Traffic Impact Assessment of Moving Work Zone Operations

Final Report
October 2017

SWZDI
Smart Work Zone Deployment Initiative

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16. Abstract

Road maintenance activities involve both short-term stationary work zones and moving work zones. Moving work zones typically involve striping, sweeping, pothole filling, shoulder repairs, and other quick maintenance activities. Existing traffic analysis tools for work zone scheduling are not designed to model moving work zones. A review of existing literature showed that many of the existing studies of moving bottlenecks are theoretical in nature, limited to certain lane configurations, and restrictive in the types of mobile work zone attributes considered. This research project sought to address this gap in existing knowledge by using field data from moving work zones to develop and calibrate a traffic impact analysis tool. This objective was accomplished through the fusion of multiple sources of work zone and traffic data. Four different data sources were used: Missouri Department of Transportation (MoDOT) electronic alerts (e-alerts), probe-based travel times, data from point detectors, and field videos of moving work zones recorded from the back of a truck-mounted attenuator (TMA). A linear regression model was developed to predict traffic speed inside a moving work zone. Predictor variables in the models included historical speed, number of lanes, type of lane closure, and time of day. The simulation tool VISSIM was calibrated for moving work zones using information extracted from videos of moving work zone operations. The three recommended calibration parameters are a safety reduction factor of 0.7, a minimum look ahead distance of 500 ft, and the use of a smooth closeup option. These calibration values can be used by departments of transportation (DOTs) to model moving work zone scenarios. The operational analysis concluded that a moving work activity lasting one hour or more operates best when traffic volumes are under 1,400 veh/hr/ln, and preferably under 1,000 veh/hr/ln. Further, scheduling shorter duration moving activities on high-volume roads at multiple times (on the same day or on different days) works better than scheduling a longer duration activity. The safety analysis generated tradeoff plots between the number of conflicts and combinations of activity duration and traffic volume. A DOT can use these plots to determine, for example, if it should conduct a moving work activity for a short duration when the volume is high or for a longer duration when the volume is lower.

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TRAFFIC IMPACT ASSESSMENT OF MOVING WORK ZONE OPERATIONS

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EXECUTIVE SUMMARY

The focus of many state departments of transportation (DOTs) has shifted from new construction to maintaining existing infrastructure. The implementation of highway work zones creates adverse operational and safety impacts. State DOTs strive to mitigate these impacts using several approaches, including improved scheduling of work activities, traffic management plans, and innovative use of available technologies.

Maintenance work involves both short-term stationary work zones and moving work zones (MWZs). MWZs typically involve striping, sweeping, pothole filling, shoulder repair, and other quick maintenance activities. State DOTs generally use traffic impact analysis tools to schedule maintenance work. However, none of the existing tools are designed to appropriately model the impact of MWZs. A review of existing literature showed that many of the existing studies of moving bottlenecks are theoretical in nature, limited to certain lane configurations, and restrictive in the types of mobile work zone attributes considered. The lack of guidance on the traffic impact assessment of moving work zones motivated this study.

The objective of this research project was to develop guidance for practitioners on how to assess the traffic impacts of MWZs. This knowledge will help practitioners improve scheduling of MWZs. Two approaches were examined to assess traffic impacts. First, real-world data were used to calibrate the VISSIM simulation tool for use in analyzing the traffic impacts of MWZs. Second, a data-driven approach was used to estimate regression models of work zone speeds as a function of various independent variables, including work zone characteristics and schedules and traffic and geometric characteristics.

Multiple data sources were used to collect work zone and traffic data for MWZs in order to develop the VISSIM calibration values and regression models. Four different data sources were used: (1) MWZ information from Missouri Department of Transportation (MoDOT) electronic alerts (e-alerts), (2) travel time data from the Regional Integrated Transportation Information System (RITIS), (3) data from traffic flow detectors, and (4) videos of MWZs from a moving work vehicle. Information contained in the e-alerts included start date and time, end date and time, location by address, and lane closure type (left, right, center). A group of MWZs on the I-44 and I-64 freeways in the St. Louis area that were active between July 2014 and July 2015 were obtained through these MoDOT e-alerts, and 30 MWZs were identified for further analysis.

MoDOT has an agreement with the owners of RITIS to receive travel time data for state roadways. The RITIS database is based on probe vehicle travel time. Queried data from the RITIS database include travel time and speed for segments and information on traffic management center (TMC) segment identifiers. The other database that was used in this research consisted of information from MoDOT traffic flow detectors, which are point detectors. The data collected by these detectors consist of vehicle spot speeds and volumes. The RITIS and point detector databases were matched using the MWZ location and time. For the 14 MWZs with durations greater than 20 minutes, speed-flow diagrams based on the detector data and speed heat maps based on the RITIS data showed that eight of the MWZs experienced congested conditions.

To evaluate the driving behavior associated with MWZs, videos were collected from the back of slow-moving trucks. Videos from 11 separate data collection activities were processed using photogrammetry to obtain the following information:

- The distance from the back of the truck to the location at which the following vehicles merged into the adjacent open lane
- The gaps available in the open lane for each lane-changing vehicle
- The speeds of the vehicles that passed the work truck
- Speed of the slow-moving work truck
- Traffic volume of vehicles that passed the truck
- Percentage of heavy vehicles

To help practitioners predict traffic speeds in MWZs, a linear regression model was developed using the collected data. The predictor variables used in the modeling are shown in Table ES.1.

Table ES.1. Predictors for work zone speed model

Predictors	Description
SpL	Speed limit (mph)
HiSp	Historical speed, week before the MWZ (mph)
NoL	Number of lanes
LR	Lane closure indicator: 0 if left lane is closed, 1 otherwise
DN	0 for nighttime MWZs between 12 and 6 a.m., 1 otherwise

The developed linear regression model is as follows:

$$WZSp = -26.738 + 0.962 \times SpL + 0.345 \times HiSp + 2.015 \times NoL - 10.184 \times LR - 5.607 \times DN$$

The speed distributions obtained from the detector data and the lane change information obtained from the MWZ videos were used to calibrate VISSIM for use with MWZs. An 18-mile segment of a three-lane urban freeway was used as the test network. The simulation duration was 4 hours, with 1,400 seconds of warm-up. Two categories of VISSIM driving behavior parameters related to car following and lane changing were tested and modified. The recommended calibration parameters are as follows:

- Safety distance reduction factor (SRF) = 0.7
- Minimum look ahead distance = 500 ft
- Smooth closeup = True

The calibrated parameters were then applied in VISSIM to test networks with different durations and lengths to evaluate the operational impacts of MWZs. The calibrated parameters provided results that were more consistent with the videos than the results generated by the VISSIM default parameters. The simulation was run for five different durations and five different volumes; vehicle trajectories were then plotted. The results showed that moving work zones lead to increased delays, queuing, and stops. These impacts increased as the volume and moving work zone duration increased.

From the operational analysis, it was concluded that a moving work activity lasting one hour or more is best scheduled for times when the traffic volume is under 1,400 veh/hr/ln, and preferably under 1,000 veh/hr/ln. Further, scheduling shorter duration moving activities on high-volume roads at multiple times (on the same day or on different days) is preferable to scheduling a longer duration activity. As volumes approach 1,800 veh/hr/ln, even a 30-minute activity can generate a 3.2-mile-long queue, which increases to 6.5 miles for a 60-minute activity and 13 miles for a 120-minute activity.

The safety impacts of moving work zones were assessed using the trajectories of vehicles from the simulation and the Surrogate Safety Assessment Model (SSAM). Both rear end and lane change conflicts were assessed. The impacts of work zone duration on conflicts increased as volumes exceeded 700 veh/hr/ln. The results show a near-linear increase in the number of conflicts with duration until the volume reaches 1,800 veh/hr/ln, after which the increase becomes non-linear.

Tradeoff plots between the number of conflicts and combinations of activity duration and traffic volume were also generated. A DOT can use these plots to determine, for example, if it should conduct a moving work activity for a short duration when the volume is high or for a longer duration when the volume is lower. This study also recommends that if a moving activity must be scheduled during higher volume conditions (1,000 veh/hr/ln or more), then a shorter duration (i.e., 60 minutes or less) would work best to avoid significant negative safety impacts.

1 INTRODUCTION

In the US, about $700 million is lost in fuel consumption annually due to congestion resulting from work zones (FHWA 2012). About 10% of highway congestion in the country is attributed to work zones (FHWA 2005). Traffic safety in work zones is also a concern. Approximately 40,000 injuries and 1,000 fatalities occur annually in work zones in the US. (FHWA 2009a). State departments of transportation (DOTs) strive to improve safety and mobility in work zones using several approaches, including better scheduling of work activity, better traffic management plans, and innovative use of available technologies.

Due to the funding shortfalls in recent years, the focus of many DOTs has shifted from new construction to maintaining existing infrastructure. Maintenance work involves both short-term stationary work zones and mobile work zones. Mobile work zones typically involve striping, sweeping, pothole filling, shoulder repair, and other quick maintenance activities. State DOTs generally use traffic impact analysis tools to schedule maintenance work. However, none of the existing tools are designed to appropriately model moving work zones (MWZs). This is because a MWZ creates a different type of bottleneck than a stationary work zone. Driver behavior at moving bottlenecks created by moving work activities is not well understood and has not been investigated in prior research. This is in part due to the challenges with the collection of data at MWZs.

The objective of this research project was to develop practitioner guidance on how to assess the traffic impacts of moving work zones. This knowledge will help practitioners improve the scheduling of moving work activities. To achieve this objective, multiple data sources were used to collect work zone and traffic data for MWZs. The data included videos from the back of moving work trucks, probe-based travel time data, and traffic detector data. Two approaches were used to assess traffic impacts. First, real-world data were used to calibrate the VISSIM simulation tool for use in analyzing the traffic impacts of MWZs. Second, a data-driven approach was used to estimate regression models of work zone speeds as a function of various independent variables, including work zone characteristics and schedules and traffic and geometric characteristics.

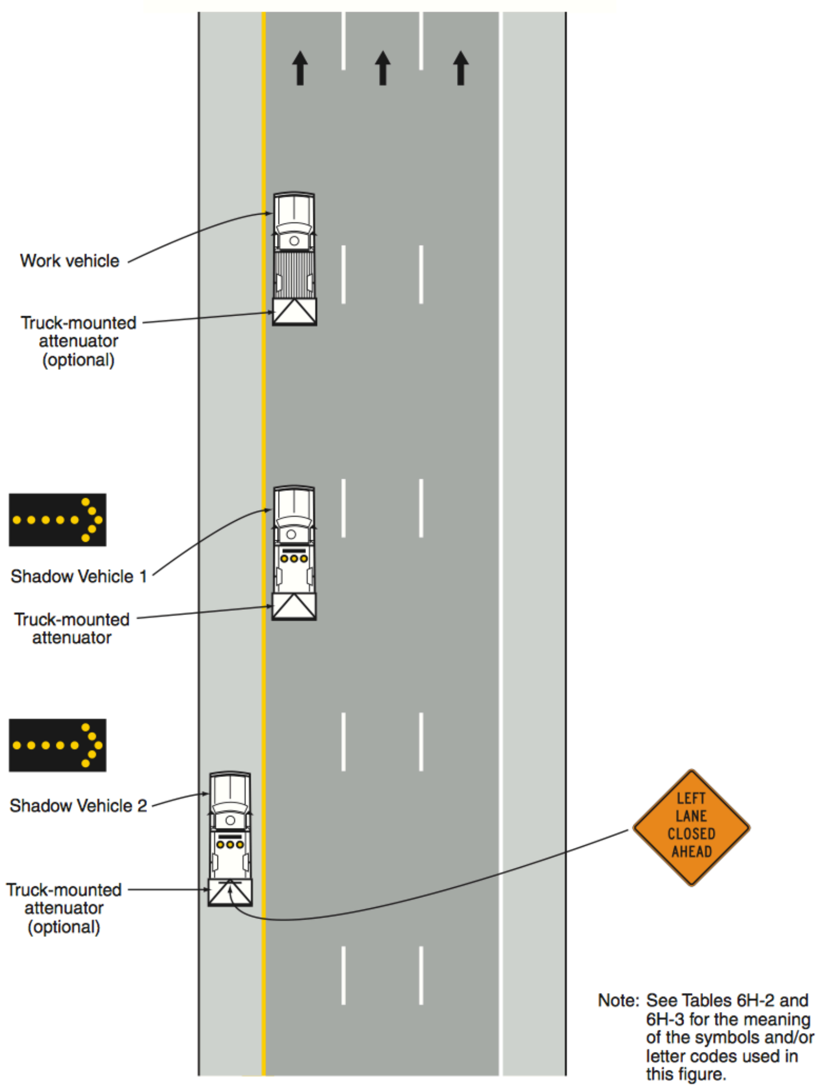
The rest of this report is organized as follows. Chapter 2 presents the literature review and review of existing practices. Chapter 3 describes the data that were used in the project. Chapter 4 presents the work zone speed prediction models that were developed in the study, and Chapter 5 presents the methodology for and results of the VISSIM calibration. Conclusions are provided in Chapter 6.

2 LITERATURE REVIEW

A literature review was conducted to gain an understanding of the current state of the practice regarding mobile work zones. The various aspects of mobile work zones covered in the literature review included standards and best practices, operational impacts, and safety countermeasures.

2.1 Mobile Work Zone Standards

The *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009b) provides typical applications (TAs) for three types of mobile operations: mobile operations on a shoulder, mobile operations on a two-lane road, and mobile operations on a multi-lane road. The MUTCD TA for a multi-lane road configuration is shown in Figure 2.1.



FHWA 2009b

Figure 2.1. MUTCD TA for a mobile work zone on a multi-lane highway

To help alert drivers to the presence of a mobile work zone, various measures such as shadow vehicles, arrow boards, and signs are utilized. Truck-mounted attenuators (TMAs) are sometimes mounted on construction vehicles to help mitigate the effects of collisions. Some of the MUTCD standards and recommendations for mobile work zones are summarized as follows:

- If stationary signs are placed in advance of the work zone, the distance between the advance warning sign and work area should be less than 5 miles.
- Flashing or strobe lights must be used on shadow and work vehicles. Shadow and work vehicles must not utilize hazard warning signals in lieu of strobe lights.
- Caution mode must be implemented for arrow boards when arrow boards are used.
- Vehicle-mounted signs must be visible to drivers traveling through the work zone.

- TMAs may be used on the work vehicle or shadow vehicle.
- The shadow vehicle should slow down in areas where sight distance is limited.
- For mobile work zones on two-lane roads, the work and shadow vehicles should occasionally pull to the side of the road to permit vehicles to pass.
- For mobile work zones on multi-lane highways, arrow boards must be used for lane closures.

Many states have supplemented the MUTCD with their own guidance and standards. For example, the Indiana Department of Transportation (INDOT) provides work zone guidelines and TAs for several different mobile work zone configurations, including mobile work zone on shoulders greater than 8 ft; mobile work zone on a two-lane, two-way road; mobile work zone on a two-lane road using flaggers; mobile work zone on a two-lane divided road; and mobile work zone on a multi-lane divided road (INDOT 2013). The INDOT guidelines include tables with recommended roll-ahead distances between the shadow vehicle and work area for both stationary and mobile work zones based on vehicle speed.

The work zone guidelines from the Michigan Department of Transportation (MDOT) provide TAs for the following types of mobile work zones: shoulder work (less than 10,000 AADT and adequate sight distance), shoulder work (two-lane, two-way roadway), shoulder work (divided highway or freeway), work outside the shoulder, lane closure on a multi-lane roadway (curbs and speed limit less than 45 mph), mobile operation on a two-lane highway, mobile operation on a multi-lane highway, operation on an urban freeway, and moving lane closure on a two-lane highway (MDOT 2007). The MDOT guidelines include a table specifying which TA should be used based on location of work, traffic volume, and sight distance. MDOT defines mobile work zones based on the type of work, including 12 activities such as sweeping, litter pickup, vegetation control, and gravel shoulder maintenance. MDOT recommends the use of a TMA when a shadow vehicle is deployed and provides a table with the roll-ahead distance and weight of the shadow vehicle based on posted speed in advance of the work zone.

The *Engineering Policy Guide* (EPG) from the Missouri Department of Transportation (MoDOT) includes the following TAs for mobile work zones: flagger control or moving operation (one-lane, two-way operation), mobile operation on a two-lane highway with edgelines, mobile operation on a two-lane highway without edgelines, and mobile operation on a divided or multi-lane undivided highway. MoDOT recommends the use of a light bar and emergency alert lights on the shadow vehicle during striping and sweeping operations on multi-lane highways (MoDOT 2015). MoDOT also provides guidance for sign spacing based on the normal posted speed of the facility.

The New York State Department of Transportation (NYSDOT) has also developed guidelines for work zone traffic control (NYSDOT 2015). NYSDOT provides 13 TAs for mobile work zone operations, as follows:

- Lane closure (two-lane highway)
- Lane closure or encroachment (parkway, grass shoulder or no shoulder)
- Right shoulder closure (two-lane highway, paved shoulder width less than 8 ft)

- Right shoulder closure (freeway or expressway, paved shoulder width less than 8 ft)
- Right shoulder closure (freeway or expressway, paved shoulder width equals or exceeds 8 ft)
- Right lane closure (freeway or expressway, paved shoulder width less than 8 ft)
- Right lane closure (freeway or expressway, paved shoulder width equals or exceeds 8 ft)
- Right two-lane closure (freeway or expressway, paved shoulder width less than 8 ft)
- Right two-lane closure (freeway or expressway, paved shoulder width equals or exceeds 8 ft)
- Left shoulder closure (freeway or expressway, paved shoulder width less than 8 ft)
- Left lane closure (freeway or expressway, paved shoulder width less than 8 ft)
- Left two-lane closure (freeway or expressway, paved shoulder width less than 8 ft)
- Left shoulder closure on ramp (freeway or expressway)

NYSDOT also provides a table for roll-ahead distances. The roll-ahead distances in the NYSDOT guidelines are based on shadow vehicle weight, prevailing speed, and the weight of the impacting vehicle.

The maintenance work zone guidelines for the North Carolina Department of Transportation (NCDOT) differentiate between mobile operations and moving operations (NCDOT 2014). According to the NCDOT definition, a mobile operation includes work that intermittently moves or stops for less than 15 minutes. In a moving operation, the work proceeds at a speed of at least 3 mph. The NCDOT guidelines include TAs for various construction and maintenance activities such as mowing, spraying, shoulder sweeping, and pothole patching.

The Washington State Department of Transportation (WSDOT) maintenance work zone guidelines emphasize the importance of crew coordination and the consideration of site characteristics for mobile work zone operations (WSDOT 2014). WSDOT provides five TAs for typical mobile work zone operations, including left shoulder closure (freeway), left-lane operation (freeway), middle-lane operation (freeway), lane closure operation (two-lane highway), and shoulder closure operation (two-lane highway). WSDOT requires the use of TMAs on freeways and recommends their use on two-lane highways. On freeways, WSDOT recommends a 2 ft minimum lateral clearance between the edge of the travel lane and the work vehicle. WSDOT requires that the shadow vehicle maintain between 500 ft and 1,000 ft of sight distance to opposing traffic. Recommendations for specific values of roll-ahead distances are not provided. Instead, WSDOT suggests that roll-ahead distances should be determined based on work zone and site-specific characteristics.

Additional insights regarding the practices of state DOTs for mobile lane closures can be found in a NCHRP study (NCHRP 2009) that included both a literature review and a survey of state DOTs and Canadian provinces. The results of the literature review indicated that many agencies follow their own procedures for mobile lane closures. In addition, the study found that providing information to motorists in advance of the work zone helps to prepare motorists and reduce risks. Some of the knowledge gaps identified from the literature review are as follows:

- More clarification is needed regarding the difference between mobile lane closures and short-term operations.

- There is a lack of data pertaining to mobile lane closures.
- There is a need for more guidance regarding proper location of construction workers within the mobile work zone and the required spacing between shadow vehicles and work vehicles.
- Additional research regarding training for workers in mobile work zones is needed.

The survey included 74 questions regarding agencies' practices, experiences, and technology needs related to mobile work zones. Responses were obtained from participants representing 28 US states and 3 Canadian provinces. A summary of some of the key findings from the survey participants in the United States is provided below:

- Approximately 85% of the respondents did not believe that there are problems in their agency with misunderstandings of the definition of a mobile work zone.
- Various types of temporary traffic control procedures are used by the agencies surveyed.
- More than half of the survey participants indicated that their agency requires the use of TMAs on shadow vehicles.
- Most of the DOTs surveyed do not use mobile work zone intrusion alarms frequently.
- Almost two-thirds of the DOTs surveyed do not prohibit workers on foot in the mobile work zone or utilize equipment to limit workers' exposure to vehicular traffic.
- Most of the DOTs surveyed implement temporary signs before the mobile work zone to provide information to motorists.
- More than half of the respondents indicated that their DOT uses flaggers for mobile work zones involving lane closures on two-lane highways.
- Many of the DOTs surveyed are not able to link mobile work zones to crashes due to existing limitations in crash data.
- Only 20% of the survey participants had knowledge of advances in research or technology to help improve the safety of mobile work zones.

Because mobile work zones at night require special consideration, the Federal Highway Administration (FHWA) has developed guidelines for nighttime mobile work zones (Bryden 2003). Although traffic volumes are lower at night, there are other challenges, such as lower sight distance, increased speeds, and changes in driver behavior. The FHWA recommends that flaggers should not be used at night due to the reduced visibility. Special nighttime TAs are provided for several different conditions for night striping and other mobile operations on two-lane and multi-lane highways. TAs are provided for both slow-dry and rapid-dry pavement marking applications. Slow-dry pavement markings require the use of cones to protect them from vehicular traffic. It is recommended that the distance between the shadow vehicle and work vehicle should be determined based on traffic conditions.

2.2 Moving Bottlenecks

Existing research regarding the operational impacts of MWZs is very limited and is focused on the investigation of moving bottlenecks using theoretical methods. For example, Gazis and Herman (1992) developed a model to explain the formation and development of a moving queue on a roadway with two lanes in one direction. They indicated that one of the important considerations was the rate at which vehicles escape the queue and provided recommendations for procedures that could be used to validate the model. Newell (1998) also studied moving bottlenecks for facilities with two lanes in one direction using a moving coordinate system to convert the problem to a stationary bottleneck. The developed theoretical model was applied to a case of trucks going up grades. Lattanzio et al. (2011) studied a model of moving bottlenecks using incremental time steps.

Some studies utilized experimental methods or simulation to test the developed methods. A study of moving bottlenecks by Muñoz and Daganzo (2002) involved both the development of a theoretical model and experimental observations. The model was based on two assumptions. The first assumption was that bottleneck speed and bottleneck passing rate are related. The second assumption involved the use of kinematic wave theory. The study used detector data sets from a California freeway and experiments on a two-lane and a three-lane freeway to investigate the model. The study found that an increase in bottleneck speed led to an increase in downstream capacity. Daganzo and Laval (2005) presented a numerical method to model kinematic waves produced by slow-moving vehicles. Their proposed model converges in flows, densities, and speeds with no oscillations. Laval (2006) developed a methodology for estimating the capacity of moving bottlenecks created by slow-moving vehicles. The model was tested using simulations for a situation with short uphill grades. Leclercq (2007) proposed an extension of the Lighthill-Whitham-Richards (LWR) model to explain the fixed traffic flow close to fixed and moving bottlenecks with more accuracy. Leclercq's (2007) model was coupled with noise emission laws to evaluate traffic operations strategies. Juran et al. (2009) developed a dynamic traffic assignment (DTA) model to assess the impacts of moving bottlenecks with respect to travel times and route paths. The DTA model used mesoscopic simulation to load the network. The model was tested experimentally on a metropolitan road network. The results of the test indicated that increased bottleneck speed led to less delay.

Kerner and Klenov (2010) used numerical methods to analyze congestion due to moving bottlenecks on multi-lane highways. They found that if the upstream flow rate is great enough, there is a critical speed for a moving bottleneck at which traffic breakdown occurs. The higher the flow rate, the larger the critical speed. On-off ramps have an effect on the critical speed-flow relationship. Li et al. (2011) utilized VISSIM software to simulate traffic flow with different mix rates of slow-moving trucks. The simulation results indicated that increasing the traffic flow and the truck mix rate decreases the traffic speed and expressway capacity. Yuan et al. (2013) assessed the impacts of moving bottlenecks through the application of a full velocity model to a two-lane highway. A model to replicate lane changing was also developed in this research. Numerical simulation was used to evaluate the model with respect to its impacts on traffic flow. The results indicated that the moving bottleneck had greater impacts under higher traffic density, but an increase in the speed of the slow-moving vehicle helped to mitigate these impacts. Fadhloun et al. (2014) studied the effects of a moving bottleneck on its abreast vehicles. The authors developed a general model to estimate passing rate using simulated data from INTEGRATION software. Fadhloun et al. (2014) concluded that passing rate varies in a quadratic function of the bottleneck speed. Delle Monache and Goatin (2016) introduced a coupled partial-ordinary differential equation (PDE-ODE) system to describe the bottlenecks created by the presence of several buses on a circular route of unit length. The buses moved at the same speed.

In summary, many of the existing studies are theoretical in nature, limited to certain lane configurations, and restrictive in the types of mobile work zone attributes considered. The existing literature on moving bottlenecks does provide preliminary indications for some of the attributes that affect moving work zone capacity, such as traffic density and the speed of the shadow and work vehicles in the moving work zone. However, an investigation of other factors, such as mobile work zone activity type, lane configuration, and geometrics, is needed for an assessment of mobile work zone impacts.

2.3 Studies of Safety Countermeasures in Mobile Work Zones

To help improve safety in mobile work zones, agencies have tried implementing a variety of countermeasures. Some previous studies have evaluated the effectiveness of these safety countermeasures for mobile work zones. Brown et al. (2015) investigated two types of mobile work zone alarm systems: an alarm device and a directional audio system (DAS). The systems were tested in the following three operating modes: continuous, manual, and actuated. The study utilized field data to investigate sound levels and merging distances and speeds. The results of the sound level testing indicated that the sound levels were in conformance with national standards. All of the alarm setups except for the alarm device in actuated operating mode led to an increase in the merging distance of vehicles. Vehicle speeds also decreased with the DAS in continuous operating mode. There were occasional instances of undesirable driving behavior, but the link between this behavior and the mobile work zone alarm system was uncertain.

Another possible countermeasure to help reduce vehicle speeds in mobile work zones involves the use of radar speed display signs. The effectiveness of this countermeasure was investigated by Gambatese and Jafarnejad (2015). Truck-mounted radar speed signs were evaluated in the field for several different types of mobile work zone operations, including relamping, sweeping, vactoring, and spraying. Temporary speed sensors were utilized to measure vehicle speeds. The results of the study indicated that the use of the radar speed signs helped to lower vehicles' speeds through the work zone. The study recommended different types of messages for the sign depending on the speed limit.

A study by Ullman and Iragavarapu (2014) investigated the effectiveness of TMAs in reducing crash severity and costs. In this study, 186 crashes from the NYSDOT work zone crash database were reviewed. Some of the crashes involved a work zone vehicle with a TMA, while other crashes involved a work zone vehicle without a TMA. The study found that the crash cost was four times greater when the work zone vehicle did not have a TMA and that the use of the TMA resulted in a crash cost savings of approximately $200,000 per crash.

The use of truck-mounted changeable message signs (TMCMSs) to help convey information to drivers in mobile work zones was investigated in another study (Ullman et al. 2011). This research consisted of a human factors survey in which drivers were shown different TMCMS messages and asked to determine their meaning. The study found that TMCMSs can be beneficial in providing information to drivers but that the effectiveness of the TMCMS messages depended on the content of the messages. The researchers provided recommendations regarding message content for different types of mobile operations, such as striping, sweeping, and workers out of the vehicle.

The California Department of Transportation (Caltrans) developed a device named the Balsi Beam to help protect workers in mobile work zones in response to a crash in which a Caltrans maintenance employee was injured when a vehicle crossed into a work zone at a steep angle and went past the shadow vehicle (Caltrans 2007). The system is attached to a semi-trailer and includes two telescoping beams (Figure 2.2). The system has been used for various types of work zones, including bridge deck and rail repairs.

Caltrans 2007

Figure 2.2. Caltrans Balsi Beam

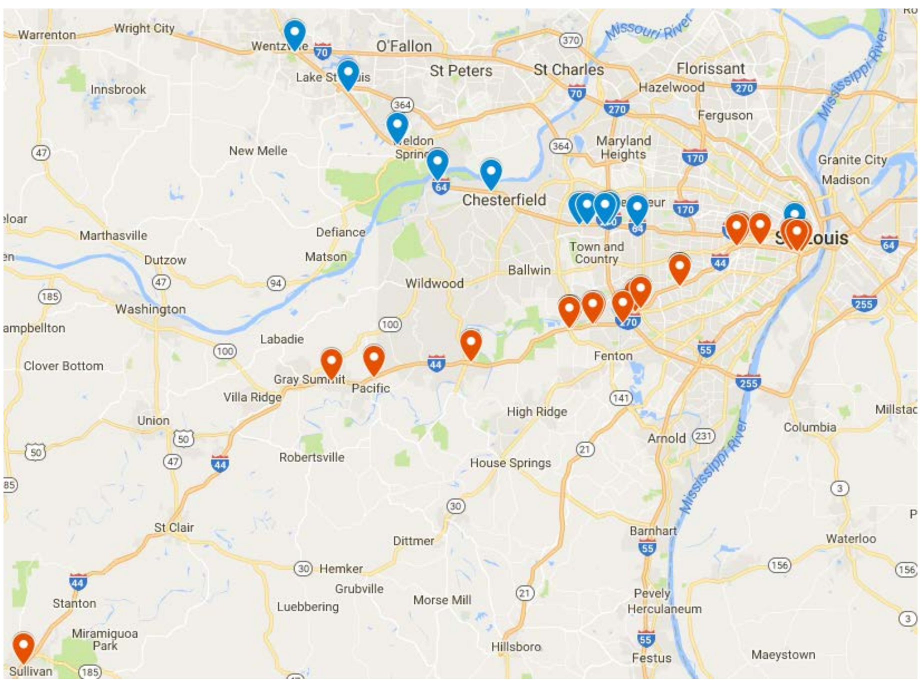
3 DATA

In this study, four different data sources were used: MWZ information from MoDOT electronic alerts (e-alerts), travel time data from the Regional Integrated Transportation Information System (RITIS), traffic flow data from point detectors on I-44 and I-64 near St. Louis, and video data recorded from cameras mounted on the back of MWZ TMAs.

3.1 MWZ Characteristics

The MoDOT TMC in the St. Louis region, Gateway Guide, provides e-alerts for various events, including MWZs. These e-alerts include start date and time, end date and time, location by address, and lane closure type (left, right, center). Information on a group of MWZs on the I-44 and I-64 freeways in the St. Louis area between July 2014 and July 2015 were queried through these MoDOT e-alerts. Among these MWZs, only 34 had all of the needed information, such as start/end date and time, start location, and lane closure. There was no information about the MWZs' end location, speed, and type of work.

The start locations of the 34 MWZs are shown in Figure 3.1, and a summary of the 34 MWZs is provided in Table 3.1.



