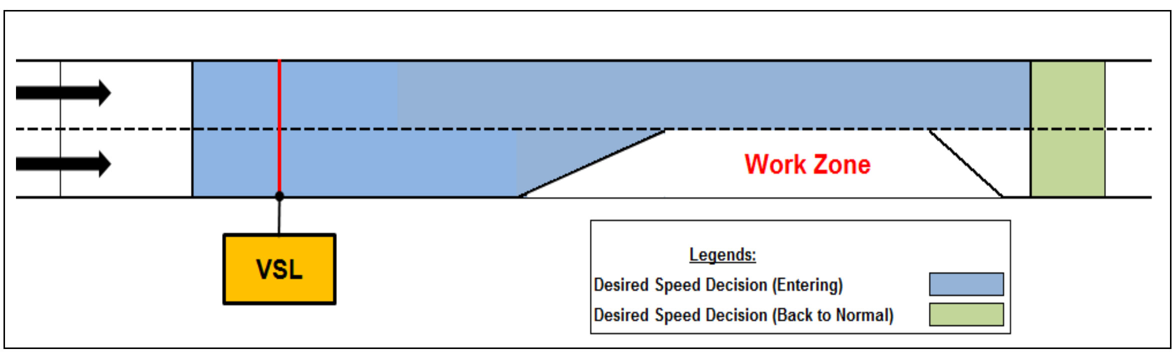


Figure 4.3.7: Desired Speed Decisions for VSL

4.3.4 VISSIM Model for Combined SDLMS and VSL System

Like those of the SDLMS only and VSL systems only, first step for combined SDLMS and VSL System is also the calculation of average speed. In this case SDLMS is the primary control whereas VSL is the supplemental control. Similarly, the loop detectors calculate the average speed of the vehicles travelling in the advance warning area close to the taper. The speed is checked with the threshold. If the speed falls below the threshold, either early or late SDLMS is activated and the required messages are displayed on the PCMS. Average speed measured from the sensors for VSL is posted on the VSL in the multiple of 5 mph. Drivers start merging depending upon the signs displayed on the PCMS. When the threshold is reached again, the DLM is deactivated and the VSL also changes the speed limit as per the new average speed. Vehicles start random merging as soon as this threshold is achieved. Figure 4.3.8 shows the VAP logic required in VISSIM for this model.

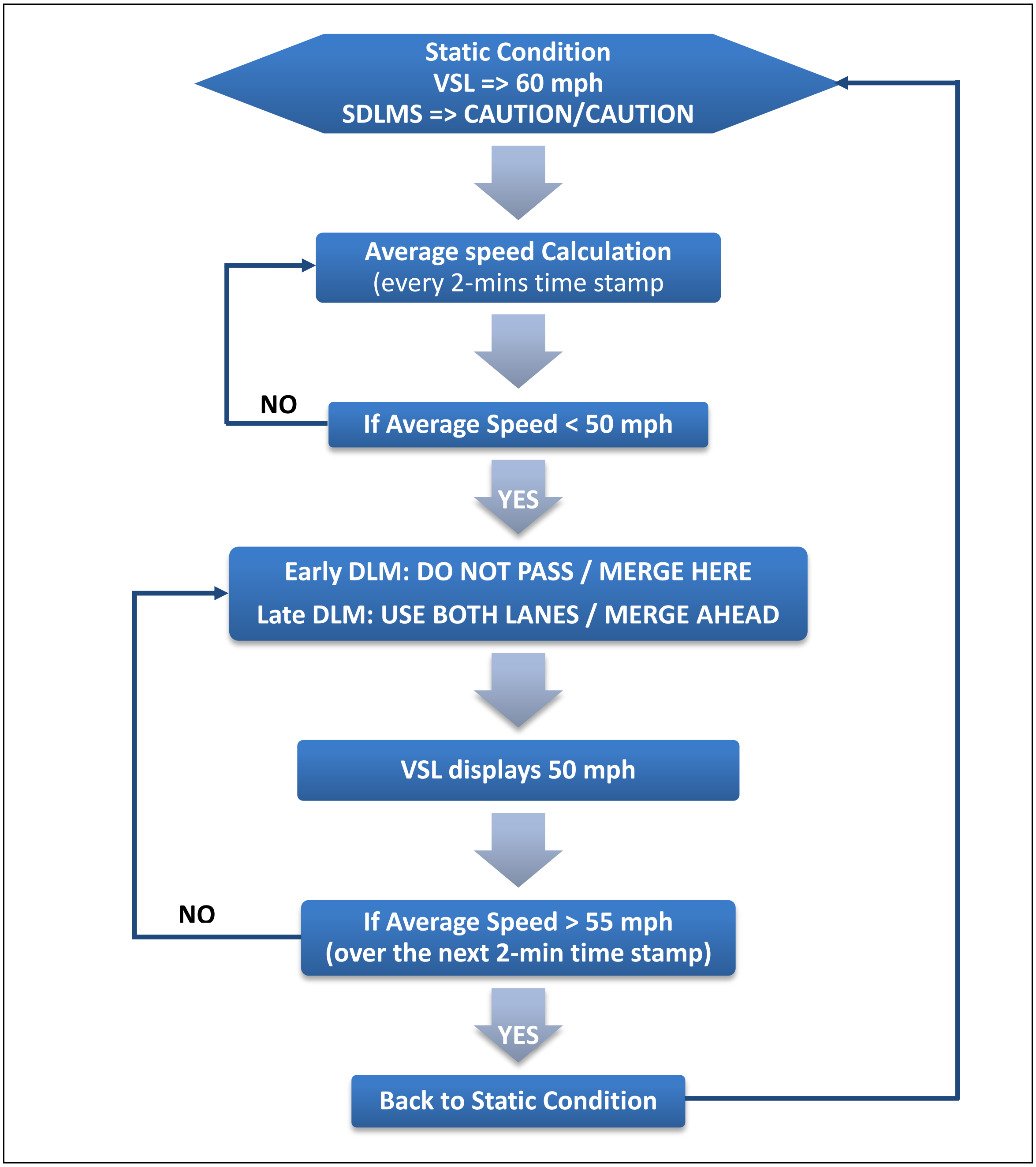


Figure 4.3.8: VAP Logic for Combined VSL and SDLMS in VISSIM

Two desired speed decision points are placed in each lane 4,780 feet (0.9 miles) upstream of the taper. These desired speed decision points served as VSL with their posted speed changes in accordance with the above mentioned VAP logic. This integrated SDLMS with VSL scenario is similar to their respective merge strategy except the addition of VSL logic and added desired speed decision points. Following figures 4.3.9 and 4.3.10 illustrate of VSL desired speed decision points for both early and late SDLMS+VSL combinations, respectively.

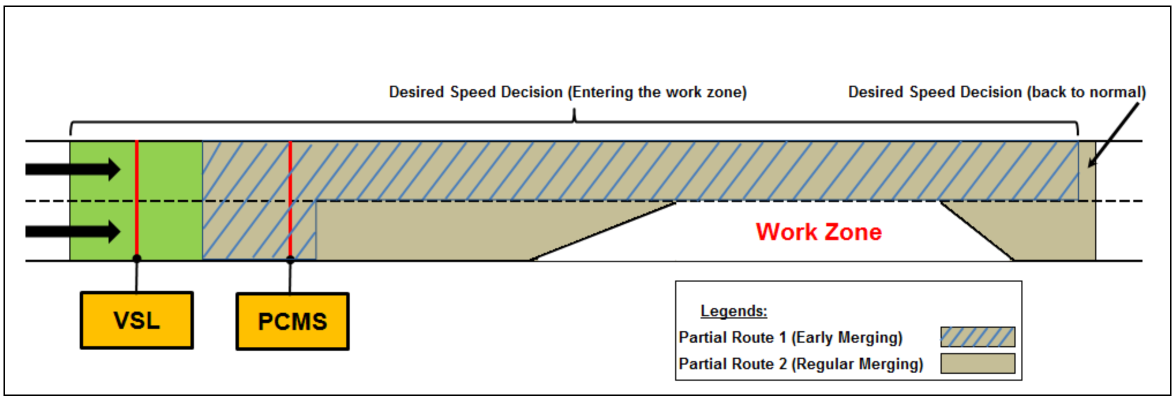


Figure 4.3.9: Routing Decisions for Early SDLMS and VSL System

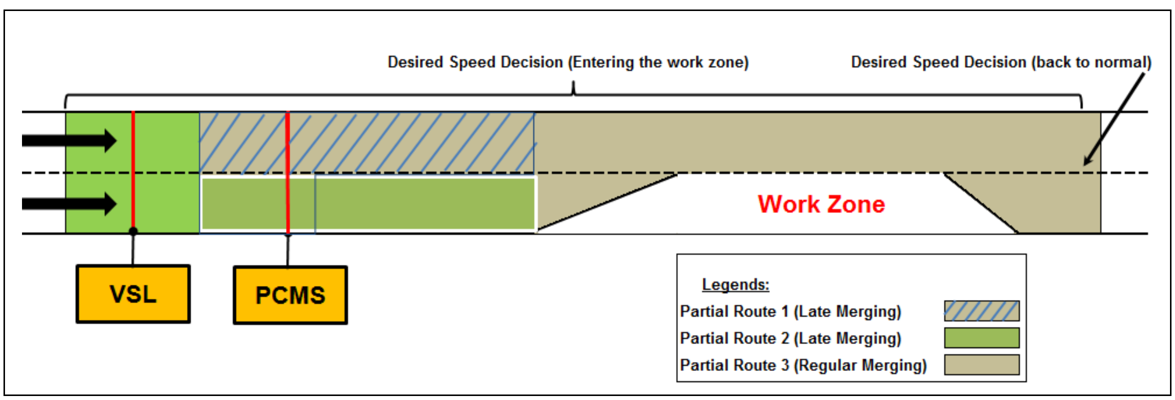


Figure 4.3.10: Routing Decisions for Late SDLMS and VSL System

4.3.5 Vehicle Classification, Desired Speed Decisions and Drivers' Compliance

Driver's adherence to the static or dynamic signs on the roadway is one of the most important aspect of simulation models. In a simulation environment, various vehicle classes can be created and then the compliance of each vehicle is controlled by that specific vehicle class. These vehicle classes can also be assigned different partial routes and desired speed decisions. For this simulation similar methodology has been adopted because VISSIM cannot specifically simulate VSL and SDLMS. At first four vehicle classes were created namely Obey Car, Obey Truck, Disobey Car and Disobey Truck. As the name of each class also indicate, obey cars are and obey trucks are the class of vehicles that comply with the displaying messages when travelling in the work zone. Vehicles in these classes will obey all the desired speed, dynamic merge messages and all partial routing decisions. On the other hand, disobey car and disobey truck are the non-compliant vehicle classes. By non compliant vehicles, it is meant that vehicles in these classes will not willingly follow the instructions of either VSL or SDLMS and the partial routing decisions. The vehicles continue to travel in the same speed as they enter the network unless they are following a compliant vehicle which forces them to reduce their speeds. Different desired speeds were designated to these vehicle classes.

Review of the literature related to simulation studies, revealed that performance of a system can be analyzed by varying the compliance rates of the vehicles. Yadlapati and Park (2004) used varied compliance rates for network evaluation in VISSIM. Lee et al., (2004) also suggested low and higher compliance rates for evaluation of safety aspect by the use of VSL. For obey car and obey trucks, VSL and SDLMS instructions were controlled through four compliance rates proportions (20%, 40%, 60% and 80%). However, for disobey cars and disobey trucks, no compliance was assigned as they travel with the speed assessed according to the network condition. No partial routing decision was assigned to non compliant vehicles.

4.4 Background of Available Data

As already mentioned in literature review, Harb et al. (2008) collected the field data on Interstate-95 (I-95) in Malabar, Florida. I- 95 is two-lane per direction limited access rural freeway with 70 mph speed limit (reduced to 60 mph during work). The work zone consisted of a resurfacing and milling job on the south bound of I-95 on a 13 mile stretch. A two to one lane closure configuration was adopted and the work zone moved on a daily basis covering a length of approximately three miles per day. Data was collected on homogenous basic freeway segment of I-95 with no on/off ramps (Harb et al., 2009).

4.5 Simulation Model Calibration and Validation

As already mentioned, the VISSIM simulation model used for this study was calibrated for SDLMS previously at CATSS (University of Central Florida) by Harb et al. (2010b). The calibration process that was adopted is briefly described hereunder;

Travel time through the work zone was chosen as the index of comparison. Secondly, the required number of simulation runs was established. Then an initial evaluation was conducted with the VISSIM's driving behavior's default parameters. An examination of the key parameters was conducted and calibration parameters were determined. Multiple runs with different values of the key parameters were run by trial and error until the calibration is completed. Finally, for the model validation, the work zone throughput (different dataset) was used to verify the homogeneity between the real and simulated environment.

The above mentioned calibrated model was then validated. The validation of the VISSIM work zone model consisted of several parts. First, the early SDLMS was validated using throughput at the onset of congestion as the MOE. Second, the late SDLMS was validated with the same driving behavior parameter sets using travel time and throughput at the onset of congestion as MOEs. Third, the MAS was validated with the same driving behavior parameter sets using throughput at the onset of congestion as a MOE. From the calibration process, runs that resulted in an acceptable p-values (>0.05) and acceptable errors (<5%) were used for the validation process. For each validation run 10 iterations with different seed numbers were completed and the resulting throughputs were collected Harb et al. (2010b). Table 4.5.1 summarizes the validation process.

Table 4.5.1: Summary of SDLMS and MAS Validation Process (Source: Harb et al. 2010b)

Base Driving Behaviour Parameter Set			Early SDLMS	Late SDLMS	MAS
			Run Number		
Car Following Model Default Parameter Values		Default	Final Validation Runs		
CC0	Standstill Distance (ft)	4.92	4.92	4.92	4.92
CC1	Headway Time (sec)	1.20	0.50	0.50	0.50
CC2	Following Variation (ft)	13.12	10.00	10.00	10.00
CC3	Threshold for Entering "Following"	-8.00	-8.00	-8.00	-8.00
CC4	Negative "Following Threshold"	-0.35	-0.35	-0.35	-0.35
CC5	Positive "Following Threshold"	0.35	0.35	0.35	0.35
CC6	Speed Dependency of Oscillation	11.44	11.44	11.44	11.44
CC7	Oscillation Acceleration (ft/s^2)	0.82	0.82	0.82	0.82
CC8	Standstill Acceleration (ft/s^2)	11.48	11.48	11.48	11.48
CC9	Acceleration at 50 mph (ft/s^2)	4.92	4.92	4.92	4.92
Lane Changing Model Default Parameter Values					
Own		**Trailing**			
Maximum Deceleration (-13.12 ft/s^2)		-9.48	-9.48	-9.48	-9.48
(-1 ft/s^2) per Distance 100 ft		100.00	100.00	100.00	100.00
Accepted Deceleration (-3.28 ft/s^2)		-1.64	-1.64	-1.64	-1.64
Waiting Time Before Diffusion (sec)		60.00	60.00	60.00	60.00
Minimum Headway (front/rear) (ft)		1.64	1.64	1.64	1.64
To Slower Lane if Collision Time Above (sec)		11.00	11.00	11.00	11.00
Safety Reduction Factor		0.10	0.40	0.40	0.40
Maximum Deceleration for Cooperative Braking (ft/s^2)		-29.00	-29.00	-29.00	-29.00
THROUGHPUT EVALUATION					
Average Simulated Throughput (vph)			1,262.00	1,100.20	1,014.60
Average Observed Throughput (vph)			1,271.60	1,062.33	970.50
Percentage Error (%)			-0.075%	3.56%	4.54%
T-Test			0.47	0.18	0.34

CHAPTER 5
ANALYSIS AND RESULTS

Previous studies have been conducted on both the use of VSL and DLM in work zones. But very little work has been done on the use of VSL and DLM combined. This is expected that the integrated control can take full advantage of the strengths from both DLM and VSL controls, and offer the operational environment that is likely to yield a higher traffic throughput and lower speed variance than those operated independently.

5.1 Data Collection

For the purpose of this study, throughputs and travel time are chosen as operational measures of effectiveness whereas speed variance and deceleration rate are chosen as safety measures of effectiveness. To collect throughput in a work zone, a data collection point is placed in the simulation model at the end of the activity area. Travel time through the work zone is measured by two data collection points placed at the start of the advance warning area and one at the end of the activity area. The total length of the work zone (including advance warning, transition and activity area) is 18,400 ft. In order to collect speed and deceleration data, two data collection points are placed upstream of the taper at the same location where the detectors are placed for measuring average speed for the VSL in the advance warning area.

All the work zone simulation scenarios have data collection points at the same location to get the best comparison of the various scenarios.

5.2 Data Analyses

As already mentioned in the literature review that compliance to VMS, heavy vehicles in the traffic stream and different traffic demand volumes give different results. For this purpose, to find out the most effective MOT type from all the six work zone scenarios, a range of these variables have been created. Drivers' compliance rate to VMS (for both VSL and SDLMS) instructions has four levels namely C20, C40, C60 and C80 indicating 20%, 40%, 60% and 80% compliance rate respectively whereas traffic demand volume is divided into five levels that are 500vph, 1,000vph 1,500vph, 2,000vph and 2,500vph denoted by V0500, V1000, V1500, V2000 and V2500 respectively. All these traffic demand levels contain 10%, 20% and 30% trucks in traffic composition designated by T10, T20 and T30 respectively.

Five traffic demand volumes, three truck percentages and four driver compliance rates add up to 60 combinations each for VSL only, early SDLMS, late SDLMS, early SDLMS+VSL and late SDLMS+VSL. As MAS does not have any VMS instruction compliance so MAS only has 15 combinations. Ten iteration runs were executed for every single simulation model with a different seed number.

To attain the objective of determining the most efficient MOT type with different drivers' compliance rates, truck volumes and total vehicular demand volumes from this simulation study, a statistical analysis was carried out. A statistical summary for each of the MOE is provided in the respective sections.

5.3 Mobility Evaluation

As already discussed in previous chapters that throughput and travel time have been taken as mobility or operational MOEs. Following is the detailed analysis all the MOT types for throughput and travel time. For each combination an overall F-test was conducted with a null hypothesis that mean throughputs and travel times under all six MOT types are the same. If the null hypothesis is rejected, pair wise Tukey's comparisons are completed to determine the difference between each pair of throughput means and travel time. In the following tables "blank cells" indicate that there was no need for Tukey's comparisons as null hypothesis was not rejected. The highlighted cells in the same tables depict that there was significant difference between the variables at 0.05 confidence interval.

5.3.1 Throughput Analysis

Graphical representation of the mean throughputs in different combinations of compliance rates, percentage trucks, traffic demand volumes and MOT type is shown in the figures 5.3.1 to 5.3.4. It is clearly evident from these figures that for the volume levels of V0500, V1000 and V1500, there is not much difference in the mean throughputs. There are some more different trends of mean throughputs for the volume levels of V2000 and V2500. Effects of compliance rates and truck percentages are explained as under;

5.3.1.1 Effect of Compliance Rates on Mean Throughputs

Figures 5.3.1 and 5.3.2 and Table 5.3.1 clearly indicate that all the SDLMS combinations i.e., early and late SDLMS and VSL with both early and late SDLMS combinations are statistically not much different from each other when the compliance rate is 40% or less for the demand volume levels of V0500, V1000 and V1500.

However, Figure 5.3.5 shows that for a given percentage of trucks and demand volume of V2000, mean throughputs generally increase as the compliance rate increases for all the MOT types except for VSL only and early SDLMS+VSL. When mean throughputs are compared for the effect of VSL against MAS, early SDLMS and Late SDLMS, it can be seen from Figure 5.3.5 and Table 5.3.1, that VSL out performs MAS but shows less throughput when compliance is 80%. Mean throughputs from early SDLMS and early DLM+VSL are not statistical different except for the compliance rate of 60% and for all truck percentages where early SDLMS+VSL produces significantly lower throughputs than early SDLMS. Late SDLMS and late SDLMS+VSL are almost similar except on one occasion where late SDLMS+VSL is significantly lower than late SDLMS for the combination C60-T30.

For the demand volume of V2500, VSL improves throughput with increase in compliance rate except when the compliance is 80% for all the three truck percentages. Early SDLMS performs better again when compared with the early SDLMS+VSL and produces significantly more mean throughputs. However, the throughput means of late SDLMS and late SDLMS+VSL are similar again except for the compliance of 60% and the truck volume 10%, 20% and 30% where mean throughput from late SDLMS is significantly higher than the late SDLMS+VSL.

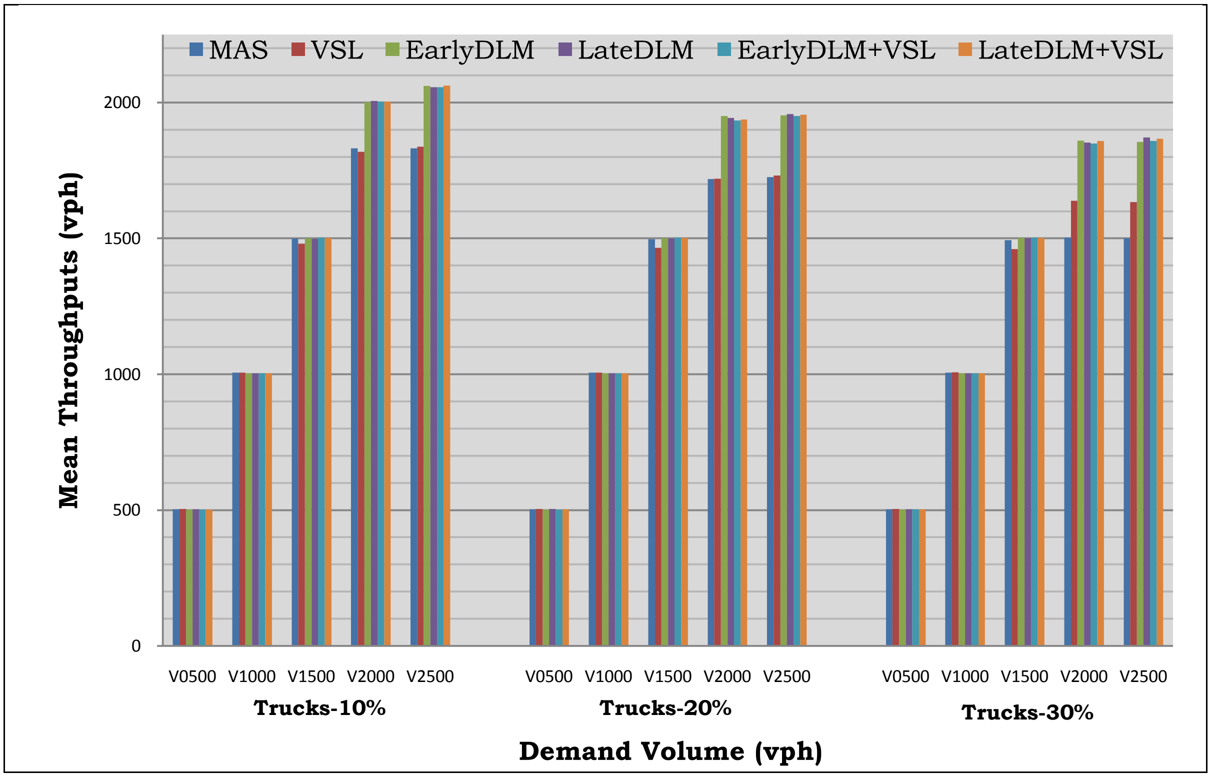


Figure 5.3.1: Comparison of Throughputs (Compliance 20%)

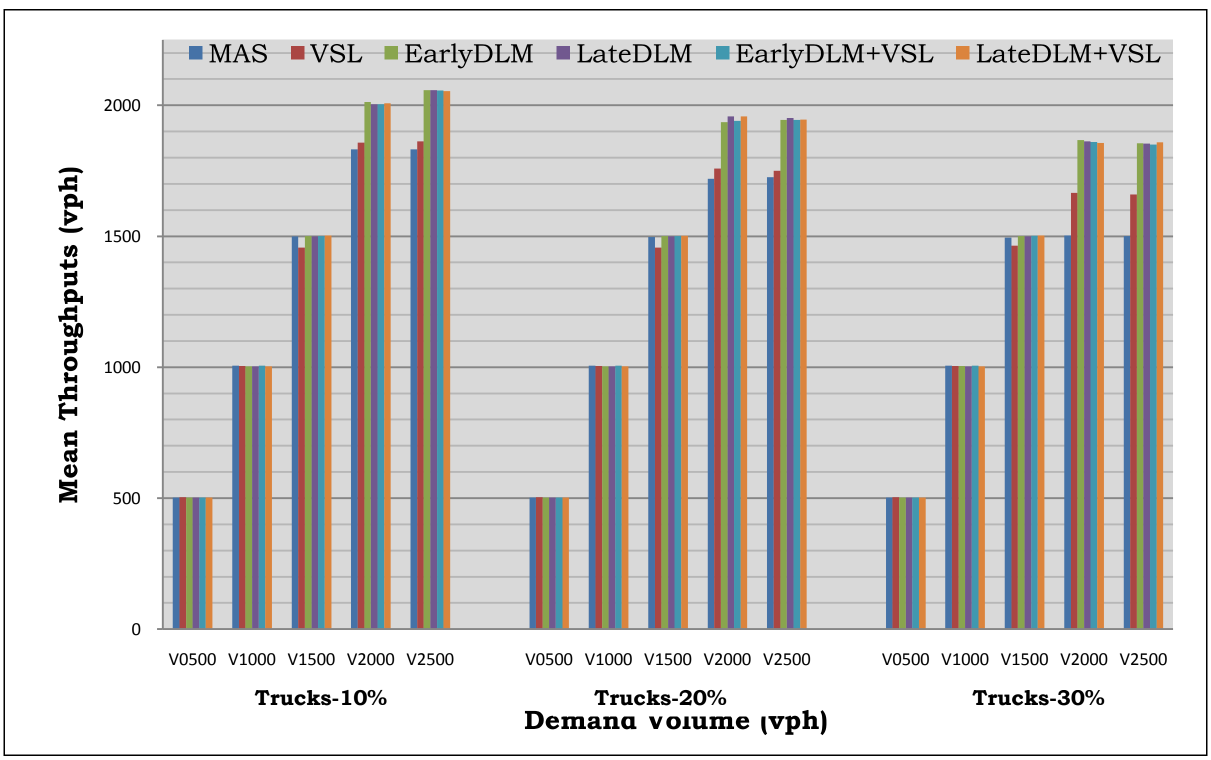


Figure 5.3.2: Comparison of Throughputs (Compliance 40%)

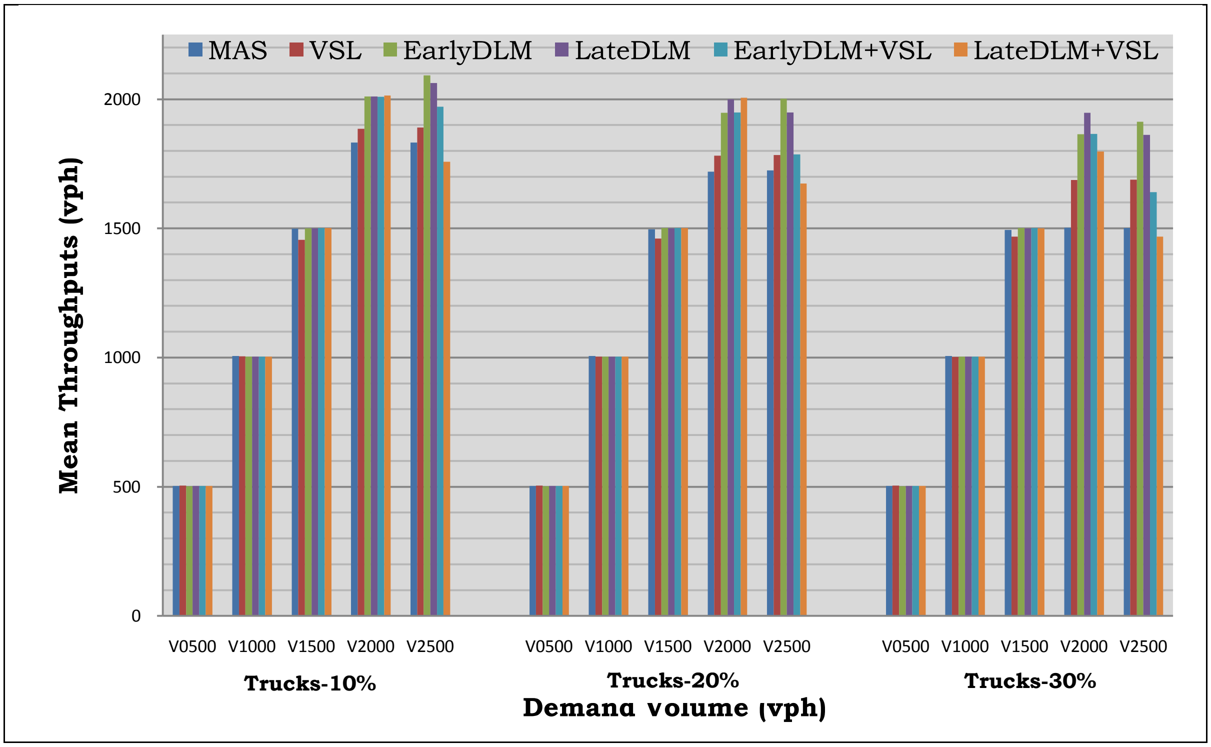


Figure 5.3.3: Comparison of Throughputs (Compliance 60%)

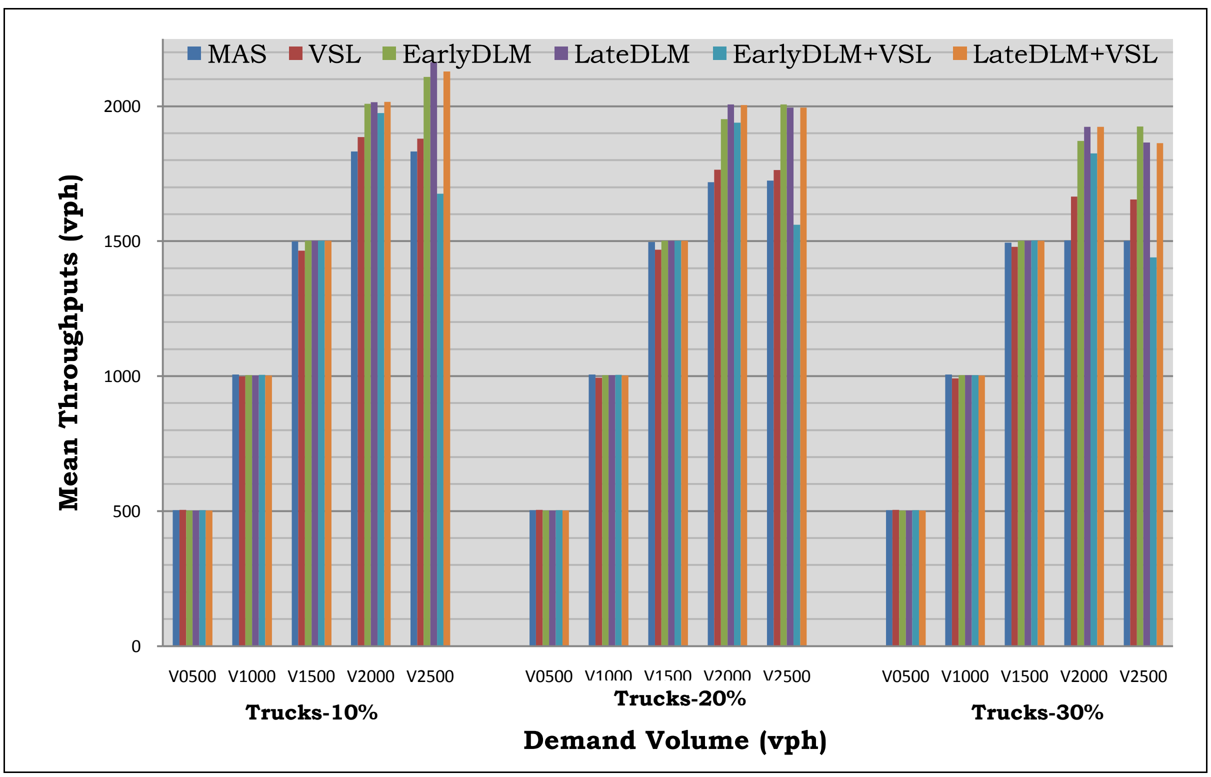


Figure 5.3.4: Comparison of Throughputs (Compliance 80%)

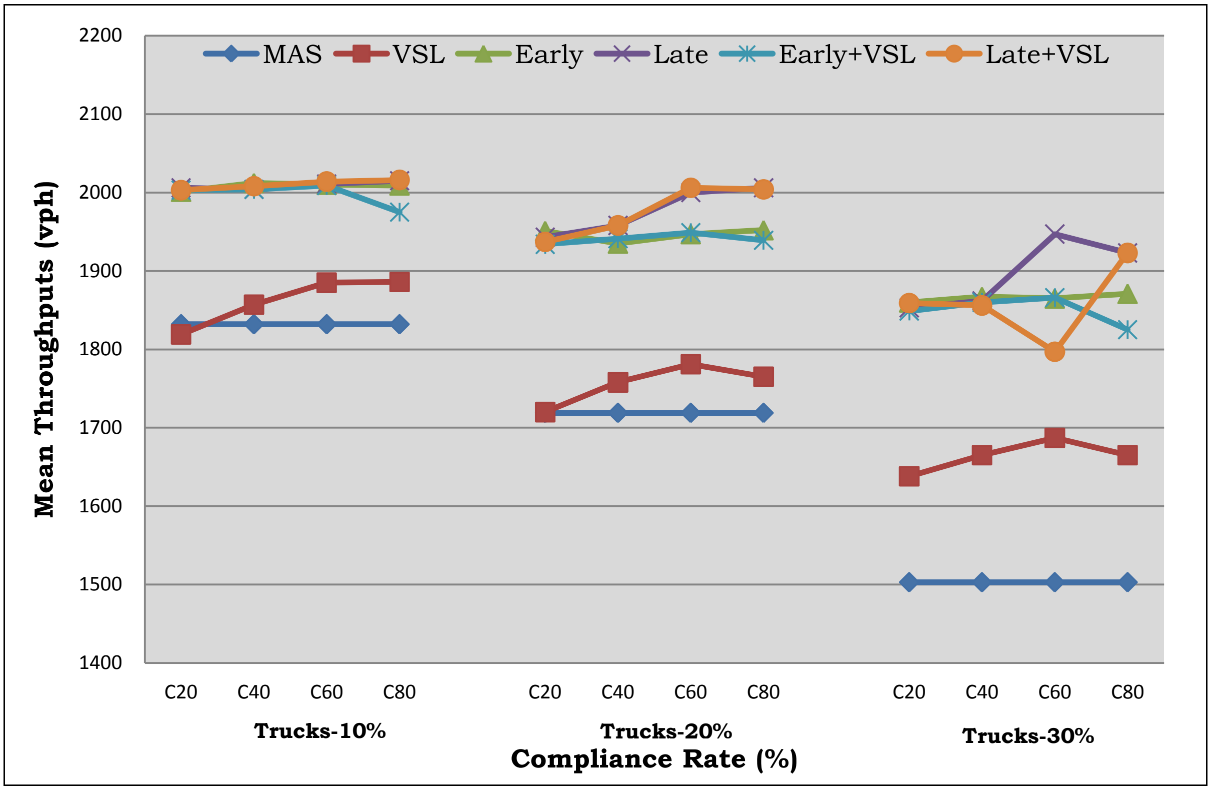


Figure 5.3.5: Comparison of Throughputs (V2000)

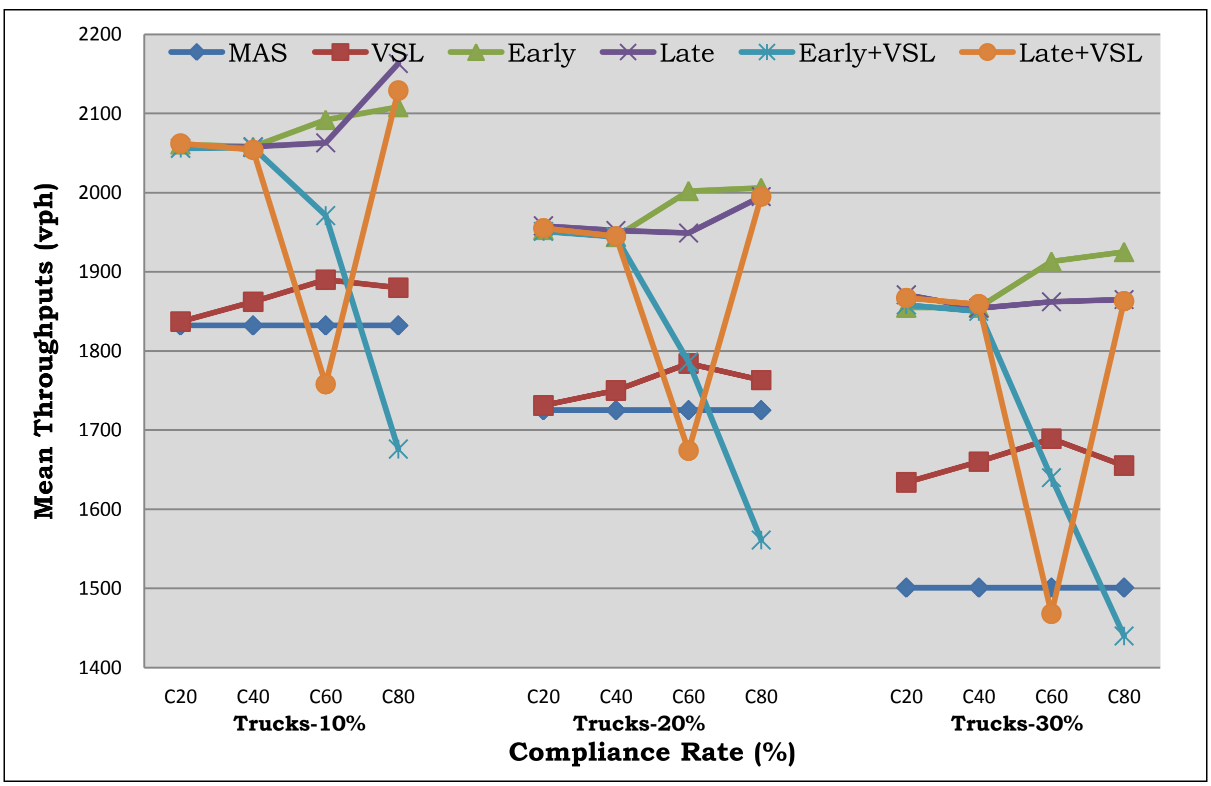


Figure 5.3.6: Comparison of Throughputs (V2500)

As a whole, for higher volume levels (V2000 and V2500), late SDLMS with and without VSL produced higher mean throughputs for all compliance rates and truck percentages except when the demand volume was 2,500 vph and compliance of 60%, where it produces the significantly lower mean throughputs..

5.3.1.2 Effect of Truck Percentage on Mean Throughputs

It can be seen from the figures 5.3.1 and 5.3.4 that the mean throughput is not much affected by the increasing truck percentage for the traffic demand volumes of V0500, V1000 and V1500. However, for the traffic demand levels of V2000 and V2500, mean throughputs decrease as the truck percentage increases.

Table 5.3.1: Comparison of Throughputs (with Compliance 20% and 40%)

THROUGHPUT ANALYSES (vph)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary												Overall F-Test P-value (P>F)	Tukey's Comparison														
			MAS		VSL		EarlyDLM		LateDLM		EarlyDLM+ VSL		LateDLM+ VSL			$\mu_{MAS}-\mu_{VSL}$	$\mu_{MAS}-\mu_{EarlyDLM}$	$\mu_{MAS}-\mu_{LateDLM}$	$\mu_{MAS}-\mu_{EarlyDLM+VSL}$	$\mu_{MAS}-\mu_{LateDLM+VSL}$	$\mu_{VSL}-\mu_{EarlyDLM}$	$\mu_{VSL}-\mu_{LateDLM}$	$\mu_{VSL}-\mu_{EarlyDLM+VSL}$	$\mu_{VSL}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM}$	$\mu_{EarlyDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM+VSL}$	$\mu_{LateDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}-\mu_{LateDLM+VSL}$
			Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD																
20	10	V0500	503	28.20	504	29.18	502	43.76	503	39.30	502	44.93	502	43.24	1.0000															
		V1000	1006	35.4	1006	35.44	1004	56.28	1003	58.82	1004	61.01	1003	59.99	0.9997															
		V1500	1499	63.82	1480	61.48	1501	63.78	1498	61.39	1503	71.84	1502	62.28	0.7401															
		V2000	1832	26.03	1819	38.88	2001	48.99	2006	49.16	2003	46.28	2003	49.16	<0.0001															
		V2500	1832	25.14	1837	21.91	2061	30.41	2056	26.92	2056	26.73	2062	27.84	<0.0001															
	20	V0500	503	28.20	504	29.35	502	43.76	504	39.48	502	44.97	502.4	43.24	1.0000															
		V1000	1006	35.42	1006	35.27	1004	56.80	1003	58.90	1004	61.39	1003	56.46	0.9998															
		V1500	1497	61.39	1465	85.57	1501	63.79	1499	62.93	1503	73.99	1502	64.81	0.2476															
		V2000	1719	22.02	1720	23.56	1951	35.84	1943	37.19	1934	44.06	1937	32.62	<0.0001															
		V2500	1725	19.64	1731	23.14	1953	33.62	1958	35.33	1951	34.82	1955	32.77	<0.0001															
	30	V0500	503	28.26	504	29.35	502	43.76	503	39.68	503	45.02	503	43.76	1.0000															
		V1000	1006	36.20	1007	35.77	1004	57.79	1003	59.15	1004	61.53	1003	57.24	0.9997															
		V1500	1494	51.95	1461	84.58	1502	63.32	1500	63.11	1503	71.01	1502	64.89	0.1198															
		V2000	1503	18.26	1638	18.69	1860	39.83	1853	32.50	1849	27.90	1859	28.35	<0.0001															
		V2500	1501	22.28	1634	27.17	1855	36.98	1871	29.91	1858	31.22	1867	39.29	<0.0001															
40	10	V0500	503	28.20	504	29.46	502	43.85	503	39.16	503	44.22	503	41.75	1.0000															
		V1000	1006	35.4	1005	39.44	1004	57.08	1003	59.03	1006	61.13	1003	57.36	0.9997															
		V1500	1499	63.82	1457	84.23	1501	63.33	1500	62.20	1501	67.96	1503	62.87	0.0657															
		V2000	1832	26.03	1857	21.88	2012	56.51	2004	47.26	2004	47.58	2008	43.19	<0.0001															
		V2500	1832	25.14	1862	24.00	2058	25.59	2058	30.14	2057	30.58	2054	32.76	<0.0001															
	20	V0500	503	28.20	504	29.66	502	43.85	503	39.49	503	44.42	503	41.75	1.0000															
		V1000	1006	35.42	1005	40.63	1004	56.99	1003	58.98	1006	61.65	1003	58.14	0.9998															
		V1500	1497	61.39	1457	76.76	1501	63.12	1500	61.78	1501	66.39	1502	61.99	0.0518															
		V2000	1719	22.02	1758	24.78	1935	33.46	1958	42.24	1941	33.98	1958	37.12	<0.0001															
		V2500	1725	19.64	1750	24.47	1944	29.76	1952	31.61	1944	36.43	1945	33.15	<0.0001															
	30	V0500	503	28.26	504	29.63	502	43.55	503	39.49	503	43.95	503	41.75	1.0000															
		V1000	1006	36.20	1005	40.56	1005	56.97	1003	59.10	1006	60.83	1003	57.60	0.9999															
		V1500	1494	51.95	1464	86.19	1501	61.67	1500	62.00	1502	67.16	1503	63.48	0.1694															
		V2000	1503	18.26	1665	25.97	1867	36.00	1862	39.36	1860	29.43	1856.4	33.19	<0.0001															
		V2500	1501	22.28	1660	22.42	1855	28.45	1854	26.33	1850	28.20	1859	35.56	<0.0001															

Table 5.3.2: Comparison of Throughputs (with Compliance 60% and 80%)

THROUGHPUT ANALYSES (vph)

Compliance(%)	Trucks (%)	Volume (vph)	MAS Mean (μ)	MAS SD	VSL Mean (μ)	VSL SD	EarlyDLM Mean (μ)	EarlyDLM SD	LateDLM Mean (μ)	LateDLM SD	EarlyDLM+ VSL Mean (μ)	EarlyDLM+ VSL SD	LateDLM+ VSL Mean (μ)	LateDLM+ VSL SD	Overall F-Test P-value (P>F)	$\mu_{MAS}-\mu_{VSL}$	$\mu_{MAS}-\mu_{EarlyDLM}$	$\mu_{MAS}-\mu_{LateDLM}$	$\mu_{MAS}-\mu_{EarlyDLM+VSL}$	$\mu_{MAS}-\mu_{LateDLM+VSL}$	$\mu_{VSL}-\mu_{EarlyDLM}$	$\mu_{VSL}-\mu_{LateDLM}$	$\mu_{VSL}-\mu_{EarlyDLM+VSL}$	$\mu_{VSL}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM}$	$\mu_{EarlyDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM+VSL}$	$\mu_{LateDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}-\mu_{LateDLM+VSL}$
		V0500	503	28.20	504	30.40	502	43.52	503	40.28	503	43.04	503	42.03	1.0000															
		V1000	1006	35.4	1005	41.69	1004	57.07	1003	59.76	1004	61.26	1003	57.24	0.9999															
	10	V1500	1499	63.82	1456	72.27	1500	62.54	1500	62.56	1501	68.97	1501	64.18	0.0460															
		V2000	1832	26.03	1885	27.97	2010	2014	2011	60.45	2009	51.60	2014	60.93	<0.0001															
		V2500	1832	25.14	1890	27.20	2092	51.69	2063	40.06	1971	167.96	1758	171.5	<0.0001															
		V0500	503	28.20	504	30.26	502	43.13	503	40.28	503	43.04	503.33	42.53	1.0000															
		V1000	1006	35.42	1003	41.25	1004	56.95	1003	59.49	1004	60.87	1003	57.93	1.0000															
60	20	V1500	1497	61.39	1460	77.87	1501	63.30	1500	62.93	1502	66.58	1501	63.93	0.1063															
		V2000	1719	22.02	1781	27.14	1947	36.37	2000	52.29	1949	41.92	2006	58.13	<0.0001															
		V2500	1725	19.64	1784	29.91	2002	51.44	1949	31.33	1786	214.06	1674	187.44	<0.0001															
		V0500	503	28.26	504	30.44	502	43.27	503	40.17	503	42.93	503	42.53	1.0000															
		V1000	1006	36.20	1002	41.87	1004	57.26	1003	60.08	1004	67.06	1004	57.35	0.9999															
	30	V1500	1494	51.95	1468	79.45	1501	62.71	1500	64.14	1502	67.06	1500	65.04	0.3144															
		V2000	1503	18.26	1687	26.58	1865	29.94	1947	61.89	1866	29.46	1797	183.55	<0.0001															
		V2500	1501	22.28	1689	29.14	1913	60.45	1862	27.24	1640	177.16	1468	110.58	<0.0001															
		V0500	503	28.20	504	30.96	502.27	43.76	502.4	39.66	503	42.49	502	42.04	1.0000															
		V1000	1006	35.4	999	41.92	1004	55.98	1003	59.69	1005	62.29	1003	57.24	0.9964															
	10	V1500	1499	63.82	1465	87.33	1501	63.26	1501	64.75	1501	68.89	1501	65.26	0.2500															
		V2000	1832	26.03	1886	22.54	2009	49.62	2015	61.53	1975	135.73	2016	62.34	<0.0001															
		V2500	1832	25.14	1880	26.26	2108	71.47	2163	75.56	1676	288.79	2129	177.74	<0.0001															
		V0500	503	28.20	504	30.96	502	43.76	502	43.76	503	42.60	502	42.04	1.0000															
		V1000	1006	35.42	994	46.83	1004	56.72	1004	58.73	1005	61.03	1003	57.53	0.9644															
80	20	V1500	1497	61.39	1468	83.98	1501	63.67	1501	64.50	1502	69.07	1501	63.22	0.3206															
		V2000	1719	22.02	1765	25.96	1952	34.34	2006	65.33	1939	32.08	2004	54.70	<0.0001															
		V2500	1725	19.64	1763	37.69	2006	60.92	1995	61.81	1561	151.90	1995	62.69	<0.0001															
		V0500	503	28.26	504	30.96	502	43.55	502	39.99	503	42.45	502	42.04	1.0000															
		V1000	1006	36.20	992	4531	1004	57.40	1004	58.98	1004	61.31	1003	57.94	0.9319															
	30	V1500	1494	51.95	1479	72.12	1501	63.83	1502	64.58	1503	63.81	1501	64.72	0.6815															
		V2000	1503	18.26	1665	31.80	1871	37.10	1923	71.92	1825	145.46	1923	61.52	<0.0001															
		V2500	1501	22.28	1655	29.09	1925	66.68	1865	72.76	1440	70.87	1863	61.43	<0.0001															

5.3.2 Travel Time Analysis

Graphical representation of the travel time in different combinations of compliance rates, percentage trucks, traffic demand volumes and MOT type is shown in the figures 5.3.7 to 5.3.10. Detail of travel time for every combination is provided in the tables 5.3.3 and 5.3.4. It is clearly evident from these figures that for the volume levels of V0500 and V1000, there is not much difference in the travel times. These figures also indicate that for demand volume of V1500, the travel time for VSL is the worst as compared to other MOT types. All other MOT types have somewhat similar travel time range irrespective of the compliance rate and truck percentage.

There are some more different trends of average travel times for the volume levels of V1500, V2000 and V2500. Effects of compliance rates and truck percentages are explained as under;

5.3.2.1 Effect of Compliance Rates on Travel Time

Tables 5.3.3 and 5.3.4 depict that for demand volumes of V0500, V1000 and V1500, travel time for all the MOT types increases with increase in compliance rate for any given percentage of trucks.

For the demand volume of 2,000 vph, early SDLMS, late SDLMS and late SDLM+VSL showed slight improvement as the compliance increased, however, early SDLMS on one occasion when truck percentage was 30%. Travel time for early SDLMS+VSL increased with increase in compliance. VSL alone showed slight improvement as the compliance increased except for the combinations C40-T10, C80-T20 and C80-T30 where higher travel time was recorded. VSL was also the worst MOT type in terms of travel time. Figure 5.3.11 can be consulted for behavior of various MOT types against increasing compliance rates.

For the demand volume of 2,500 vph (Figure 5.3.12), the travel time shows mixed trends with the increase in compliance rates. Both early and late SDLMS resulted in lesser travel time with increase in compliance rate. Similar trend was observed in late SDLMS+VSL except for the two occurrences where higher travel time was recorded i.e. C60-T10 and C60-T30. Early SDLMS+VSL also showed reduction in travel time for compliance of 60% or less but for 80%, it resulted in higher travel times through the work zone. VSL in comparison to MAS performed badly in terms of travel time as it increased the travel time through work zone. For 10% trucks in the demand volume, travel time decreased when the compliance rate to obey VSL was increased but the opposite results were observed when the truck percentage was 30% in the traffic mix.

As a whole, the early SDLMS performed better as compared to other MOT types for the V2500 volume level whereas late SDLMS and late SDLMS+VSL showed better performance for the demand volumes of V2000 and under.

5.3.2.2 Effect of Truck Percentage on Travel Time

It can be seen from the figures 5.3.7 and 5.3.10 that the travel time is not much affected by the increasing truck percentage for the traffic demand volumes of V0500, V1000 and V1500. However, for the traffic demand levels of V2000 and V2500, travel time through the work zone increase as the truck percentage increases.

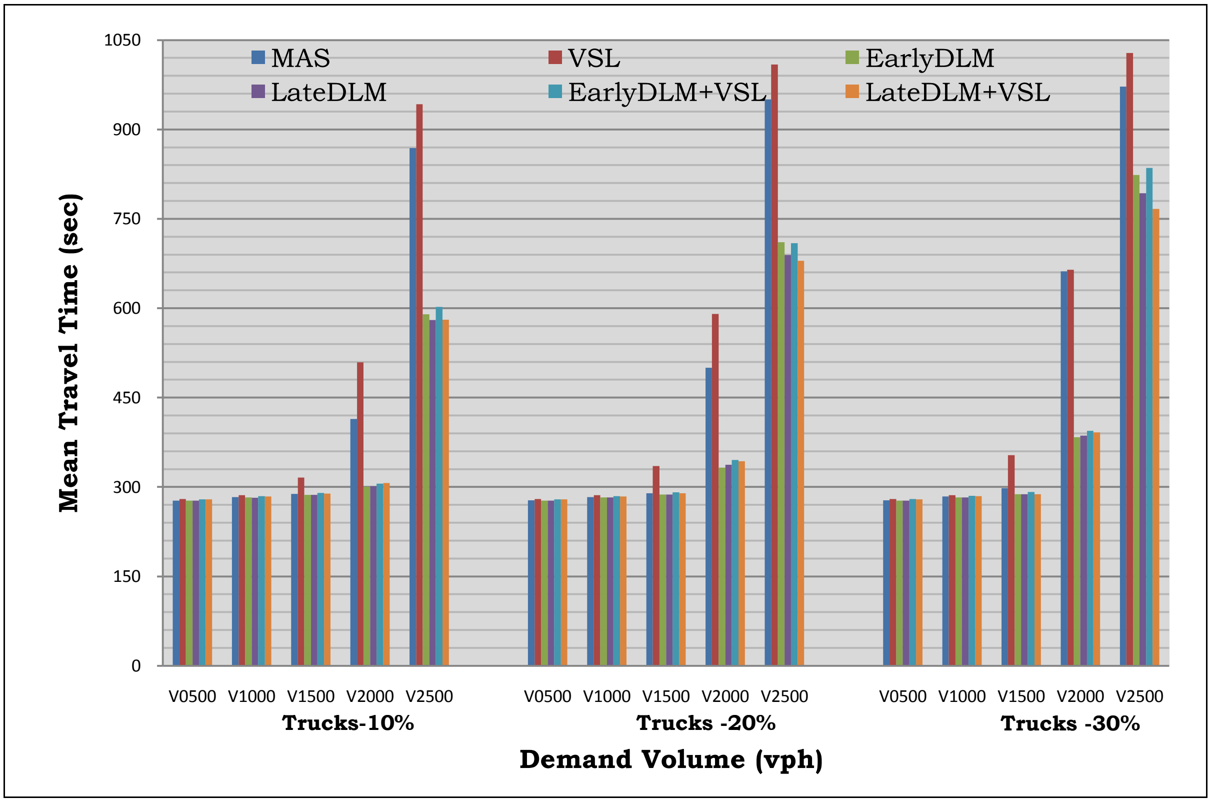


Figure 5.3.7: Comparison of Travel Times (Compliance 20%)

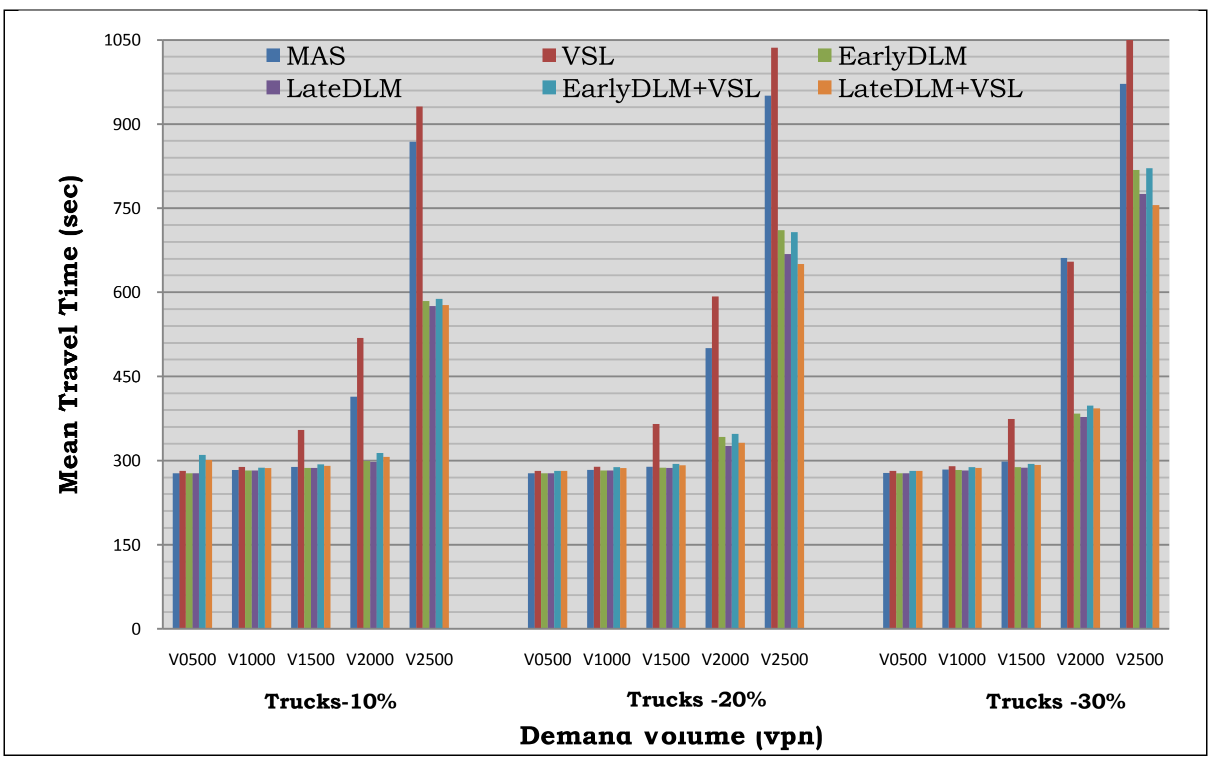


Figure 5.3.8: Comparison of Travel Times (Compliance 40%)

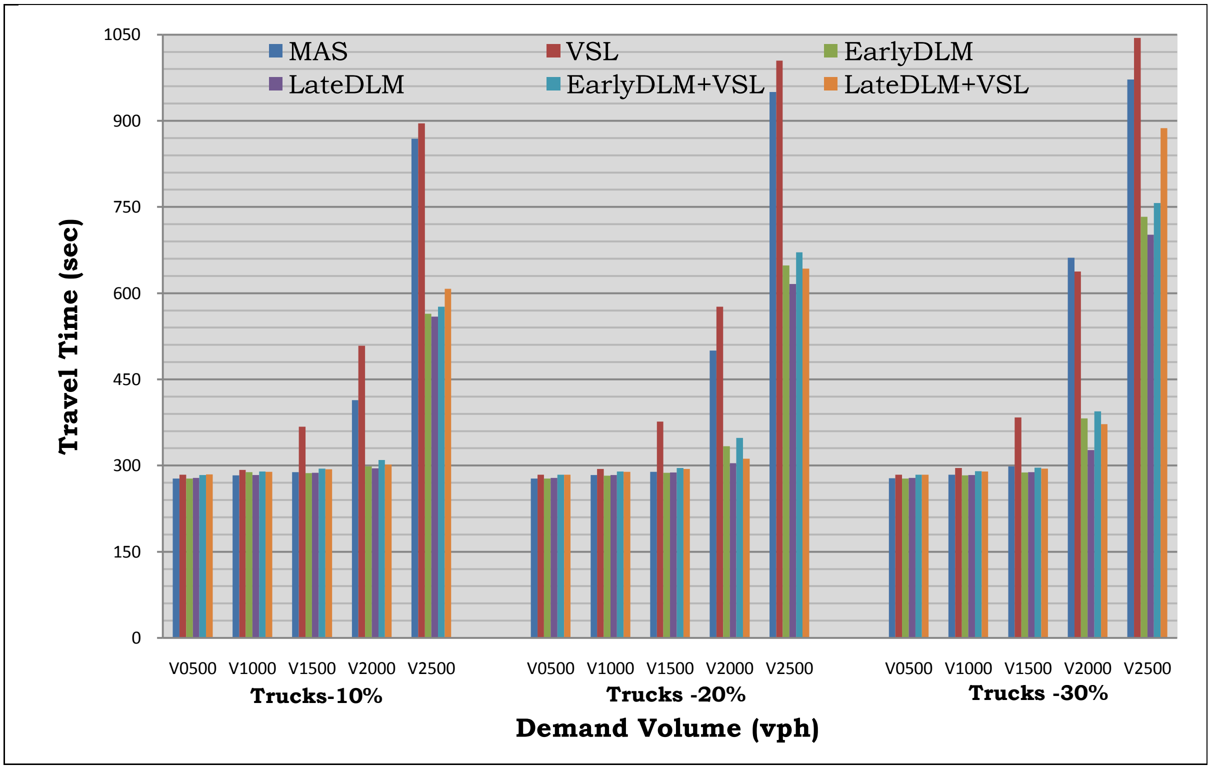


Figure 5.3.9: Comparison of Travel Times (Compliance 60%)

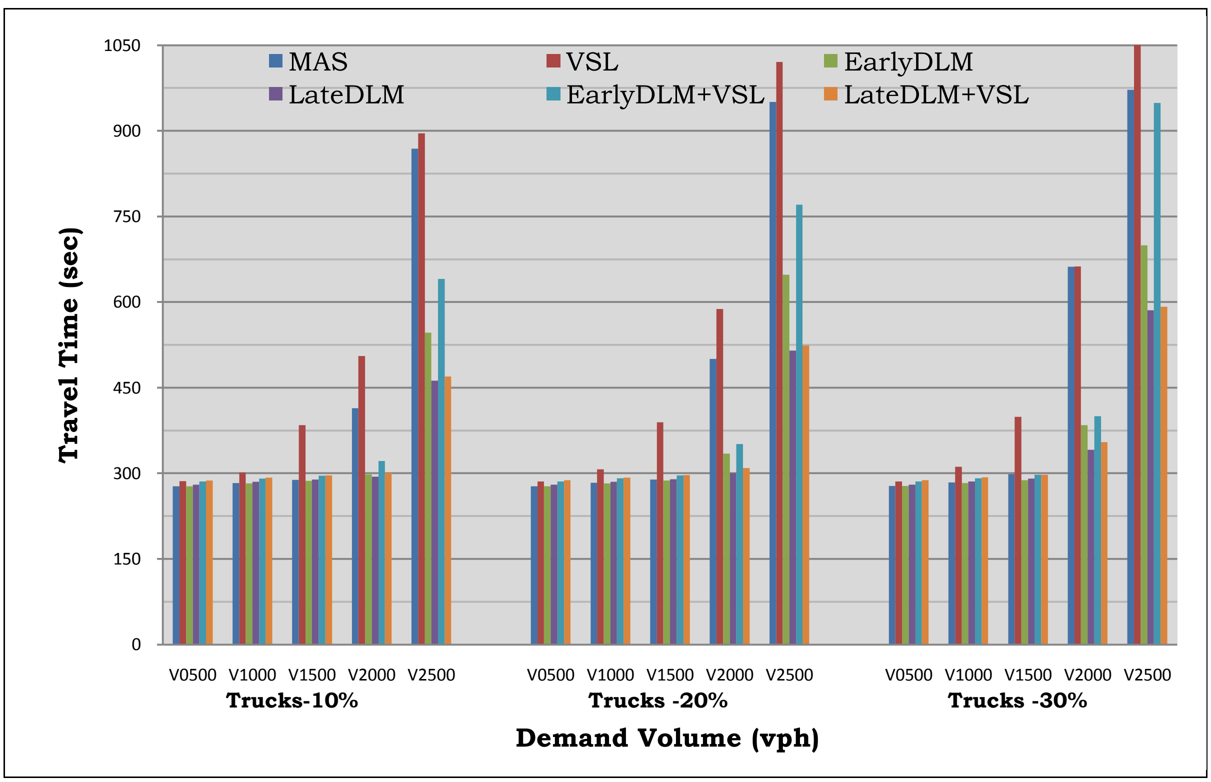


Figure 5.3.10: Comparison of Travel Times (Compliance 80%)

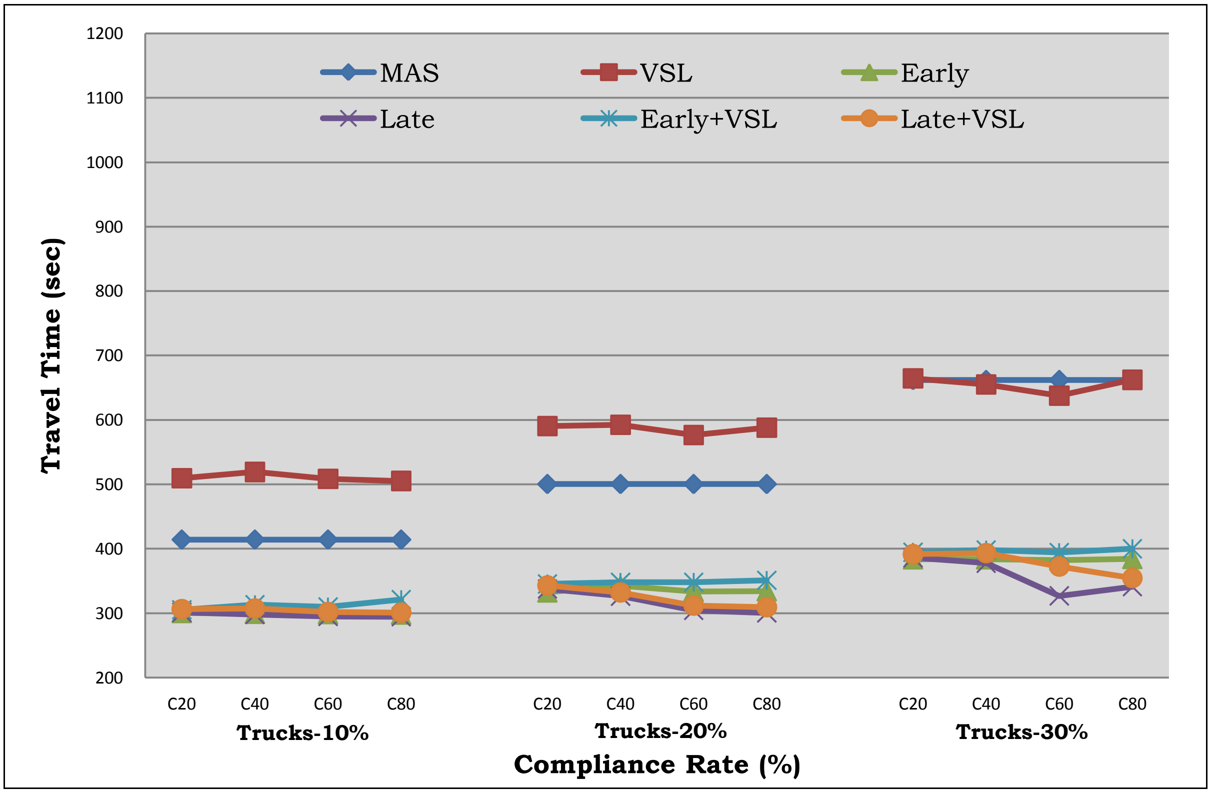


Figure 5.3.11: Comparison of Travel Time (V2000)

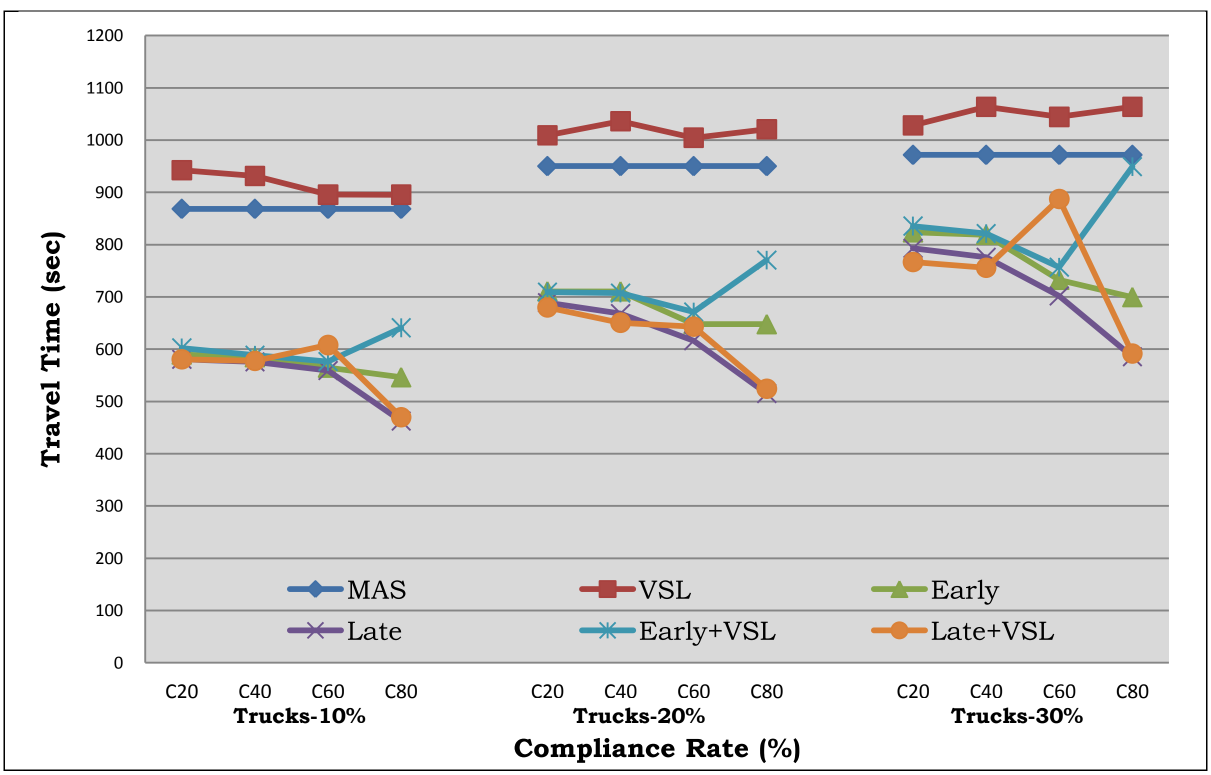


Figure 5.3.12: Comparison of Travel Time (V2500)

Table 5.3.3: Comparison of Travel Times (with Compliance 20% and 40%)

TRAVEL TIME (seconds)																														
Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary												Overall F-Test P-value (P>F)	Tukey's Comparison														
			MAS		VSL		EarlyDLM		LateDLM		EarlyDLM+ VSL		LateDLM+ VSL																	
			Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD		$\mu_{MAS}-\mu_{VSL}$	$\mu_{MAS}-\mu_{EarlyDLM}$	$\mu_{MAS}-\mu_{LateDLM}$	$\mu_{MAS}-\mu_{EarlyDLM+VSL}$	$\mu_{MAS}-\mu_{LateDLM+VSL}$	$\mu_{VSL}-\mu_{EarlyDLM}$	$\mu_{VSL}-\mu_{LateDLM}$	$\mu_{VSL}-\mu_{EarlyDLM+VSL}$	$\mu_{VSL}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM}$	$\mu_{EarlyDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM+VSL}$	$\mu_{LateDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}-\mu_{LateDLM+VSL}$
20	10	V0500	277.35	2.28	279.83	2.75	277.13	2.02	277.08	2.08	279.47	2.42	279.26	2.29	0.5829															
		V1000	283.09	1.31	286.02	1.69	282.29	1.66	282.10	1.62	284.60	1.84	284.07	1.75	0.7616															
		V1500	288.57	1.45	315.83	28.69	287.02	1.69	286.71	1.57	290.25	2.30	288.86	1.85	<0.0001	■					■	■	■	■						
		V2000	414.08	98.19	509.49	112.46	300.42	16.83	301.14	13.46	305.37	12.35	306.47	19.87	<0.0001	■	■	■	■	■	■	■	■	■						
		V2500	868.62	153.19	942.48	128.85	589.69	213.43	580.41	193.91	602.24	218.20	580.59	194.97	<0.0001		■	■	■	■	■	■	■	■						
	20	V0500	277.42	2.29	279.93	2.78	277.24	2.08	277.17	2.05	279.54	2.43	279.33	2.31	0.6289															
		V1000	283.27	1.31	286.19	1.67	282.51	1.68	282.37	1.66	284.82	1.91	284.25	1.80	0.6690															
		V1500	289.26	1.77	335.09	37.49	287.44	1.89	287.12	1.67	290.90	2.75	289.49	2.47	<0.0001	■					■	■	■	■						
		V2000	500.31	148.71	590.39	150.92	332.42	41.89	337.58	47.61	345.31	44.57	343.08	51.17	<0.0001	■	■	■	■	■	■	■	■	■						
		V2500	950.39	70.86	1009.1	56.71	710.66	231.83	689.07	212.59	709.13	214.95	679.62	212.59	<0.0001		■	■	■	■	■	■	■	■						
	30	V0500	277.65	2.30	280.01	2.79	277.35	2.07	277.28	2.05	279.63	2.41	279.39	2.27	0.5339															
		V1000	283.86	1.32	286.49	1.72	282.69	1.68	282.58	1.65	285.04	2.01	284.53	1.85	0.6179															
		V1500	298.34	13.35	353.44	43.17	288.06	2.16	287.74	1.77	291.69	3.19	287.74	2.74	<0.0001	■					■	■	■	■	■					
		V2000	661.76	233.81	664.52	186.86	383.8	81.35	386.12	85.30	394.53	81.48	391.57	81.96	<0.0001		■	■	■	■	■	■	■	■						
		V2500	971.98	7.04	1028.11	29.57	823.40	183.25	793.08	176.90	835.53	177.15	766.67	144.96	<0.0001		■	■	■	■	■	■	■	■						
40	10	V0500	277.35	2.28	281.89	2.74	277.15	2.02	277.28	2.21	310.34	126.07	300.92	94.78	0.0549															
		V1000	283.09	1.31	288.53	1.84	282.30	1.64	282.18	1.61	287.76	2.08	286.22	1.75	0.6151															
		V1500	288.57	1.45	354.65	41.22	287.00	1.60	286.67	1.63	293.47	2.22	291.10	2.07	<0.0001	■					■	■	■	■						
		V2000	414.08	98.19	519.19	82.66	299.14	10.81	297.84	12.80	313.29	19.63	307.15	18.67	<0.0001	■	■	■	■	■	■	■	■	■						
		V2500	868.62	153.19	931.25	145.46	584.45	206.78	575.66	196.45	588.36	196.97	577.39	183.24	<0.0001		■	■	■	■	■	■	■	■						
	20	V0500	277.42	2.29	281.97	2.73	277.29	2.02	277.42	2.21	281.88	2.92	281.56	2.84	0.6884															
		V1000	283.27	1.31	289.01	2.18	282.53	2.03	282.43	1.63	287.99	2.03	286.56	1.76	0.4357															
		V1500	289.26	1.77	364.9	43.01	287.46	1.77	287.06	1.65	294.09	2.36	291.59	2.06	<0.0001	■				■	■	■	■	■						
		V2000	500.31	148.71	592.41	131.38	342.33	45.45	326.47	44.40	348.04	47.01	332.07	44.64	<0.0001	■	■	■	■	■	■	■	■	■						
		V2500	950.39	70.86	1036.1	86.07	710.52	211.94	668.12	203.54	707.37	206.81	650.67	183.41	<0.0001		■	■	■	■	■	■	■	■						
	30	V0500	277.65	2.30	282.03	2.76	277.42	2.04	277.51	2.22	281.99	2.93	281.78	2.93	0.6612															
		V1000	283.86	1.32	289.59	2.15	282.77	1.64	282.63	1.66	288.27	2.09	286.85	1.76	0.4313															
		V1500	298.34	13.35	374.31	45.06	288.07	2.10	287.51	1.86	294.59	2.57	292.28	2.41	<0.0001	■					■	■	■	■						
		V2000	661.76	233.81	654.89	175.60	383.82	76.19	377.63	79.06	398.02	80.57	393.10	79.62	<0.0001		■	■	■	■	■	■	■	■						
		V2500	971.98	7.04	1063.7	62.16	818.61	184.61	775.66	16.76	821.34	174.15	755.84	142.12	<0.0001	■	■	■	■	■	■	■	■	■						

Table 5.3.4: Comparison of Travel Times (with Compliance 60% and 80%)

TRAVEL TIME (seconds)																														
Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary												Overall F-Test P-value (P_r>F)	Tukey's Comparison														
			MAS		VSL		EarlyDLM		LateDLM		EarlyDLM+ VSL		LateDLM+ VSL			$\mu_{MAS}-\mu_{VSL}$	$\mu_{MAS}-\mu_{EarlyDLM}$	$\mu_{MAS}-\mu_{LateDLM}$	$\mu_{MAS}-\mu_{EarlyDLM+VSL}$	$\mu_{MAS}-\mu_{LateDLM+VSL}$	$\mu_{VSL}-\mu_{EarlyDLM}$	$\mu_{VSL}-\mu_{LateDLM}$	$\mu_{VSL}-\mu_{EarlyDLM+VSL}$	$\mu_{VSL}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM}$	$\mu_{EarlyDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM+VSL}$	$\mu_{LateDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}-\mu_{LateDLM+VSL}$
			Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD	Mean (μ)	SD																
60	10	V0500	277.35	2.28	283.80	2.50	277.23	1.93	278.27	2.14	283.70	2.44	284.5	2.45	0.8839															
		V1000	283.09	1.31	292.14	3.89	283.81	1.64	283.26	1.57	289.63	1.92	288.85	1.73	<0.0001															
		V1500	288.57	1.45	367.82	42.72	287.00	1.59	287.61	1.68	294.89	1.90	293.42	1.64	<0.0001															
		V2000	414.08	98.19	508.53	69.43	298.76	11.49	295.02	6.25	309.75	14.69	301.73	10.96	<0.0001															
		V2500	868.62	153.19	895.66	149.87	564.41	181.64	559.17	195.14	576.37	182.82	607.89	230.96	<0.0001															
	20	V0500	277.42	2.29	283.88	2.48	277.31	1.94	278.43	2.10	283.82	2.42	284.17	2.46	0.8902															
		V1000	283.27	1.31	294.31	5.77	282.49	1.63	283.46	1.59	289.88	1.95	289.10	1.69	<0.0001															
		V1500	289.26	1.77	376.53	41.79	287.45	1.78	287.99	1.71	295.58	2.19	293.87	1.67	<0.0001															
		V2000	500.31	148.71	576.56	118.14	333.79	4357	304.37	18.88	347.96	44.02	311.73	16.94	<0.0001															
		V2500	950.39	70.86	1004.5	91.77	648.11	179.29	616.16	218.75	671.34	192.52	642.91	239.91	<0.0001															
	30	V0500	277.65	2.30	283.99	2.48	277.44	1.93	278.505	2.10	283.96	2.38	284.23	2.34	0.8998															
		V1000	283.86	1.32	295.99	7.42	282.70	1.64	283.68	1.61	290.13	1.93	289.35	1.76	<0.0001															
		V1500	298.34	13.35	383.83	40.46	288.00	1.07	288.54	2.03	296.21	2.37	294.49	1.83	<0.0001															
		V2000	661.76	233.81	637.49	163.39	382.34	76.92	326.86	43.24	394.39	75.96	372.24	90.43	<0.0001															
		V2500	971.98	7.04	1044.4	70.07	732.65	150.14	701.84	201.42	756.86	162.47	887.20	211.01	<0.0001															
80	10	V0500	277.35	2.28	286.38	2.44	277.37	2.05	280.02	2.37	285.46	2.20	287.57	2.97	0.5476															
		V1000	283.09	1.31	301.63	10.16	282.28	1.63	284.90	1.61	290.97	2.11	292.28	1.75	<0.0001															
		V1500	288.57	1.45	384.46	34.88	286.96	1.65	289.12	1.56	295.80	1.80	296.29	1.87	<0.0001															
		V2000	414.08	98.19	505.21	66.72	298.00	9.11	294.27	3.46	321.38	56.31	300.90	2.47	<0.0001															
		V2500	868.62	153.19	895.52	152.74	546.11	164.65	462.30	119.46	640.81	233.84	469.56	134.12	<0.0001															
	20	V0500	277.42	2.29	285.61	2.42	277.46	2.08	280.21	2.44	285.64	2.25	287.69	2.98	0.5735															
		V1000	283.27	1.31	307.21	13.90	282.50	1.68	285.23	1.68	291.10	1.81	292.22	1.70	<0.0001															
		V1500	289.26	1.77	389.32	31.64	287.42	1.70	289.69	1.61	296.27	1.87	296.69	1.77	<0.0001															
		V2000	500.31	148.71	588.04	126.15	334.36	47.25	300.39	12.91	350.98	46.78	309.41	20.38	<0.0001															
		V2500	950.39	70.86	1020.8	88.75	647.63	170.37	514.87	125.7	770.53	305.72	524.14	125.87	<0.0001															
	30	V0500	277.65	2.30	285.71	2.45	277.54	2.07	280.33	2.31	285.77	2.19	287.82	2.99	0.4735															
		V1000	283.86	1.32	311.48	16.91	282.71	1.74	285.54	1.80	291.38	1.89	292.69	1.85	<0.0001															
		V1500	298.34	13.35	398.94	27.64	287.96	1.87	290.43	1.86	297.17	2.35	297.35	1.88	<0.0001															
		V2000	661.76	233.81	662.30	175.35	384.41	75.91	341.24	59.17	400.01	92.34	354.59	60.57	<0.0001															
		V2500	971.98	7.04	1063.6	64.62	699.49	117.82	585.63	79.34	949.07	256.31	591.64	78.10	<0.0001															

5.4 Safety Evaluation

Two safety MOEs selected for this study i.e. speed variance and deceleration rate are evaluated in detail in the following sections.

