

# A Tool for Designing MnPASS Access Spacing

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## FINAL REPORT

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# TABLE OF CONTENTS

<b>CHAPTER 1: Introduction</b> .....	<b>1</b>
<b>CHAPTER 2: Functional Specifications</b> .....	<b>3</b>
2.1 Stakeholder Input .....	3
2.1.1 Inputs and Data Sources.....	3
2.1.2 Running Interface.....	3
2.1.3 Outputs.....	3
2.2 System Architecture .....	4
2.3 Inputs.....	4
2.4 Data Sources.....	4
<b>CHAPTER 3: Open-Access Module</b> .....	<b>6</b>
3.1 Part A – Characteristic Shockwave Distributions.....	6
3.1.1 Part A1 – User Input .....	7
3.1.2 Part A2 – Producing Characteristic Distributions .....	8
3.2 Part B – Assessing Historical or Simulated Data .....	8
3.2.1 Part B1 – User Input .....	10
3.2.2 Part B2 – Assessing Historical Data .....	10
3.3 Part C – Producing Cumulative Shockwave Distributions .....	12
3.4 Corridor-Level Assessment .....	13
<b>CHAPTER 4: Closed-Access Module</b> .....	<b>19</b>
4.1 Optimal Lane Changing Region (OLCR) Model .....	19
4.1.1 Traffic Flow Reconstruction .....	20
4.1.2 Modeling Lane Changes .....	23
4.1.3 Simulation Process .....	24
4.2 Implementing the Proposed Methodology on I-394.....	25
<b>CHAPTER 5: User Manual</b> .....	<b>29</b>
5.1 Web Interface Implementation .....	30
5.2 Site Layout .....	30
5.3 Using the Web Interface.....	33
5.3.1 Working with Projects .....	33
5.3.2 Defining a New Network Configuration .....	39
5.3.3 Creating a New Characteristic Shockwave Distribution Set.....	40
5.3.4 Creating a New Parameter Profile.....	43
<b>CHAPTER 6: Conclusions</b> .....	<b>45</b>
<b>REFERENCES</b> .....	<b>47</b>

## LIST OF FIGURES

Figure 3.1 Part A of ZAR algorithm - developing characteristic shockwave distributions.....	9
Figure 3.2 Part B of ZAR algorithm – assessing historical or simulated data.....	11
Figure 3.3 Part C of ZAR algorithm - producing cumulative shockwave distributions.....	13
Figure 3.4. Important speed-density regions.....	14
Figure 3.5. Surface rendering of a sample comprehensive shockwave distribution.....	15
Figure 3.6. Comprehensive shockwave distribution using full day historical data.....	16
Figure 3.7. Proportion of speed-density regions for full-day data. Traffic flows.....	17
Figure 3.8. Proportion of speed-density regions for peak-periods-only data. Traffic flows.....	17
Figure 4.1 Comparison of trajectory lengths for cases above and below capacity. ....	20
Figure 4.2 Fitted Fundamental Diagrams for Lanes 1-4 at the I-35W Test Site.....	21
Figure 4.3 Surface of Distributions used for generating vehicle headways.....	22
Figure 4.4 Distribution modeling the time drivers spend between lanes. ....	23
Figure 4.5 Comparison of cumulative distribution functions between observed and simulated trajectory lengths with unimodal TAP. ....	24
Figure 4.6 Schematic outlining the methodology for defining HOT access points at a location. ....	25
Figure 4.7 Visualizing the output of the Optimal Lane Changing Region model. ....	25
Figure 4.8 Test Site on I-394 in relation to the upstream entrance ramp. ....	26
Figure 4.9 Test Site on I-394 in relation to the downstream exit ramp.....	26
Figure 4.10 Proposed design.....	27
Figure 4.11 Simulated trajectory lengths.....	27
Figure 4.12 Detector signal comparison - flow (vehicles/hour).....	28
Figure 5.1 User dashboard page, providing a broad overview of the user’s work.....	30
Figure 5.2 Project overview page, showing information about all of the user’s projects. ....	31
Figure 5.3 Network configuration overview page (left) and detail page (right).....	31
Figure 5.4 Density prediction overview page (left) and detail page (right).....	31
Figure 5.5 Characteristic shockwave distribution overview page (left) and detail page (right).....	32
Figure 5.6 Shockwave model parameter profile overview page (left) and detail page (right).....	32
Figure 5.7 Fundamental relationship profile overview page (left) and detail page (right). ....	32
Figure 5.8 Lane change model profile overview page (left) and detail page (right).....	32
Figure 5.9 Trash overview page (left) and example of trashed object detail page (right). ....	33
Figure 5.10 Link to create a new project. ....	34
Figure 5.11 Selecting a network configuration for a project. ....	34
Figure 5.12 Checkbox to enable/disable HOT detector requirement for data retrieval. ....	34
Figure 5.13 Selecting a characteristic shockwave distribution set for a project. ....	34
Figure 5.14 Link to select corridor segment for a project.....	35
Figure 5.15 Corridor segment selection page.....	35
Figure 5.16 Link to select traffic data for a project.....	35
Figure 5.17 Traffic data selection form.....	36
Figure 5.18 Form for generating shockwave propagation results.....	36
Figure 5.19 Project page after results are generated, including color plots showing shockwave severity (left column) and plots showing a visualization of the traffic data used to generate the color plot. ....	37
Figure 5.20 Dropdown menu for selecting a station for exploring access restriction in high-shockwave areas.....	37
Figure 5.21 Button for starting data retrieval for running lane change simulations.....	38