Map data ©2017 Google

Figure 3.1. MWZ start locations based on e-alerts

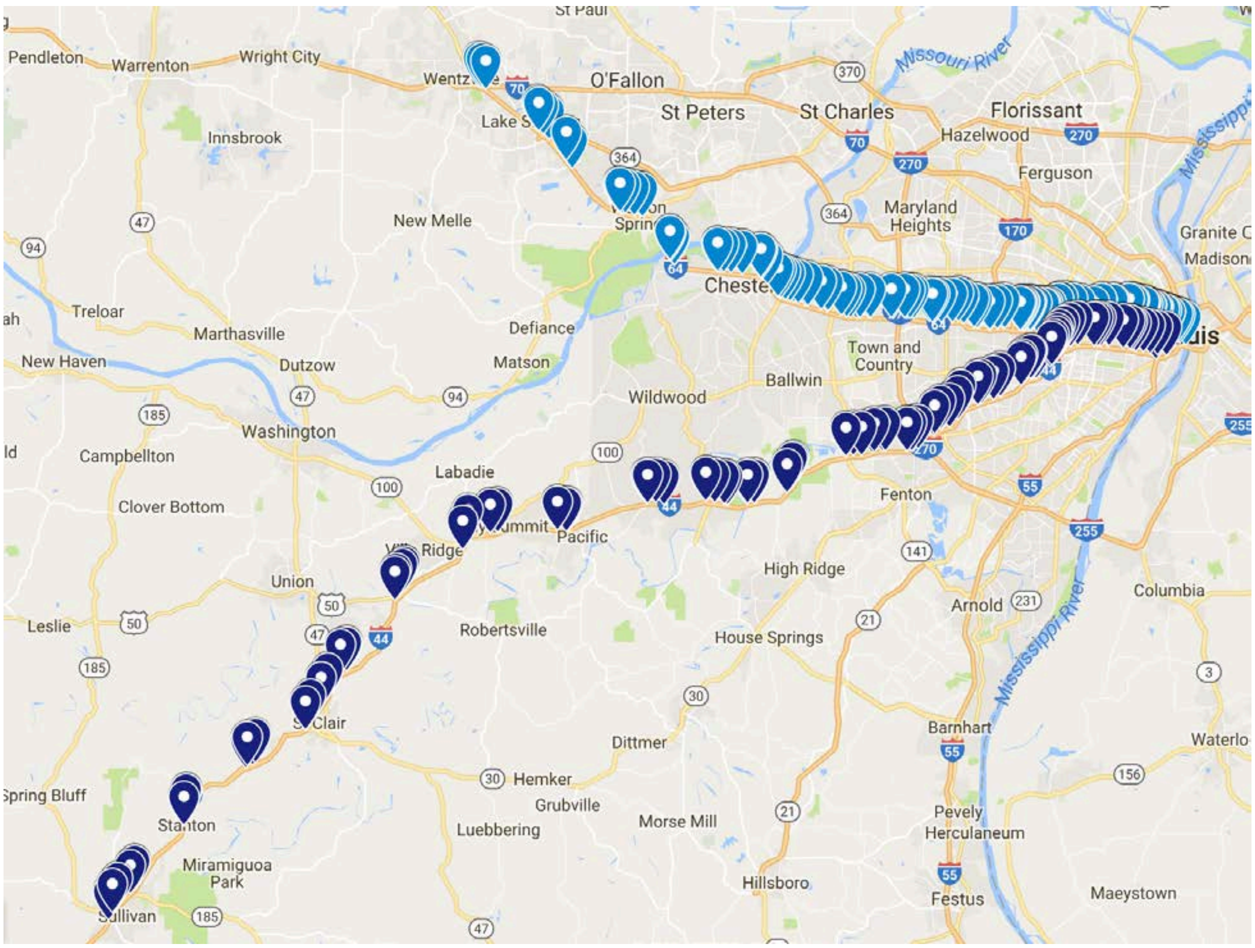
Table 3.1. Summary of information extracted from e-alerts for 34 MWZs

ID	Route	Direction	Lane Closure	Start Date	Start Time	Duration (Hours)
1	44	EB	RIGHT LANE	7/3/2014	7:32	0.02
2	44	EB	2 LEFT LANES	8/4/2014	22:52	1.63
3	44	WB	2 LEFT LANES	8/5/2014	0:38	2.17
4	44	WB	RIGHT LANE	9/9/2014	1:09	3.22
5	44	EB	RIGHT LANE	2/14/2015	8:32	0.80
6	44	WB	LEFT LANE	4/8/2015	9:35	0.50
7	44	EB	RIGHT LANE	4/8/2015	10:19	0.45
8	44	EB	LEFT LANE	4/8/2015	10:47	0.28
9	44	EB	LEFT LANE	4/8/2015	12:15	1.18
10	44	EB	LEFT LANE	4/8/2015	13:52	0.48
11	44	EB	RIGHT LANE	4/21/2015	14:08	0.68
12	44	WB	LEFT LANE	6/9/2015	10:25	0.25
13	44	WB	LEFT LANE	4/21/2015	13:01	1174.07
14	44	WB	LEFT LANE	6/9/2015	11:05	0.08
15	44	WB	LEFT LANE	4/8/2015	9:01	1491.55
16	44	WB	LEFT LANE	4/21/2015	12:47	1174.15
17	44	WB	LEFT LANE	6/29/2015	1:14	0.18
18	44	WB	CENTER LANES	6/29/2015	1:25	0.32
19	44	WB	RIGHT LANE	6/29/2015	1:44	1.75
20	44	WB	LEFT LANE	6/29/2015	1:08	0.98
21	44	EB	LEFT LANE	6/9/2015	12:55	0.05
22	44	EB	LEFT LANE	6/9/2015	11:49	0.07
23	64	WB	LEFT LANE	6/12/2014	21:46	2.60
24	64	WB	RIGHT LANE	7/14/2014	6:56	7.28
25	64	EB	LEFT LANE	12/10/2014	21:14	7.52
26	64	EB	RIGHT LANE	1/17/2015	9:12	3.47
27	64	EB	RIGHT LANE	4/08/2015	13:32	0.10
28	64	WB	RIGHT LANE	4/21/2015	10:57	167.93
29	64	EB	RIGHT LANE	4/28/2015	10:53	0.52
30	64	EB	RIGHT LANE	4/28/2015	12:47	1.73
31	64	EB	LEFT LANE	6/09/2015	13:25	0.08
32	64	EB	LEFT LANE	6/19/2015	5:20	1.18
33	64	EB	PREPARE TO STOP	6/19/2015	6:31	0.62
34	64	WB	LEFT LANE	7/28/2015	9:33	2.60

The durations of the MWZs ranged from 1 minute to 62 days. The durations of some of the MWZs were too long to be accurate. Therefore, the unreasonably long MWZs were dropped from further analysis, i.e., MWZs with IDs 13, 15, 16, and 28. The final sample included 30 MWZs.

3.2 RITIS Travel Time and Traffic Flow Detector Data

MoDOT has an agreement with the owners of RITIS to receive travel time data for state roadways. The RITIS database is based on probe vehicle travel time. In this database, routes are divided into segments of different lengths. Queried data from the RITIS database include travel time and speed for segments and information on TMC segment identifiers. The TMC segment information includes road, direction, intersection, start and end latitude/longitude, segment length, and road functional type. A map of the RITIS segments is shown in Figure 3.2.



Map data ©2017 Google

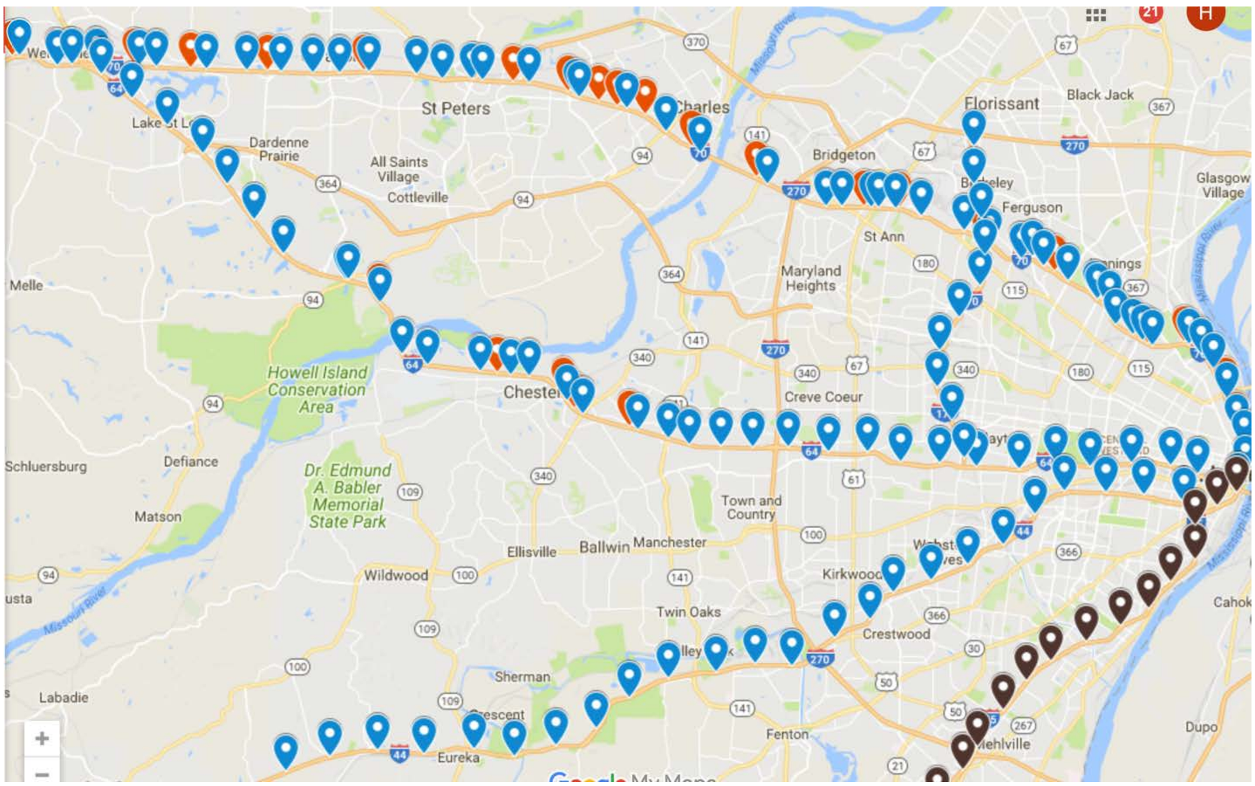
Figure 3.2. Map of RITIS travel time segments

The RITIS speed and travel time data are recorded in 30-second intervals and have a confidence factor (CF) between zero and one, as shown in Table 3.2. Data used in this study were of high confidence.

Table 3.2. RITIS confidence factors

CF	Description
$0.7 < CF \leq 1$	High confidence, based on real-time data
$0.5 < CF \leq 0.7$	Medium confidence, based on combination of historic and real-time data
$0 < CF \leq 0.5$	Low confidence, based primarily on reference speed

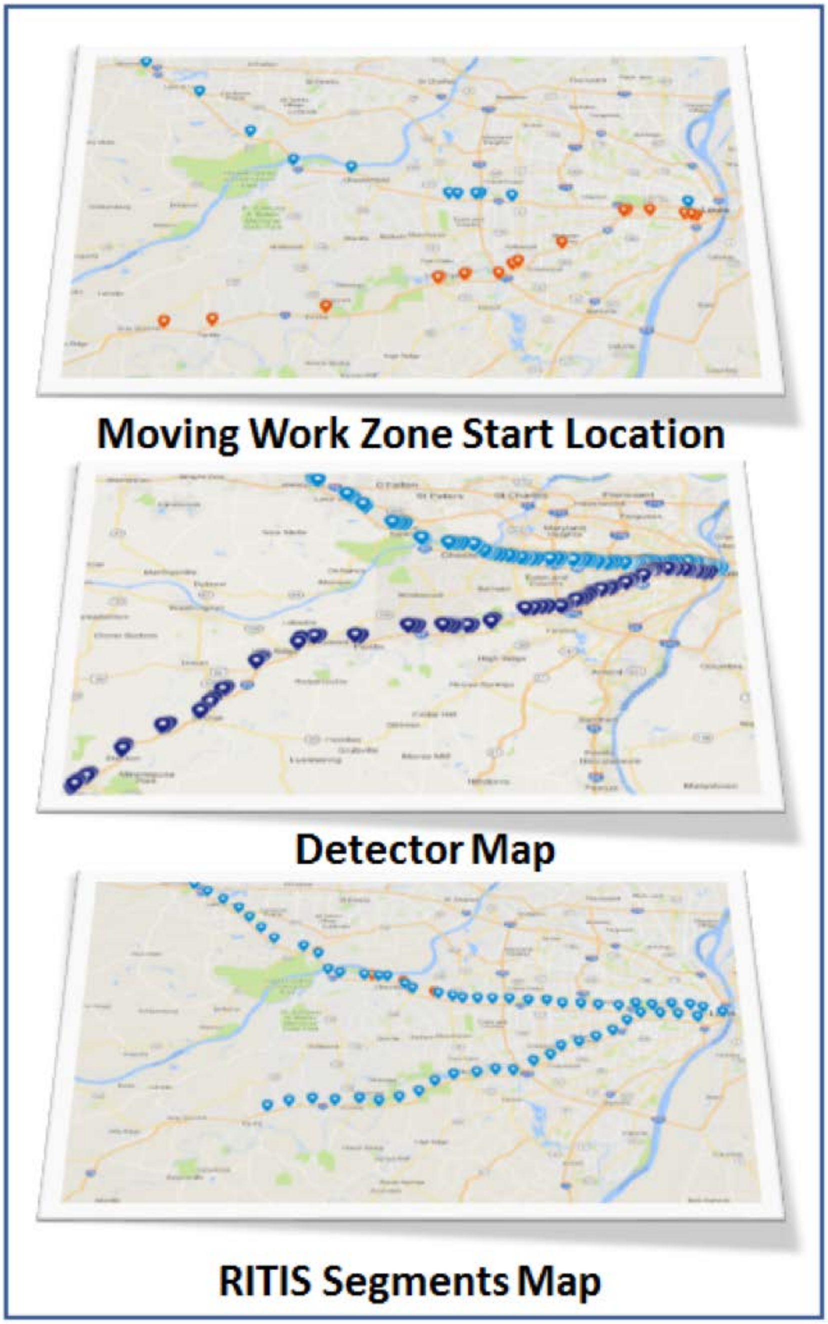
The traffic flow and speed data were collected from MoDOT's point detectors. Figure 3.3 provides the locations of point detectors on major freeways in the St. Louis region.



Map data ©2017 Google

Figure 3.3. Map of MoDOT traffic flow detectors

The RITIS and detector data needed to be matched with the location and time of each MWZ. Figure 3.4 shows the MWZ start locations, detector locations, and RITIS segments. These work zones are mobile in nature, and the e-alerts do not include the MWZs' end locations or speeds.



Google Maps 2017

Figure 3.4. MWZ start locations, detector locations, and RITIS segments

To overcome the challenge regarding the uncertainty of the exact locations of the work zones, five RITIS segments were analyzed for each of the 30 MWZs: the segment that included the start location of the MWZ, two segments upstream of the MWZ, and two segments downstream of the MWZ. For the traffic flow detectors, the detector closest to the start location, the detector immediately upstream, and the detector immediately downstream were chosen for each MWZ.

The RITIS database includes travel time on segments in 30-second intervals by lane. The RITIS data were aggregated for every minute across all lanes. The RITIS segments have various lengths. Travel times were divided by segment length to obtain the average travel time per mile.

The detector database includes the number of vehicles that passed the detector location every minute in every lane and the vehicles' speeds. Data were aggregated into five-minute and hourly volumes for use in simulation and regression models.

For the 14 MWZs with durations greater than 20 minutes, speed-flow diagrams based on the detector data and speed heat maps based on the RITIS data were plotted. For other locations, either the RITIS data or detector data were missing, and hence such plots could not be generated. An example of one such plot is shown in Figure 3.5 for work zone ID 23. Plots for the remaining work zones are shown in Appendix A.

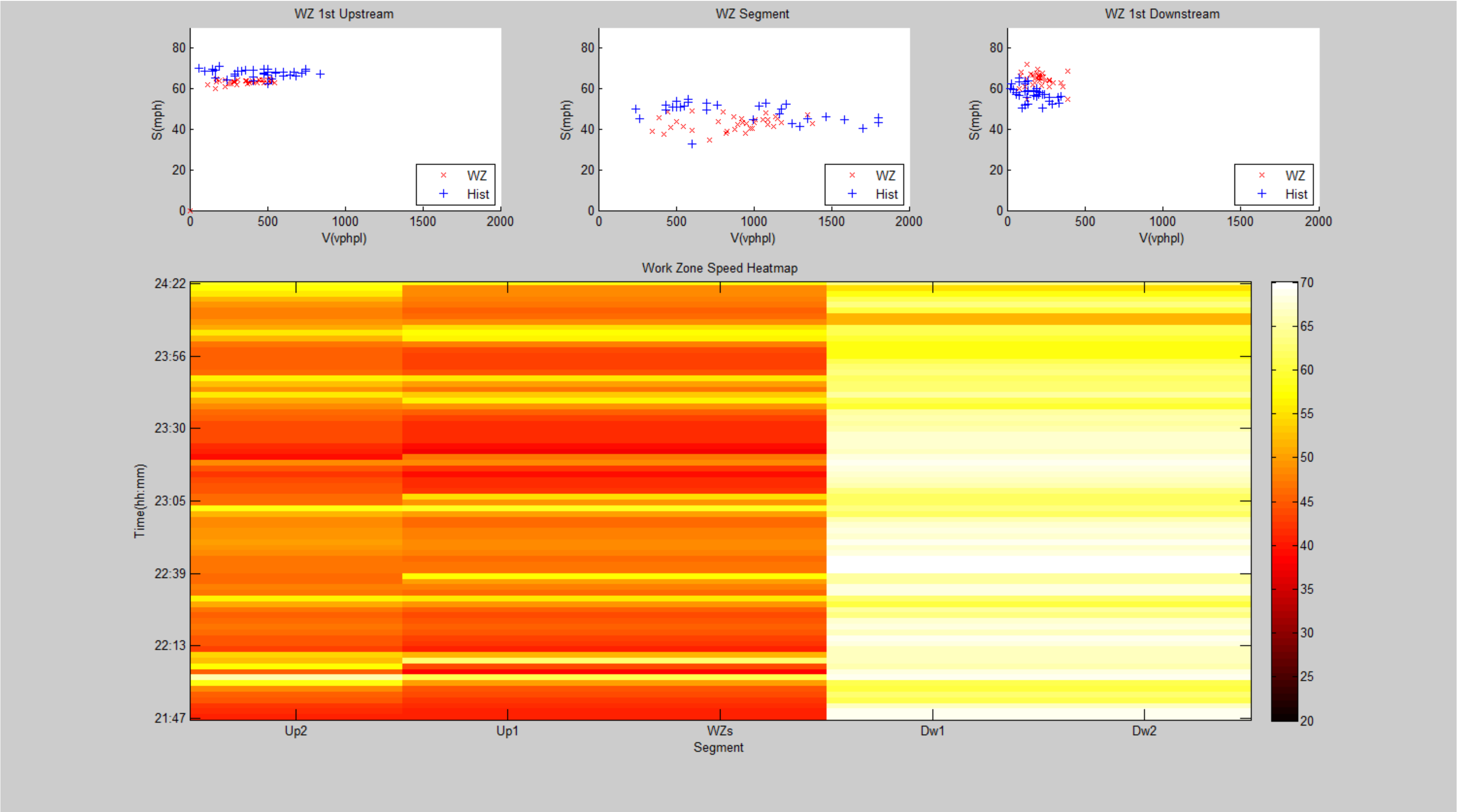


Figure 3.5. Speed-flow diagram and speed heat map for I-64 work zone ID 23

Figure 3.5 contains three speed-flow diagrams: the work zone segment, first upstream segment, and first downstream segment. These plots show speed versus flow on these segments when the MWZ was present and one week earlier at the same time and location, the latter serving as historical data. The heat map shows the average vehicle speeds for five segments: the work zone segment, two segments upstream, and two segments downstream. The heat map's time axis bounds show the start and end time of each MWZ. In the heat map, the darker the color, the lower the speed. The speed color scale is shown on the right-hand side of the plot. The heat maps revealed that congestion occurred at the following MWZs: IDs 9, 23, 24, 25, 29, 30, 33, and 34. There was no considerable congestion at the six remaining MWZs.

All of the detector data for the work zone locations, first upstream locations, and first downstream locations were aggregated and plotted as shown in Figure 3.6.

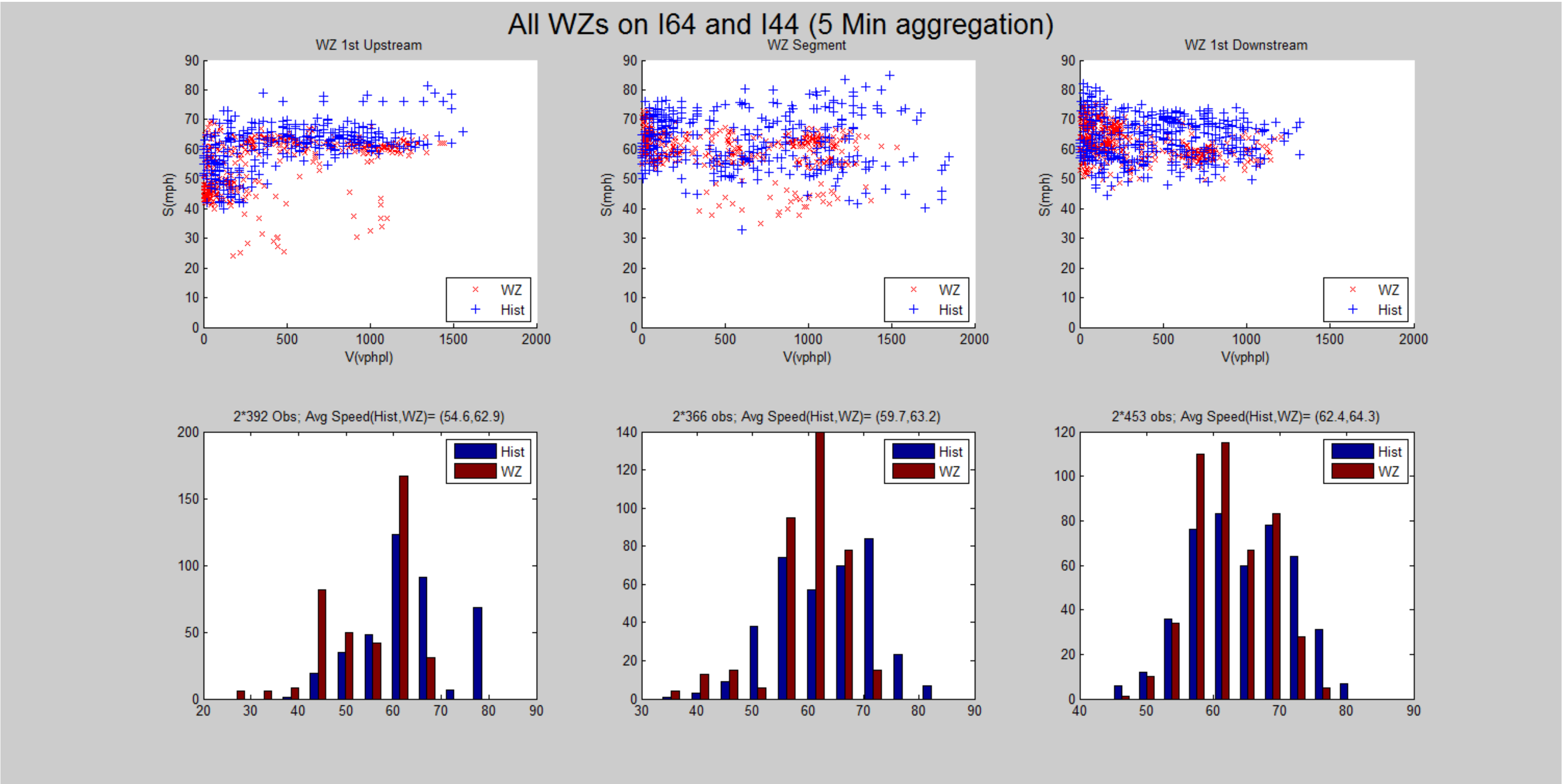


Figure 3.6. Speed-flow plots and speed histograms for all work zones

As can be seen in the speed-flow diagrams, when work zones were present (indicated by red X's) the segments experienced lower speeds for the same flows than under normal conditions (i.e., the historical data). The work zone speed histograms for the MWZ segments, first upstream segments, and first downstream segments also show this shift toward the left when work zones were present compared to the historical data. The mean speeds for the first upstream segments, MWZ segments, and first downstream segments in the presence of a MWZ were 8.3, 3.5, and 1.9 mph less than the respective mean speeds in the historical data.

There are different nonparametric statistical tests to compare two sample distributions, such as the t-test, Kolmogorov-Smirnov (KS) test, and Mann-Whitney-Wilcoxon (MWW) test. The t-test assumes a normal distribution. The KS test faces a problem in computing the p-value when there are ties (observations with the same values) between two samples. The MWW test does not have such issues. The MWW test was performed on the data extracted from the point detector database. For the MWW test, the null hypothesis is that both the MWZ and historical data have the same distribution, while the alternative hypothesis is that the work zone speeds are lower than the historical speeds. The p-values of the MWW tests for speed in the first upstream segment, MWZ segment, and first downstream segment are 2.2×10^{-16}, 9.8×10^{-8}, and 2.3×10^{-5}, respectively. So, for all three locations the null hypothesis was rejected, indicating that the work zone speeds are lower than those of the historical data for the first upstream segment, MWZ segment, and first downstream segment.

For use in the simulation model, the cumulative probability distribution of speeds when MWZs were not present was generated using the historical data from the detectors. The start locations for the 30 work zones on I-64 and I-44 were determined. The detectors closest to each of these locations were found. Each detector was linked to its relevant MWZ. For each MWZ, the detector data were collected one week before the MWZ began. For example, consider a MWZ that was on I-64 between 7:32 a.m. and 10:50 a.m. on June 28, 2015; the detector data between 7:32 a.m. and 10:50 a.m. on June 21, 2015 represent the historical data. Figure 3.7 shows the cumulative probability distribution of speed for this location.

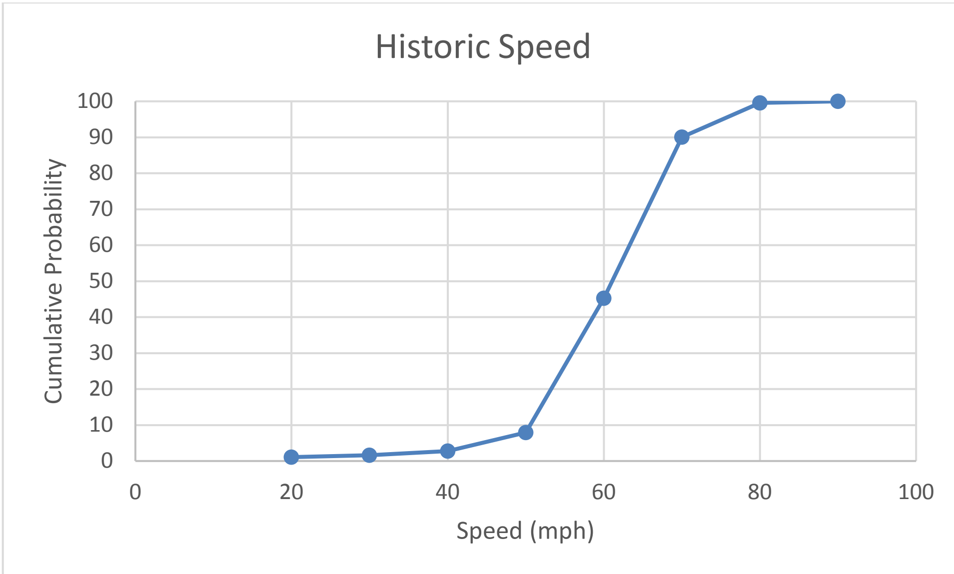


Figure 3.7. Cumulative distribution of historical speed without work zone presence

3.3 MWZ Video Data

To evaluate the driving behavior associated with MWZs, videos were collected from the back of slow-moving trucks. The videos were obtained from two sources: 11 videos recorded by MoDOT at MWZs in the Kansas City area in November 2016 and videos recorded by the researchers in the Kansas City area in November 2013 as part of a prior research project to evaluate mobile work zone alarms for MoDOT (Brown et al. 2015). Table 3.3 summarizes the locations and dates of the MWZ videos. The total duration of the video footage that was used for analysis was 3 hours and 27 minutes.

Table 3.3. Summary of locations and dates for MWZ videos

Date	Route	Location	Description
11/19/2013	I-435	NW Cookingham Dr. to Shoal Creek Pkwy.	Control test
11/9/2016	I-435	I-70 to I-49	Striping
11/14/2016	I-435	I-49 to Kansas State Line	Striping
11/15/2016	I-435	NE Cookingham Dr. (MO 291) to I-29	Striping
11/16/2016	I-435	I-29 to Kansas State Line	Striping
11/17/2016	MO 350	I-470 to I-435	Striping

Figure 3.8 shows a screenshot of one of the videos recorded by MoDOT in November 2016.

Figure 3.8. Sample screenshot from a MWZ video

Vehicles that are behind a slow-moving truck tend to change lanes to avoid the speed reduction. The purpose of the video data processing was to collect the following information:

- The distance from the back of the truck to the location at which the following vehicles merged into the adjacent open lane
- The gaps available to each lane-changing vehicle in the adjacent lane
- Vehicle speed at the overtaking moment
- Speed of the slow-moving truck
- Traffic volume of vehicles that overtook the truck
- Percentage of heavy vehicles

To collect this information from the videos, photogrammetry was used.

3.3.1 Video Photogrammetry

The goal of the video photogrammetry in this study was to measure the distances and determine the timestamps of the various events mentioned in the previous section. To estimate the distances using photogrammetry, the spacing between the centerline striping was used as a reference. MoDOT applies a standard distance of 40 ft between the beginning of one stripe and the beginning of the next one (one skip = 40 ft). It can be seen in Figure 3.8 that the skips farther than five or six skips away from the camera can hardly be identified.

For each video, a simple modeling process was used to find the relationship between the distances in the image and the real distances. Figure 3.9 shows the calibration plot for one of the videos.

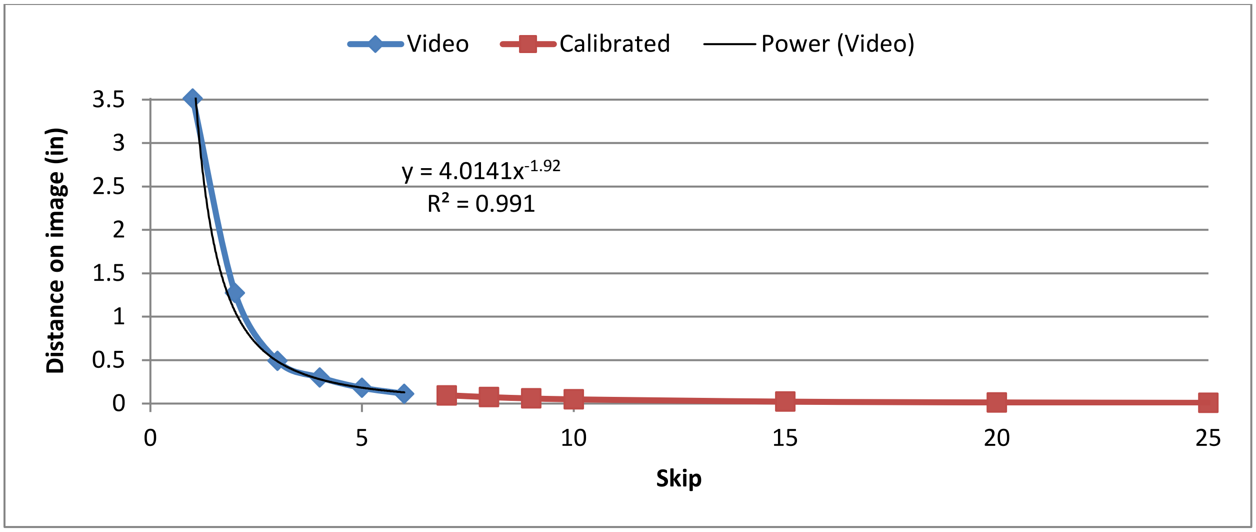


Figure 3.9. Sample MWZ video calibration plot

The calibrated equation and a background image were used to construct a ladder-shaped drawing in AutoCAD for each video (Figure 3.10).

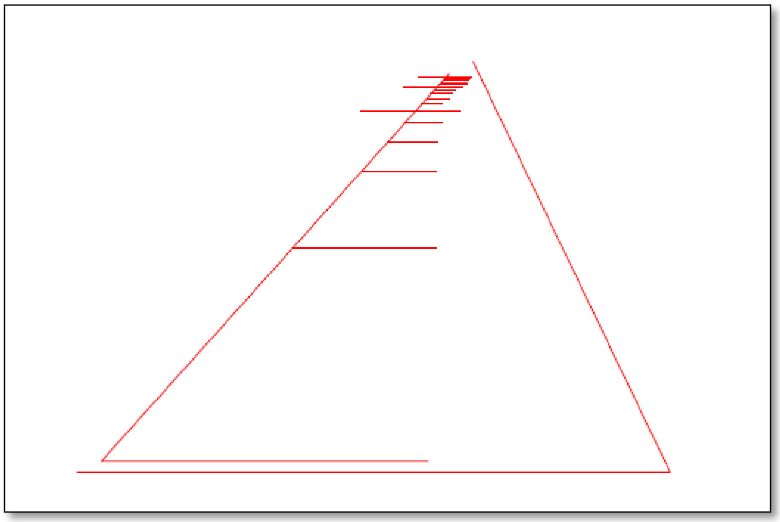


Figure 3.10. Sample background image for MWZ videos

The ladder-shaped image was then overlaid on each video using Adobe Premiere Pro. Figure 3.11 shows a screenshot of one of the final videos with the background image. In the overlaid video, the skips are easier to identify.

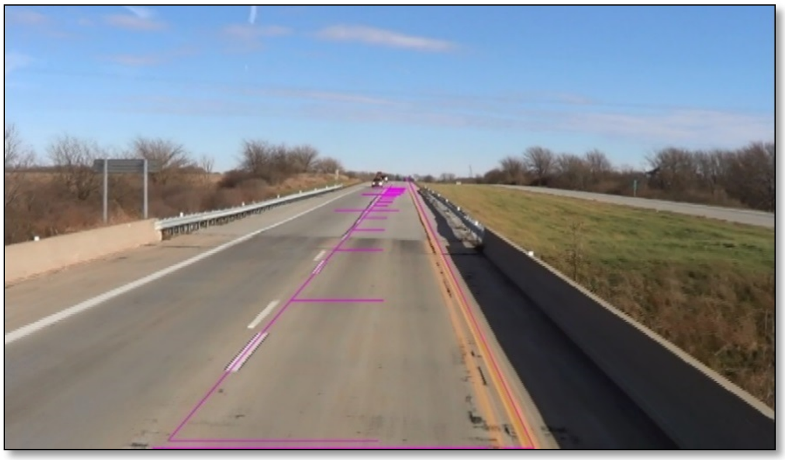


Figure 3.11. Sample screenshot of background image overlaid on MWZ video

The distance between the merging vehicle and the back of the MWZ at the time of the merge was extracted from the video data. Merge distances at 25 skips or closer were recorded by counting the skips. The time of merging and descriptive information about the merging vehicle (e.g., gray crossover, red truck, etc.) were also recorded. To increase the accuracy of the timestamps, a video player that could move the video forward and backward frame by frame with a resolution of 30 frames/second was used.

The gaps available to each lane-changing vehicle were collected by recording the timestamp of the vehicles that passed the truck in the adjacent lane. Additionally, the overtaking speed was calculated by measuring the time and distance traveled by the lane-changing vehicle. The end time was first collected when the merging vehicle was close to the MWZ. The video was then reversed until the vehicle had travelled back 10 skips, at which point the time was again recorded. The speed was calculated using this distance and the elapsed time. The slow-moving truck’s speed was also collected using the same method but with 20 skips.

Because the slow-moving truck’s speed was around 10 mph, it was assumed that all of the traffic would overtake the truck. Therefore, the traffic volume was found by counting the number of vehicles that overtook the truck. Vehicles were also classified in order to determine the percentage of trucks.

3.3.2 Video Data Descriptive Statistics

This section explains the descriptive statistics for the video data that were collected.

3.3.2.1 Lane Change Distance

The distance from the back of truck to the location where the following vehicles merged into the adjacent lane is almost normally distributed, as shown in Figure 3.12. The median, mean and standard deviation of the lane change distance were 400, 432, and 173.8 ft, respectively.