5.4.1 Speed Variance Analysis

As already mentioned in the literature review, crash occurrence (Taylor et al., 2000) and crash percentage (Garber and Gadiraju, 1989) increase with increase in speed variance in a particular roadway section. For that matter, speed variance has been taken as a safety surrogate measure to assess safety for all the MOT types. Tables 5.4.1 to 5.4.4 provide the detailed summary statistics for all the MOT types for each traffic demand level, compliance rate and truck percentage. To figure out the statistical difference between the speed variances of all MOT types for each combination, overall Levene's test was performed with a null hypothesis that speed variances are not significantly different from each other. In situations where the null hypothesis was rejected, pair-wise comparison of all scenarios was made using Levene's test. Furthermore, empirical cumulative distribution function (CDF) plots were created, to visualize the effect of speed reduction for each MOT type, compliance rate, truck percentage and traffic demand volume level. All these plots are attached as Appendix-A.

In order to get the better picture of speed changes in open and closed lanes, speed variances were separately analyzed in both lanes as explained in the following section.

5.4.1.1 Speed Variance in Open Lane

Tables 5.4.1 and 5.4.2 provide the detailed summary statistics for all the MOT types for each traffic demand level, compliance rate and truck percentage travelling in the open lane. It is evident from Table 5.4.1 that for lower demand volumes (V0500) and compliances of 20%, MAS has the significantly lowest speed variance for all the truck percentages in the open lane when compared to other scenarios except on one incident of C20-T10 where MAS gives significantly the highest speed variance. Speed variances under late SDLMS are the significantly lower for demand volume levels of V1000 and V1500 for compliance rate of 20% and trucks percentage of 10% and 20% of the demand volume. For the same compliance rate and for 30% trucks in demand volumes of 1,000 vph and 1,500 vph, early SDLMS and late SDLMS produced significantly lower variances respectively. For demand volume of 2,000 vph, VSL produces significantly lowest speed variances whereas for V2500, significant lower speed variances are observed under MAS, for all truck percentages at the compliance rate of 20%.

Again from Table 5.4.1, for V0500 and compliances of 40%, MAS has significantly lowest speed variance for all the truck percentages. For demand volume of 2,000 vph, speed variances under early SDLMS are significantly lowest for compliance rate of 20% and trucks percentage of 10% and 20% whereas for 30% trucks, late SDLMS produced the significantly lower variances. For the similar compliance rate, significantly lower speed variances were recorded under late SDLMS for all the truck percentages (10%, 20% and 30%) in the demand volume of 1,500 vph. For demand volume of 2,000 vph, VSL produces significantly lowest speed variances whereas for V2500, significantly lowest speed variances are observed under MAS, for all truck percentages at the compliance rate of 40%.

From Table 5.4.2, at 60% compliance rate and truck percentage of 10%, early SDLMS produces significantly smallest speed variance of all the MOT types for low and medium volume levels (V0500, V1000 and V1500). Whereas for the truck percentage of 20% an 30%, MAS resulted in significantly lower speed variance for V0500 and late SDLMS presented significantly minimum variances for V1000 and V1500. For the same compliance rate and demand volume levels of V2000 and V2500, it was found that the VSL and MAS produced significantly lowest speed variances respectively.

From Table 5.4.3, at 80% compliance rate and truck percentage of 10%, early SDLMS produces significantly minimum speed variance of all the MOT types for low and medium volume levels (V0500 and V1000).

Whereas for the truck percentage of 20% an 30%, MAS resulted in the significantly lower speed variance for V0500 and late SDLMS gave significantly minimum variances for V1000 and V1500. For the same compliance rate and demand volume levels of V2000 and V2500, it was found that the VSL and MAS produced significantly lowest speed variances respectively.

As already mentioned, the scope of this study is to evaluate the effects of combined VSL and SDLM systems. If we look at the tables 5.4.1 and 5.4.2 closely, it is obvious that the addition of VSL significantly enhances the safety of the system when the demand volume is 2,000 vph and is the second best option after MAS for demand volumes of 2,500 vph. It is also shown in the results that the addition of VSL to the already installed SDLMS (either Early or Late) made those merge systems more safer than those without VSL.

If we discard the individual performance of VSL and MAS and only compare SDLMS' with SDLMS-VSL combinations, it is clear that VSL helps in significantly decreasing the speed variances when higher volumes are involved. Tables 5.4.1 and 5.4.2 demonstrate that addition of VSL does not get much improvement in decreasing the speed variances for any compliance rate or truck percentage for low and medium demand volume levels i.e. V0500, V1000 and V1500. But for higher demand volumes like V2000 and V2500, both early SDLMS+VSL and late

SDLMS+VSL resulted in significantly lower speed variances when compared from respective SDLMS without VSL. Except for the four instances where SDLMS+VSL showed significantly higher speed variances. These are; V2000-C20-T10, V2000-C40-T10, V2500-C40-T20 and V2000-C80-T10.

Table 5.4.1: Comparison of Speed Variances in Open Lane (with Compliance 20% and 40%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Levene's Test for Pair-wise Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		MAS - VSL	MAS - EarlyDLM	MAS - LateDLM	MAS - EarlyDLM+VSL	MAS - LateDLM+VSL	VSL - EarlyDLM	VSL - LateDLM	VSL - EarlyDLM+VSL	VSL - LateDLM+VSL	EarlyDLM - LateDLM	EarlyDLM - EarlyDLM+VSL	EarlyDLM - LateDLM+VSL	LateDLM - EarlyDLM+VSL	LateDLM - LateDLM+VSL	EarlyDLM+VSL- LateDLM+VSL
			SD	SD	SD	SD	SD	SD																
20	10	V0500	5.79	5.78	2.89	2.90	5.74	5.72	<0.0001															
		V1000	3.39	6.64	3.09	2.98	5.98	5.85	<0.0001															
		V1500	7.53	25.20	5.32	4.32	9.16	6.69	<0.0001															
		V2000	19.71	8.62	25.63	26.44	25.87	26.55	<0.0001															
		V2500	1.66	1.70	15.37	15.78	13.20	14.49	<0.0001															
	20	V0500	2.85	5.81	2.90	2.90	5.75	5.71	<0.0001															
		V1000	3.42	6.79	3.11	3.03	6.09	5.87	<0.0001															
		V1500	10.20	25.24	6.49	5.09	11.11	8.18	<0.0001															
		V2000	13.35	4.52	26.15	26.58	22.21	25.19	<0.0001															
		V2500	1.82	1.85	3.48	3.47	3.47	3.46	<0.0001															
	30	V0500	2.85	5.85	2.91	2.90	5.77	5.72	<0.0001															
		V1000	3.99	7.25	3.26	3.17	6.25	5.90	<0.0001															
		V1500	25.66	21.88	9.08	6.72	12.94	9.36	<0.0001															
		V2000	8.36	3.18	22.92	24.66	19.94	21.96	<0.0001															
		V2500	2.24	2.02	3.56	3.62	3.60	3.57	<0.0001															
40	10	V0500	2.85	6.72	2.89	2.93	6.63	6.67	<0.0001															
		V1000	3.39	7.54	3.07	3.14	6.75	6.60	<0.0001															
		V1500	7.53	21.34	4.88	4.02	9.43	8.03	<0.0001															
		V2000	19.71	3.52	25.40	23.25	34.34	24.95	<0.0001															
		V2500	1.66	2.99	16.07	17.46	10.57	14.86	<0.0001															
	20	V0500	2.85	6.70	2.89	2.94	6.63	6.66	<0.0001															
		V1000	3.42	8.14	3.20	3.20	6.90	6.56	<0.0001															
		V1500	10.20	18.46	6.11	4.45	10.88	8.11	<0.0001															
		V2000	13.35	3.70	24.43	28.88	19.48	26.04	<0.0001															
		V2500	1.82	3.09	3.52	6.64	3.54	6.99	<0.0001															
	30	V0500	2.85	6.71	2.89	2.85	6.65	6.64	<0.0001															
		V1000	3.99	8.43	3.31	3.24	7.09	6.60	<0.0001															
		V1500	25.66	16.71	8.17	5.56	11.95	9.38	<0.0001															
		V2000	8.36	3.63	21.70	25.48	17.07	21.13	<0.0001															
		V2500	2.24	3.23	3.61	3.57	3.60	3.57	<0.0001															

Table 5.4.2: Comparison of Speed Variances in Open Lane (with Compliance 60% and 80%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Levene's Test for Pair-wise Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		MAS - VSL	MAS - EarlyDLM	MAS - LateDLM	MAS - EarlyDLM+VSL	MAS - LateDLM+VSL	VSL - EarlyDLM	VSL - LateDLM	VSL - EarlyDLM+VSL	VSL - LateDLM+VSL	EarlyDLM - LateDLM	EarlyDLM - EarlyDLM+VSL	EarlyDLM - LateDLM+VSL	LateDLM - EarlyDLM+VSL	LateDLM - LateDLM+VSL	EarlyDLM+VSL-LateDLM+VSL
			SD	SD	SD	SD	SD	SD																
60	10	V0500	5.79	6.37	2.88	3.01	6.54	6.54	<0.0001															
		V1000	3.39	8.31	3.03	3.18	6.12	6.17	<0.0001															
		V1500	7.53	15.12	5.1	4.64	7.92	6.6	<0.0001															
		V2000	19.71	3.65	24.83	17.99	23.02	16.7	<0.0001															
		V2500	1.66	3.25	16.22	20.28	12.62	15.99	<0.0001															
	20	V0500	2.85	6.38	2.98	3.05	6.5	6.53	<0.0001															
		V1000	3.42	9.98	3.12	3.11	6.17	6.19	<0.0001															
		V1500	10.2	13.28	6.34	4.62	9.09	6.89	<0.0001															
		V2000	13.35	3.66	27.08	24.65	18.84	20.63	<0.0001															
		V2500	1.82	3.43	9.63	19.97	8.91	16.29	<0.0001															
	30	V0500	2.85	6.47	2.98	3.05	6.49	6.48	<0.0001															
		V1000	3.99	11.29	3.31	3.16	6.31	6.14	<0.0001															
		V1500	25.66	11.68	8.08	6.19	11.22	8.2	<0.0001															
		V2000	8.36	3.7	22.66	26.8	16.88	21.71	<0.0001															
		V2500	2.24	3.53	10.72	10.69	8.22	9.12	<0.0001															
80	10	V0500	5.79	4.97	2.89	2.96	5.18	5.3	<0.0001															
		V1000	3.39	9.61	2.99	3.01	4.91	4.97	<0.0001															
		V1500	7.53	8.85	5.09	3.71	6.18	5.05	<0.0001															
		V2000	19.71	3.63	24.9	9.09	21.34	9.93	<0.0001															
		V2500	1.66	3	23.44	15.15	16	13.62	<0.0001															
	20	V0500	2.85	5.05	2.88	2.96	5.2	5.27	<0.0001															
		V1000	3.42	11.35	3.15	2.96	5.04	4.84	<0.0001															
		V1500	10.2	7.45	5.93	3.78	7.24	5.54	<0.0001															
		V2000	13.35	3.5	26.79	12.12	19.74	11.87	<0.0001															
		V2500	1.82	3.2	23.4	11.25	9.42	9.42	<0.0001															
	30	V0500	2.85	5.08	2.9	2.97	5.2	5.27	<0.0001															
		V1000	3.99	11.95	3.2	2.96	5.34	4.99	<0.0001															
		V1500	25.66	6.44	7.38	4.96	10.15	6.37	<0.0001															
		V2000	8.36	3.6	23.23	13.08	18.64	11.67	<0.0001															
		V2500	2.24	3.32	24.61	9.95	12.19	9.18	<0.0001															

5.4.1.2 Speed Variance in Closed Lane

Tables 5.4.3 and 5.4.4 provide the detailed summary statistics for all the MOT types for each traffic demand level, compliance rate and truck percentage travelling in the closed lane. It is evident from these tables, that for lower and medium demand volumes (V0500, V1000 and V1500), late SDLMS has the significantly lowest speed variance for all compliance rates and truck percentages in the closed lane when compared to other scenarios except on two occasions; V0500-C20-T30 and V1000-C60-T10, where MAS and late SDLMS+VSL gives significantly lowest speed variance respectively.

Tables 5.4.3 and 5.4.4 further reveal that for demand volume of 2,000 vph, significantly lowest speed variances were observed under VSL alone operations for all compliance rates and truck percentages. Whereas, for demand volume of 2,500 vph, MAS resulted in significantly lowest speed variances for all compliance rates and truck percentages except for compliance rate of 20% and 30% trucks.

Same as in the case of open lane, tables 5.4.3 and 5.4.4 clearly depict that the addition of VSL significantly enhances the safety of the vehicles travelling in the closed lane when traffic demand volume is 2,000 vph and is the second best option after MAS for demand volumes of 2,500 vph.

Tables 5.4.3 and 5.4.4 demonstrates that addition of VSL does not show much improvement in decreasing the speed variances for any compliance rate or truck percentage for low and medium demand volume levels i.e. V0500, V1000 and V1500. For demand volume of 2,000 vph and for any compliance rate or truck percentage, early SDLMS+VSL resulted in significantly lower speed variance when compared with early SDLMS without VSL. Similarly, late SDLMS+VSL resulted in significantly lower speed variance for all compliance rate or truck percentages when compared with late SDLMS without VSL except for on three occurrences i.e., C20-T10, C40-T10 and C80-T10, where late SDLMS+VSL showed significantly higher speed variances.

For demand volume of 2,500 vph and for any compliance rate or truck percentage, early SDLMS+VSL resulted in significantly lower speed variance except for combinations C20-T30, C60-T10, C60-T20 and C60-T30. Late SDLMS+VSL resulted in significantly lower speed variance when compared with late SDLMS without VSL for compliance rate of 80% and all truck percentages. For 60% compliance, late SDLMS without VSL performed better in terms of generating lesser speed variances than with VSL. For combinations C20-T10, C40-T20 and C40-T30 late SDLMS resulted in significantly lower variances whereas late SDLMS+VSL showed significant lower variances for the rest of combinations.

Table 5.4.3: Comparison of Speed Variances in Closed Lane (with Compliance 20% and 40%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Levene's Test for Pair-wise Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		MAS - VSL	MAS - EarlyDLM	MAS - LateDLM	MAS - EarlyDLM+VSL	MAS - LateDLM+VSL	VSL - EarlyDLM	VSL - LateDLM	VSL - EarlyDLM+VSL	VSL - LateDLM+VSL	EarlyDLM - LateDLM	EarlyDLM - EarlyDLM+VSL	EarlyDLM - LateDLM+VSL	LateDLM - EarlyDLM+VSL	LateDLM - LateDLM+VSL	EarlyDLM+VSL-LateDLM+VSL
			SD	SD	SD	SD	SD	SD																
20	10	V0500	2.57	3.92	2.63	2.46	4.78	2.72	<0.0001															
		V1000	4.66	7.20	3.68	2.94	5.76	3.45	<0.0001															
		V1500	11.02	24.69	7.25	5.44	9.16	5.98	<0.0001															
		V2000	18.24	9.12	26.32	27.28	25.19	27.35	<0.0001															
		V2500	1.69	1.78	13.82	13.56	12.03	13.64	<0.0001															
	20	V0500	2.56	3.97	2.76	2.49	4.84	2.71	<0.0001															
		V1000	5.26	7.85	3.83	3.07	6.55	3.46	<0.0001															
		V1500	13.89	24.27	9.03	6.85	14.27	9.34	<0.0001															
		V2000	12.10	5.71	23.46	23.96	20.51	23.83	<0.0001															
		V2500	1.80	1.91	3.61	3.61	3.60	3.61	<0.0001															
	30	V0500	2.52	4.20	2.81	2.60	4.70	2.84	<0.0001															
		V1000	6.43	9.09	3.91	3.06	7.34	3.78	<0.0001															
		V1500	25.80	21.97	12.32	9.05	16.21	11.21	<0.0001															
		V2000	8.32	4.05	20.10	21.77	18.03	20.10	<0.0001															
		V2500	2.26	2.05	3.73	3.74	3.75	3.75	<0.0001															
40	10	V0500	2.57	4.31	2.62	1.91	6.35	2.31	<0.0001															
		V1000	4.66	7.79	3.58	2.69	7.14	3.01	<0.0001															
		V1500	11.02	21.34	6.92	4.71	11.51	8.12	<0.0001															
		V2000	18.24	5.45	25.73	26.12	23.69	26.99	<0.0001															
		V2500	1.69	3.94	14.38	14.35	10.80	13.82	<0.0001															
	20	V0500	2.56	4.20	2.62	1.91	6.46	2.62	<0.0001															
		V1000	5.26	8.65	3.82	2.60	7.59	3.06	<0.0001															
		V1500	13.89	20.00	8.73	5.73	13.26	8.11	<0.0001															
		V2000	12.10	5.18	21.68	27.57	19.03	26.67	<0.0001															
		V2500	1.80	4.04	3.62	5.91	3.61	7.11	<0.0001															
	30	V0500	2.52	4.26	2.71	1.98	6.53	2.34	<0.0001															
		V1000	6.43	9.32	4.10	2.78	7.89	3.56	<0.0001															
		V1500	25.80	18.36	11.24	7.40	14.28	10.50	<0.0001															
		V2000	8.32	4.91	19.04	21.34	15.85	19.17	<0.0001															
		V2500	2.26	4.11	3.71	3.69	3.67	3.82	<0.0001															

Table 5.4.4: Comparison of Speed Variances in Closed Lane (with Compliance 60% and 80%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Levene's Test for Pair-wise Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		MAS - VSL	MAS - EarlyDLM	MAS - LateDLM	MAS - EarlyDLM+VSL	MAS - LateDLM+VSL	VSL - EarlyDLM	VSL - LateDLM	VSL - EarlyDLM+VSL	VSL - LateDLM+VSL	EarlyDLM - LateDLM	EarlyDLM - EarlyDLM+VSL	EarlyDLM - LateDLM+VSL	LateDLM - EarlyDLM+VSL	LateDLM - LateDLM+VSL	EarlyDLM+VSL- LateDLM+VSL
			SD	SD	SD	SD	SD	SD																
60	10	V0500	2.57	4.44	2.69	1.49	6.62	2.11	<0.0001															
		V1000	4.66	9.2	3.34	2.34	6.93	2.2	<0.0001															
		V1500	11.02	18.69	7.41	5.17	10.07	5.93	<0.0001															
		V2000	18.24	6.05	25.47	19.26	22.6	18.56	<0.0001															
		V2500	1.69	4.72	17.02	15.17	21.22	19.77	<0.0001															
	20	V0500	2.56	4.22	3.21	1.74	6.8	2.12	<0.0001															
		V1000	5.26	11.39	3.79	1.81	7.32	2.38	<0.0001															
		V1500	13.89	17.23	9.13	5.33	12.2	6.75	<0.0001															
		V2000	12.1	5.72	24.98	23.69	18.84	23.64	<0.0001															
		V2500	1.8	4.78	12.24	14.18	22.59	19.73	<0.0001															
	30	V0500	2.52	4.92	3.24	1.66	6.85	2.12	<0.0001															
		V1000	6.43	12.81	3.92	1.92	7.77	2.63	<0.0001															
		V1500	25.8	15.88	11.11	7.56	13.58	9.24	<0.0001															
		V2000	8.32	5.48	20.17	24.61	17.49	23.47	<0.0001															
		V2500	2.26	4.8	14.17	8.84	21.88	22.59	<0.0001															
80	10	V0500	2.57	6.06	2.58	0.82	5.82	2.78	<0.0001															
		V1000	4.66	10.98	3.25	1.43	6.39	2.1	<0.0001															
		V1500	11.02	15.74	7.36	3.48	8.28	4.29	<0.0001															
		V2000	18.24	6	25.7	9.02	21.98	10.43	<0.0001															
		V2500	1.69	4.3	20.44	17.65	25.12	13.72	<0.0001															
	20	V0500	2.56	5.93	2.6	0.81	5.9	2.76	<0.0001															
		V1000	5.26	12.98	3.69	1.31	6.51	2.35	<0.0001															
		V1500	13.89	14.93	8.68	3.5	9.65	5.1	<0.0001															
		V2000	12.1	5.12	24.66	12.23	18.66	12.13	<0.0001															
		V2500	1.8	4.38	24.66	11.73	24.75	1.11	<0.0001															
	30	V0500	2.52	6.29	2.81	0.74	6.15	2.7	<0.0001															
		V1000	6.43	14.95	4.14	1.94	3.36	2.59	<0.0001															
		V1500	25.8	13.38	10.31	5.22	12.79	6.7	<0.0001															
		V2000	8.32	5.09	19.98	13.28	18.99	11.82	<0.0001															
		V2500	2.26	4.46	20.55	10.33	14.36	9.02	<0.0001															

An empirical distribution function or cumulative distribution function (CDF) plots of speed for various demand volume levels, compliance rates and truck percentages are plotted and attached as Appendix-A. These plots show that 40% to 90% vehicles travelling under integrated SDLMS and VSL reduce their respective speeds from compliance of 20% to 80% for almost all the truck percentages and traffic demand levels. This gradual reduction in speed indicates lesser sudden braking in the work zone which can pose a safety hazard. For lower and medium volume levels (V0500, V1000 and V1500), it s clearly evident (from Appendix A) that addition of VSL shifts the distribution of the speed towards the left, thus, helping in lowering the speed of vehicles within the system.

Cumulative distribution of speed for V2000 and V2500 in both open and closed lane is shown in figure 5.4.1 and 5.4.2, respectively. Only two combinations for each lane i.e. compliance rate 20% and 80% and 10% trucks, has been taken from Appendix-A for illustration. It is obvious from both graphs that speed distribution is more smoothen for integrated SDLMS+VSL than their individual controls. An abrupt drop in speed may lead to critical real end crashes in cases of early and late SDLMS. It is also revealed from these plots that with increase in compliance rate, VSL helps in decreasing the slope of the distribution curve for the integrated systems.

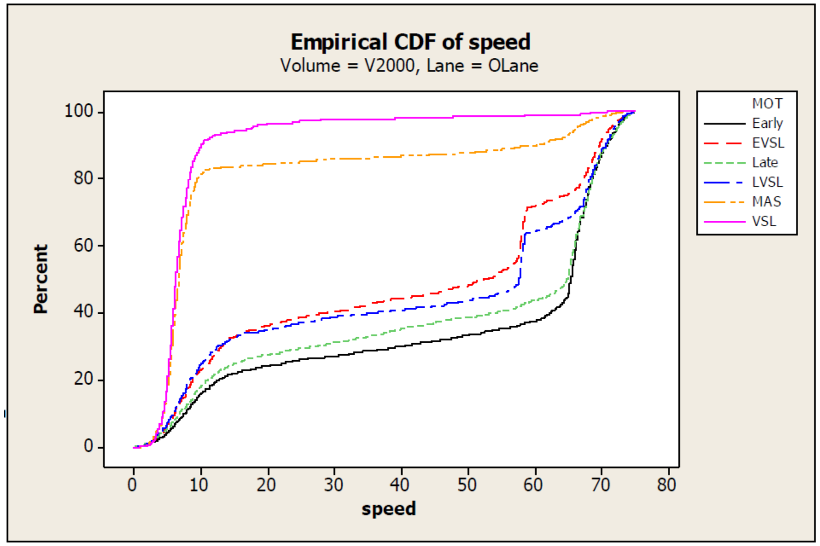
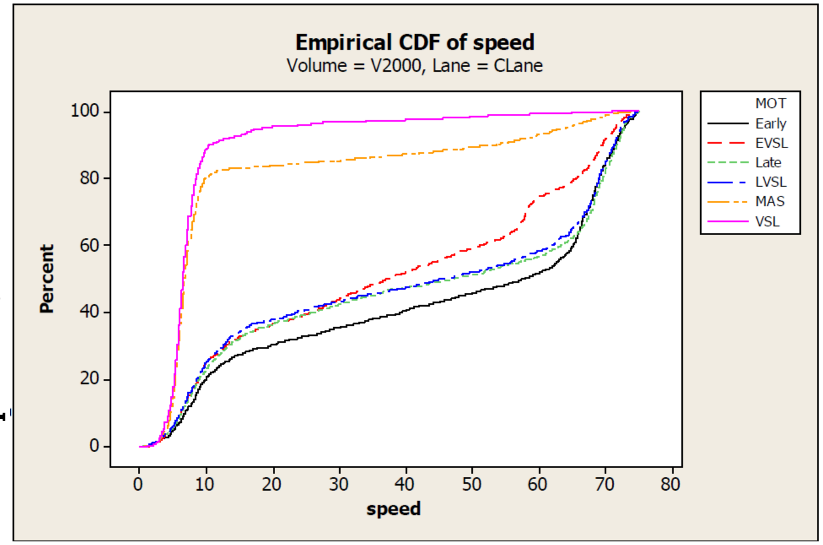
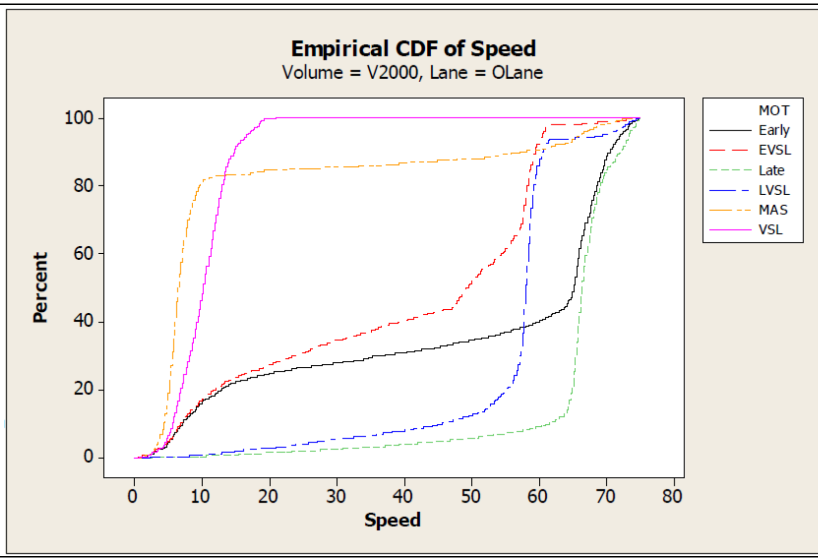
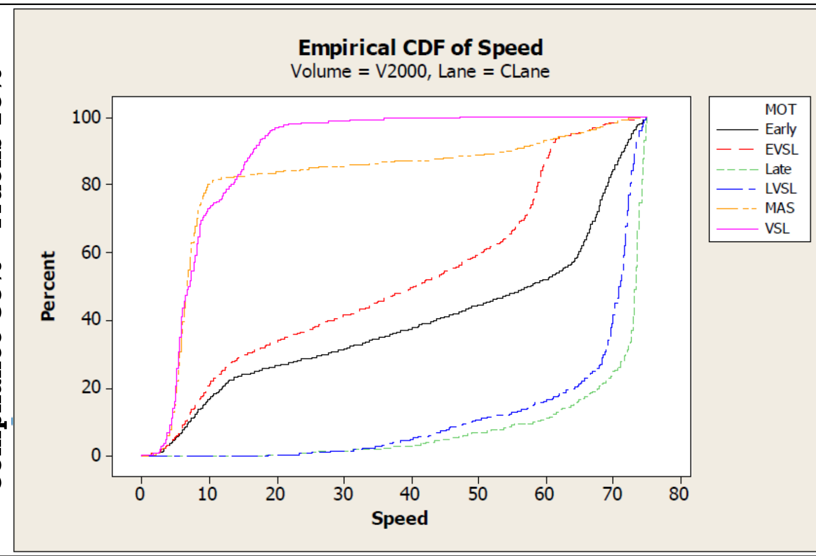
	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 20% - Trucks 10%		
Compliance 80% - Trucks 10%		

Figure 5.4.1: Empirical CDF Plots of Speed for Demand Volume V2000

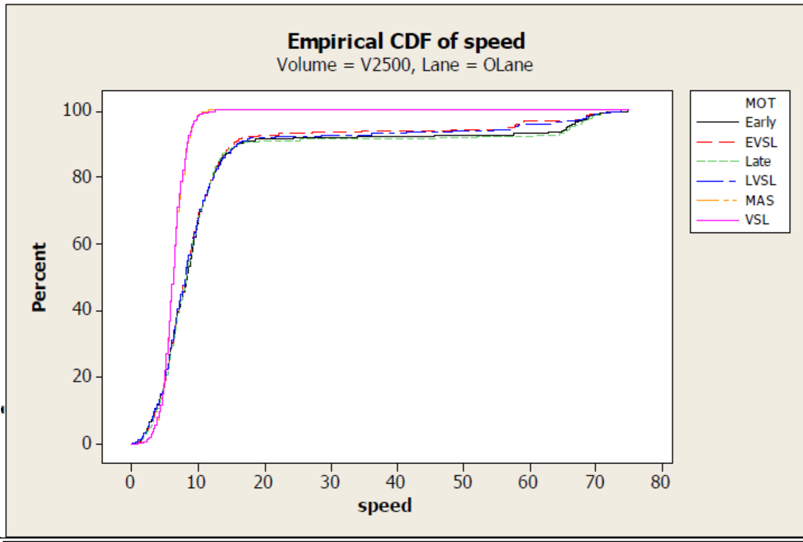
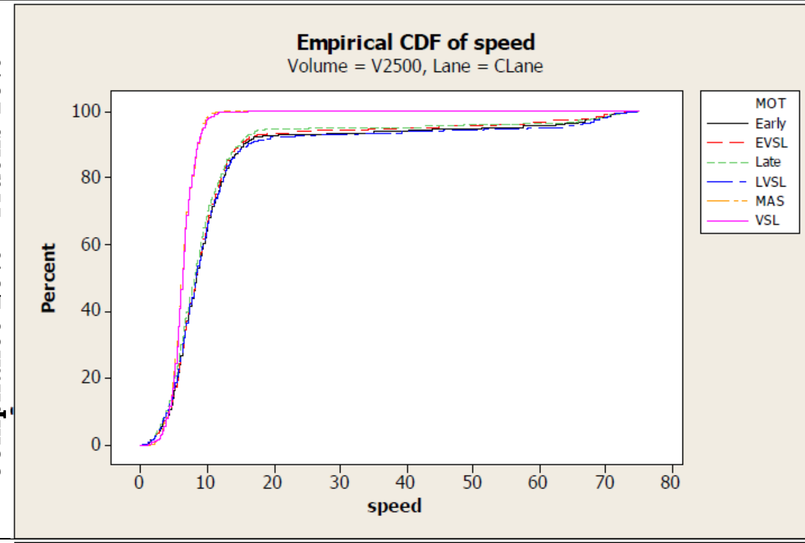
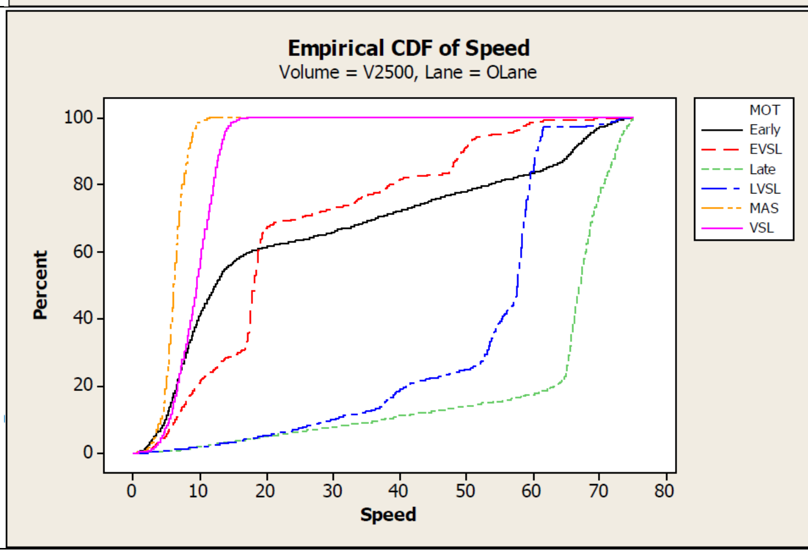
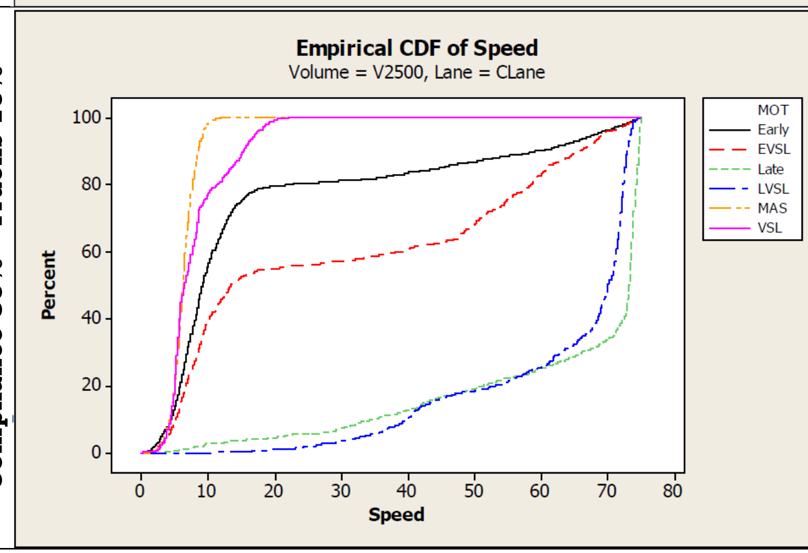
	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH
Compliance 20% - Trucks 10%		
Compliance 80% - Trucks 10%		

Figure 5.4.2: Empirical CDF Plots of Speed for Demand Volume V2500

5.4.2 Deceleration Rate Analysis

Acceleration is the change in velocity over time. When a negative increase in acceleration is observed, it is referred to as Deceleration. Rapid braking to reduce the speed results in higher deceleration rates. Lower the deceleration rate, safer is the network. A gradual decrease in deceleration, helps in maintaining a smooth flow of traffic through the work zone. For that matter, deceleration rate was another safety surrogate measure (Gettman and Head, 2003) selected for this study. Generally, a higher deceleration rate is more likely to lead to a rear-end crash (Yan et al., 2007). Tables 5.4.5 to 5.4.6 provide the detailed summary statistics for all the MOT types for each traffic demand level, compliance rate and truck percentage. To figure out the statistical difference between the deceleration rates of all MOT types for each combination, overall Levene's test was performed with a null hypothesis that deceleration rates are not significantly different from each other. In situations where the null hypothesis was rejected, pair-wise Tukey's comparisons are completed to determine the difference between each pair of deceleration rates. Moreover, empirical cumulative distribution function (CDF) plots were created, to visualize the effect of deceleration for each MOT type, compliance rate, truck percentage and traffic demand volume level. All these plots are attached as Appendix-B. Deceleration rates were separately analyzed in both lanes as explained in the following section.

5.4.2.1 Deceleration Rate in Open Lane

Tables 5.4.5 and 5.4.6 provide the detailed summary statistics for all the MOT types for each traffic demand level, compliance rate and truck percentage travelling in the open lane. It is evident from Table 5.4.5 that for demand volumes levels of V0500, V1000 and V1500, significantly lower deceleration rates were observed under late SDLMS for all compliance rates (20%,40%, 60% and 80%) and truck percentages in the traffic stream (10%, 20% and 30%). Except for the three instances: V0500-C20-T10 where early SDLMS was significantly lower whereas deceleration was significantly lowest under VSL for both V1500-C60-T30 and V1500-C80-T30, when compared to other MOT types.

From table 5.4.5, for compliance of 20% and tuck percentages 10%, 20% and 30%, deceleration means were significantly lower for higher volumes (V2000 and V2500) under VSL operations. From the same table but 40% compliance, MAS has significantly lowest deceleration rate for all the truck percentages for demand volumes of 2,000 vph and 2,500 vph except for 10% truck and V2000.

From Table 5.4.6, at 60% compliance, MAS has significantly lowest deceleration rate for truck percentages of 20% and 30% for demand volumes of 2,000 vph and 2,500 vph. For 10% trucks and demand volume levels of V2000 and V2500, VSL and MAS produced significantly smallest deceleration means, respectively. At 80% compliance and demand volume of 2,000 vph, lowest significant means were resulted under VSL for 10% and 30% trucks. For 20% trucks, MAS had the lowest significant deceleration means. Similarly, for demand volume of 2,500 vph, lowest significant means were resulted under MAS for 10% and 20% trucks but for 30% trucks, early SDLMS with VSL had the lowest significant deceleration means.

Likewise, speed variance analysis, the scope of this study is to evaluate the effects of combined VSL and SDLM systems. Again if we look at the tables 5.4.5 and 5.4.6 closely, it is obvious that the addition of VSL significantly enhances the safety of the system when the demand volume is 2,000 vph (except for C80-T30) and is the second best option after MAS for demand volumes of 2,500 vph in most cases.

If we only consider SDLMS' and SDLMS-VSL combinations, it is observed that VSL helps in significantly decreasing the deceleration near the taper when higher volumes are involved. Tables 5.4.5 and 5.4.6 demonstrate that addition of VSL does not get much improvement in lowering deceleration for any compliance rate or truck percentage for low and medium demand volume levels i.e. V0500, V1000 and V1500. But for demand volume level of V2000, introduction of VSL to SDLMS' improved the drop in deceleration rate when truck percentage was 30%. For demand volume level of V2500, early SDLMS+VSL resulted in significantly lower deceleration means than early SDLMS without VSL except on one occasion where early SDLMS+VSL showed significantly higher deceleration mean. However, late SDLMS+VSL resulted in significantly lower deceleration means than late SDLMS without VSL except at compliance rate of 80%.

Table 5.4.5: Comparison of Deceleration Rates in Open Lane (with Compliance 20% and 40%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Tukey's Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		μ_{MAS}-μ_{VSL}	μ_{MAS}-$\mu_{EarlyDLM}$	μ_{MAS}-$\mu_{LateDLM}$	μ_{MAS}-$\mu_{EarlyDLM+VSL}$	μ_{MAS}-$\mu_{LateDLM+VSL}$	μ_{VSL}-$\mu_{EarlyDLM}$	μ_{VSL}-$\mu_{LateDLM}$	μ_{VSL}-$\mu_{EarlyDLM+VSL}$	μ_{VSL}-$\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}$-$\mu_{LateDLM}$	$\mu_{EarlyDLM}$-$\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}$-$\mu_{LateDLM+VSL}$	$\mu_{LateDLM}$-$\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}$-$\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}$-$\mu_{LateDLM+VSL}$
			Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)																
20	10	V0500	-2.29	-3.14	-1.75	-1.77	-2.78	-2.83	<0.0001															
		V1000	-3.51	-4.19	-2.31	-2.20	-2.87	-2.81	<0.0001															
		V1500	-5.08	-5.10	-3.12	-2.90	-3.82	-3.30	<0.0001															
		V2000	-2.80	-1.63	-4.80	-4.97	-5.41	-5.09	<0.0001															
		V2500	-1.19	-1.17	-3.67	-3.46	-3.49	-3.60	<0.0001															
	20	V0500	-2.33	-3.19	-1.88	-1.85	-2.81	-2.85	<0.0001															
		V1000	-3.53	-4.27	-2.41	-2.27	-2.96	-2.84	<0.0001															
		V1500	-5.39	-4.25	-3.41	-3.20	-4.14	-3.61	<0.0001															
		V2000	-2.15	-1.48	-4.03	-4.05	-4.45	-4.05	<0.0001															
		V2500	-1.39	-1.32	-3.28	-3.34	-3.28	-3.27	<0.0001															
	30	V0500	-2.52	-3.27	-1.90	-1.82	-2.88	-2.90	<0.0001															
		V1000	-3.91	-4.37	-2.63	-2.52	-3.09	-2.95	<0.0001															
		V1500	-5.65	-3.54	-3.76	-3.51	-4.47	-3.84	<0.0001															
		V2000	-2.25	-1.58	-4.11	-4.08	-4.09	-3.92	<0.0001															
		V2500	-1.87	-1.52	-3.40	-3.49	-3.43	-3.47	<0.0001															
40	10	V0500	-2.29	-3.22	-1.70	-1.42	-2.97	-2.85	<0.0001															
		V1000	-3.51	-4.35	-2.30	-1.95	-3.08	-2.90	<0.0001															
		V1500	-5.08	-3.63	-3.08	-2.64	-4.06	-3.50	<0.0001															
		V2000	-2.80	-1.92	-5.09	-4.80	-5.19	-4.90	<0.0001															
		V2500	-1.19	-1.97	-3.54	-3.66	-3.53	-3.56	<0.0001															
	20	V0500	-2.33	-3.35	-1.72	-1.46	-2.98	-2.88	<0.0001															
		V1000	-3.53	-4.48	-2.38	-2.12	-3.26	-2.98	<0.0001															
		V1500	-5.39	-3.46	-3.35	-2.88	-4.37	-3.68	<0.0001															
		V2000	-2.15	-2.15	-4.10	-4.19	-4.25	-4.45	<0.0001															
		V2500	-1.39	-2.12	-3.31	-3.45	-3.27	-3.36	<0.0001															
	30	V0500	-2.52	-3.30	-1.91	-1.55	-3.03	-2.88	<0.0001															
		V1000	-3.91	-4.60	-2.52	-2.26	-3.37	-3.06	<0.0001															
		V1500	-5.65	-3.25	-3.68	-3.25	-4.58	-3.79	<0.0001															
		V2000	-2.25	-2.34	-4.10	-3.97	-4.04	-3.98	<0.0001															
		V2500	-1.87	-2.35	-3.51	-3.37	-3.45	-3.37	<0.0001															

Table 5.4.6: Comparison of Deceleration Rates in Open Lane (with Compliance 60% and 80%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Tukey's Comparison n														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		$\mu_{MAS}-\mu_{VSL}$	$\mu_{MAS}-\mu_{EarlyDLM}$	$\mu_{MAS}-\mu_{LateDLM}$	$\mu_{MAS}-\mu_{EarlyDLM+VSL}$	$\mu_{MAS}-\mu_{LateDLM+VSL}$	$\mu_{VSL}-\mu_{EarlyDLM}$	$\mu_{VSL}-\mu_{LateDLM}$	$\mu_{VSL}-\mu_{EarlyDLM+VSL}$	$\mu_{VSL}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM}$	$\mu_{EarlyDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM+VSL}$	$\mu_{LateDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}-\mu_{LateDLM+VSL}$
			Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)																
60	10	V0500	-2.29	-2.87	-1.69	-1.20	-2.93	-2.45	<0.0001															
		V1000	-3.51	-3.75	-2.25	-1.75	-3.04	-2.40	<0.0001															
		V1500	-5.08	-3.10	-3.10	-2.50	-3.65	-3.09	<0.0001															
		V2000	-2.80	-2.45	-4.99	-4.43	-5.16	-4.38	<0.0001															
		V2500	-1.19	-2.76	-4.25	-3.71	-3.25	-3.32	<0.0001															
	20	V0500	-2.33	-2.93	-1.84	-1.33	-2.94	-2.52	<0.0001															
		V1000	-3.53	-3.91	-2.46	-1.85	-3.15	-2.51	<0.0001															
		V1500	-5.39	-2.97	-3.40	-2.72	-4.13	-3.15	<0.0001															
		V2000	-2.15	-2.80	-4.22	-5.22	-4.08	-5.02	<0.0001															
		V2500	-1.39	-3.60	-4.28	-3.77	-2.88	-3.57	<0.0001															
	30	V0500	-2.52	-3.03	-1.96	-1.34	-3.01	-2.57	<0.0001															
		V1000	-3.91	-4.03	-2.62	-2.06	-3.25	-2.56	<0.0001															
		V1500	-5.65	-2.96	-3.66	-3.11	-4.33	-3.37	<0.0001															
		V2000	-2.25	-3.14	-4.02	-5.09	-3.93	-4.50	<0.0001															
		V2500	-1.87	-3.22	-4.60	-2.77	-2.64	-2.77	<0.0001															
80	10	V0500	-2.29	-2.26	-1.69	-1.08	-2.67	-1.80	<0.0001															
		V1000	-3.51	-3.09	-2.33	-1.46	-2.67	-1.85	<0.0001															
		V1500	-5.08	-2.26	-3.07	-2.21	-3.47	-2.41	<0.0001															
		V2000	-2.80	-2.45	-4.92	-3.47	-4.96	-3.58	<0.0001															
		V2500	-1.19	-2.71	-5.56	-4.29	-2.69	-4.36	<0.0001															
	20	V0500	-2.33	-2.39	-1.71	-1.15	-2.63	-1.90	<0.0001															
		V1000	-3.53	-3.14	-2.48	-1.54	-2.84	-1.93	<0.0001															
		V1500	-5.39	-2.34	-3.43	-2.25	-3.67	-2.59	<0.0001															
		V2000	-2.15	-2.98	-4.29	-3.76	-4.07	-3.96	<0.0001															
		V2500	-1.39	-3.04	-5.47	-3.52	-1.76	-3.81	<0.0001															
	30	V0500	-2.52	-2.49	-1.77	-1.21	-2.71	-1.95	<0.0001															
		V1000	-3.91	-3.24	-2.62	-1.64	-3.00	-2.06	<0.0001															
		V1500	-5.65	-2.38	-3.80	-2.53	-4.07	-2.88	<0.0001															
		V2000	-2.25	-3.32	-4.57	-3.90	-3.80	-4.17	<0.0001															
		V2500	-1.87	-3.51	-5.64	-3.67	-1.28	-3.73	<0.0001															

5.4.2.2 Deceleration Rate in Closed Lane

Tables 5.4.7 and 5.4.8 provide the detailed summary statistics of deceleration means for all the MOT types for each traffic demand level, compliance rate and truck percentage travelling in the closed lane. From table 5.4.7, one can see that for demand volume level of V0500, at 20% compliance and 10% trucks, late SDLMS resulted in significantly lower deceleration means whereas for 20% and 30% trucks, significantly lower deceleration means were recorded for early SDLMS. For a demand level of V1000 and V1500, late SDLMS showed significantly lower deceleration means for all truck percentages while VSL showed significantly lower deceleration means for all truck percentages for demand volume of 2,000 vph. Under MAS, lower significant means were observed for demand volume of 2,500 vph for truck percentages of 10% and 20 However, for 30% trucks, significantly lower deceleration means resulted under VSL.

Table 5.4.7 further showed that, at 40% compliance, late SDLMS resulted in significantly lower deceleration means for demand volume levels of V0500, V1000 and V1500. For the same compliance rate, lower significant means were observed under VSL for demand volume of 2,000 vph for truck percentages of 10% and 20%. However, for 30% trucks, MAS resulted in significantly lower deceleration means, while MAS also showed significantly lower deceleration means for all truck percentages for demand volume of 2,500 vph.

From table 5.4.8, it is shown that, at 60% compliance, late SDLMS resulted in significantly lower deceleration means for demand volume levels of V0500, V1000 and V1500 except for one incident i.e. V0500-C60-T10, where early SDLMS gave the lowest significant means. For the same compliance rate, lower significant means were observed under MAS for demand volume of 2,000 vph for truck percentages of 20% and 30% However, for 10% trucks, MAS resulted in significantly lower deceleration means. For demand volume of 2,500 vph, MAS again showed significantly lower deceleration means for all truck percentages.

From table 5.4.8, at 80% compliance and all percentages of trucks, early SDLMS resulted in significantly lower deceleration means for demand volume level of V0500. For a demand level of V1000 and V1500, late SDLMS showed significantly lower deceleration means for all truck percentages. Under MAS, lower significant means were observed for demand volume levels of V2000 and V2500 for all truck percentages except for V2000 and 10% trucks where significantly lower deceleration means resulted under VSL.

As previously discussed, if we only consider SDLMS' and SDLMS-VSL combinations, it is observed that VSL helps in significantly decreasing the deceleration near the taper when higher volumes are involved in the closed lane. Tables 5.4.7 and 5.4.8 demonstrate that addition of VSL does not get much improvement in lowering deceleration for any compliance rate or truck percentage for low and medium demand volume levels i.e. V0500, V1000 and V1500. But for demand volume level of V2000 and V2500, introduction of VSL to SDLMS' improved the drop in deceleration in the closed lane only on few occasions.

CDF plots of deceleration for various demand volume levels, compliance rates and truck percentages are also plotted and attached as Appendix-B. These plots show that for lower and medium volume levels (V0500, V1000 and V1500, deceleration drop for vehicles travelling under integrated SDLMS and VSL is more gradual than other MOT types on most occasions. This gradual reduction in deceleration rate enhances the safety through the work zone. CDF of deceleration for V2000 and V2500 in both open and closed lane is shown in figure 5.4.3 and 5.4.4, respectively. Only two combinations for each lane i.e. compliance rate 20% and 80% and 10% trucks, has been taken from Appendix-B for illustration. It is shown from both graphs that distribution of deceleration shifts to right with increasing compliance rates, depicting lesser deceleration at already reduced speeds of the vehicles travelling in both open and closed lanes. As compared to the integrated SDLMS+VSL, their individual controls have higher deceleration rates for higher travelling speeds than integrated SDLMS+VSL.

Table 5.4.7: Comparison of Deceleration Rates in Closed Lane (with Compliance 20% and 40%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Tukey's Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		$\mu_{MAS}-\mu_{VSL}$	$\mu_{MAS}-\mu_{EarlyDLM}$	$\mu_{MAS}-\mu_{LateDLM}$	$\mu_{MAS}-\mu_{EarlyDLM+VSL}$	$\mu_{MAS}-\mu_{LateDLM+VSL}$	$\mu_{VSL}-\mu_{EarlyDLM}$	$\mu_{VSL}-\mu_{LateDLM}$	$\mu_{VSL}-\mu_{EarlyDLM+VSL}$	$\mu_{VSL}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM}$	$\mu_{EarlyDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}-\mu_{LateDLM+VSL}$	$\mu_{LateDLM}-\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}-\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}-\mu_{LateDLM+VSL}$
			Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)																
20	10	V0500	-3.25	-4.99	-1.45	-1.44	-2.92	-2.71	<0.0001															
		V1000	-5.00	-6.48	-2.62	-2.32	-3.41	-3.07	<0.0001															
		V1500	-7.14	-7.25	-4.39	-3.58	-5.44	-4.04	<0.0001															
		V2000	-3.42	-1.94	-6.15	-6.12	-6.98	-6.22	<0.0001															
		V2500	-1.13	-1.16	-3.75	-3.55	-3.71	-3.76	<0.0001															
	20	V0500	-3.33	-5.06	-1.52	-1.59	-3.01	-2.80	<0.0001															
		V1000	-5.25	-6.68	-2.94	-2.48	-3.78	-3.25	<0.0001															
		V1500	-7.45	-6.15	-4.94	-4.08	-5.88	-4.54	<0.0001															
		V2000	-2.43	-1.68	-4.60	-4.57	-4.88	-4.72	<0.0001															
		V2500	-1.31	-1.31	-3.27	-3.32	-3.29	-3.25	<0.0001															
	30	V0500	-3.65	-5.25	-1.55	-1.84	-2.99	-2.99	<0.0001															
		V1000	-5.76	-6.92	-2.99	-2.57	-4.12	-3.45	<0.0001															
		V1500	-7.31	-5.12	-5.39	-4.55	-6.41	-4.95	<0.0001															
		V2000	-2.33	-1.66	-4.43	-4.27	-4.53	-4.38	<0.0001															
		V2500	-1.81	-1.49	-3.42	-3.41	-3.40	-3.43	<0.0001															
40	10	V0500	-3.25	-5.71	-1.46	-1.46	-2.88	-2.85	<0.0001															
		V1000	-5.00	-7.34	-2.58	-2.23	-3.82	-3.27	<0.0001															
		V1500	-7.14	-6.25	-4.42	-3.26	-5.93	-4.35	<0.0001															
		V2000	-3.42	-2.21	-6.62	-6.07	-6.42	-6.42	<0.0001															
		V2500	-1.13	-2.01	-3.81	-3.75	-3.86	-3.89	<0.0001															
	20	V0500	-3.33	-5.98	-1.55	-1.52	-3.14	-2.99	<0.0001															
		V1000	-5.25	-7.69	-2.83	-2.40	-4.18	-3.49	<0.0001															
		V1500	-7.45	-5.67	-4.89	-3.54	-6.40	-4.67	<0.0001															
		V2000	-2.43	-2.23	-4.61	-4.78	-4.99	-5.59	<0.0001															
		V2500	-1.31	-2.12	-3.36	-3.46	-3.27	-3.43	<0.0001															
	30	V0500	-3.65	-6.19	-1.92	-1.62	-3.37	-3.14	<0.0001															
		V1000	-5.76	-7.96	-3.05	-2.34	-4.55	-3.69	<0.0001															
		V1500	-7.31	-5.31	-5.19	-3.98	-6.68	-5.03	<0.0001															
		V2000	-2.33	-2.42	-4.64	-4.19	-4.59	-4.46	<0.0001															
		V2500	-1.81	-2.26	-3.46	-3.41	-3.43	-3.43	<0.0001															

Table 5.4.8: Comparison of Deceleration Rates in Closed Lane (with Compliance 60% and 80%)

Compliance(%)	Trucks (%)	Volume (vph)	Statistical Summary						Levene's Test P-value (P_r>F)	Tukey's Comparison														
			MAS	VSL	EarlyDLM	LateDLM	EarlyDLM + VSL	LateDLM + VSL		μ_{MAS}-μ_{VSL}	μ_{MAS}-$\mu_{EarlyDLM}$	μ_{MAS}-$\mu_{LateDLM}$	μ_{MAS}-$\mu_{EarlyDLM+VSL}$	μ_{MAS}-$\mu_{LateDLM+VSL}$	μ_{VSL}-$\mu_{EarlyDLM}$	μ_{VSL}-$\mu_{LateDLM}$	μ_{VSL}-$\mu_{EarlyDLM+VSL}$	μ_{VSL}-$\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM}$-$\mu_{LateDLM}$	$\mu_{EarlyDLM}$-$\mu_{EarlyDLM+VSL}$	$\mu_{EarlyDLM}$-$\mu_{LateDLM+VSL}$	$\mu_{LateDLM}$-$\mu_{EarlyDLM+VSL}$	$\mu_{LateDLM}$-$\mu_{LateDLM+VSL}$	$\mu_{EarlyDLM+VSL}$-$\mu_{LateDLM+VSL}$
			Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)	Mean (μ)																
60	10	V0500	-3.25	-6.19	-1.45	-1.55	-3.07	-3.28	<0.0001															
		V1000	-5.00	-8.35	-2.57	-2.00	-3.73	-3.51	<0.0001															
		V1500	-7.14	-6.46	-4.36	-3.05	-5.10	-4.37	<0.0001															
		V2000	-3.42	-2.76	-6.62	-6.13	-6.48	-6.55	<0.0001															
		V2500	-1.13	-2.58	-5.48	-4.78	-7.00	-6.87	<0.0001															
	20	V0500	-3.33	-6.54	-1.57	-1.53	-3.39	-3.37	<0.0001															
		V1000	-5.25	-8.84	-2.60	-1.95	-4.00	-3.64	<0.0001															
		V1500	-7.45	-6.06	-4.75	-3.22	-5.69	-4.54	<0.0001															
		V2000	-2.43	-2.71	-5.22	-7.78	-4.82	-8.02	<0.0001															
		V2500	-1.31	-2.60	-5.66	-4.44	-7.90	-6.25	<0.0001															
	30	V0500	-3.65	-6.75	-1.70	-1.44	-3.51	-3.48	<0.0001															
		V1000	-5.76	-9.21	-2.85	-2.26	-4.28	-3.91	<0.0001															
		V1500	-7.31	-5.61	-5.16	-3.60	-6.17	-4.87	<0.0001															
		V2000	-2.33	-2.77	-4.67	-7.76	-5.24	-8.07	<0.0001															
		V2500	-1.81	-2.75	-6.31	-4.11	-9.11	-6.93	<0.0001															
80	10	V0500	-3.25	-6.51	-1.36	-1.56	-2.61	-3.38	<0.0001															
		V1000	-5.00	-8.88	-2.33	-1.91	-3.31	-3.81	<0.0001															
		V1500	-7.14	-6.31	-4.34	-2.79	-4.64	-4.45	<0.0001															
		V2000	-3.42	-2.57	-6.39	-3.77	-6.17	-5.40	<0.0001															
		V2500	-1.13	-2.40	-5.56	-5.14	-6.00	-5.80	<0.0001															
	20	V0500	-3.33	-6.71	-1.44	-1.53	-2.87	-3.48	<0.0001															
		V1000	-5.25	-9.02	-2.82	-1.84	-3.76	-3.99	<0.0001															
		V1500	-7.45	-5.63	-4.76	-2.91	-5.11	-4.57	<0.0001															
		V2000	-2.43	-2.48	-4.97	-4.58	-4.60	-5.96	<0.0001															
		V2500	-1.31	-2.46	-5.19	-4.13	-7.05	-4.88	<0.0001															
	30	V0500	-3.65	-6.97	-1.57	-1.57	-3.01	-3.54	<0.0001															
		V1000	-5.76	-8.84	-3.13	-2.17	-4.12	-4.15	<0.0001															
		V1500	-7.31	-5.02	-5.31	-3.11	-5.67	-4.76	<0.0001															
		V2000	-2.33	-2.50	-4.81	-4.84	-4.82	-5.81	<0.0001															
		V2500	-1.81	-2.50	-5.63	-3.81	-8.41	-5.05	<0.0001															

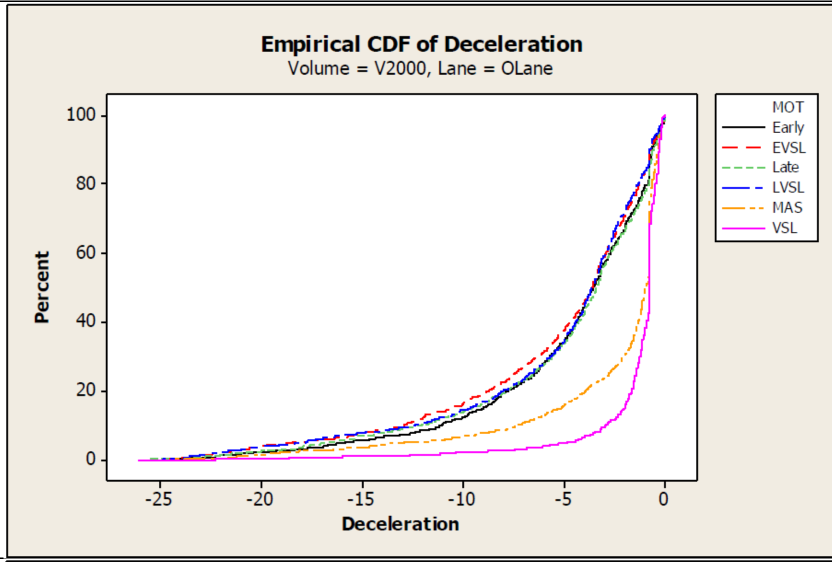
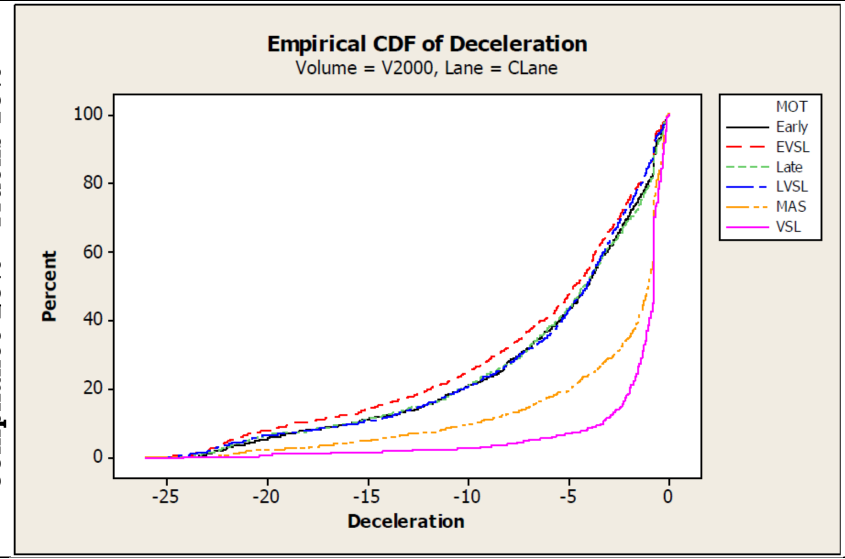
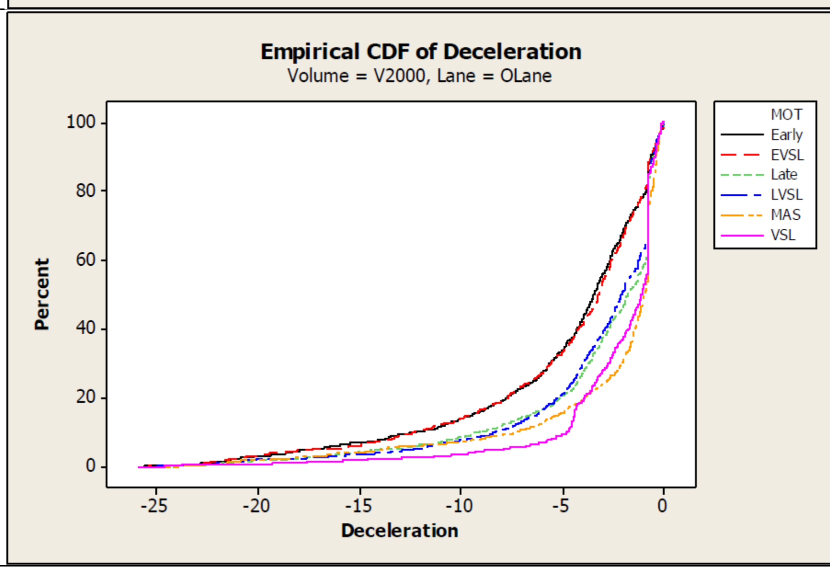
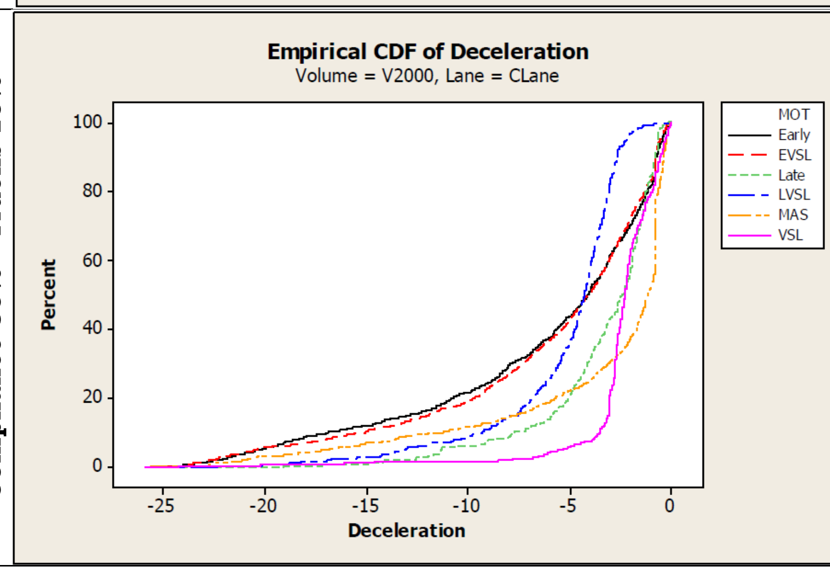
	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 20% - Trucks 10%		
Compliance 80% - Trucks 10%		

Figure 5.4.3: Empirical CDF Plots of Deceleration for Demand Volume V2000

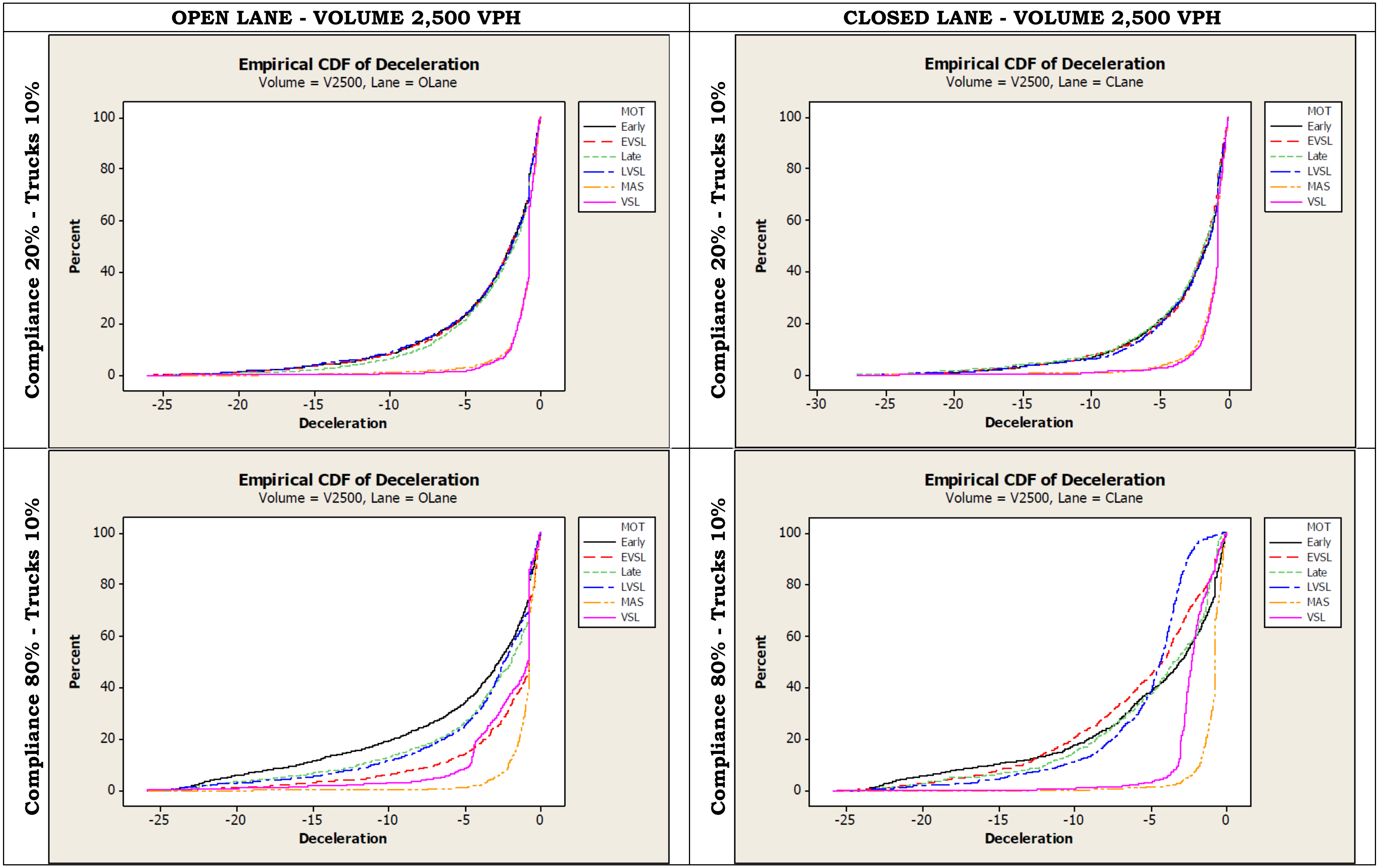


Figure 5.4.4: Empirical CDF Plots of Deceleration for Demand Volume V2500

5.5 Conclusions

The field study conducted by Harb et al. (2009), on a two-to-one work zone lane closure configuration was limited to certain traffic demand level and to a certain motorists' adherence level to lane management instructions. Also in the field, there was a fixed PSL (Posted Speed Limit) at the start of the advance warning area instead of a VSL. Therefore, a simulated work zone model was created in VISSIM, calibrated and validated with the field data. This simulated work zone model was further modified by replacing the PSL by VSL with its respective coding in the model. One of the objective of this simulation study was to provide guidelines on the implementation of the integrated early and late SDLMS with VSL and the other objective was to evaluate operational and safety performance of the system on a two-to-one work zone lane closure configuration under different traffic demand volumes and different drivers' compliance rates to the messages displayed by the systems.