Figure 5.22 Form for running lane change simulations and diagram to help the user. ....	38
Figure 5.23 Plot with histogram of simulated lane changes and recommended gate position. ....	39
Figure 5.24 Link to create a new network configuration. ....	39
Figure 5.25 Form for creating a new network configuration, with a file uploaded. ....	40
Figure 5.26 Form for creating a new network configuration, without a file uploaded (will retrieve the latest). ....	40
Figure 5.27 List of network configurations showing user-created options along with default. Note the values in the "Config Timestamp" column, which indicate the date that the corresponding metro_config.xml file was updated. ....	40
Figure 5.28 Link to create a new Characteristic Shockwave Distribution set. ....	40
Figure 5.29 Form for creating a new Characteristic Shockwave Distribution set. ....	41
Figure 5.30 Characteristic Shockwave Distribution page before simulations are started. ....	41
Figure 5.31 Characteristic Shockwave Distribution page during a running simulation, showing progress and a cancel button. ....	42
Figure 5.32 Button to generate plots of the Characteristic Shockwave Distribution set. ....	42
Figure 5.33 Section of the Characteristic Shockwave Distribution set plot. ....	43
Figure 5.34 Link to create a new Shockwave Model Parameter Profile. ....	43
Figure 5.35 Form for editing Shockwave Model Parameter values. ....	44
Figure 5.36 New Shockwave Model available for selection when creating or editing a Characteristic Shockwave Distribution set. ....	44

## LIST OF TABLES

Table 4.1 Fitted parameters for the Gap Acceptance Model .....	23
Table 4.2 Fundamental Diagram Parameters GPLs on test site. ....	26



## EXECUTIVE SUMMARY

Congestion during peak demand periods within major urban freeway networks is a perennial and chronic issue that plagues roadway managers worldwide. Among the many tools available to help mitigate delays and reduce jams, High-Occupancy Toll (HOT) lane facilities have been an important component in dealing with severe congestion in the Minneapolis and St Paul, Minnesota metropolitan area. Two major freeways in the Twin Cities currently include designated HOT lanes and several more freeways with HOT lanes are planned or under construction. These freeways include designated lanes that multi-occupant vehicles can use freely while single-occupant vehicles may opt to use the lane for a small, variable toll. Although such facilities can be found in a wide variety of major metropolitan areas nationwide, design for the lanes has been largely influenced by broad rules-of-thumb and engineering judgment. A strong framework for assessing the particular layout of a HOT lane facility has been lacking, from both a safety and a mobility perspective. This empiricism has resulted in a variety of approaches towards the implementations of such infrastructures.

Two broad design alternatives can be acknowledged in the context of the connection between General Purpose (GP) and Managed Lane (ML) or High Occupancy Toll (HOT) facilities, the – open- and closed-access methods. Closed-access facilities separate the HOT lane from the GP lanes, often simply using double white lines to prohibit lane changes along facility. Vehicles may only enter or exit the HOT lane at pre-specified ‘gate’ locations which are generally located near major ramps to provide mobility for those using the HOT. Alternatively, open-access HOT lanes do not use gates and simply allow vehicles to move between the GP and HOT lanes freely. While this greatly increases mobility by permitting vehicles to access the HOT lane as quickly as they are able after entering the freeway and exit the HOT lane as desired in order to reach any exit ramp throughout the corridor, there may be some safety concerns with allowing lane changes at any point. Since the HOT lane is controlled, albeit not strictly, by the tolling mechanism on the lane, the HOT lane tends to retain a notably lower density than the adjacent GP lane and thus retains a higher prevailing speed. This is ultimately the goal of the HOT lane: to provide a higher level of service and a more reliable journey to those willing to pay.

However, the disparity in speeds between the HOT lane and adjacent GP lane can be quite significant. A properly managed HOT lane can continue operating at 50 mph or higher while the mainline has broken down significantly. Thus, vehicles next to each other experience a speed differential on the order of 25 mph or more. In such circumstances, vehicles attempting to traverse the lane boundary must negotiate the speed change and, in doing so, stand a high chance of causing vehicles to approach behind them and form a shockwave. These shockwaves are the focus of this research effort. Shockwaves, especially those that form in the HOT lane, are a cause for concern because the prevailing speed on the lane is higher and consequently any vehicles approaching the tail of the shockwave must brake harder to avoid a collision. An increase in reaction time from distraction or an error in speed estimation further increases the likelihood of a crash.