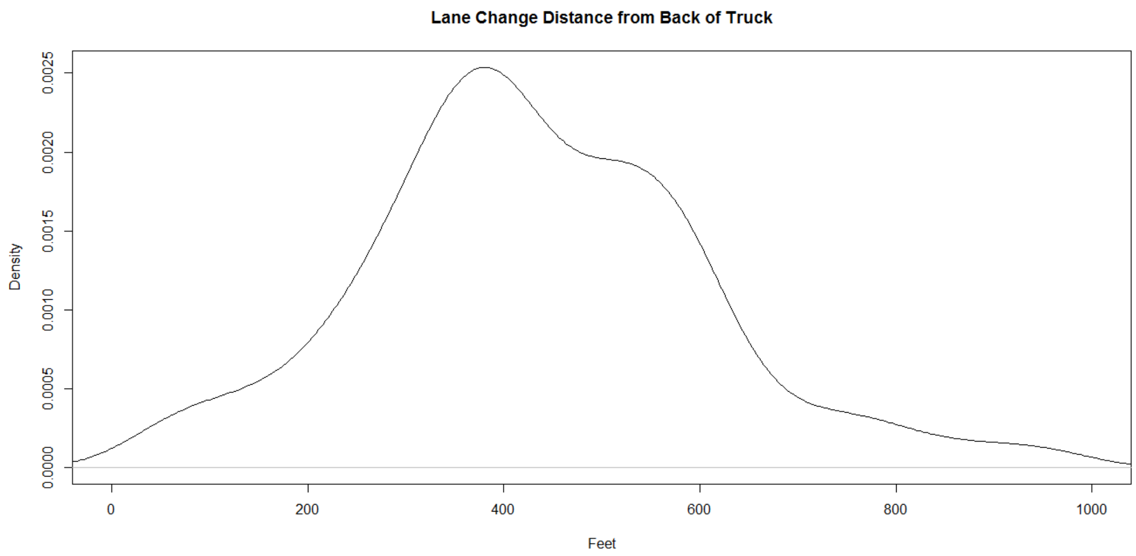


Figure 3.12. Distribution plot for lane change distance from the back of the truck

3.3.2.2 Gaps Available to Lane-Changing Vehicle

The gaps available to each lane changing-vehicle were extracted from the videos. The distributions of accepted and rejected gaps are shown in Figure 3.13. The figure includes gaps under 20 seconds. From the figure, it can be seen that the rejected gap distribution is skewed towards zero in comparison to the accepted gaps. The peaks of the distributions for the rejected and accepted gaps are 2 and 5 seconds, respectively.

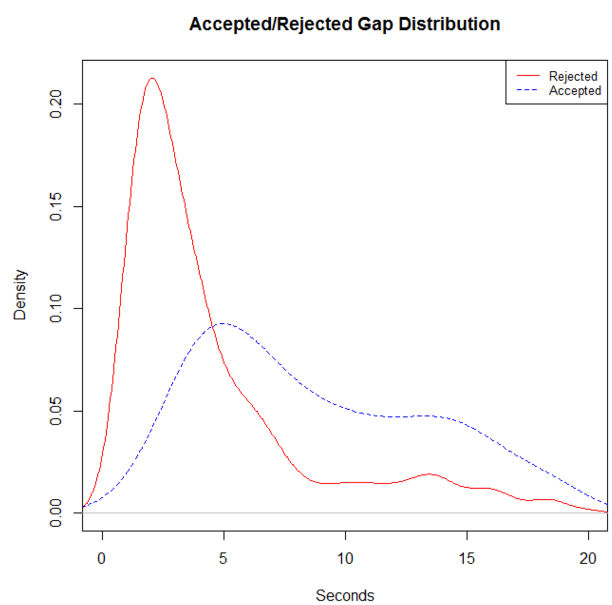


Figure 3.13. Accepted and rejected gap distributions

3.3.2.3 Overtaking Speed

Vehicle speeds at the moment the vehicles overtook the truck were collected using the methodology previously described. Figures 3.14 and 3.15 show the overtaking speed distribution and its cumulative probability distribution plot, respectively. Table 3.4 shows the cumulative distribution probability values.

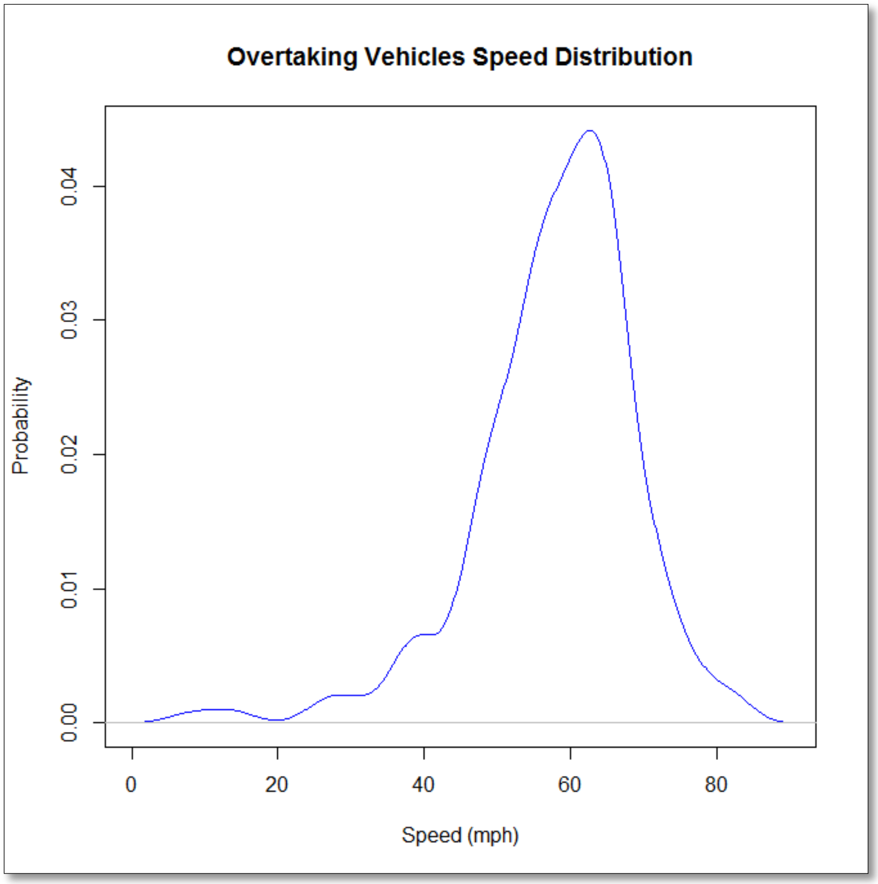


Figure 3.14. Distribution of overtaking speeds

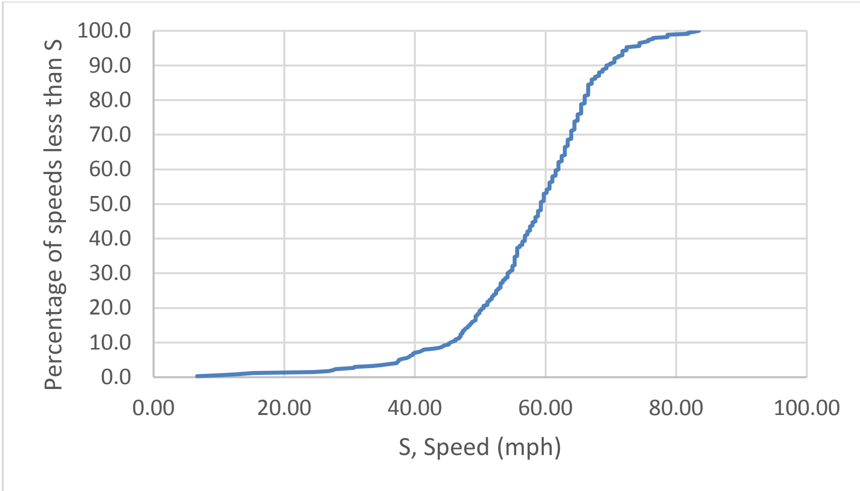


Figure 3.15. Cumulative distribution of overtaking speeds

Table 3.4. Cumulative distribution of overtaking speeds

Speed (mph)	**Cumulative percentage**
<20	1.2
20–30	2.4
30–40	7.1
40–50	19.1
50–60	52.9
60–70	90.6
70–80	98.8
>80	100.0

3.3.2.4 MWZ Speed

The speeds of the slow-moving trucks observed in the field videos were distributed between 4.57 and 19.06 mph. Figure 3.16 shows the histogram for the moving trucks' speeds collected from the video data. The median, mean, and standard deviation of the slow-moving trucks' speeds were 10.37, 10.59, and 2.6, respectively. The mean speed was used as an input for the MWZ in the simulation.

Figure 3.16. Distribution of slow-moving trucks' speeds

3.3.2.5 Traffic Volume

The average traffic volume of vehicles that overtook the truck among all videos was 357 vehicles per hour per lane, with a standard deviation of 79.9. In the simulation, an input volume of 350 vehicles per hour per lane was used for a three-lane freeway segment.

3.3.2.6 Percentage of Heavy Vehicles

The average percentage of heavy vehicles in the videos was 16.2. This value was used as an input for the MWZ simulation.

4 MWZ Speed Model

In this chapter, the speed of traffic near the moving work zone is estimated using analytical models. The RITIS and point detector databases were used for modeling speed inside a MWZ. The RITIS database includes travel time on segments every 30 seconds for each lane. However, 30-second speed data exhibit high fluctuations. Therefore, the data were aggregated into 5-minute speeds to reduce fluctuations. Traffic flow data were also aggregated into 5-minute intervals.

The dependent variable in the speed estimation model was work zone speed (WZSp), which represents the average speed of traffic inside the MWZ. The independent variables were speed limit (SpL), historical speed (HiSp), number of lanes (NoL), segment traffic volume (Vol), duration (Dur), MWZ position (LR, left = 0, right = 1), and time indicator (DN, day = 1, night = 0). Table 4.1 lists the predictors, their units, and the database from which the data were extracted.

Table 4.1. Predictors for work zone speed model

Predictors	Description	Source Database
SpL	Speed limit (mph)	RITIS
HiSp	Historical speed, week before the MWZ (mph)	RITIS
NoL	Number of lanes	RITIS
LR	Lane closure indicator: 0 if left lane is closed, 1 otherwise	MoDOT e-alerts
DN	0 for nighttime MWZs between 12 and 6 a.m., 1 otherwise	MoDOT e-alerts

4.1 Linear Regression Model

The stepwise regression method was used to find the best regression model. The final linear regression model included the predictors listed in Table 4.1. Table 4.2 displays the descriptive statistics of the data.

Table 4.2. Descriptive statistics for variables in work zone speed linear regression model

	Data Set without Volumes (266 Observations)			
Predictor	**Minimum**	**Maximum**	**Mean**	**Std Dev**
WZSp (mph)	22.5	66.1	55.85	9.53
SpL (mph)	55.0	65.0	61.48	2.37
HiSp (mph)	42.7	68.7	61.87	4.02
NoL	2	5	3.3	0.91
Vol (Veh/Hr)	144	4,272	1,392	1,090
Dur (Hr)	0.02	2.17	1.15	0.78
LR	0	1	0.19	
DN	0	1	0.46	
Observations		266		

As shown in Table 4.2, the average speed of the segments in the presence of the work zones ranged between 22.5 and 66.1 mph, with a mean of 55.85 mph. There were three speed limits (55, 60, and 65 mph) on the road segments in the database. The average speed of the segments one week before the work zone ranged between 42.7 and 68.7 mph, with an average of 61.87 mph. As expected, the minimum, maximum, and mean of the segment speeds in the presence of MWZs were lower than those of the historic data. The database included segments with volumes between 144 and 4,272 vehicles per hour, with an average of 1,392 vehicles per hour. The average duration of the work zones was 1.36 hours. About 73% of the moving work zones were located in the left lane, and 51% of the work zones were active during nighttime.

The best linear regression model was found to be the following:

$$WZSp = -26.738 + 0.962 \times SpL + 0.345 \times HiSp + 2.015 \times NoL - 10.184 \times LR - 5.607 \times DN$$

All coefficients were statistically significant at the 95% confidence level (p-values < 0.001), with an R^2 of 0.482.

5 SIMULATION

This chapter describes the use of simulation as a tool to measure the traffic and safety impacts of a MWZ. The simulation software used in this research was VISSIM (version 7.00-13). VISSIM is a microscopic, stochastic, psychophysical driver behavior-based simulation software package (Wiedemann 1991). The information extracted from video data, described in Chapter 3, was used as VISSIM input. An 18-mile segment of a three-lane urban freeway was used as the test network. The slow-moving truck's speed was 10.6 mph, with a truck percentage of 16.2% and a volume of 350 vehicles per hour per lane. The speed distribution from the detector data (Figure 3.20) was used as the desired speed distribution in VISSIM.

The simulation duration was 4 hours, with 1,400 seconds of warm-up. After warm-up, the first hour of simulation represented normal conditions without a moving work zone. At 5,000 seconds simulation time (1,400 of warm-up + 3,600 of normal conditions), two slow-moving trucks separated by a distance of 250 ft entered the right lane and remained in the network for an hour. The downstream truck represented the work truck, while the upstream truck represented the shadow truck with the TMA. This is a common moving work zone setup recommended by the MUTCD. The slow-moving trucks entered the link at a distance of 1,000 ft from the beginning of the link (Figure 5.1).

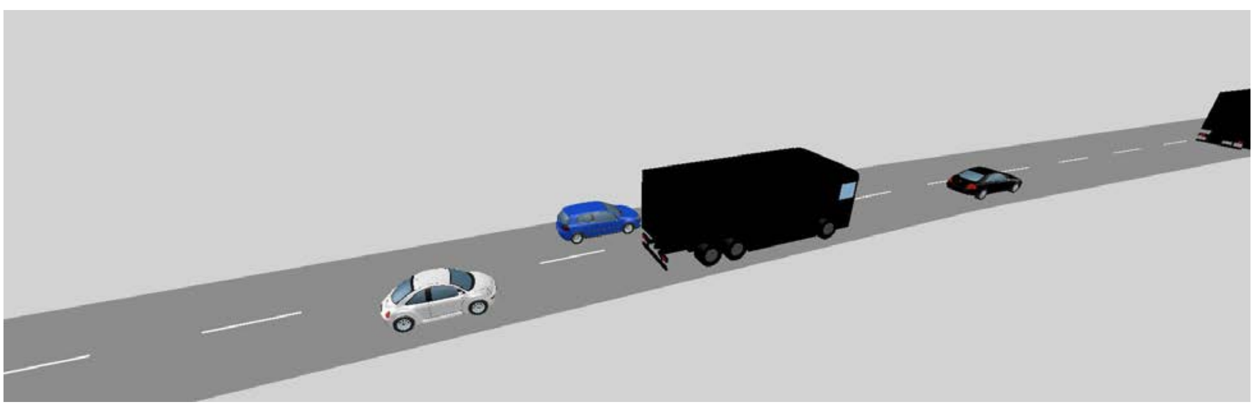


Figure 5.1. Slow-moving truck in VISSIM network

The slow-moving trucks exited the network at 8,600 seconds. After that, the simulation ran for another two hours to ensure that the entire queue dissipated and normal conditions returned. The activities occurring during the different simulation time periods are summarized in Table 5.1. The slow-moving trucks were introduced onto and removed from the network using the VISSIM Component Object Model (COM) in Visual Basic for Applications (VBA). VISSIM COM gives access to data and functions contained in the software.

Table 5.1. Simulation time periods

Simulation Seconds	Activity
0–1,400	Warm-up
1,400–5,000	Non-MWZ condition
5,000	MWZ enters the beginning of the first segment
5,000–8,600	MWZ presence
8,600	MWZ exits the road
8,600–12,200	Queue dissipates
12,200–15,800	Non-MWZ condition

The next section describes the calibration of the VISSIM network through the use of the lane change distance distribution derived from the video data.

5.1 Calibration Methodology

This section explains the parameters that were changed to calibrate VISSIM to simulate the effects of a MWZ. Two categories of VISSIM driving behavior parameters related to car following (Figure 5.2) and lane changing (Figure 5.3) were adjusted to calibrate the model.

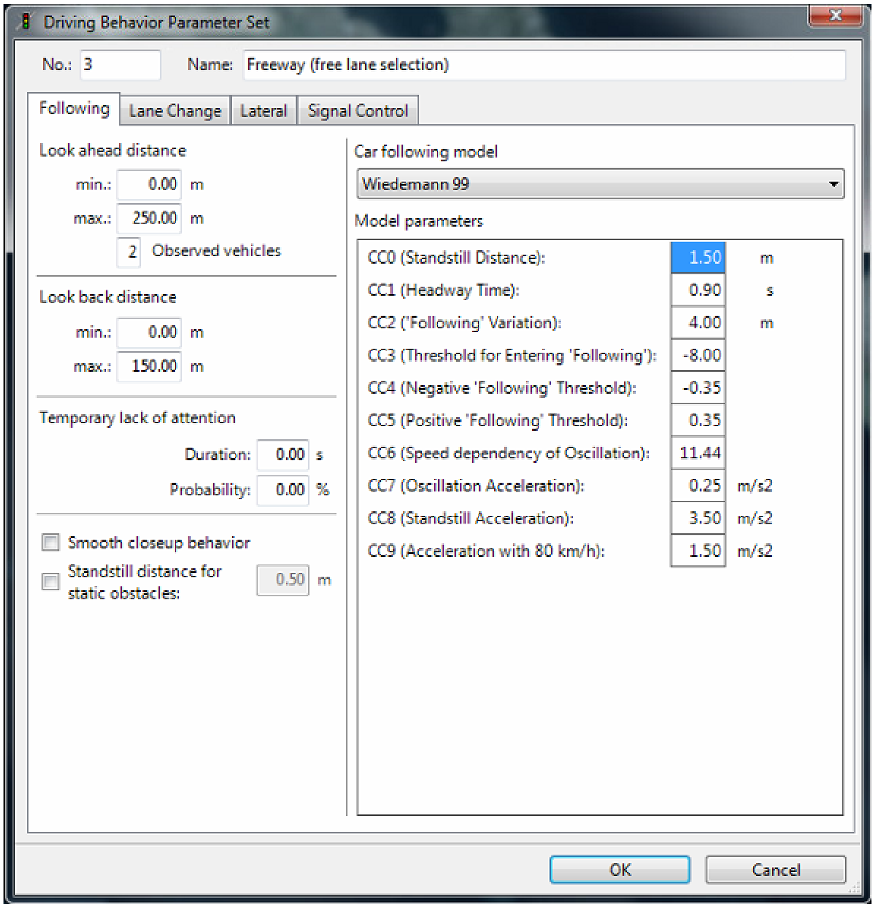


Figure 5.2. VISSIM car following parameters

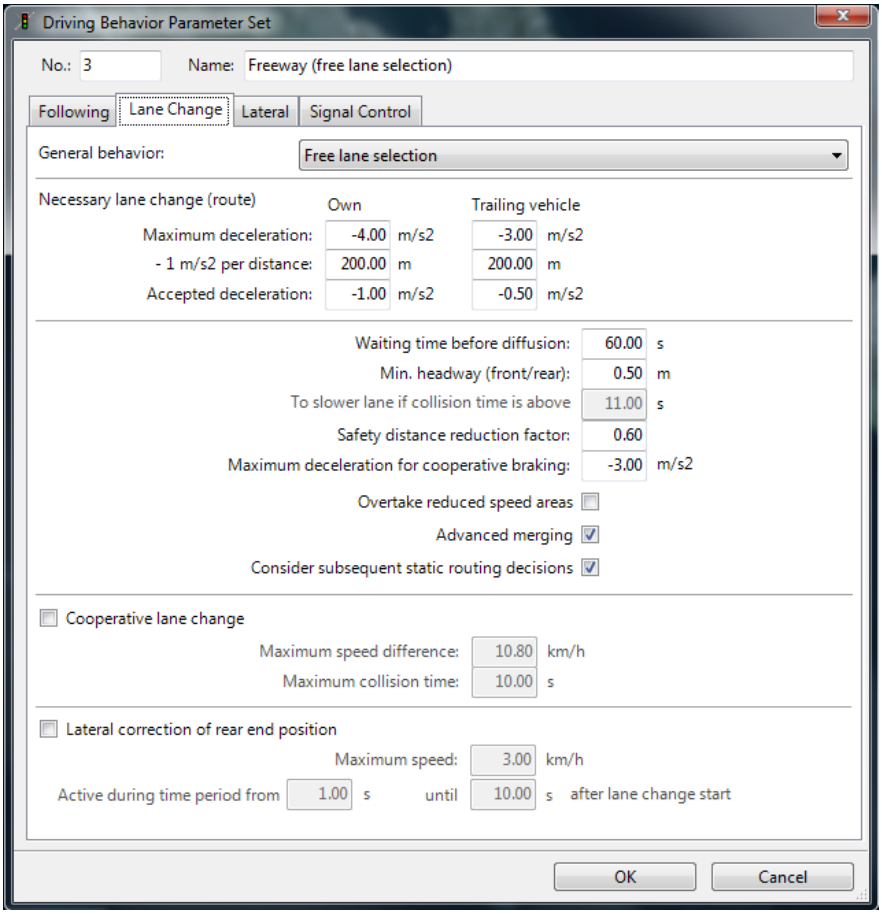


Figure 5.3. VISSIM lane changing parameters

The calibration measure used was the distance between the lane change and the moving work zone. Because the maximum visible distance in the videos was 1,000 ft, the lane changes that occurred within 1,000 ft of the slow-moving truck were collected in the VISSIM simulation. The goal of the calibration was to make the VISSIM output match the field data extracted from videos.

To collect the lane changes that occurred within 1,000 ft of the slow-moving trucks, three different types of information were collected from the VISSIM outputs:

- The lane changes that occurred behind the truck to the adjacent open lane
- Truck location when a lane change occurred
- Lane change distance (LCD) (calculated by subtracting the location of the lane-changing vehicle from the location of the truck when the lane change occurred)

5.1.1 Driving Behavior - Car Following Parameters

5.1.1.1 Look Ahead Distance (Minimum, Maximum, and Number of Observed Vehicles)

Look ahead distance is the distance that a driver can see forward for the purpose of reacting to other vehicles in the same lane or in adjacent lanes. In addition to look ahead distance, driving behavior is affected by the number of preceding observed vehicles in the link. The number of observed vehicles affects how well a driver predicts the preceding vehicles' movements and reacts accordingly (PTV Group 2013). The VISSIM default values of minimum look ahead distance, maximum look ahead distance, and number of observed vehicles are 0 ft, 820 ft and two vehicles, respectively.

5.1.1.2 Smooth Closeup behavior

By selecting this option, vehicles slow down more uniformly as they approach a stationary obstacle. At the maximum look ahead distance from a stationary obstacle, a following vehicle can plan to stop (PTV Group 2013). By selecting this option, the following vehicles continue their normal driving behavior until a preceding vehicle's speed drops to less than 1 mph. This parameter helps to simulate driving behavior more realistically upstream of a stop-and-go traffic flow condition. This option is not selected in the VISSIM default parameters.

5.1.1.3 Look Back Distance

This option defines the minimum and maximum distance that a driver can see backwards in order to react to the vehicles behind his/her vehicle (PTV Group 2013). The minimum look back distance affects lateral vehicle behavior. The VISSIM default values of minimum look back distance and maximum look back distance are 0 ft and 150 ft, respectively. Various values for these options were tested, and no positive effect was found on the distribution of the distance between the lane change and the back of the truck.

5.1.2 Driving Behavior - Lane Change Parameters

5.1.2.1 Safety Distance Reduction Factor

Safety distance reduction factor (SRF) is the reduction multiplier applied to the safe following distance during lane changes. The default value is 0.6, which reduces the safety distance by 40% during a lane change. Different values for this parameter were tested and found to have an impact on the model's performance.

5.1.2.2 Other Parameters

The other parameters affecting lane changing behavior were free lane selection, maximum deceleration for cooperative braking, cooperative lane changing and its parameters, minimum headway, and advanced merging. These parameters were adjusted during calibration but did not show any significant effects.

5.2 Parameter Calibration Process

5.2.1 Selection of Parameter Combinations

The measure used to calibrate the parameters was the distribution of LCDs relative to the truck that were collected from the field videos. Table 5.2 shows all of the parameters that were tested for calibration. The values were chosen based on extensive study and suggested values in the literature.

Table 5.2. Parameters considered for the VISSIM calibration.

Parameter	Settings
Maximum look ahead distance	400, 600, 820, 1,000, 1,350, 1,700, 2,000, 3,000
Minimum look ahead distance	0, 300, 350, 390, 425, 500, 700
Safety distance reduction factor	0.3, 0.4, 0.5, 0.6, 0.7, 0.8
Number of observed vehicles	2, 5, 7, 10
Maximum look back distance	150, 300
Smooth closeup behaviour	Checked, unchecked
Cooperative lane change	Checked, unchecked
Max speed difference	8, 10.8, 12, 20
Max collision time	2, 6, 8, 10

There are 45,696 possible combinations of parameters based on the values in Table 5.2. Running VISSIM for all of these combinations would be very time consuming. As a solution, each of these parameters was tested separately. The LCD of each was compared to the LCDs from the videos. The parameter values that showed any effect were chosen for further combination analysis. By this method, 85 combinations of various parameters were found. Thus, a total of 123 trials (38 individual parameter values and 85 combinations) were conducted to find the optimal set of parameters for calibration. Each set of parameters was run with five different random seeds, and the results were averaged.

5.2.2 Selection of Calibrated Parameter Values

The Vehicle Records output feature in VISSIM was used for calibration. The KS statistical test was used to compare the VISSIM LCDs with those of the video data. The KS test hypotheses are as follows:

- H_0: Two samples come from the same distribution.
- H_A: Two samples come from different distributions.

Table 5.3 shows the KS test results for various calibration candidates.

Table 5.3. Comparison results for VISSIM parameters

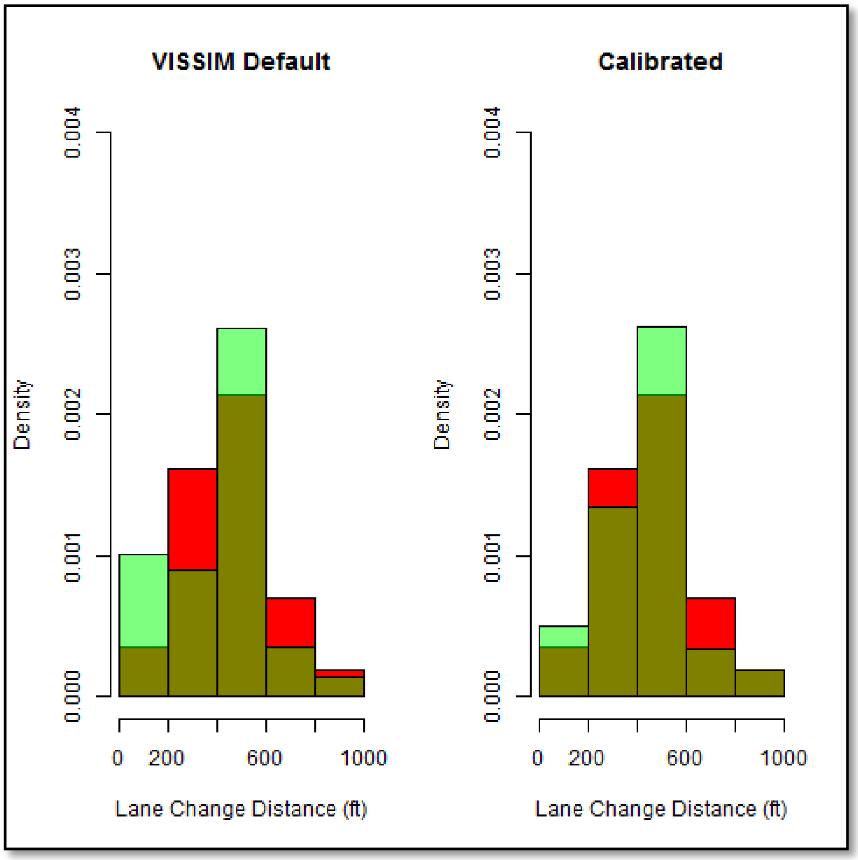
Parameters	Distance	P-Value
Baseline with default VISSIM parameters	0.1290	0.042
Smooth Closeup Checked	0.1190	0.085
Smooth Closeup Checked, SRF=0.7	0.1069	0.151
Smooth Closeup Checked, SRF=0.7, Min Look Ahead Distance 350 ft	0.0927	0.284
Smooth Closeup Checked, SRF=0.7, Min Look Ahead Distance 500 ft	0.0970	0.235
Smooth Closeup Checked, SRF=0.7, Min Look Ahead Distance 390 ft, Observed Vehicles 2	0.0998	0.203
Smooth Closeup Checked, SRF=0.7, Min Look Ahead Distance 390 ft, Observed Vehicles 5	0.0932	0.268

The p-value for the default VISSIM parameters was 0.042, which means that at the 95% confidence level the null hypothesis was rejected, thus confirming the need for calibration. For the remaining parameter combinations, the p-values were more than 0.05. Therefore, there was no evidence for rejecting the null hypothesis for the calibrated parameters.

As Table 5.3 shows, the distance according to the KS test results is smallest for the parameters shown in the fourth row of the table. These parameters are the recommended parameters and are summarized as follows:

- Smooth Closeup Checked
- SRF = 0.7
- Min Look Ahead Distance = 500 ft

Figure 5.4 shows the LCD histograms for the baseline (using VISSIM default parameters) and calibrated parameters in comparison to the LCDs from the video data. From Figure 5.4, it can be seen that the calibrated parameters provide results that more closely match the observed data.



Light green = VISSIM; red = video; dark green = overlap

Figure 5.4. Lane change distance for VISSIM default (left) and calibrated (right) parameters

5.3 Simulation Results

The calibrated simulation model was used to study the traffic impacts of different moving work zone durations. VISSIM outputs several performance measures, including travel time, delay, number of stops, and queue length. Five work zone durations were simulated: 15 minutes, 30 minutes, 45 minutes, 60 minutes, and 120 minutes. As an example, the traffic impacts of a MWZ with a duration of 60 minutes is presented below. The results of the simulations for the other four durations are shown in Appendix B.

A work truck moving at a speed of 10.6 mph on the outside lane of a three-lane freeway represented the moving work zone. A work zone duration of 60 minutes and a network length of 11.1 miles were used. The simulation was run for 204 minutes, including 24 minutes of warm-up, 60 minutes without the moving work zone, 60 minutes with the moving work zone, and another 60 minutes after the truck exited the network, i.e., the flow recovery period. Tables 5.4 and 5.5 show the results for the operational measures. In these tables, 1st, 2nd, and 3rd refer to each 60-minute interval after the end of warm-up period. The 1st hour conditions when the MWZ was not present served as the baseline for comparison.

Table 5.4. VISSIM mobility performance measures for MWZ duration of 1 hour

Vol/	Travel Time (S)			Speed (mph)			Total Delay (Hr)			Avg Delay (S)			Total Stops			Stops per Vehicle		
Ln	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
350	688	688	694	58.1	57.4	57.6	2.8	3.1	3.0	8	9	9	0	0	0	0	0	0
700	712	715	716	56.0	55.7	55.5	20.0	18.6	20.6	29	27	30	0	0	0	0	0	0
1,000	753	759	759	53.3	52.4	52.6	58.9	62.8	70.8	58	62	67	0	0	0	0	0	0
1,400	848	904	874	46.9	44.1	45.7	201.2	267.7	223.9	138	179	150	2	1,699	95	0.00	0.32	0.02
1,800	1,004	1,183	1,251	39.8	30.9	34.3	489.0	882.4	770.6	253	448	356	453	36,511	20,569	0.07	5.15	2.64

Table 5.5. VISSIM travel time increase, total delay increase, and downstream volume for MWZ duration of 1 hour

Vol/	Travel Time Increase (%)		Total Delay Increase (Hr)		Downstream Volume (Veh/Hr)		
Ln	2nd	3rd	2nd	3rd	1st	2nd	3rd
350	0.0	0.9	0.3	0.2	1,059	1,050	1,060
700	0.4	0.6	-1.4	0.6	2,108	2,086	2,045
1,000	0.8	0.8	3.9	11.9	3,092	3,016	3,146
1,400	6.6	3.1	66.5	22.7	4,232	4,154	4,318
1,800	17.8	24.6	393.4	281.6	5,397	4,641	6,412

For volumes under 1,400 veh/hr/ln, the MWZ did not adversely impact the travel times, delays, or stops. However, when traffic volumes were 1,400 and 1,800 veh/hr/ln, the travel times increased 6.6% and 18.7%, respectively, due to the work zone in the 2nd hour. During the 3rd hour, the travel times increased by 3.1% and 24.6% when traffic volumes were 1,400 and 1,800 veh/hr/ln, respectively. The same trend was observed for the other measures. Total delay increased by 66.5 and 393.4 hours and stops increased by 1,697 and 36,058 when traffic volumes were 1,400 and 1,800 veh/hr/ln, respectively. Therefore, it can be concluded that a moving work activity lasting one hour should be scheduled for times when the traffic volume is under 1,400 veh/hr/ln, and preferably under 1,000 veh/hr/ln.

Vehicle trajectories were also recorded from the VISSIM simulations. The vehicle trajectories for a work zone 60 minutes in duration are plotted in Figures 5.5 to 5.9 for different traffic volumes. For legibility reasons, only 20% of randomly chosen vehicle trajectories are drawn.