Operational and safety evaluation of the six MOT types tested through the VISSIM model are,

- Work Zone without VSL and without SDLMS
- Work Zone with VSL and without SDLMS
- Work Zone with VSL and Early SDLMS
- Work Zone with VSL and Late SDLMS

- Work Zone with early SDLMS and without VSL
- Work Zone with late SDLMS and without VSL

Table 5.5.1 below summarizes the operational effectiveness of these MOT types. In Table 5.5.1, each combination of compliance rate, truck percentage in the traffic composition and demand volume level has been summarized for throughputs and travel time. Only statistically significant results are presented in this table. For each combination the results were numbered 1, through 6, 1 being the best and 6 being the worst. The best MOT types to use (usually number 1) are highlighted with *Orange color* in this table. Those MOT types are also highlighted which are not the best but still not significantly different from the best option to use. The cells left blank in table 5.5.1 reflect no significant difference between the combinations. Upon looking at Table 5.5.1, one can see that in terms of throughputs, there is no difference in all MOT types for low and medium volume levels i.e. V0500, V1000 and V1500. For higher demand volumes (2,000 and 2,500 vph), throughputs for both SDLMS (early and late SDLMS) and their VSL combinations were significantly different from MAS and VSL only for all compliance rates and truck percentages. But they were not significantly different from each other except on a few instances.

In terms of travel time through the work zone, there is no significant difference between MOT types for demand levels of V0500 and

V1000 when compliance is 40% or less but for compliance of 60% and more, only demand volume level that is not significantly different from other MOT types is V0500.

On the operational parameters, addition of VSL to the SDLMS did not significantly improve the throughput and travel time but at the same time it was found that it is not drastically different in most cases when compared with SDLMS' without VSL. With a few exceptions, early SDLMS outperformed other MOT types in terms of throughputs whereas in terms of travel time, late SDLMS was found to be the best option.

Table 5.5.1: Summary of Operational MOEs

Compliance (%)	Trucks (%)	Volume (vph)	Throughputs						Travel Time					
			MAS	VSL	Early DLM	Late DLM	Early DLM +VSL	Late DLM +VSL	MAS	VSL	Early DLM	Late DLM	Early DLM +VSL	Late DLM +VSL
20	10	V0500												
		V1000												
		V1500							3	6	2	1	5	4
		V2000	5	6	4	1	2	3	5	6	1	2	3	4
		V2500	6	5	2	3	3	1	5	6	3	1	4	2
	20	V0500												
		V1000												
		V1500							3	6	2	1	5	4
		V2000	5	6	1	2	4	3	5	6	1	2	4	3
		V2500	6	5	3	1	4	2	5	6	4	1	3	2
	30	V0500												
		V1000												
		V1500							5	6	3	1	4	1
		V2000	6	5	1	3	4	2	5	6	1	2	4	3
		V2500	6	5	4	1	3	2	5	6	3	2	4	1
40	10	V0500												
		V1000												
		V1500							3	6	1	2	5	4
		V2000	6	5	1	3	3	2	5	6	2	1	4	3
		V2500	6	5	1	1	2	3	5	6	3	1	4	2
	20	V0500												
		V1000												
		V1500							3	6	2	1	5	4
		V2000	6	5	3	1	2	1	5	6	3	1	4	2
		V2500	6	5	3	1	3	2	5	6	4	2	3	1
	30	V0500												
		V1000												
		V1500							5	6	2	1	4	3
		V2000	6	5	1	2	3	4	5	6	2	1	4	3
		V2500	6	5	1	3	4	1	5	6	3	2	4	1
60	10	V0500												
		V1000							1	6	3	2	5	4
		V1500							2	6	1	3	5	4
		V2000	6	5	3	2	4	1	5	6	2	1	4	3
		V2500	5	4	1	2	3	6	5	6	3	2	3	4
	20	V0500												
		V1000							2	6	1	3	5	4
		V1500							3	6	1	2	5	4
		V2000	6	5	4	2	3	1	5	6	3	1	4	2
		V2500	5	4	1	2	3	6	5	6	3	1	4	2
	30	V0500												
		V1000							3	6	1	2	5	4
		V1500							5	6	1	2	4	3
		V2000	6	5	3	1	2	4	5	6	3	1	4	2
		V2500	5	3	1	2	4	6	5	6	2	1	3	4
80	10	V0500												
		V1000							2	6	1	3	4	5
		V1500							2	6	1	3	5	4
		V2000	6	5	3	2	4	1	5	6	2	1	4	3
		V2500	5	4	3	1	6	2	5	6	3	1	4	2
	20	V0500												
		V1000							2	6	1	3	4	5
		V1500							2	6	1	3	4	5
		V2000	6	5	3	1	4	2	5	6	3	1	4	2
		V2500	5	4	1	2	6	2	5	6	3	1	4	2
	30	V0500												
		V1000							2	6	1	3	4	5
		V1500							5	6	1	2	3	4
		V2000	6	5	3	1	4	1	5	6	3	1	4	2
		V2500	5	4	1	2	6	3	5	6	3	1	4	2

Legend: Best Option: 1 Worst Option: 6

Table 5.5.2 and 5.5.3 below summarize the safety effectiveness of the six MOT types. In Table 5.5.2, each combination of compliance rate, truck percentage in the traffic composition and demand volume level has been summarized for speed variances of the vehicles travelling in the open and closed lane of the work zone. Similarly, in table 5.5.3, summary of deceleration means of the vehicles travelling in the open and closed lane is reported. Again, only statistically significant results are presented in these tables. For each combination the results were numbered 1, through 6, 1 being the best and 6 being the worst. The best MOT types to use are highlighted *Orange Color* in this table. Additionally, cells are highlighted with a *Green Color* in cases where either early or late SDLMS with VSL showed lesser speed variance or deceleration mean than their respective SDLMS type without VSL. From table 5.5.2, one can see that in terms of speed variances, generally, early and late SDLMS performed better in both open and closed lane than all other MOT types for low and medium volume levels (V0500, V1000 and V1500). For demand volumes of V2000 and V2500, VSL and MAS were significantly better than SDLMS combinations, respectively. It was a noteworthy finding that no matter early and late SDLMS performed poorly as compared to VSL and MAS when higher volumes were involved, but the addition of VSL improved their safety aspect by decreasing the speed variance of the vehicles travelling in both open and a closed lane. This fact was also observed in deceleration analysis with a few exceptions.

Table 5.5.2: Summary of Safety MOE (Speed Variance)

Compliance (%)	Trucks (%)	Volume (vph)	Speed Variance (Open Lane)						Speed Variance (Closed Lane)					
			MAS	VSL	Early DLM	Late DLM	Early DLM +VSL	Late DLM +VSL	MAS	VSL	Early DLM	Late DLM	Early DLM +VSL	Late DLM +VSL
20	10	V0500	6	5	1	2	4	3	2	5	3	1	6	4
		V1000	3	6	2	1	5	4	4	6	3	1	5	2
		V1500	4	6	2	1	5	3	5	6	3	1	4	2
		V2000	2	1	3	5	4	6	2	1	4	5	3	6
		V2500	1	2	5	6	3	4	1	2	6	4	3	5
	20	V0500	1	6	2	2	4	3	2	5	4	1	6	3
		V1000	3	6	2	1	5	4	4	6	3	1	5	2
		V1500	4	6	2	1	5	3	4	6	2	1	5	3
		V2000	4	1	5	6	2	3	2	1	4	6	3	5
		V2500	1	2	6	5	4	3	1	2	4	6	3	5
	30	V0500	1	6	2	3	4	5	1	5	3	2	6	4
		V1000	3	6	1	2	5	4	4	6	3	1	5	2
		V1500	6	5	2	1	4	3	6	5	3	1	4	2
		V2000	2	1	5	6	3	4	2	1	5	6	3	4
		V2500	2	1	5	6	3	4	2	1	3	4	5	6
40	10	V0500	1	6	2	3	4	5	3	5	4	1	6	2
		V1000	3	6	1	2	5	4	4	6	3	1	5	2
		V1500	3	6	2	1	5	4	4	6	2	1	5	3
		V2000	2	1	5	3	6	4	2	1	4	5	3	6
		V2500	1	2	5	6	3	4	1	2	6	5	3	4
	20	V0500	1	6	2	3	4	5	2	5	3	1	6	4
		V1000	3	6	1	2	5	4	4	6	3	1	5	2
		V1500	4	6	2	1	5	3	5	6	3	1	4	2
		V2000	2	1	5	6	3	4	2	1	4	6	3	5
		V2500	1	2	3	5	4	6	1	4	3	5	2	6
	30	V0500	1	6	3	2	5	4	3	5	4	1	6	2
		V1000	3	6	2	1	5	4	4	6	3	1	5	2
		V1500	6	5	2	1	4	3	6	5	3	1	4	2
		V2000	2	1	5	6	3	4	2	1	4	6	3	5
		V2500	1	2	6	4	5	3	1	6	4	3	2	5
60	10	V0500	3	4	1	2	5	5	3	5	4	1	6	2
		V1000	3	6	1	2	5	4	4	6	3	2	5	1
		V1500	4	6	1	2	5	3	5	6	3	1	4	2
		V2000	4	1	6	3	5	2	2	1	6	4	5	3
		V2500	1	2	5	6	3	4	1	2	4	3	6	5
	20	V0500	1	4	2	3	5	6	3	5	4	1	6	2
		V1000	3	6	2	1	4	5	4	6	3	1	5	2
		V1500	5	6	2	1	4	3	5	6	3	1	4	2
		V2000	2	1	5	6	3	4	2	1	6	5	3	4
		V2500	1	2	5	6	3	5	1	2	3	4	6	5
	30	V0500	1	4	2	3	6	5	3	5	4	1	6	2
		V1000	3	6	2	1	5	4	4	6	3	1	5	2
		V1500	6	5	2	1	4	3	6	5	3	1	4	2
		V2000	2	1	5	6	3	4	2	1	4	6	3	5
		V2500	1	2	6	5	3	4	1	2	4	3	5	6
80	10	V0500	6	3	1	2	4	5	2	6	3	1	5	4
		V1000	3	6	1	2	4	5	4	6	3	1	5	2
		V1500	5	6	3	1	4	2	5	6	3	1	4	2
		V2000	4	1	6	2	5	3	4	1	6	2	5	3
		V2500	1	2	6	5	3	4	1	2	5	4	6	3
	20	V0500	1	4	2	3	5	6	2	6	3	1	5	4
		V1000	3	6	2	1	5	4	4	6	3	1	5	2
		V1500	6	5	2	1	4	3	5	6	4	1	3	2
		V2000	4	1	6	3	5	2	2	1	6	4	5	3
		V2500	1	2	6	5	3	4	1	2	6	4	5	3
	30	V0500	1	4	2	3	5	6	2	6	4	1	5	3
		V1000	3	6	2	1	5	4	5	6	4	1	3	2
		V1500	6	3	4	1	5	2	6	5	3	1	4	2
		V2000	2	1	6	5	4	3	2	1	6	4	5	3
		V2500	1	2	6	4	5	3	1	2	6	4	5	3

Legend: Best Option: 1 Worst Option: 6 When SDLMS+VSL Performs Better:

Table 5.5.3: Summary of Safety MOE (Deceleration Means)

Compliance (%)	Trucks (%)	Volume (vph)	Deceleration (Open Lane)						Deceleration (Closed Lane)					
			MAS	VSL	Early DLM	Late DLM	Early DLM +VSL	Late DLM +VSL	MAS	VSL	Early DLM	Late DLM	Early DLM +VSL	Late DLM +VSL
20	10	V0500	3	6	1	2	4	5	5	6	2	1	4	3
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	5	6	2	1	4	3	5	6	3	1	4	2
		V2000	2	1	3	4	6	5	2	1	4	3	6	5
		V2500	2	1	6	3	4	5	1	2	5	3	4	6
	20	V0500	3	6	2	1	4	5	5	6	1	2	4	3
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	6	5	2	1	4	3	6	5	3	1	4	2
		V2000	2	1	3	4	6	5	2	1	4	3	6	5
		V2500	2	1	4	5	4	3	1	1	4	5	5	3
	30	V0500	3	6	2	1	4	5	5	6	1	2	3	3
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	6	2	3	1	5	4	6	3	4	1	5	2
		V2000	2	1	6	4	5	3	2	1	5	3	6	4
		V2500	2	1	3	6	4	5	2	1	5	4	3	6
40	10	V0500	3	6	2	1	5	4	5	6	1	1	4	3
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	5	4	2	1	3	6	6	5	3	1	4	2
		V2000	2	1	5	3	6	4	2	1	6	3	4	4
		V2500	1	2	4	6	3	5	1	2	4	3	5	6
	20	V0500	3	6	2	1	5	4	4	6	2	1	5	3
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	6	3	2	1	5	4	6	4	3	1	5	2
		V2000	1	1	2	3	4	5	2	1	3	4	5	6
		V2500	1	2	4	6	3	5	1	2	4	6	3	5
	30	V0500	3	6	2	1	5	4	5	6	2	1	4	3
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	6	1	3	1	5	4	6	4	3	1	5	2
		V2000	1	2	6	3	5	4	1	2	6	3	5	4
		V2500	1	2	6	3	5	3	1	2	6	3	4	4
60	10	V0500	3	5	2	1	6	4	4	6	1	2	3	5
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	6	3	3	1	5	2	6	5	2	1	4	3
		V2000	2	1	5	4	6	3	2	1	6	3	4	5
		V2500	1	2	6	5	3	4	1	2	4	3	6	5
	20	V0500	3	5	2	1	6	4	3	6	2	1	5	4
		V1000	5	6	2	1	4	3	5	6	2	1	4	3
		V1500	6	2	4	1	5	3	6	5	3	1	4	2
		V2000	1	2	4	6	3	5	1	2	4	5	3	6
		V2500	1	4	6	5	2	3	1	2	4	3	6	5
	30	V0500	3	6	2	1	5	4	5	6	2	1	4	3
		V1000	6	5	3	1	4	2	5	6	2	1	4	3
		V1500	6	1	4	2	5	3	6	4	3	1	5	2
		V2000	1	2	4	6	3	5	1	2	3	5	4	6
		V2500	1	5	6	3	2	3	1	2	4	3	6	5
80	10	V0500	5	4	2	1	6	3	4	6	1	2	3	5
		V1000	6	5	3	1	4	2	5	6	2	1	3	4
		V1500	6	2	4	1	5	3	6	5	2	1	4	3
		V2000	2	1	5	3	6	4	2	1	6	3	5	4
		V2500	1	3	6	4	2	5	1	2	4	3	6	5
	20	V0500	4	5	2	1	6	3	5	6	1	2	3	4
		V1000	6	5	3	1	4	2	5	6	2	1	3	4
		V1500	6	2	4	1	5	3	6	5	3	1	4	2
		V2000	1	2	6	3	5	4	1	2	5	3	4	6
		V2500	1	3	6	4	2	5	1	2	5	3	6	4
	30	V0500	5	4	2	1	6	3	5	6	1	1	3	4
		V1000	6	5	3	1	4	2	5	6	2	1	3	4
		V1500	6	1	4	2	5	3	6	5	3	1	4	2
		V2000	1	2	6	4	3	5	1	2	3	5	4	6
		V2500	2	3	6	4	1	5	1	2	5	3	6	4

Legend: Best Option: 1 Worst Option: 6 When SDLMS+VSL Performs Better:

Overall results of the simulation study show that it is a trade-off between operations and safety through a 2-to-1 lane closure work zone. SDLMS and SDLMS with VSL are not statistically different from each other but outperform MAS and VSL, in terms of operational MOEs (throughput and travel time). On the other hand, SDLMS with VSL are statistically significant in terms of safety MOEs (speed variance and deceleration rate) as compared to their respective SDLMS' which proves that addition of VSL in the SDLMS operations makes the system more safe and in some cases able to provide better operations in a work zone.

CHAPTER 6
CONCLUSIONS AND DISCUSSION

To improve traffic operations and safety in a highway work zone, this study was focused mainly on evaluating the integrated dynamic merge and speed control systems in comparison to the systems having either dynamic merge control or speed control but not both integrated in one system. In order to achieve this task, following scenarios were evaluated on operational and safety performances by simulating a 2-to-1 lane closure work zone configuration under different traffic demand volumes and different drivers' compliance rates to the messages displayed by the systems. These scenarios are,

- Work Zone without VSL and without SDLMS
- Work Zone with VSL and without SDLMS
- Work Zone with VSL and Early SDLMS
- Work Zone with VSL and Late SDLMS
- Work Zone with early SDLMS and without VSL
- Work Zone with late SDLMS and without VSL

6.1 Research Findings

A brief summary of research findings from this study are is presented below;

1. An already calibrated and validated VISSIM model is modified with a VSL through VAP programming. Three different logics were coded each for VSL alone, early SDLMS+VSL and late SDLMS+VSL. All these logics were fine tuned with several test runs before finalizing it for the final simulation.
2. It is found through the simulation of above mentioned scenarios, that for low and medium volume levels (V0500, V1000 and V1500), in terms of throughput, there is no significant difference between the MOT types (Harb et al., 2010a). For higher volume levels (V2000 and V2500), late SDLMS with and without VSL produced higher mean throughputs for all compliance rates and truck percentages (Kwon et al., 2006) except when the demand volume was 2,500 vph and compliance of 60%, where it produces the significantly lower mean throughputs.
3. In terms of travel time through the work zone, results indicated that there is no significant difference between MOT types for demand levels of V0500 and V1000 when compliance is 40% or less but for compliance of 60% and more, only demand volume level that is not significantly different from other MOT types is

V0500. This study revealed that VSL increases travel time through the work zone (Yadlapati and Park, 2004). The reason of increase in travel time may be because of the fact that non-compliant vehicles have to follow the compliant vehicle ahead unless they get sufficient gap in adjacent lane to pass the compliant vehicle.

4. It is also found out that VSL makes the system safer in higher volumes (2,000vph and 2,500 vph). This was observed through safety surrogate measures selected for this study.
5. Another outcome of this study is that the addition of VSL to the dynamic merge systems helps in improving the overall safety of the system by lowering speed variances (Yadlapati and Park, 2004) and deceleration means (Mitra and Pant, 2005) of the vehicles travelling in the work zone. The passage of traffic through the work zone is made safer when a speed control is integrated to a dynamic merge system.
6. It can be inferred from the simulation results that integrated SDLMS and VSL systems have better performance in terms of traffic mobility and safety than existing individual controls and also show that the integrated SDLMS and VSL system has more potential than each individual systems.

6.2 Recommendations and Future Research Considerations

To improve traffic operations and safety in a highway work zone, this study emphasized mainly on evaluating the integrated dynamic merge and speed control systems in comparison to the systems having either dynamic merge control or speed control but not both integrated in one system. Based on this study, following are the recommendations and future research consideration;

1. The simulation results may be verified through a field study as per modified MOT plans having the VSL trailer at the start of the advance warning area of the work zone instead of a PSL sign.
2. Further studies can be conducted by adding one or more VSL signs in this simulation model before and through the work zone.
3. Future research may also be done on simulating the three-to-two work zone lane closure and determining the safety and operational effectiveness of the integrated dynamic merge speed control system under different traffic demand volume levels, different motorists' adherence level to lane management instructions and different trucks percentages in the traffic composition.
4. Future research may also focus on studying the safety of the different MOT types using different safety surrogate measure such as lane changing conflicts, time to collision at different locations in a work zone and ratio of the standard deviation to the means of

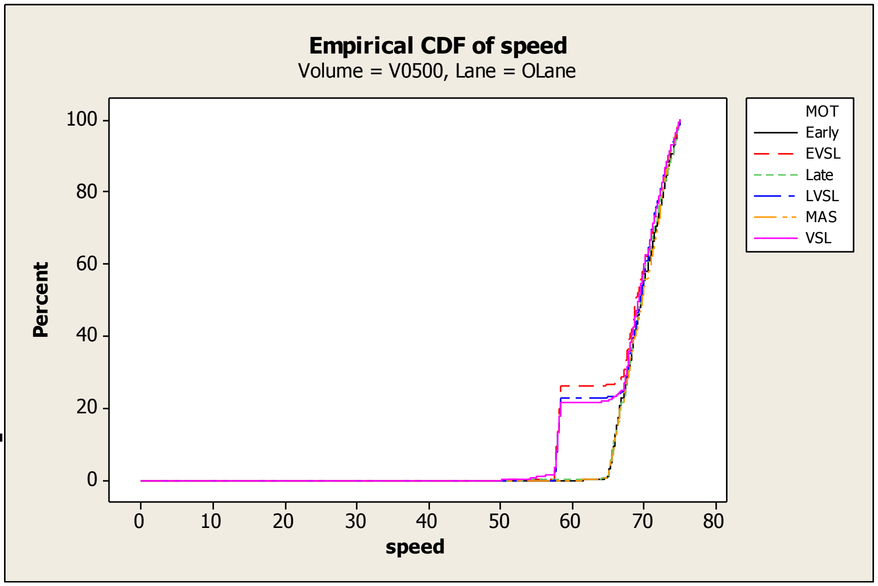
speed for a more realistic comparison of safety at low and high volumes.

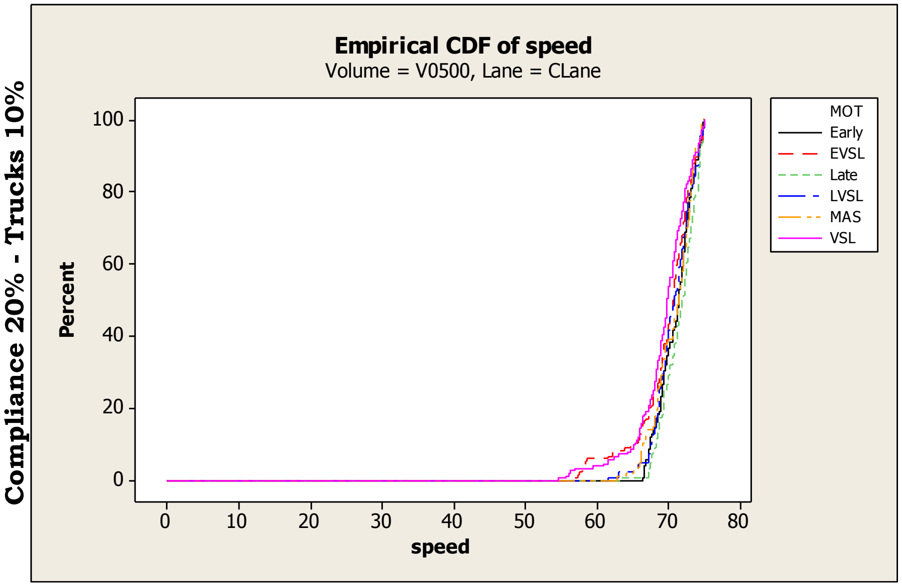
5. As it's a known fact that higher speed variance is related to higher crash rates on freeways but still there is a need to verify speed variance and deceleration rate as a safety surrogate measure for work zones. The future study may solely focus on the behavior of drivers in the reduced speed zones.

APPENDIX A
EMPIRICAL CDF OF SPEED

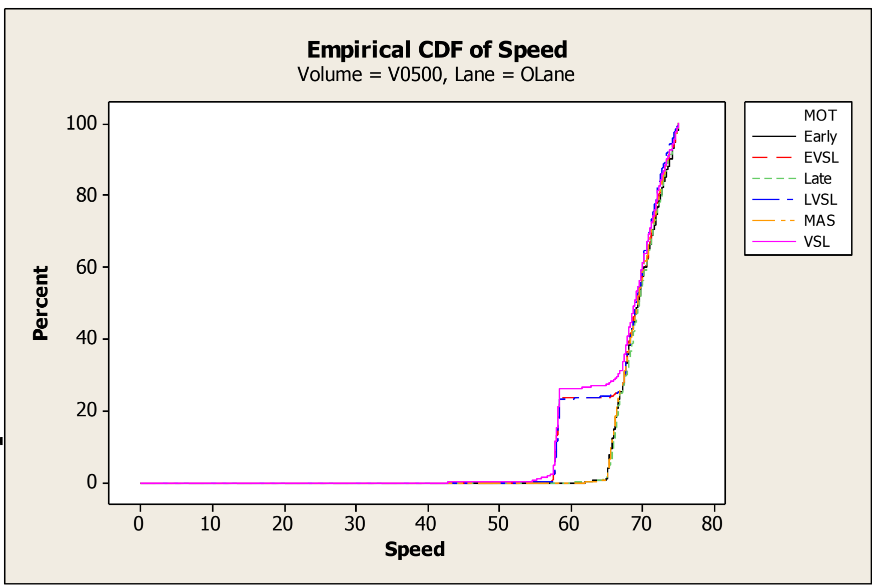
OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH

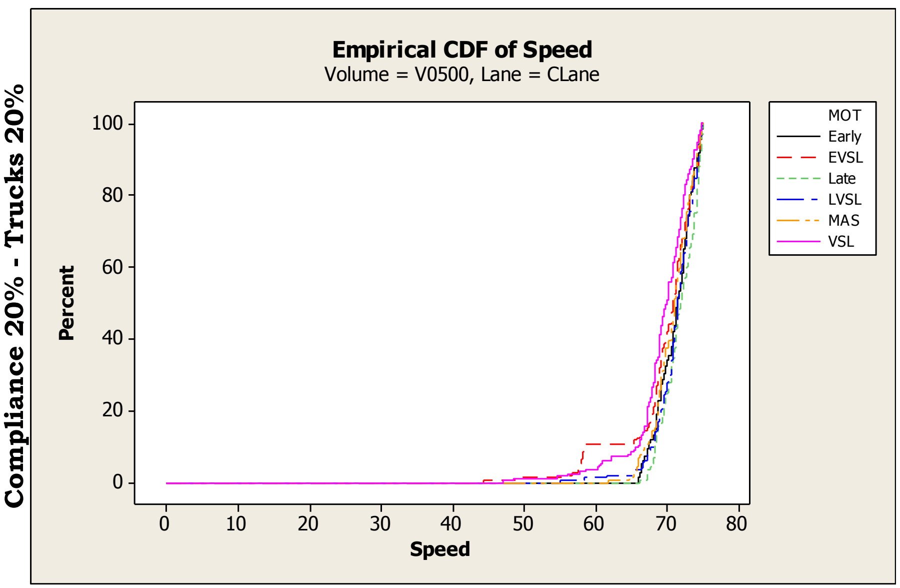
Compliance 20% - Trucks 10%

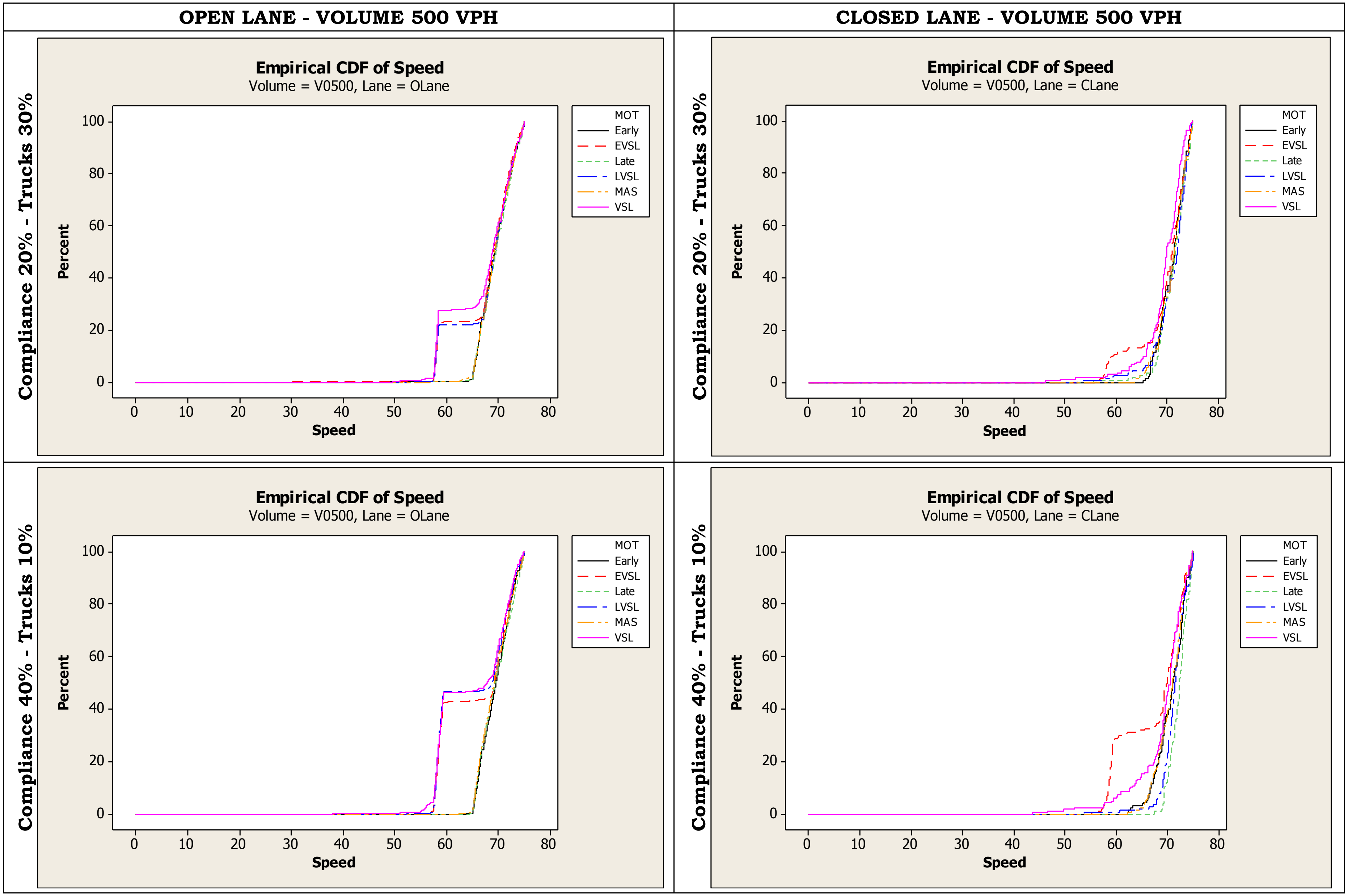


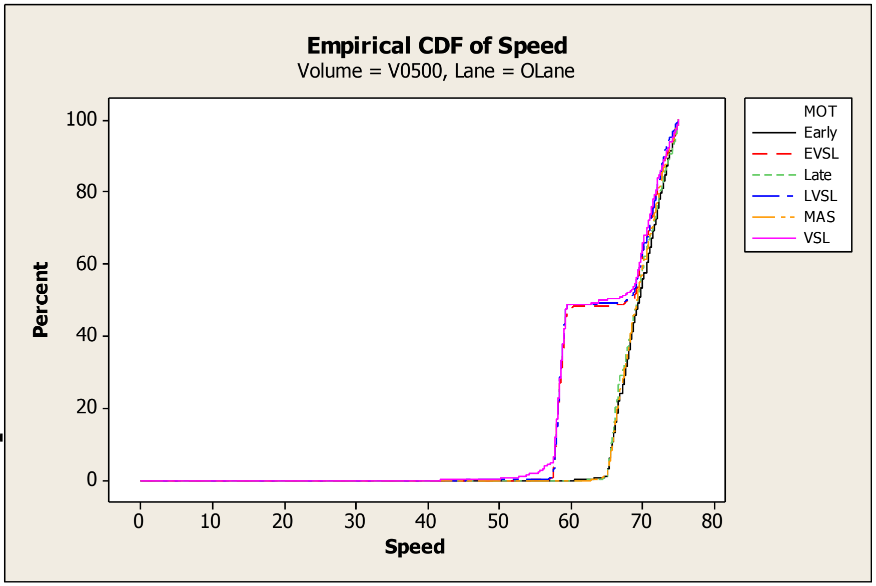
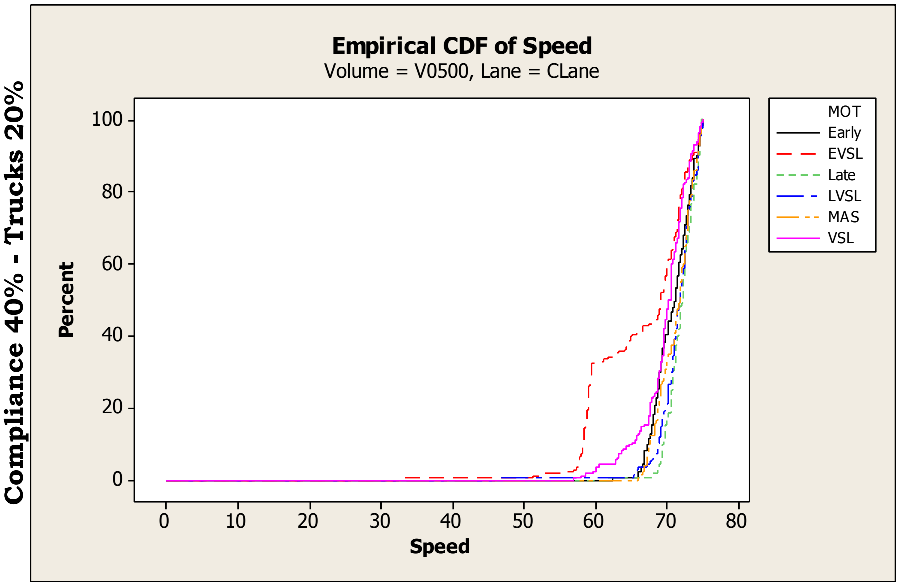
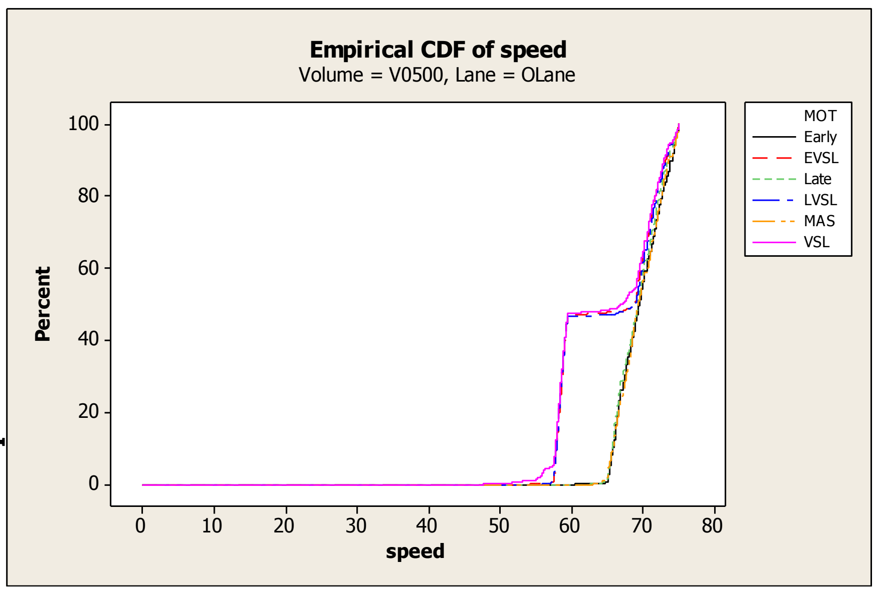
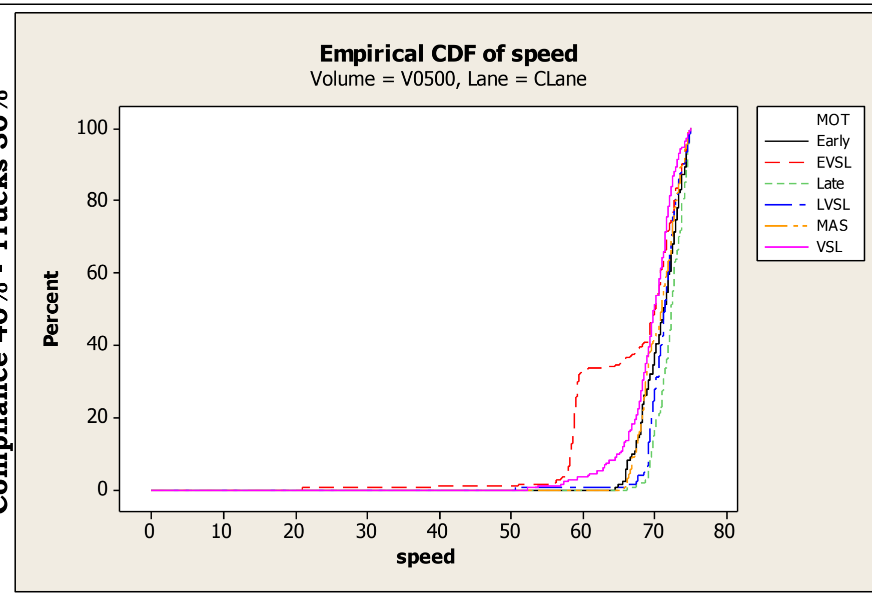


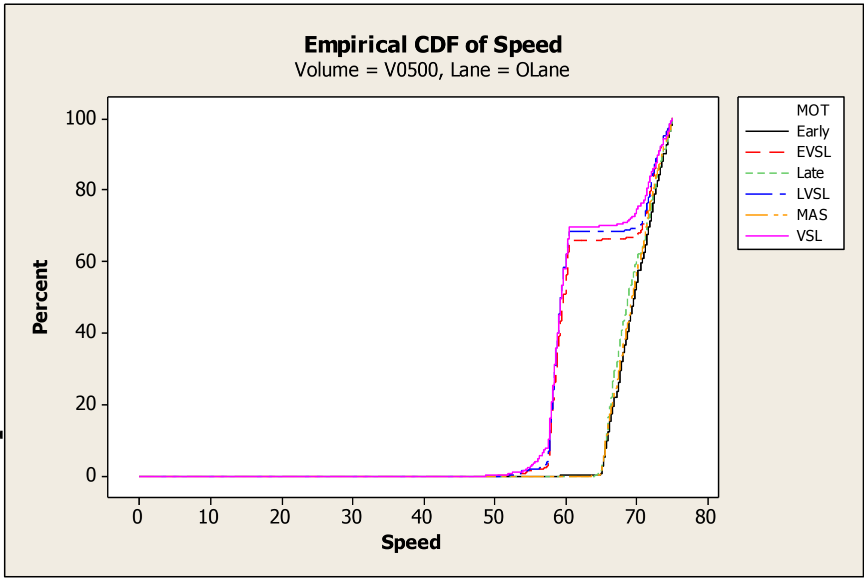
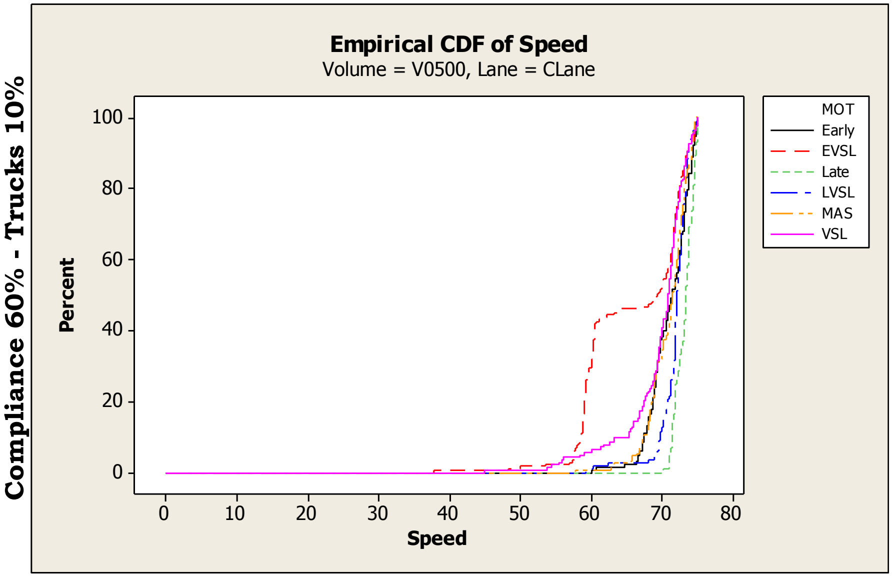
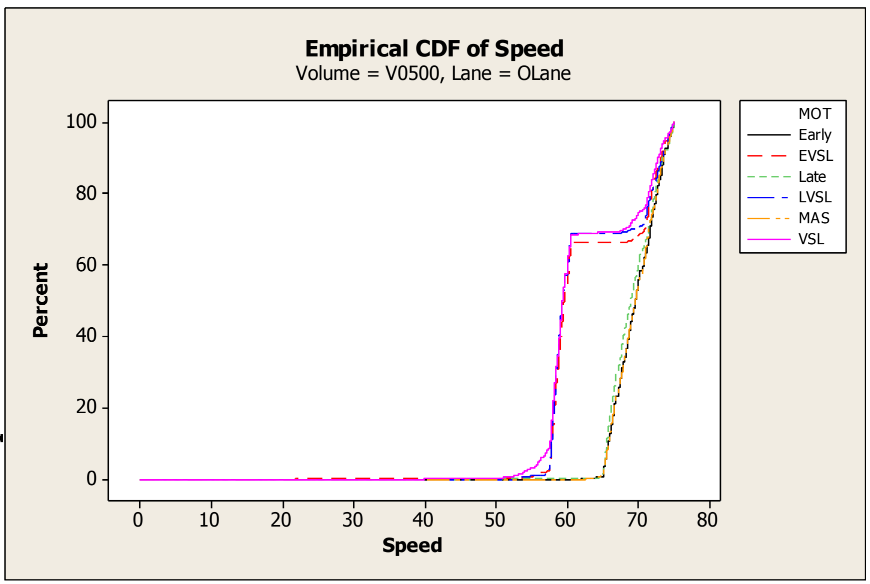
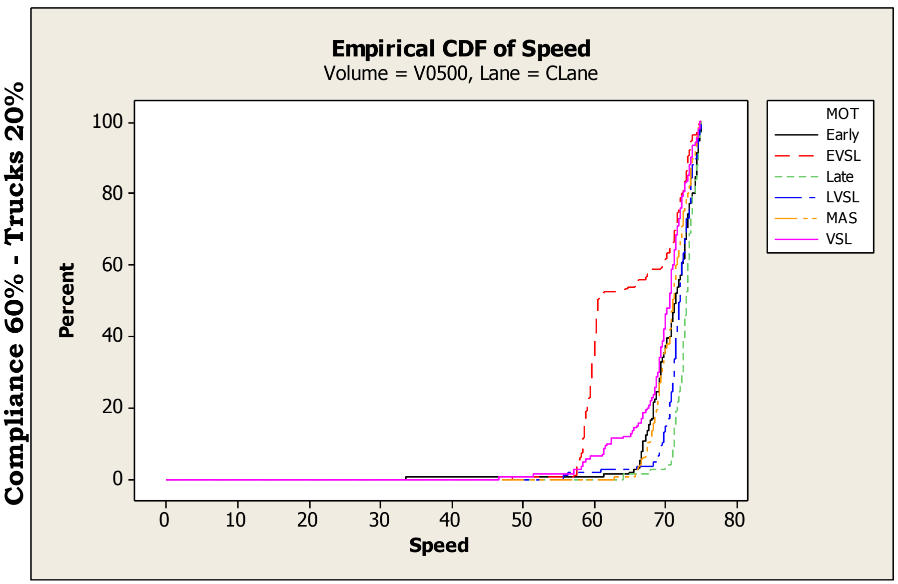
Compliance 20% - Trucks 20%





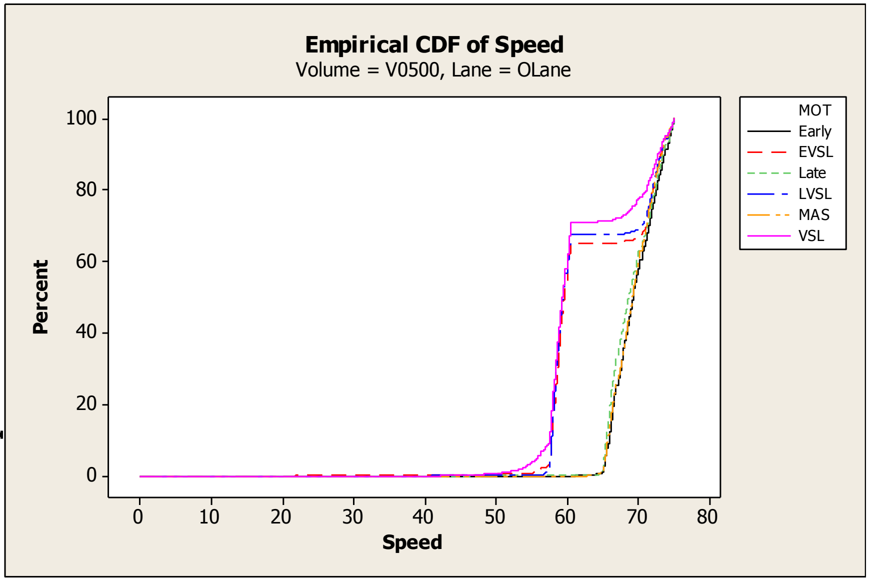

OPEN LANE - VOLUME 500 VPH
CLOSED LANE - VOLUME 500 VPH
Compliance 20% - Trucks 30%
Compliance 40% - Trucks 10%
Empirical CDF of Speed
Volume = V0500, Lane = OLane
Volume = V0500, Lane = CLane
Percent
Speed
MOT
Early
EVSL
Late
LVSL
MAS
VSL
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80

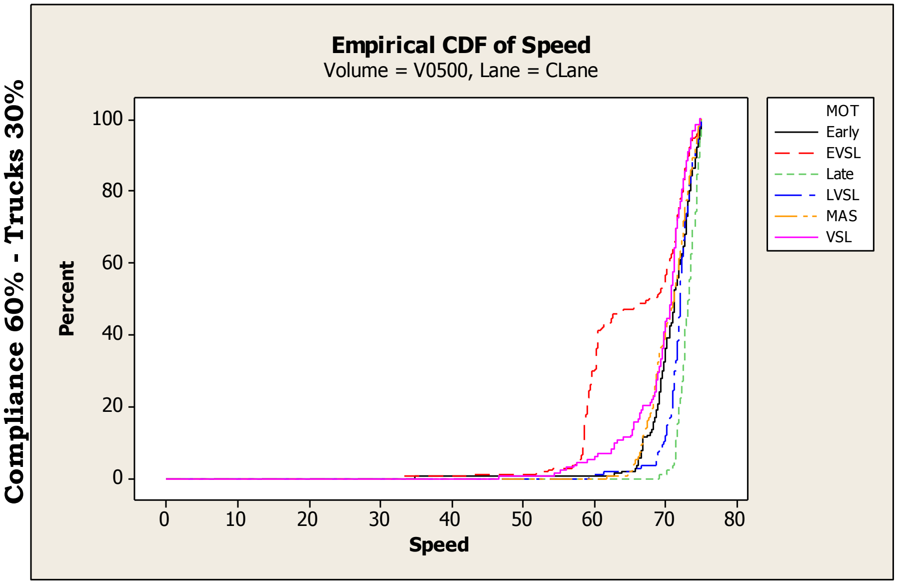
	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH
Compliance 40% - Trucks 20%		
Compliance 40% - Trucks 30%		

	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH
Compliance 60% - Trucks 10%		
Compliance 60% - Trucks 20%		

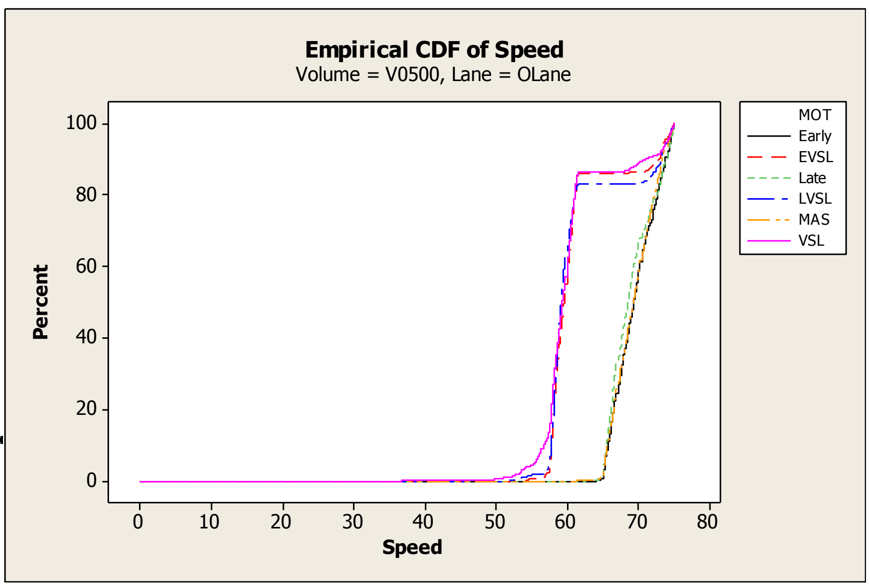
	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH

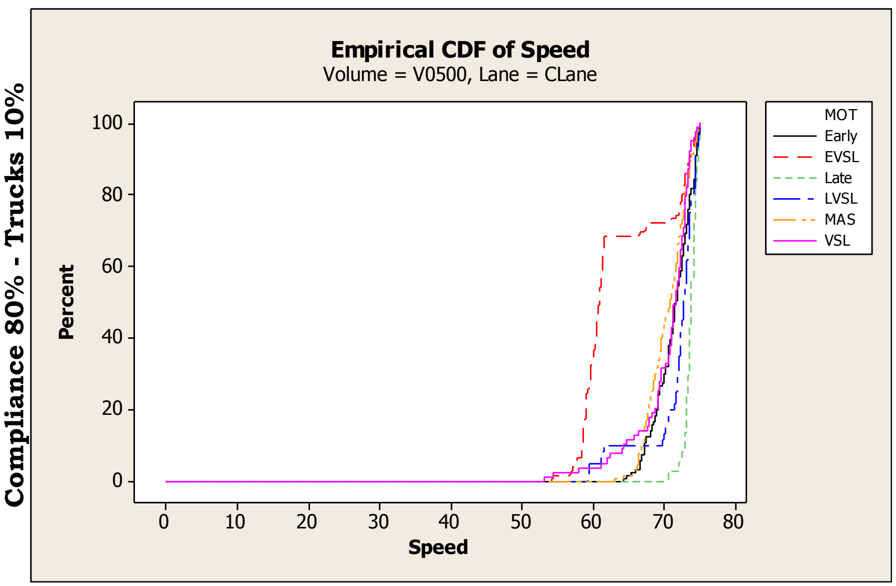
Compliance 60% - Trucks 30%

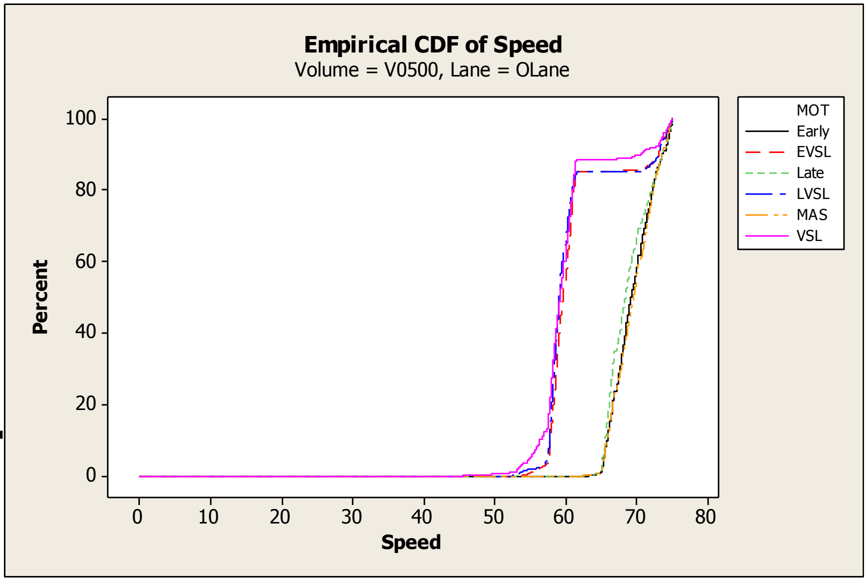
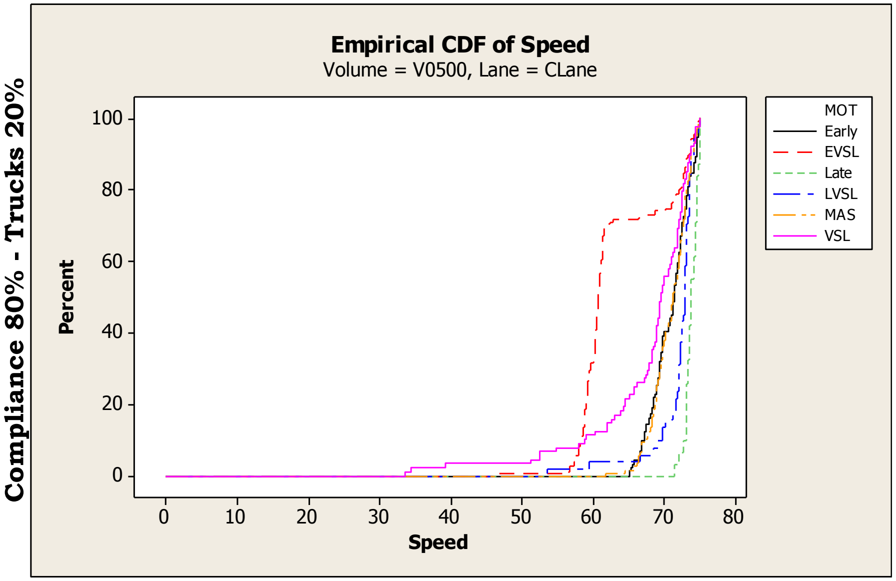
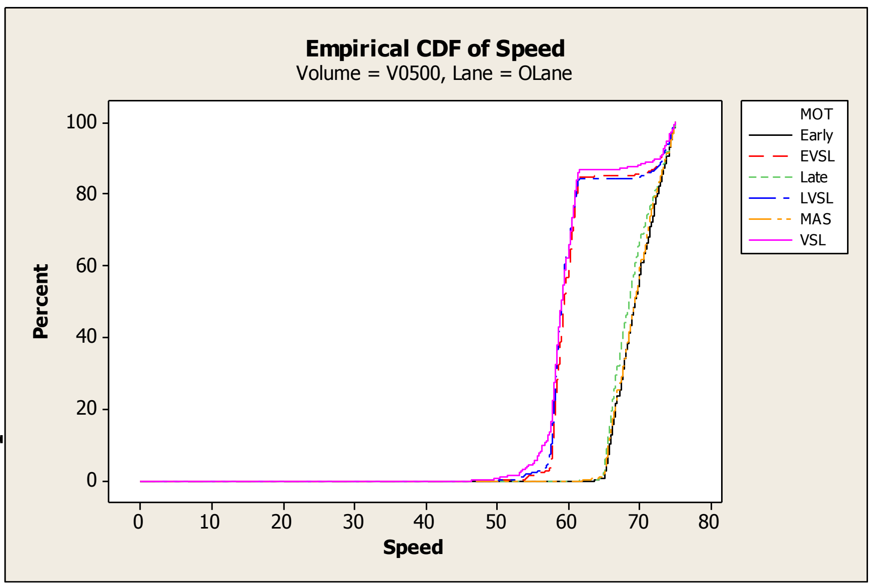
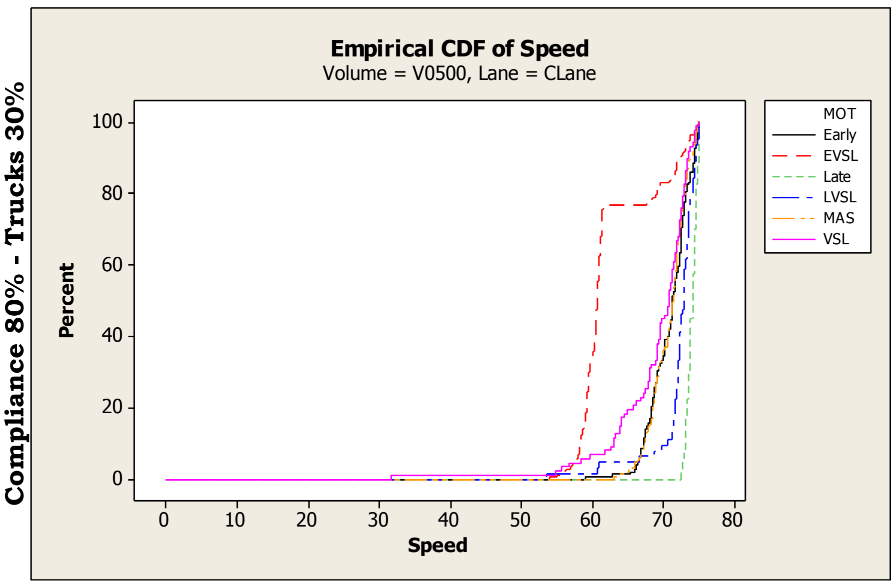


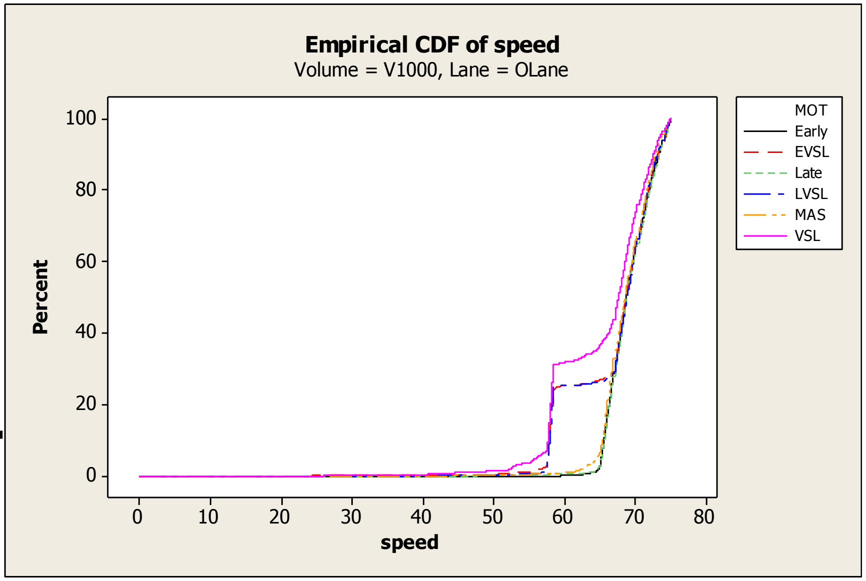
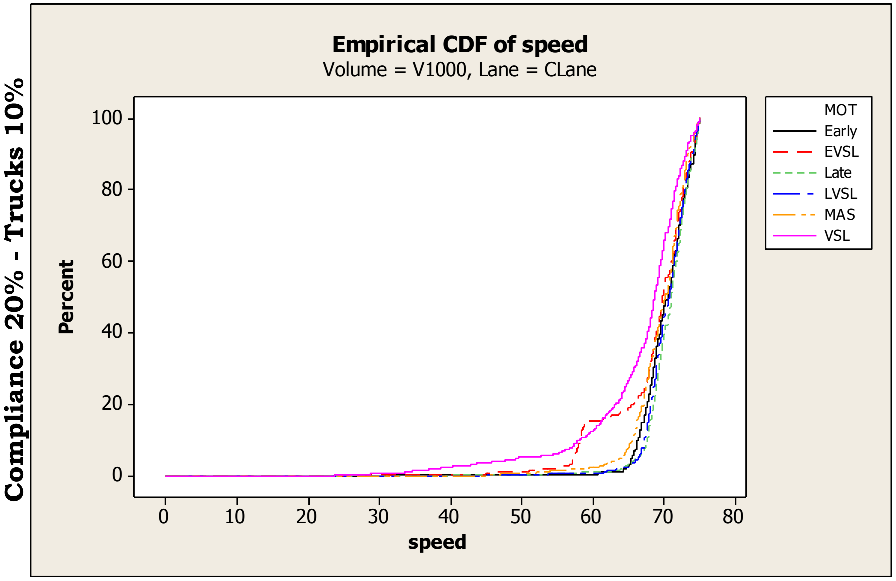
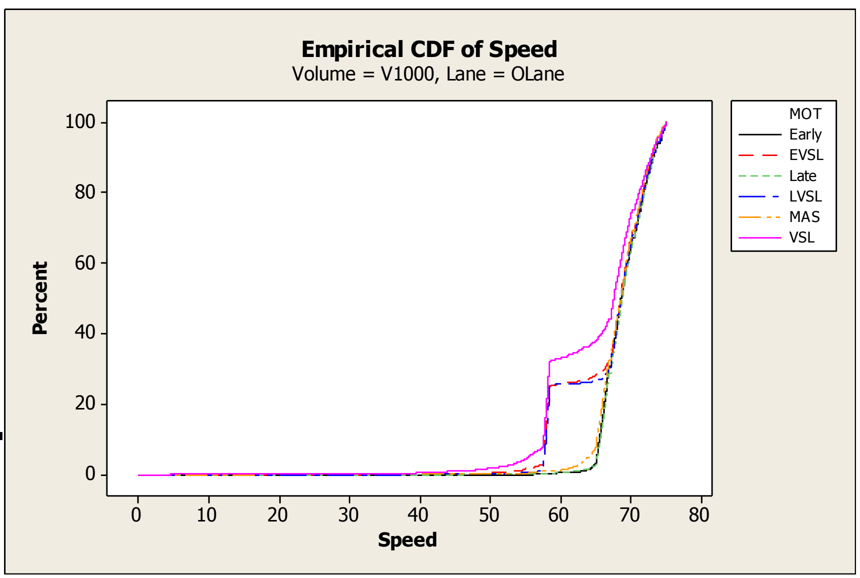
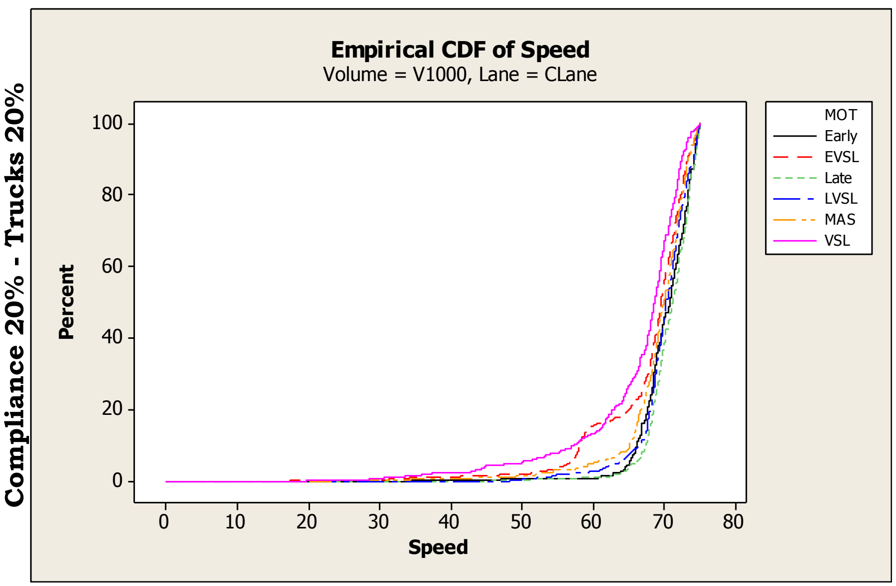


Compliance 80% - Trucks 10%



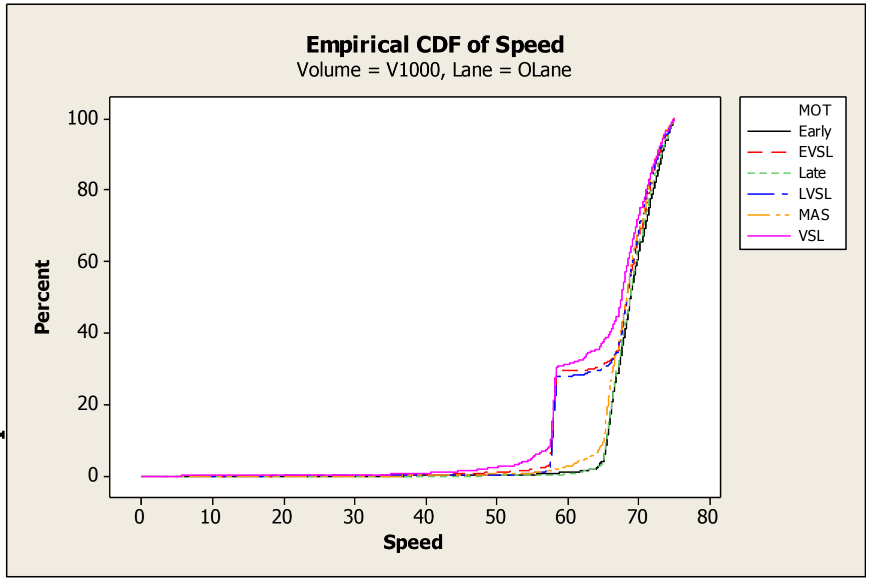


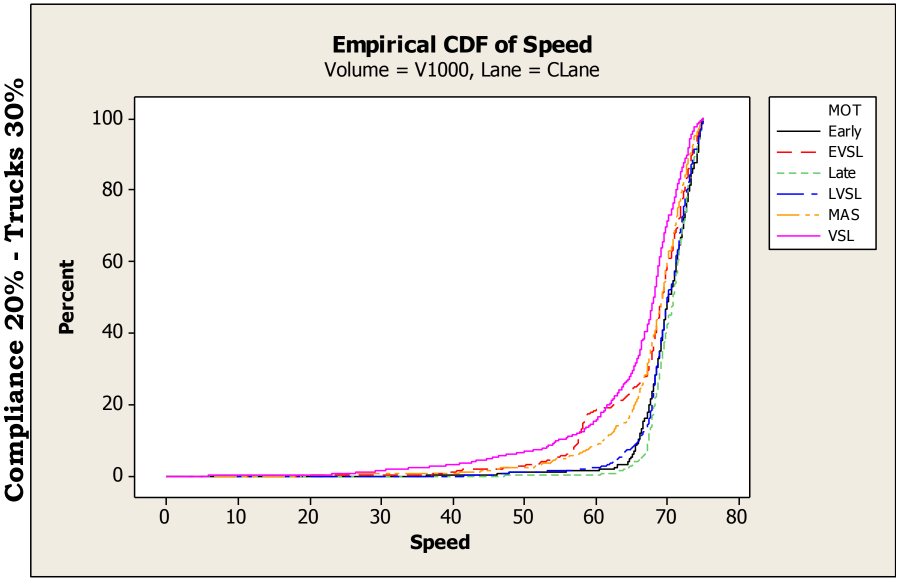
	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH
Compliance 20% - Trucks 10%		
Compliance 20% - Trucks 20%		