The product of this project, the MnPASS Access Design application, provides a tool for traffic managers and planners to examine the conditions within an existing or prospective corridor and the distribution of shockwave lengths which are expected. From the distribution of shockwave lengths, decisions can be made regarding access restriction on the HOT lane to ensure that drivers do not attempt to make lane changes at locations prone to dangerous conditions. This tool provides support for the managers and planners by aggregating the entire behavior of the HOT lane within the corridor into a framework for simplified consideration.

The MnPASS design tool consists of three main components: the Access Design Modules (core model), the Data Generation Module, and the Web based interface that encapsulates these in a user friendly application. The Access Design Module takes inputs of traffic data and driver behavior model parameters and output recommended access changes. In consultation with MnDOT engineers, the tool assumes an open-access strategy, produces relevant results, and provides design suggestions for closed-access segments in locations where mobility and safety concerns are identified. The Open-Access Module provides estimates of shockwave activity given the traffic conditions in the HOT and the adjacent GP lane as well as a score quantifying the expected frequency of potentially unsafe states based on historical information. The Closed-Access Module provides suggested zones for opening access on closed-access HOT lanes based on the path length distribution and success rate curve of vehicles attempting to cross the GP lanes to reach the HOV lane or a freeway exit. The Data Generation Module creates a statistical library of shockwave distributions from a set of input data over a range of traffic conditions. This module is separate from the two access design modules to reduce the computational requirements of each run and allows the user to more quickly explore the variation of the suggested solutions as traffic conditions change and aggregate the data to better capture the general patterns of the corridor.

The Web Application provides the user with a simple interface for specifying input data, describing the physical layout of the corridor, and varying the modeled traffic conditions to compare alternative scenarios. It also handles things like input validation, error reporting, and progress tracking to give the user a predictable experience. Together, these components allow the user to quantify the operation of an existing HOT lane operating under open-access conditions in terms of mobility and safety, as well as explore different levels of HOT demand.

## CHAPTER 1: INTRODUCTION

Congestion during peak periods within major urban freeway networks is a perennial and chronic issue that plagues roadway managers worldwide. Among the many tools available to help mitigate delays and reduce jams, High-Occupancy Toll (HOT) lane facilities have been an important component in dealing with severe congestion in the Minneapolis and St Paul, Minnesota metropolitan area. Two major freeways in the Twin Cities currently include designated HOT lanes and several more freeways with HOT lanes are planned or under construction. These freeways include designated lanes that multi-occupant vehicles can use freely while single-occupant vehicles may opt to use the lane for a small, variable toll.

Although such facilities can be found in a wide variety of major metropolitan areas nationwide, design for the lanes has been largely influenced by broad rules-of-thumb and engineering judgment. A strong framework for assessing the particular layout of a HOT lane facility has been lacking, from both a safety and a mobility perspective. This empiricism has resulted in a variety of approaches towards the implementations of such infrastructures.

Two broad design alternatives can be acknowledged in the context of the connection between General Purpose and Managed Lane facilities, the – open- and closed-access methods. Closed-access facilities separate the HOT lane from the General Purpose (GP) lanes, often simply using double white lines to prohibit lane changes along the majority of the lane. Vehicles may only enter or exit the lane at pre-specified ‘gate’ locations which are generally located near major ramps to provide mobility for those using the HOT.

Alternatively, open-access HOT lanes do not use gates and simply allow vehicles to move between the GP and HOT lanes freely. While this greatly increases mobility by permitting vehicles to access the HOT lane as quickly as they are able after entering the freeway and exit the HOT lane as desired in order to reach any exit ramp throughout the corridor, there may be some safety concerns with allowing lane changes at any point. These concerns stem from the key difference between the HOT and GP lanes within the corridor: the HOT lane is managed.

Since the HOT lane is controlled, albeit not strictly, by the tolling mechanism on the lane, the HOT lane tends to retain a notably lower density than the adjacent GP lane and thus retains a higher prevailing speed. This is ultimately the goal of the HOT lane: to provide a higher level of service and a more reliable journey to those willing to pay.

However, the disparity in speeds between the HOT lane and adjacent GP lane can be quite significant. A properly managed HOT lane can continue operating at 50 mph or higher while the mainline has broken down significantly. Thus, vehicles next to each other experience a speed differential on the order of 25 mph or more. In such circumstances, vehicles attempting to traverse the lane boundary must negotiate the speed change and, in doing so, stand a high chance of causing vehicles to approach behind them and form a shockwave. These shockwaves are the focus of this research effort. Shockwaves, especially those that form in the HOT lane, are a cause for concern because the prevailing speed on the lane is higher and consequently any vehicles approaching the tail of the shockwave must brake harder to avoid a collision. An increase in reaction time from distraction or an error in speed estimation further increases the likelihood of a crash.

The methodology, which will be described in the coming chapters, reconstructs traffic on the HOT lane for a variety of density conditions and models the generation of shockwaves from vehicles entering the HOT lane and accelerating to the prevailing speed on the lane. By iterating through this methodology

using a Monte Carlo framework, the likely distribution of shockwave lengths that would propagate on the HOT lane can be developed for any arbitrary conditions that may arise on the roadway. In conjunction with an examination of historical data for a complete corridor, the Monte Carlo simulation tool can produce a unified assessment of shockwave generation and map key areas that may require localized lane-change prohibitions in the form of double-white striping or some other type of lane control.