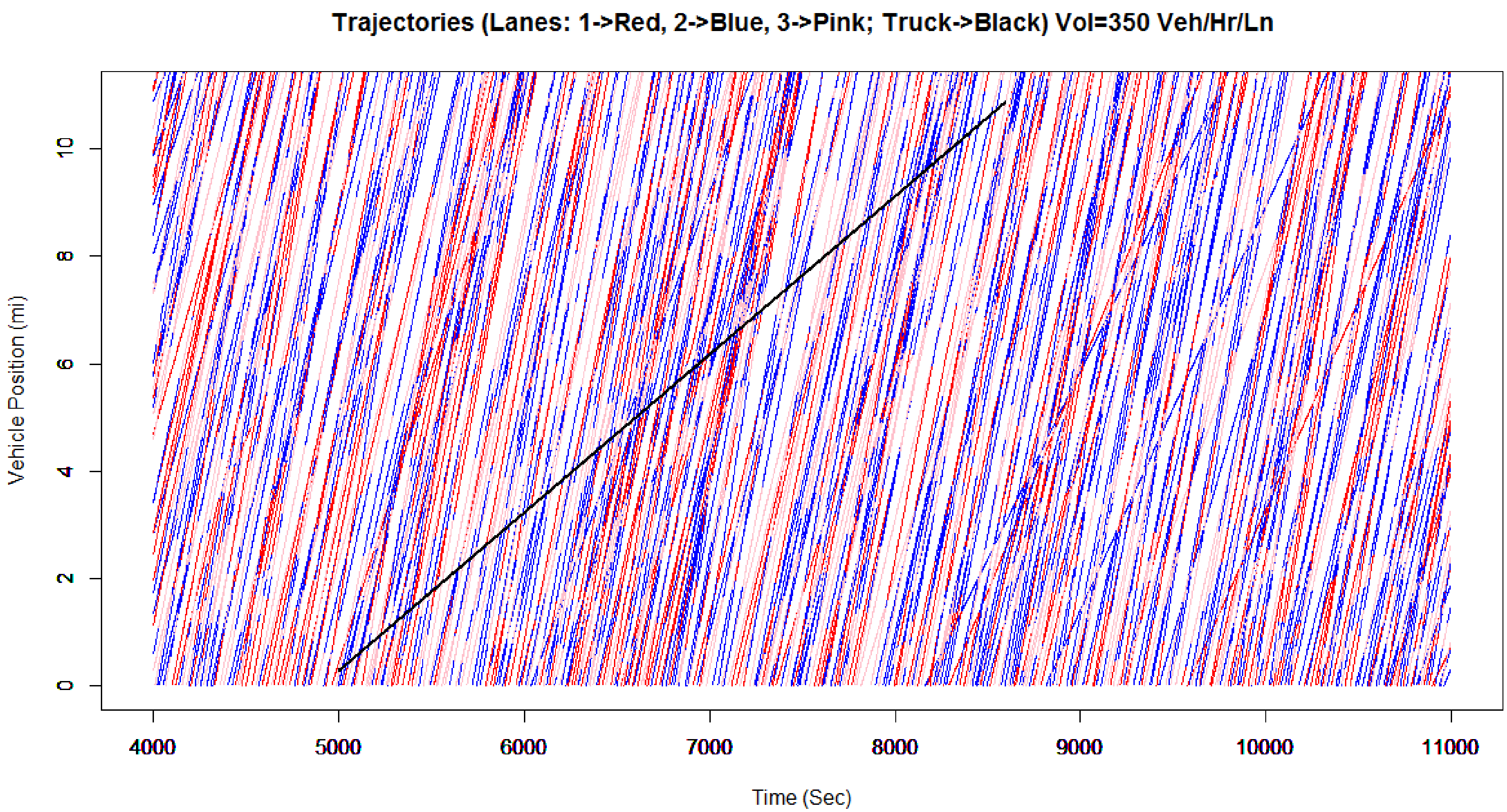


Figure 5.5. Plot of VISSIM vehicle trajectories (MWZ duration = 1 hour, volume = 350 veh/hr/ln)

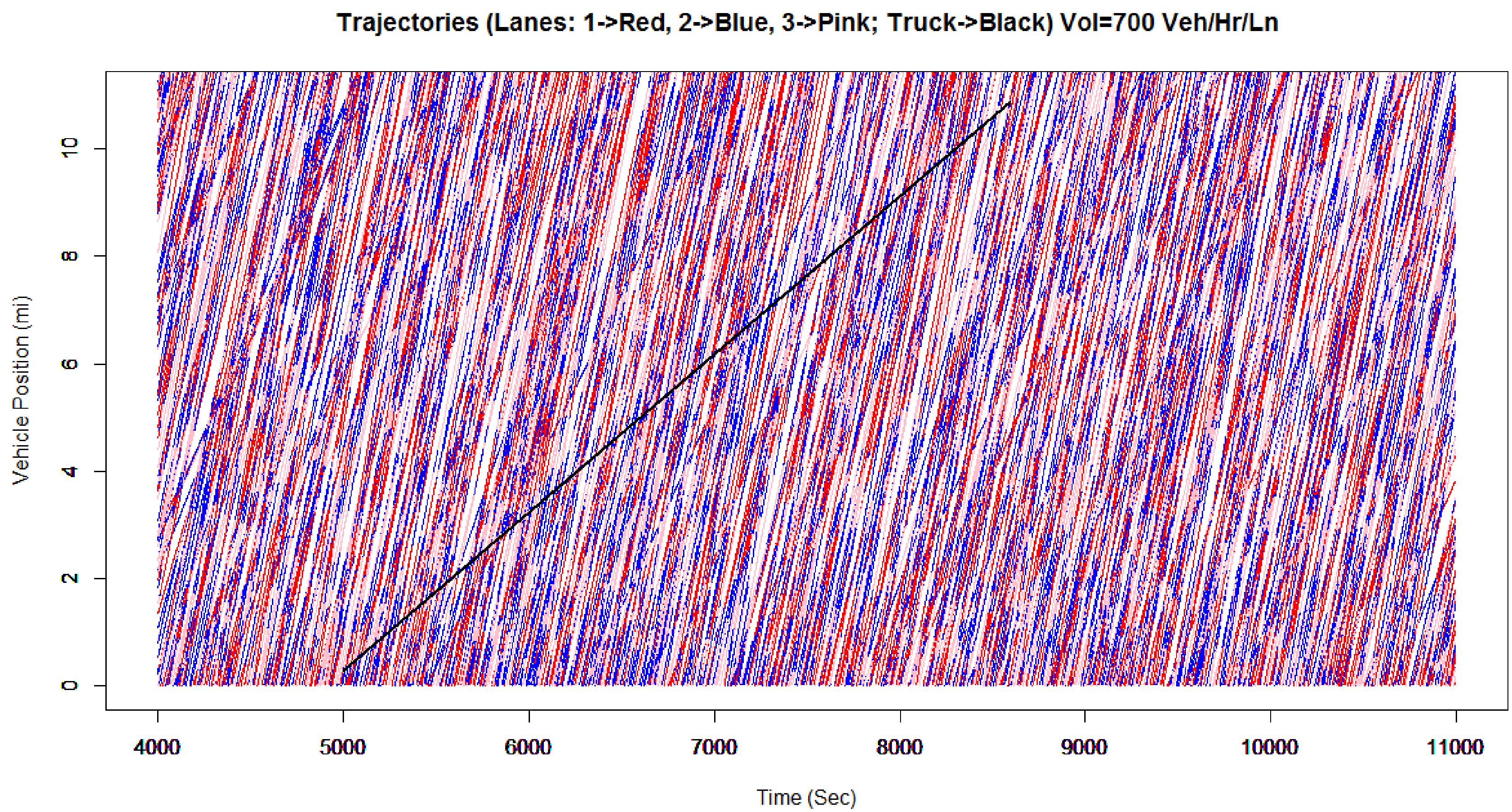


Figure 5.6. Plot of VISSIM vehicle trajectories (MWZ duration = 1 hour, volume = 700 veh/hr/ln)

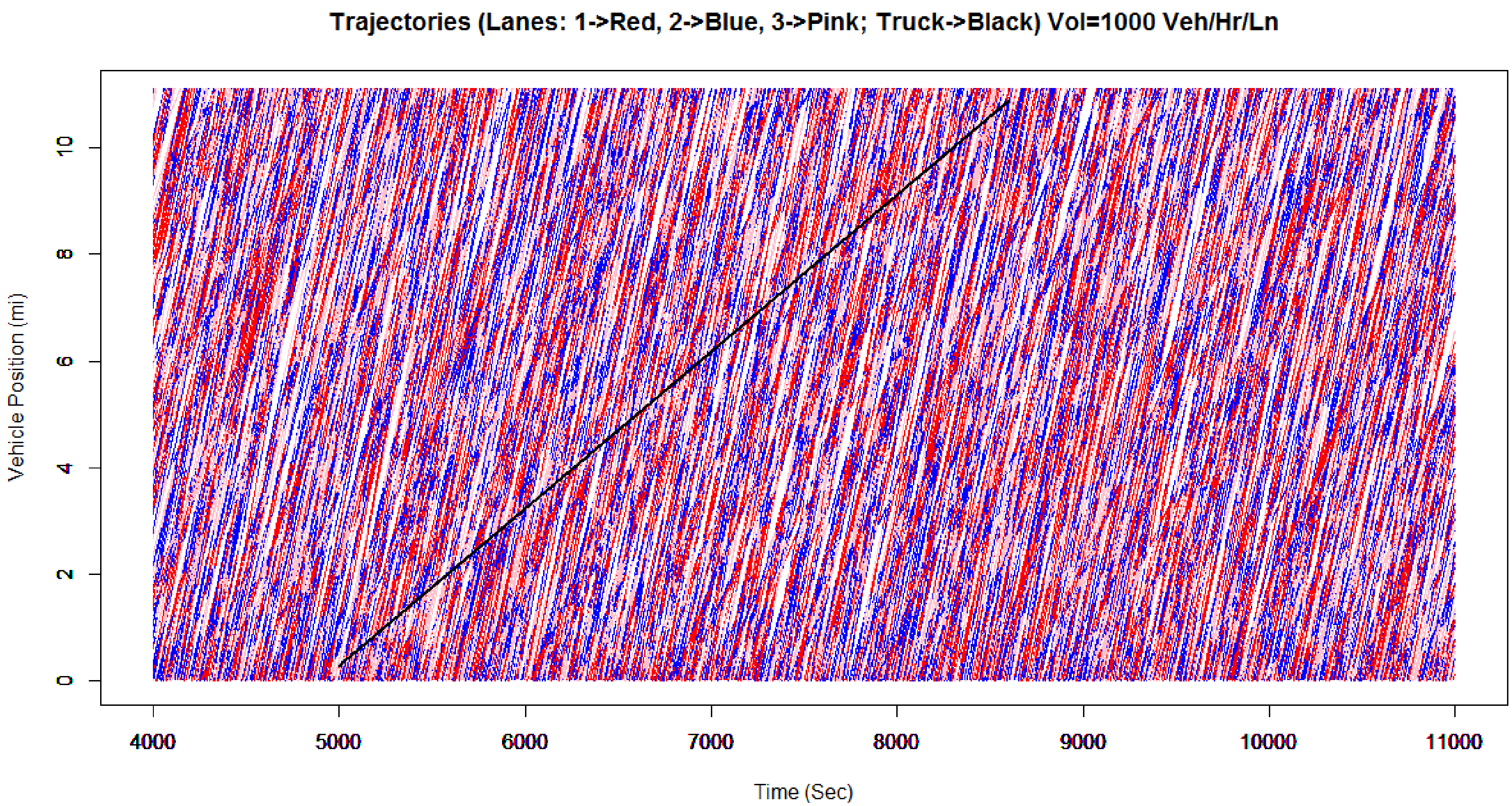


Figure 5.7. Plot of VISSIM vehicle trajectories (MWZ duration = 1 hour, volume = 1,000 veh/hr/ln)

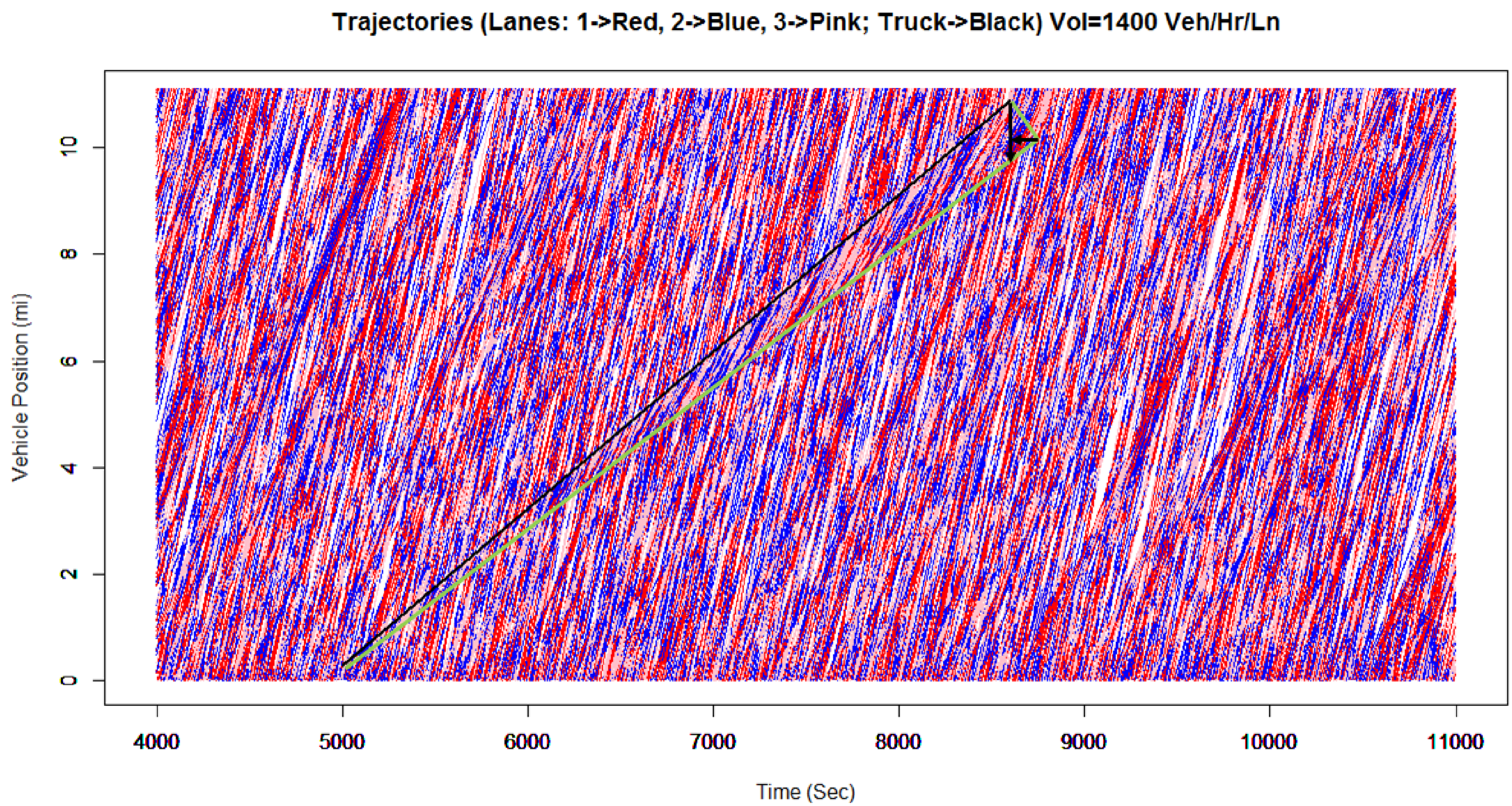


Figure 5.8. Plot of VISSIM vehicle trajectories (MWZ duration = 1 hour, volume = 1,400 veh/hr/ln)

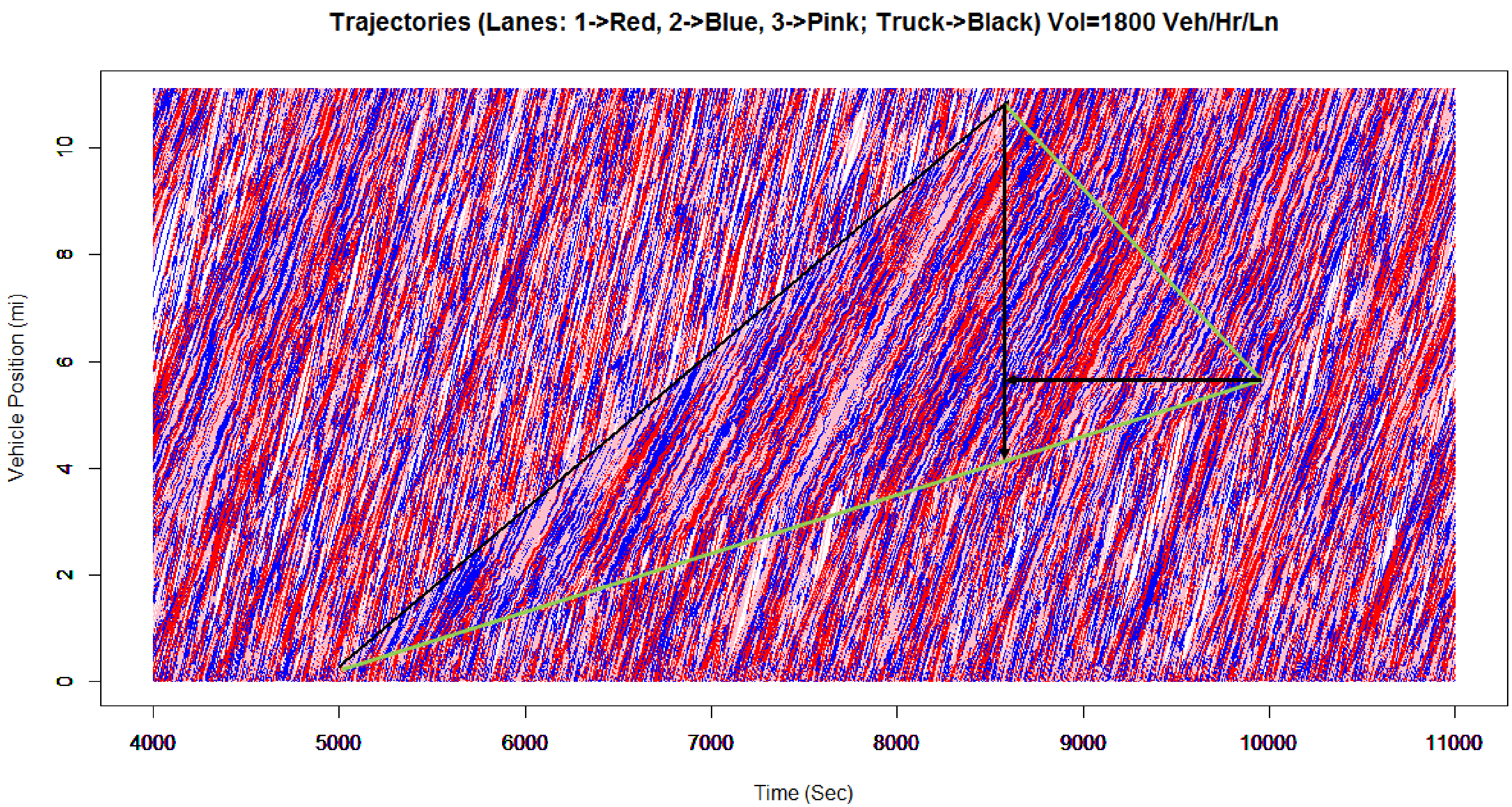


Figure 5.9. Plot of VISSIM vehicle trajectories (MWZ duration = 1 hour, volume = 1,800 veh/hr/ln)

In Figures 5.5 to 5.9, a unique trajectory is drawn for each of the chosen vehicles. The steeper the slope of the trajectory, the higher the vehicle speed. A color coding scheme is utilized to assist with lane recognition. The truck (MWZ) was in the right lane, and its trajectory is shown in black. For a vehicle in the outside lane (i.e., the rightmost lane), the trajectory is shown in red. The trajectories of the vehicles in the 2nd (middle) and 3rd (innermost) lanes are shown in blue and pink, respectively. According to this color coding, when a vehicle changes its lane, the trajectory color changes.

A decrease in the slope of a trajectory indicates a speed reduction. At any instant in time, the furthest upstream location at which a speed reduction occurs represents the end of the queue. Thus, queue length at any time can be computed from the trajectory plots, as long as a representative sample of the trajectories is plotted. The green lines in the trajectory plots (e.g., in Figure 5.8) indicate the change in slope, i.e., the vehicle speeds. Thus, the area inside the green and black (i.e., the MWZ truck trajectory) lines denotes the shockwave boundary. In this area, congestion occurs that leads to stop-and-go conditions. As seen in Figures 5.5 to 5.7, there is no visible shockwave area in the network for volumes under 1,000 veh/hr/ln.

While the MWZ is in the network, the queue length increases. After the MWZ leaves the network, the queue length starts to decrease. Therefore, the maximum queue length is expected to occur at the moment that the MWZ leaves the network. The maximum queue lengths were computed for all volume conditions. From Figures 5.5 to 5.7, it is clear that no queueing occurred for volumes under 1,000 veh/hr/ln. In Figures 5.8 and 5.9, the vertical black arrows show the maximum queue length. The maximum queue lengths when volumes were 1,400 and 1,800 veh/hr/ln were 1.2 and 6.5 miles, respectively. The queue dissipation times were 155 seconds and 1350 seconds after the truck exited the network, computed as the length of the horizontal black arrows in Figures 5.8 and 5.9.

The travel time, maximum queue length, and queue dissipation time after the truck exited the network are shown for all five MWZ durations in Tables 5.6 and 5.7 for traffic volumes of 1,400 and 1,800 veh/hr/ln, respectively.

Table 5.6. Operational measures for 1,400 veh/hr/ln volume

MWZ duration	Travel time increase (%)	Maximum Queue Length (mi)	Queue dissipation time (seconds after truck exits)
15 minutes	3.8	0.4	40
30 minutes	7.1	0.45	75
45 minutes	5	1.1	100
60 minutes	6.6	1.2	155
120 minutes	8.8	1.4	250

Table 5.7. Operational measures for 1,800 veh/hr/ln volume

MWZ duration	Travel time increase (%)	Maximum Queue Length (mi)	Queue dissipation time (seconds after truck exits)
15 minutes	6.7	1.5	200
30 minutes	8.6	3.2	800
45 minutes	17.7	5	1,200
60 minutes	17.8	6.5	1,350
120 minutes	29.5	13	2,650

For a volume of 1,400 veh/hr/ln, the travel times and maximum queue length increased as the activity's duration increased. The maximum queue length was close to a mile for durations under 60 minutes and about 1.5 miles when the duration was 120 minutes. The longest time for queue dissipation after the moving truck exited the network was about 4 minutes.

While the trends in operational measures when the volume was 1,800 veh/hr/ln were similar to those when the volume was 1,400 veh/hr/ln, the magnitudes were significantly higher. For example, the impact of a 60-minute work activity on travel time and maximum queue length was two times that of a 30-minute activity. This leads to the suggestion that DOTs could consider scheduling shorter duration moving activities on high-volume roads at different times of day or on different days rather than scheduling a longer duration activity. This is critical as volumes approach 1,800 veh/hr/ln, because even a 30-minute activity can generate a 3.2-mile-long queue, which increases to 6.5 miles for a 60-minute activity and 13 miles for a 120-minute activity.

5.4 Safety Analysis

The safety impacts of moving work zones were assessed using the simulated trajectories and the Surrogate Safety Assessment Model (SSAM) (Kim et al. 2007, Gettman et al. 2008). Table 5.8 shows the total number of conflicts for the different activity durations.

Table 5.8. Total number of conflicts for different activity durations

Activity Duration (min)	Traffic volume (veh/hr/ln)				
	350	700	1,000	1,400	1,800
15	3	25	95	284	886
30	5	78	237	651	3,600
45	14	145	480	1,542	10,204
60	14	229	762	2,608	18,737
120	32	516	1,848	6,080	74,584

Only two types of conflicts are included, rear end and lane change conflicts, because there were no crossing movements on the simulated freeway work zone. Few conflicts were observed for volumes under 350 veh/hr/ln. The impact of work zone duration on conflicts increased as volumes reached 700 veh/hr/ln. The results show a near-linear increase (Figure 5.10) in the number of conflicts as the duration increases until the volume reaches 1,800 veh/hr/ln, after which the relationship becomes non-linear (Figure 5.11).

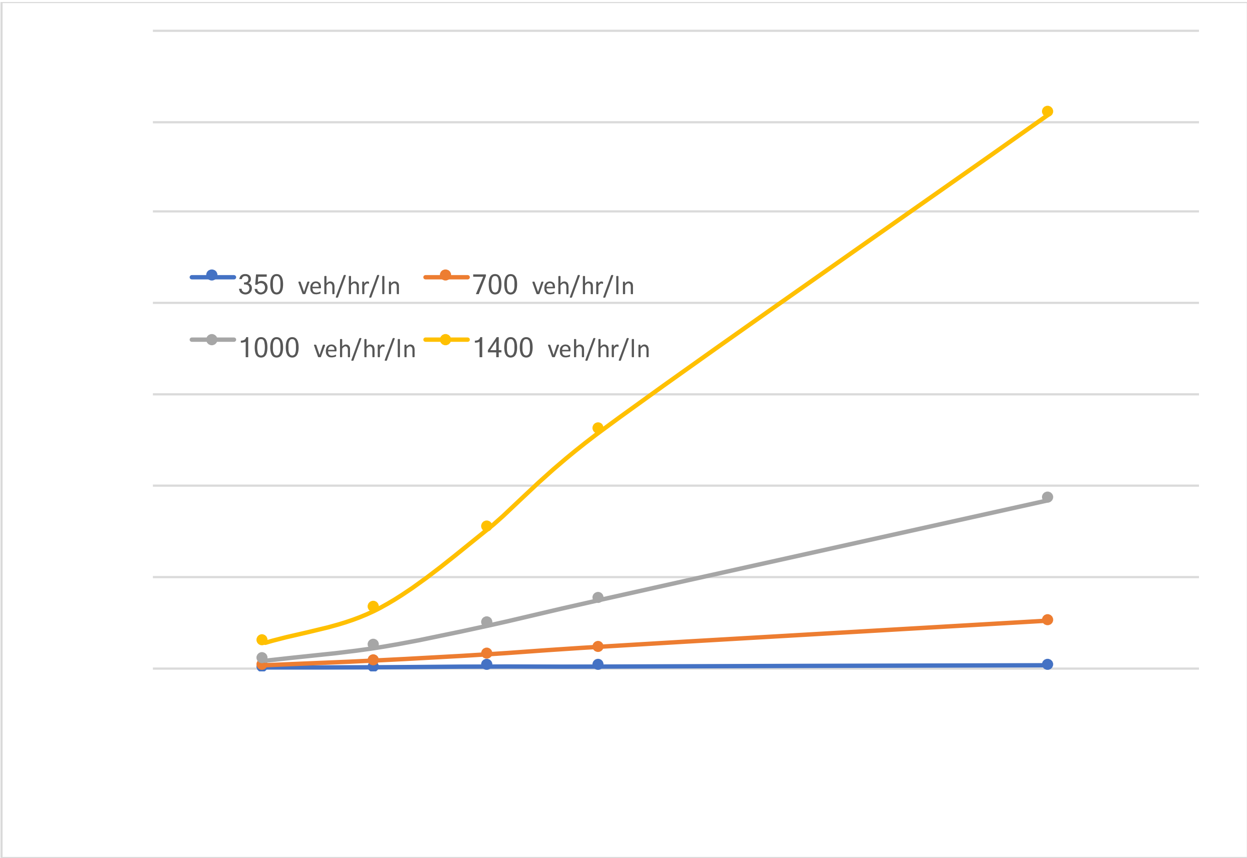


Figure 5.10. Conflicts versus moving activity duration (volume < 1,800 veh/hr/ln)

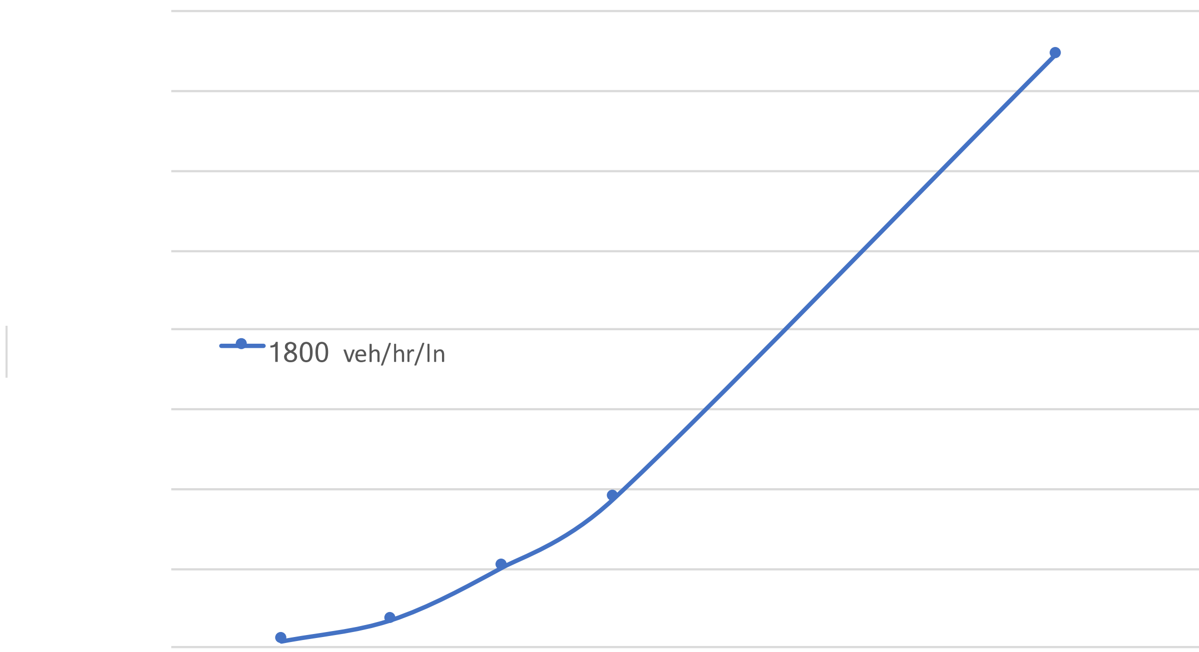


Figure 5.11. Conflicts versus moving activity duration (volume = 1,800 veh/hr/ln)

The gaps between the different plots in Figure 5.10, showing the differences in the number of conflicts, increased as the work zone duration increased. This indicates that if a moving activity must be scheduled for higher volume conditions (1,000 veh/hr/ln or more), its duration should be short (i.e., 60 minutes or less). Further, the number of conflicts sharply increased when the duration of the work zone activity was greater than 60 minutes and when the traffic volume was 1,800 veh/hr/ln, indicating that moving activities lasting longer than 1 hour on a freeway with a volume of 1,800 veh/hr/ln or higher will result in significant negative safety impacts. The plots shown in Figure 5.10 indicate the tradeoffs between the number of conflicts and combinations of activity duration and traffic volume. A DOT can choose to conduct a moving work activity for a short duration when the volume is high or for a longer duration when the volume is lower. The tradeoff plots present a holistic picture of the safety impacts of scheduling moving work activities.

6 CONCLUSIONS

Moving work activities are part and parcel of roadway maintenance. Despite their ubiquity, little guidance exists for practitioners on scheduling them. DOTs typically schedule moving work activities during off-peak hours to take advantage of lower volume conditions. However, unlike for stationary work activities, the literature contains no clear understanding of the traffic impacts of moving work activities.

This project addressed this need by examining data from 30 MWZs in Missouri. Regression models were developed to predict traffic speed in a MWZ as a function of work activity, traffic, and geometric characteristics. Second, calibration parameters were recommended for VISSIM to accurately simulate moving work zones. The three recommended calibration parameters are a safety reduction factor of 0.7, a minimum look ahead distance of 500 ft, and the use of VISSIM's smooth closeup option. While simulating a moving work zone is more difficult than simulating a stationary work zone, the recommended values will help practitioners to successfully implement MWZs in VISSIM.

From the operational analysis, it was concluded that a moving work activity lasting one hour or more operates best when the traffic volume is under 1,400 veh/hr/ln, and preferably under 1,000 veh/hr/ln. Further, scheduling shorter duration moving activities on high-volume roads at multiple times (on the same day or on different days) is preferable to scheduling a longer duration activity. For volumes approaching 1,800 veh/hr/ln, even a 30-minute activity can generate a 3.2-mile-long queue, which increases to 6.5 miles for a 60-minute activity and 13 miles for a 120-minute activity.

In the safety analysis, tradeoff plots were generated between the number of conflicts and combinations of activity duration and traffic volume. A DOT can use these plots to determine, for example, if it should conduct a moving work activity for a short duration when the volume is high or for a longer duration when the volume is lower. It is also recommended that if a moving activity must be scheduled for higher volume conditions (1,000 veh/hr/ln or more) its duration should be short (i.e., 60 minutes or less) to avoid significant negative safety impacts.