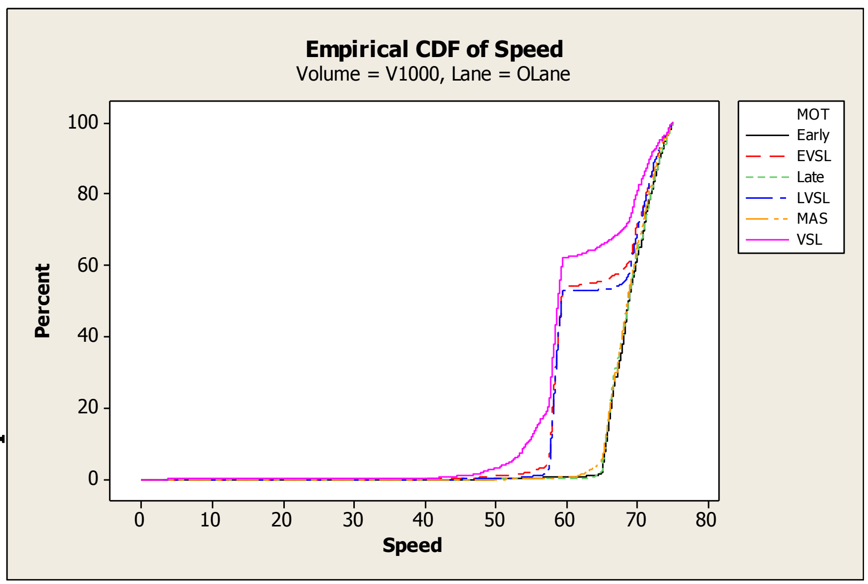
OPEN LANE - VOLUME 1,000 VPH | **CLOSED LANE - VOLUME 1,000 VPH**

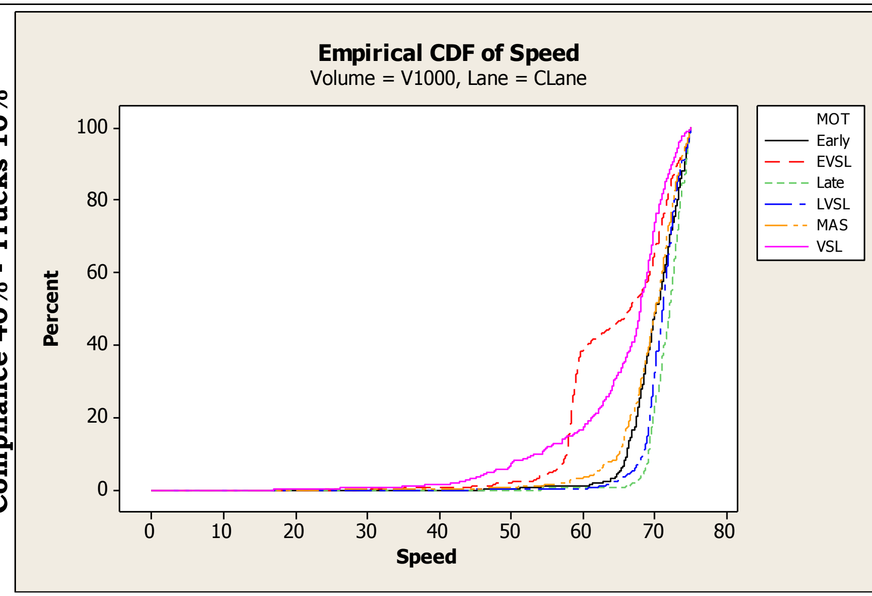
Compliance 20% - Trucks 30%

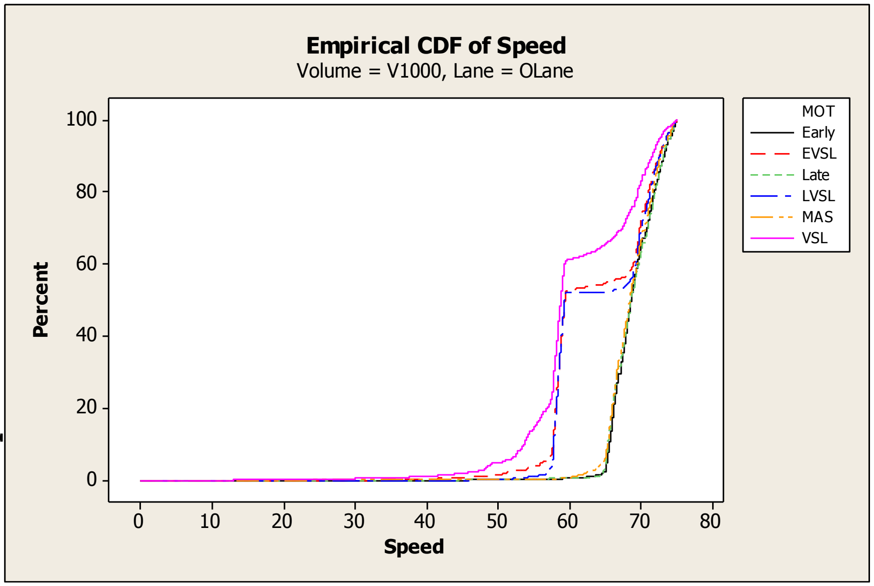
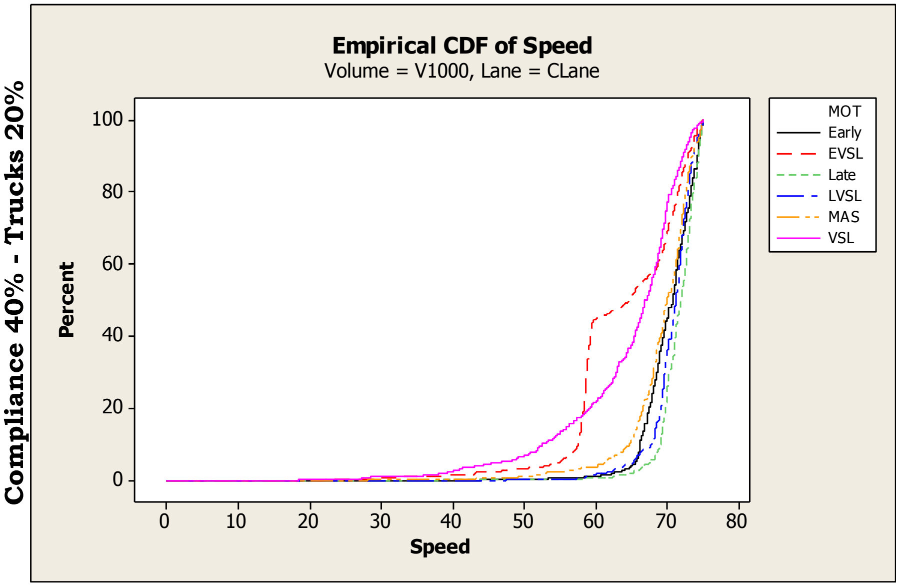
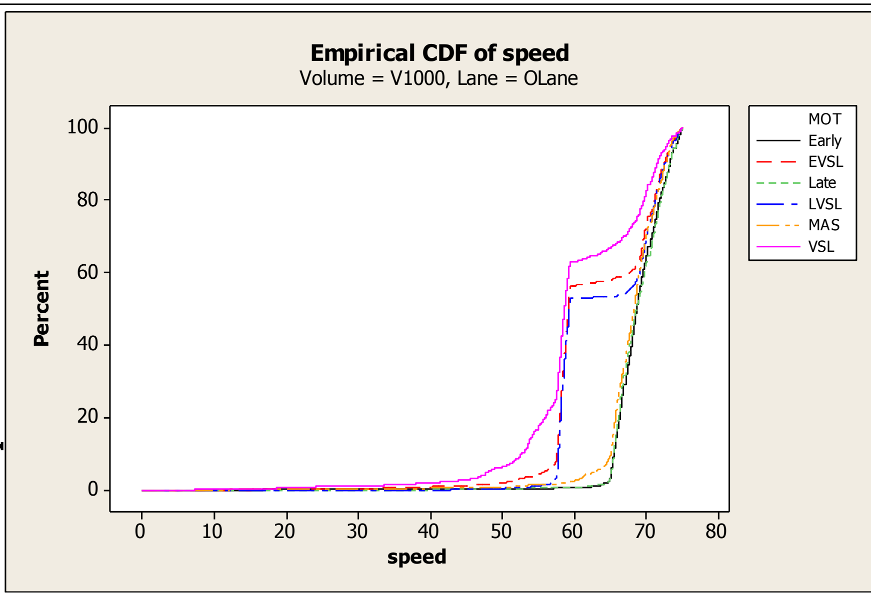
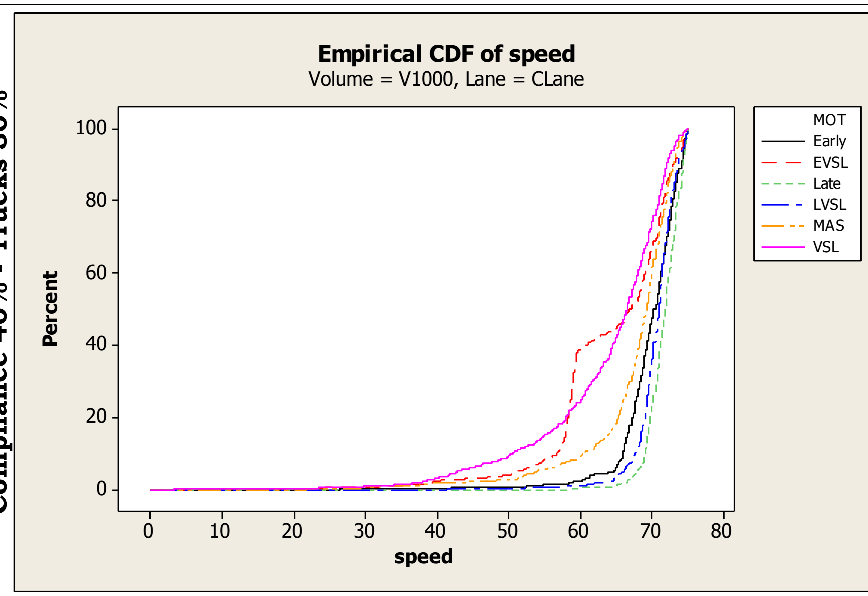


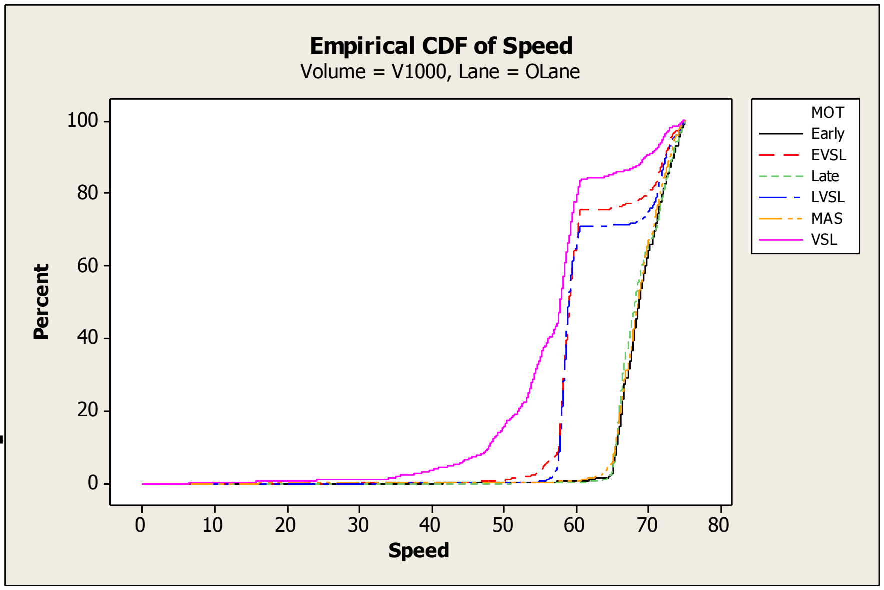
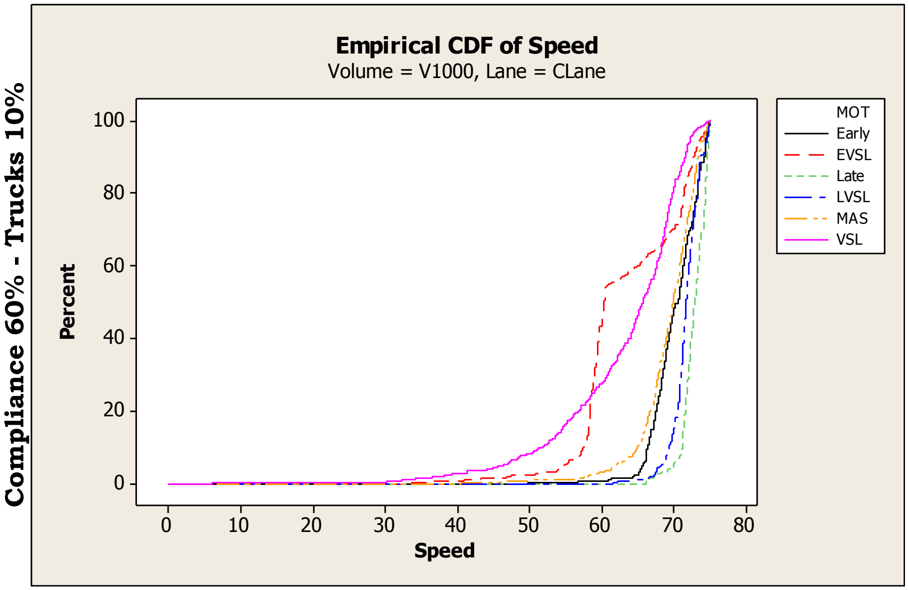
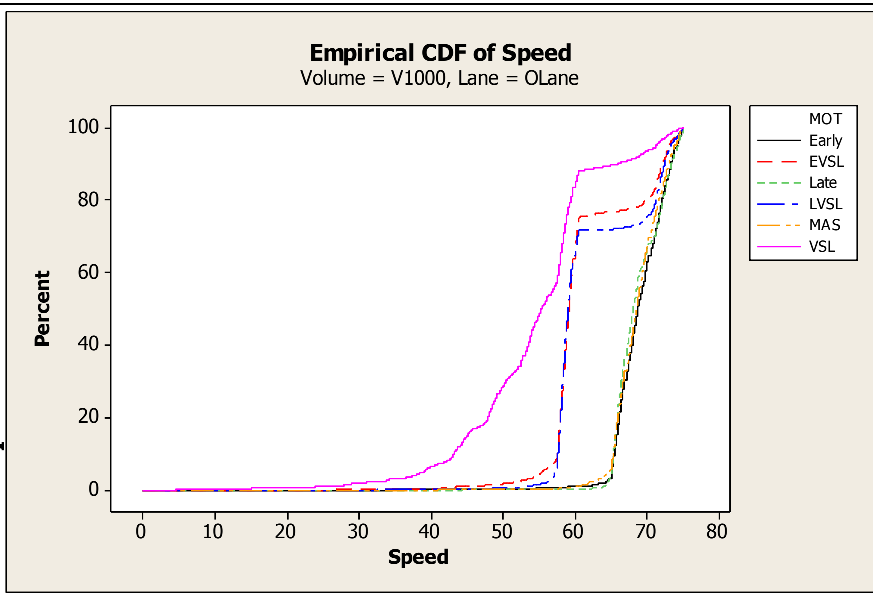
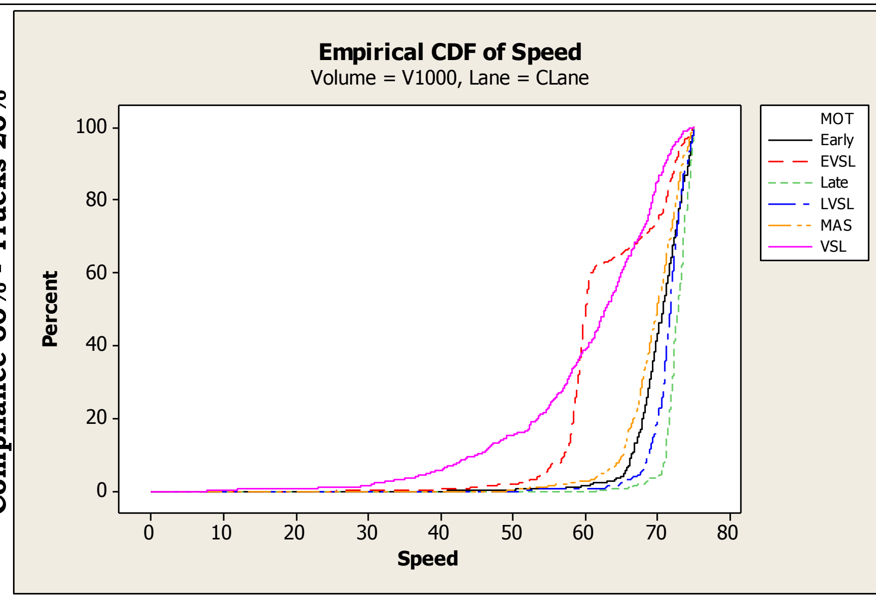


Compliance 40% - Trucks 10%



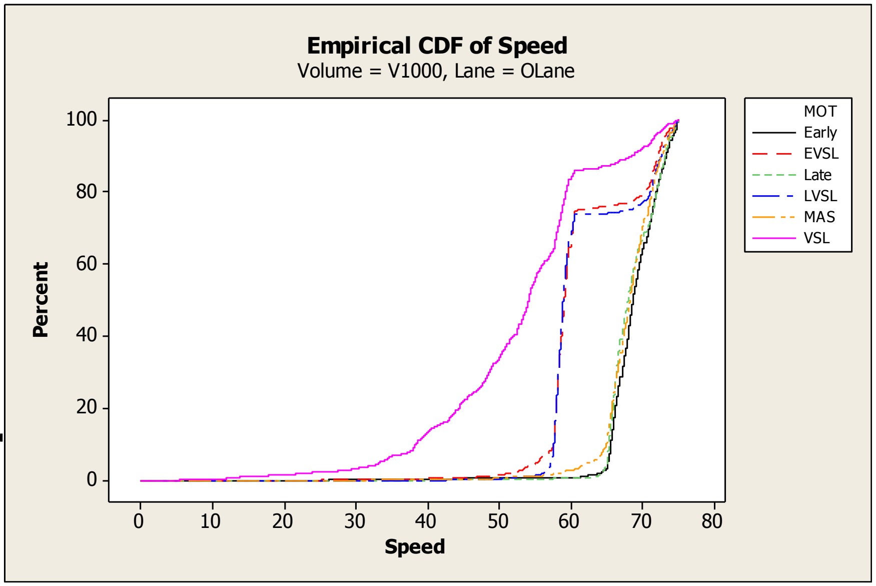


	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH
Compliance 40% - Trucks 20%		
Compliance 40% - Trucks 30%		

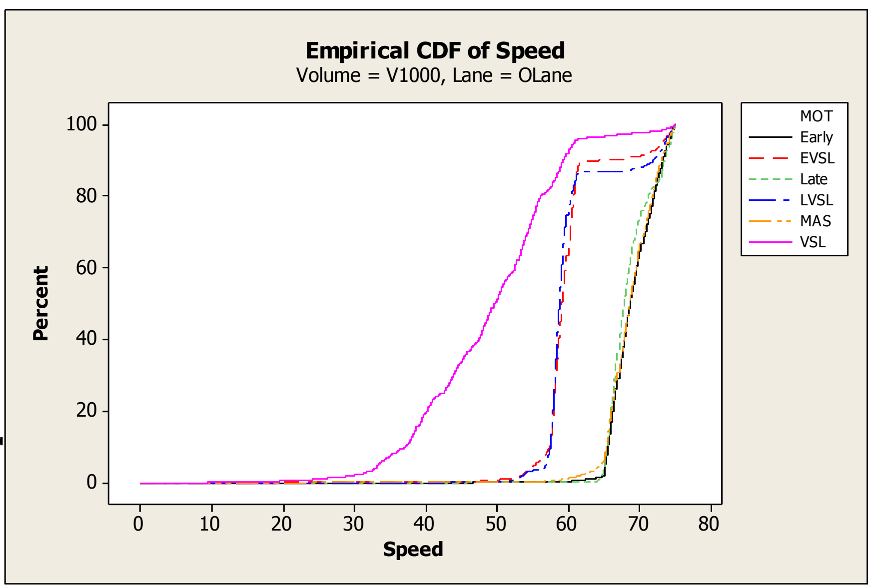
	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH
Compliance 60% - Trucks 10%		
Compliance 60% - Trucks 20%		

OPEN LANE - VOLUME 1,000 VPH

Compliance 60% - Trucks 30%

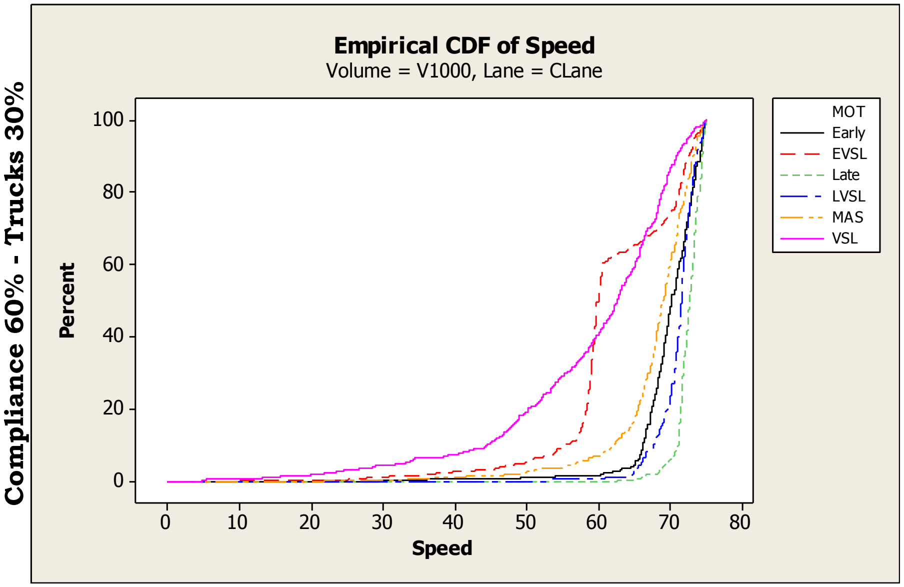


Compliance 80% - Trucks 10%

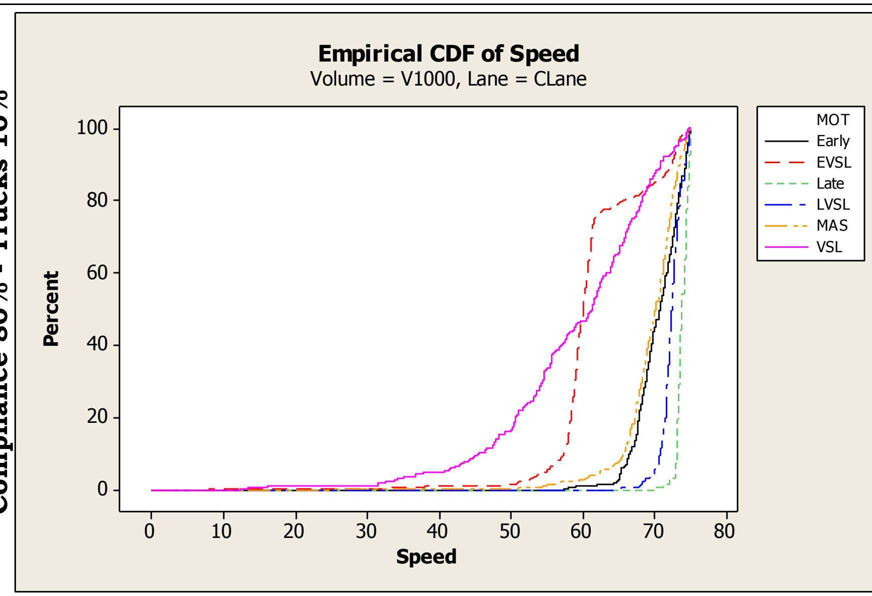


CLOSED LANE - VOLUME 1,000 VPH

Compliance 60% - Trucks 30%

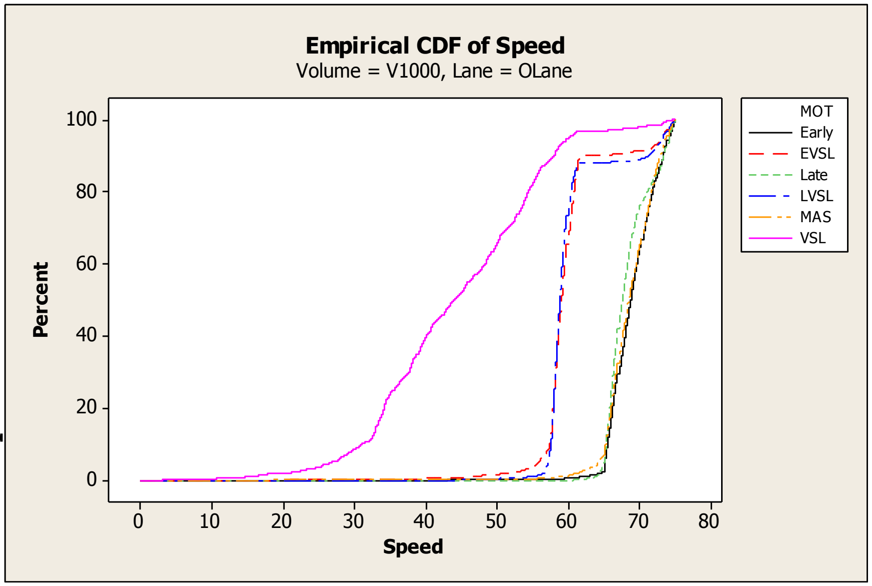


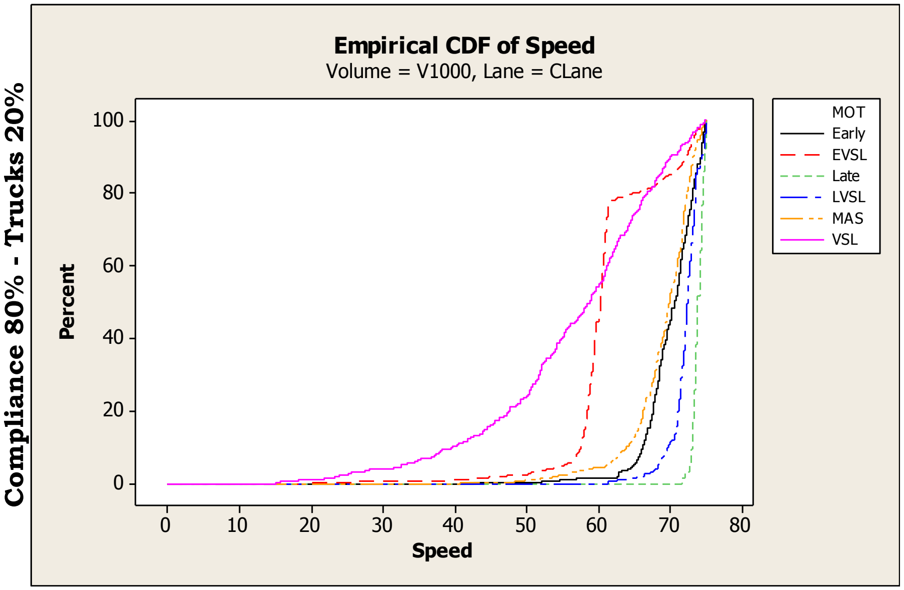
Compliance 80% - Trucks 10%



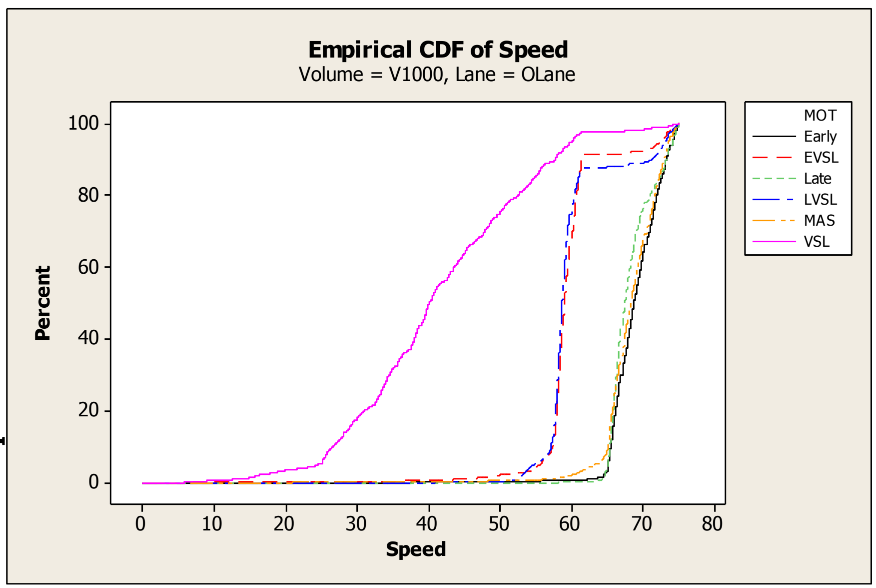
OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH

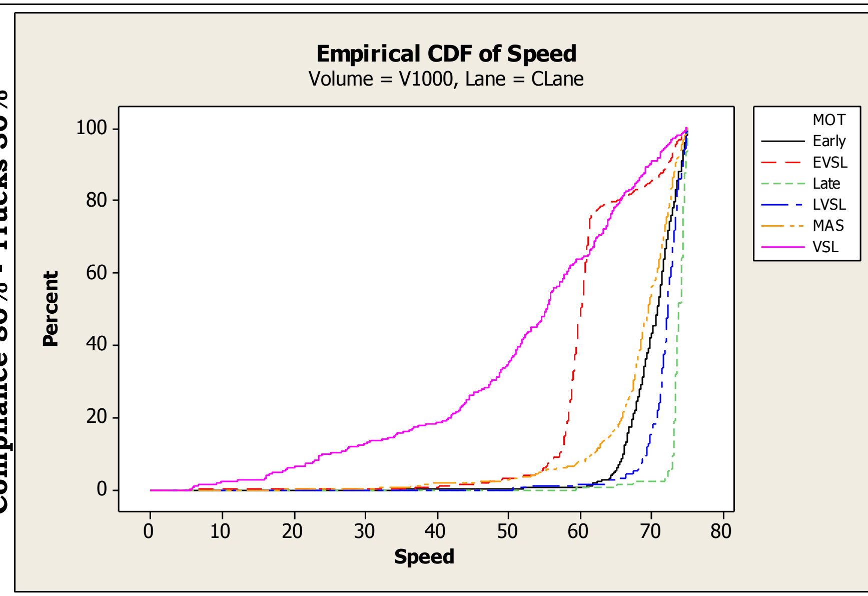
Compliance 80% - Trucks 20%





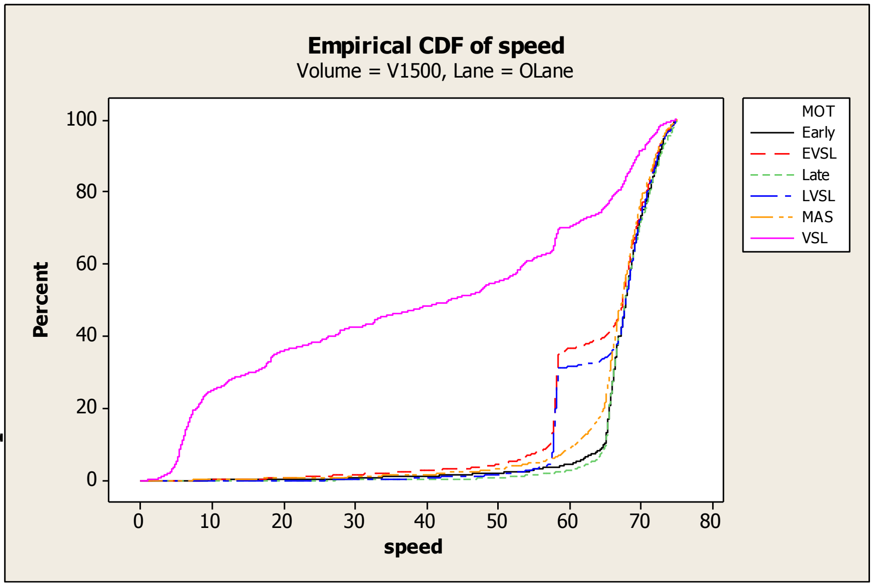
Compliance 80% - Trucks 30%



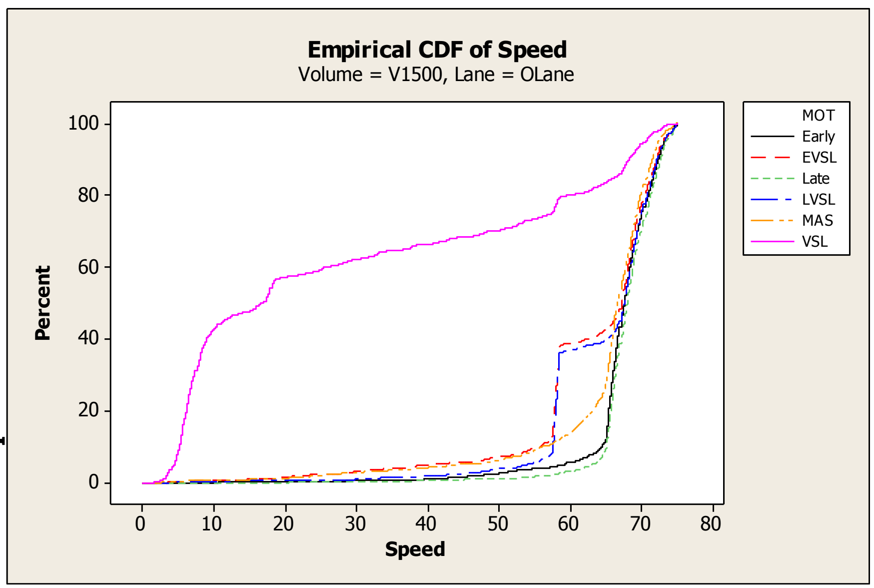


OPEN LANE - VOLUME 1,500 VPH

Compliance 20% - Trucks 10%

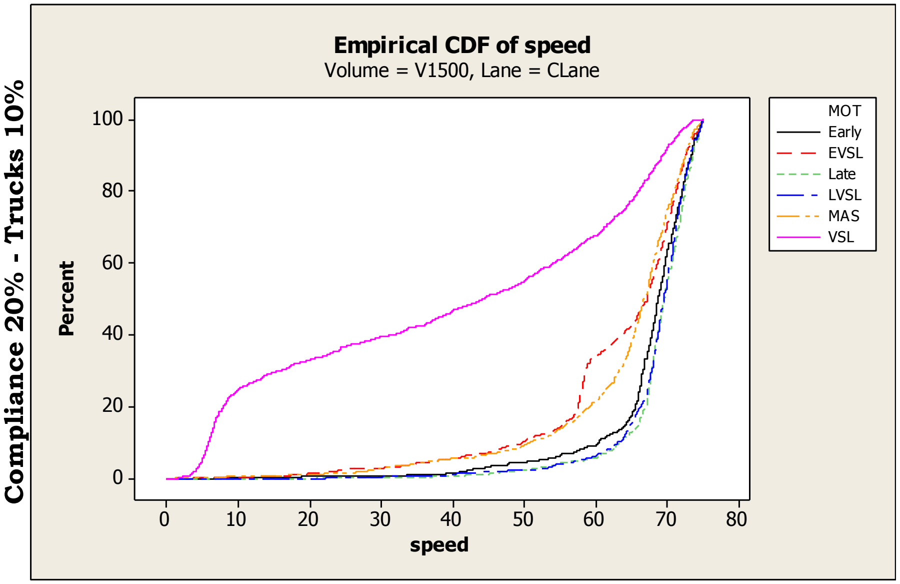


Compliance 20% - Trucks 20%

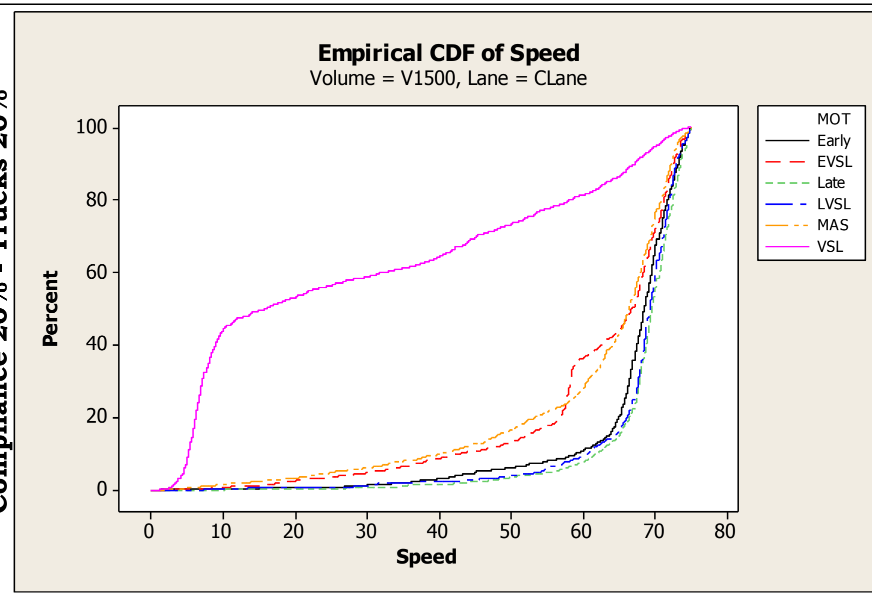


CLOSED LANE - VOLUME 1,500 VPH

Compliance 20% - Trucks 10%

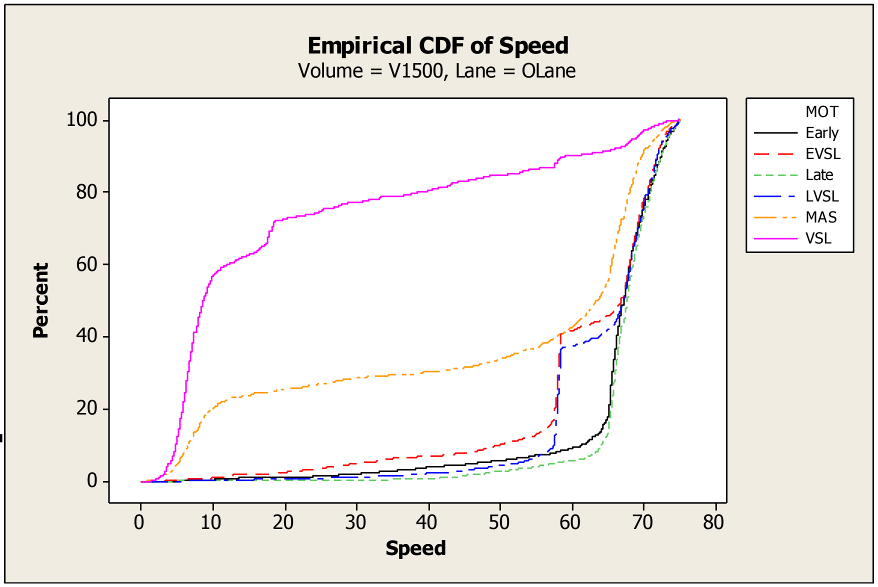


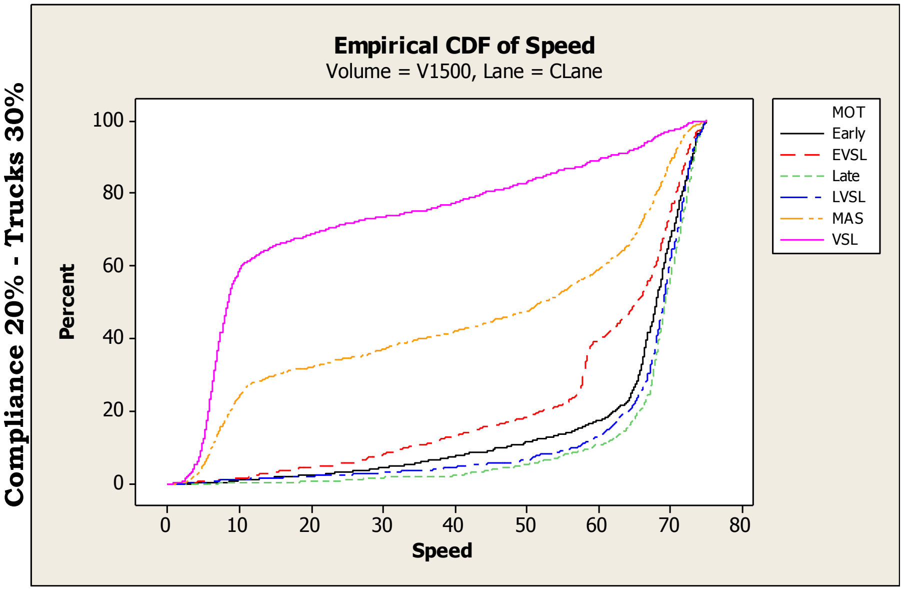
Compliance 20% - Trucks 20%



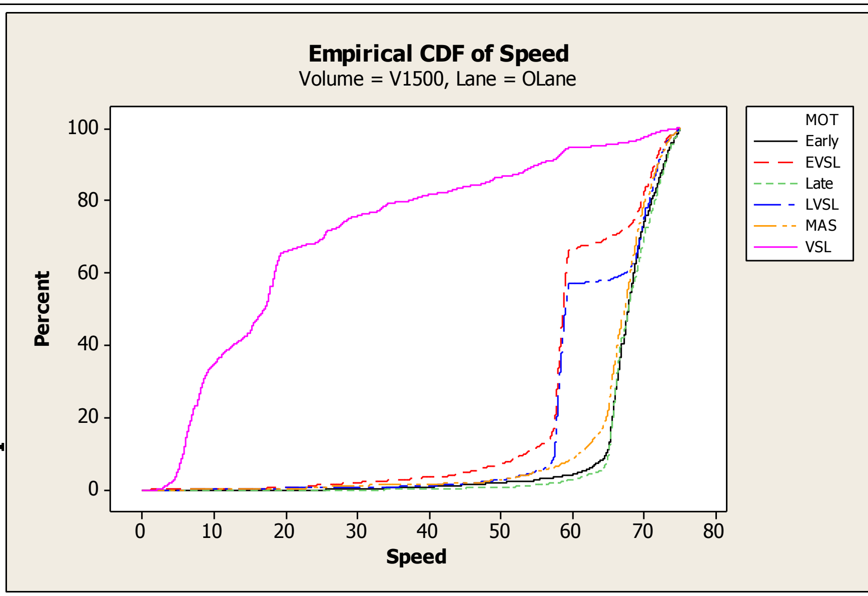
	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH

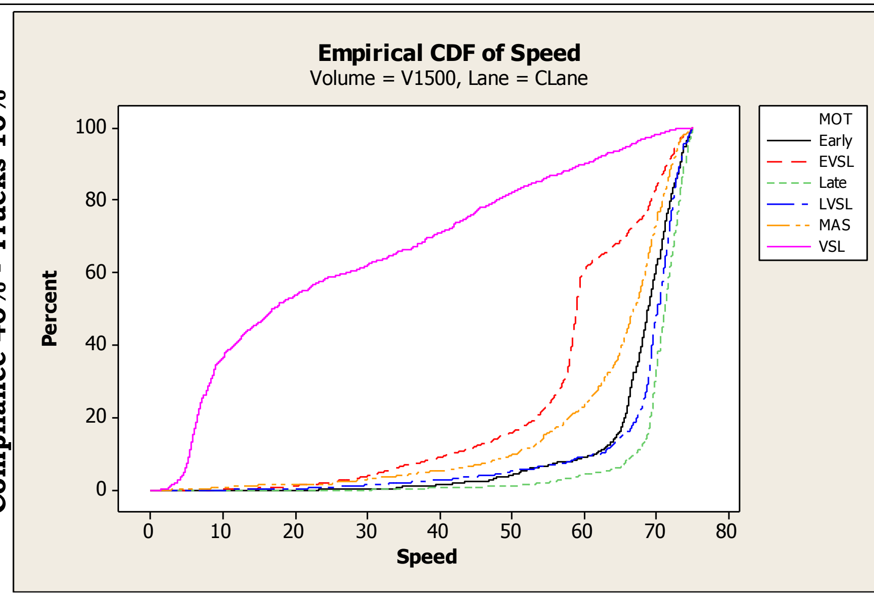
Compliance 20% - Trucks 30%





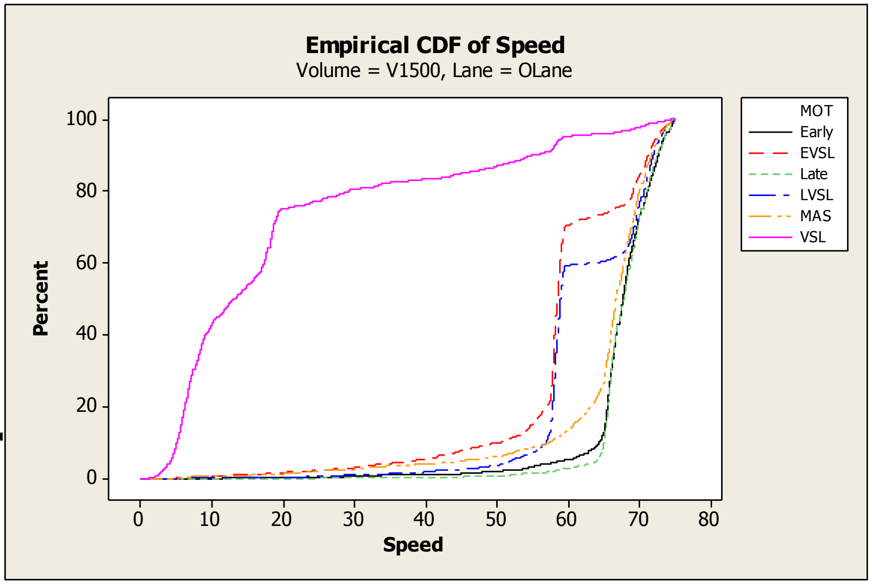
Compliance 40% - Trucks 10%

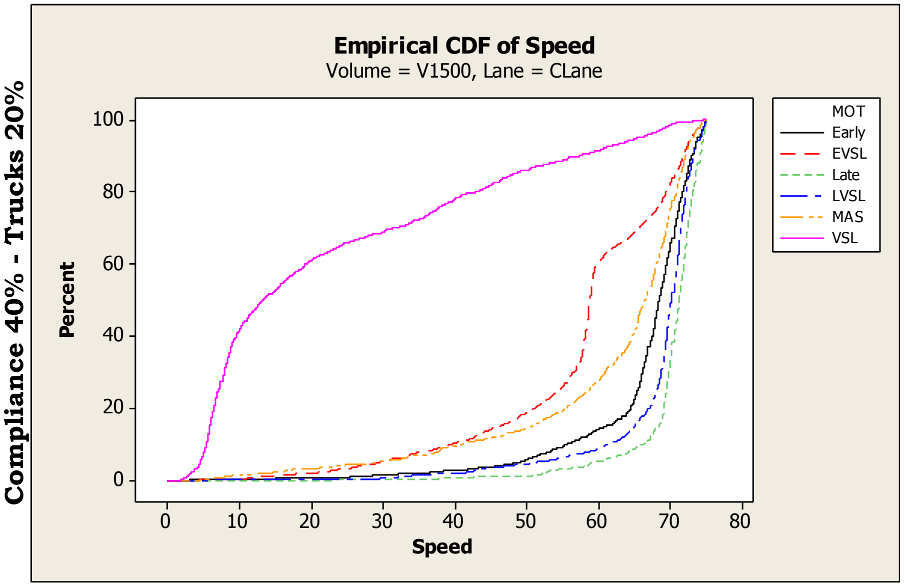




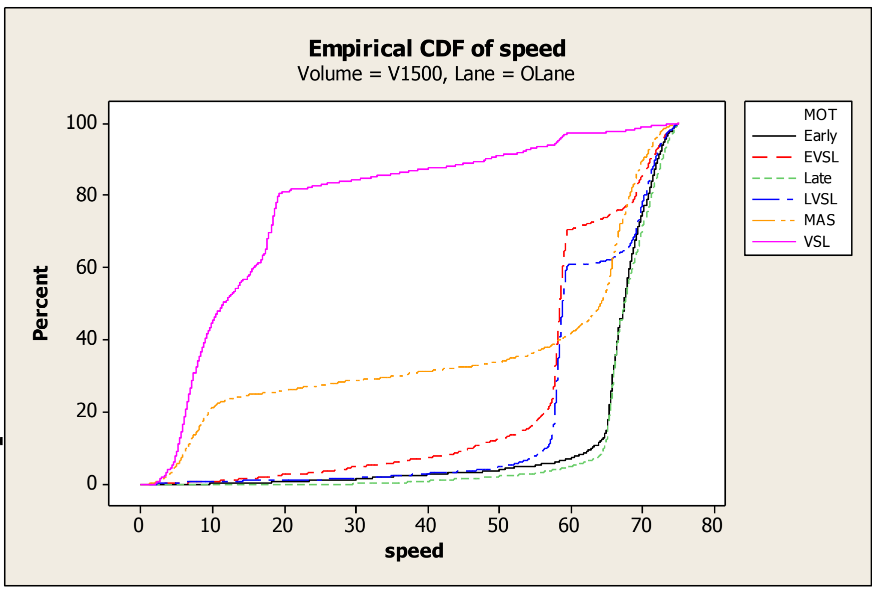
OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH

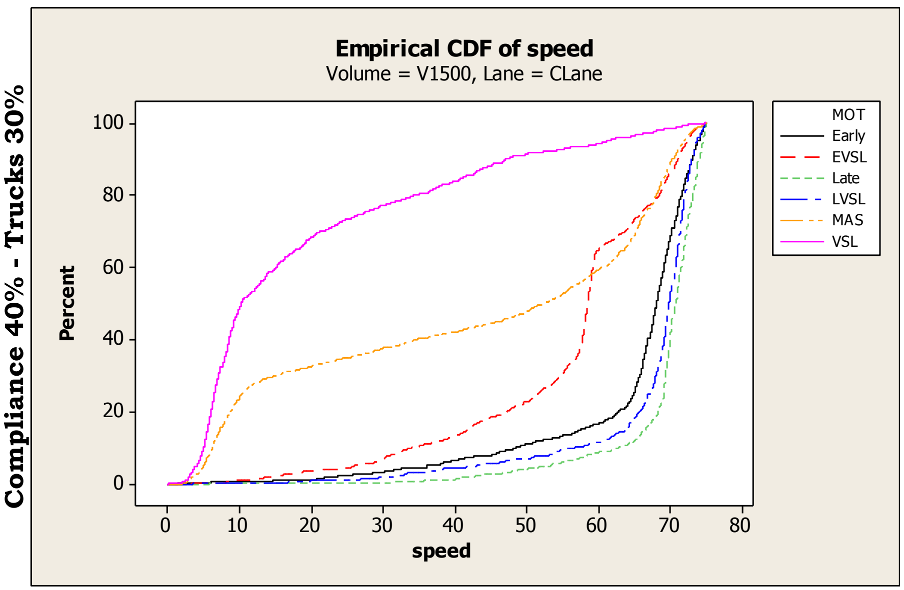
Compliance 40% - Trucks 20%

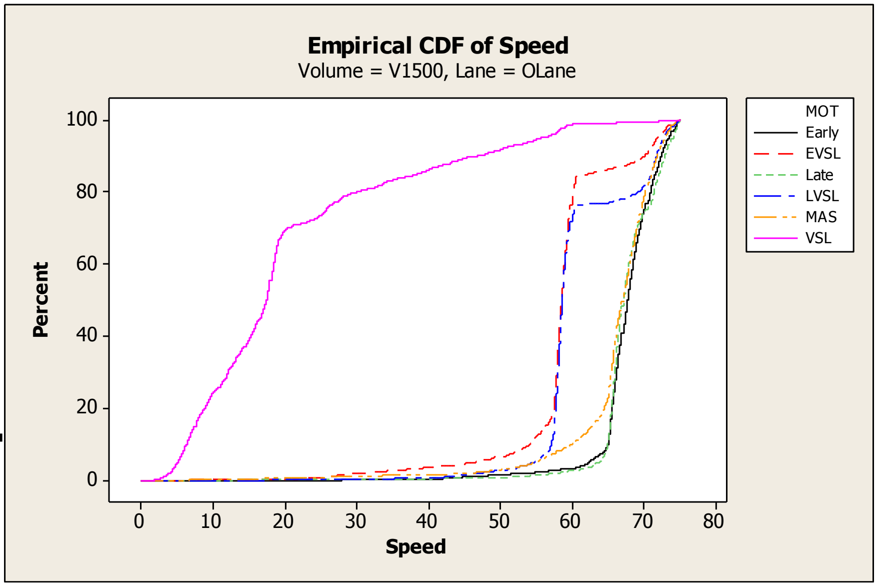
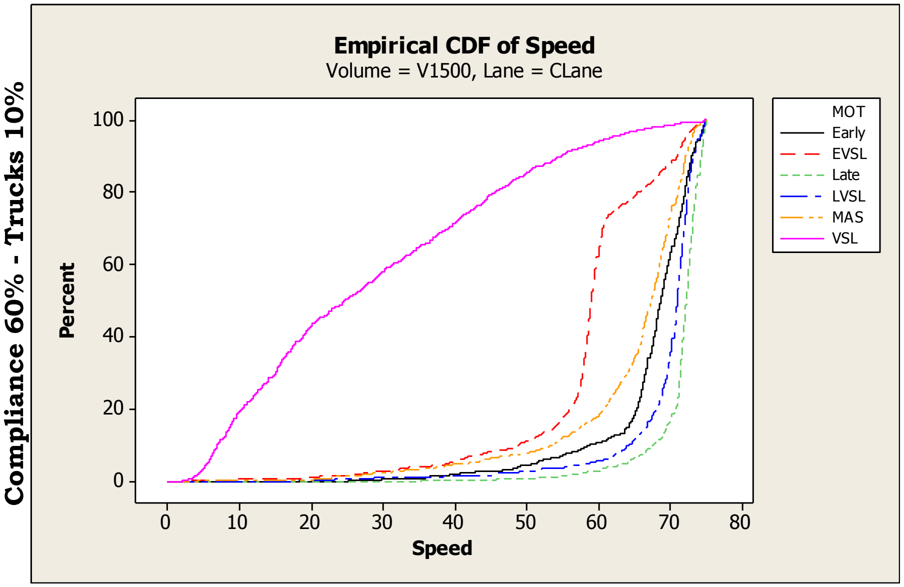
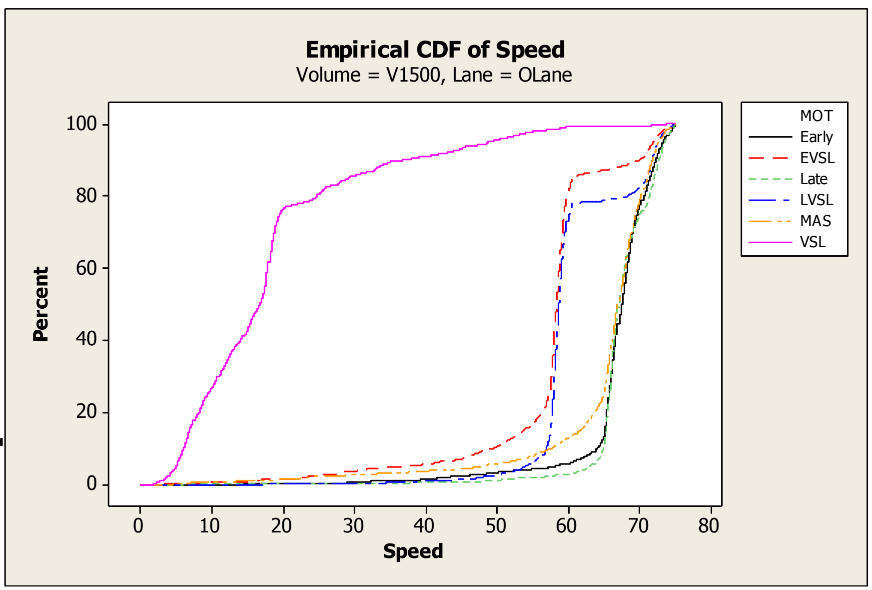
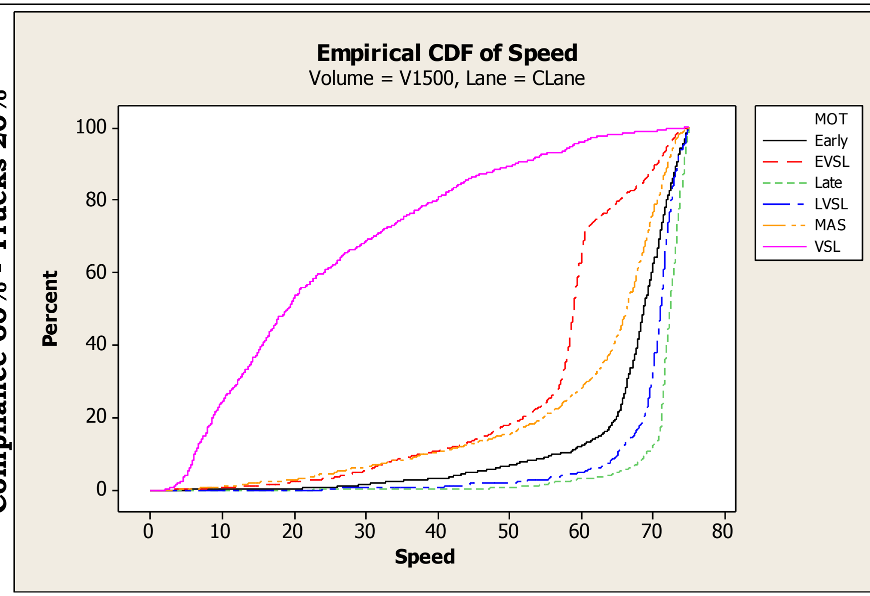




Compliance 40% - Trucks 30%

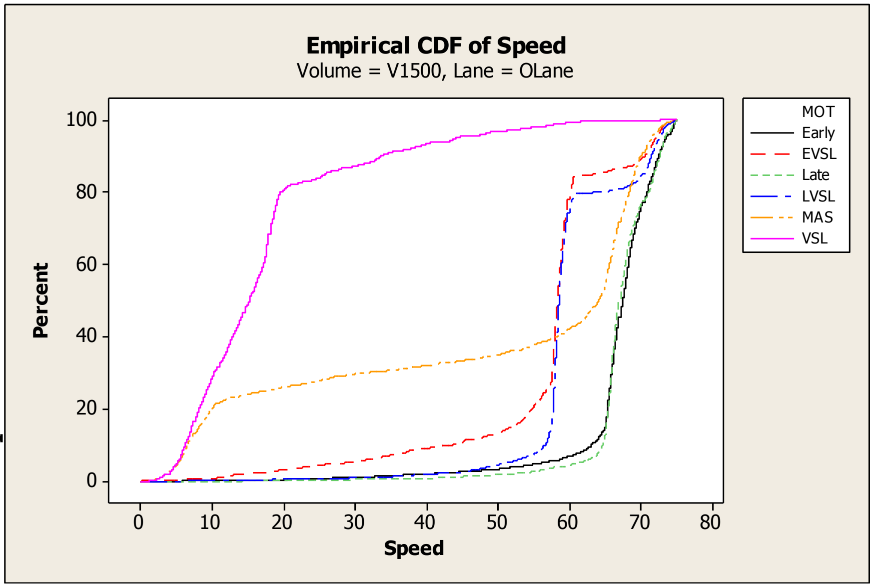


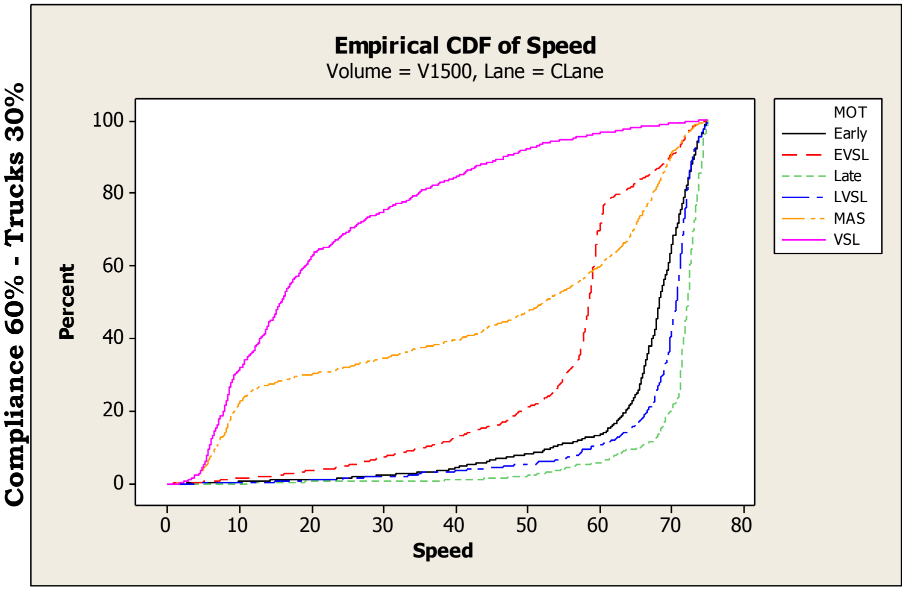


	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH
Compliance 60% - Trucks 10%		
Compliance 60% - Trucks 20%		

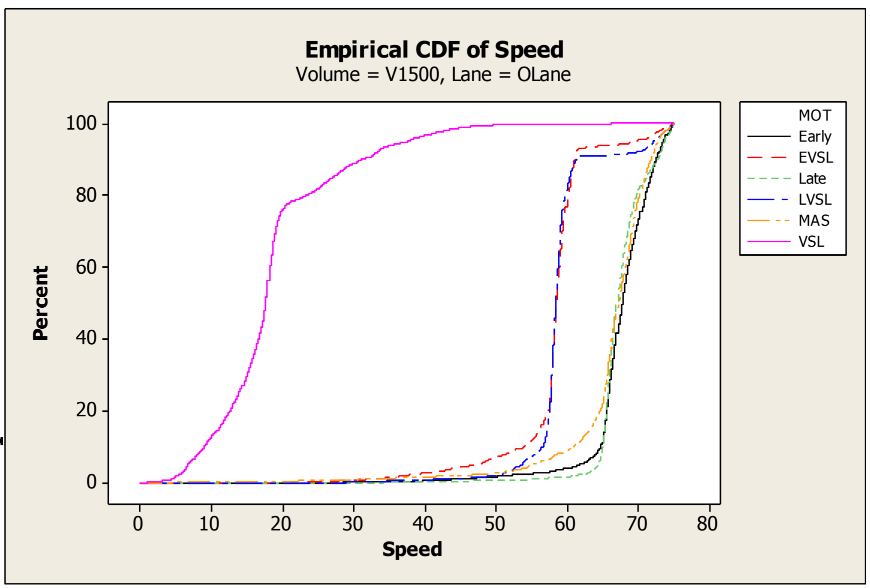
OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH

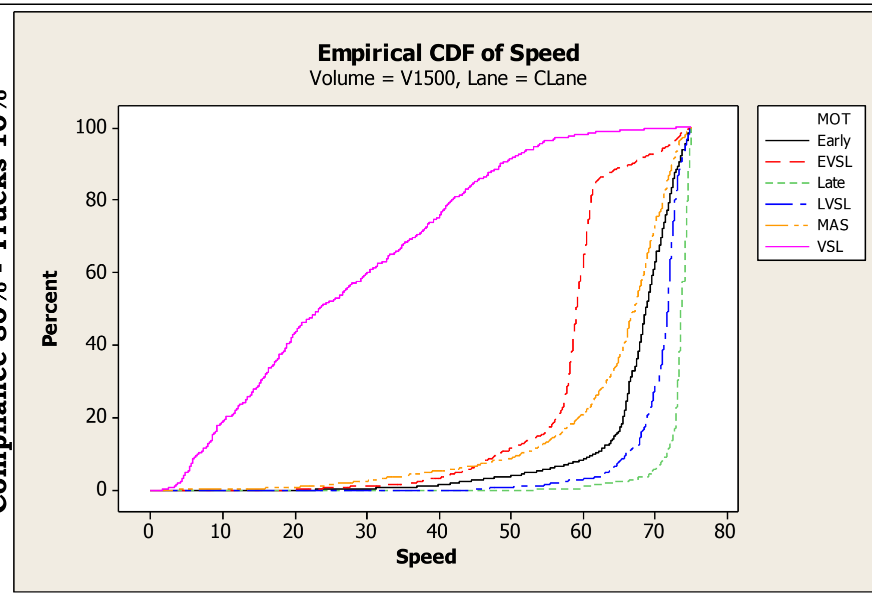
Compliance 60% - Trucks 30%

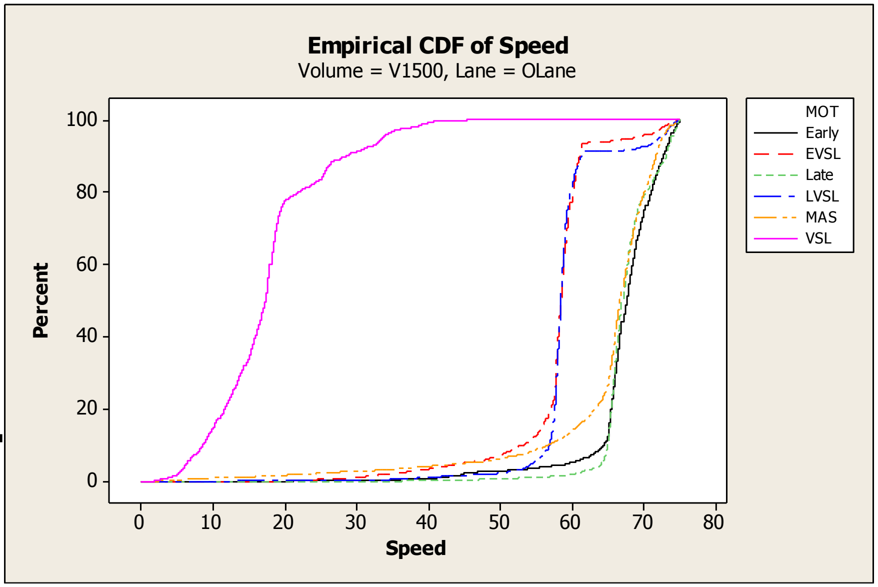
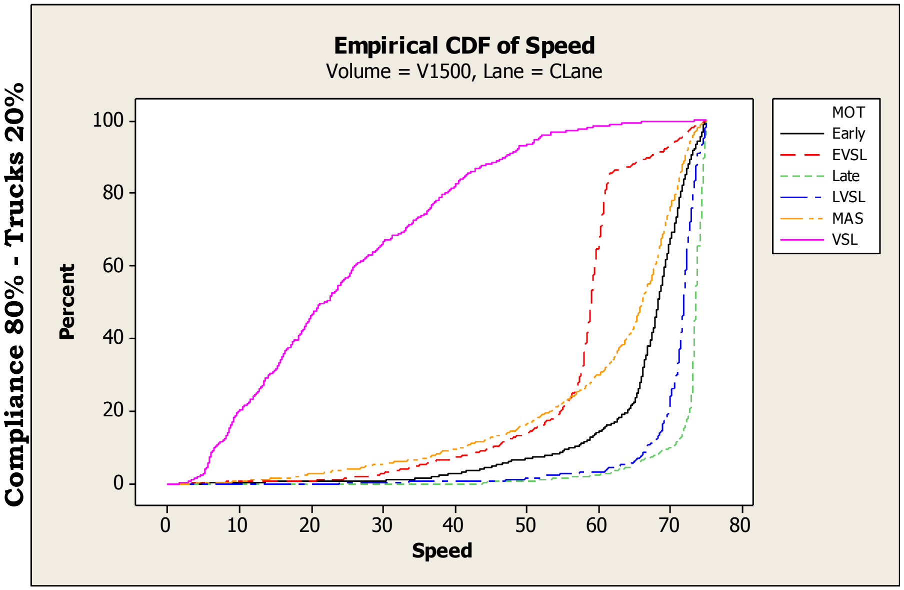
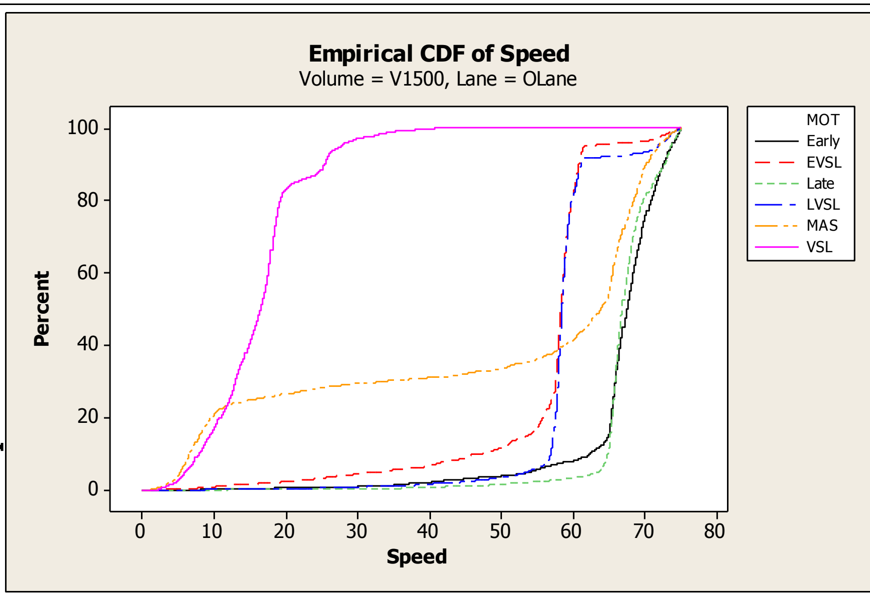
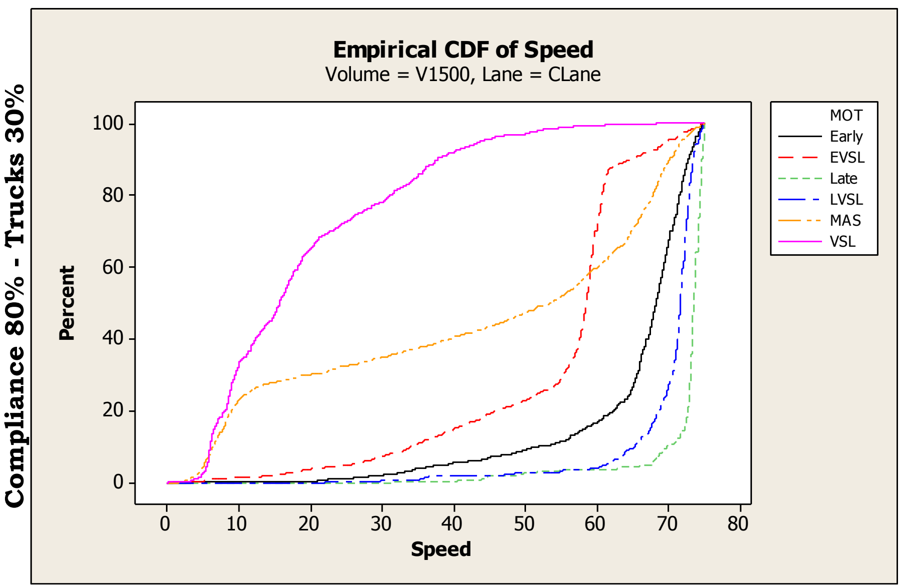