This simulation structure is founded on data describing traffic patterns and shockwave generation along I-35W and I-394 in Minneapolis first introduced by Stanitsas in 2013. The models used in this methodology are a notable improvement from those presented previously, in particular the General Motors (GM) (Chanlder et. al., 1958) car following model used for both validating the reconstructed stream to ensure realistic vehicle parameters and propagating shockwaves within the simulation procedure.

The methodology that will be presented here is founded on developing a stream of traffic that is representative of the HOT lane and introducing a vehicle to it at a lower speed to generate a shockwave. Doing so replicates the respective behaviors of the HOT lane and adjacent GP lane at times and locations where vehicles attempt to enter the HOT lane, often bypassing significant congestion in the mainline. By repeating the shockwave generation methodology many times within a Monte Carlo framework, a realistic shockwave distribution can be determined for any arbitrary pair of conditions on the two lanes of interest.

This methodology significantly expands on the model introduced by Stanitsas and improves on several underlying assumptions. Key among these improvements is the incorporation of the General Motors car following model and a methodology for calibrating the car following parameters based on data from the HOT lane. The overall structure of the methodology can be broken into several major components, which will be discussed in turn in the following sections: constructing a first-estimate traffic stream; validating the stream using the car following model; and introducing a disturbance and developing a shockwave.

## CHAPTER 2: FUNCTIONAL SPECIFICATIONS

This chapter serves to document the required features of the MnPASS Access Spacing design tool developed by the University of Minnesota. The development of those functional specifications was influenced by its intended use by project stakeholders. The objective of this project was to develop a software application for determining the ideal location and size of access points to and from a High-Occupancy Toll (HOT) managed lane facility over the length of a user-defined corridor of variable geometry and traffic conditions. During a previous study by the University, the impact of these access points on safety and mobility was assessed in order to create a methodology for designing access to a facility based on the common traffic conditions in a corridor. This project builds on that research by adding components and adjusting the methodology to improve ease of use and integration with MnDOT's existing information technology infrastructure and modeling software. The following is a breakdown of the application features requested by MnDOT and other stakeholders to maximize the utility of the resulting tool.

### 2.1 STAKEHOLDER INPUT

#### 2.1.1 Inputs and Data Sources

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For the program to be a user-friendly and helpful tool for engineers, it must have a graphical interface to allow the user to define the layout of an existing or planned facility. To reduce the required development time, the scope of the application is limited to situations where an existing freeway is modified to include an HOT facility on an existing lane or planned additional lane but did not consider situations where an entirely new freeway is to be constructed. This interface must integrate well with other applications and data sources already offered by MnDOT to provide the user with a consistent experience and to simplify distribution to third party users. In light of this, MnDOT expressed a preference for a web-based application that can be centrally managed by MnIT. The development path involved the creation of a web-based form where the user can input and/or select the necessary information and pass it to the underlying modeling routines to perform the analysis.

In line with this, the program must be able to use MnDOT's existing databases as well as simulation tools, namely IRIS and CORSIM, as data sources for informing the underlying models. This ensures that the MnPASS Access Design Tool can be applied in a wide range of scenarios to provide engineers and planners with the ability to make a fully-informed decision. The tool was designed to be as interoperable with MnDOT's systems as possible to minimize the effort required to exchange data between tools.

#### 2.1.2 Running Interface

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To ensure that the user can verify that the tool is performing the analysis as expected, the tool must provide the user with meaningful status updates and error messages. In conjunction with this, it must also perform some degree of input validation during the initialization phase to allow the user the chance to reformat their inputs without having to wait for errors in the model. Together these help reassure the user that their inputs were read correctly, inform them when the model is running and when it completes, and allow them to more easily identify the source of any errors that may be encountered.

#### 2.1.3 Outputs

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The primary outputs of the MnPASS Access Design tool are limited to the recommended access/restriction regions and some measure of the underlying decision criteria, such as the distribution of shockwaves in the HOT lane or path lengths of vehicles entering and exiting the corridor. The tool

results are output in a form that allows for direct use in technical reports. This involves having explanatory statements included in the result page as well as controls for changing the format and colors of the graphic results.

## 2.2 SYSTEM ARCHITECTURE

The MnPASS design tool consists of three main components: the Access Design Modules (core model), the Data Generation Module, and the Web Application.

The Access Design Modules take inputs of traffic data and driver behavior model parameters and output recommended access changes. Originally, the targeted design considered the two access types (open or closed) as parallel alternatives. Following further consultation with MnDOT engineers, it was decided that the tool would assume an open-access strategy, produce relevant results, and provide design suggestions for closed-access segments in designated locations. Regardless, the two access modules are still independent. The Open-Access Module provides estimates of shockwave activity given the traffic conditions in the HOT and the adjacent GP lane as well as a score quantifying the expected frequency of potentially unsafe states based on historical information. The Closed-Access Module provides suggested zones for opening access on closed-access HOT lanes based on the path length distribution and success rate curve of vehicles attempting to cross the GP lanes to reach the HOV lane or a freeway exit.