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APPENDIX A: SPEED VERSUS FLOW DATA AND HEAT MAPS

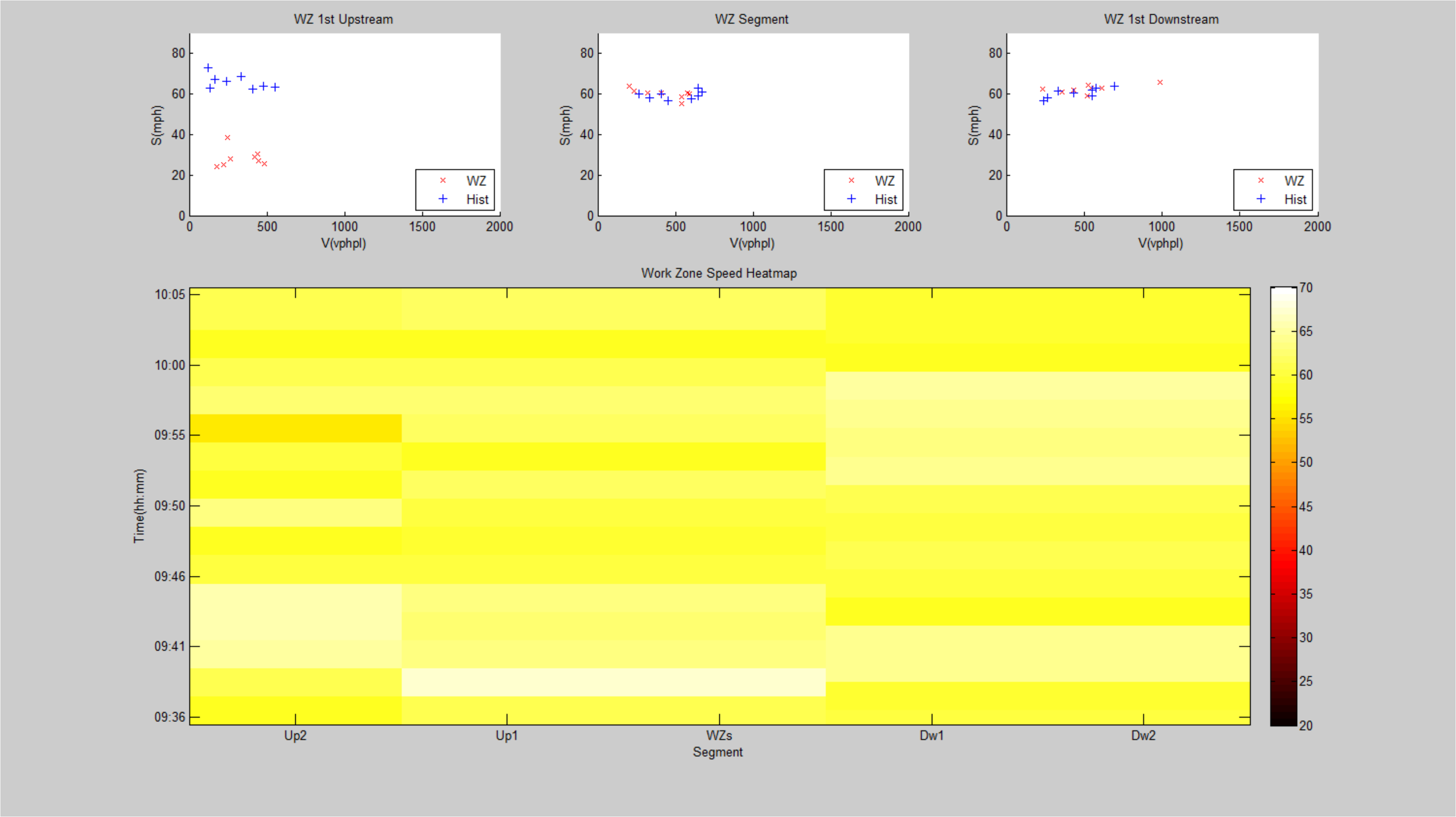

Figure A.1. Speed-flow diagram and speed heat map for I-44 work zone ID 6

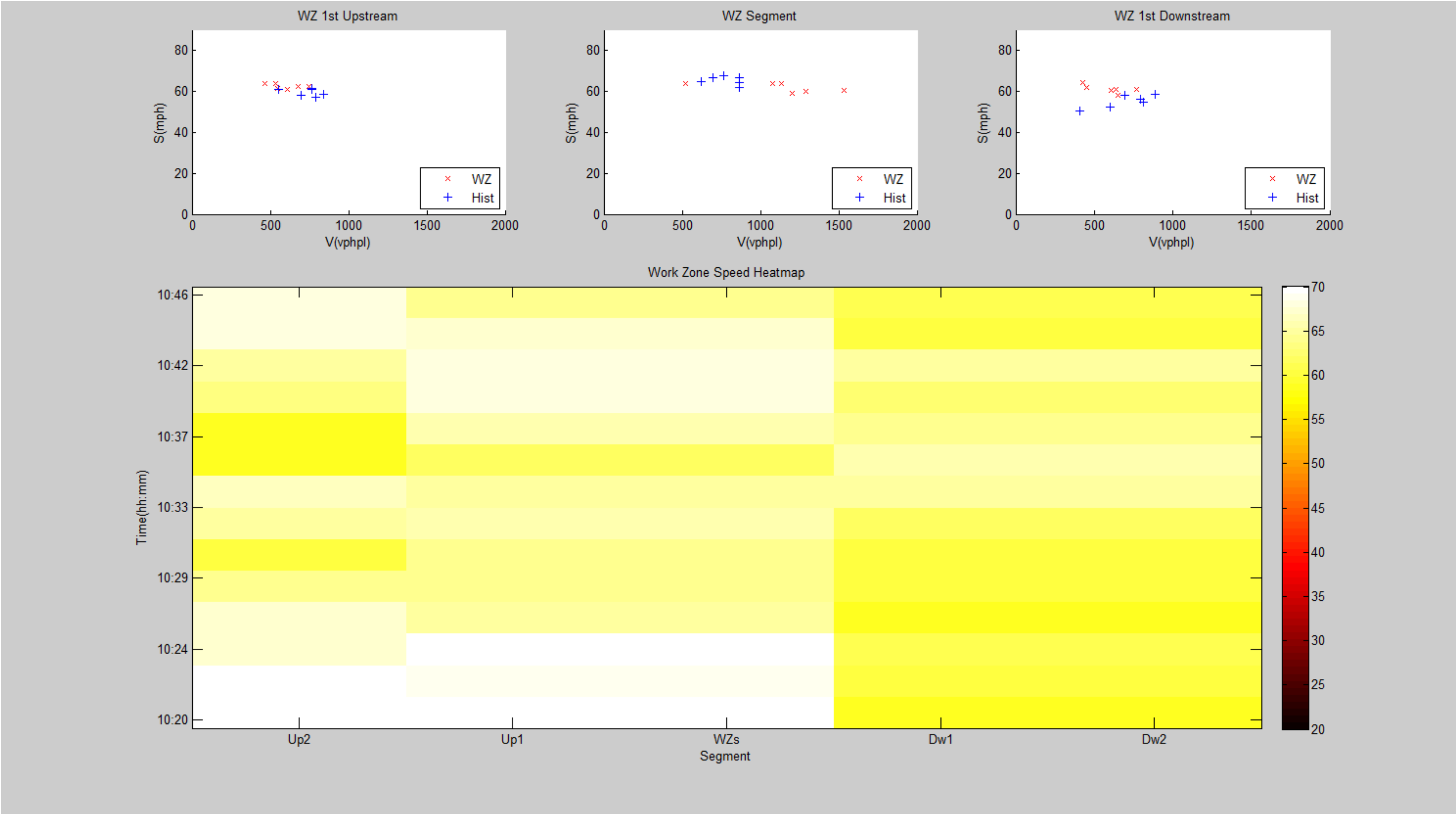

Figure A.2. Speed-flow diagram and speed heat map for I-44 work zone ID 7

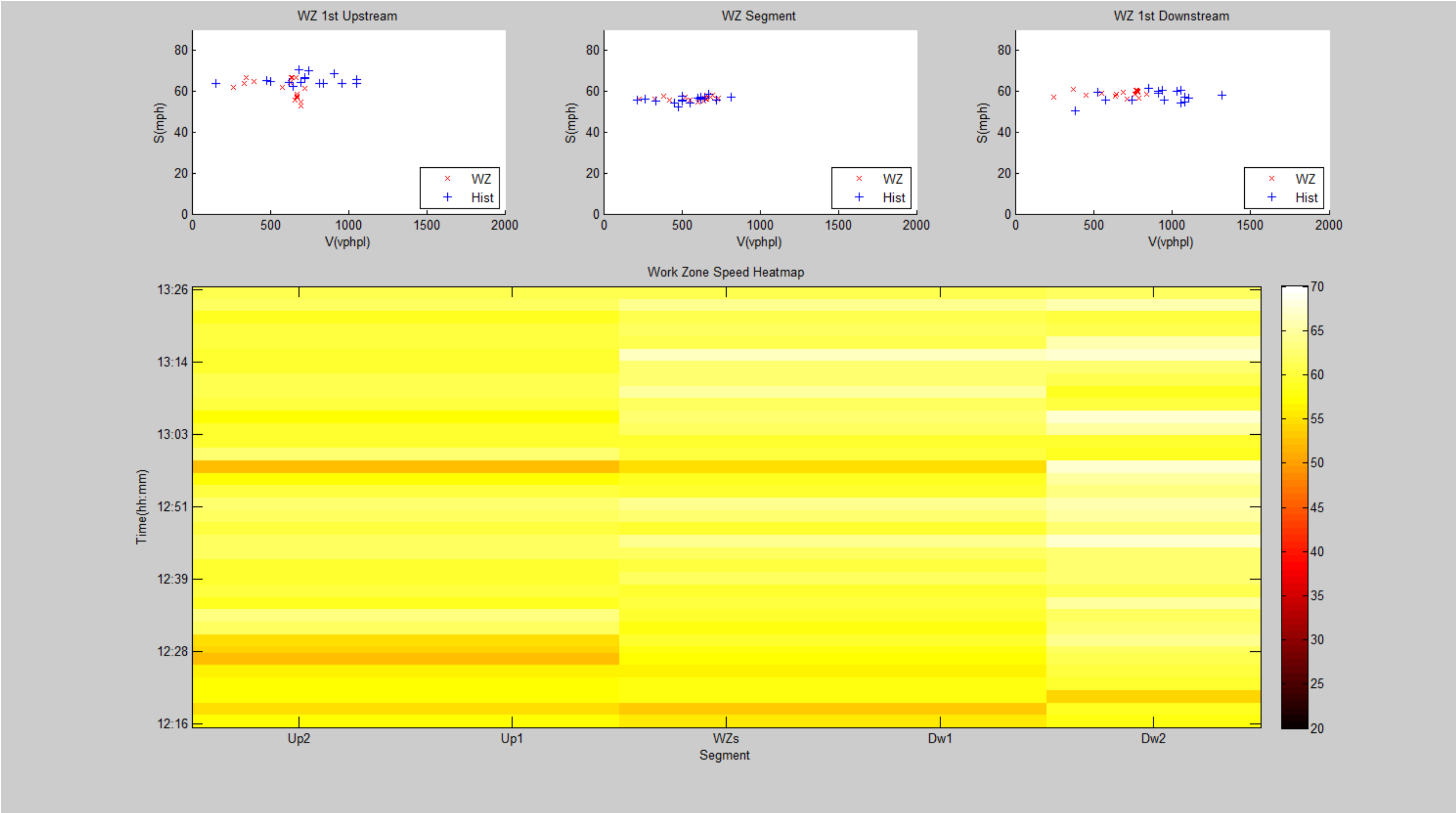

Figure A.3. Speed-flow diagram and speed heat map for I-44 work zone ID 9

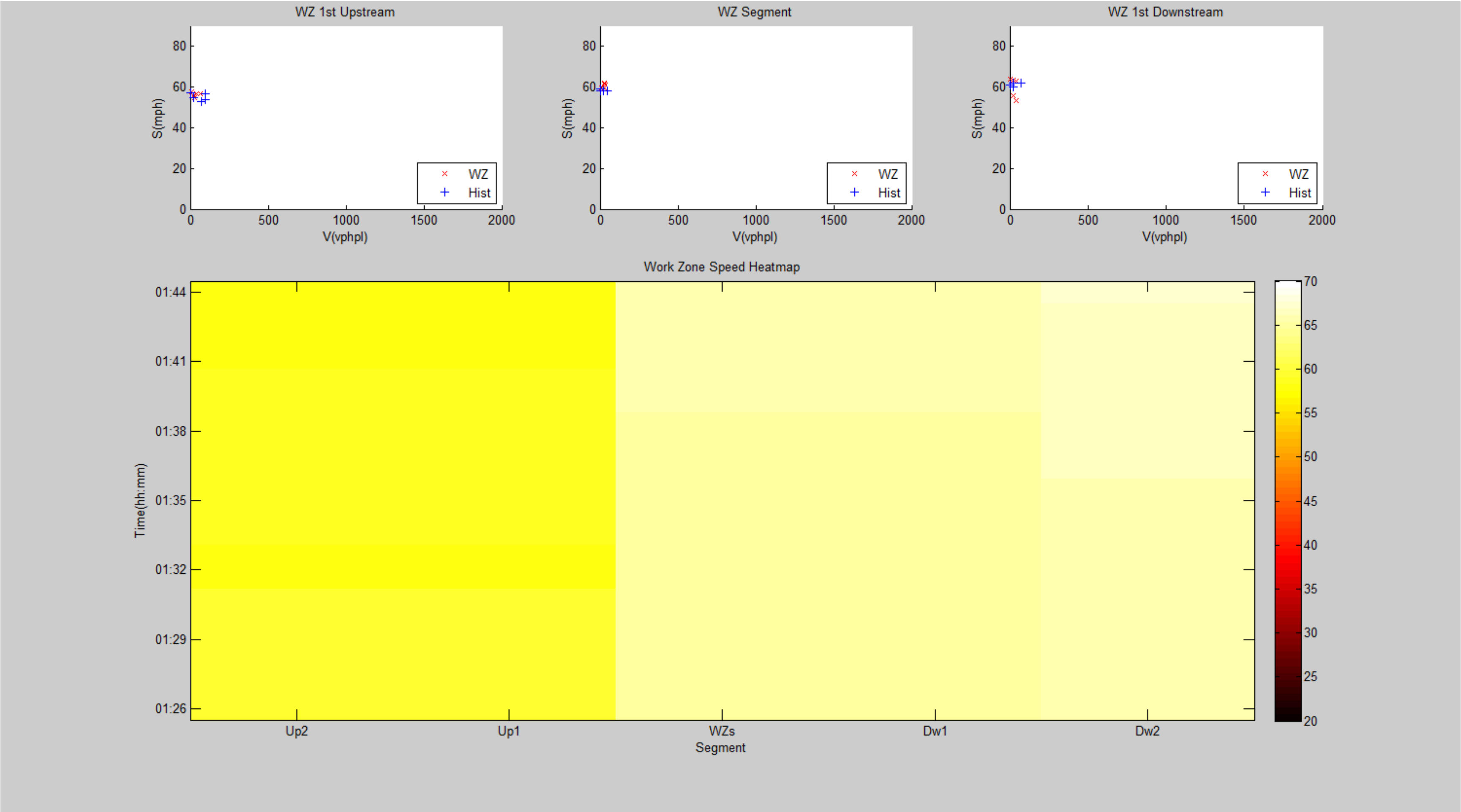

Figure A.4. Speed-flow diagram and speed heat map for I-44 work zone ID 18

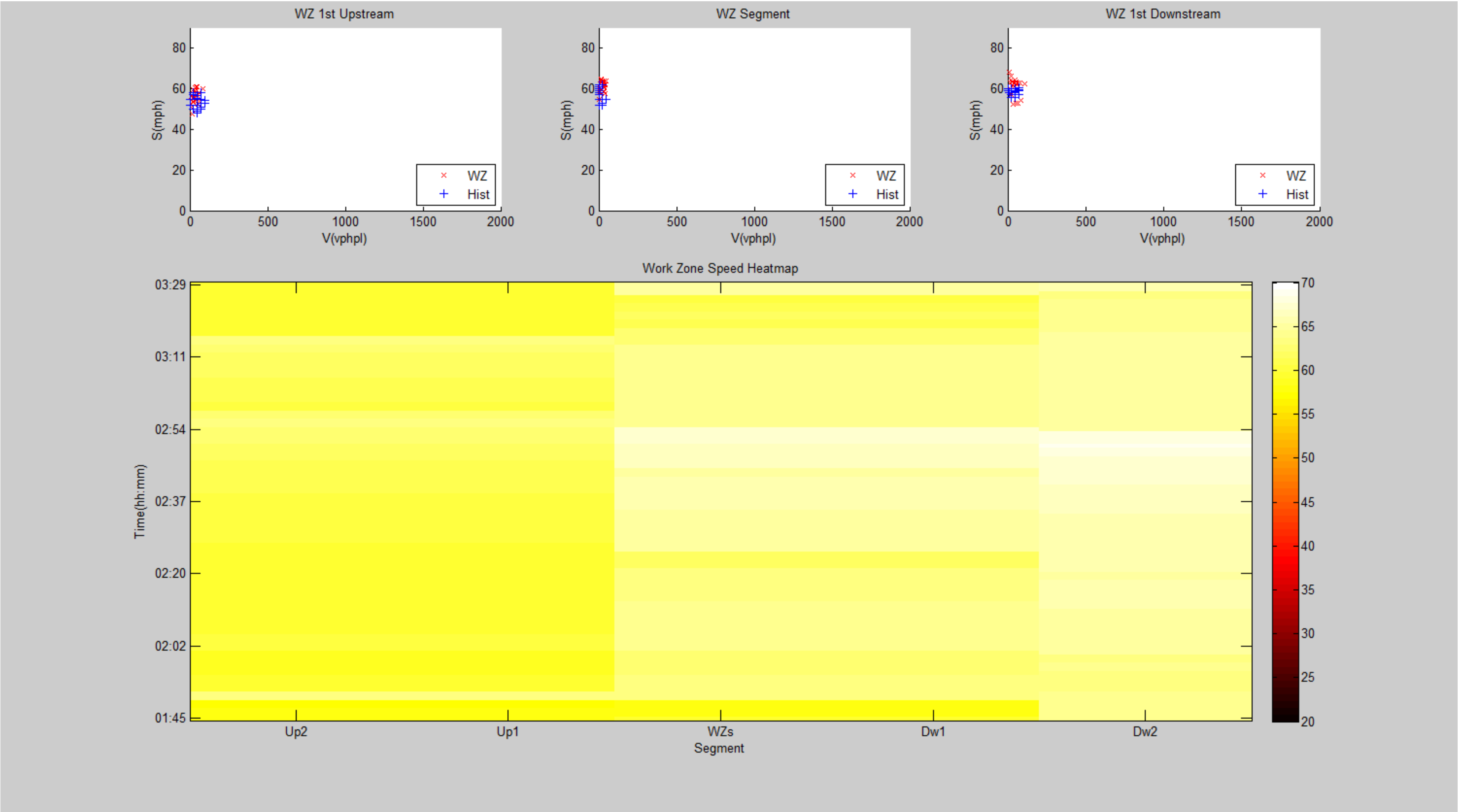

Figure A.5. Speed-flow diagram and speed heat map for I-44 work zone ID 19

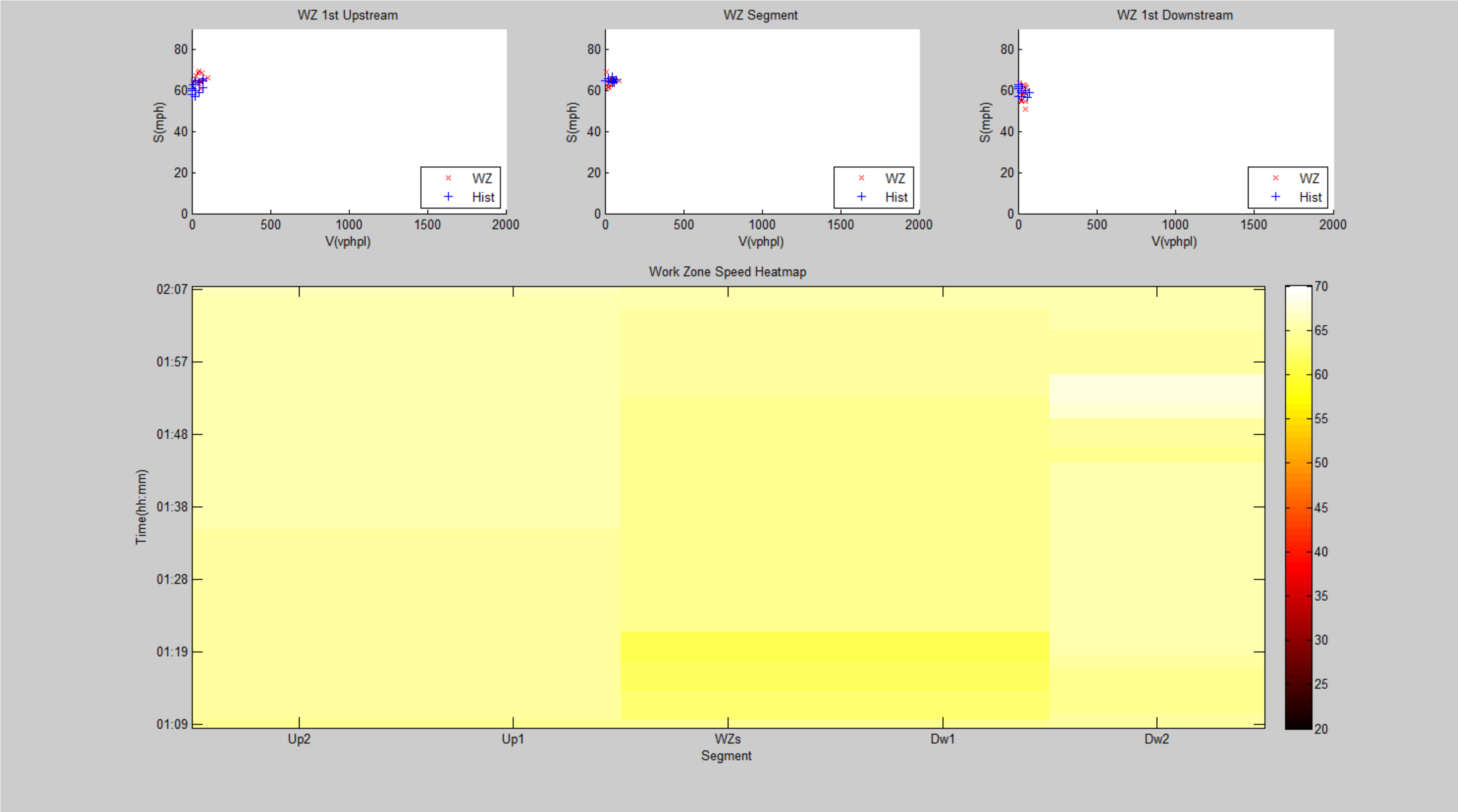

Figure A.6. Speed-flow diagram and speed heat map for I-44 work zone ID 20

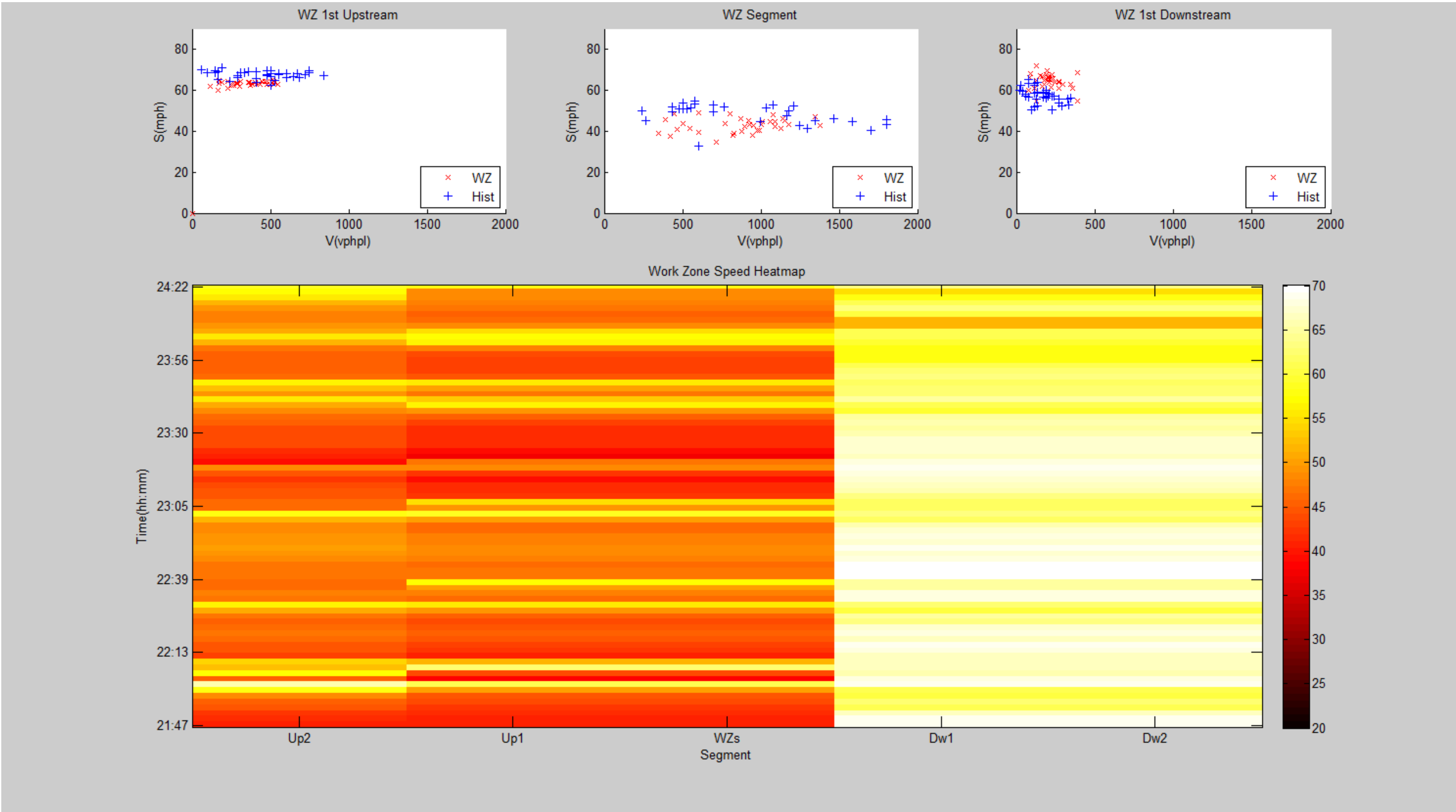

Figure A.7. Speed-flow diagram and speed heat map for I-64 work zone ID 23

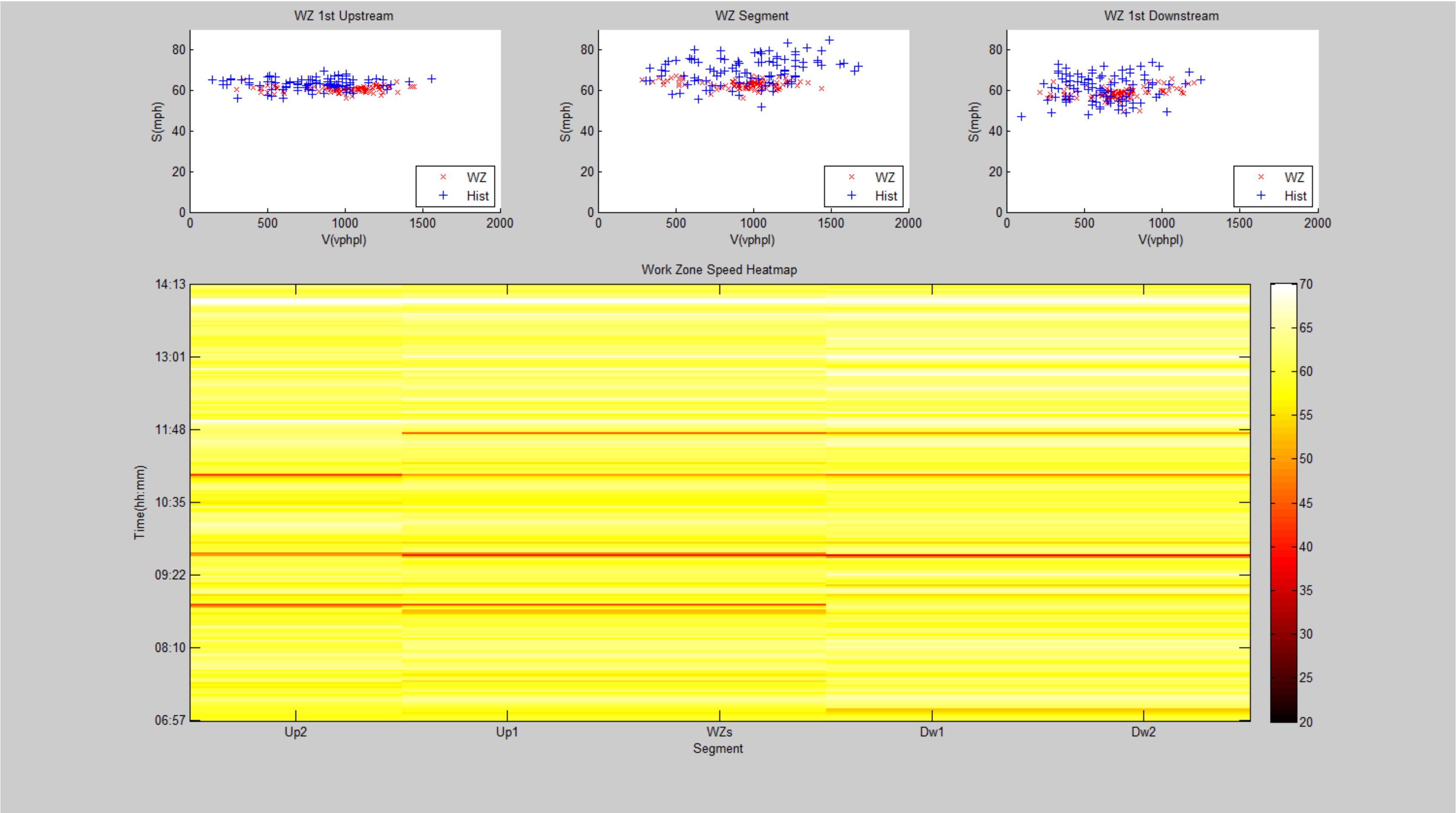

Figure A.8. Speed-flow diagram and speed heat map for I-64 work zone ID 24

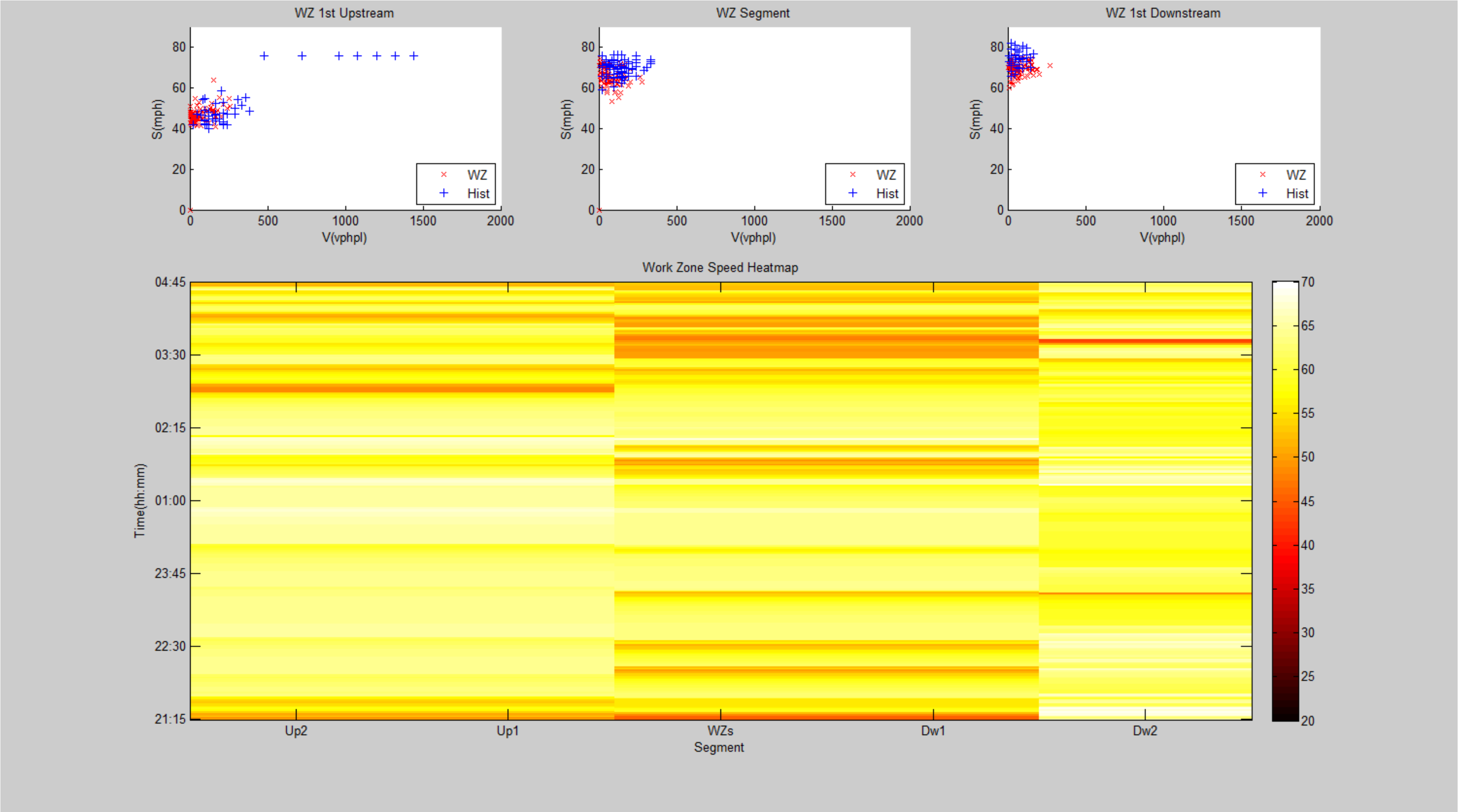

Figure A.9. Speed-flow diagram and speed heat map for I-64 work zone ID 25

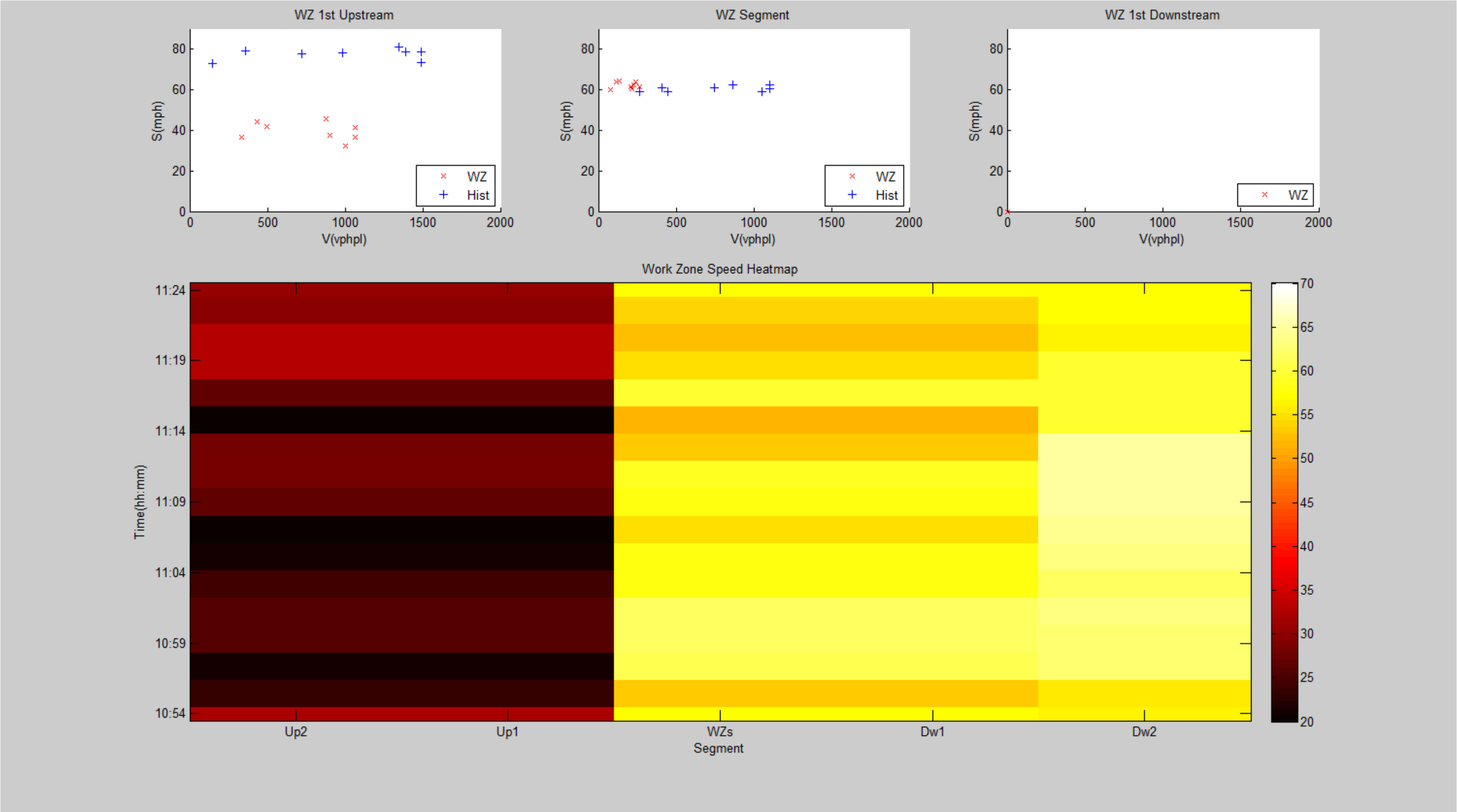

Figure A.10. Speed-flow diagram and speed heat map for I-64 work zone ID 29

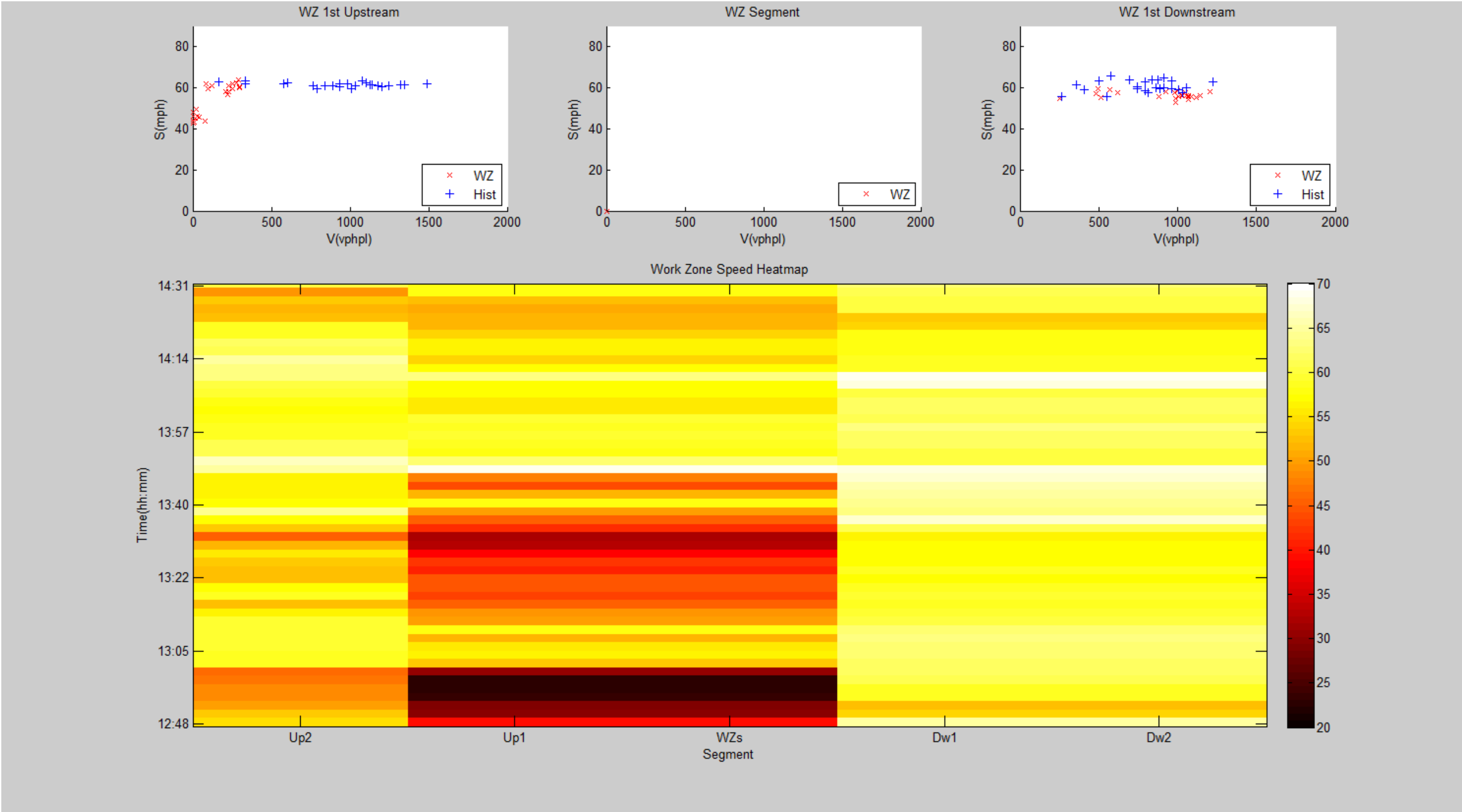

Figure A.11. Speed-flow diagram and speed heat map for I-64 work zone ID 30

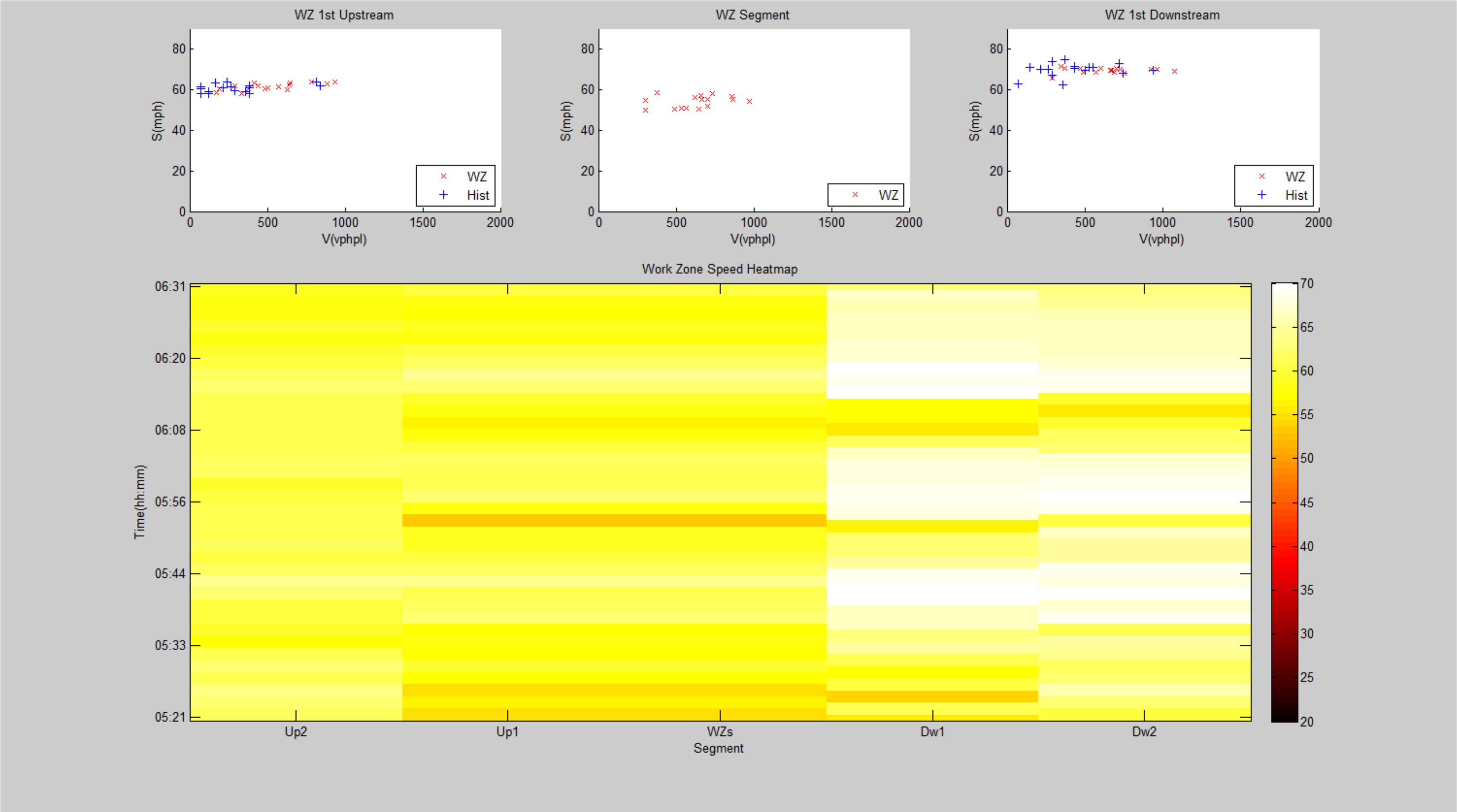

Figure A.12. Speed-flow diagram and speed heat map for I-64 work zone ID 32

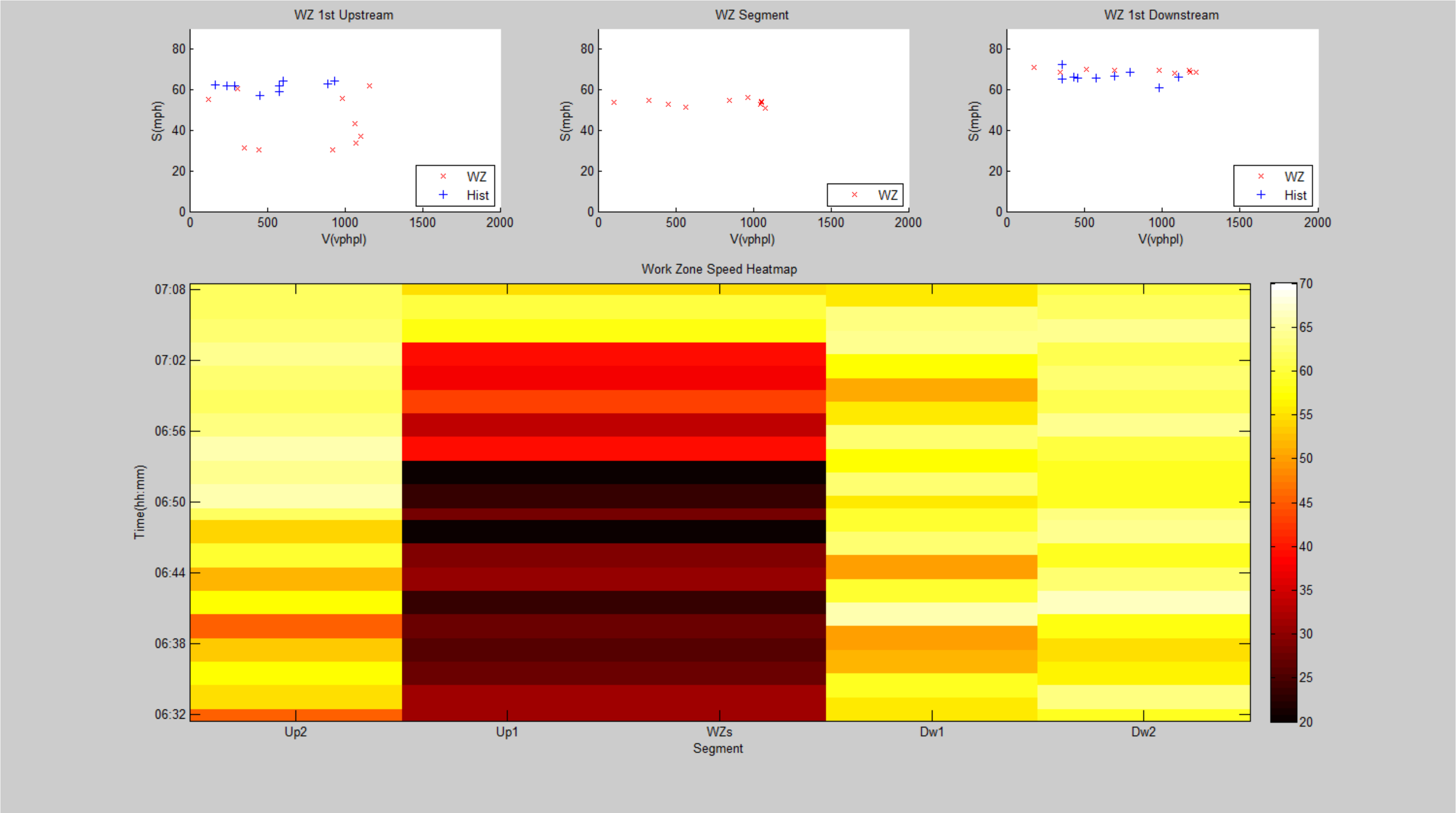

Figure A.13. Speed-flow diagram and speed heat map for I-64 work zone ID 33

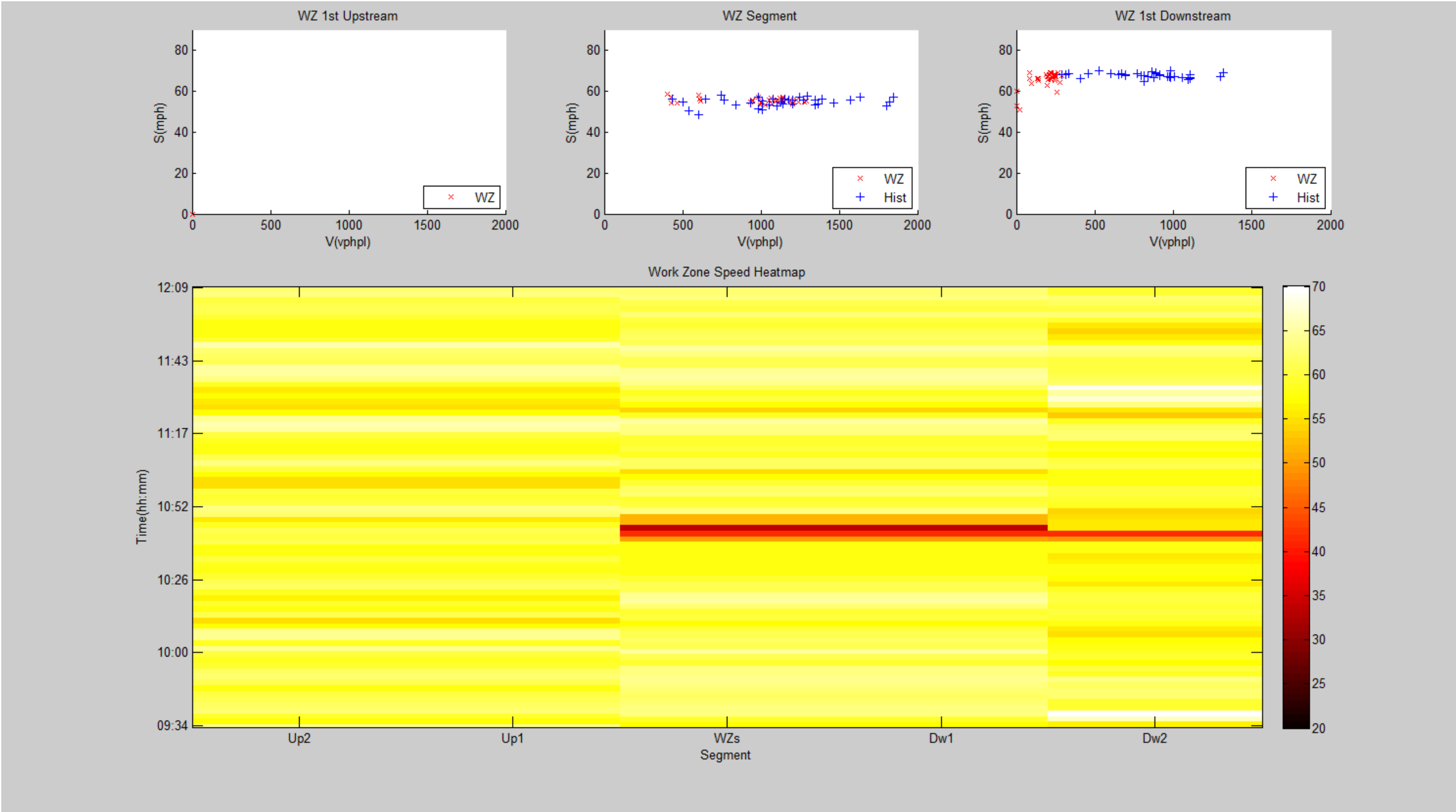

Figure A.14. Speed-flow diagram and speed heat map for I-64 work zone ID 34

APPENDIX B: ADDITIONAL OPERATIONAL PERFORMANCE RESULTS