Compliance 80% - Trucks 10%



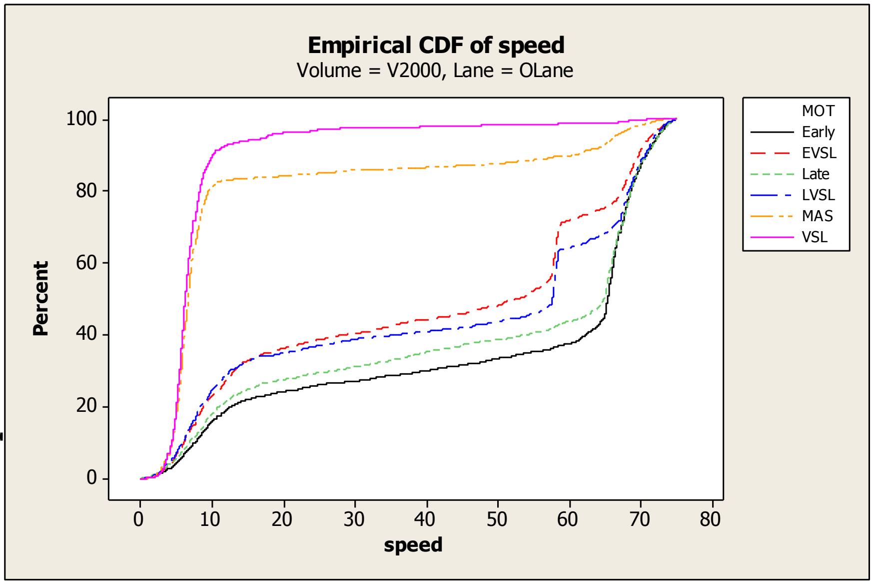


	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

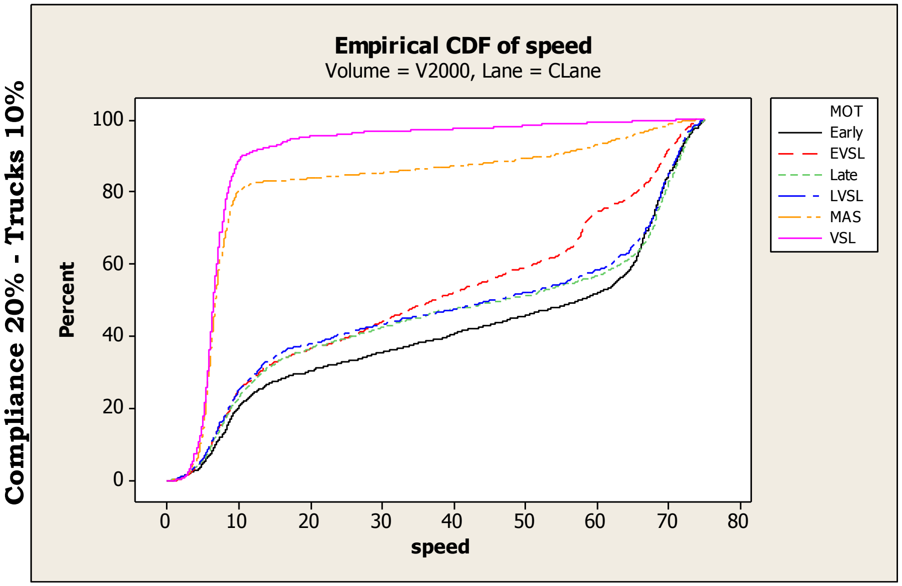
	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH

Compliance 20% - Trucks 10%

OPEN LANE - VOLUME 2,000 VPH

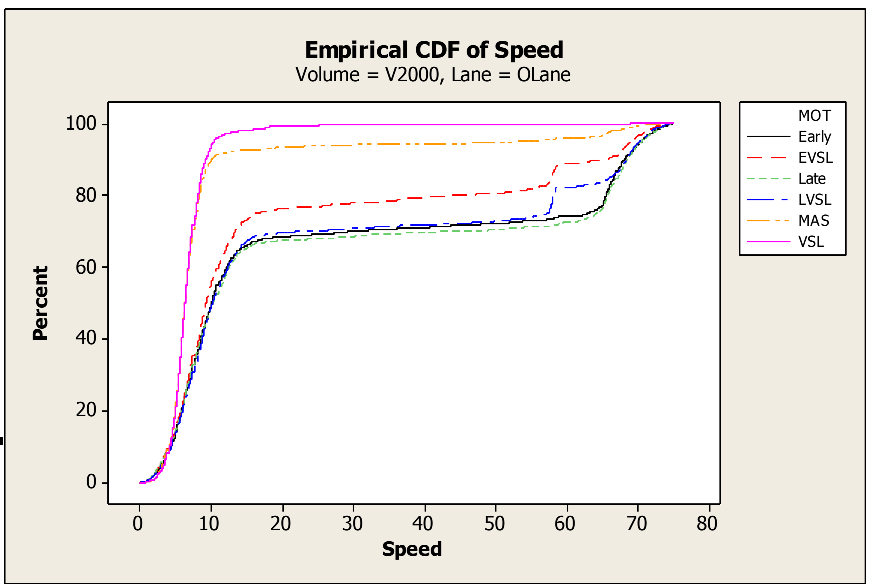


CLOSED LANE - VOLUME 2,000 VPH

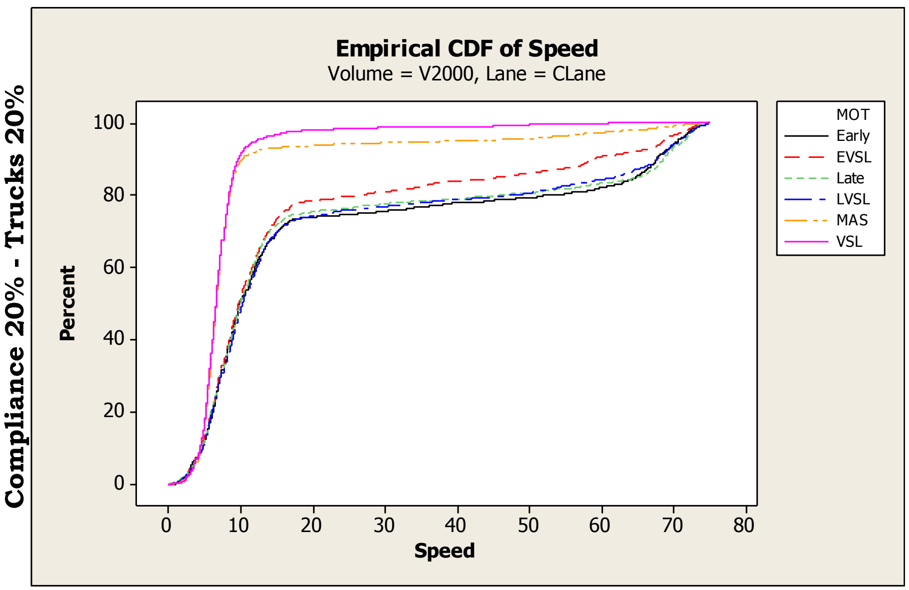


Compliance 20% - Trucks 20%

OPEN LANE - VOLUME 2,000 VPH

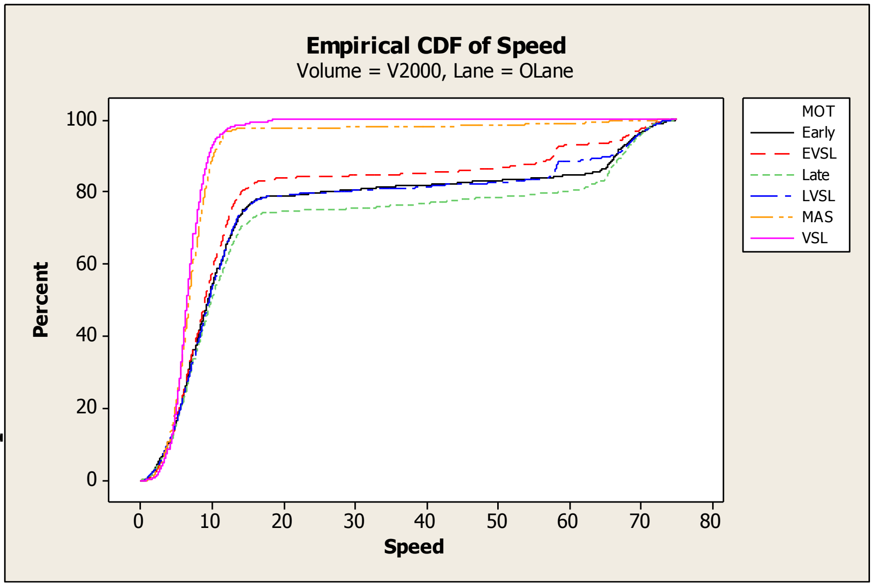


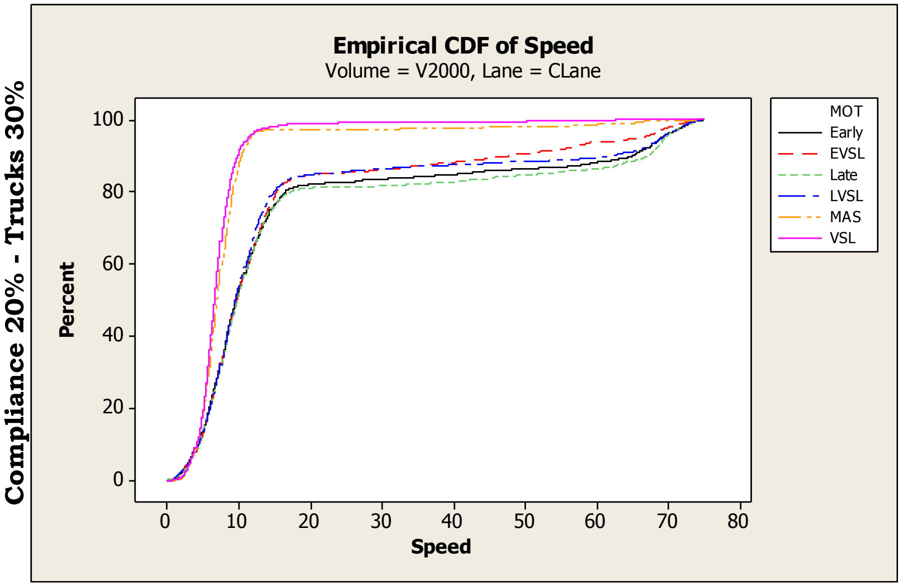
CLOSED LANE - VOLUME 2,000 VPH



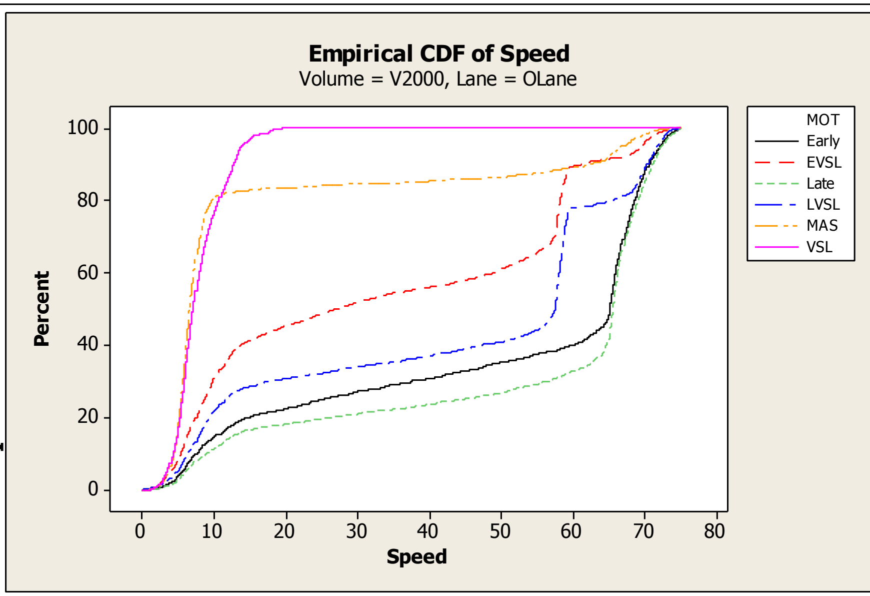
	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH

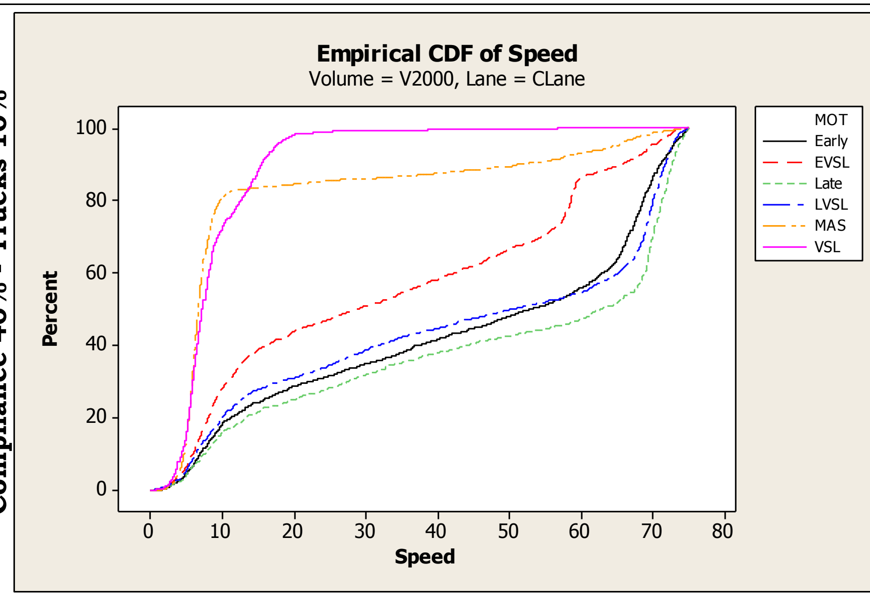
Compliance 20% - Trucks 30%

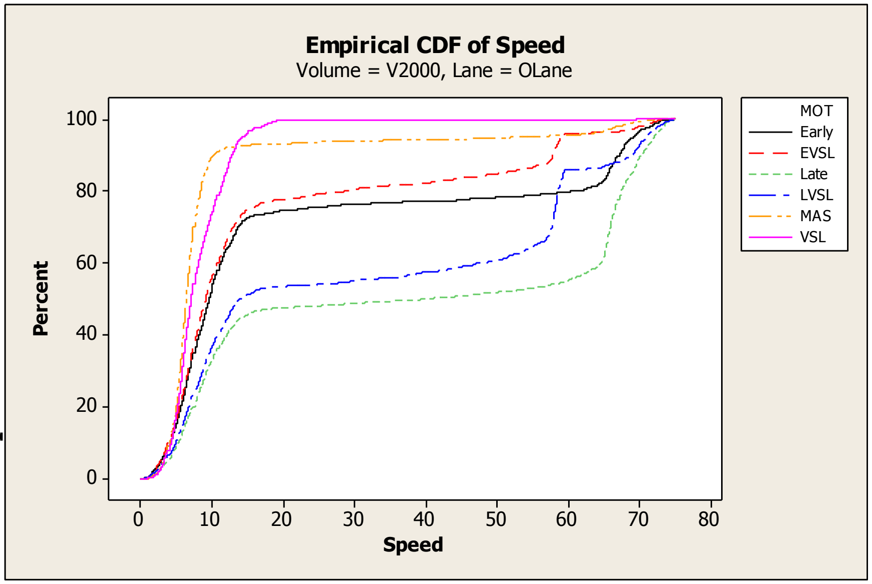
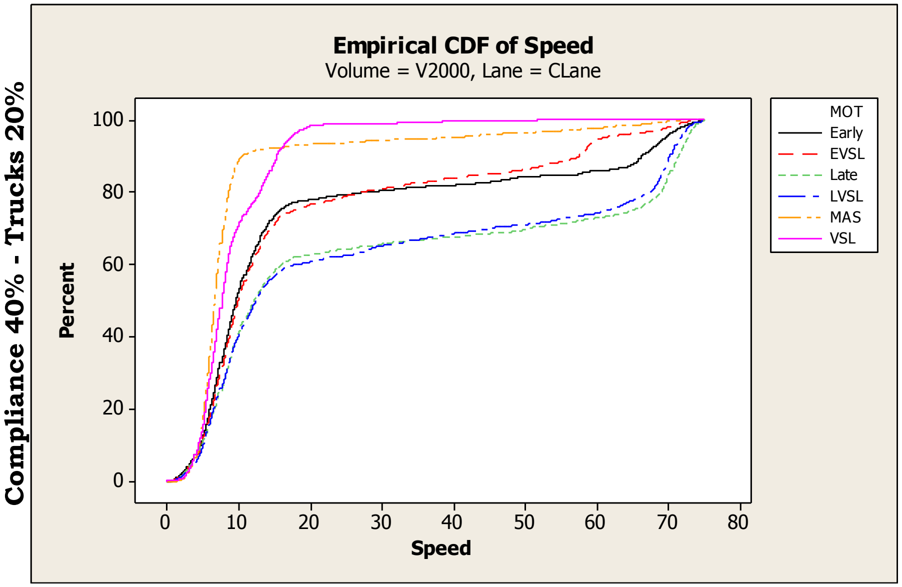
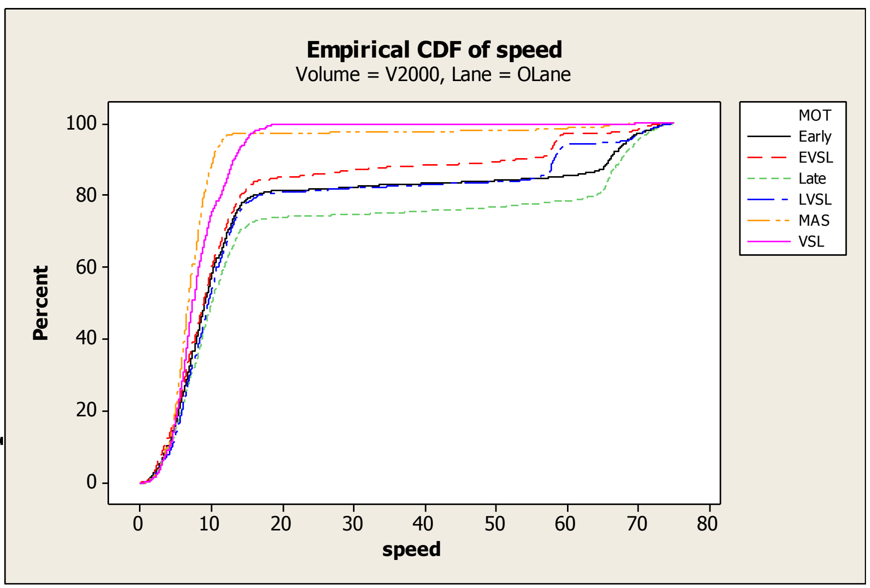
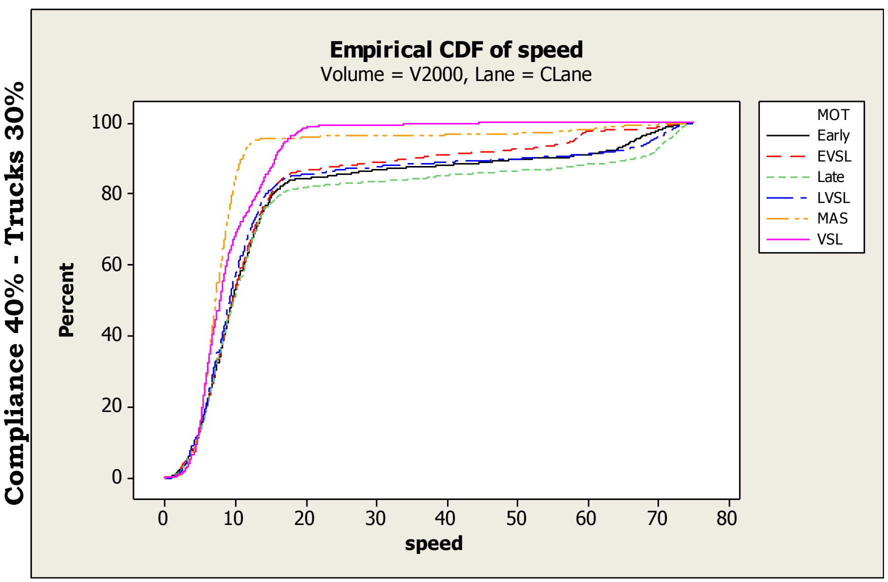


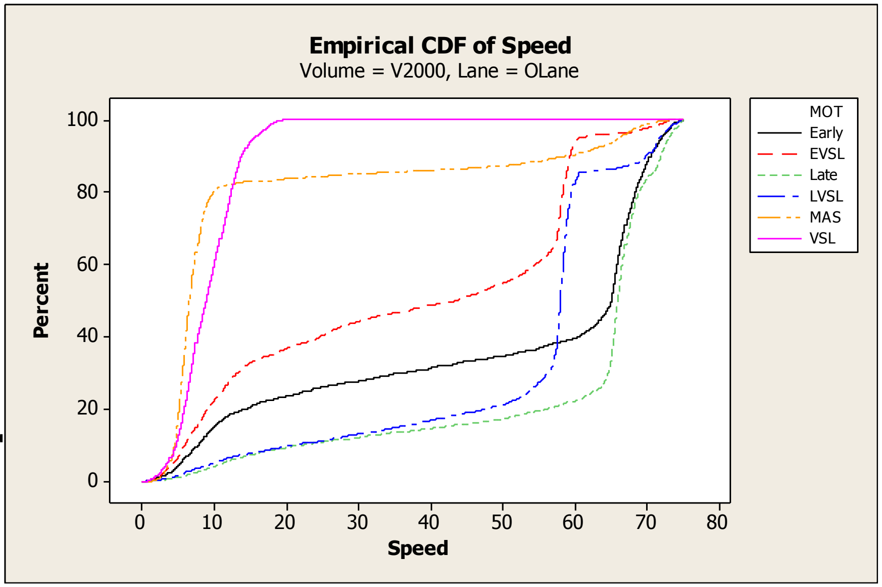
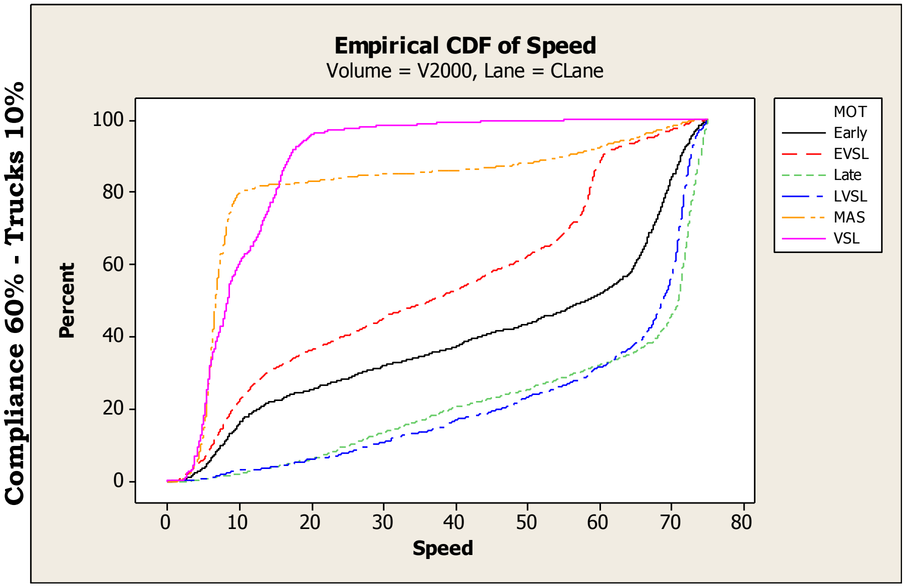
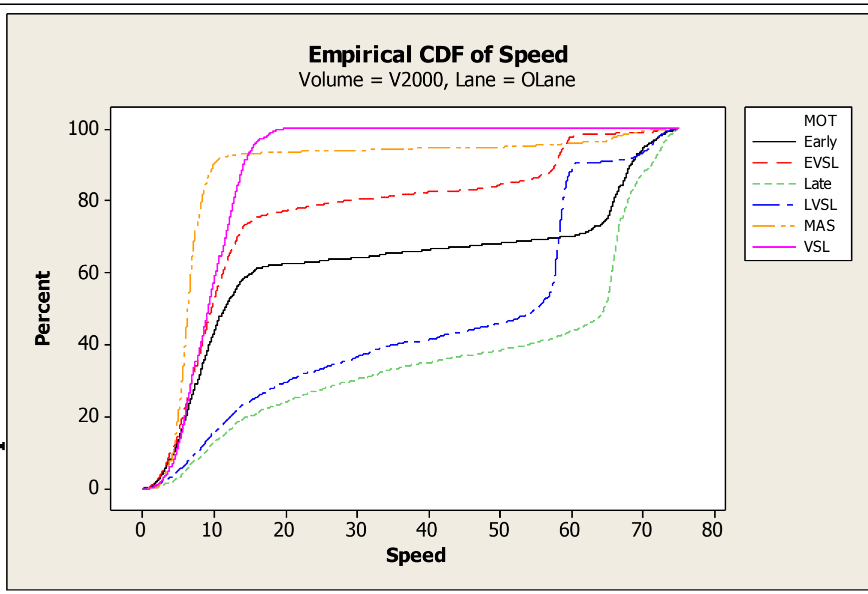
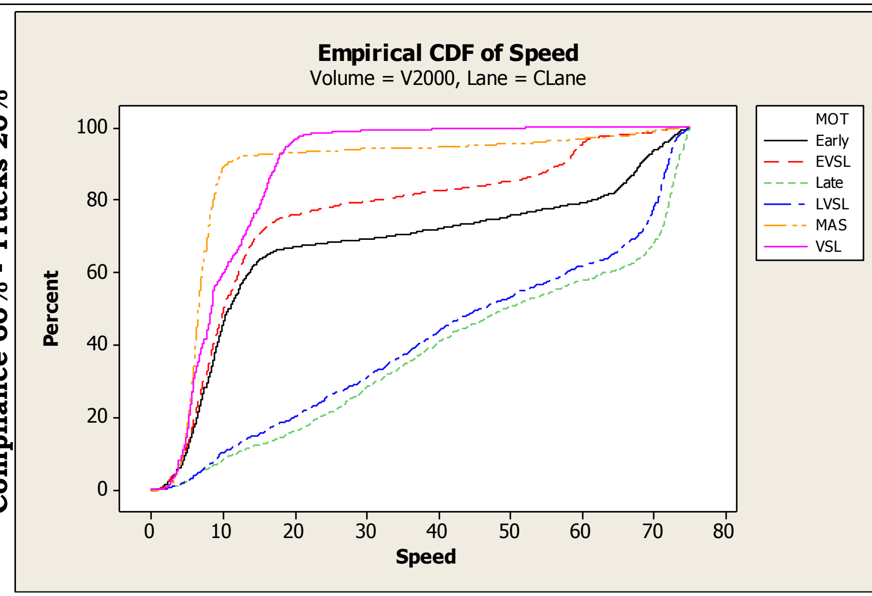


Compliance 40% - Trucks 10%



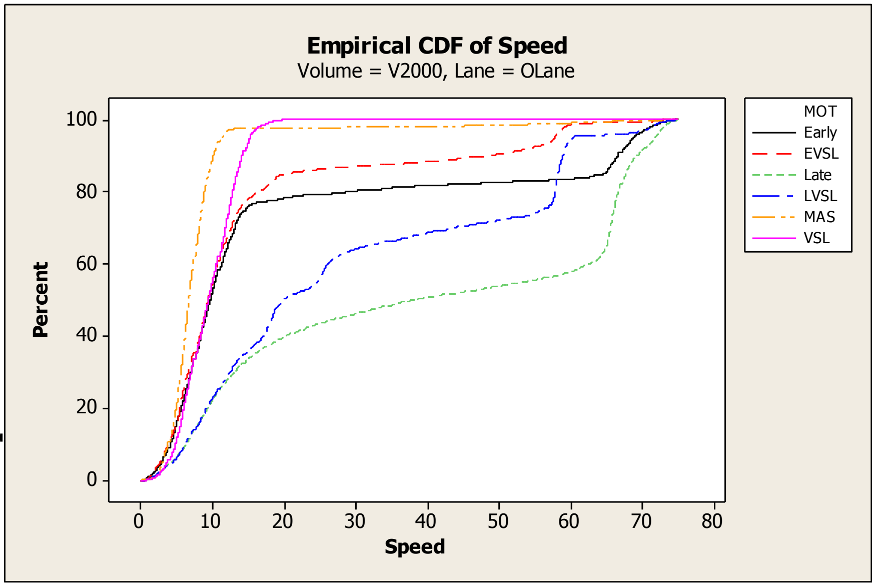


	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 40% - Trucks 20%		
Compliance 40% - Trucks 30%		

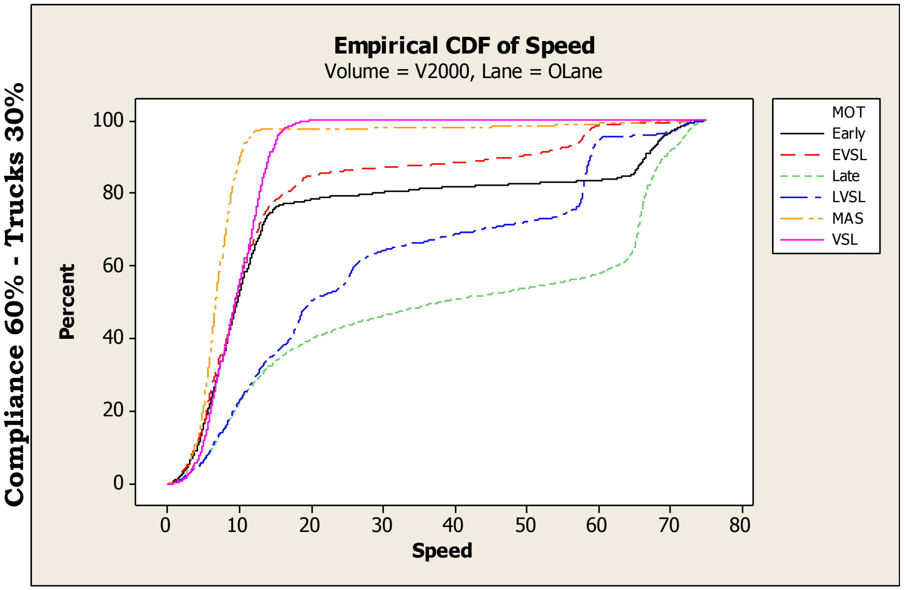
	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 60% - Trucks 10%		
Compliance 60% - Trucks 20%		

	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 60% - Trucks 30%	See first chart below	See second chart below
Compliance 80% - Trucks 10%	See third chart below	See fourth chart below

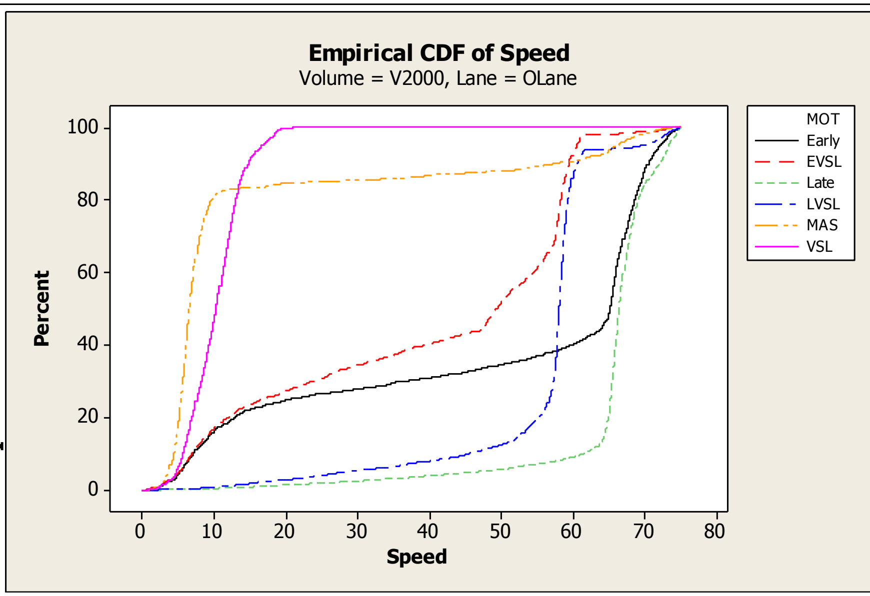
OPEN LANE - VOLUME 2,000 VPH — Compliance 60% - Trucks 30%



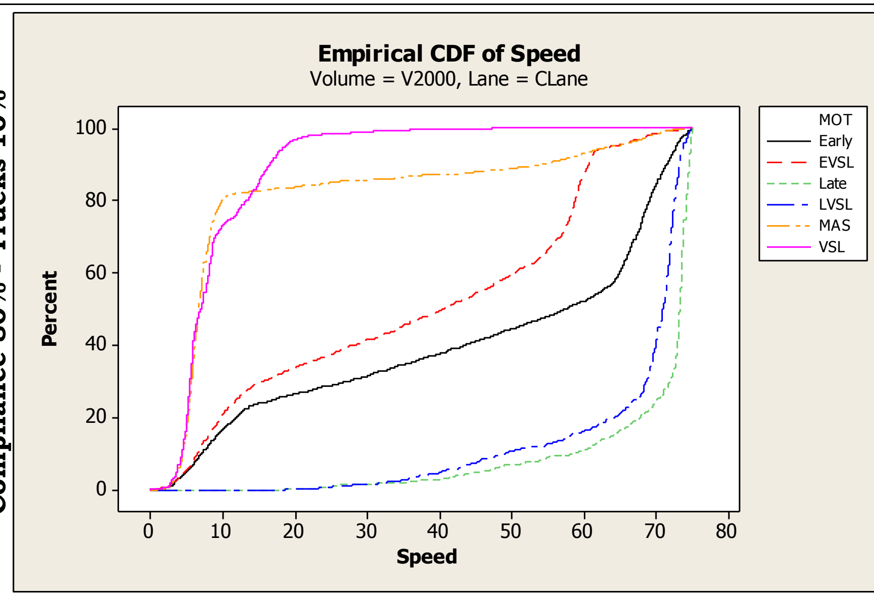
CLOSED LANE - VOLUME 2,000 VPH — Compliance 60% - Trucks 30%



OPEN LANE - VOLUME 2,000 VPH — Compliance 80% - Trucks 10%

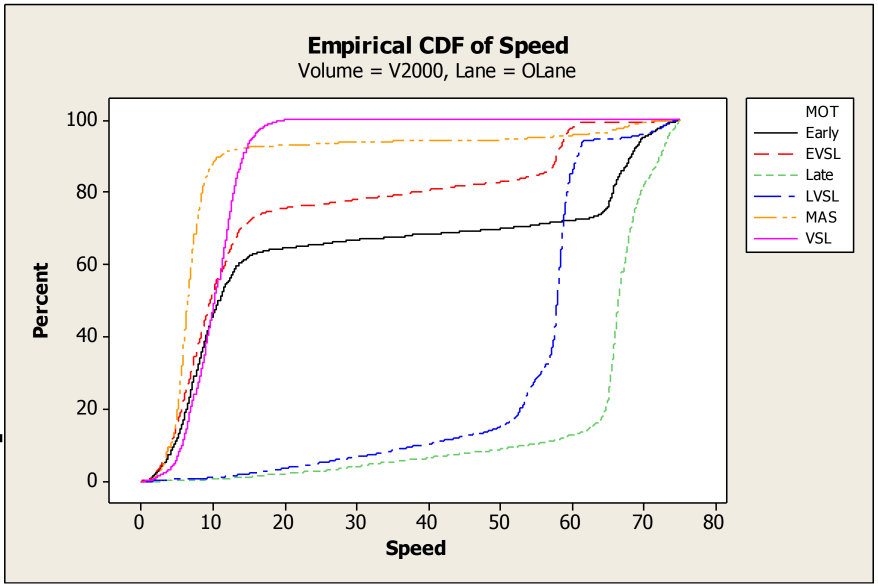


CLOSED LANE - VOLUME 2,000 VPH — Compliance 80% - Trucks 10%

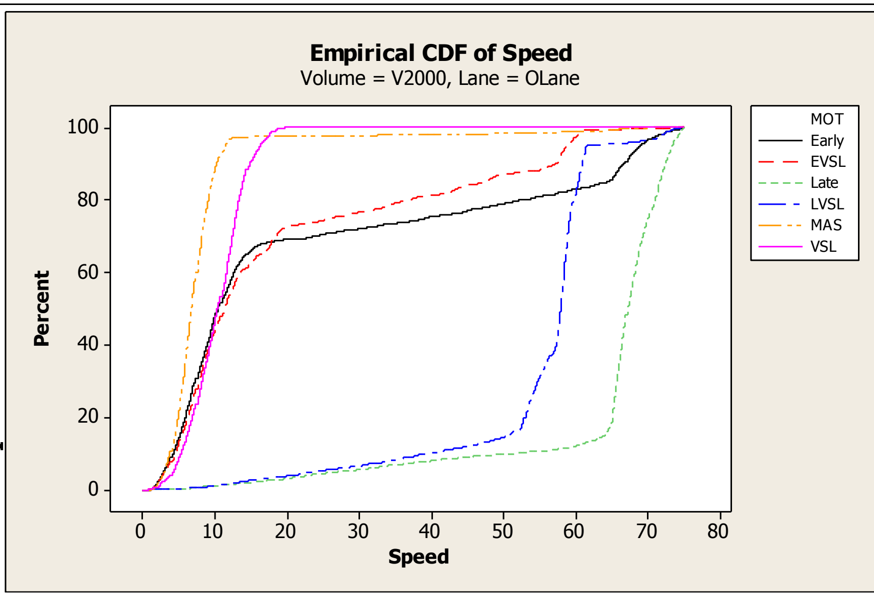


OPEN LANE - VOLUME 2,000 VPH

Compliance 80% - Trucks 20%

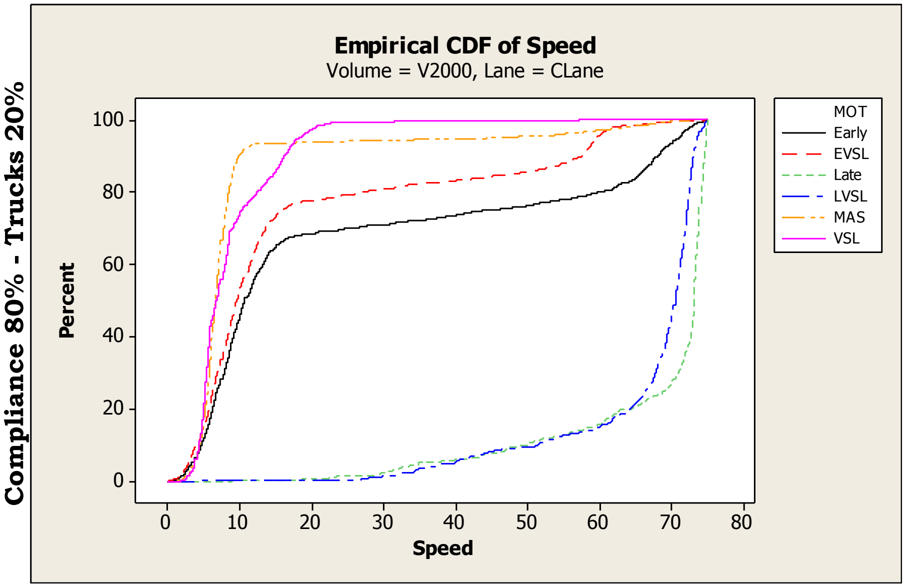


Compliance 80% - Trucks 30%

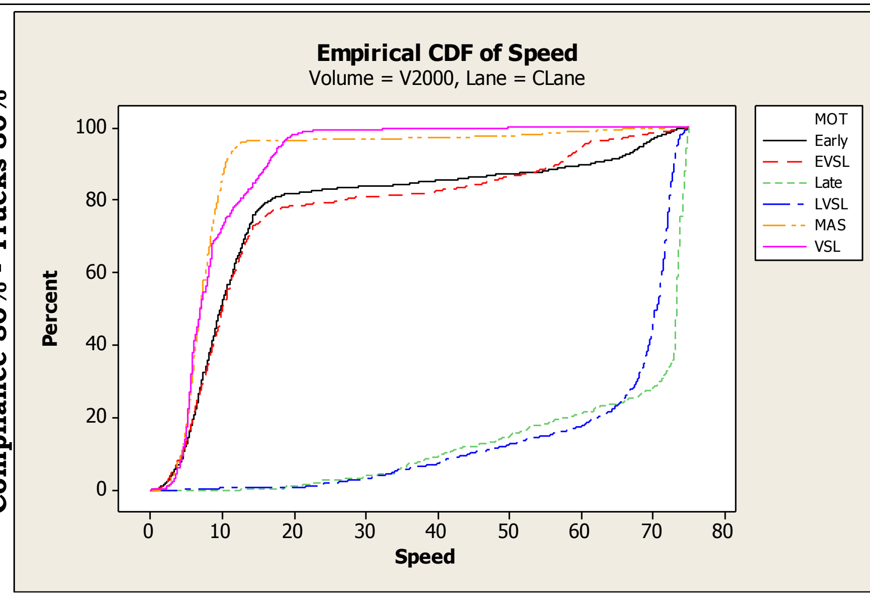


CLOSED LANE - VOLUME 2,000 VPH

Compliance 80% - Trucks 20%

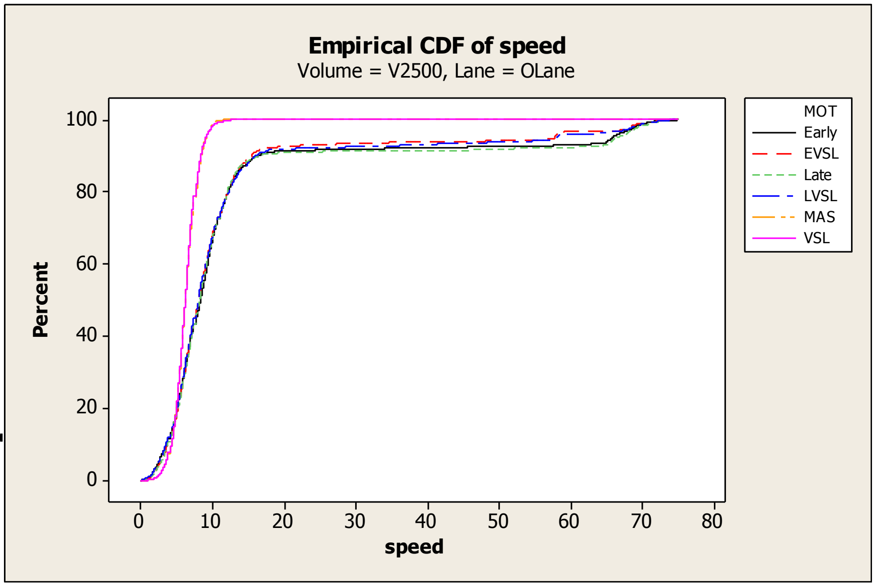


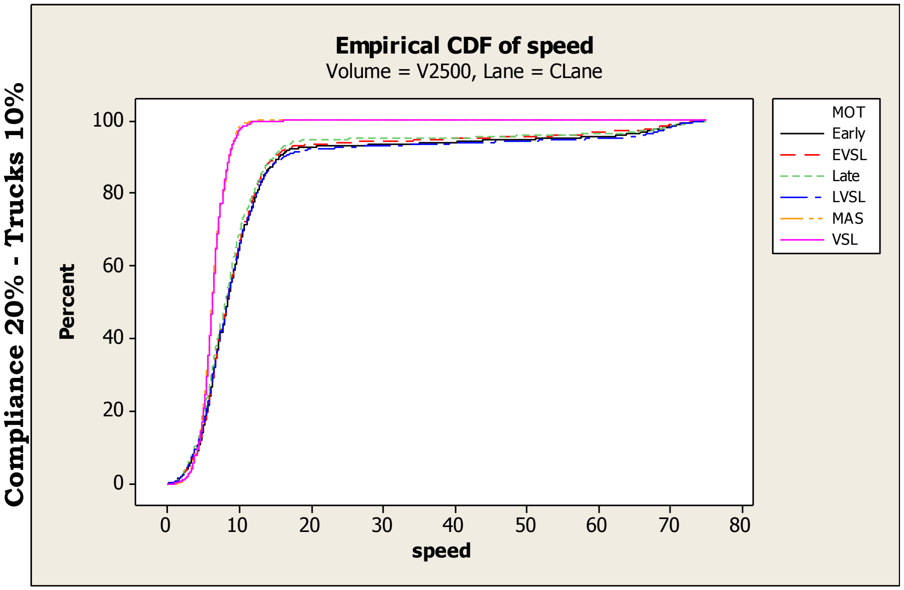
Compliance 80% - Trucks 30%



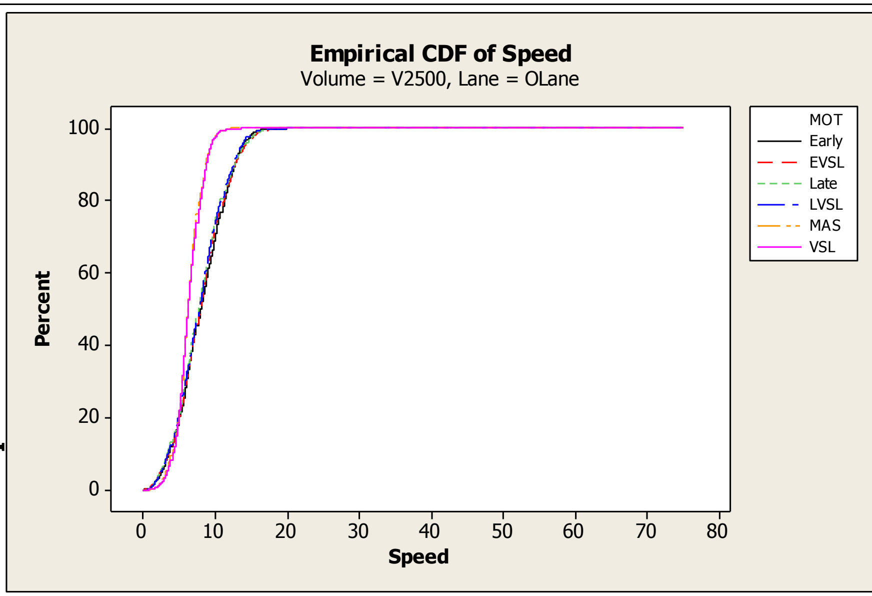
OPEN LANE - VOLUME 2,500 VPH | **CLOSED LANE - VOLUME 2,500 VPH**

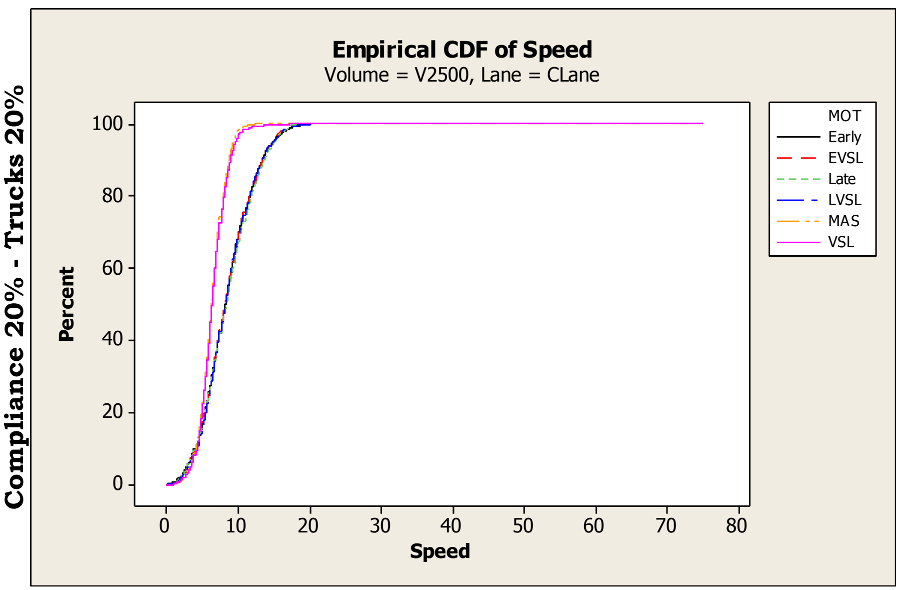
Compliance 20% - Trucks 10%

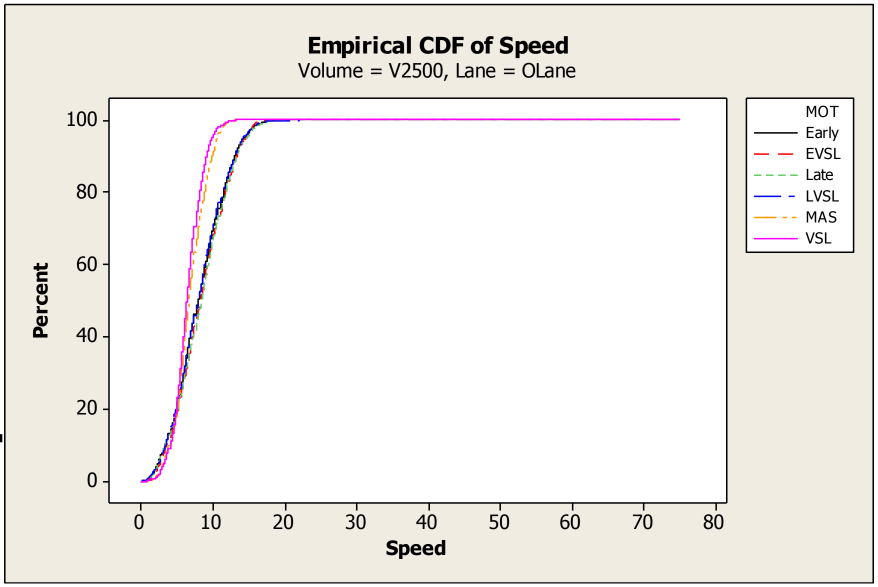
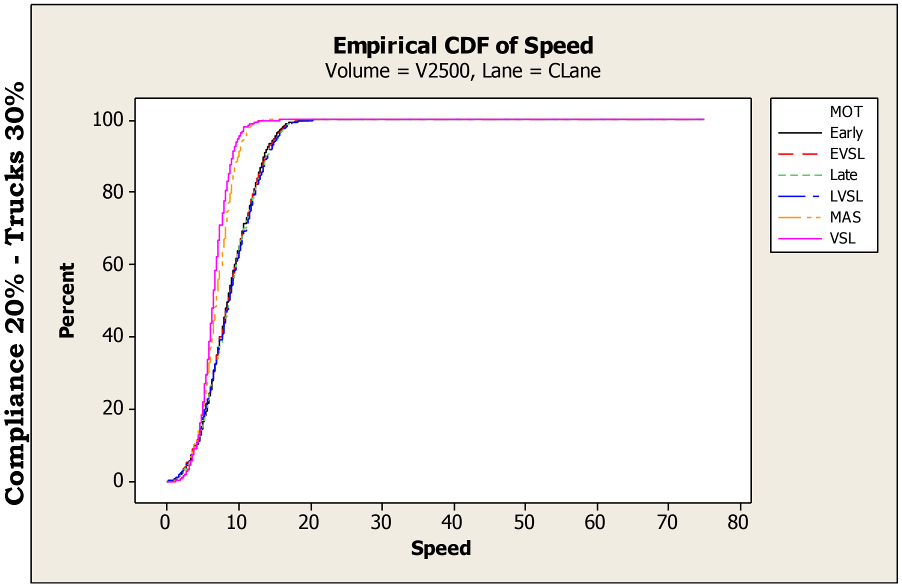
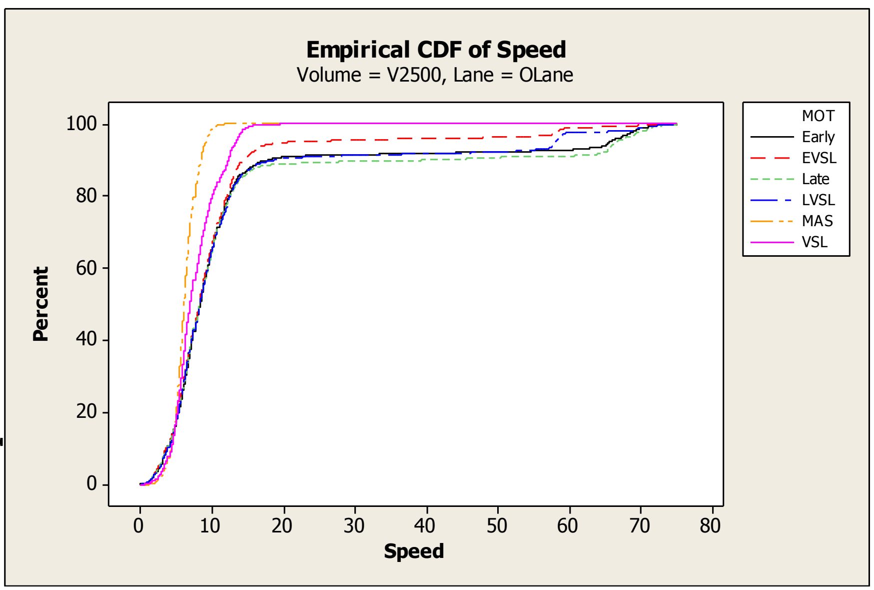
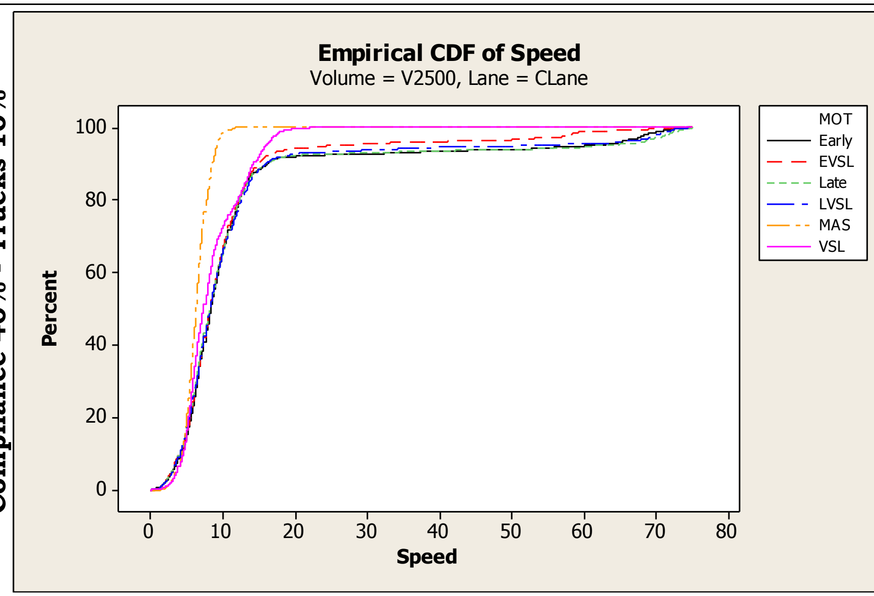




Compliance 20% - Trucks 20%





	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH
Compliance 20% - Trucks 30%		
Compliance 40% - Trucks 10%		

Compliance 20% - Trucks 30%, OPEN LANE - VOLUME 2,500 VPH:

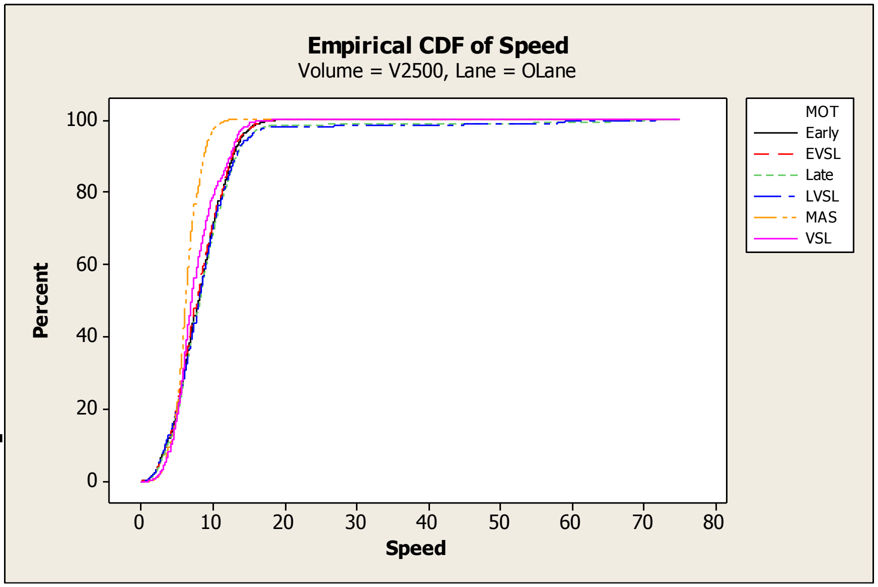
Compliance 20% - Trucks 30%, CLOSED LANE - VOLUME 2,500 VPH:

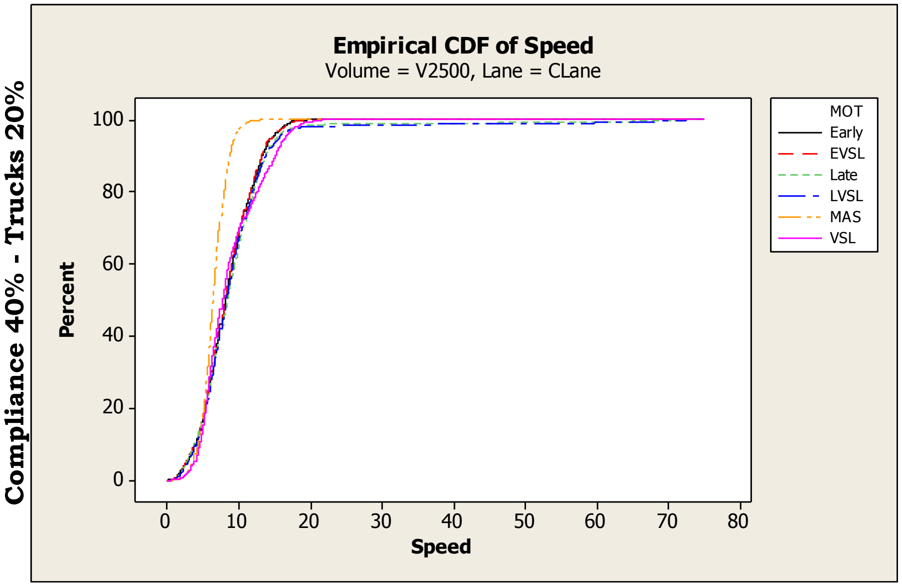
Compliance 40% - Trucks 10%, OPEN LANE - VOLUME 2,500 VPH:

Compliance 40% - Trucks 10%, CLOSED LANE - VOLUME 2,500 VPH:

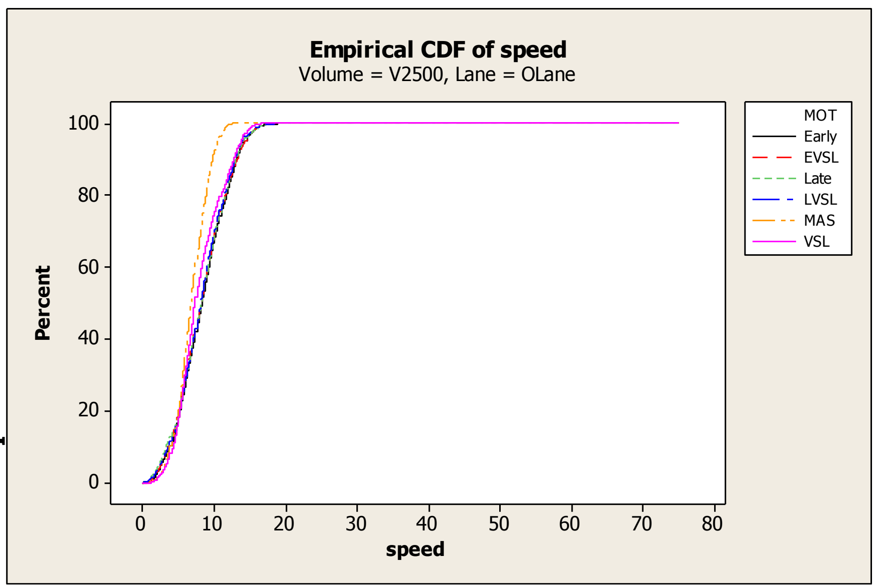
OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH

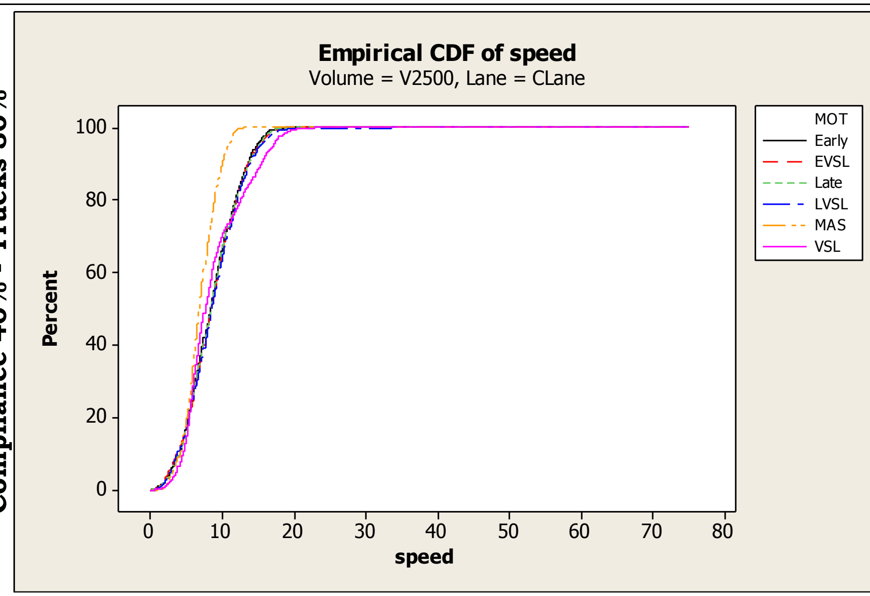
Compliance 40% - Trucks 20%





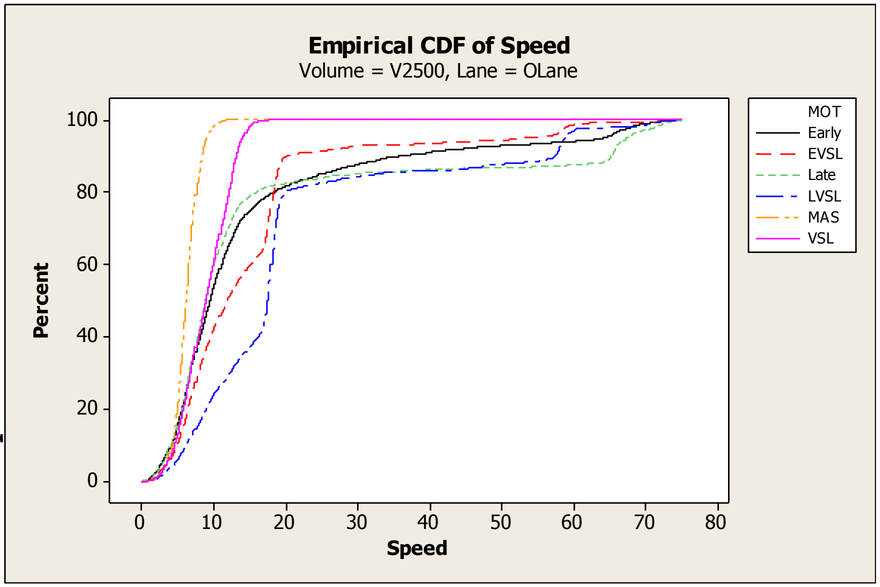
Compliance 40% - Trucks 30%

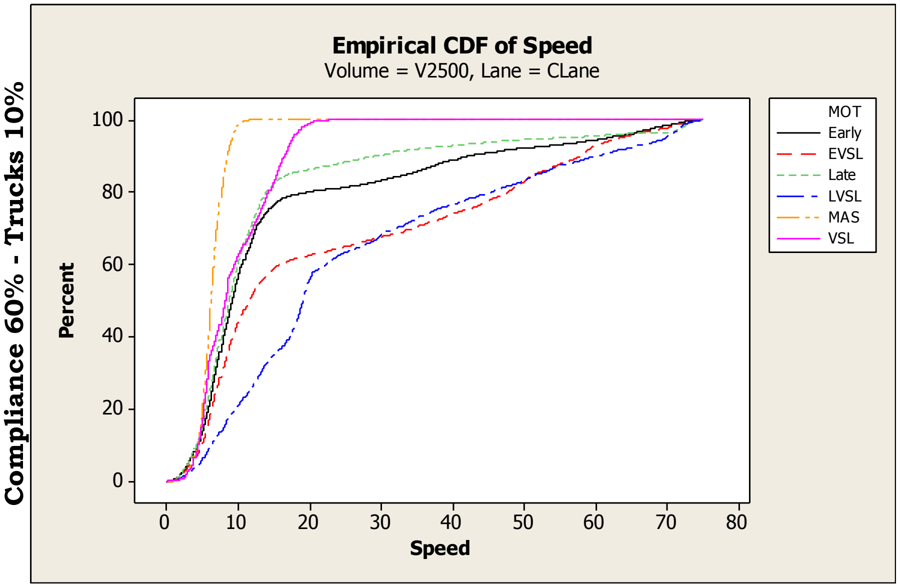




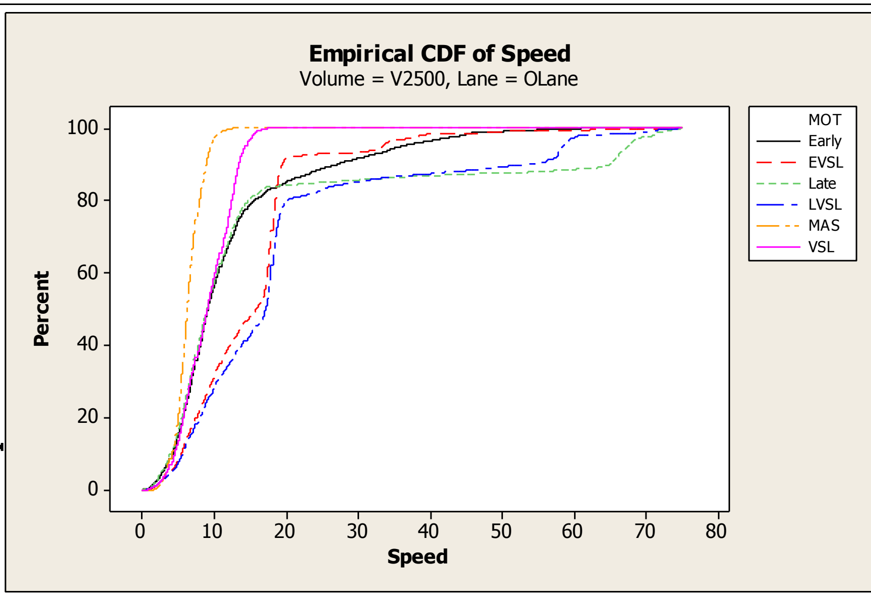
OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH

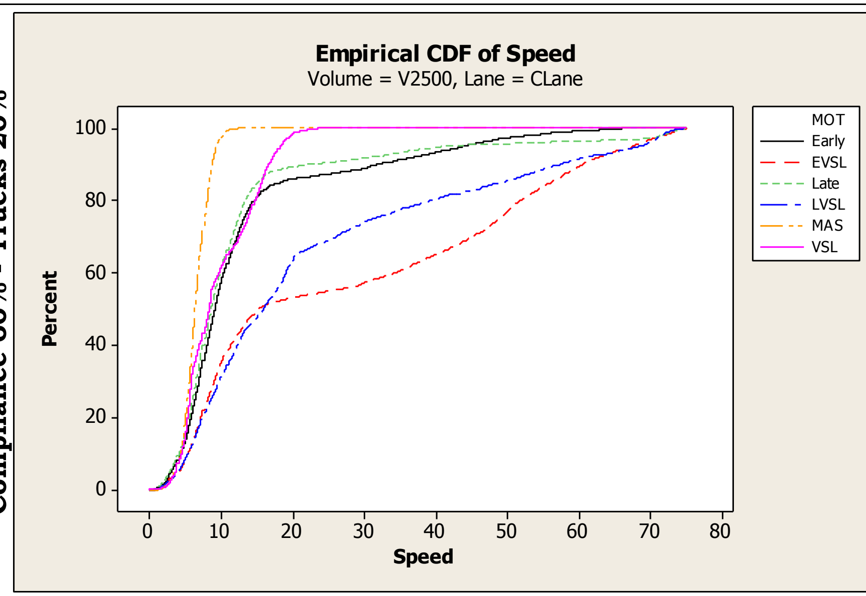
Compliance 60% - Trucks 10%



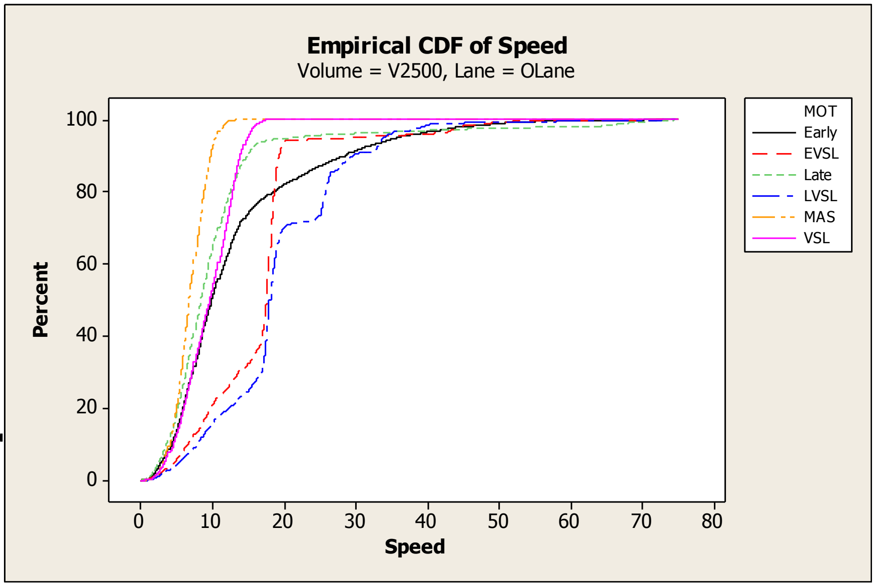


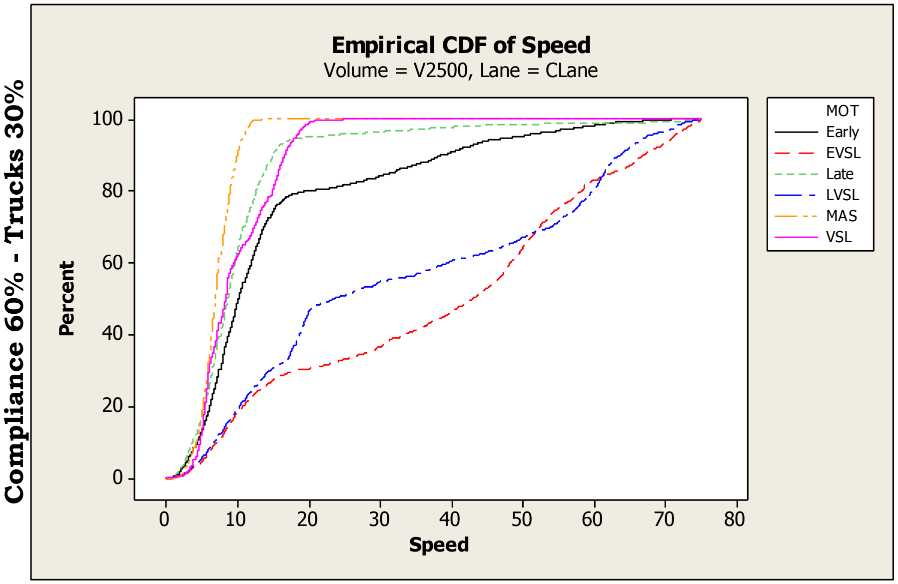
Compliance 60% - Trucks 20%

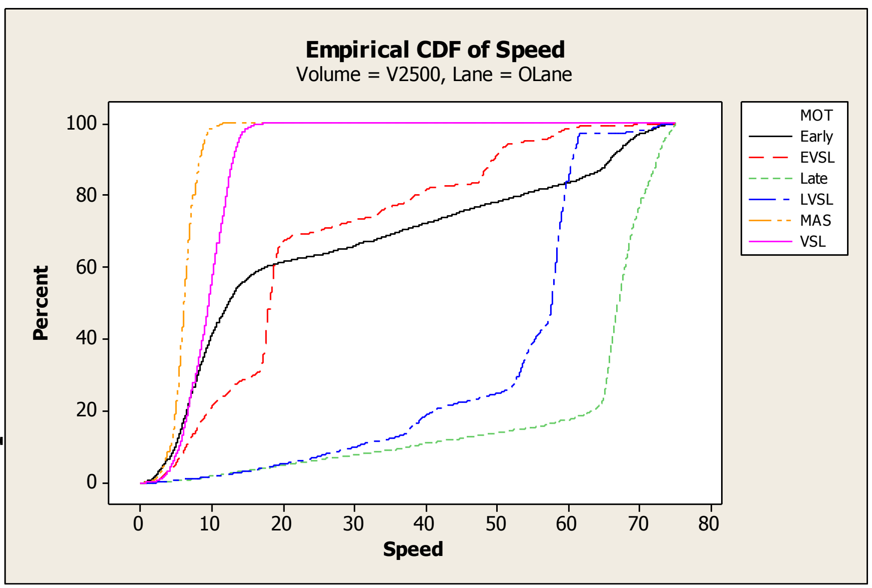


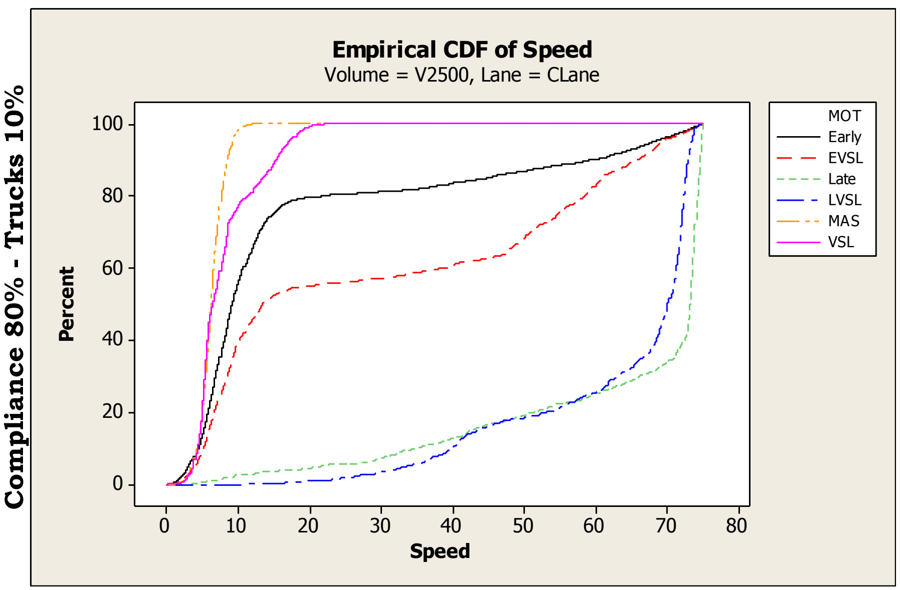


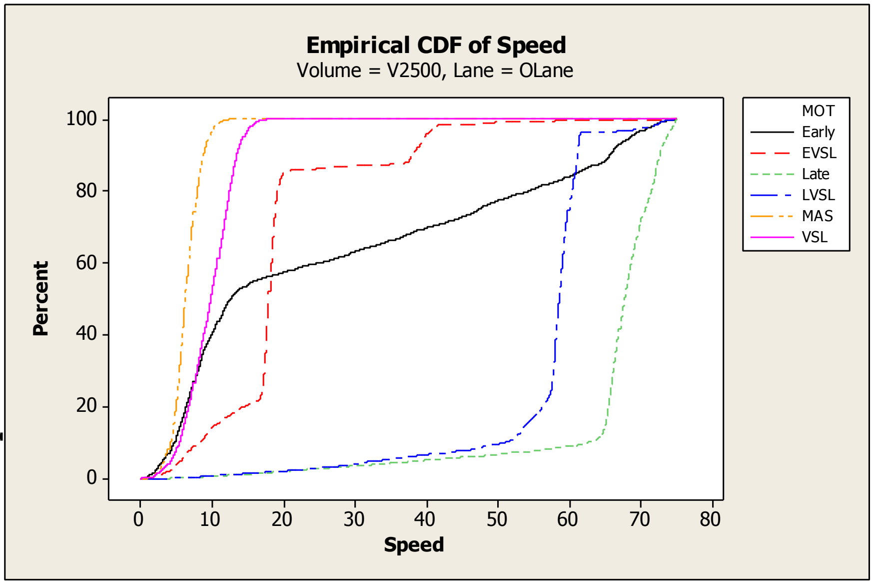
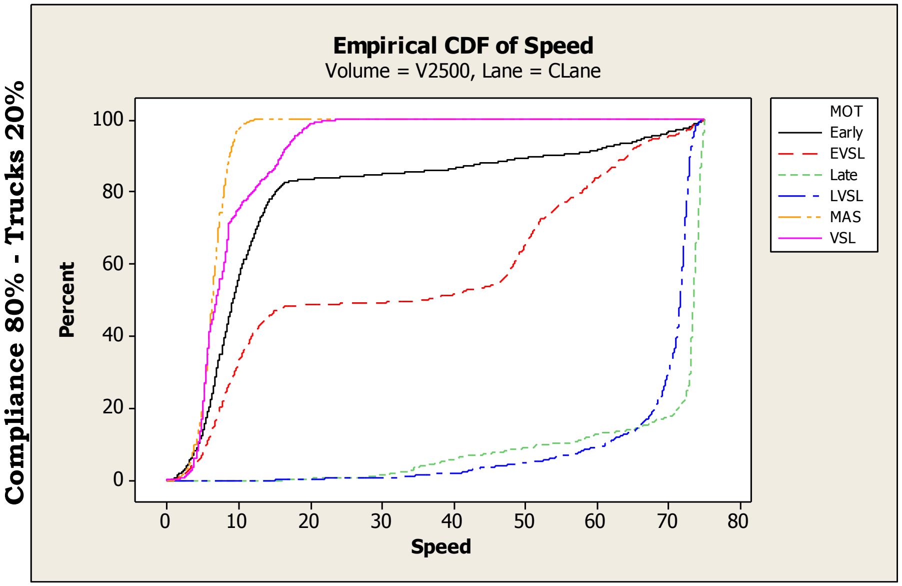
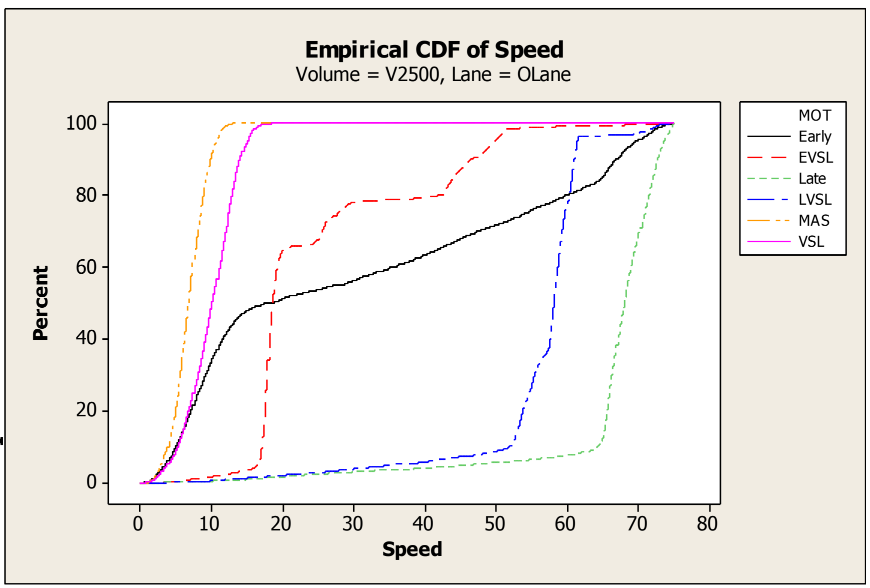
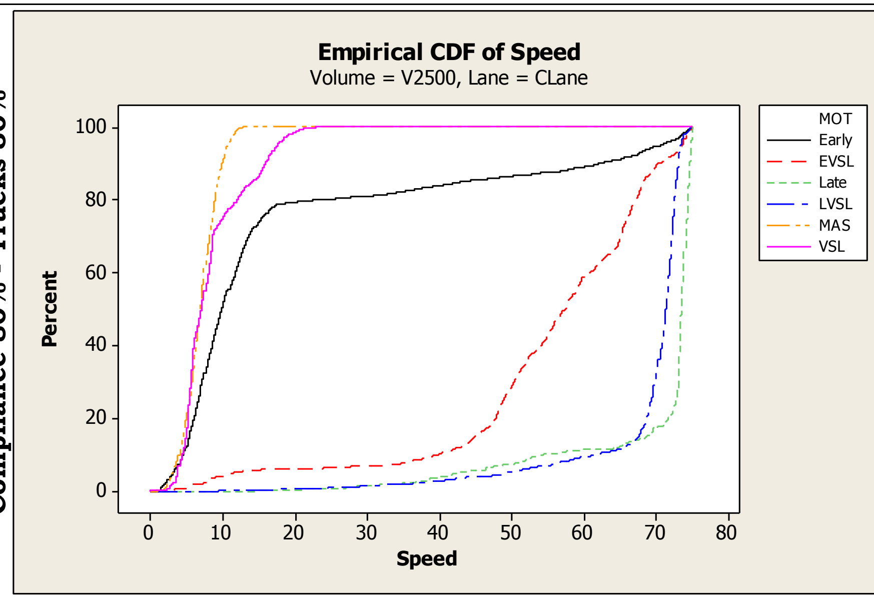
	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH
Compliance 60% - Trucks 30%	(a)	(b)
Compliance 80% - Trucks 10%	(c)	(d)







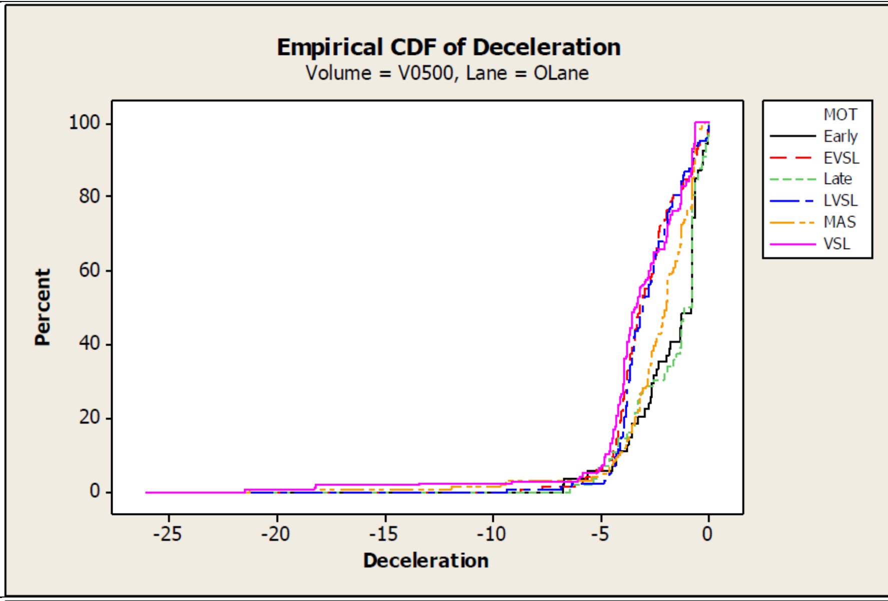


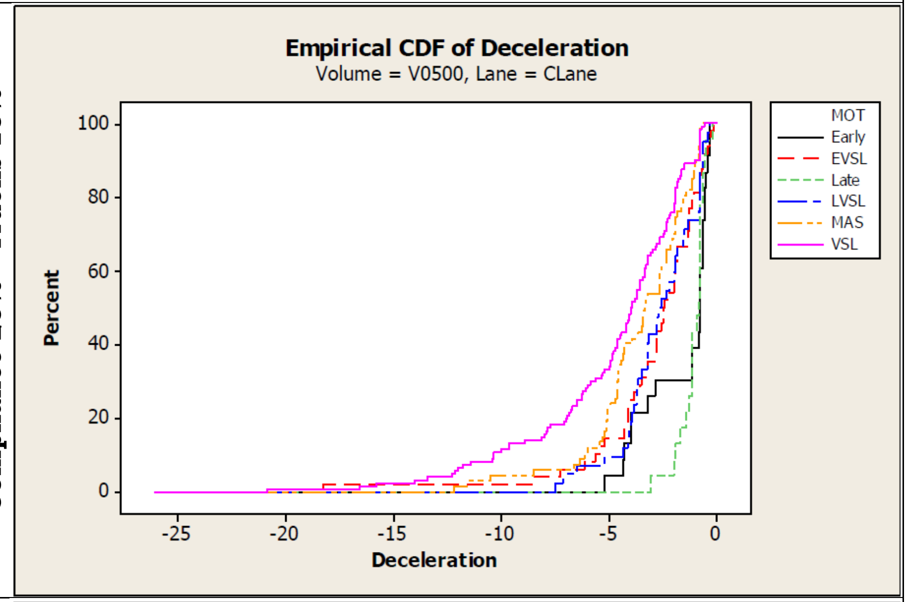
	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

APPENDIX B
EMPIRICAL CDF OF DECELERATION

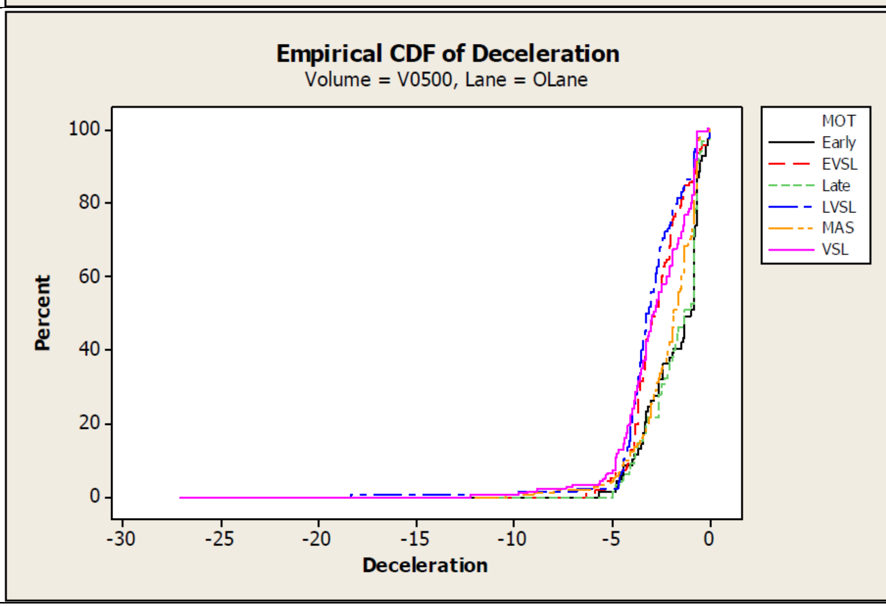
OPEN LANE - VOLUME 500 VPH | **CLOSED LANE - VOLUME 500 VPH**

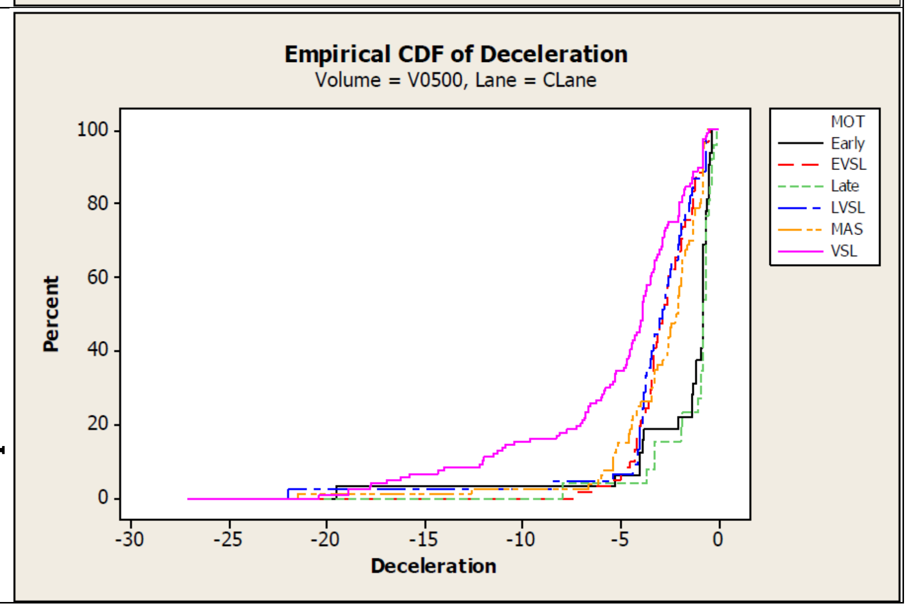
Compliance 20% - Trucks 10%

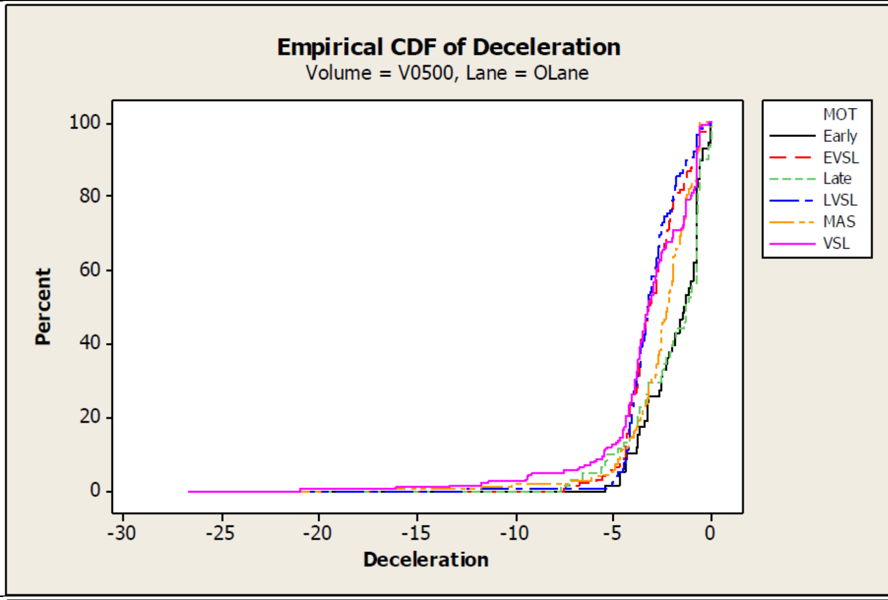
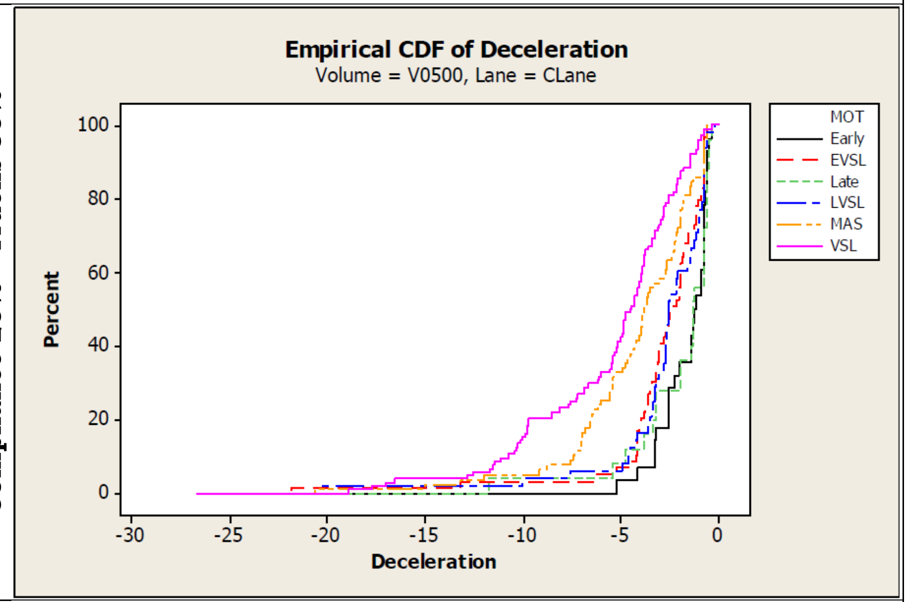
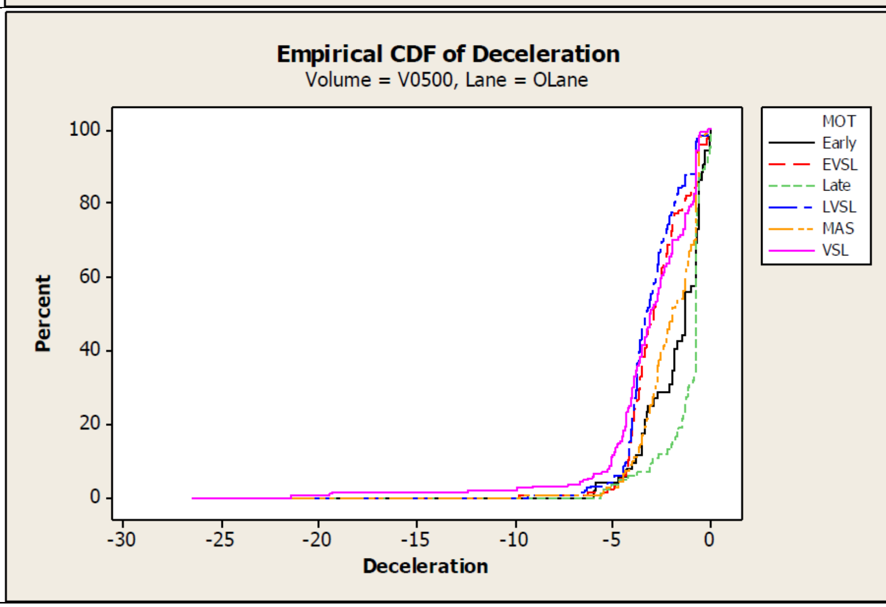
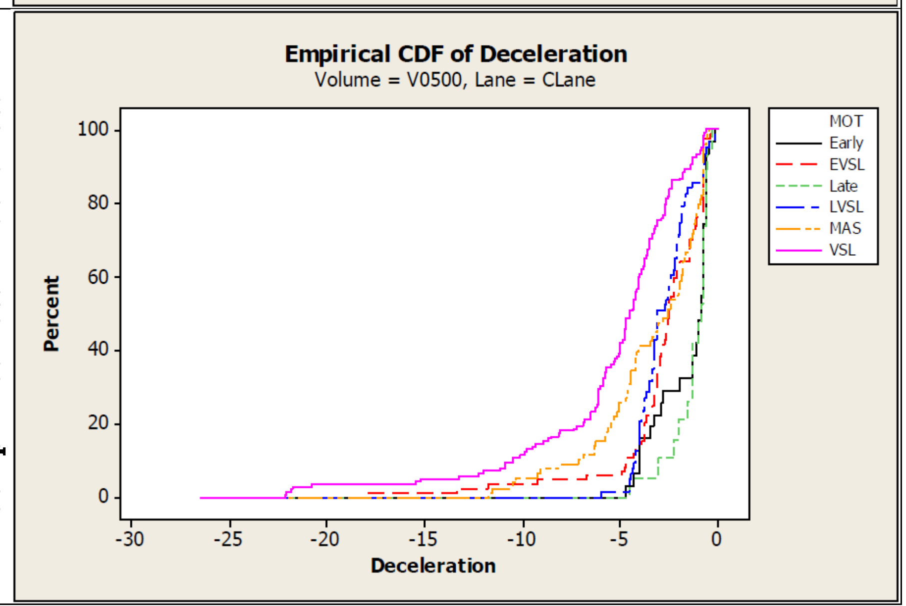


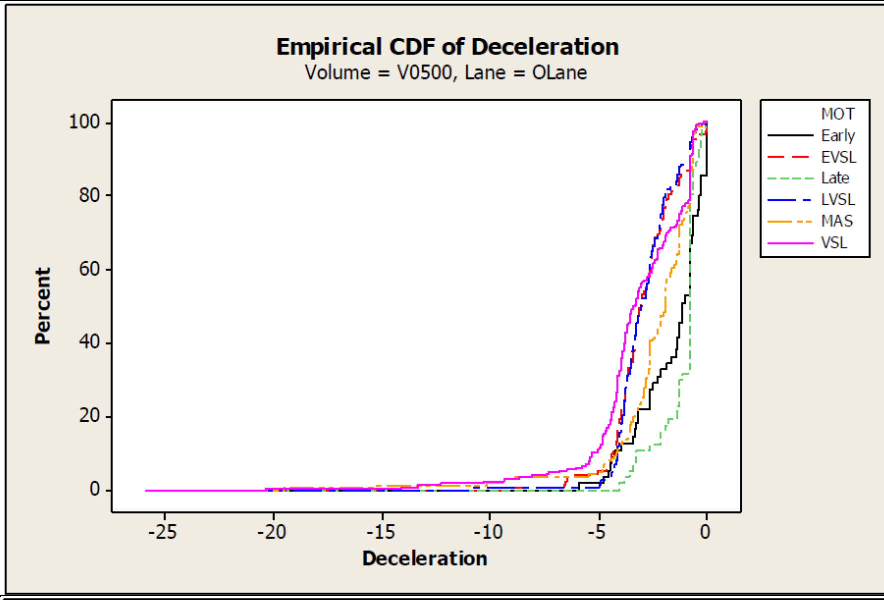
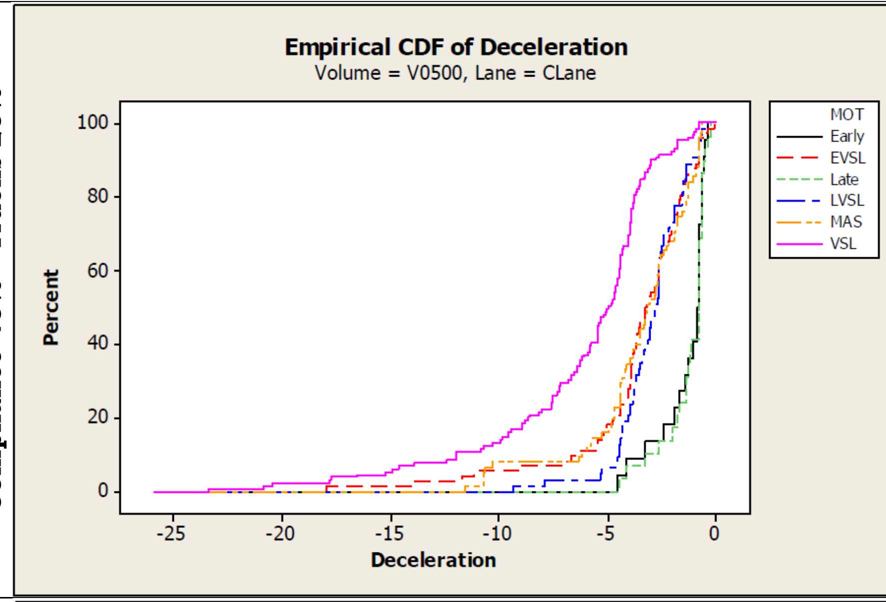
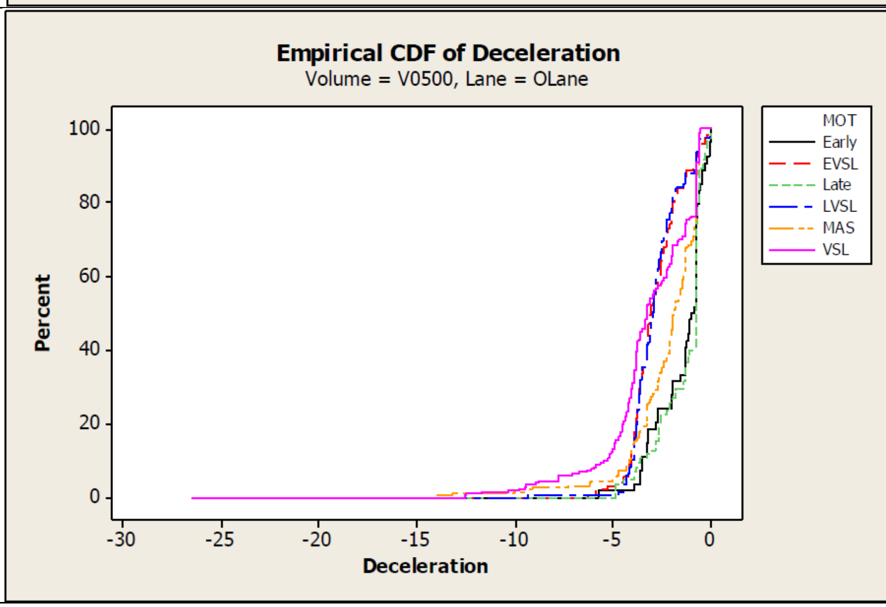
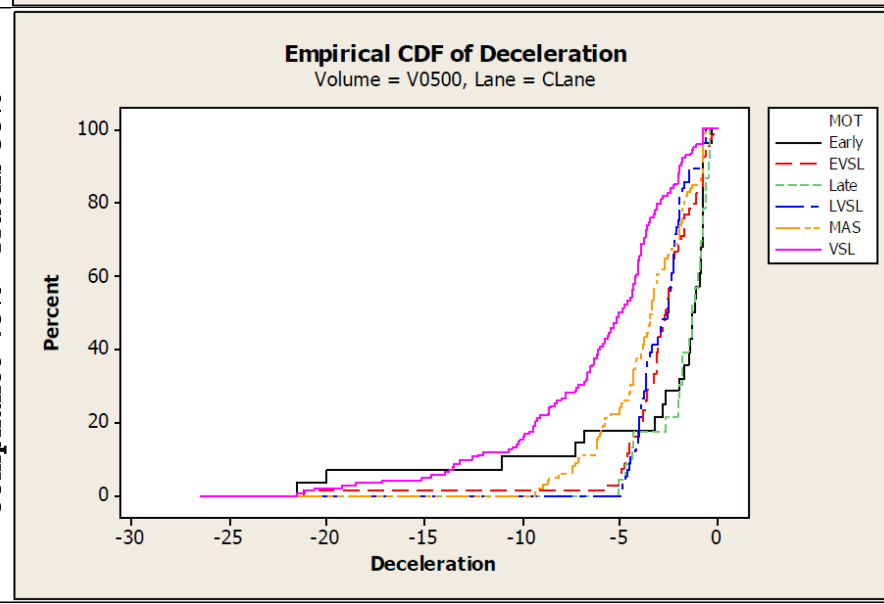


Compliance 20% - Trucks 20%



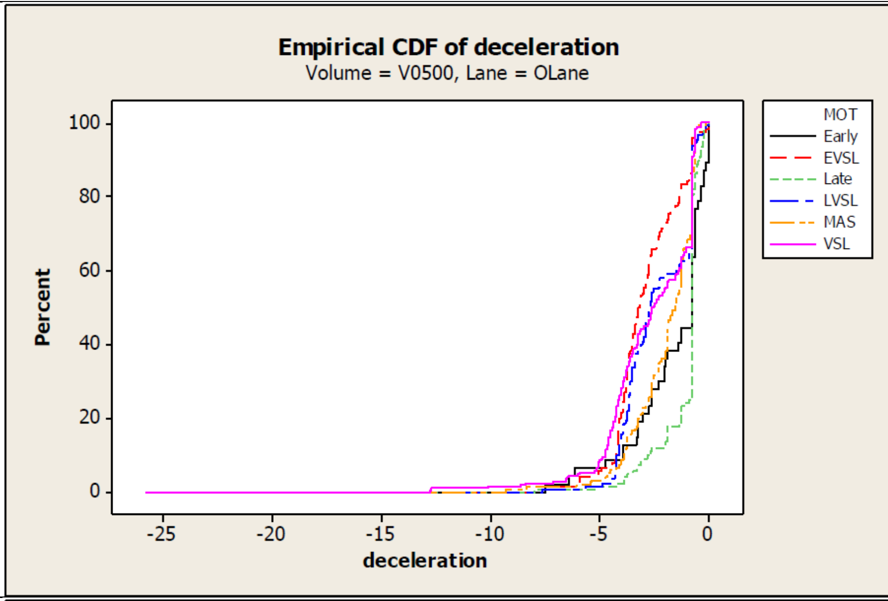


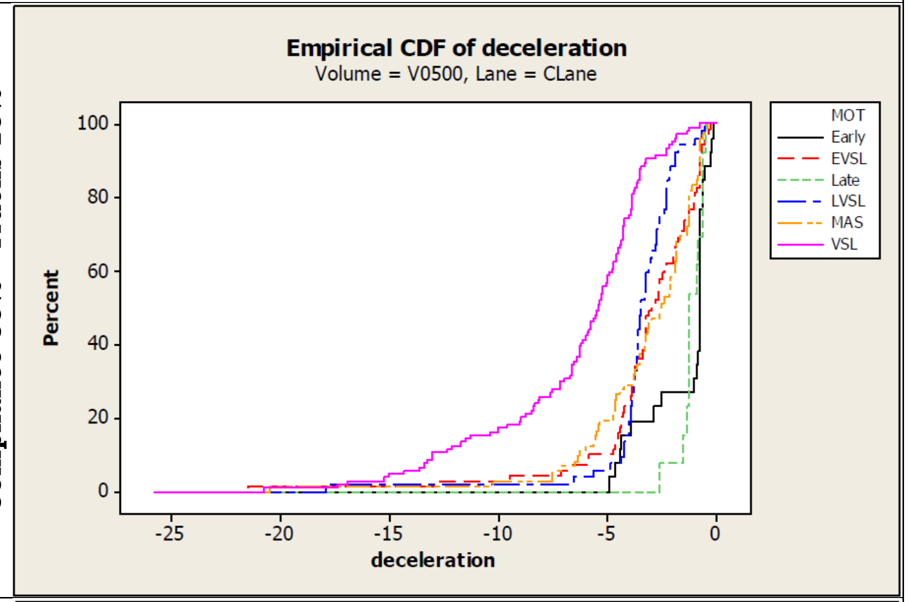
	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH
Compliance 20% - Trucks 30%		
Compliance 40% - Trucks 10%		

	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH
Compliance 40% - Trucks 20%		
Compliance 40% - Trucks 30%		

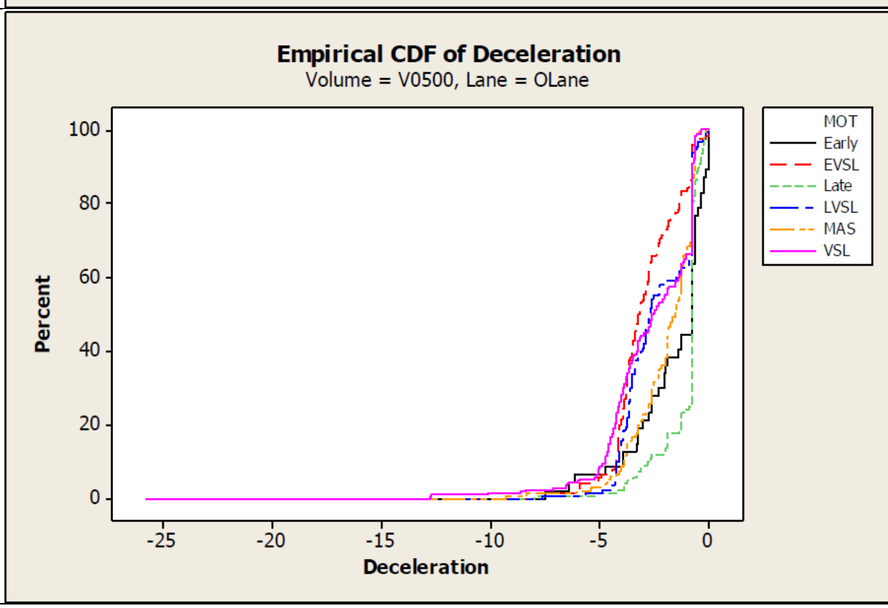
	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH

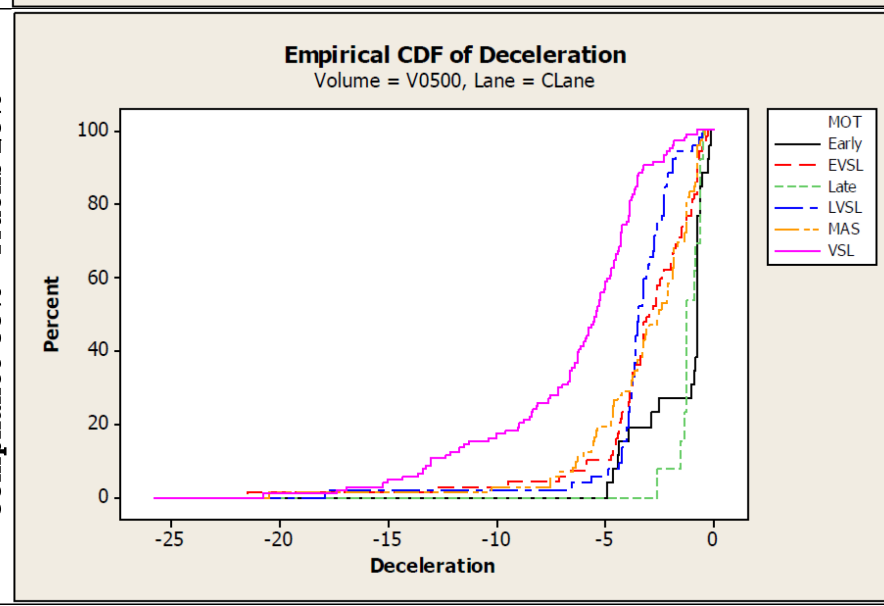
Compliance 60% - Trucks 10%





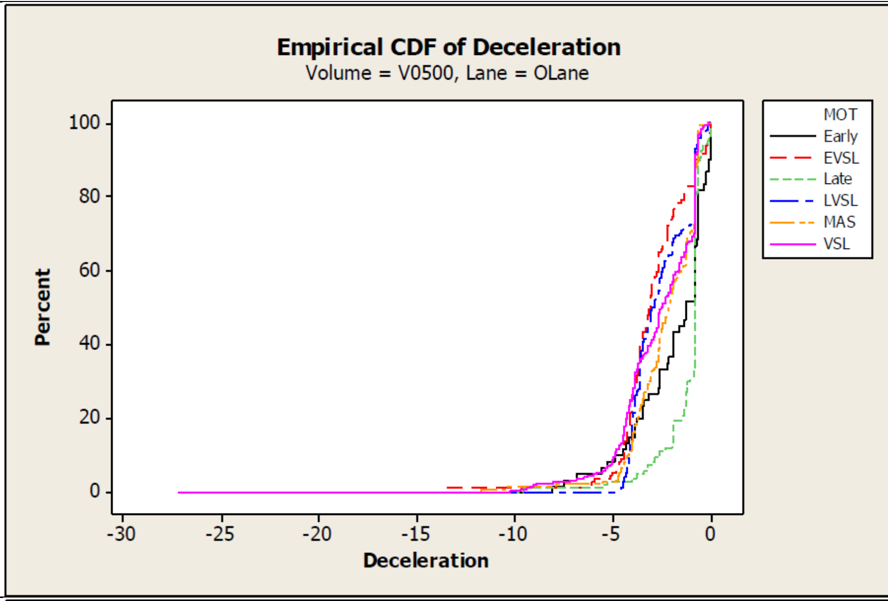
Compliance 60% - Trucks 20%

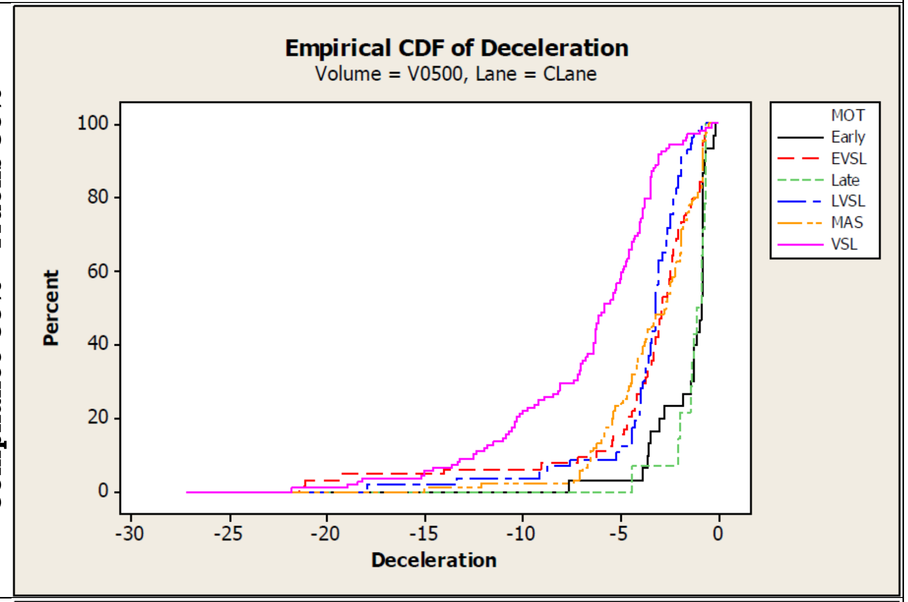




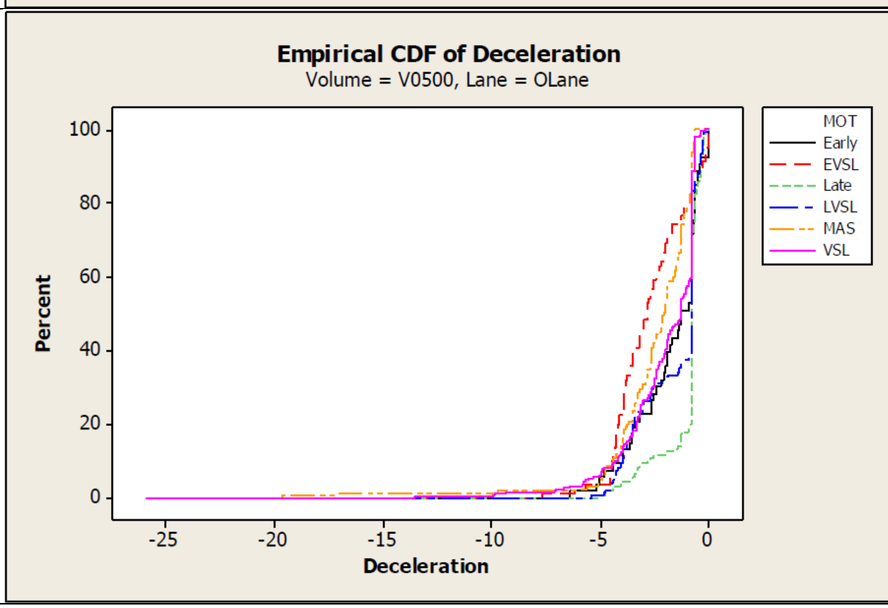
OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH

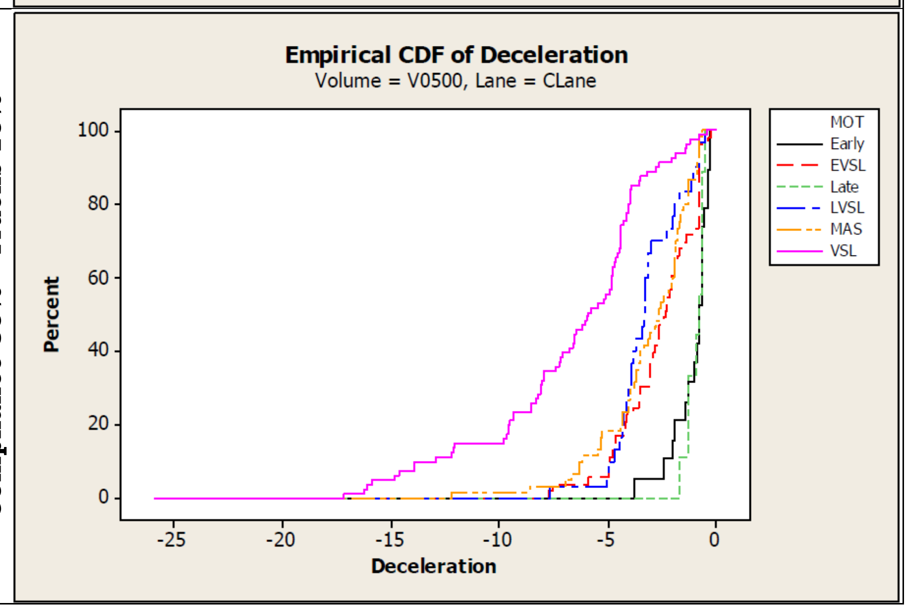
Compliance 60% - Trucks 30%

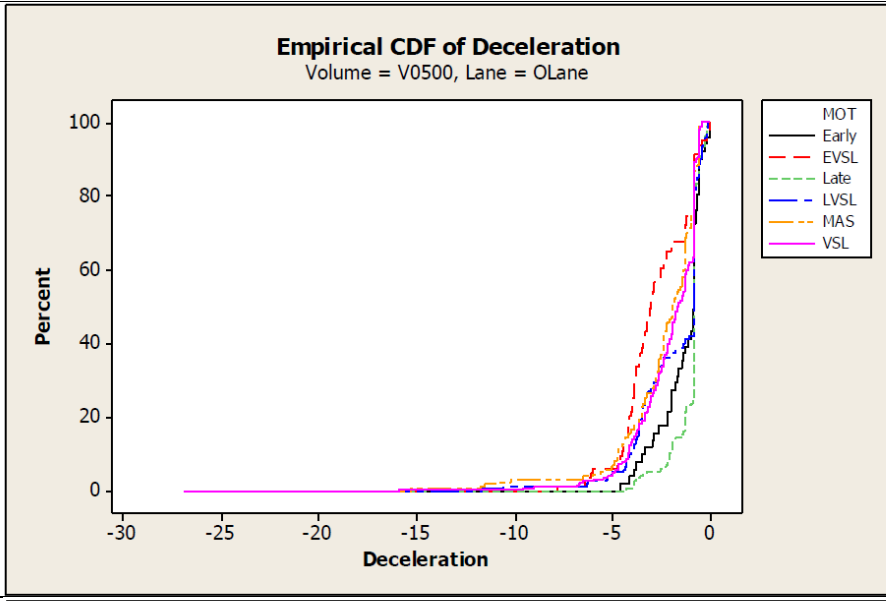
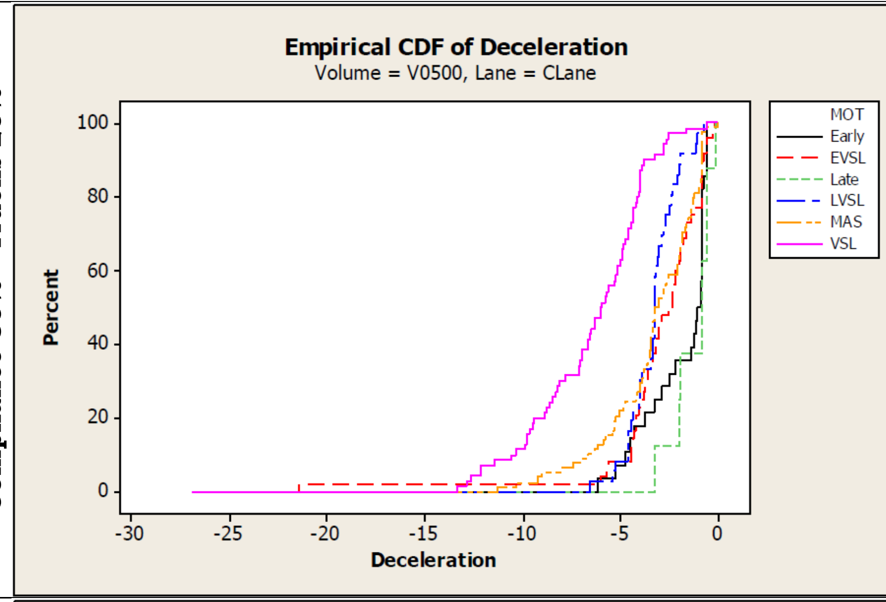
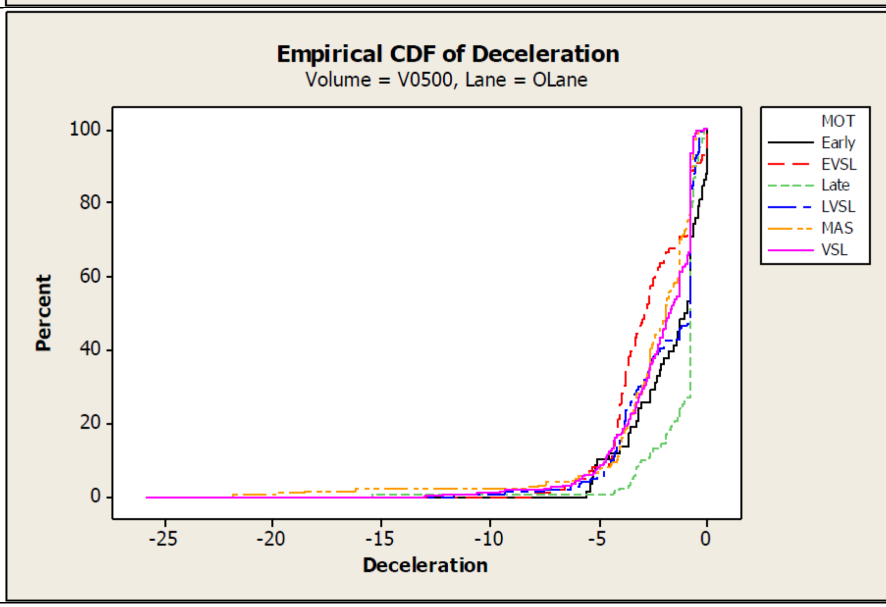
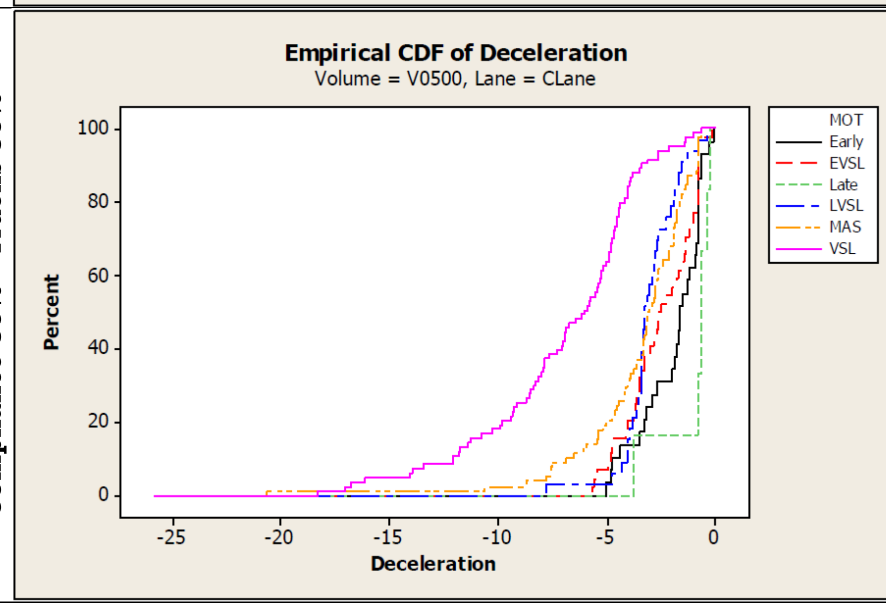




Compliance 80% - Trucks 10%

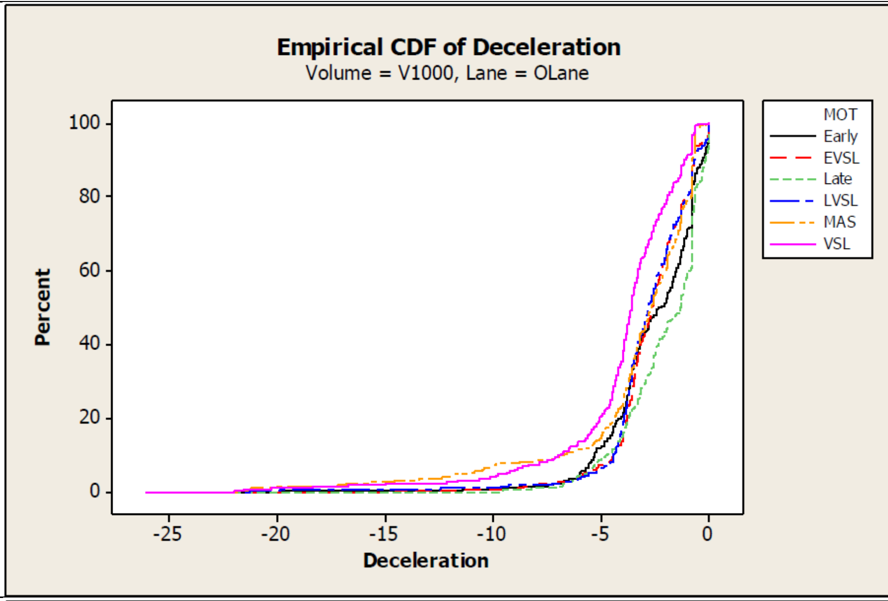


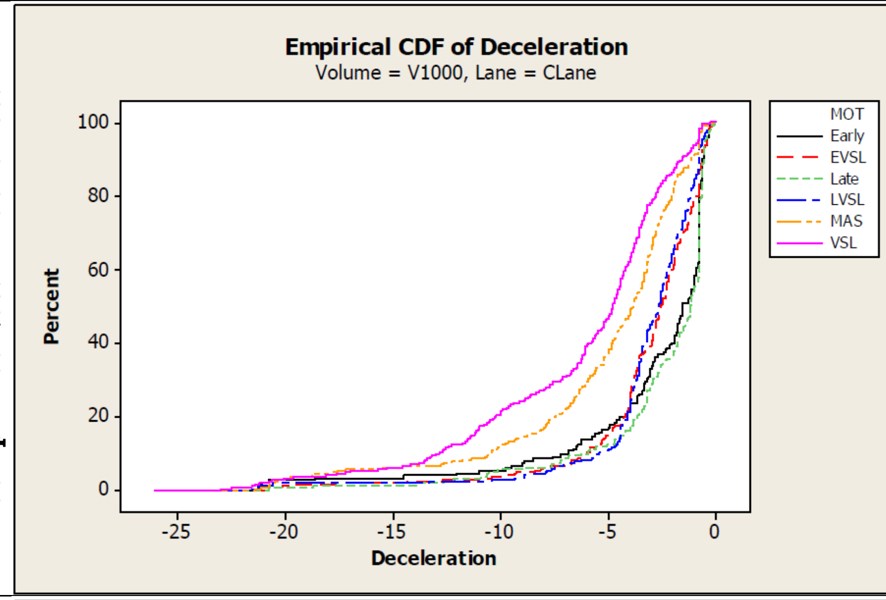


	OPEN LANE - VOLUME 500 VPH	CLOSED LANE - VOLUME 500 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

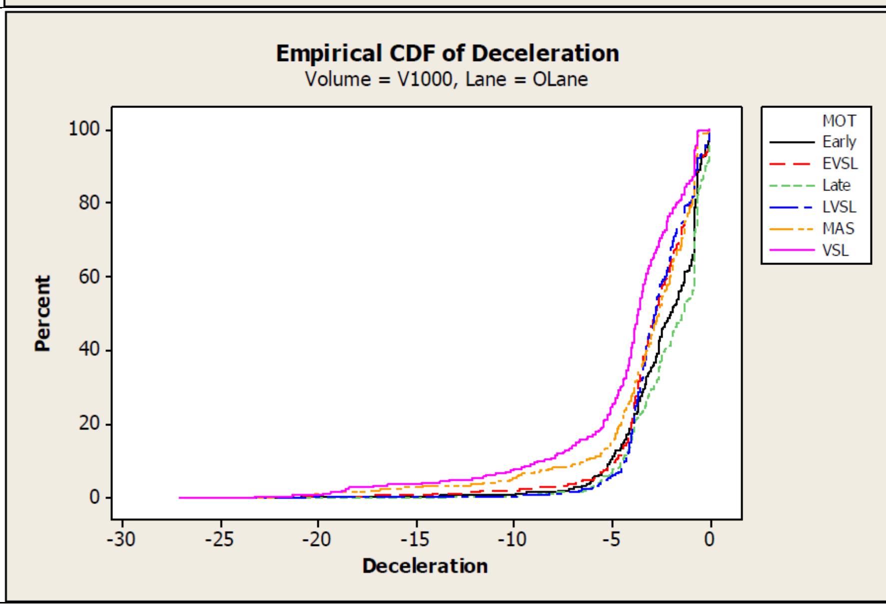
	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH

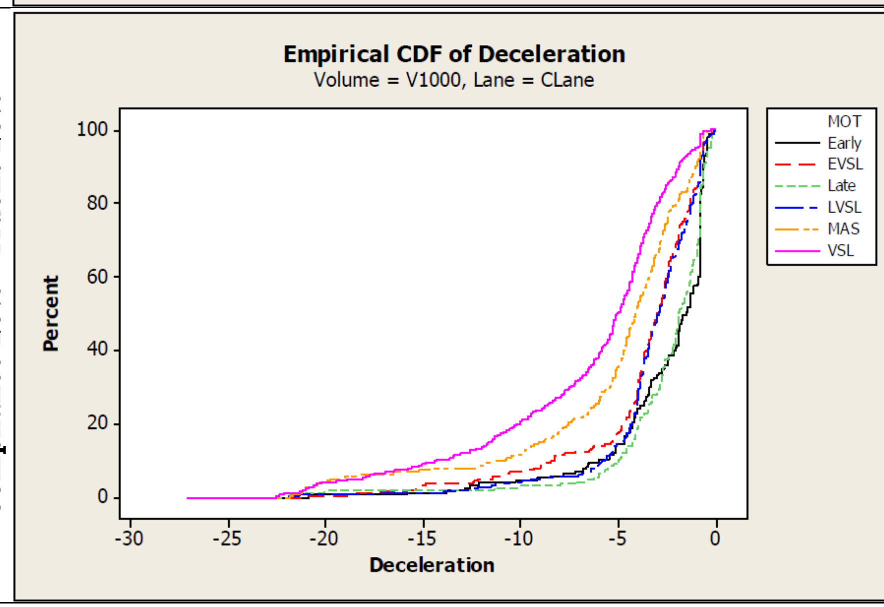
Compliance 20% - Trucks 10%





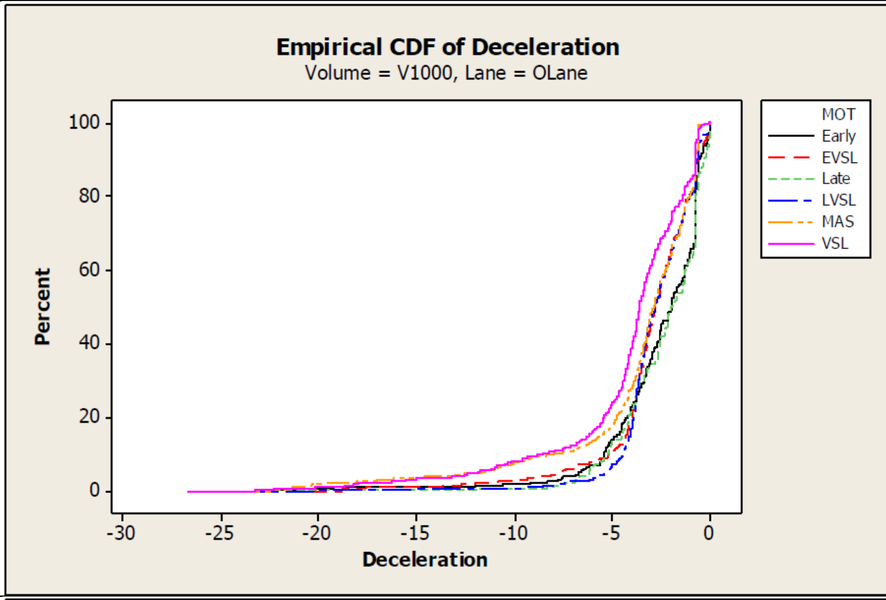
Compliance 20% - Trucks 20%



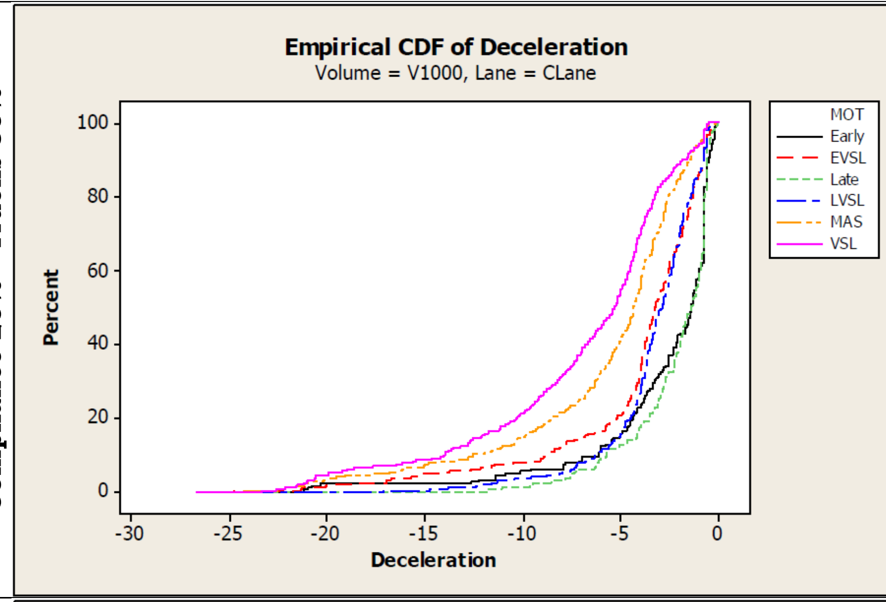


	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH
Compliance 20% - Trucks 30%	(chart 1)	(chart 2)
Compliance 40% - Trucks 10%	(chart 3)	(chart 4)

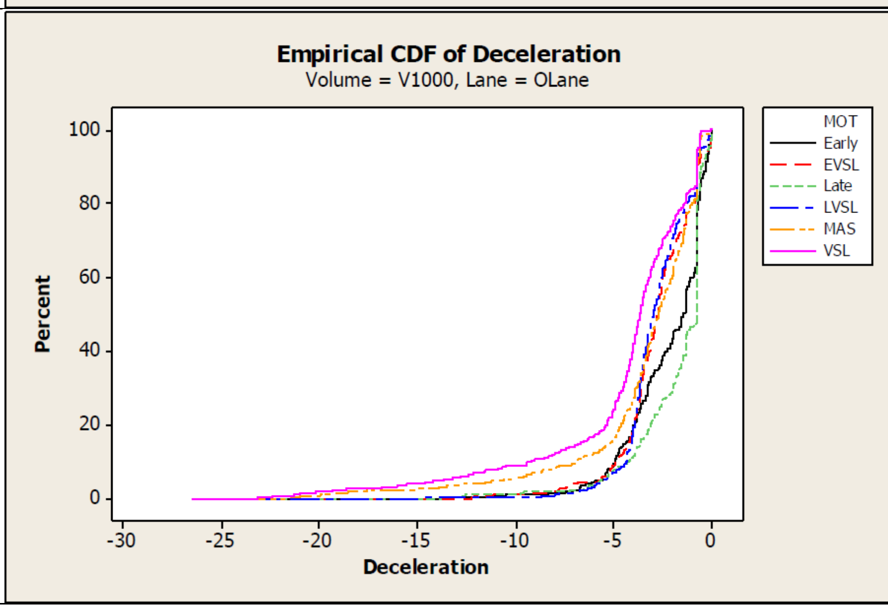
OPEN LANE - VOLUME 1,000 VPH — Compliance 20% - Trucks 30%



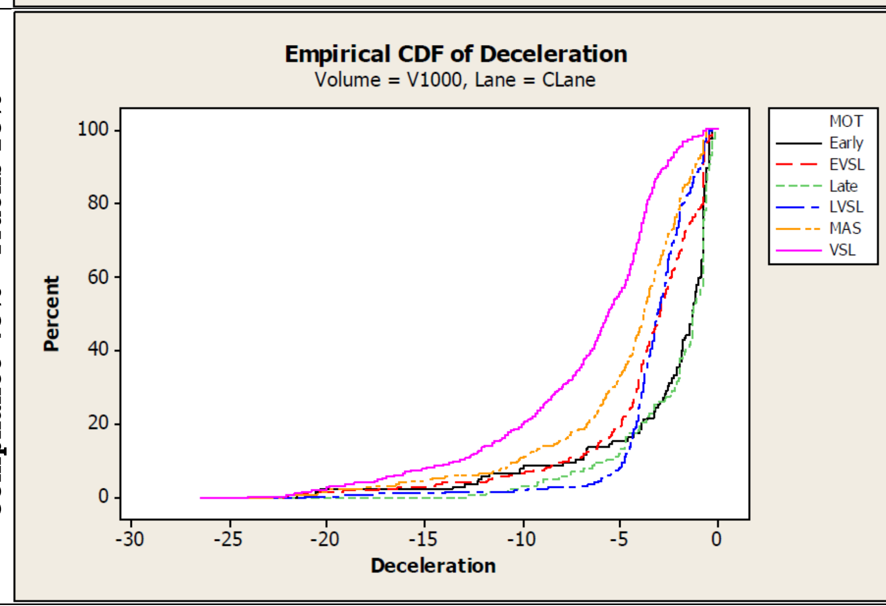
CLOSED LANE - VOLUME 1,000 VPH — Compliance 20% - Trucks 30%

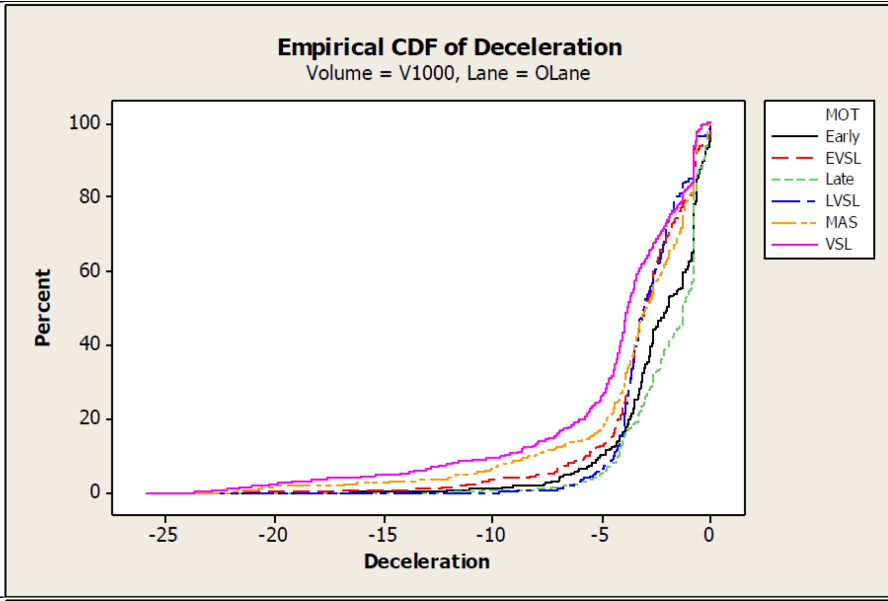
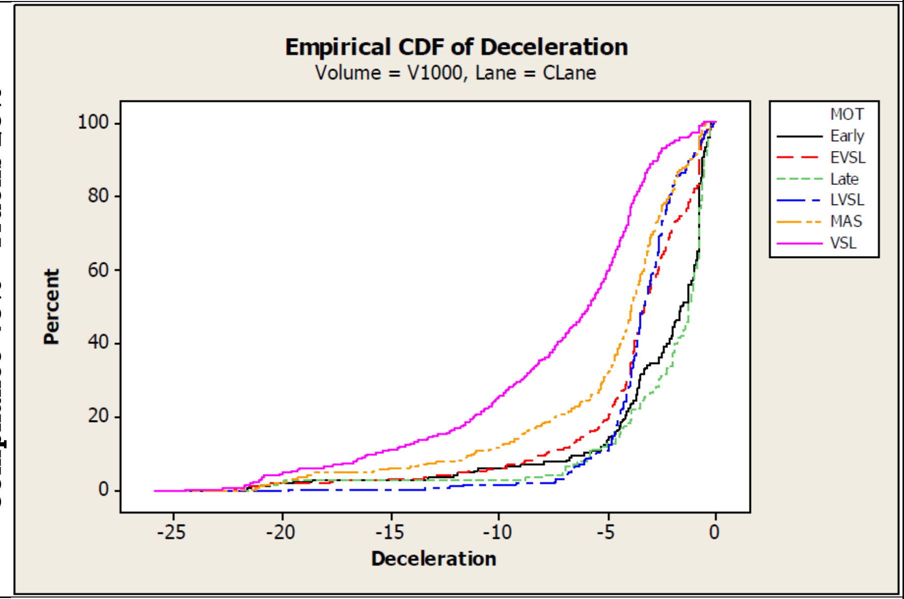
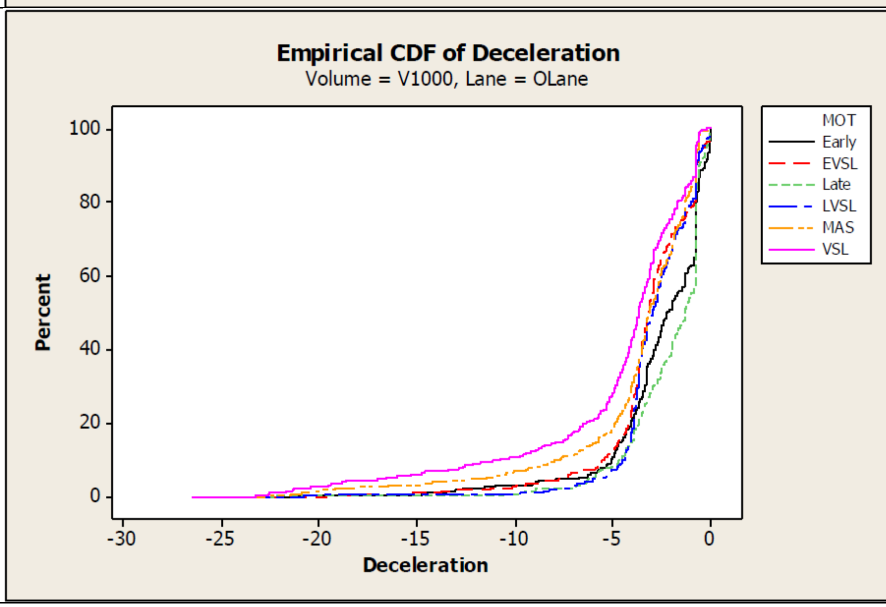
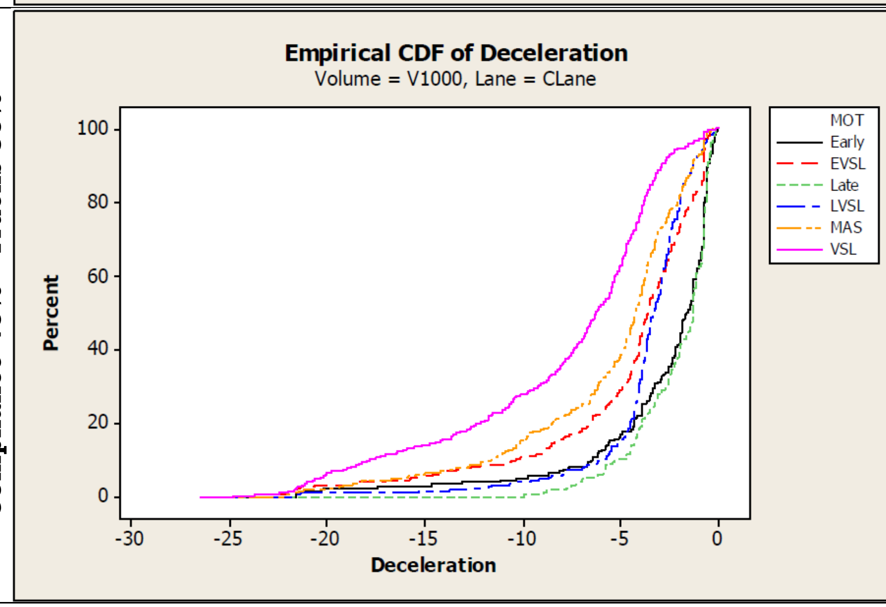