The Data Generation Module creates a statistical library of shockwave distributions from a set of input data over a range of traffic conditions. This module is separate from the Access Design Modules to reduce the computational requirements of each run and allow the user to more quickly explore the variation of the suggested solutions as traffic conditions change and aggregate the data to better capture the general patterns of the corridor. The retrieval of data from various sources is handled by this module.

The Web Application provides the user with a simple interface for specifying input data, describing the physical layout of the corridor, and varying the modeled traffic conditions to compare alternative scenarios. It also handles things like input validation, error reporting, and progress tracking to give the user a predictable experience. Together, these components allow the user to quantify the operation of an existing HOT lane operating under open-access conditions in terms of mobility and safety, as well as explore different levels of HOT demand. The tool is theoretically capable of creating recommendations in the less-common case where a HOT lane is to be added to a completely new freeway however this is not handled directly due to the fact that the HOT lane densities must be externally provided. Details of these components and how they are integrated is explained in the following sections.

## 2.3 INPUTS

Because the MnPASS Access Design Tool needs to interface with MnDOT's existing data sources, the inputs to the program are limited to the corridor the user would like to model, the conditions or data range that the user is interested in, and the driver behavior parameters for the car-following model. The corridor is defined by selecting a road and the start and end points that bound the corridor of interest. This selection is used to obtain the lane configuration and detector layout as read from the IRIS network configuration file, "metro\_config.xml" that is, in turn, used to generate the input data for the Access Design Modules

## 2.4 DATA SOURCES

To simplify implementation and accelerate the development of the tool, the final application interfaces with the RTMC detector database. This design reduces the effort necessary for a user to assess current

HOT lane level of mobility and safety but slightly increases the effort required to use the tool with hypothetical or simulated data. Using the corridor information read from the IRIS network configuration file and the user input, the program retrieves data from these sources through the Data Generation Module as part of the process of developing the statistical “library” of shockwave distributions. This process takes HOT lane density data and adjacent GP lane speed data that matches the range of conditions specified by the user and iteratively models the generation of shockwaves until their distribution over the range of density and speed conditions converges. This distribution can then be used to inform the Access Design Modules so the user can experiment with the varying conditions that emerge from the input parameters.

In cases where simulation data is needed to model a new lane, the program requires that the user provides a custom “metro config.xml” file that contains the IDs and locations of all existing and simulated detectors for the particular corridor. In order to get detector data from CORSIM, the raw CORSIM output is processed by an application developed by SEH, Inc. that creates detector data from link data. This step reduces the development effort required to incorporate this feature into the design tool and keeps the format of input data standardized at the detector level. Because this application is actively used by MnDOT simulation staff, the process of integrating the design tool into existing workflows should be fairly simple. The simulated detector data produced by the SEH application must be added into the IRIS database for the date range required for the analysis. In the future, the SEH application will either be expanded to streamline this step or replaced by a new application.

## CHAPTER 3: OPEN-ACCESS MODULE

Open-access corridors allow vehicles to move freely in and out of the high-occupancy toll (HOT) lane at any point along the corridor. Under certain circumstances, however, allowing lane changes can lead to the formation of shockwaves in the HOT and GP lanes. The length of these shockwaves can be considered as surrogate measures of safety and mobility with longer shockwaves representing a larger safety risk than short shockwaves due to the increase in vehicles that must respond and may make a mistake leading to a crash. The frequency of these shockwaves is an indication of HOT lane performance since each shockwave represents a set of vehicle decelerations to speeds below the desired uncongested level.

In a corridor with a HOT lane, these risks can be further accentuated when conditions in the GP lanes become highly congested. During severe congestion, vehicles on the lane adjacent to the HOT lane travel at significantly reduced speeds while those in the HOT lane continue to travel near typical freeway speeds because the HOT lane is managed to ensure a high level of service. As such, any vehicles choosing to move between the HOT lane and the adjacent GP lane will need to negotiate a significant speed change. This notable speed differential between lanes increases both the likelihood of a shockwave developing and the length of the shockwave once it has developed.

To deal with the potential safety concerns of shockwaves in these circumstances, a methodology for modeling the distribution of shockwave lengths within a corridor was developed. This methodology, which will be laid out in the following sections, analyzes the traffic conditions along a corridor and models shockwave generation across a range of pairs of HOT lane densities and adjacent GP lane speeds. The modeled shockwaves are weighted and aggregated across time to produce a complete assessment of the shockwave generation patterns at each location along the corridor. This map can then be analyzed to determine which locations may require management to reduce lane changes and ameliorate safety concerns.