The operational performance measures for a moving work zone with a duration of 1 hour were presented in the report. In this appendix, the operational performance measures for work zones with durations of 15 minutes, 30 minutes, 45 minutes, and 120 minutes are presented. The tables show travel times, delays, and stops. The figures show the vehicle trajectory plots that were generated and the extracted queue lengths and dissipation times.

Table B.1. VISSIM mobility performance measures for MWZ duration of 15 minutes

	Travel Time (S)			Speed (mph)			Total Delay (Hr)			Avg Delay (S)			Total Stops			Stops per Vehicle		
Vol/Ln	**1st**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**
350	193	197	191	58.8	55.7	58.7	0.2	0.3	0.1	2	3	2	0	0	0	0	0	0
700	199	200	203	56.6	55.6	55.5	1.1	1.0	1.8	6	6	10	0	0	0	0	0	0
1,000	207	214	214	54.2	51.8	53.1	3.1	5.3	4.0	13	20	16	0	0	0	0	0	0
1,400	237	246	228	47.2	45.5	50.2	14.0	15.7	9.5	38	43	25	0	81	5	0	0.06	0
1,800	290	310	309	39.0	36.0	38.4	37.1	43.1	39.5	77	89	74	1	905	237	0	0.52	0.12

Table B.2. VISSIM travel time increase, total delay increase, and downstream volume for MWZ duration of 15 minutes

	Travel Time Increase (%)		Total Delay Increase (Hr)		Downstream Volume (Veh/Hr)		
Vol/Ln	**2nd**	**3rd**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**
350	1.9	-0.9	0.1	-0.1	1,044	1,044	1,092
700	0.8	1.9	-0.1	0.7	2,132	1,968	2,288
1,000	3.1	3.0	2.2	0.9	2,812	3,152	2,944
1,400	3.8	-3.8	1.7	-4.5	4,180	4,008	4,428
1,800	6.7	6.4	6.0	2.4	5,388	4,672	6,040

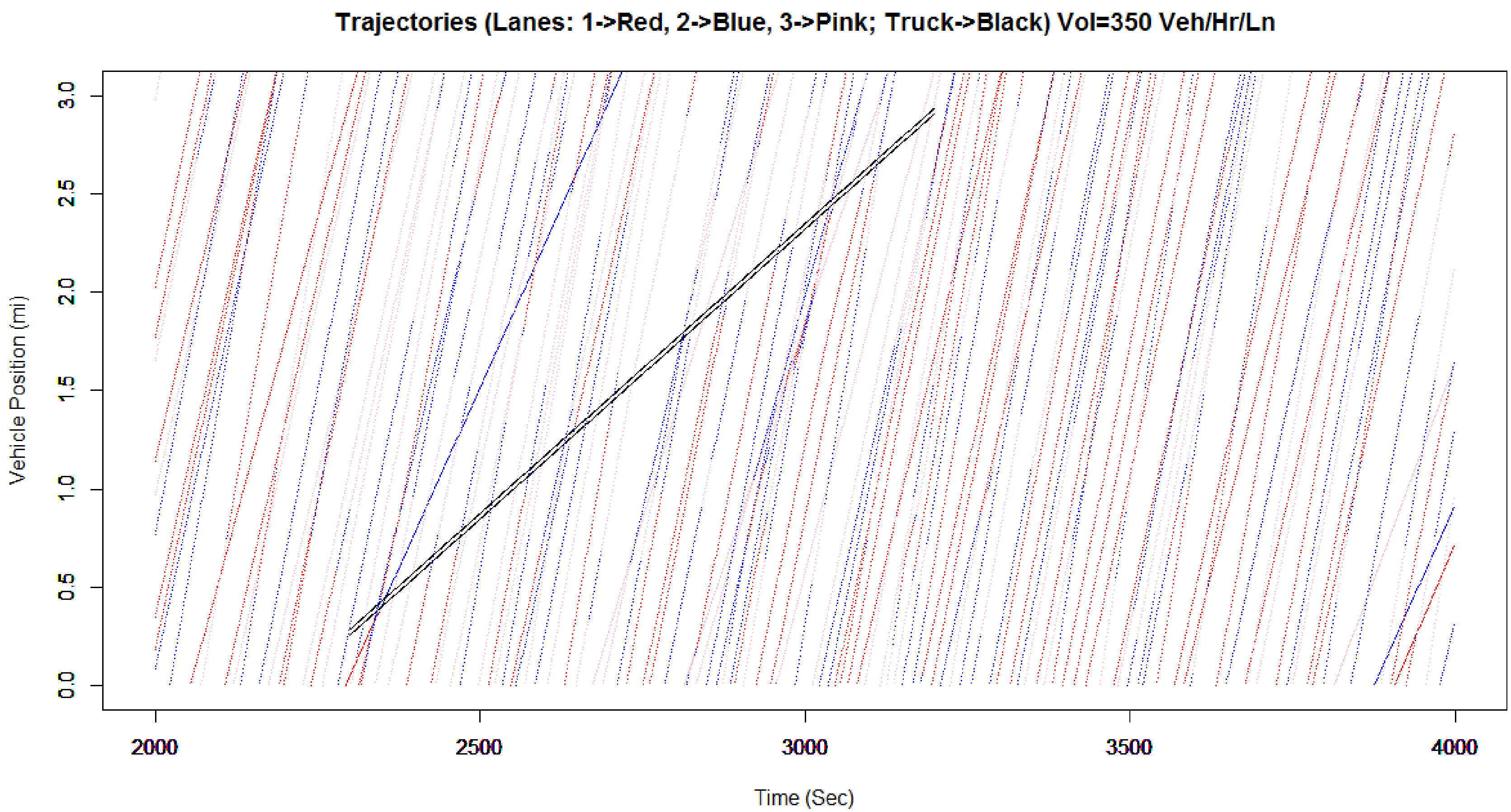

Figure B.1. Plot of VISSIM vehicle trajectories (MWZ duration = 15 minutes, volume = 350 veh/hr/ln)

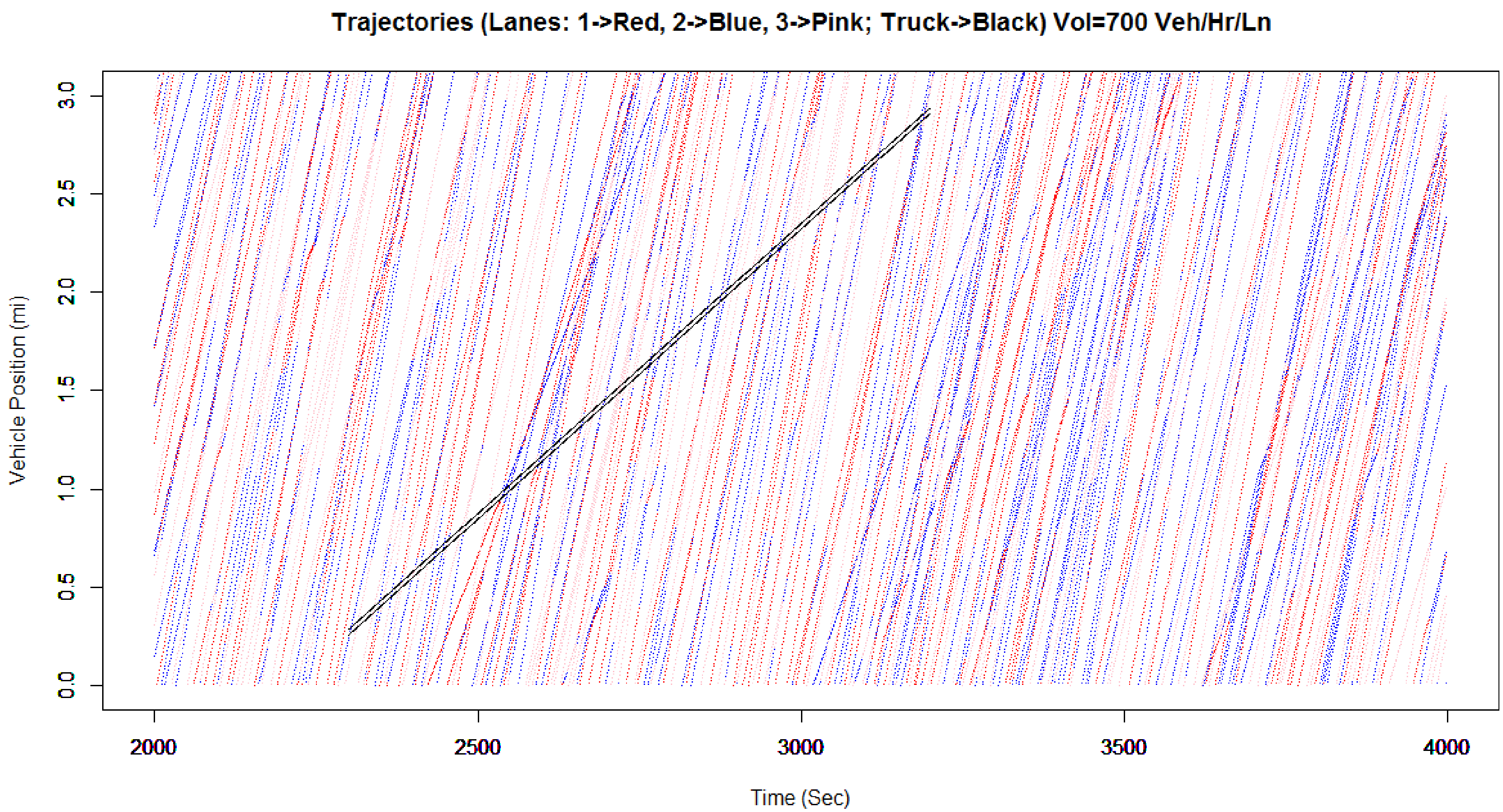

Figure B.2. Plot of VISSIM vehicle trajectories (MWZ duration = 15 minutes, volume = 700 veh/hr/ln)

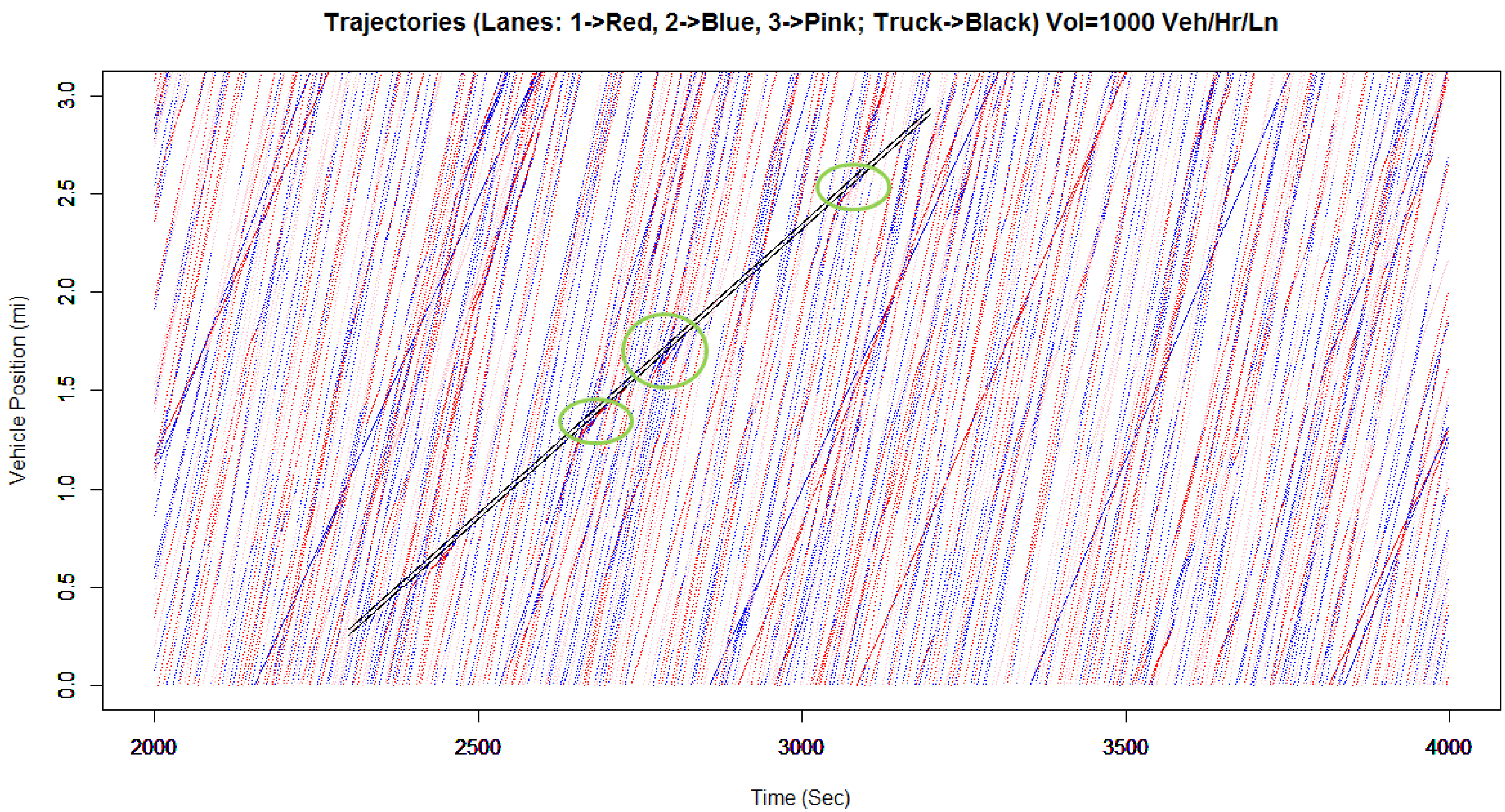

Figure B.3. Plot of VISSIM vehicle trajectories (MWZ duration = 15 minutes, volume = 1,000 veh/hr/ln)

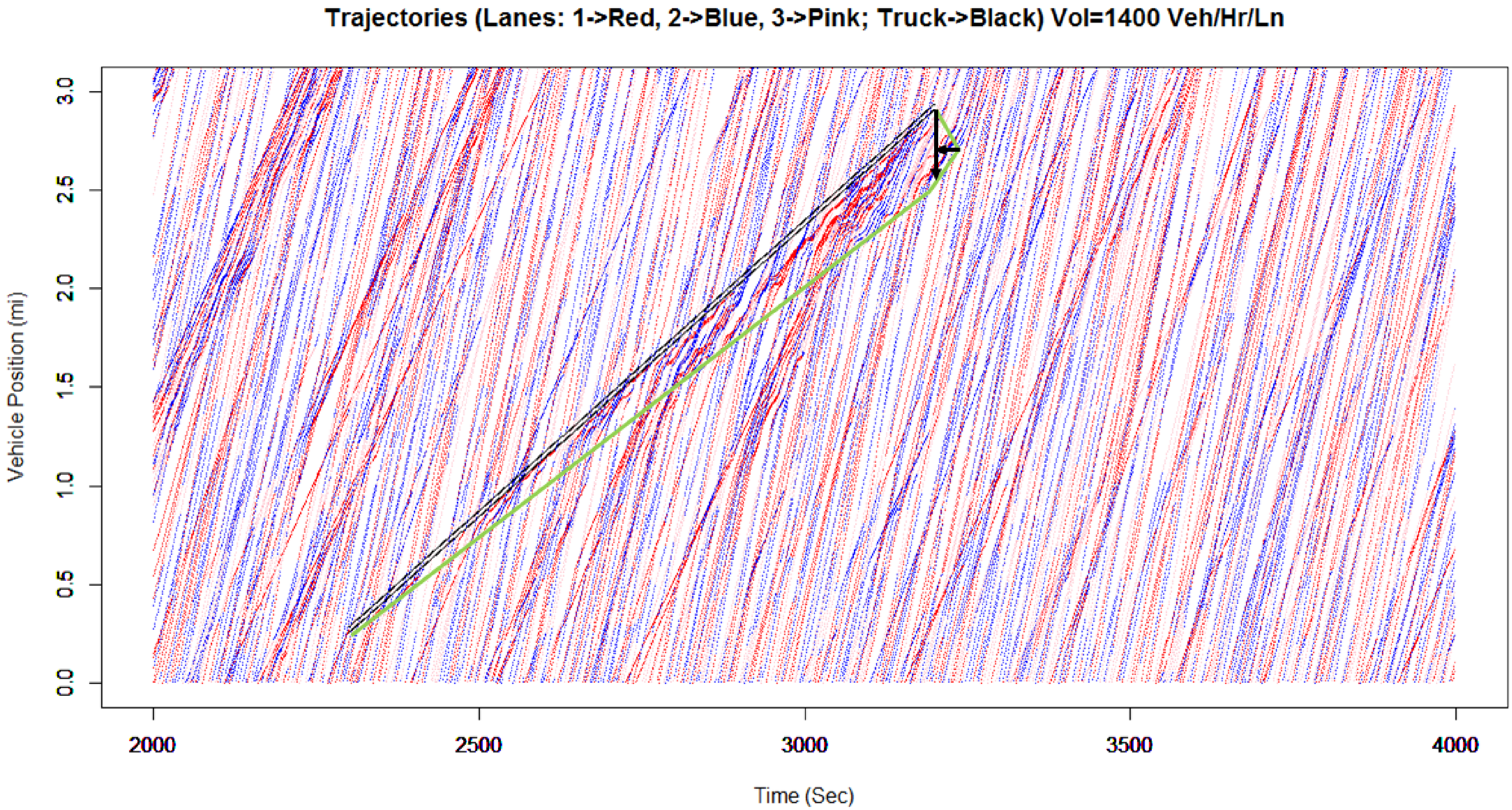

Figure B.4. Plot of VISSIM vehicle trajectories (MWZ duration = 15 minutes, volume = 1,400 veh/hr/ln)