OPEN LANE - VOLUME 1,000 VPH — Compliance 40% - Trucks 10%



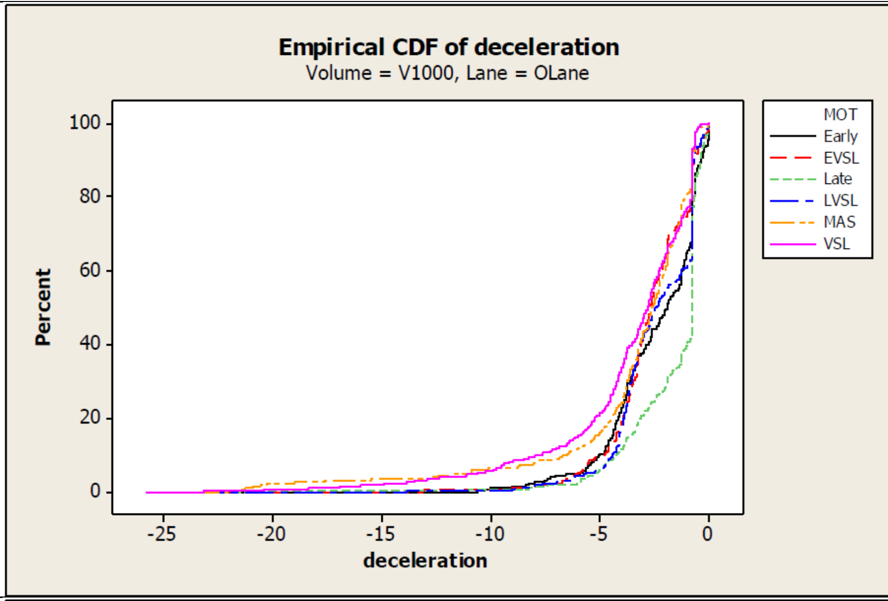
CLOSED LANE - VOLUME 1,000 VPH — Compliance 40% - Trucks 10%

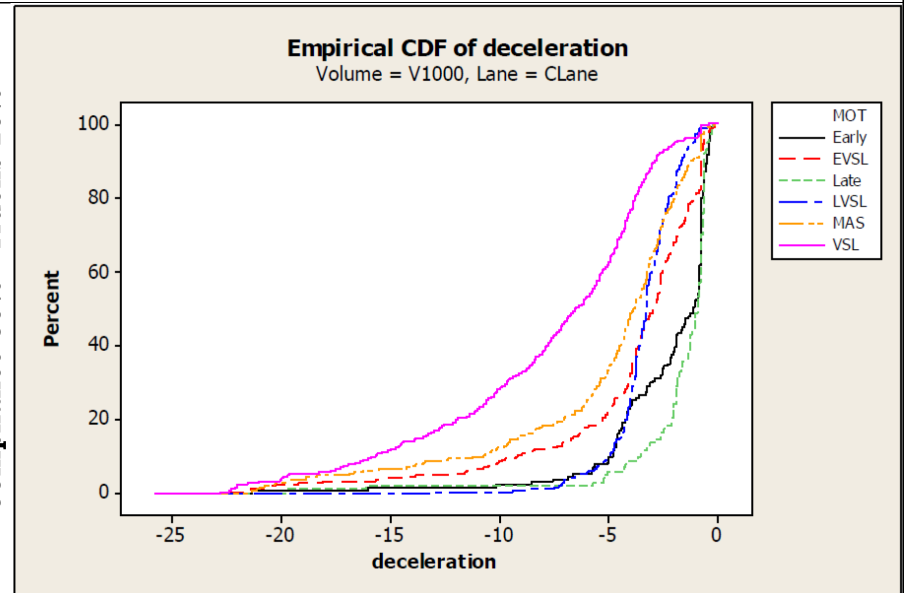


	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH
Compliance 40% - Trucks 20%		
Compliance 40% - Trucks 30%		

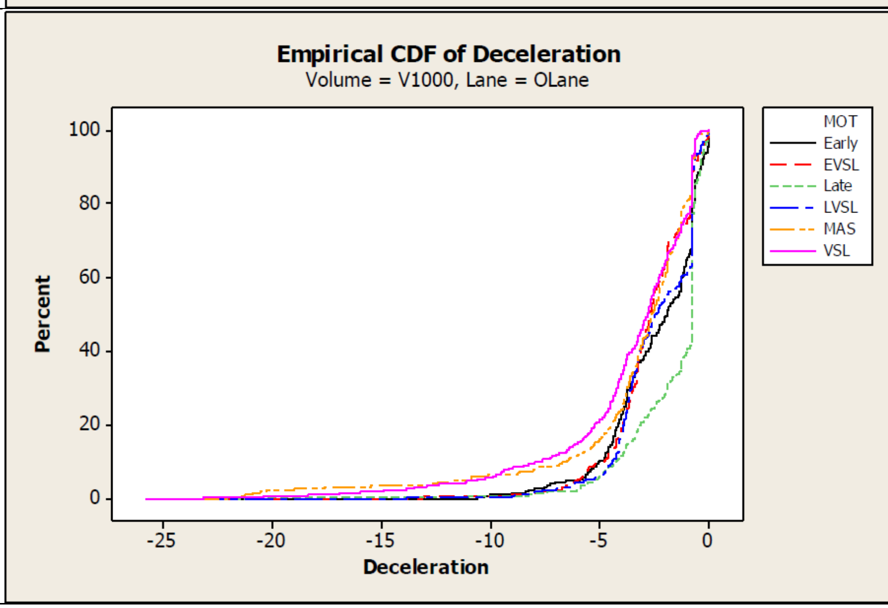
OPEN LANE - VOLUME 1,000 VPH | **CLOSED LANE - VOLUME 1,000 VPH**

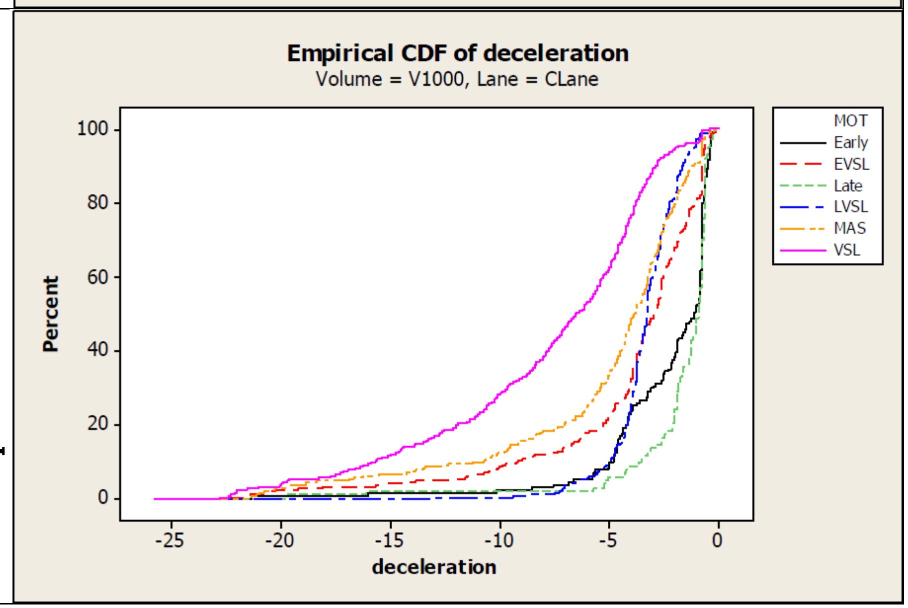
Compliance 60% - Trucks 10%

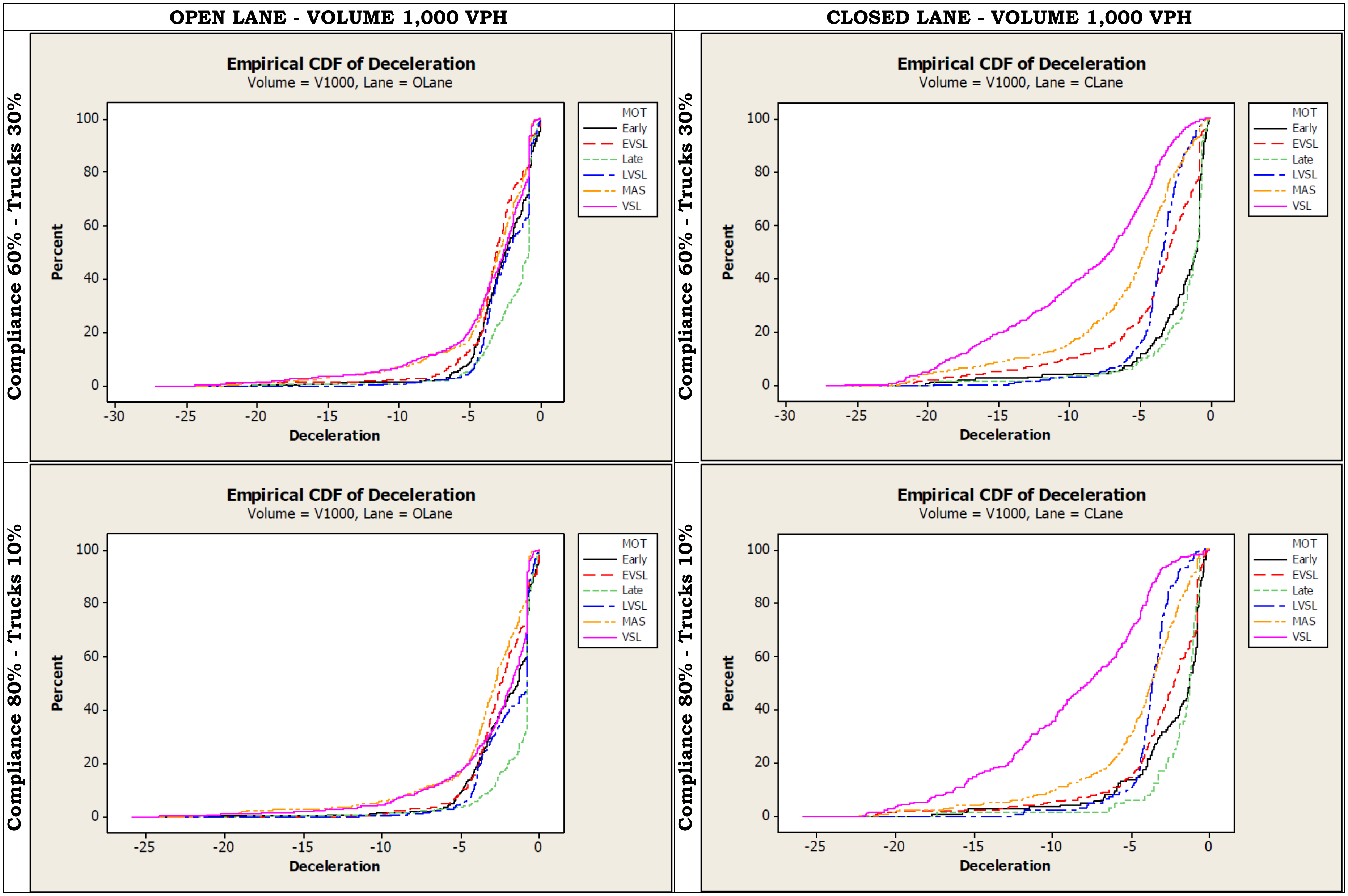


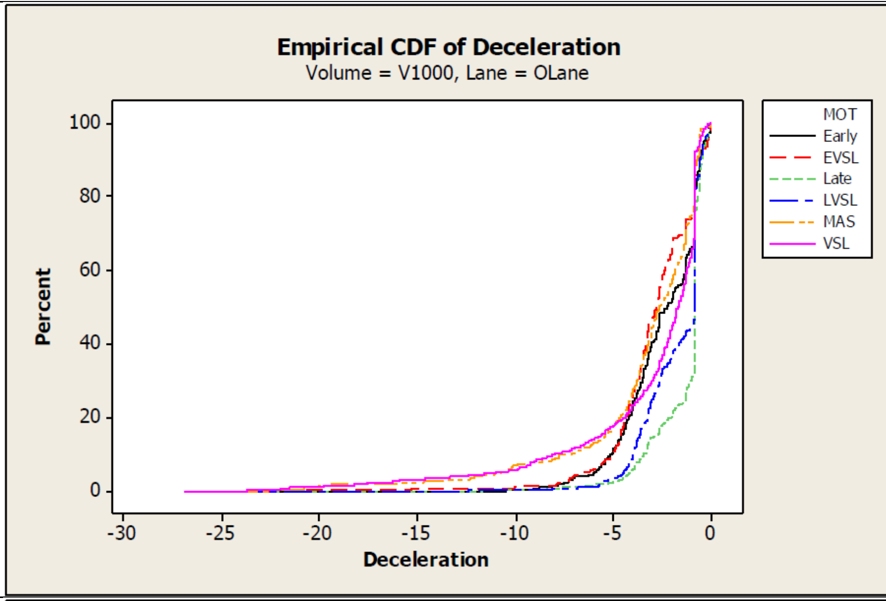
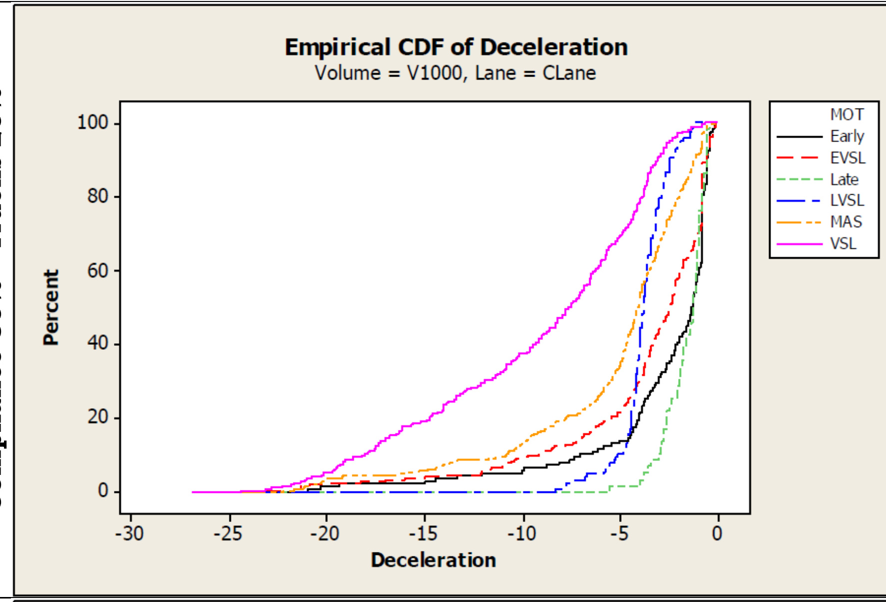
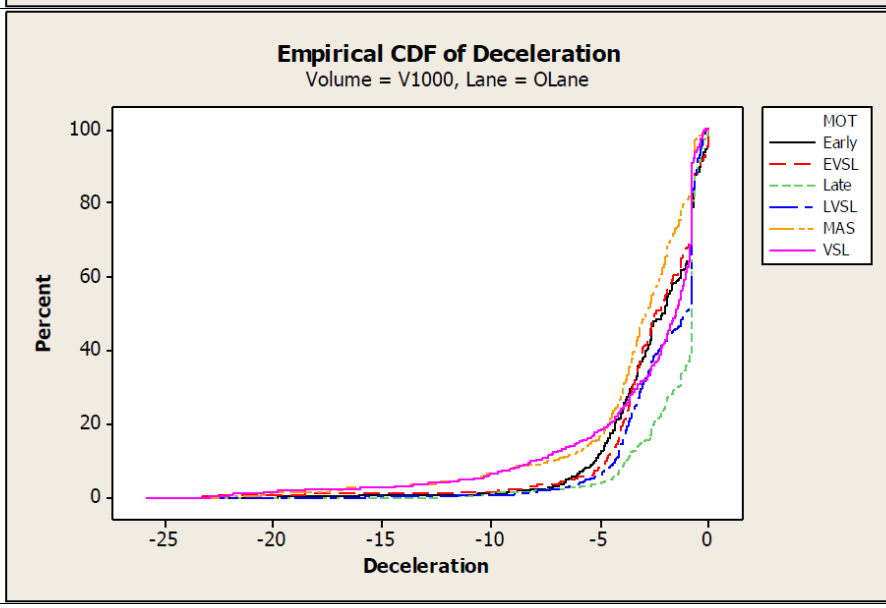
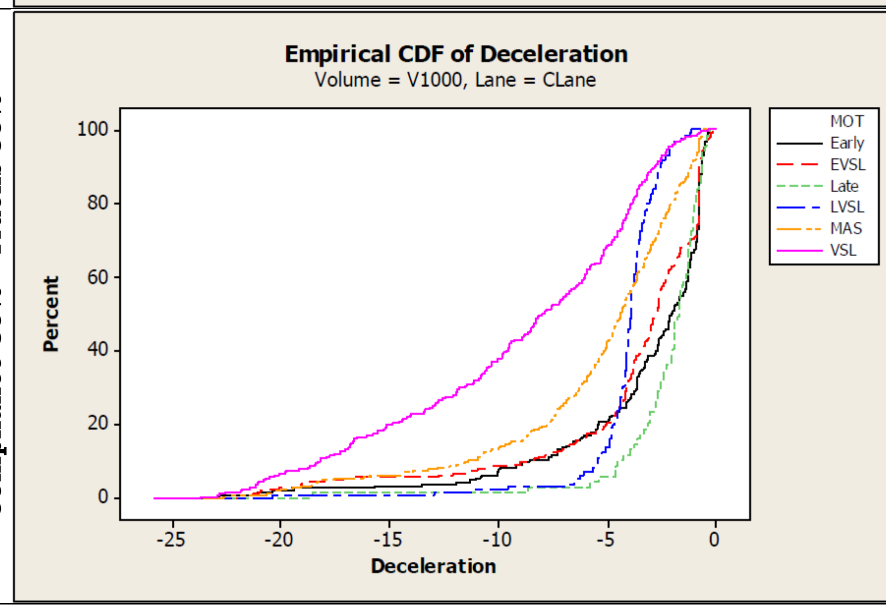


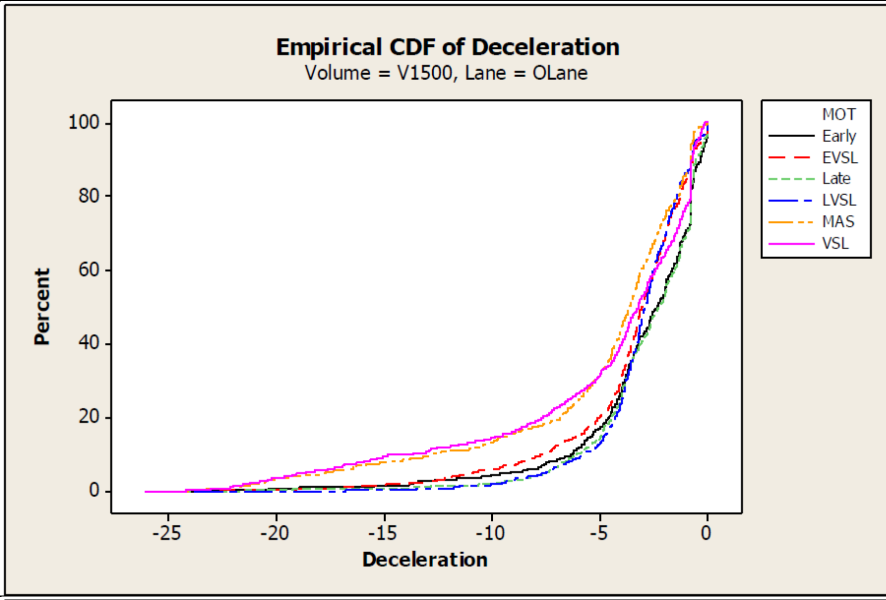
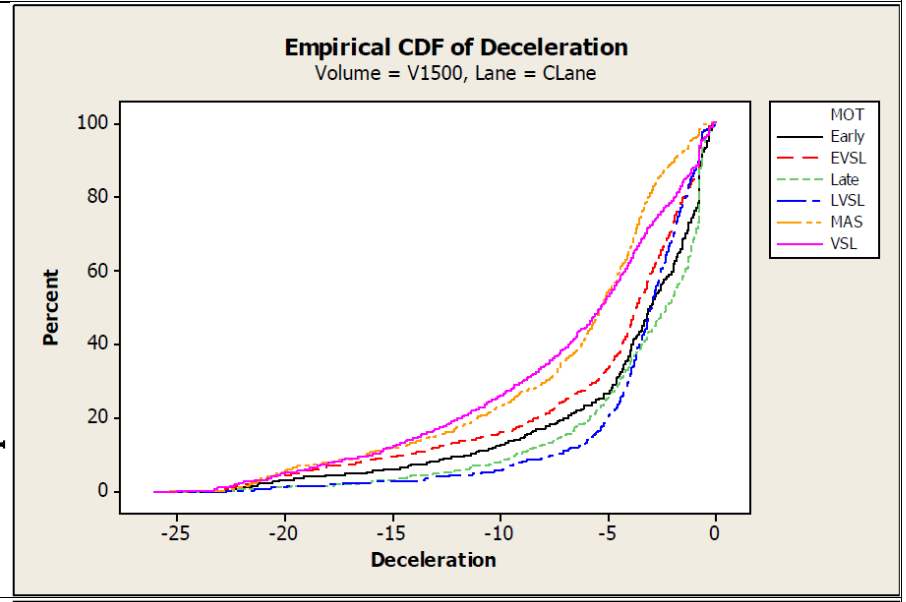
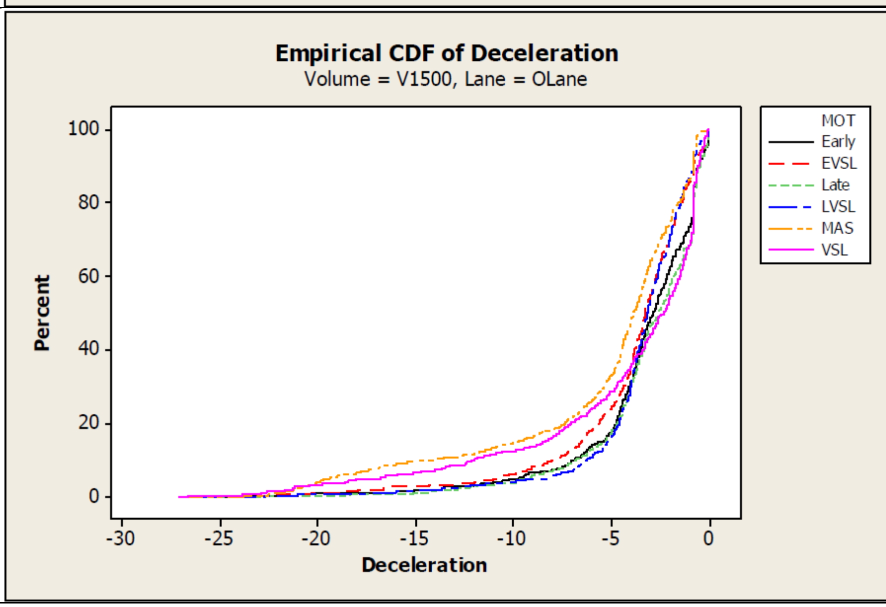
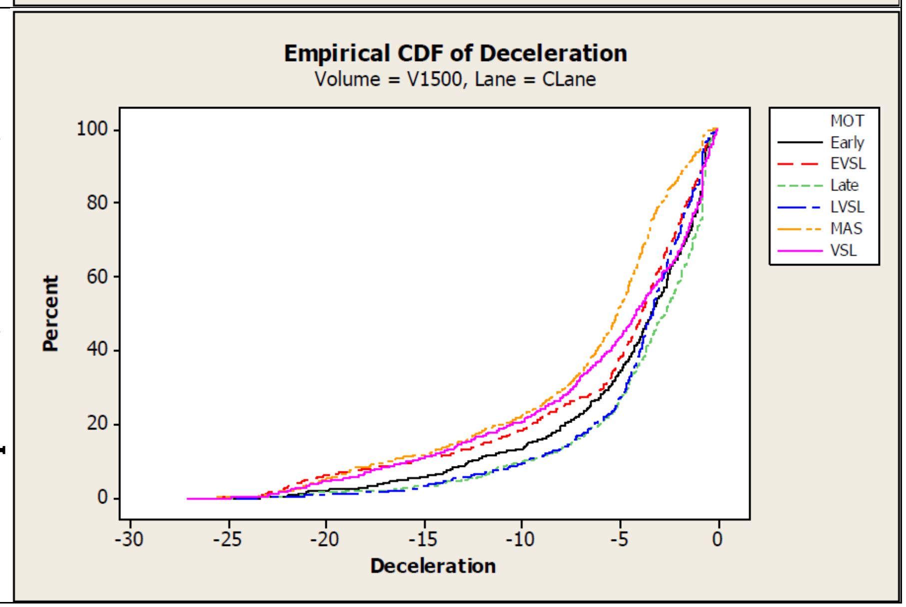
Compliance 60% - Trucks 20%





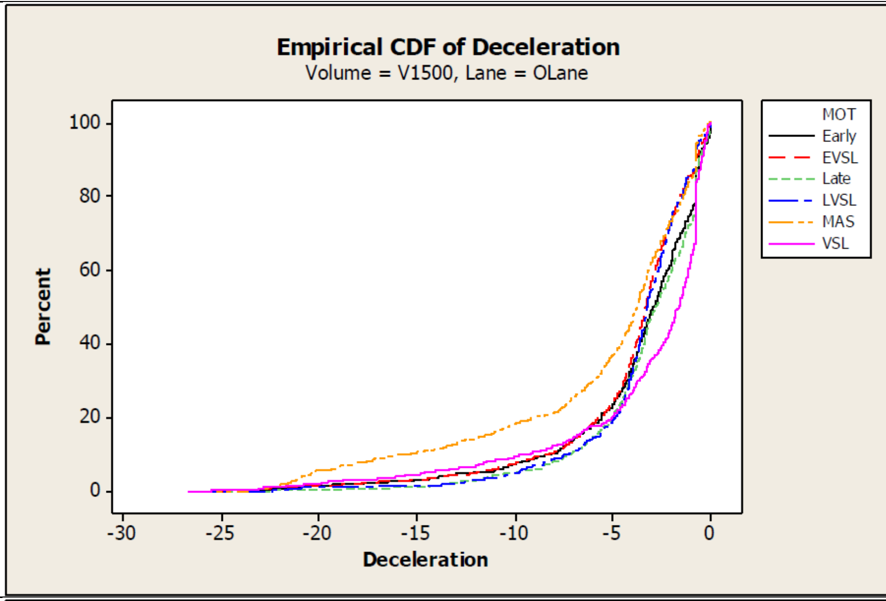

OPEN LANE - VOLUME 1,000 VPH
CLOSED LANE - VOLUME 1,000 VPH
Compliance 60% - Trucks 30%
Compliance 80% - Trucks 10%
Empirical CDF of Deceleration
Volume = V1000, Lane = OLane
Volume = V1000, Lane = CLane
Percent
Deceleration
100
80
60
40
20
0
-30
-25
-20
-15
-10
-5
0
MOT
Early
EVSL
Late
LVSL
MAS
VSL

	OPEN LANE - VOLUME 1,000 VPH	CLOSED LANE - VOLUME 1,000 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

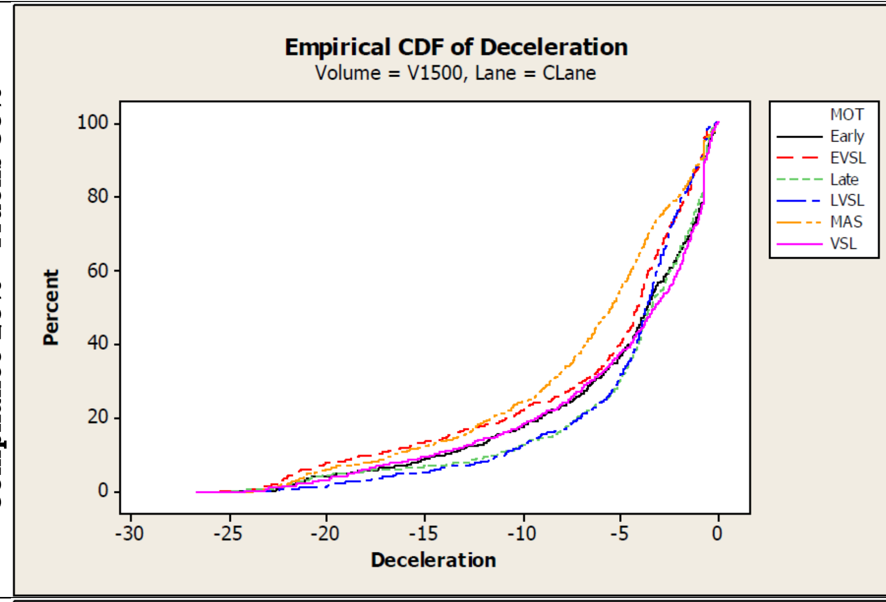
	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH
Compliance 20% - Trucks 10%		
Compliance 20% - Trucks 20%		

	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH
Compliance 20% - Trucks 30%	see first chart below	see second chart below
Compliance 40% - Trucks 10%	see third chart below	see fourth chart below

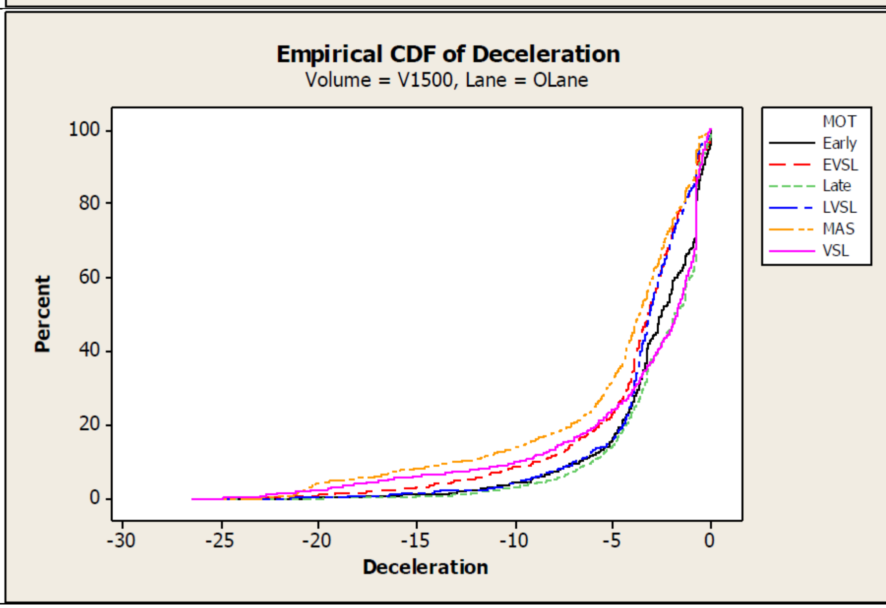
OPEN LANE - VOLUME 1,500 VPH — Compliance 20% - Trucks 30%



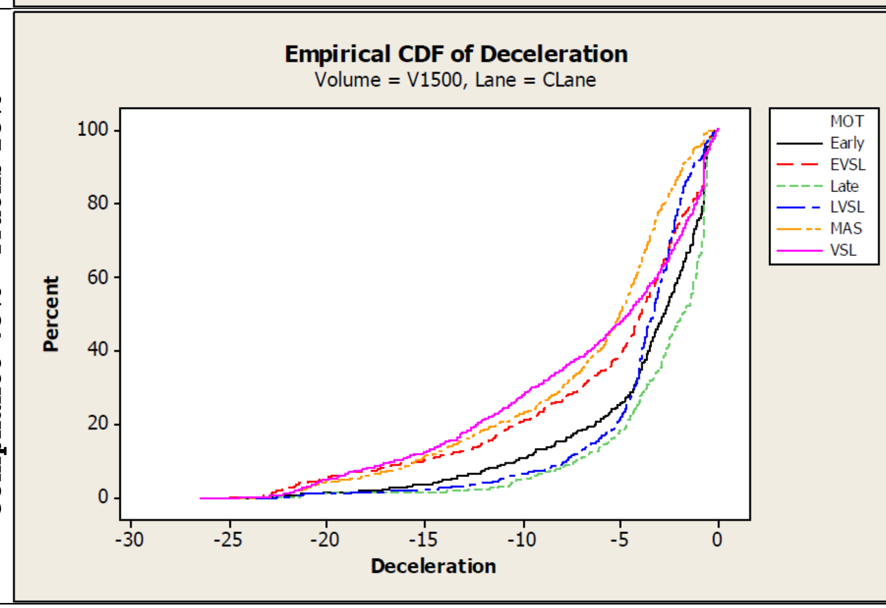
CLOSED LANE - VOLUME 1,500 VPH — Compliance 20% - Trucks 30%



OPEN LANE - VOLUME 1,500 VPH — Compliance 40% - Trucks 10%

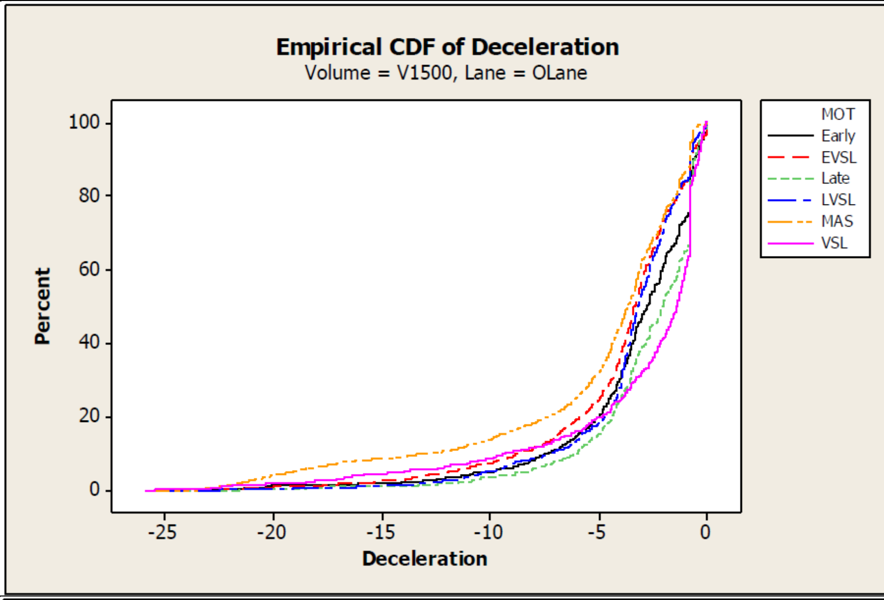


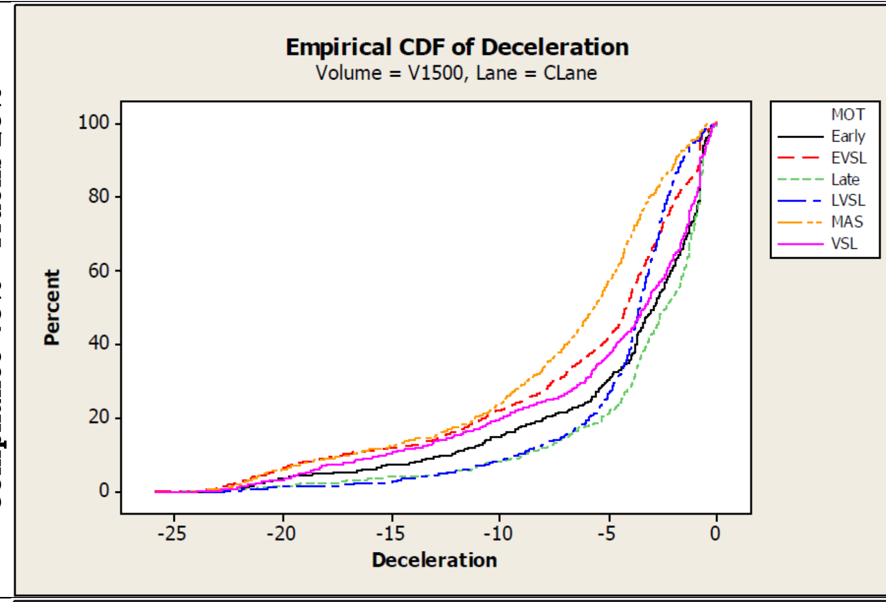
CLOSED LANE - VOLUME 1,500 VPH — Compliance 40% - Trucks 10%



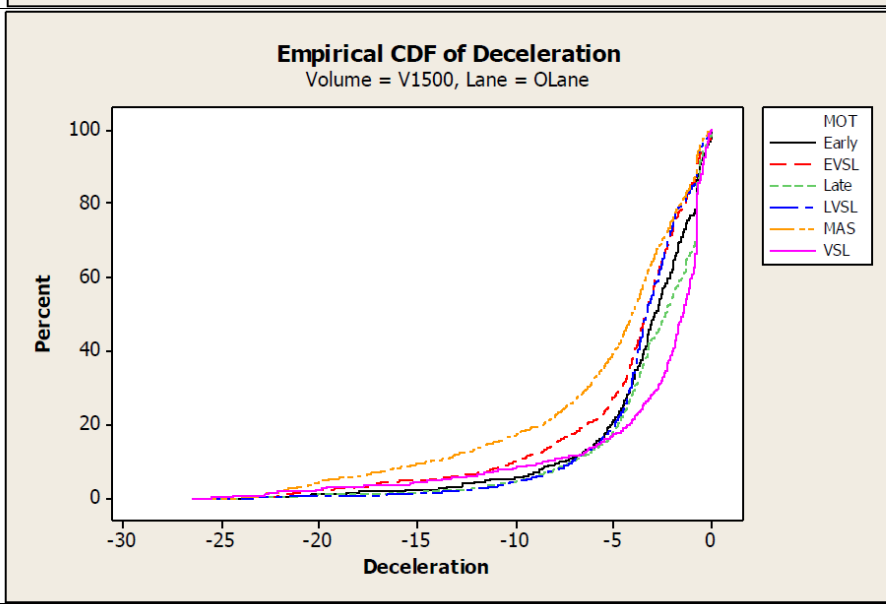
OPEN LANE - VOLUME 1,500 VPH | **CLOSED LANE - VOLUME 1,500 VPH**

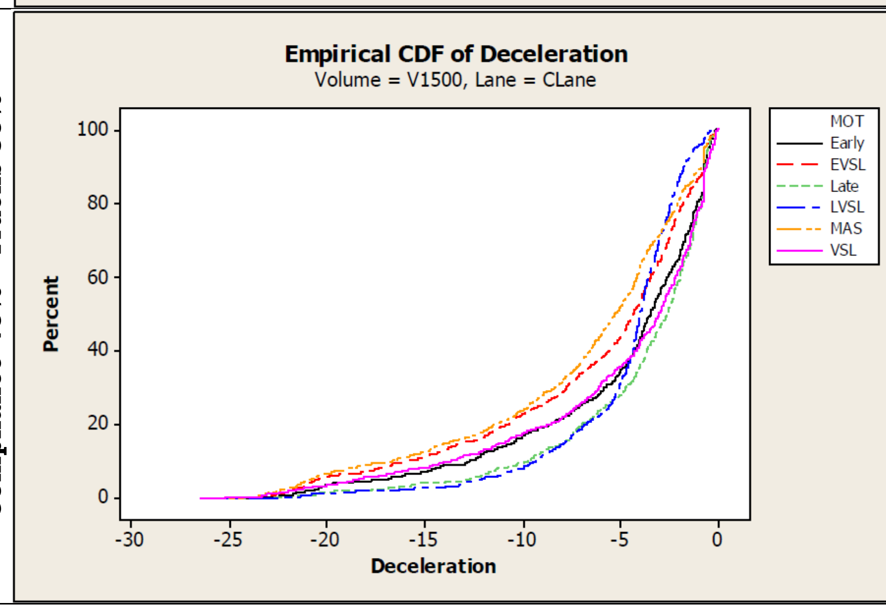
Compliance 40% - Trucks 20%





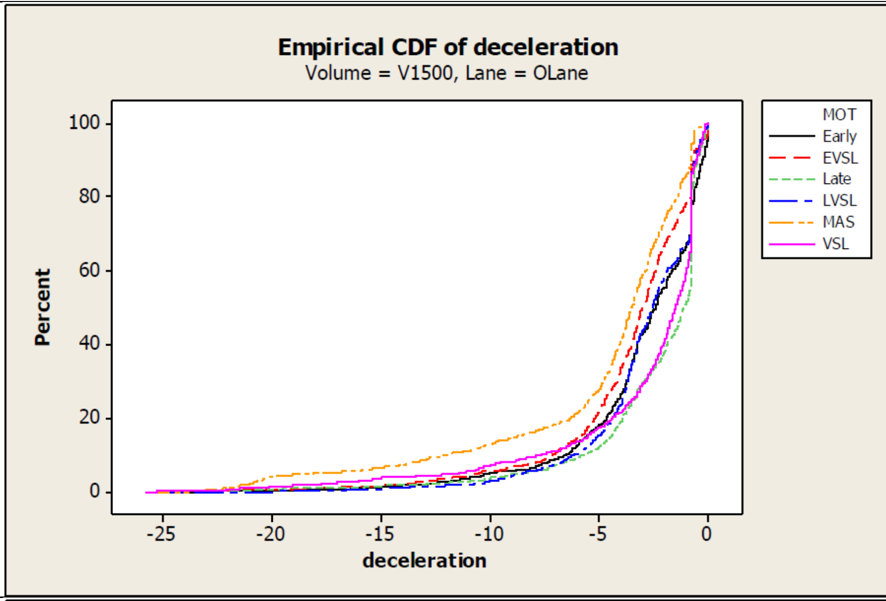
Compliance 40% - Trucks 30%



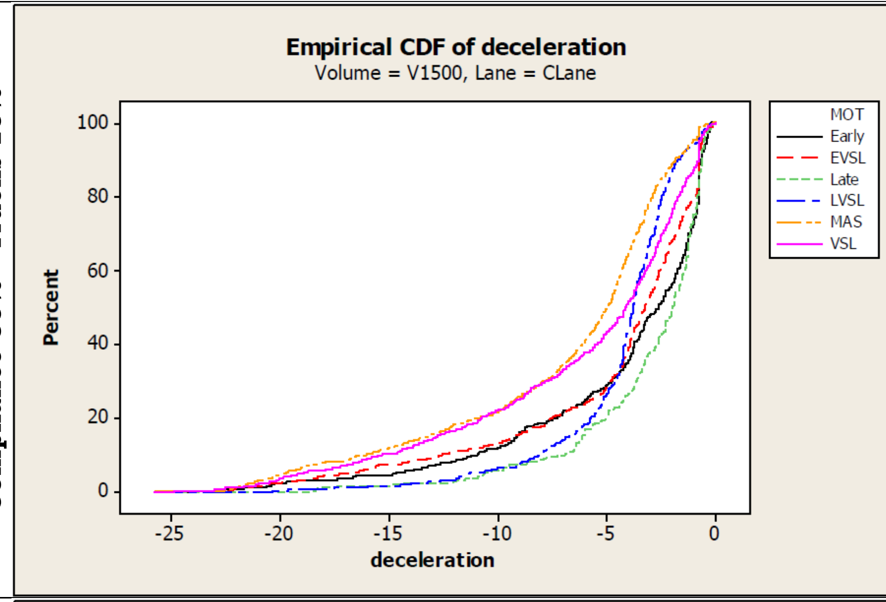


	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH
Compliance 60% - Trucks 10%	See first figure below	See second figure below
Compliance 60% - Trucks 20%	See third figure below	See fourth figure below

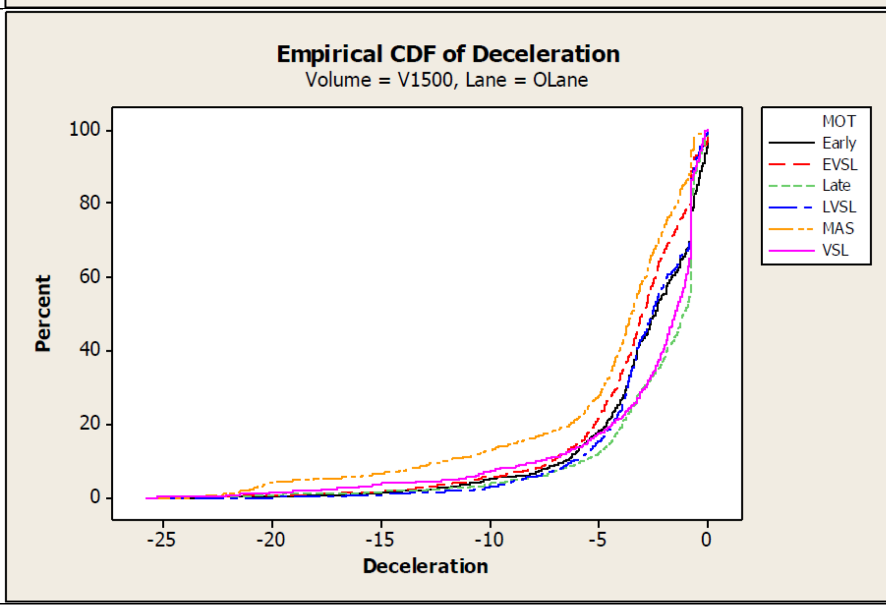
Compliance 60% - Trucks 10% — OPEN LANE - VOLUME 1,500 VPH



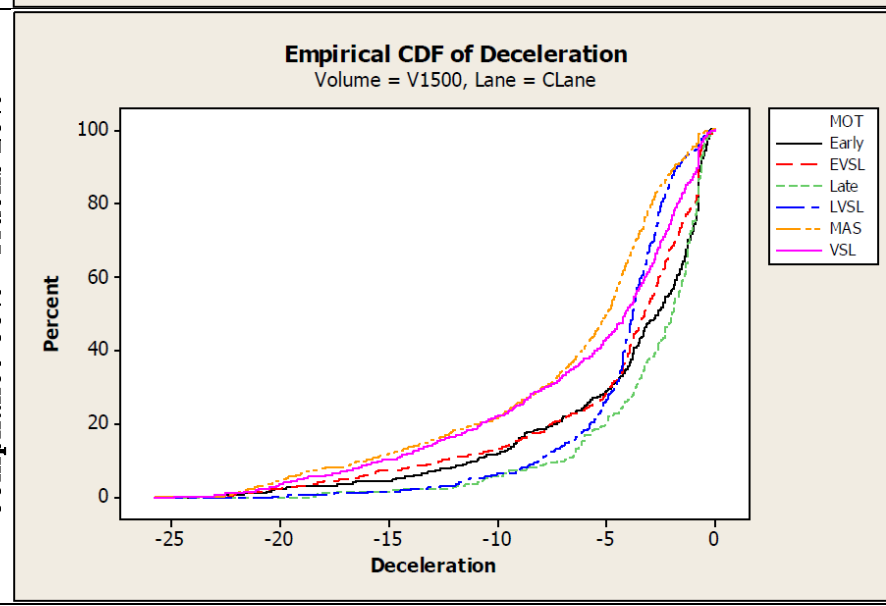
Compliance 60% - Trucks 10% — CLOSED LANE - VOLUME 1,500 VPH

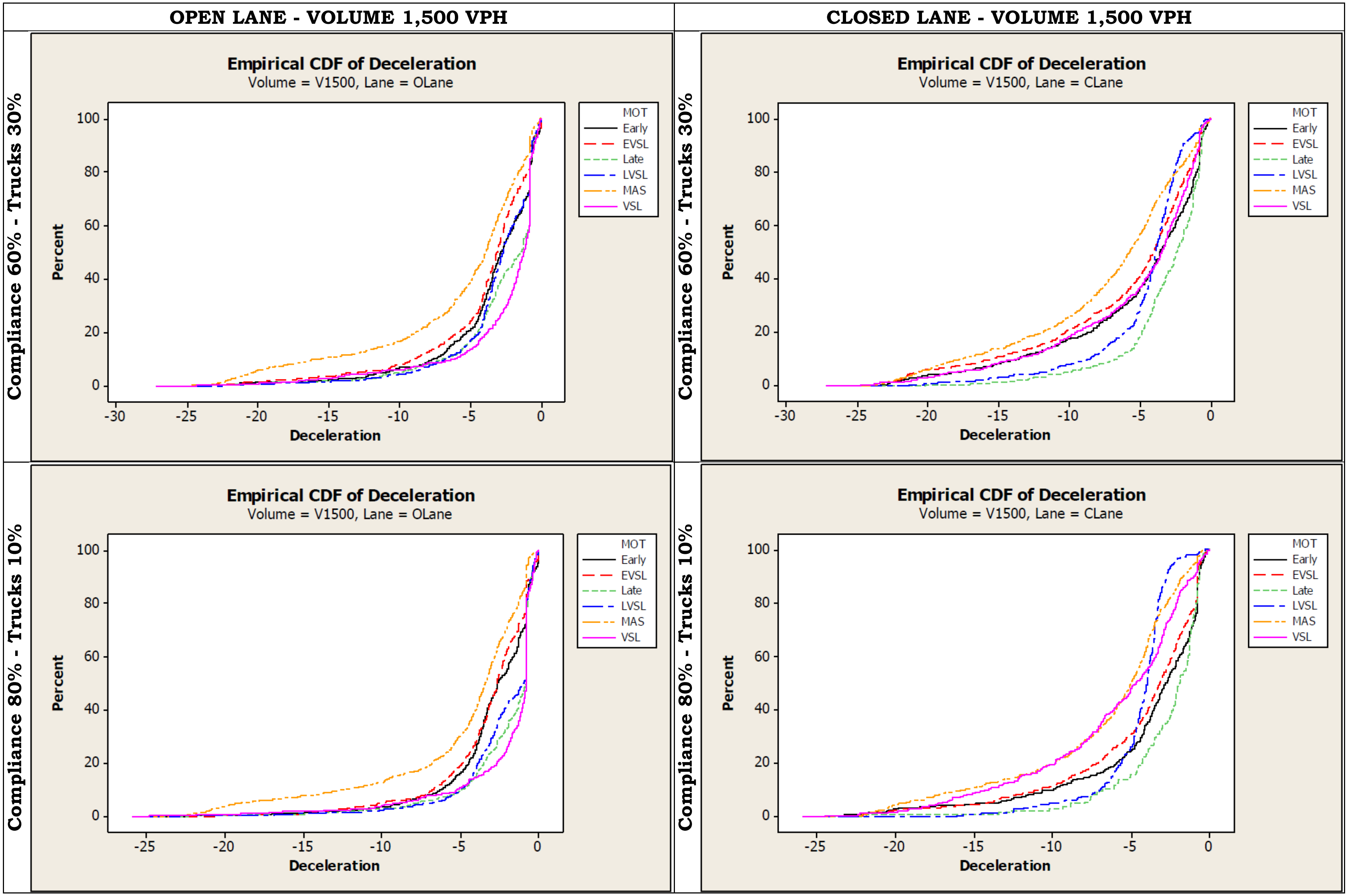


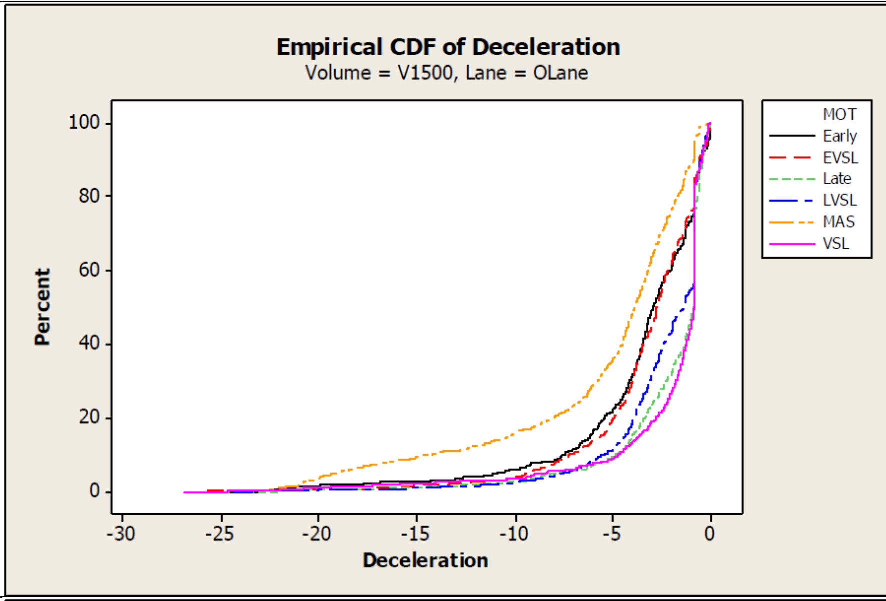
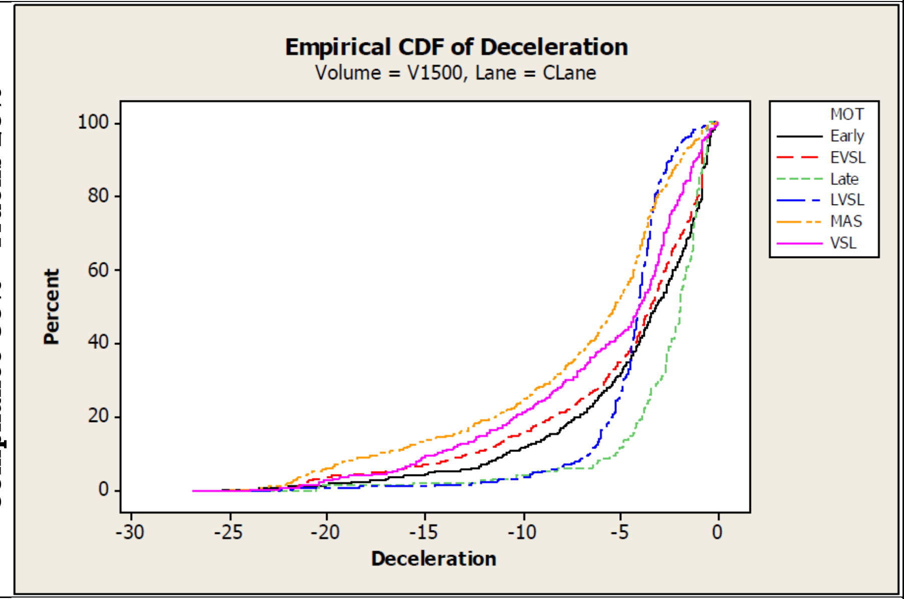
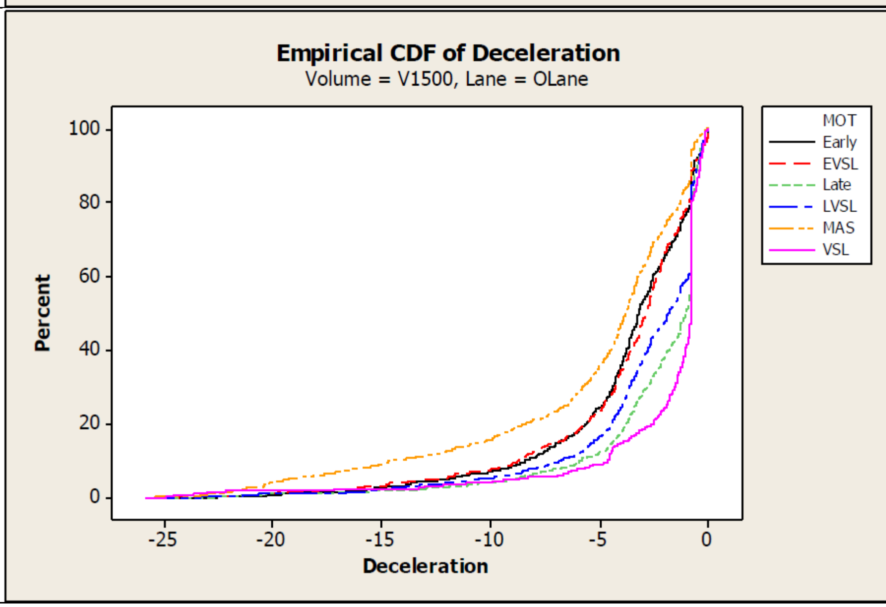
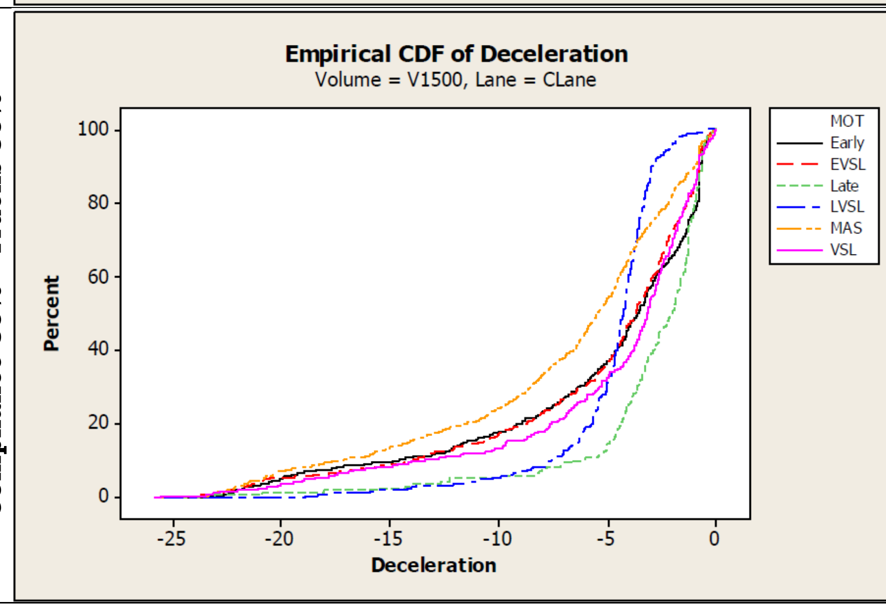
Compliance 60% - Trucks 20% — OPEN LANE - VOLUME 1,500 VPH



Compliance 60% - Trucks 20% — CLOSED LANE - VOLUME 1,500 VPH

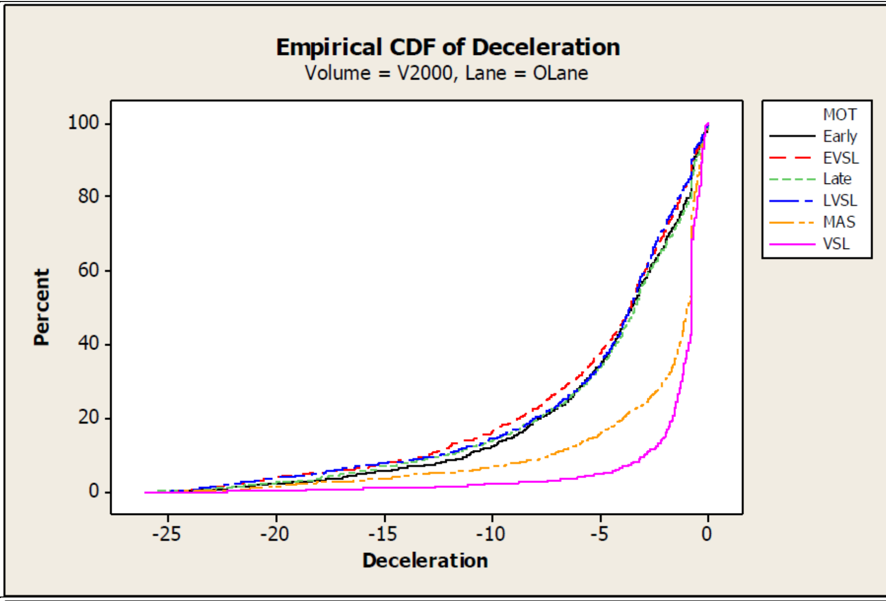



OPEN LANE - VOLUME 1,500 VPH
CLOSED LANE - VOLUME 1,500 VPH
Compliance 60% - Trucks 30%
Compliance 80% - Trucks 10%
Empirical CDF of Deceleration
Volume = V1500, Lane = OLane
Empirical CDF of Deceleration
Volume = V1500, Lane = CLane
Empirical CDF of Deceleration
Volume = V1500, Lane = OLane
Empirical CDF of Deceleration
Volume = V1500, Lane = CLane
Percent
Deceleration
MOT
Early
EVSL
Late
LVSL
MAS
VSL

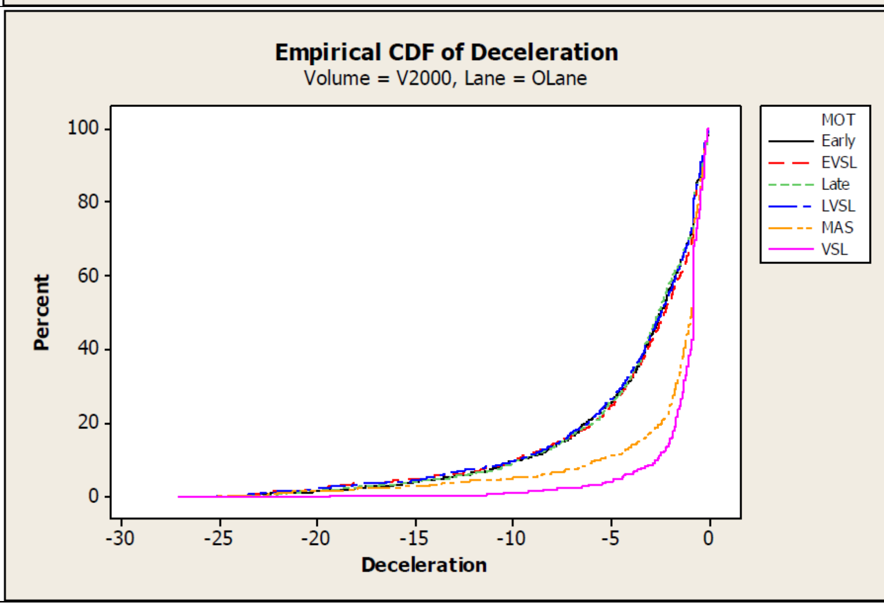
	OPEN LANE - VOLUME 1,500 VPH	CLOSED LANE - VOLUME 1,500 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

OPEN LANE - VOLUME 2,000 VPH

Compliance 20% - Trucks 10%

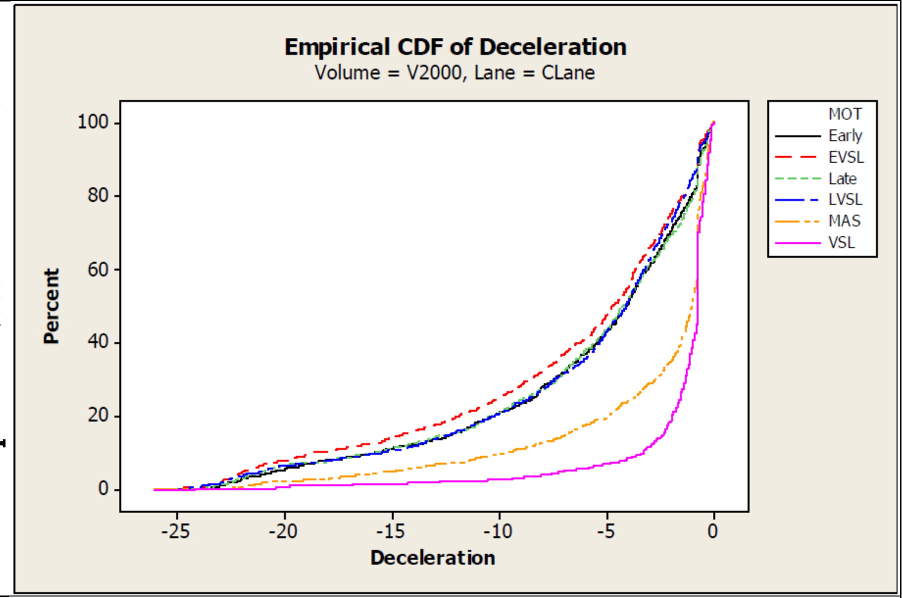


Compliance 20% - Trucks 20%

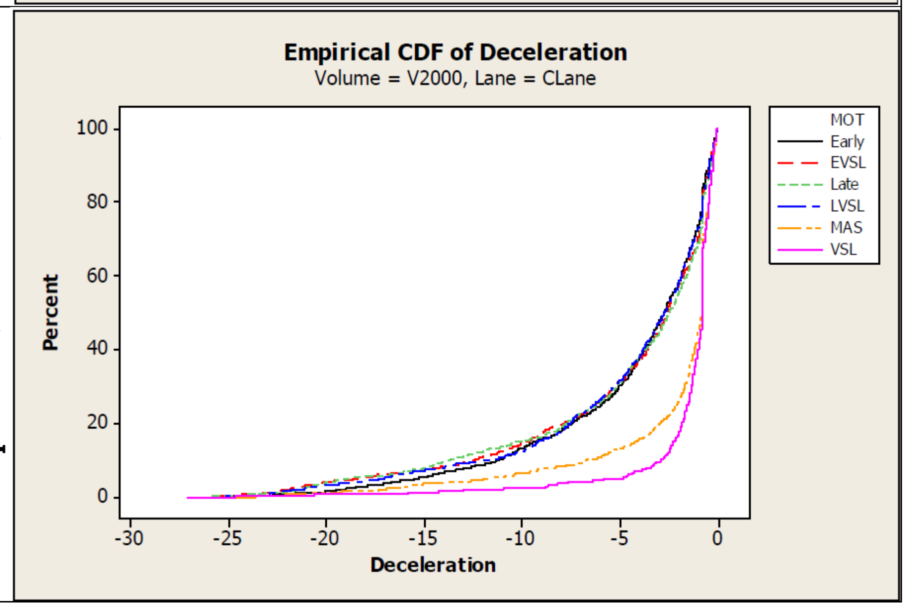


CLOSED LANE - VOLUME 2,000 VPH

Compliance 20% - Trucks 10%

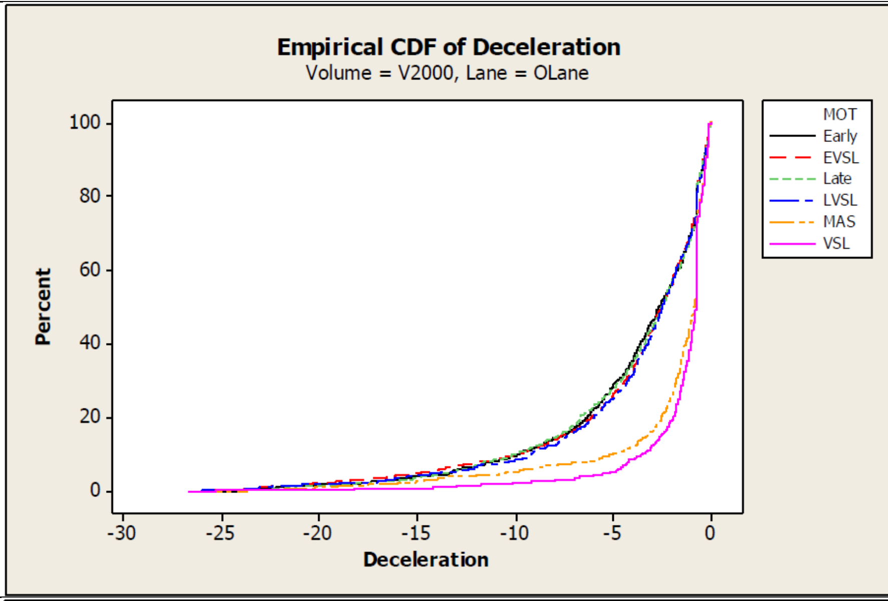


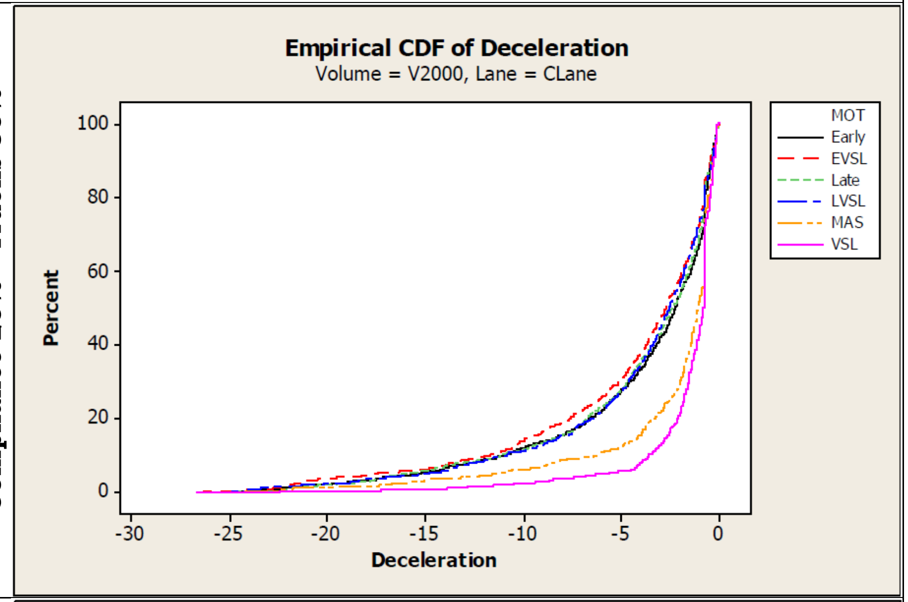
Compliance 20% - Trucks 20%



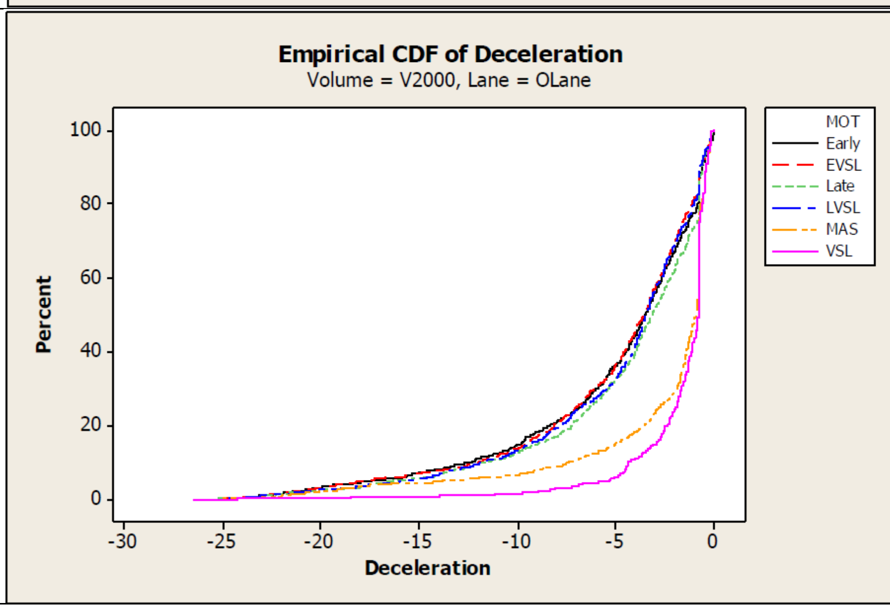
OPEN LANE - VOLUME 2,000 VPH | **CLOSED LANE - VOLUME 2,000 VPH**