The entire Zones for Access Restriction (ZAR) algorithm is broken into three parts: Part A involves creating so-called *Characteristic Shockwave Distributions* for each of the density/speed pairs of interest for analysis; Part B involves analyzing historical or simulated data for the corridor to compile data on the density/speed pairs in all lanes and determine the relative frequency for each condition; and Part C combines the characteristic distributions with the weighting parameters to produce cumulative shockwave distributions describing the behavior at each location within the corridor.

### 3.1 PART A – CHARACTERISTIC SHOCKWAVE DISTRIBUTIONS

The first part of the ZAR algorithm involves the methods required to reconstruct traffic streams for the HOT lane, select GPL gaps for lane changing, and assess car following to develop shockwaves. These methodologies are reliant on a series of input values that describe variables such as car following behavior and traffic stream characteristics, all of which are retrieved prior to any other steps.

Part A acts as a preparatory step that is performed just once prior to the analysis of road. The ultimate goal of Part A is to develop characteristic shockwave distributions that define the likelihood of observing shockwaves of various lengths given certain density/speed pairs in the HOT and adjacent GP lane, respectively. Additionally, the likelihood of gaps in the HOT lane being rejected and the likelihood of a lane change not causing shockwave are tracked. Part A is broken into two parts: Part A1, which takes in data from the user, and Part A2, which actually computes the output. A diagram of Part A is shown in Figure 3.1.



### 3.1.1 Part A1 – User Input

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Prior to any modeling, traffic parameters must be provided to describe car following behavior and traffic stream reconstruction. For traffic reconstruction, the primary values of importance are distributions for platoon size, leader headway, and follower headway. In previous research efforts, these values were taken from measurements of traffic along HOT facilities on I-394 and I-35W in Minneapolis, MN. The particular sources of these data are not considered by the ZAR algorithm. Thus, a similarly formatted set of values provided from some alternate locations or even data from a simulation could also be used.

To define each of these distributions, a large number of individual samples must be provided. For platoon sizes and leader headways, these samples are simple vectors of values that, when taken collectively, represent conditions with densities between 15 and 25 vehicles per mile. Follower headways must be provided in a more specific form: an N by 7 matrix, where N is the maximum number of samples for *any* follower index and the seven columns indicate the position of the follower in its platoon with the first column corresponding to the leader vehicle, the second column corresponding to the first follower, and so on. Since leader headways are provided separately, the first column of the follower matrix is uniformly zero. Note that since followers are limited to six, platoons are limited to being seven vehicles long or shorter. If a platoon sample has fewer than seven vehicles, its corresponding entry will have its remaining cells filled with zeros. Any platoon samples with more than seven vehicles are removed.

These three sets of samples are sufficient to produce a realistic stream of traffic. Platoons are randomly selected until a given stream size is created and each vehicle within the stream is then randomly assigned a headway from the appropriate sample list. With the traffic stream generated, a set of driver behavior parameters from the user-defined distributions are assigned to each vehicle. The parameters and their respective distributions are:

- Vehicle acceleration (and deceleration) – *normal*
- Vehicle length – *normal*
- Reaction time – *truncated normal*
- Minimum deceleration response – *normal*
- Gap entrance – *normal*
- Minimum time to collision (entering vehicle and subsequent vehicles) – *static*
- GM car following parameters (Alpha, M, L) – *static*

Vehicle acceleration describes the maximum capabilities of a given vehicle with deceleration always being double the acceleration. Reaction time is normally distributed, constrained to values greater than 0.5 seconds. The minimum deceleration response is the weakest allowable deceleration that a vehicle will employ. The Gap entrance parameter describes the location within a selected gap that vehicles will attempt to enter the stream. Two minimum time to collision (TTC) parameters are included: one for the vehicle entering the HOT lane from the adjacent GP lane and one for all subsequent vehicles in the potential shockwave. In each case, it describes the smallest time gap that will be tolerated within the shockwave. If the car following models used by the ZAR algorithm would cause a vehicle to approach its leader too closely, the gap that was being examined is rejected. This will be described in more detail below. Three parameters are involved in the GM car following model: alpha is a sensitivity coefficient on the overall acceleration response, M is an exponent on the speed of the vehicle, and L is an exponent on the gap between a vehicle and its leader.

### 3.1.2 Part A2 – Producing Characteristic Distributions

The aim of Part A2 of the ZAR algorithm is a grid that plots pairs of HOT lane density and adjacent GP lane speed. The shockwave modeling methodology essentially reconstructs a traffic stream with the desired density to describe the HOT lane and attempts to add a vehicle from the adjacent GP lane at the appropriate speed. This entering vehicle creates a disturbance and the resulting shockwave – if there is one – is recorded. If one of the two minimum TTC constraints is violated, the gap being probed is rejected and the next gap is probed in the same way. This process is repeated until a satisfactory gap is found. Using a Monte Carlo sampling technique, streams are constructed and lane changes are attempted many times in order to develop a distribution of shockwave lengths that describe shockwave behavior under the given density and speed conditions.