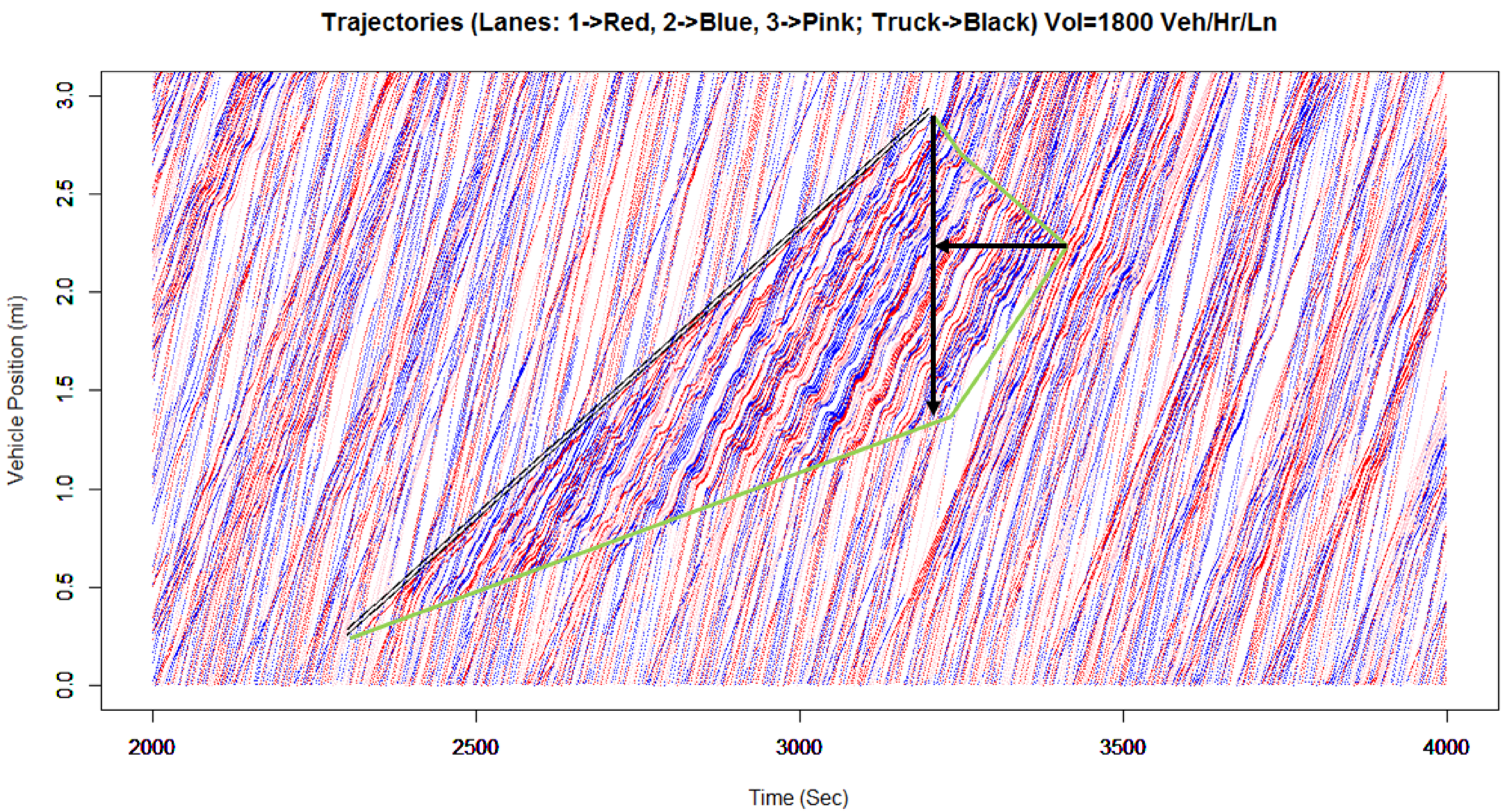

Figure B.5. Plot of VISSIM vehicle trajectories (MWZ duration = 15 minutes, volume = 1,800 veh/hr/ln)

Table B.3. VISSIM mobility performance measures for MWZ duration of 30 minutes

	Travel Time (S)			Speed (mph)			Total Delay (Hr)			Avg Delay (S)			Total Stops			Stops per Vehicle		
Vol/Ln	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
350	359	359	359	58.1	57.2	57.9	0.8	0.7	0.7	4	4	4	0	0	0	0	0	0
700	369	375	374	56.5	55.0	55.8	4.1	6.3	5.3	12	18	15	0	0	0	0	0	0
1,000	389	397	387	53.4	52.6	53.6	14.8	16.3	13.4	29	32	27	0	0	0	0	0	0
1,400	436	467	453	47.8	44.2	46.3	48.3	67.4	56.1	67	92	73	0	623	48	0	0.24	0.02
1,800	524	569	603	40.0	34.1	35.8	125.5	178.2	174.9	133	191	164	8	4,014	3,161	0	1.61	1.08

Table B.4. VISSIM travel time increase, total delay increase, and downstream volume for MWZ duration of 30 minutes

	Travel Time Increase (%)		Total Delay Increase (Hr)		Downstream Volume (Veh/Hr)		
Vol/Ln	2nd	3rd	2nd	3rd	1st	2nd	3rd
350	0.0	0.0	-0.1	-0.1	1,020	1,058	1,018
700	1.6	1.4	2.2	1.2	2,040	2,150	2,106
1,000	2.1	-0.5	1.5	-1.4	3,006	3,016	2,894
1,400	7.1	3.9	19.1	7.8	4,220	4,046	4,494
1,800	8.6	15.1	52.7	49.4	5,370	4,508	6,010

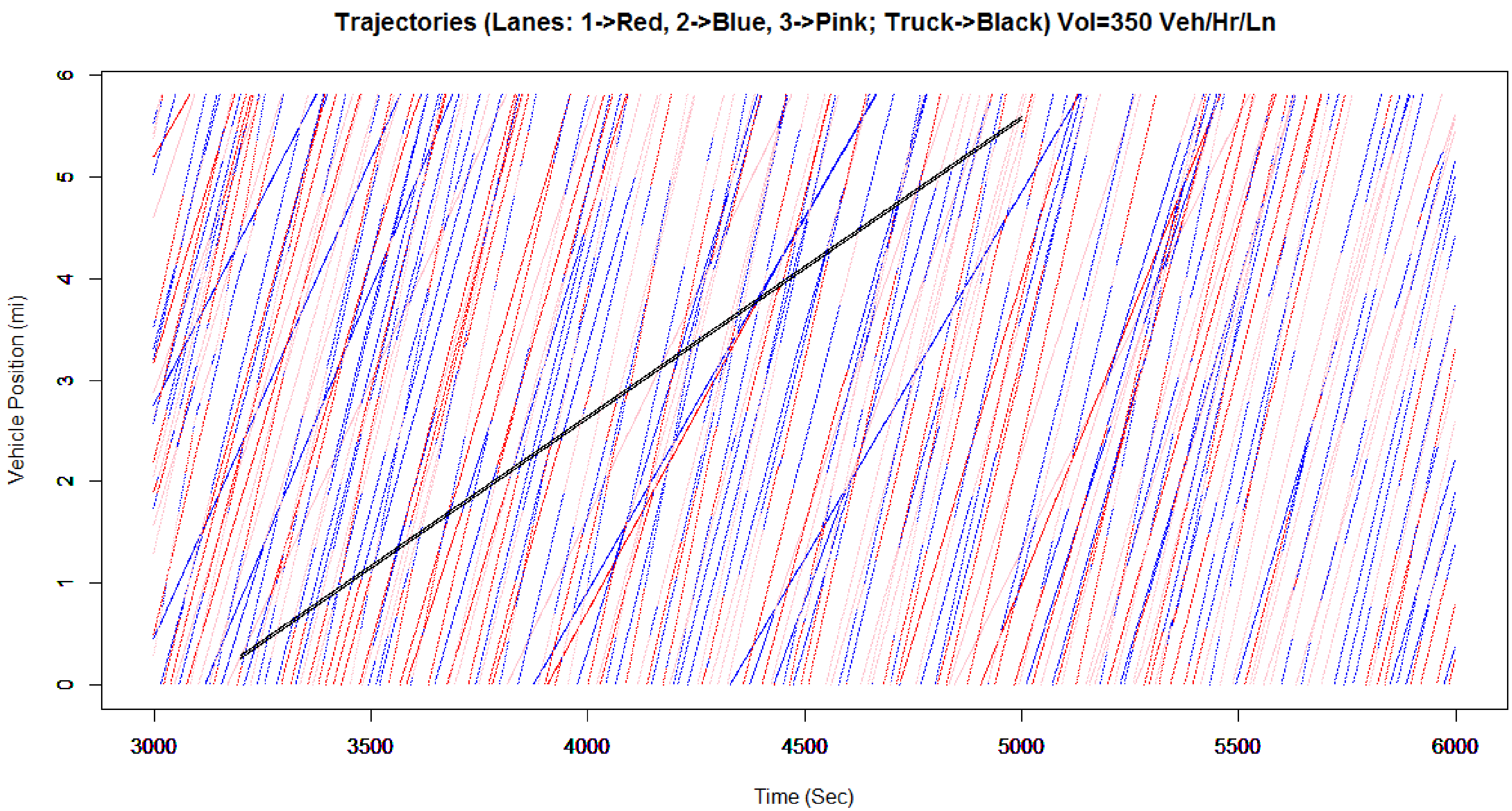

Figure B.6. Plot of VISSIM vehicle trajectories (MWZ duration = 30 minutes, volume = 350 veh/hr/ln)

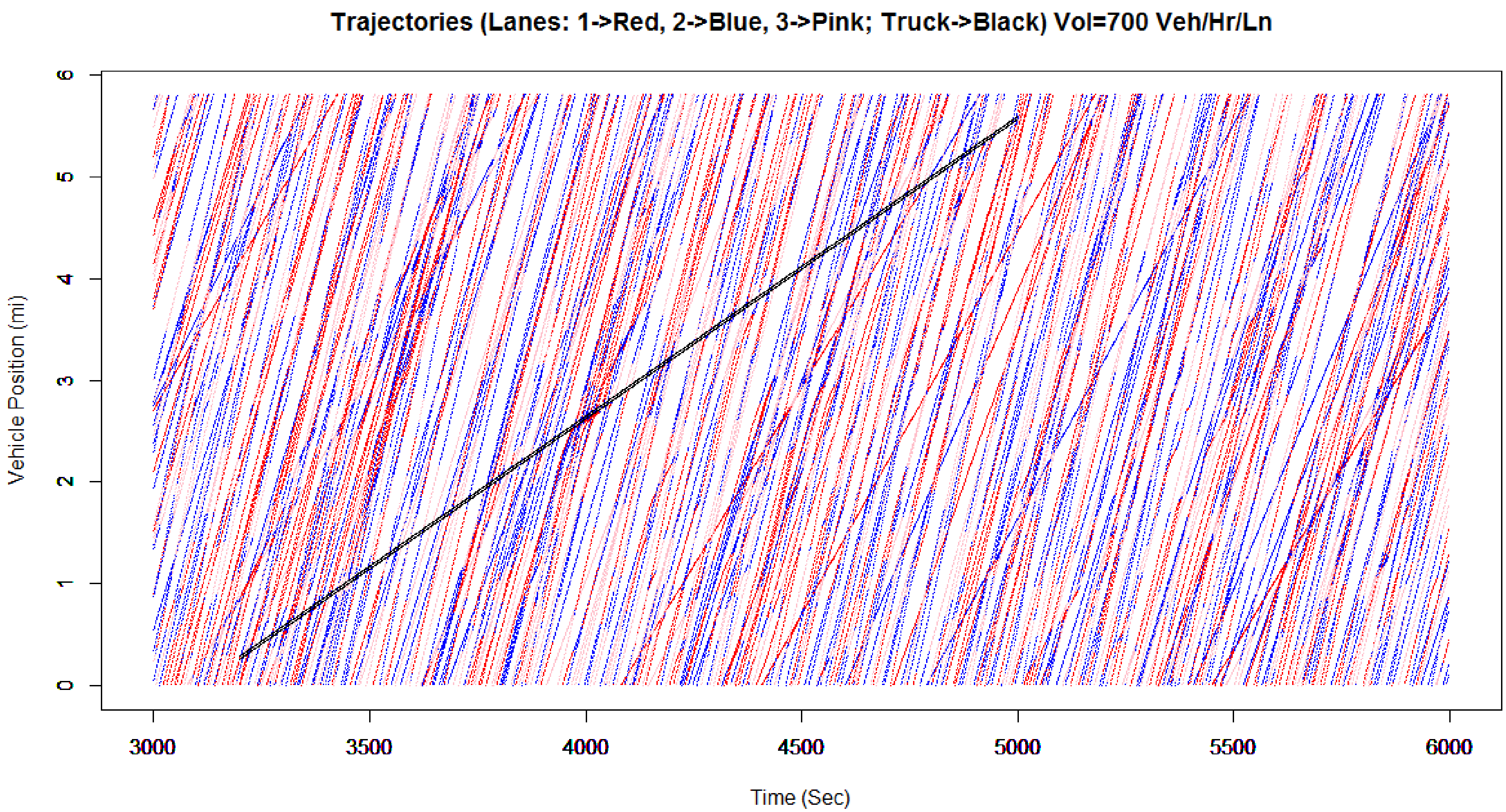

Figure B.7. Plot of VISSIM vehicle trajectories (MWZ duration = 30 minutes, volume = 700 veh/hr/ln)

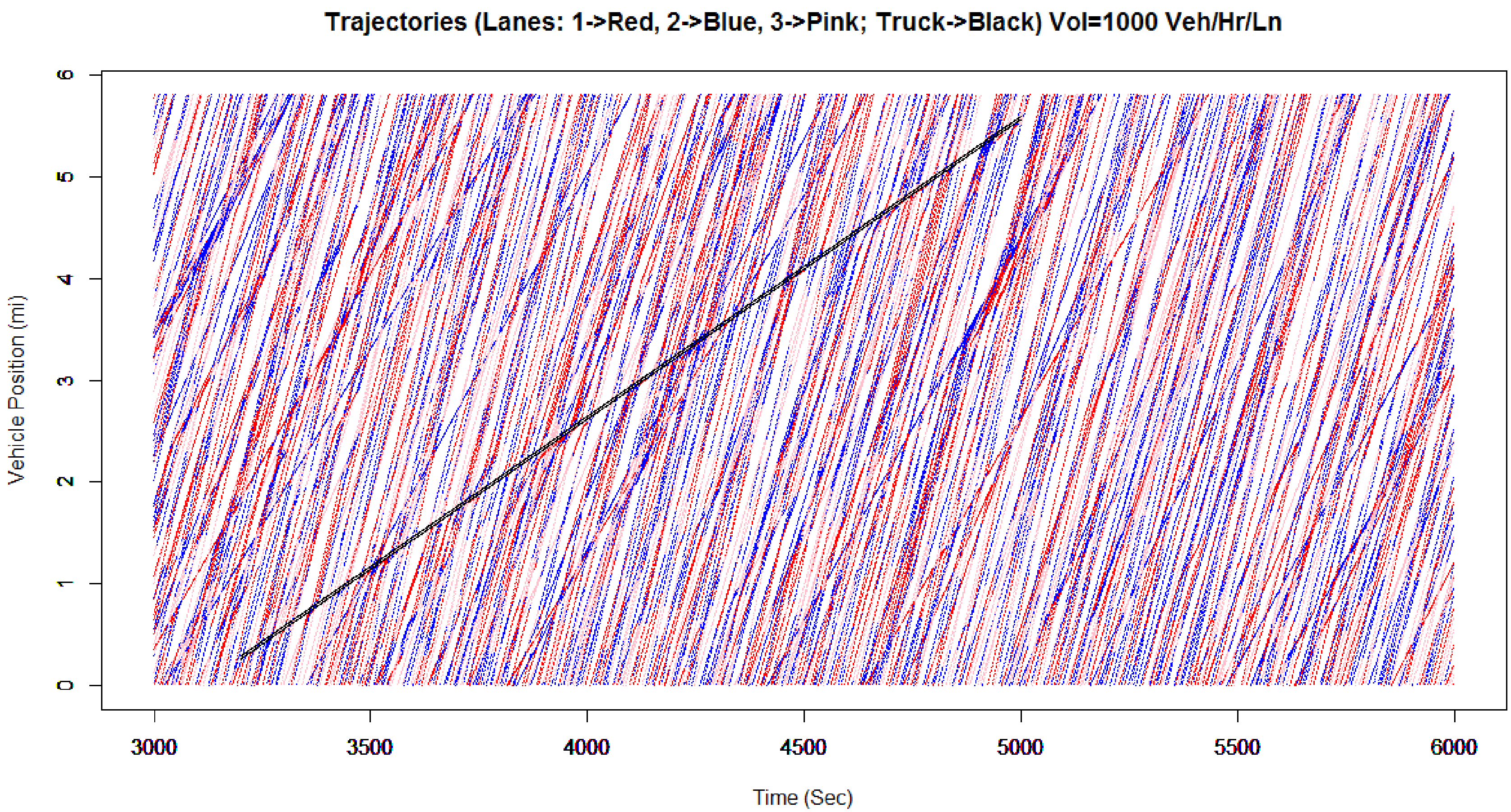

Figure B.8. Plot of VISSIM vehicle trajectories (MWZ duration = 30 minutes, volume = 1,000 veh/hr/ln)

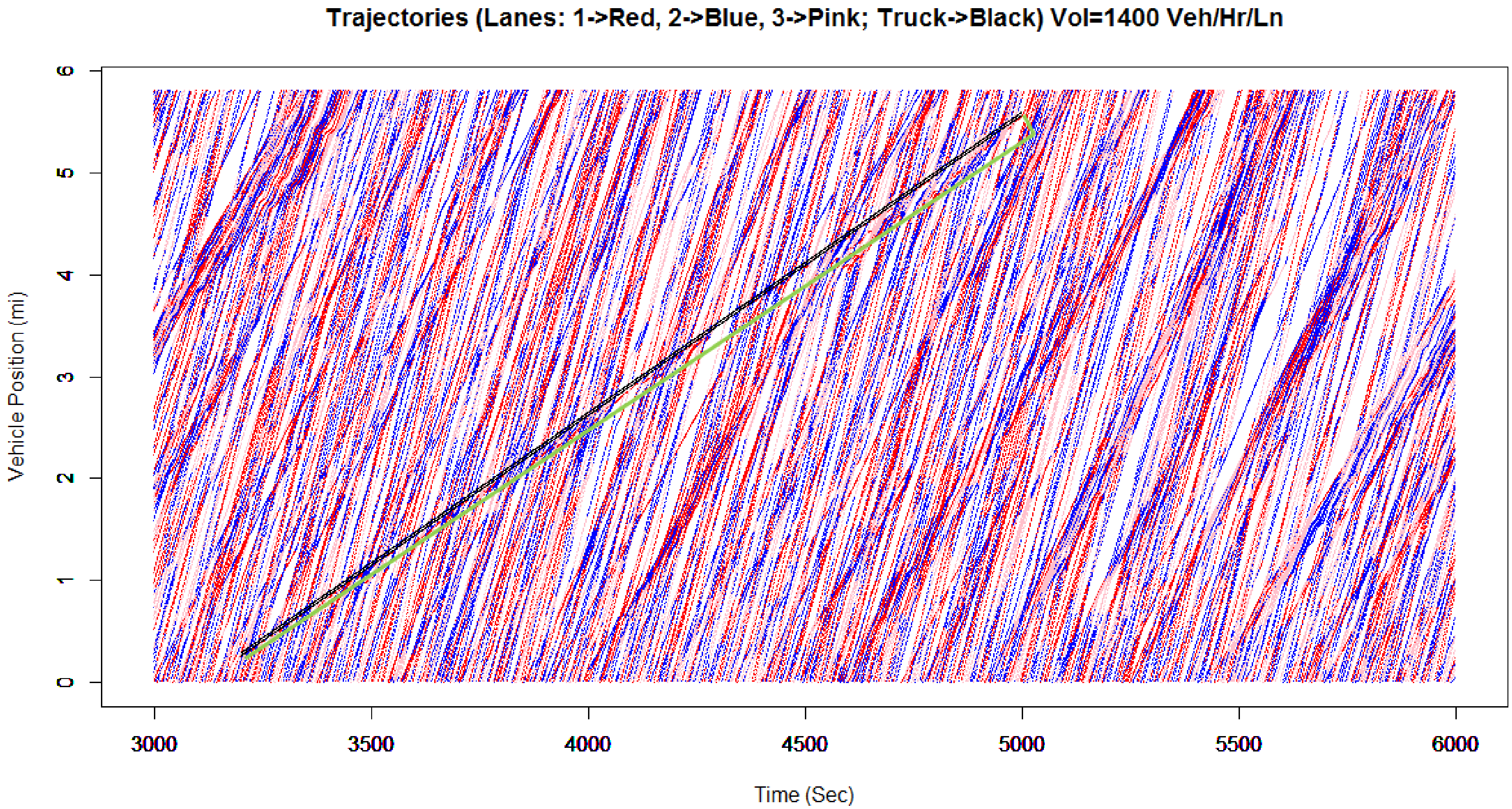

Figure B.9. Plot of VISSIM vehicle trajectories (MWZ duration = 30 minutes, volume = 1,400 veh/hr/ln)

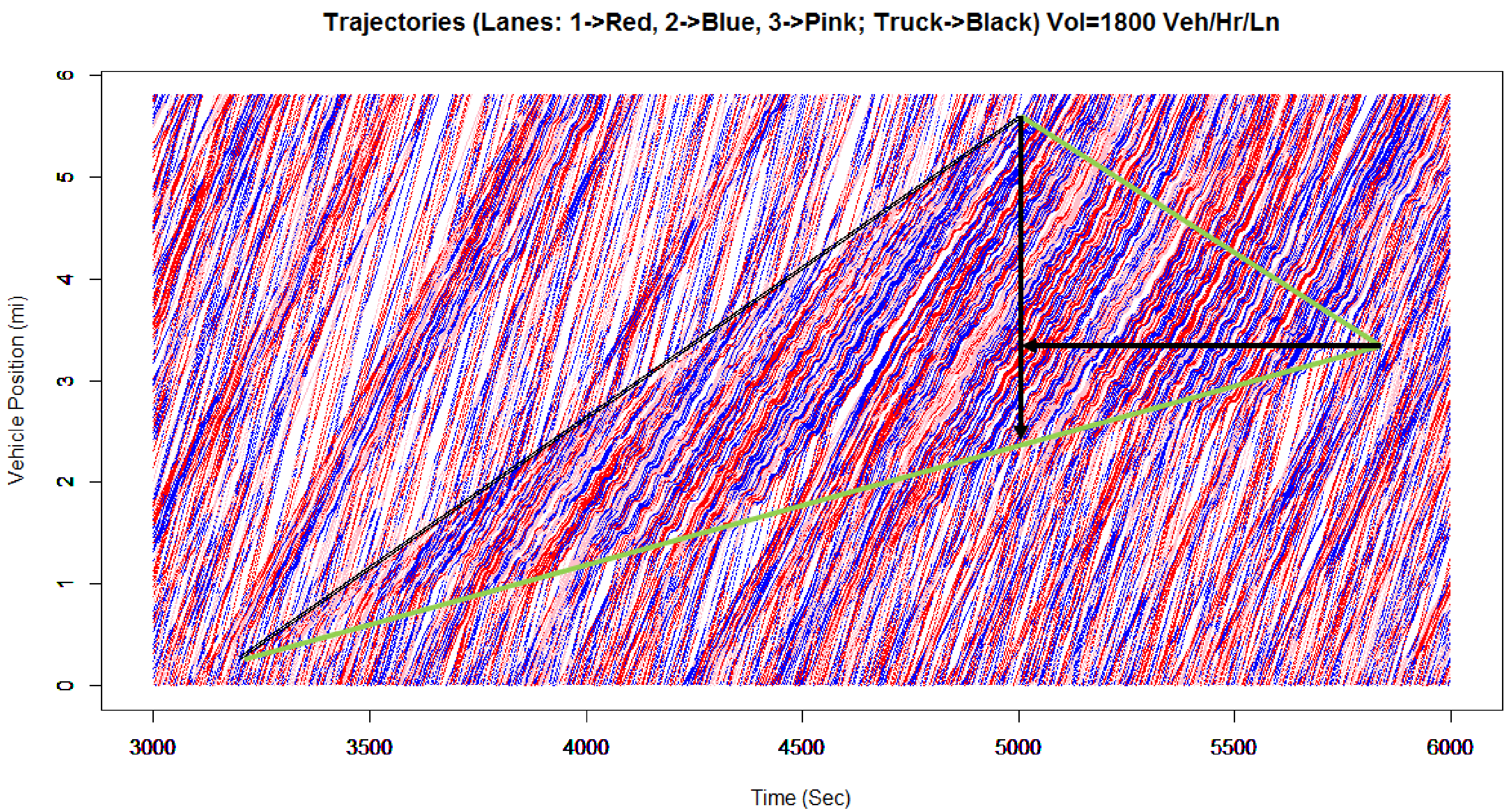

Figure B.10. Plot of VISSIM vehicle trajectories (MWZ duration = 30 minutes, volume = 1,800 veh/hr/ln)

Table B.5. VISSIM mobility performance measures for MWZ duration of 45 minutes

	Travel Time (S)			Speed (mph)			Total Delay (Hr)			Avg Delay (S)			Total Stops			Stops per Vehicle		
Vol/Ln	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
350	525	522	526	58.2	57.3	57.7	1.6	1.4	2.0	6	5	7	0	0	0	0	0	0
700	539	547	541	56.2	55.3	56.1	10.6	12.2	9.7	20	23	19	0	0	0	0	0	0
1,000	571	568	597	53.2	53.2	51.0	33.4	31.1	47.8	44	41	63	0	0	0	0	0	0
1,400	641	673	645	47.4	45.0	47.0	109.6	138.2	117.2	98	124	102	0	459	13	0	0.11	0
1,800	751	884	995	40.5	31.7	32.5	264.8	478.4	501.7	177	318	309	177	16,084	13,850	0.03	2.97	2.37

Table B.6. VISSIM travel time increase, total delay increase, and downstream volume for MWZ duration of 45 minutes

	Travel Time Increase (%)		Total Delay Increase (Hr)		Downstream Volume (Veh/Hr)		
Vol/Ln	2nd	3rd	2nd	3rd	1st	2nd	3rd
350	-0.6	0.2	-0.2	0.4	1,088	980	1,109
700	1.5	0.4	1.6	-0.9	2,080	2,109	2,033
1,000	-0.5	4.6	-2.3	14.4	2,969	2,956	2,993
1,400	5.0	0.6	28.6	7.6	4,327	4,148	4,499
1,800	17.7	32.5	213.6	236.9	5,576	4,735	6,252

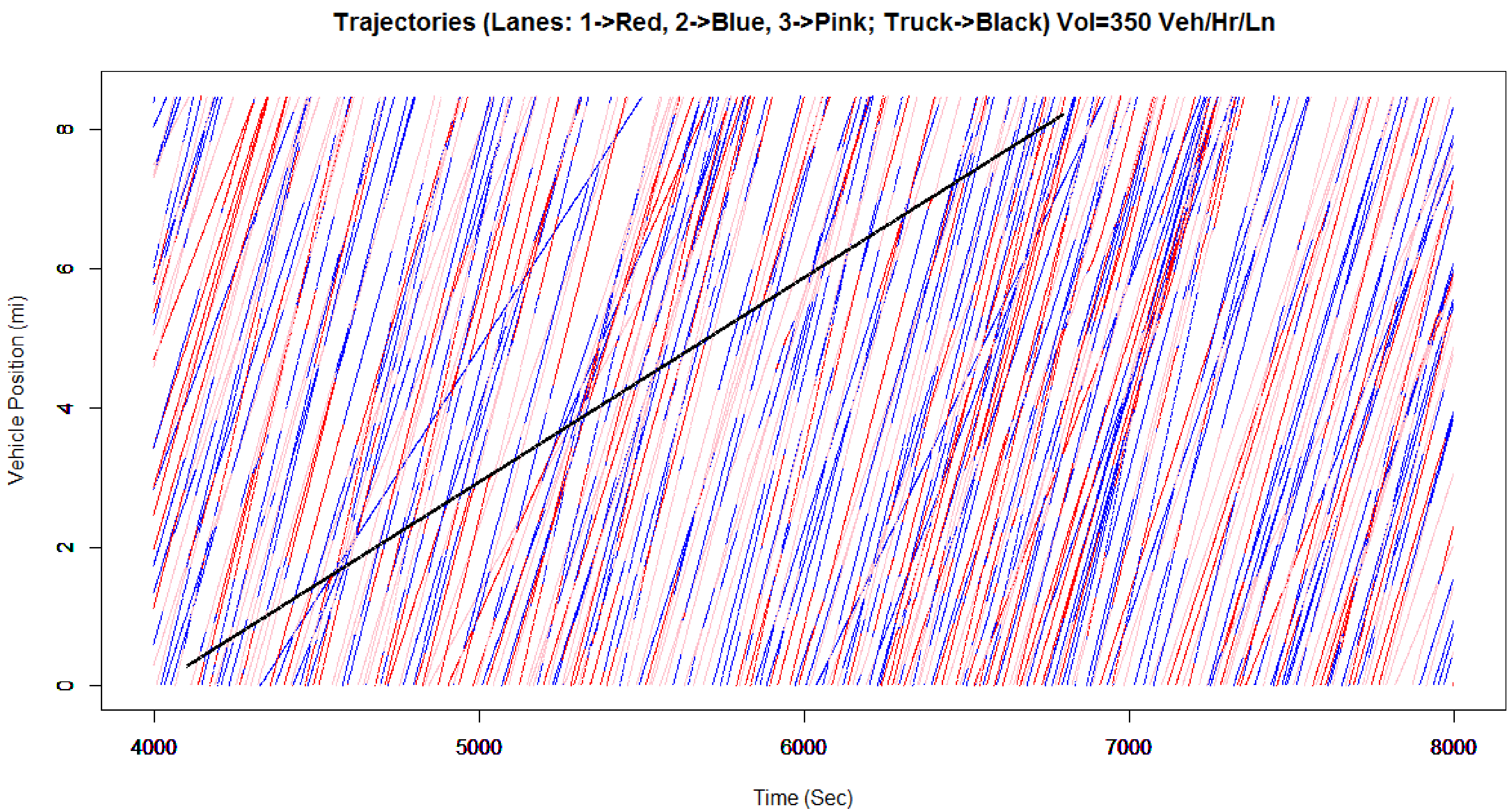

Figure B.11. Plot of VISSIM vehicle trajectories (MWZ duration = 45 minutes, volume = 350 veh/hr/ln)

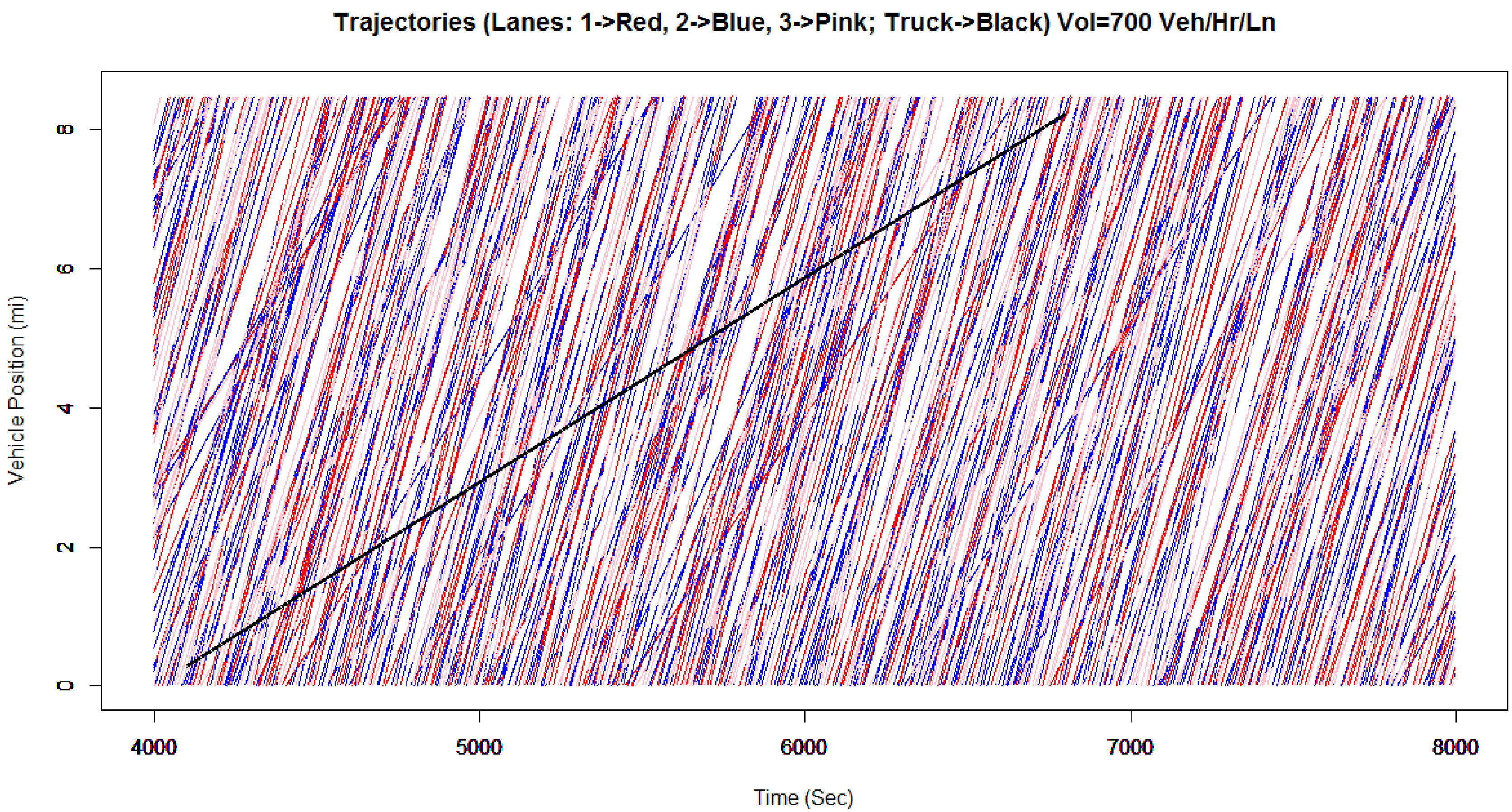

Figure B.12. Plot of VISSIM vehicle trajectories (MWZ duration = 45 minutes, volume = 700 veh/hr/ln)