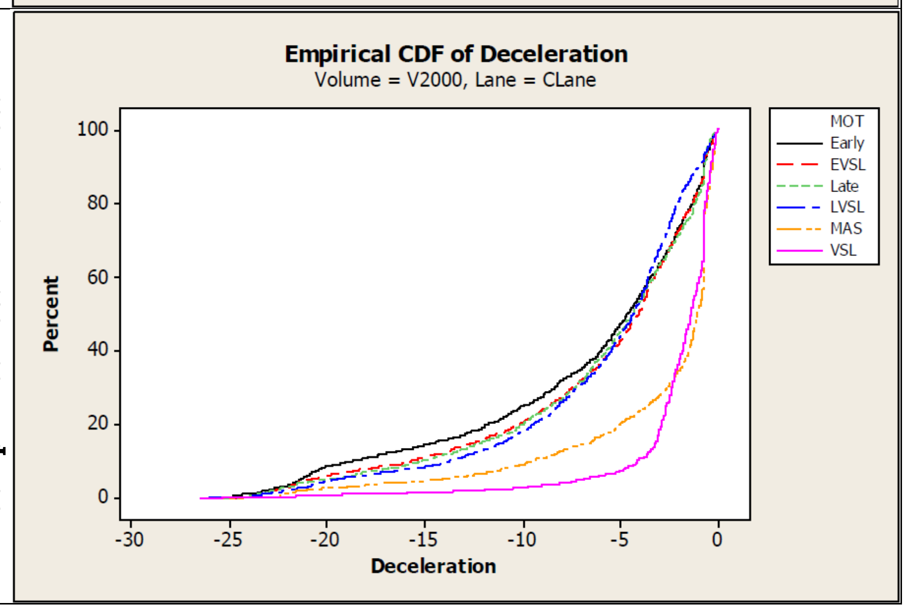
Compliance 20% - Trucks 30%





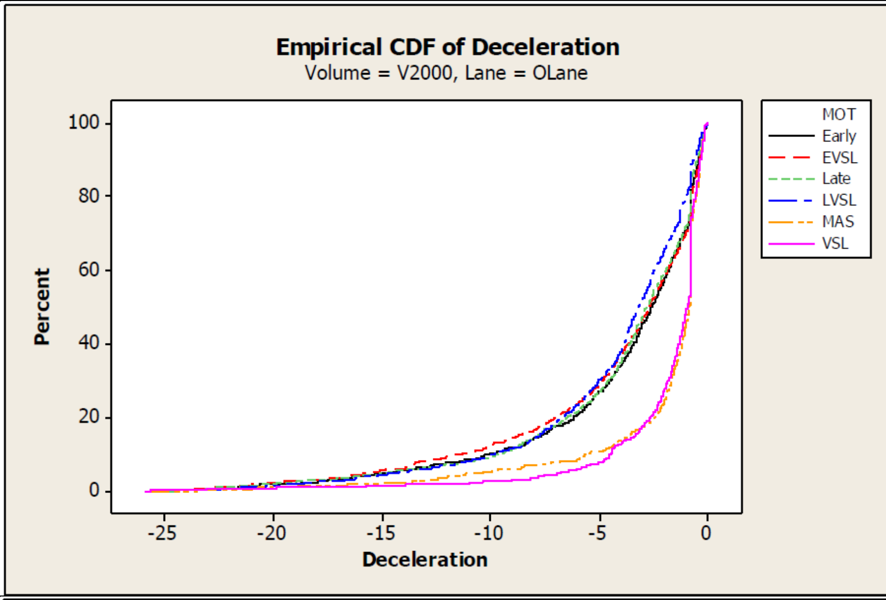
Compliance 40% - Trucks 10%





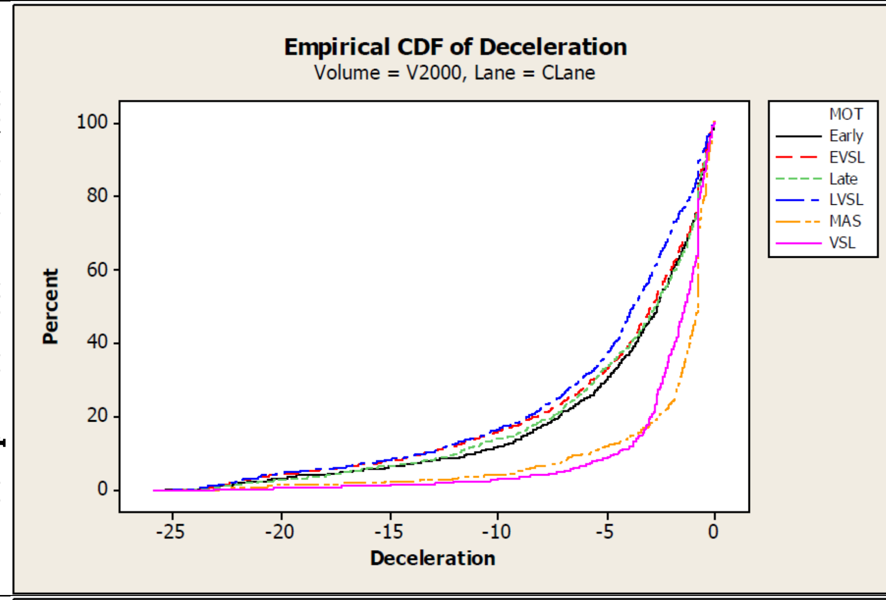
OPEN LANE - VOLUME 2,000 VPH

Compliance 40% - Trucks 20%



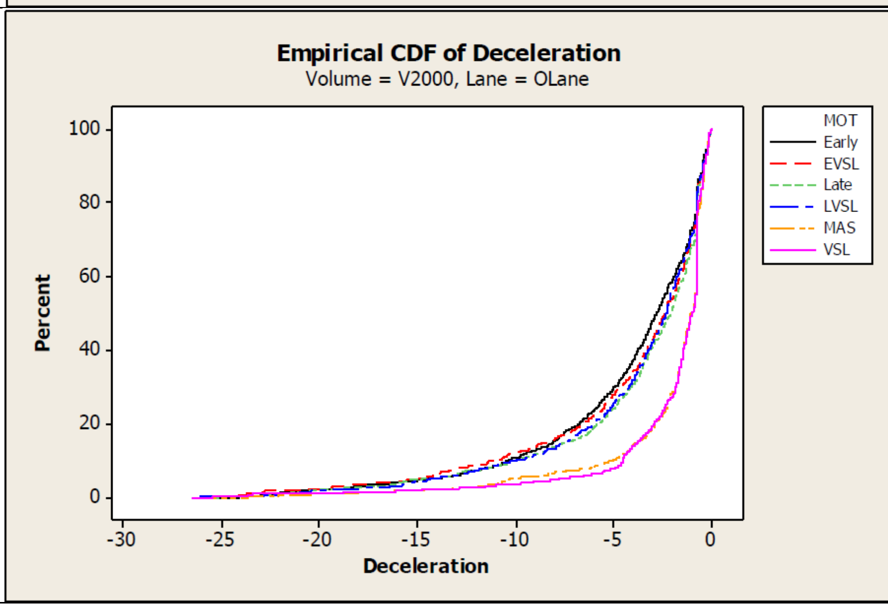
CLOSED LANE - VOLUME 2,000 VPH

Compliance 40% - Trucks 20%



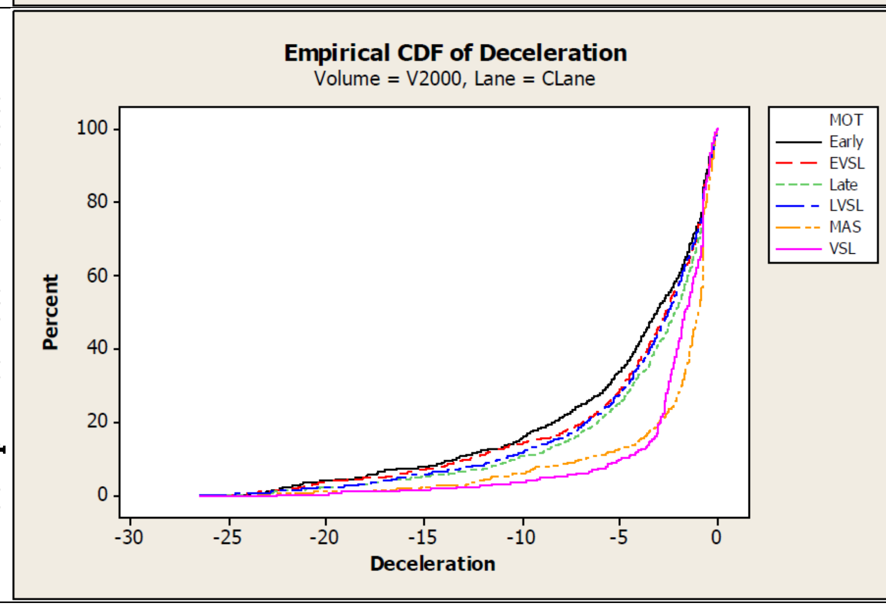
OPEN LANE - VOLUME 2,000 VPH

Compliance 40% - Trucks 30%



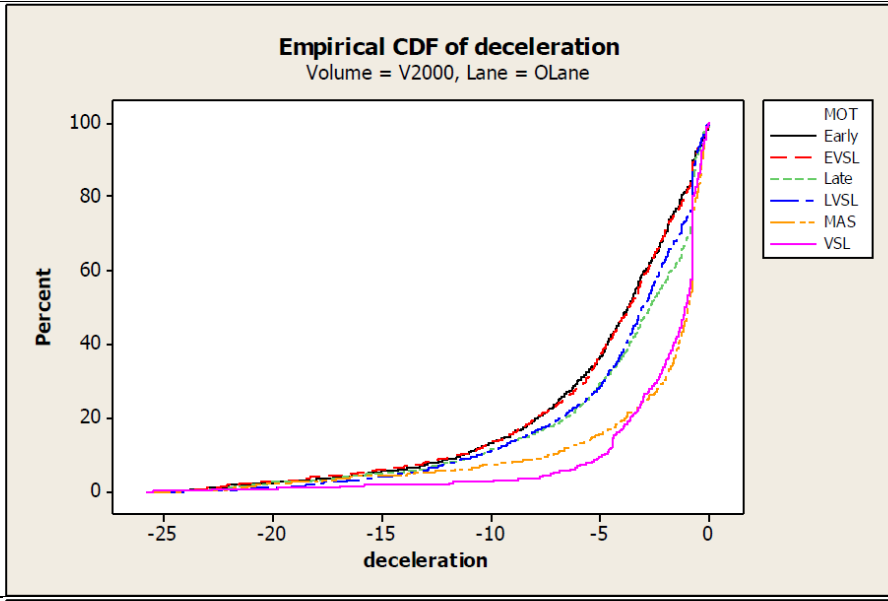
CLOSED LANE - VOLUME 2,000 VPH

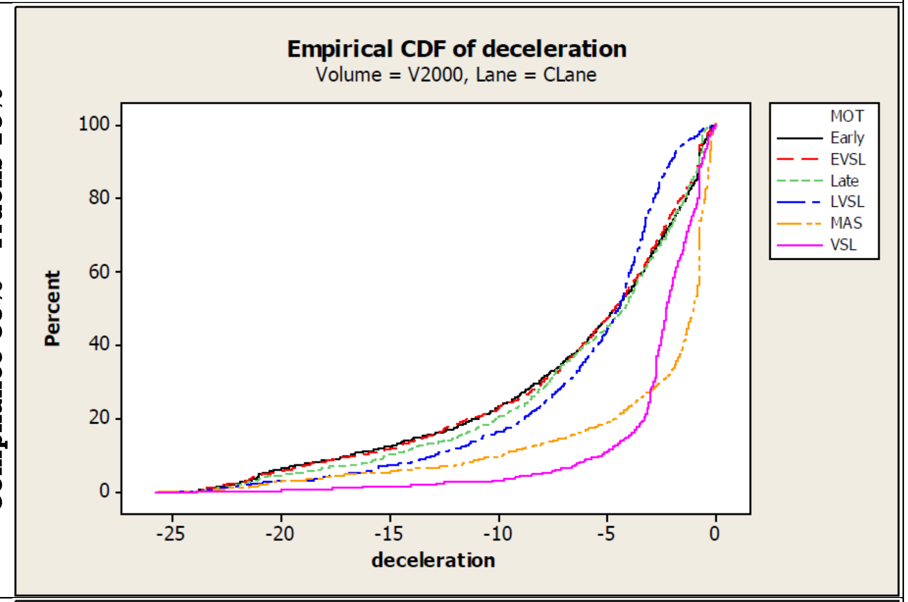
Compliance 40% - Trucks 30%



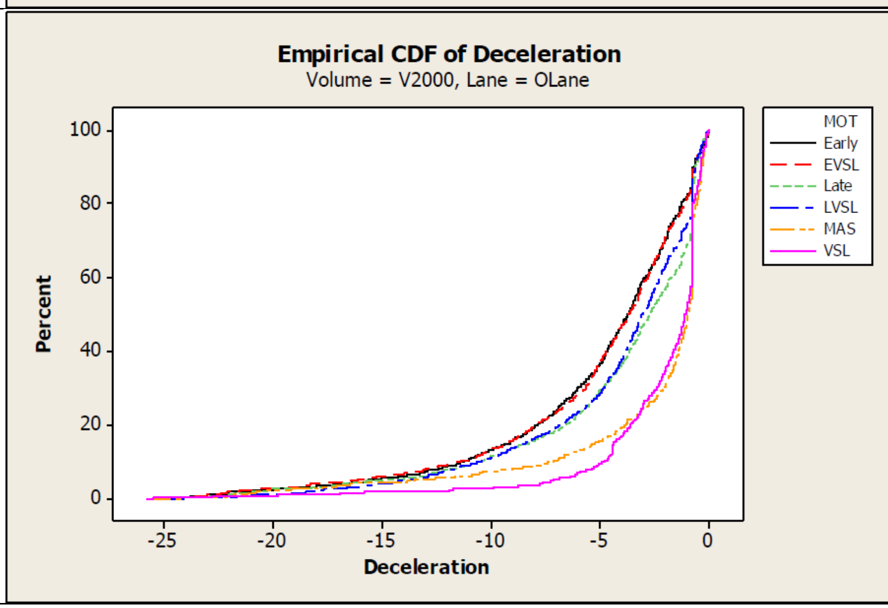
OPEN LANE - VOLUME 2,000 VPH | **CLOSED LANE - VOLUME 2,000 VPH**

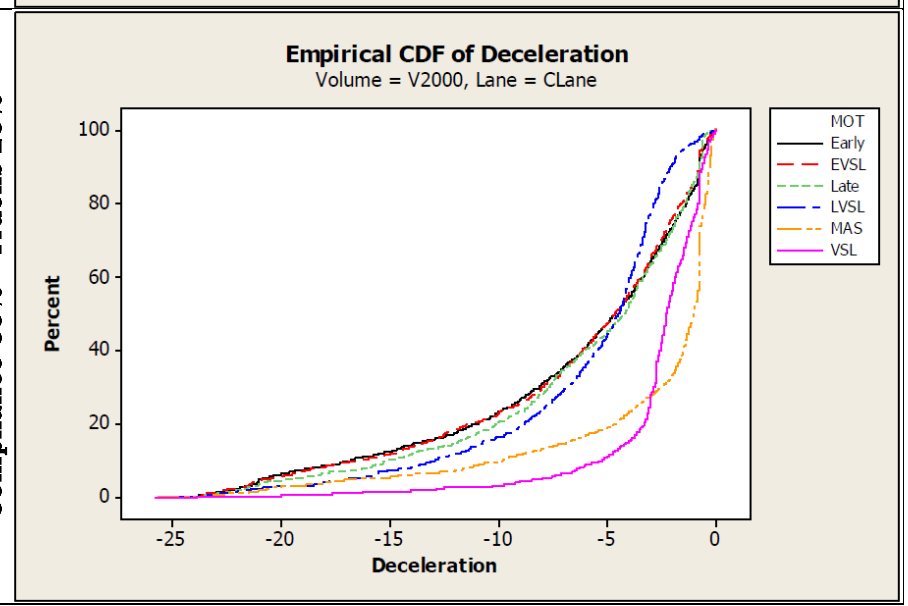
Compliance 60% - Trucks 10%

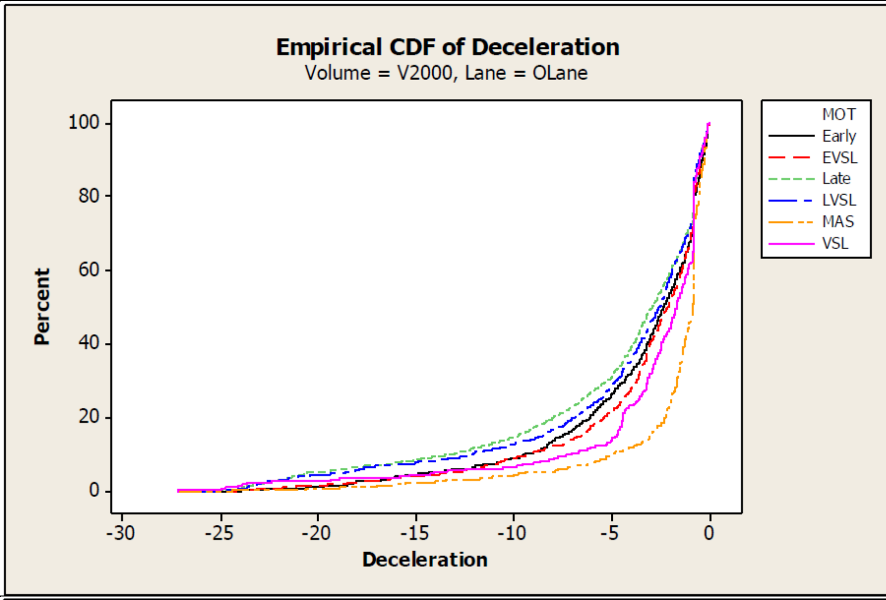
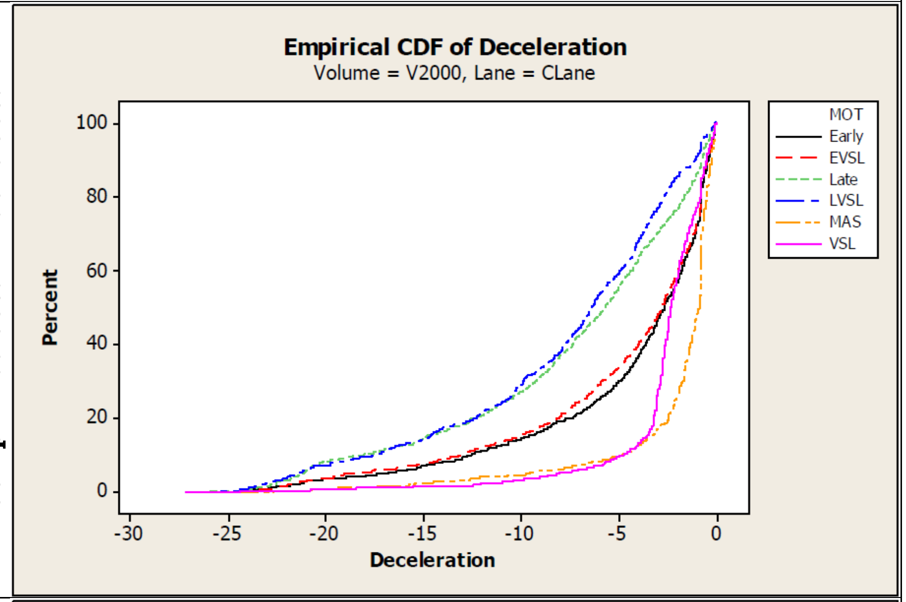
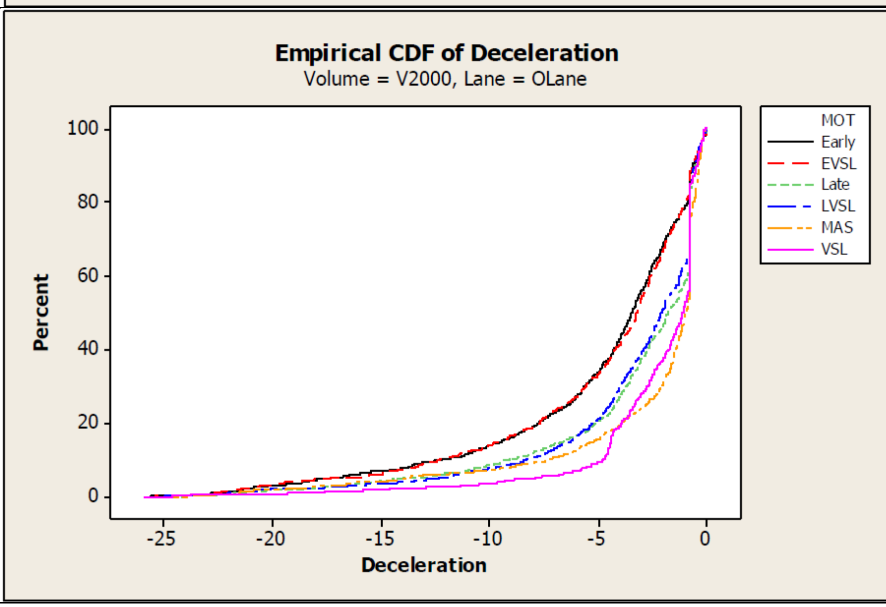
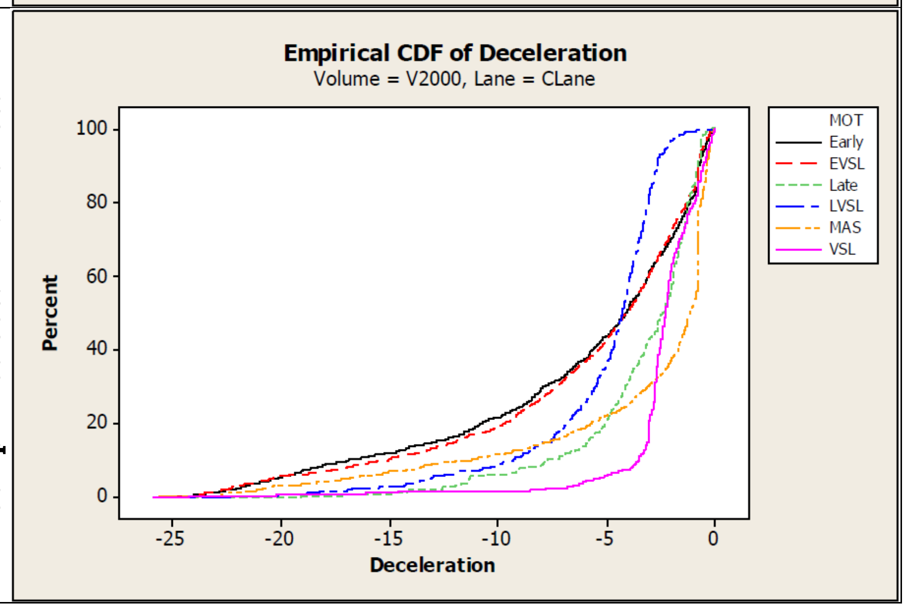


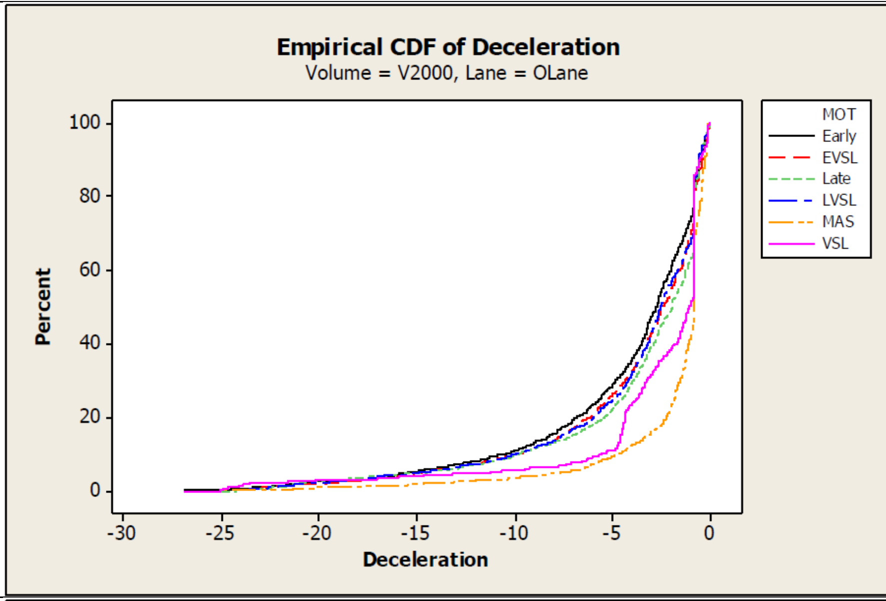
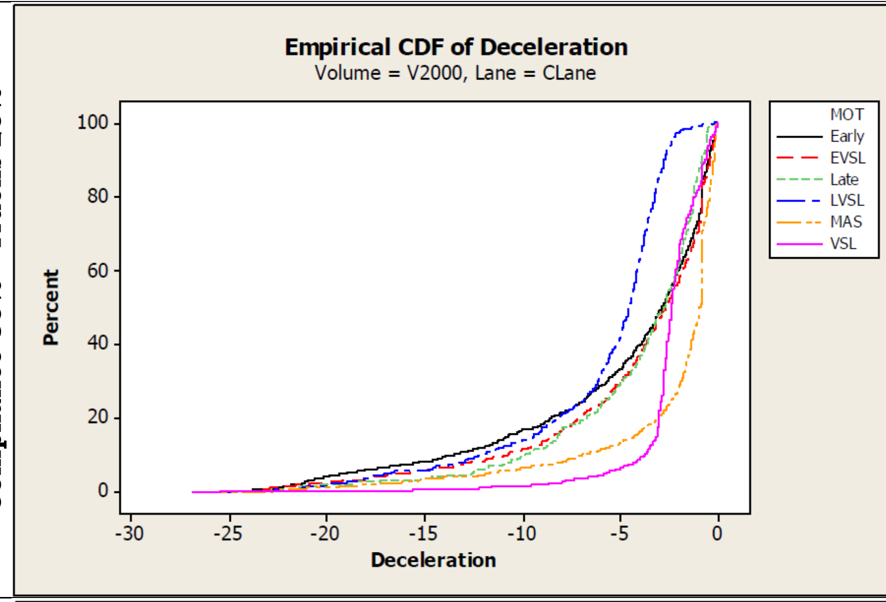
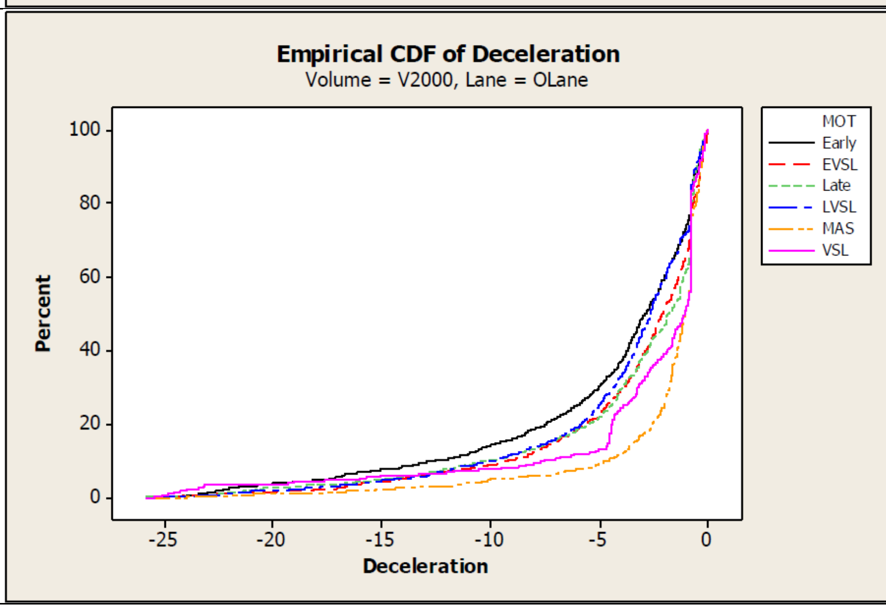
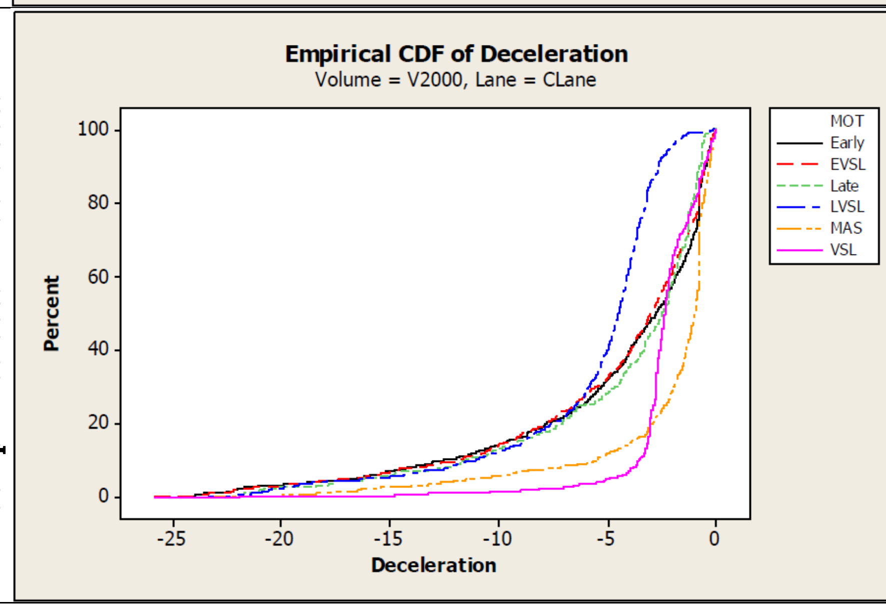


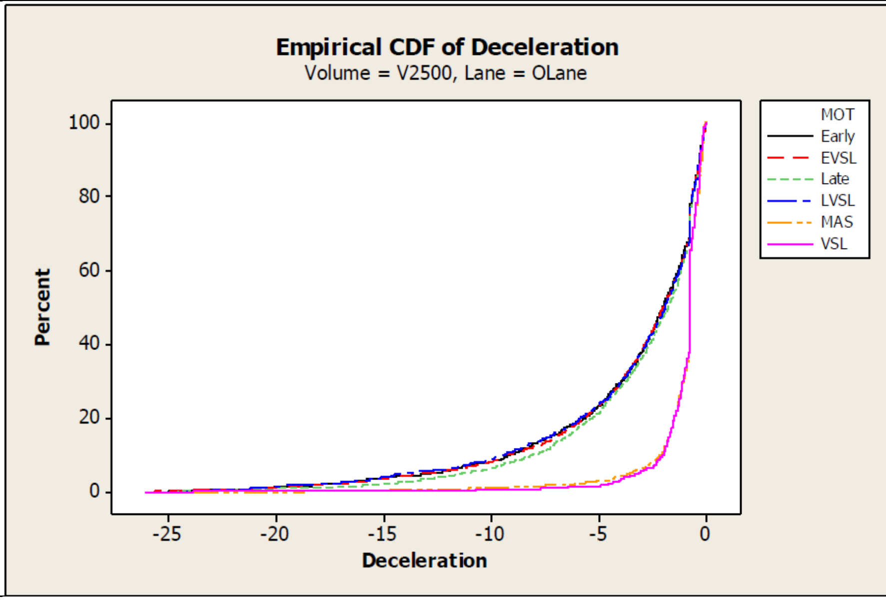
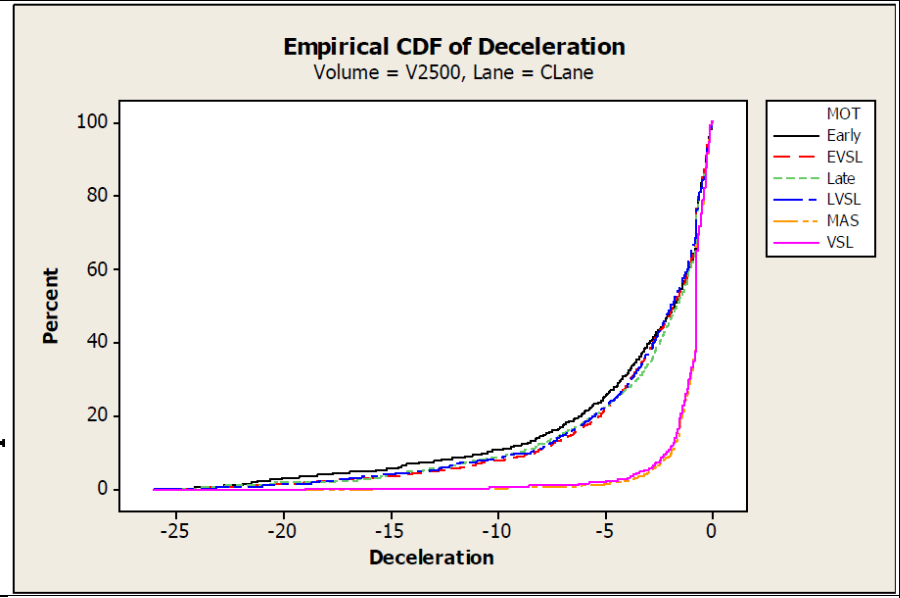
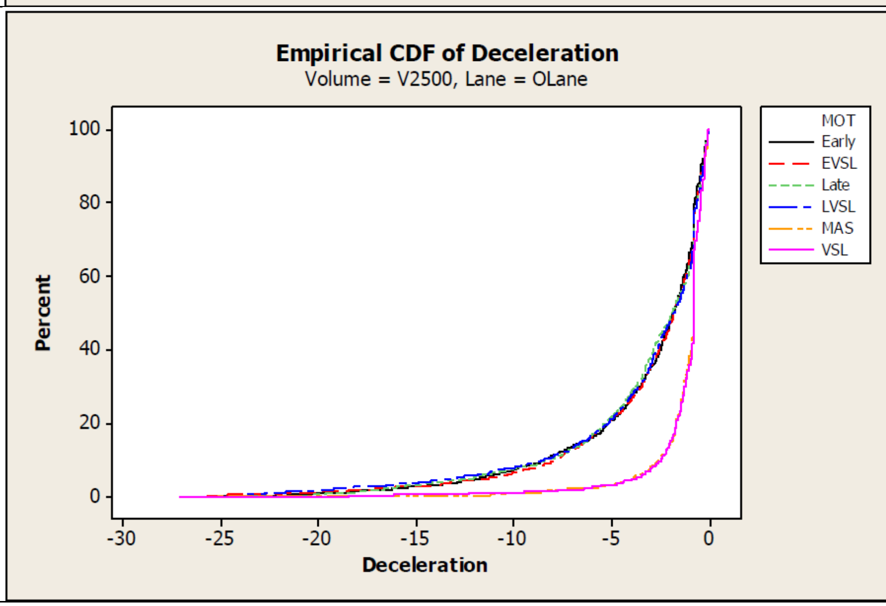
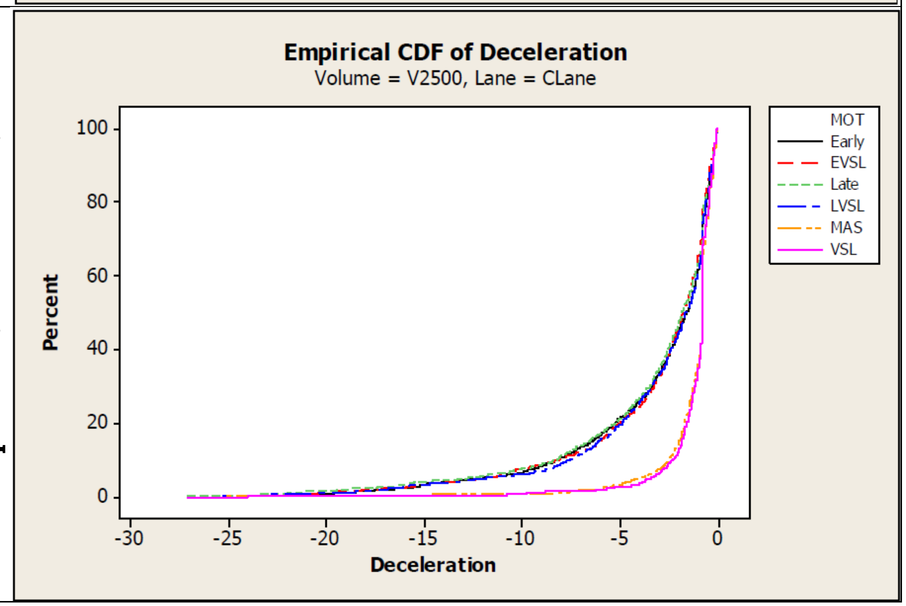
Compliance 60% - Trucks 20%

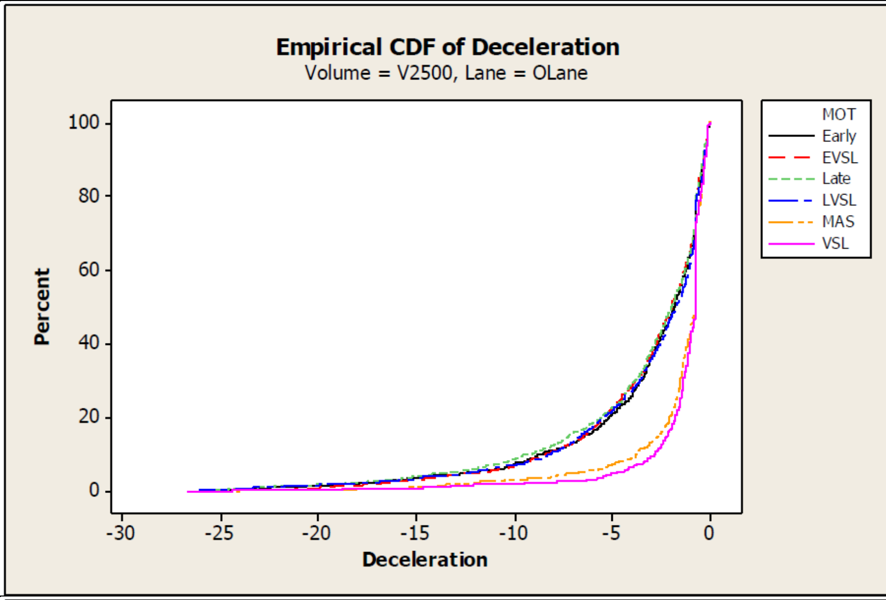
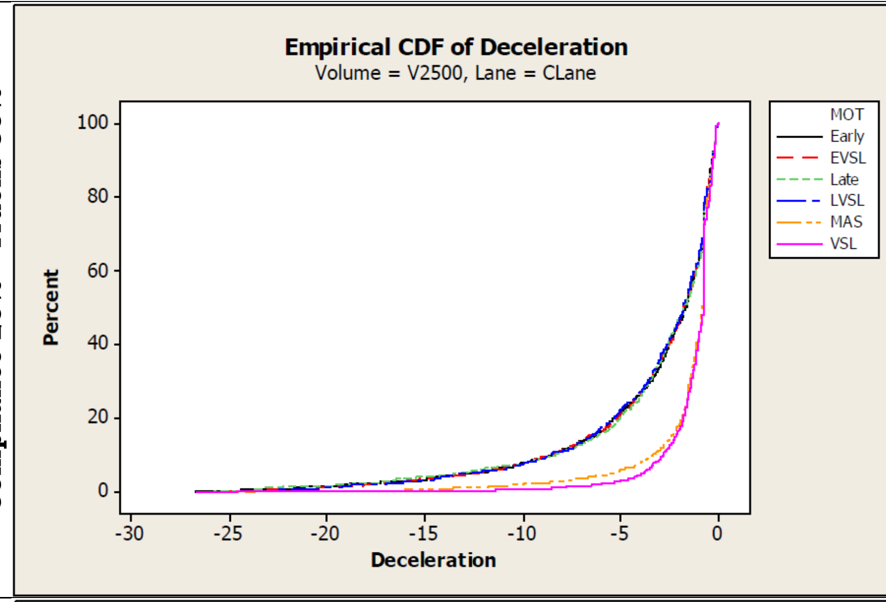
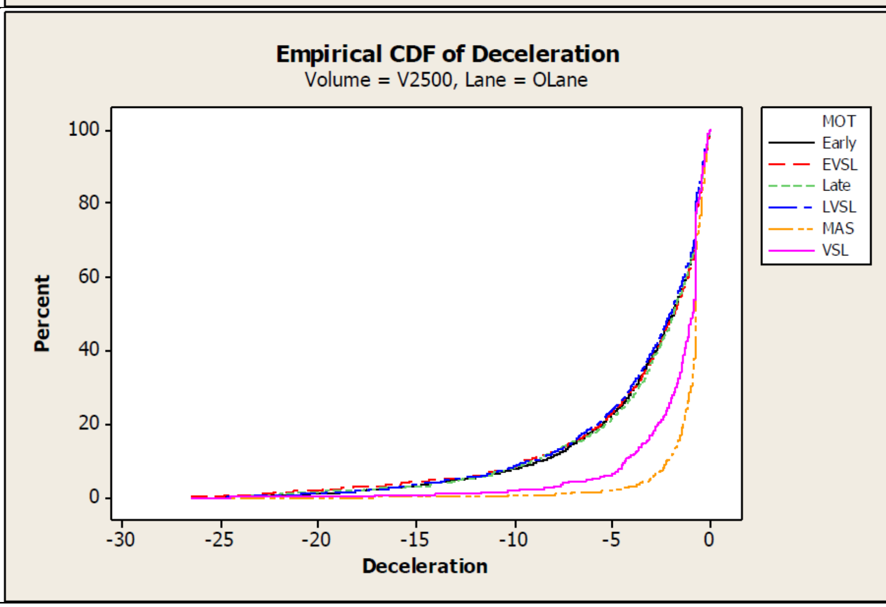
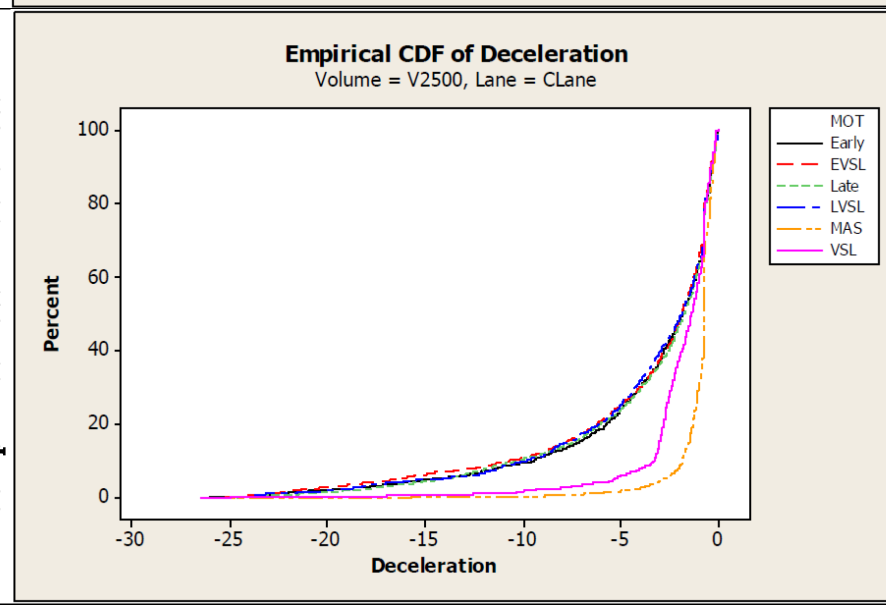




	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 60% - Trucks 30%		
Compliance 80% - Trucks 10%		

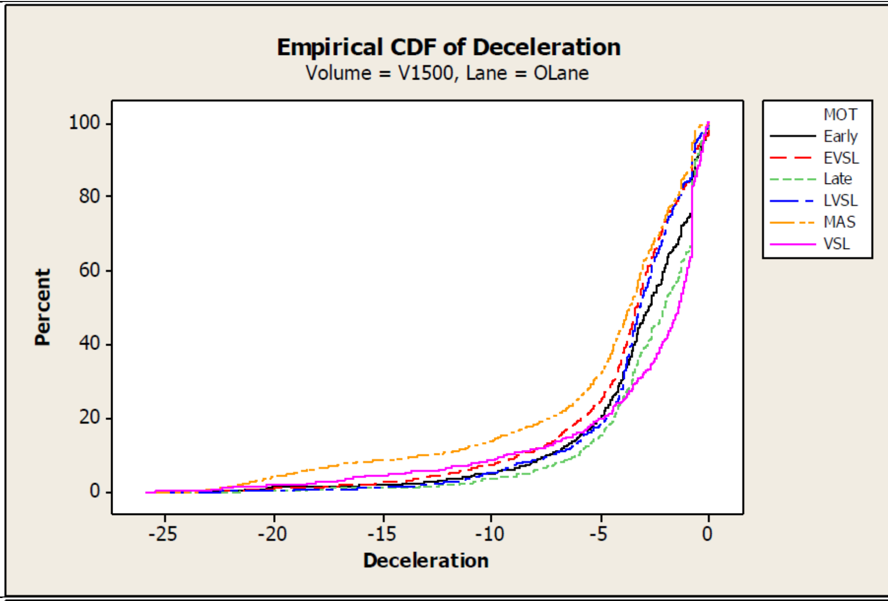
	OPEN LANE - VOLUME 2,000 VPH	CLOSED LANE - VOLUME 2,000 VPH
Compliance 80% - Trucks 20%		
Compliance 80% - Trucks 30%		

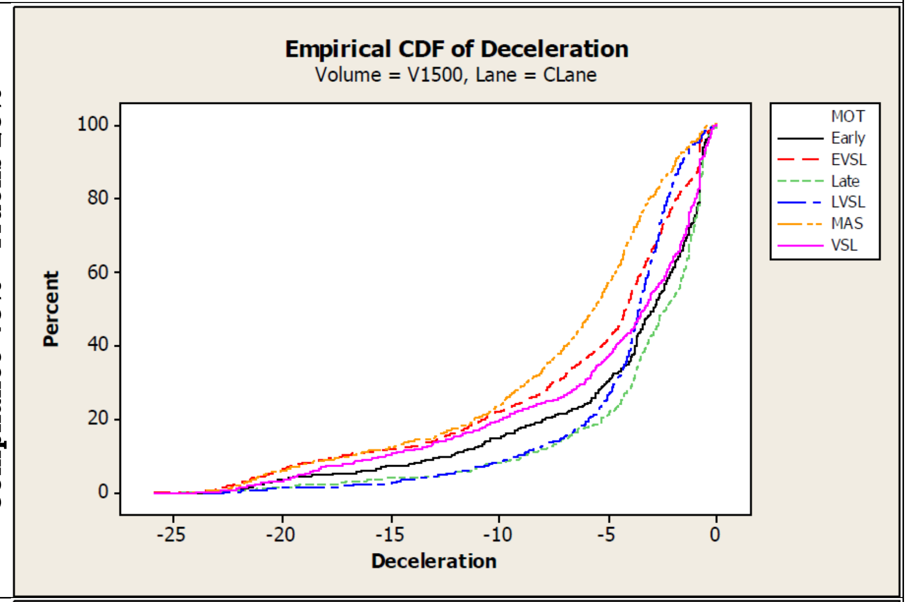
	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH
Compliance 20% - Trucks 10%		
Compliance 20% - Trucks 20%		

	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH
Compliance 20% - Trucks 30%		
Compliance 40% - Trucks 10%		

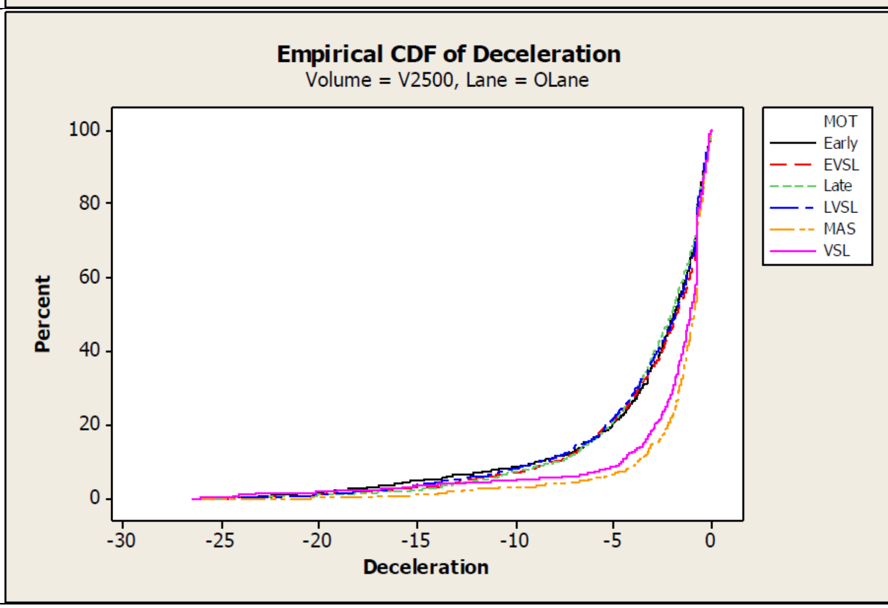
	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH

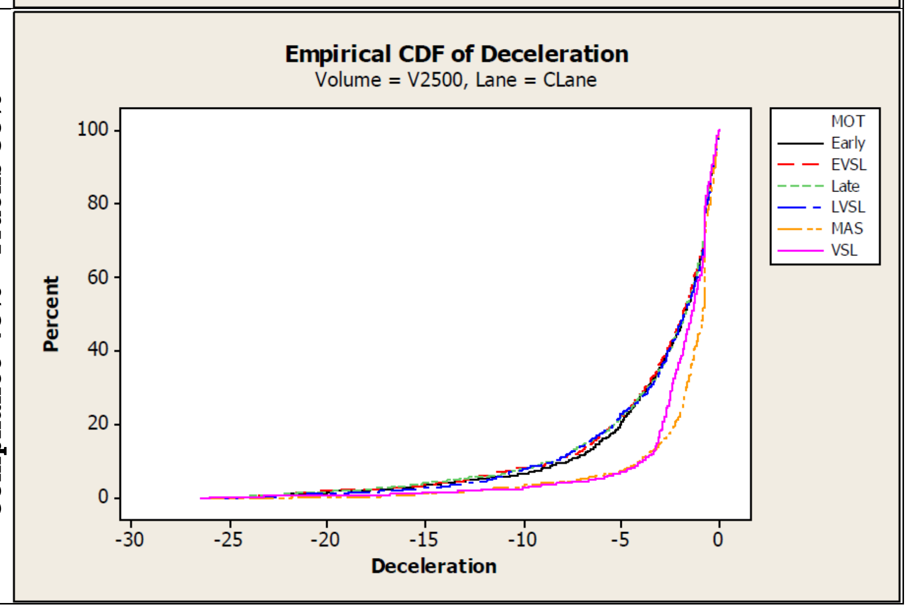
Compliance 40% - Trucks 20%





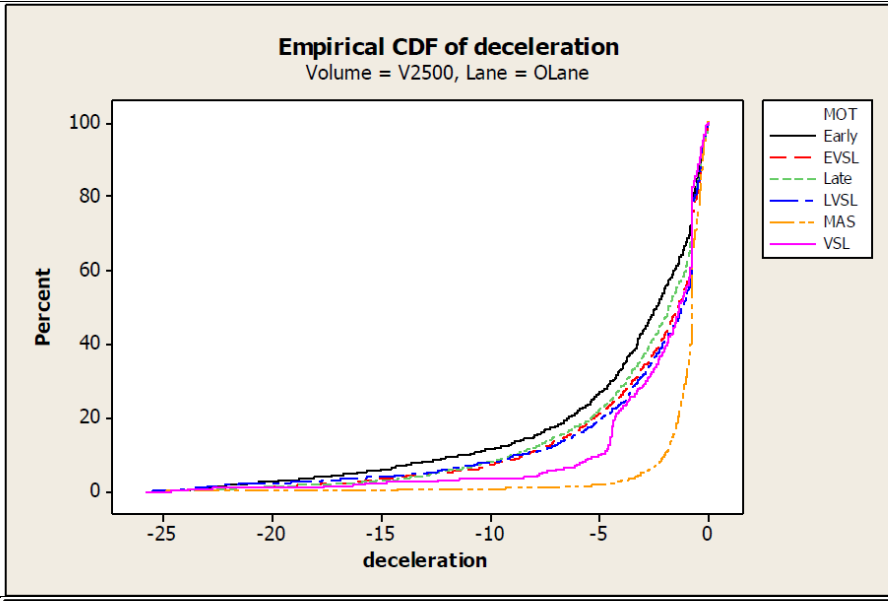
Compliance 40% - Trucks 30%

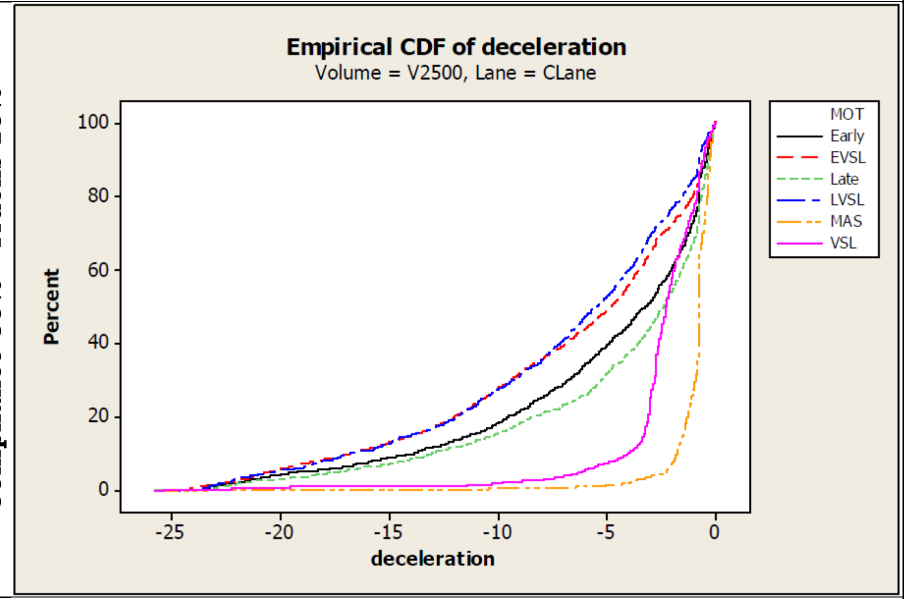




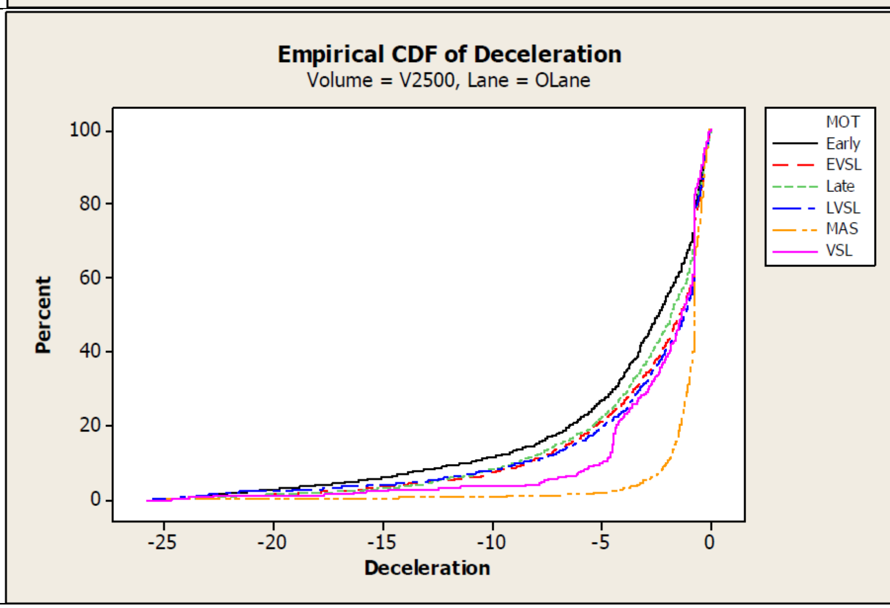
OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH

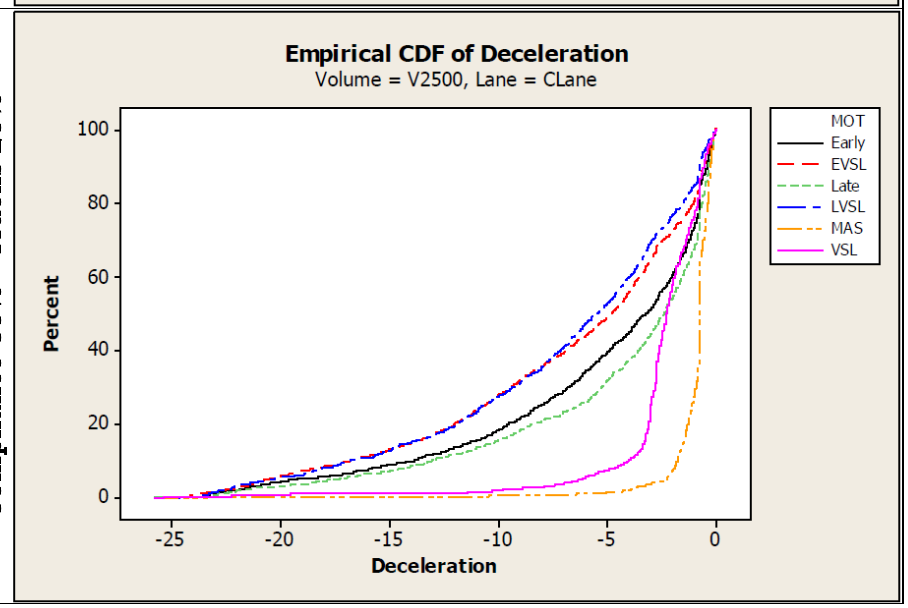
Compliance 60% - Trucks 10%





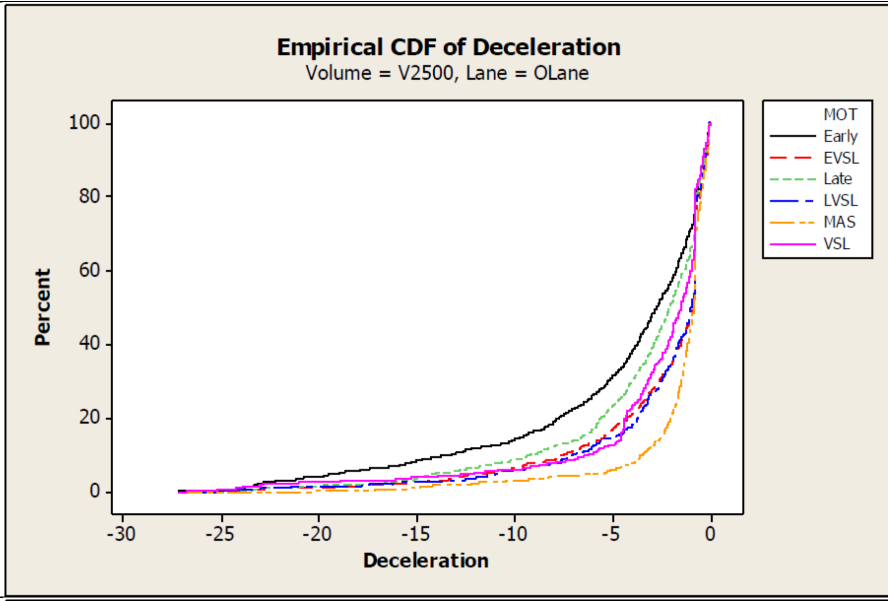
Compliance 60% - Trucks 20%

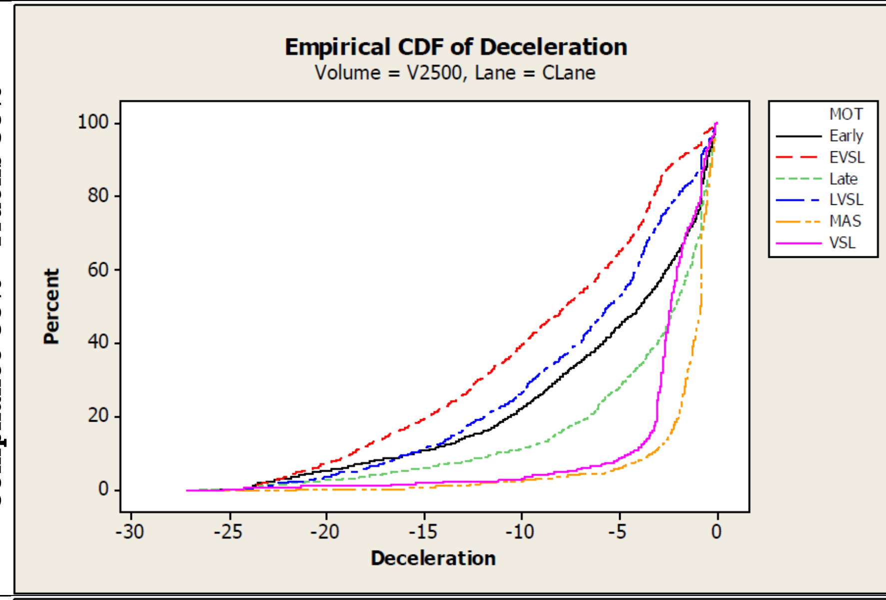




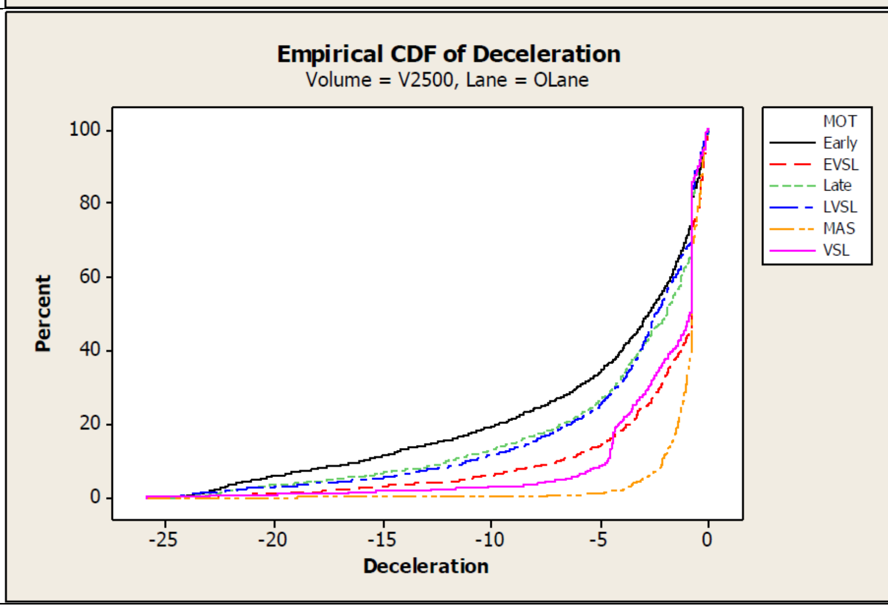
	OPEN LANE - VOLUME 2,500 VPH	CLOSED LANE - VOLUME 2,500 VPH

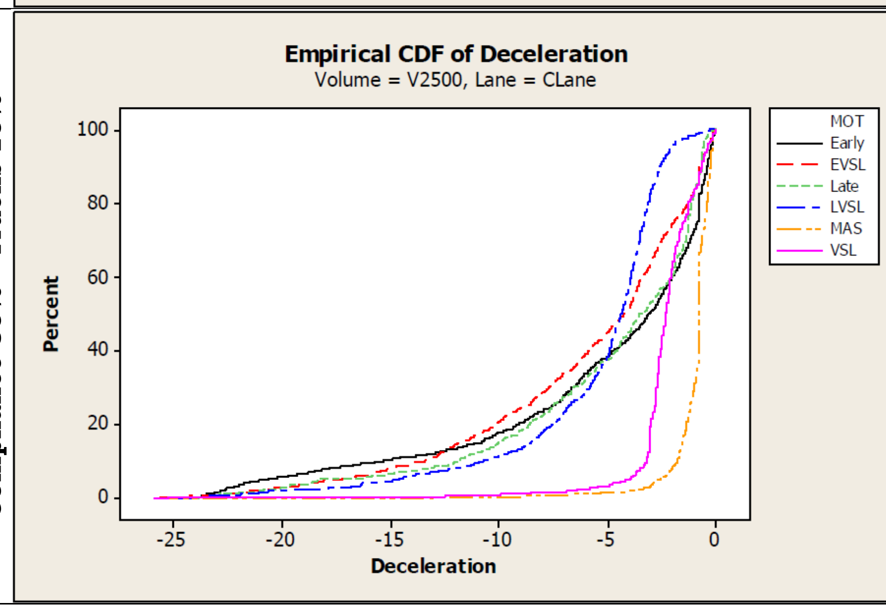
Compliance 60% - Trucks 30%



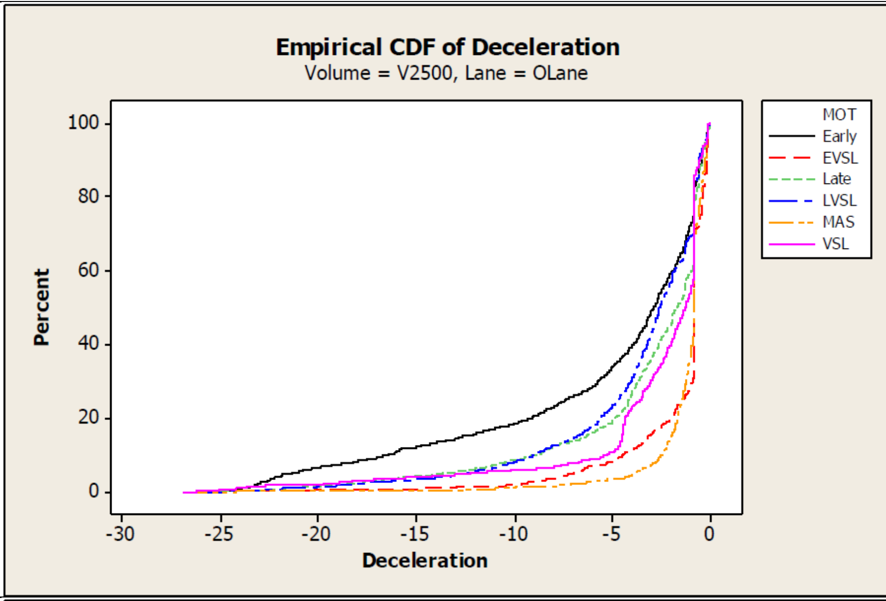


Compliance 80% - Trucks 10%

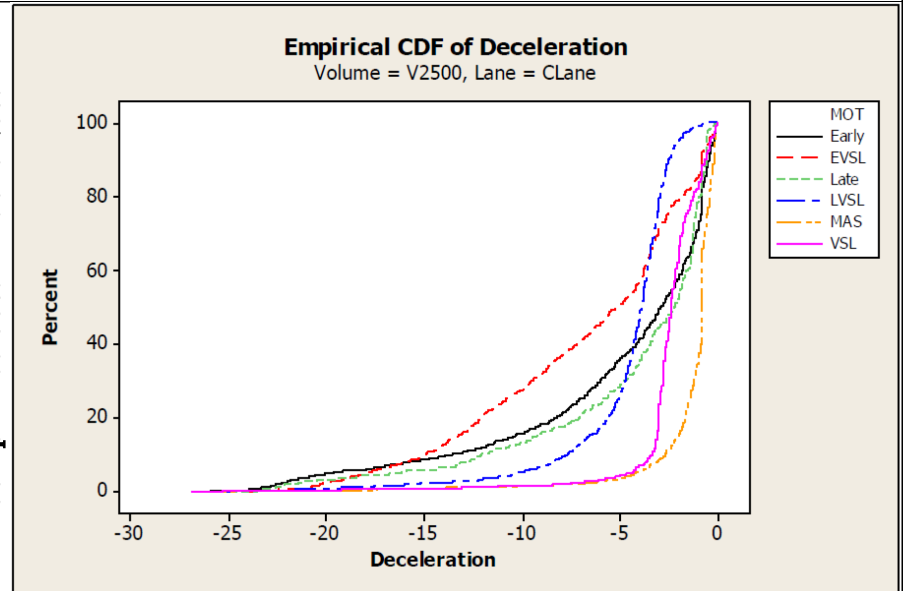




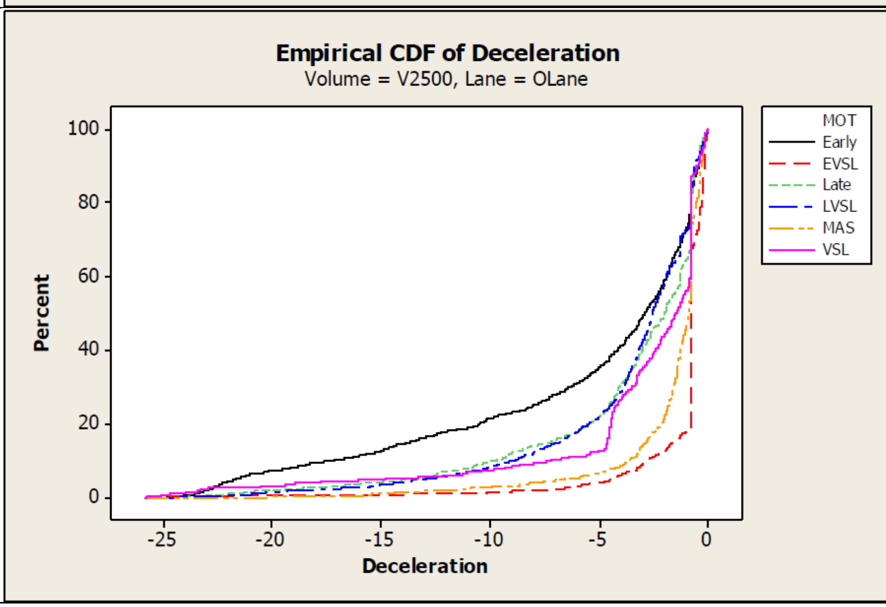
OPEN LANE - VOLUME 2,500 VPH — **Compliance 80% - Trucks 20%**



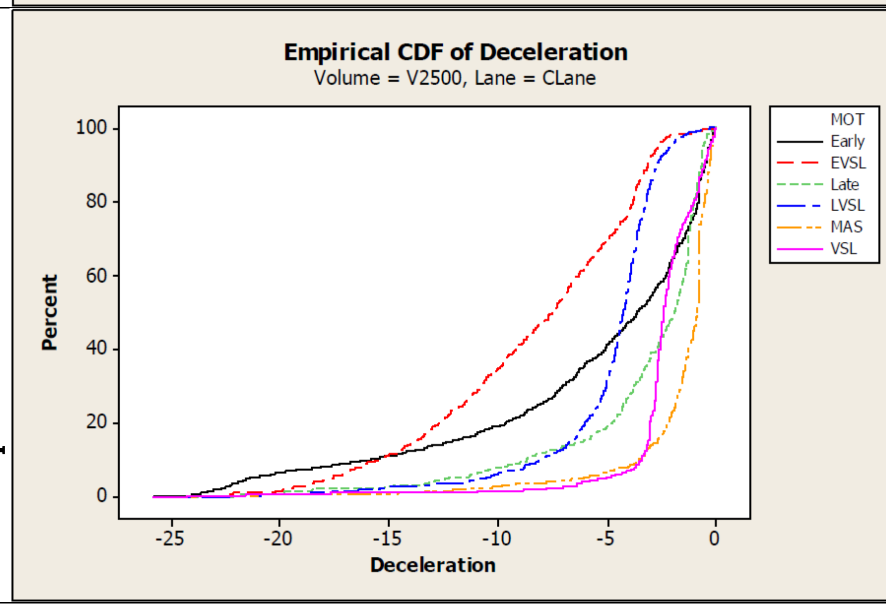
CLOSED LANE - VOLUME 2,500 VPH — **Compliance 80% - Trucks 20%**



OPEN LANE - VOLUME 2,500 VPH — **Compliance 80% - Trucks 30%**



CLOSED LANE - VOLUME 2,500 VPH — **Compliance 80% - Trucks 30%**



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