The grid of possible density/speed pairs is bounded by all densities that are between 15 and 45 vehicles per mile per lane (vpml) in the HOT lane and all speeds that are between 10 and 45 mph in the adjacent lane. Cases where speeds in the adjacent GP lane fall below 10 mph are not considered when generating characteristic distributions due to the severity of the speed differential between the HOT lane and adjacent GP lane. Note that these low-speed conditions are considered when parsing simulated or historical data for the roadway and are treated specially in the final portion of the methodology.

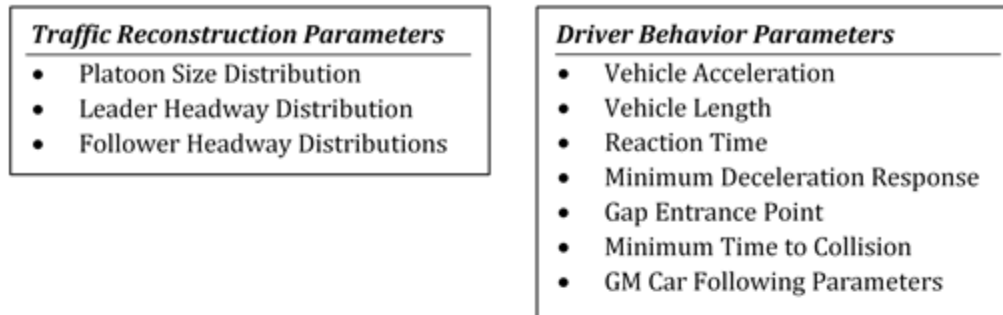
The rest of the speeds described relate to any congested conditions on the general purpose portion of the freeway. The density region in the HOT lane is bounded by the lowest density that would qualify for management by tolling (15 vpml) and the breakdown density of the HOT lane (42 vpml). The area enclosed by these density and speed bounds is broken up into 3 vpml by 5 mph “bins”, with a total of 80 possible combinations.

Within each of these bins, the Monte Carlo technique is used and the characteristic shockwave distribution, the likelihood of gap rejection, and the likelihood that a lane changes doesn’t cause a shockwave (hereafter referred to as a “non-shockwave lane change”). These 80 distributions are used for the entire corridor that will be analyzed and are prepared and stored prior to analyzing historical or simulated data for the corridor. This methodology assumes that no significant changes in driver behavior or traffic composition occur throughout the corridor.

### 3.2 PART B – ASSESSING HISTORICAL OR SIMULATED DATA

Without actual data for traffic on a particular corridor, the characteristic distributions that were developed in Part A only describe the possible states of the roadway. To understand what actually occurs on a roadway, these states must be weighted based on their frequency and aggregated to produce a single unified description of each location along a corridor. Part B of the ZAR algorithm accomplishes this by examining five-minute-aggregated density and speed data at various points along the corridor to characterize its traffic. This data may be taken from either historical data from an existing corridor (usually taken from loop detector stations) or simulated data from a modelled corridor. Part B is broken up into two distinct steps: Part B1, where the user specifies the source of the historical data, and Part B2, where the historical data is analyzed to produce weighted and aggregated characteristic distributions. A flow chart of Part B is shown in Figure 3.2.