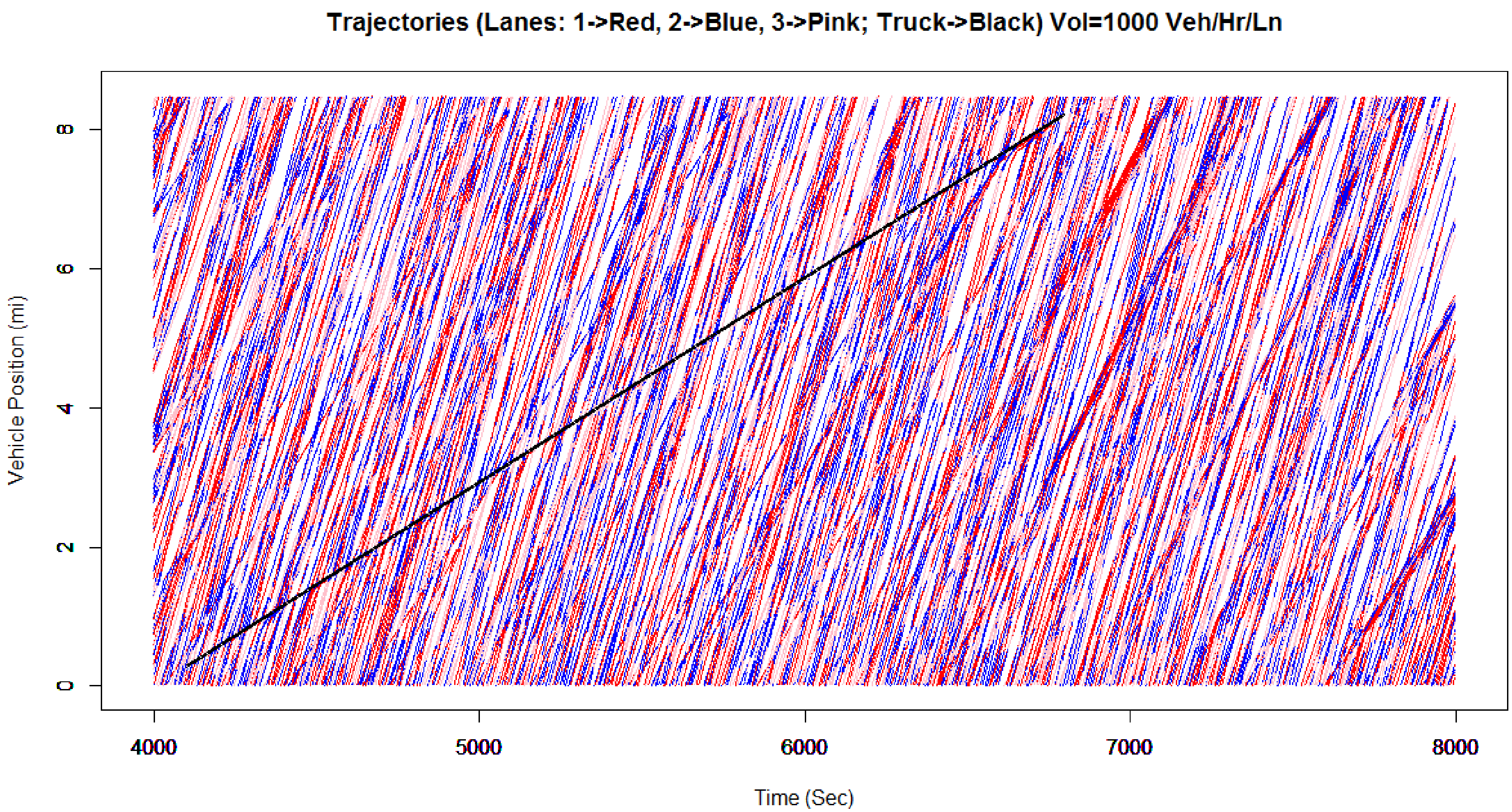

Figure B.13. Plot of VISSIM vehicle trajectories (MWZ duration = 45 minutes, volume = 1,000 veh/hr/ln)

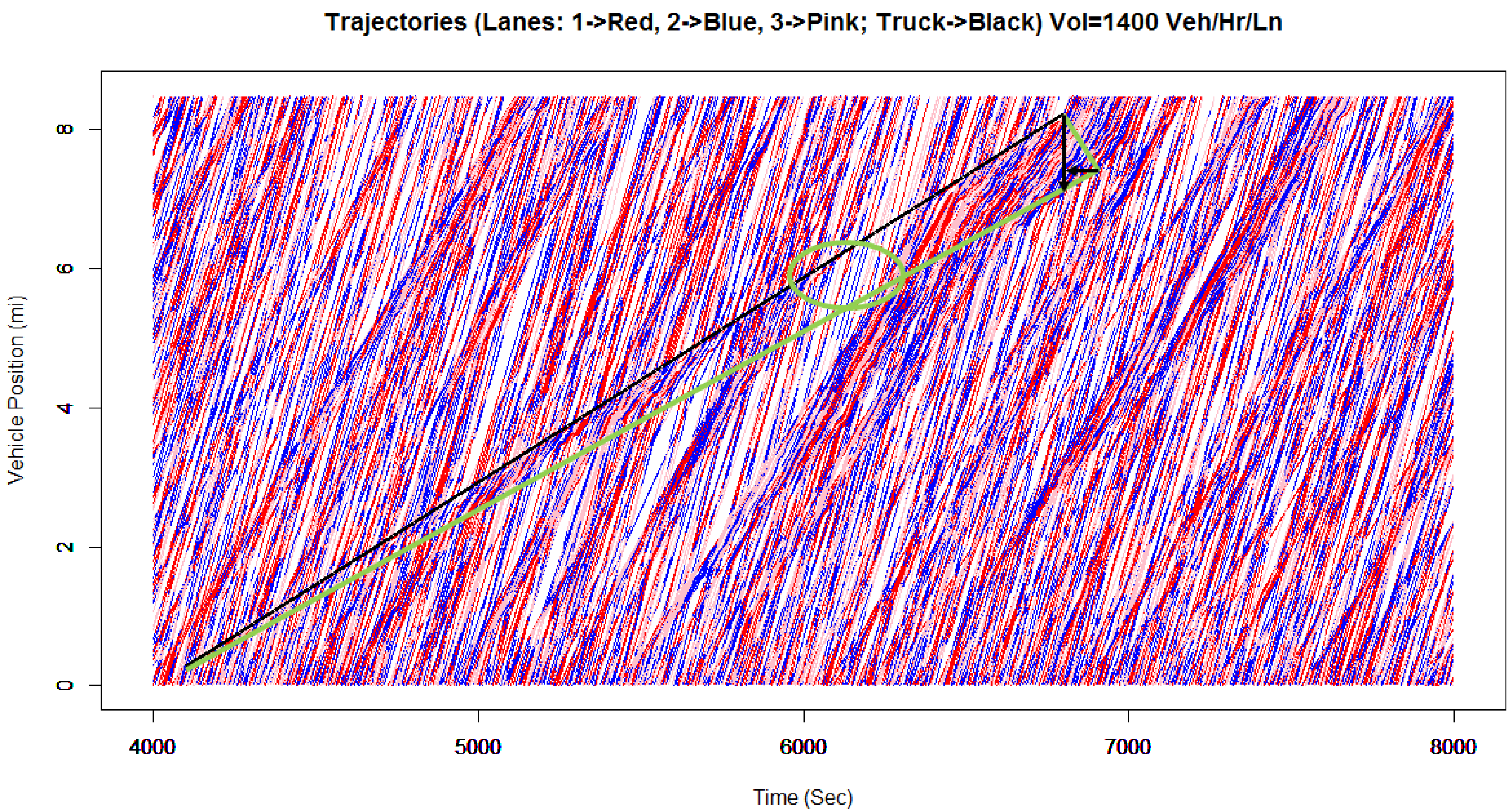

Figure B.14. Plot of VISSIM vehicle trajectories (MWZ duration = 45 minutes, volume = 1,400 veh/hr/ln)

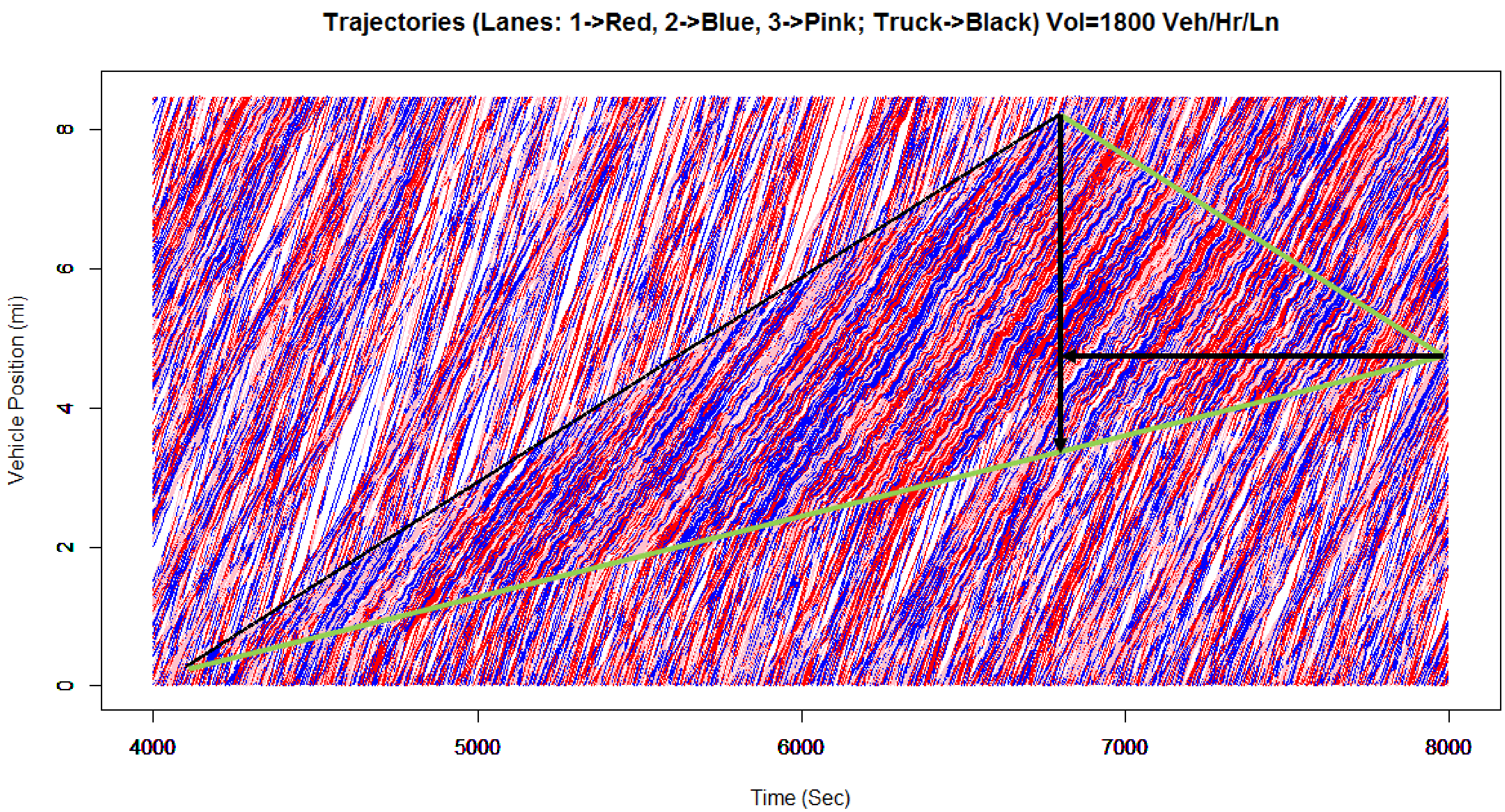

Figure B.15. Plot of VISSIM vehicle trajectories (MWZ duration = 45 minutes, volume = 1,800 veh/hr/ln)

Table B.7. VISSIM mobility performance measures for MWZ duration of 2 hours

	Travel Time (S)				Total Delay (Hr)				Avg Delay (S)				Total Stops				Stops per Vehicle			
Vol/Ln	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**
350	1,342	1,346	1,346	1,351	6	6	5	6	14	15	13	15	0	0	0	0	0	0	0	0
700	1,393	1,398	1,413	1,405	39	40	44	44	48	49	53	52	0	0	0	0	0	0	0	0
1,000	1,466	1,490	1,489	1,481	116	130	138	127	97	108	113	110	0	3	8	0	0	0	0	0
1,400	1,699	1,730	1,849	1,669	432	510	567	408	250	290	324	232	44	3108	6127	314	0.01	0.49	0.97	0.05
1,800	1,991	2,065	2,578	2,622	1,026	1,245	1,882	1,819	438	528	786	659	1,477	28,587	96,863	69,899	0.18	3.36	11.24	7.03

Table B.8. VISSIM travel time increase, total delay increase, and downstream volume for MWZ duration of 2 hours

	Travel Time Increase (%)			Total Delay Increase (Hr)			Speed (mph)				Downstream Volume (Veh/Hr)			
Vol/Ln	**2nd**	**3rd**	**4th**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**	**1st**	**2nd**	**3rd**	**4th**
350	0.3	0.3	0.7	0	-1	0	58.1	57.8	57.6	57.6	1,034	1,088	1,042	1,064
700	0.4	1.4	0.9	1	5	5	56.0	55.6	55.2	55.7	2,125	2,136	2,104	2,183
1,000	1.6	1.6	1.0	14	22	11	53.2	52.3	52.4	52.4	3,021	3,031	3,176	2,965
1,400	1.8	8.8	-1.8	78	135	-24	45.9	44.3	43.0	46.3	4,244	4,204	4,119	4,303
1,800	3.7	29.5	31.7	219	856	793	38.7	35.5	29.9	31.7	5,340	5,265	4,149	6,493

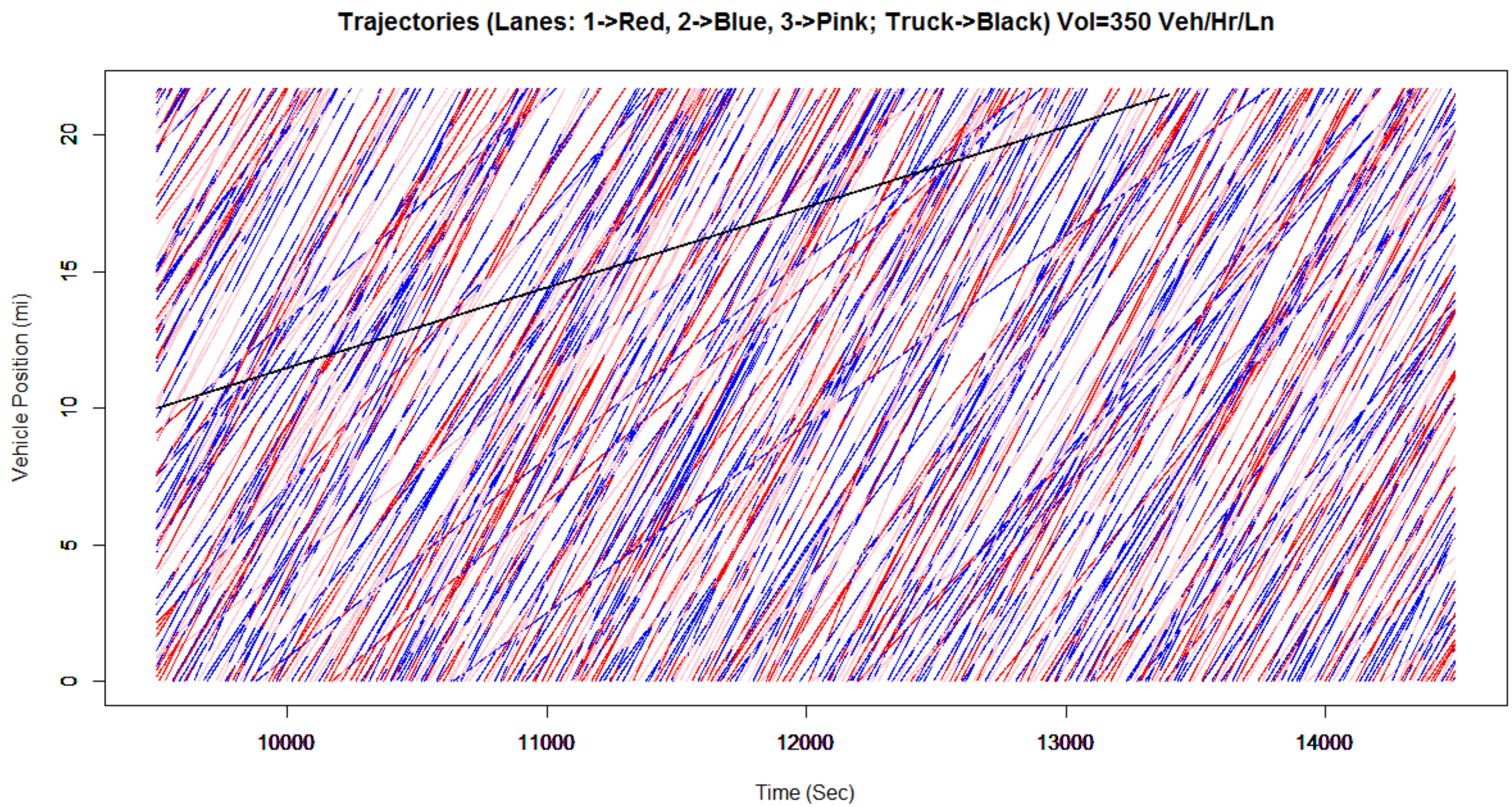

Figure B.16. Plot of VISSIM vehicle trajectories (MWZ duration = 2 hours, volume = 350 veh/hr/ln)

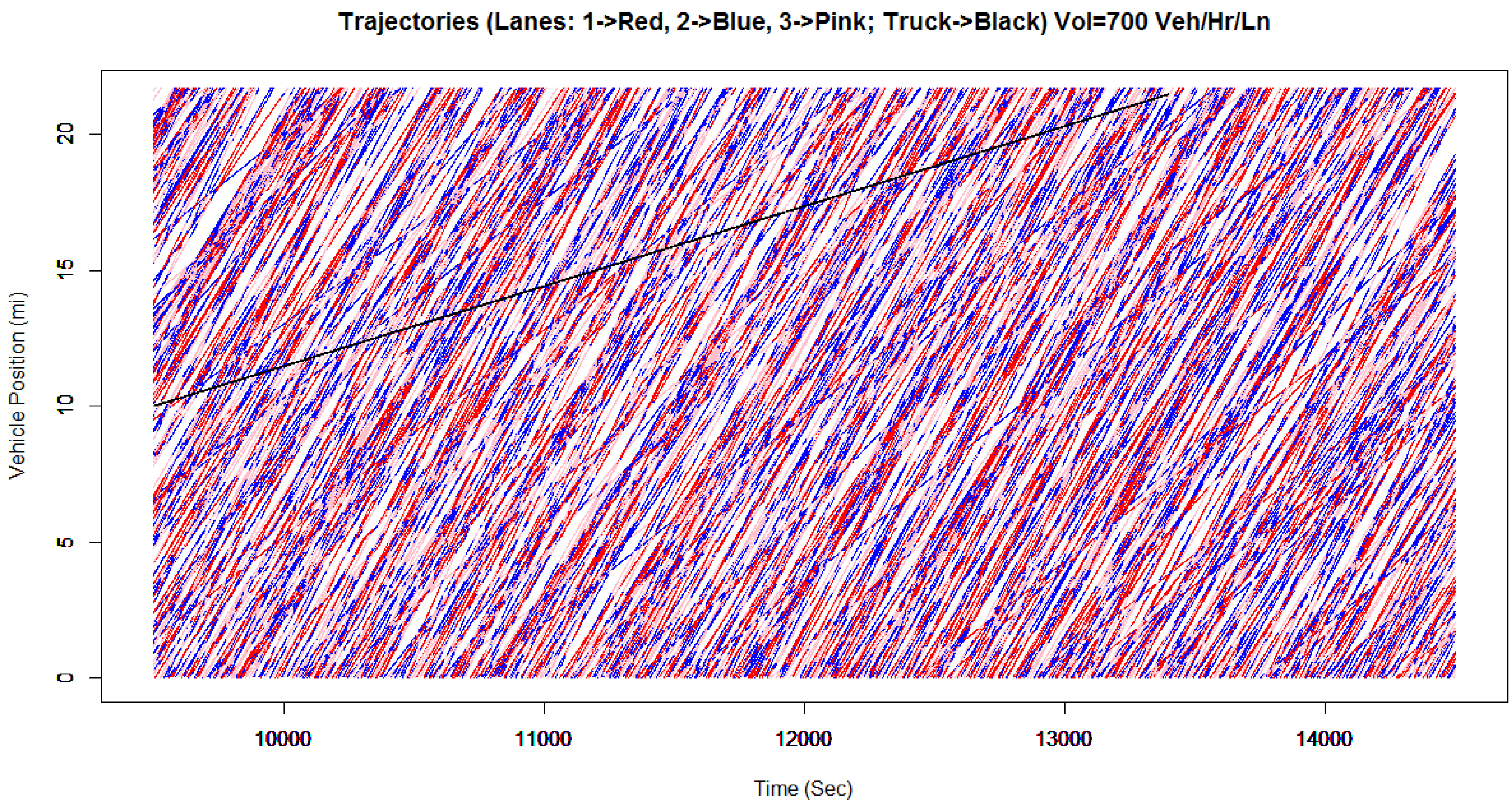

Figure B.17. Plot of VISSIM vehicle trajectories (MWZ duration = 2 hours, volume = 700 veh/hr/ln)

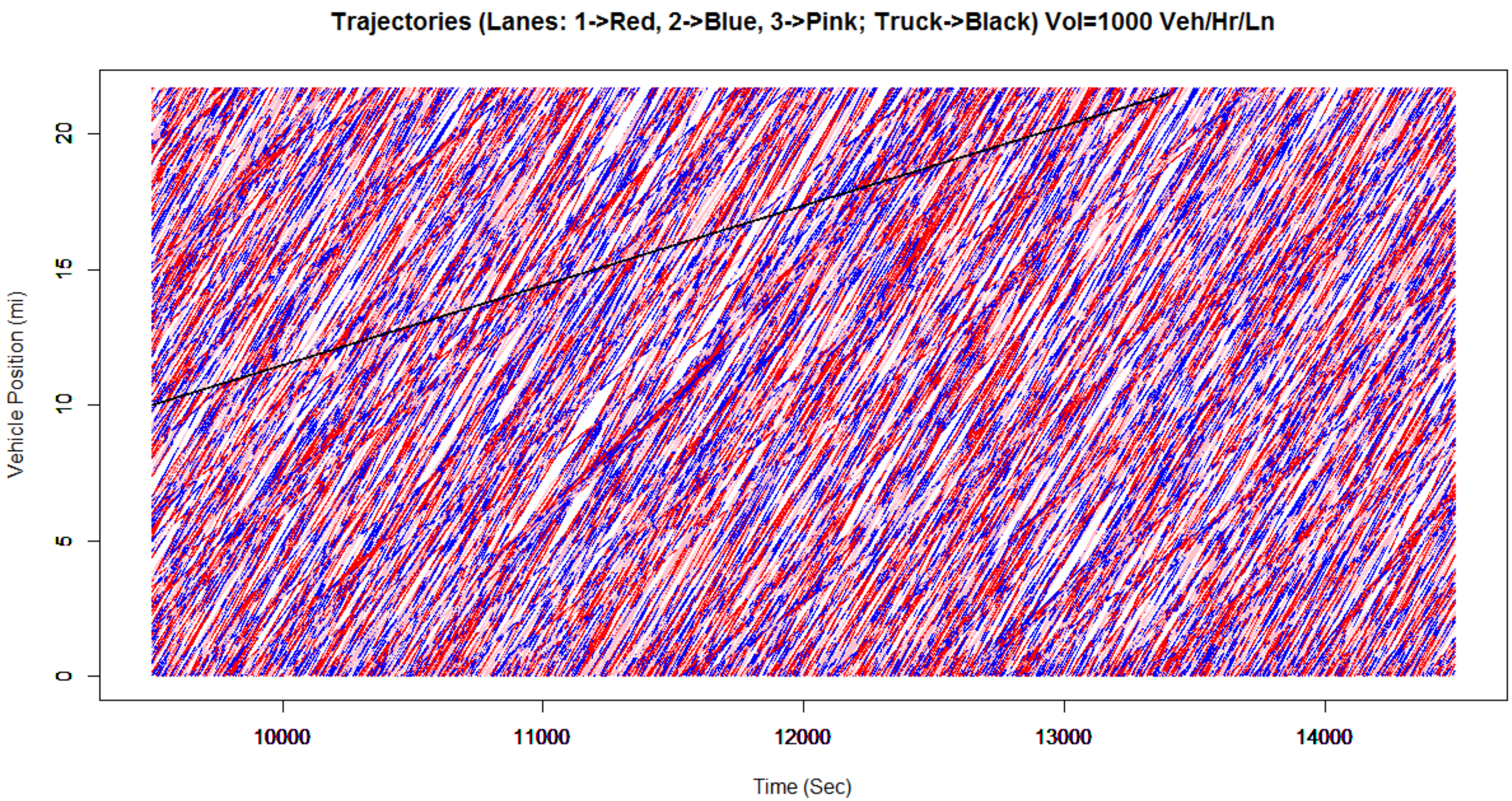

Figure B.18. Plot of VISSIM vehicle trajectories (MWZ duration = 2 hours, volume = 1,000 veh/hr/ln)

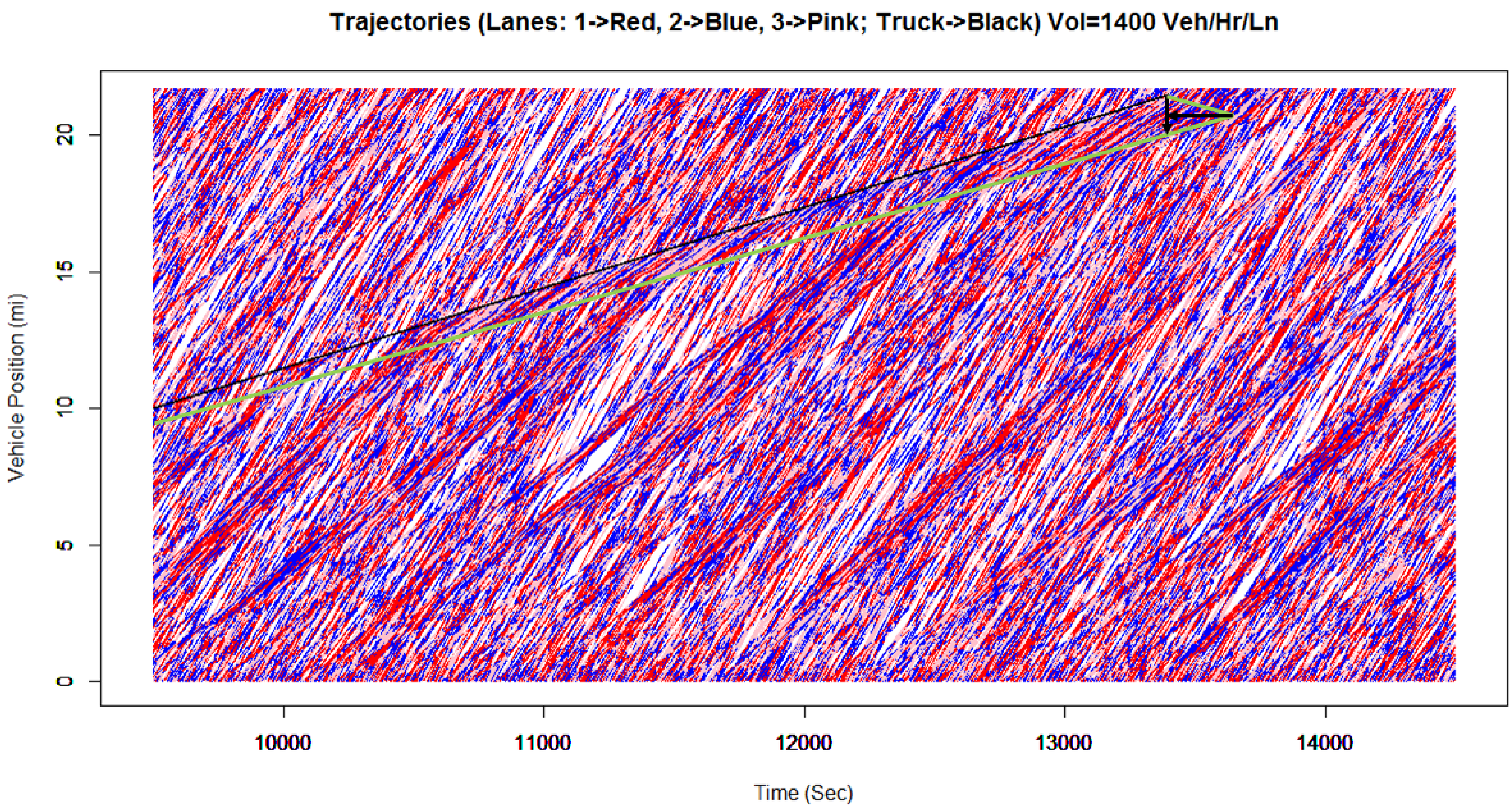

Figure B.19. Plot of VISSIM vehicle trajectories (MWZ duration = 2 hours, volume = 1,400 veh/hr/ln

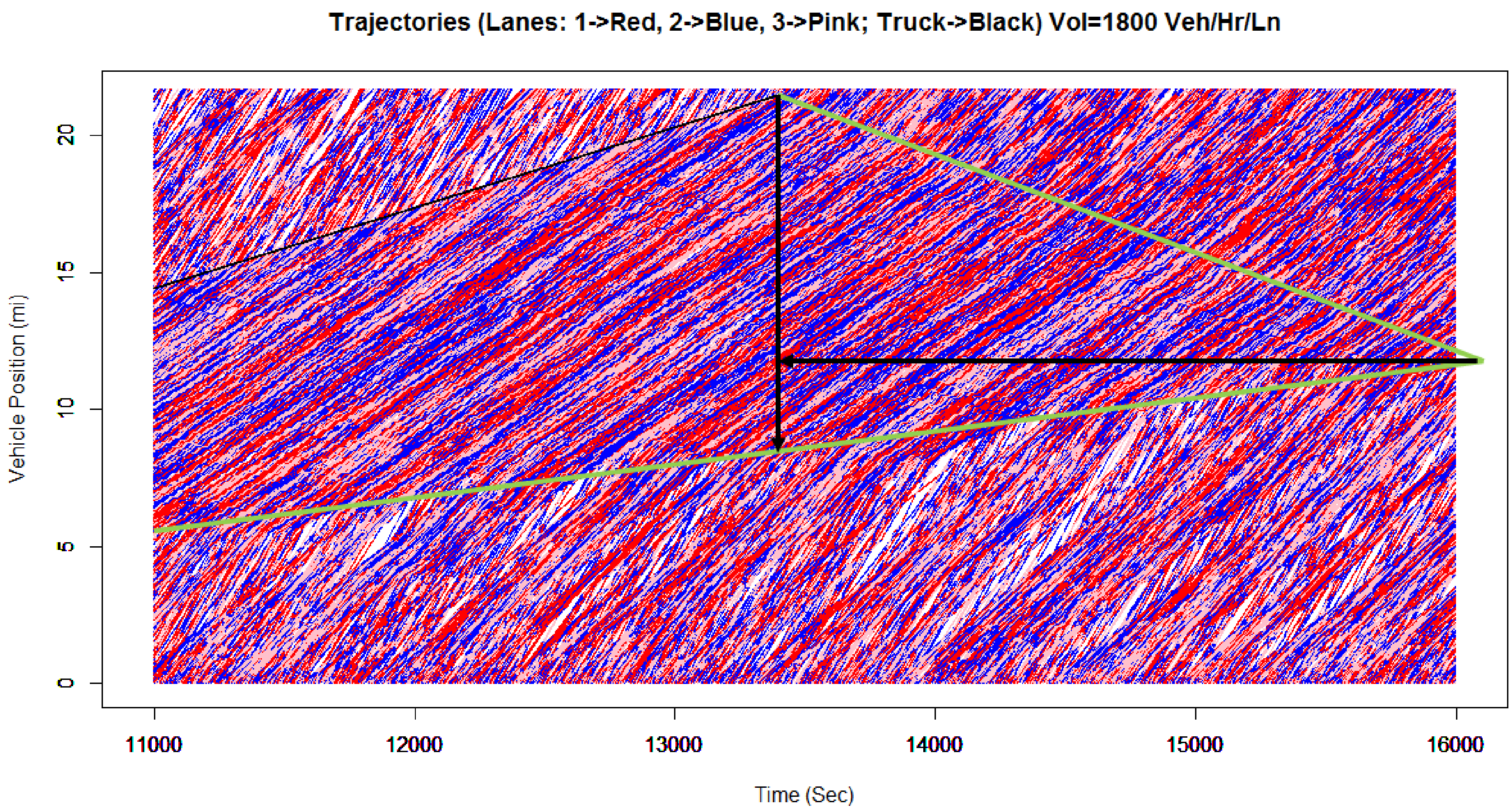

Figure B.20. Plot of VISSIM vehicle trajectories (MWZ duration = 2 hours, volume = 1,800 veh/hr/ln

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