## Part A1 - User Input



## Part A2 - Produce Characteristic Distributions

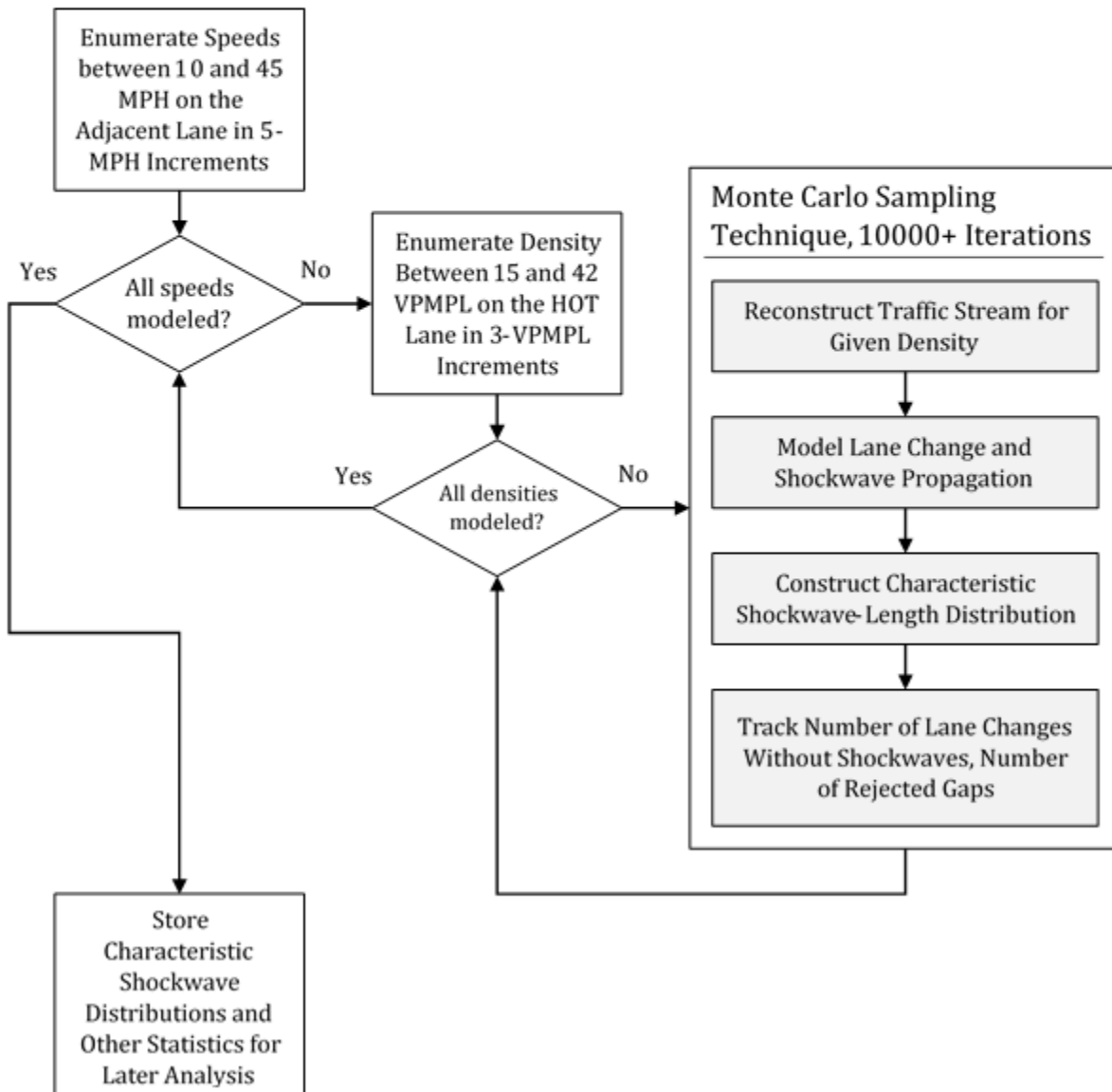


Figure 3.1 Part A of ZAR algorithm - developing characteristic shockwave distributions.

### **3.2.1 Part B1 – User Input**

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Because Part B involves analyzing actual data for a corridor, a description of the corridor itself must be given. In this case, pairs of detectors for the HOT lane and adjacent GP lane must be specified. Any number of detector pairs can be selected with each being iteratively considered for analysis. Because all detectors are assumed to be a single loop, a calibrated field length must also be specified for each.

Optionally, the data may also be limited to a specific list of dates and/or times though this is usually done in the context of historical data rather than simulated data. If these values are not specified, data analysis uses all times of day and proceeds backwards, starting from the latest date available.

### **3.2.2 Part B2 – Assessing Historical Data**

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While the characteristic distributions developed in Part A capture the behavior of vehicles under certain combinations of HOT lane density and adjacent GP lane speed, these data are not useful for understanding the overall behavior of a corridor without some measure of what conditions actually take place on the roadway. This section lays out the methodology that was developed to use historical traffic data to combine the characteristic distributions into a single parameter for a given location. The data used in the Monte Carlo framework of Part A is aggregated in 5-minute increments to smooth out the noise seen in traffic data with shorter time steps, such as the native 30-second data that is produced by the Twin Cities detector system, while still maintaining sufficient resolution to capture important variations in density and speed that occur over time. For consistency, 5-minute data is again used within this assessment methodology.

The goal of this assessment is to establish the relative frequency of each density/speed pair in a particular segment of the corridor. In keeping with the development of the characteristic distributions from Part A, density is broken into 3-vpm segments and speed is broken into 5-mph segments. However, for a complete picture of the behavior of the location, all possible density/speed pairs are considered. Thus, rather than excluding densities in the HOT lane that are not between 15 and 42 vpm and speeds in the GP lane that are not between 10 and 45 mph, densities between 0 and 240 vpm and speeds between 0 and 100 mph are considered. Note that the upper boundaries of these two ranges are much higher than what is likely to be necessary to capture all reasonable data for the corridor.

With this framework in mind, successive days of historical data can be examined and each 5-minute data point can be added to the appropriate bin within the density/speed matrix, building up a 2-dimensional histogram of past conditions. This histogram can then be transformed into relative percentages by dividing the total of each bin by the total of the entire array. These percentages are the relative frequencies of each condition appearing on the roadway. However, the relative percentages across this array may or may not be representative of the behavior of the roadway over time. In order to determine if sufficient sample days have been added, a mean squared difference index is implemented that, when sufficiently minimized, indicates that the frequency chart has converged.

For every bin, two values are compared: the frequency of that bin for all days 1 to N and the frequency for that bin for all days 1 to N-1. It is important that the counts in each bin are first transformed into a relative frequency because, as each day is added, individual bin counts continue to grow and do not converge. By instead looking at the relative frequency, convergence is possible.

User Input

- Corridor Parameters**
- Paired HOT and Adjacent General Purpose Lane Detector IDs
  - Single-Loop Detector Field Lengths

- Date Range and Days-of-Week (optional)**
- Specific Date List
  - Specific Days-of-Week inclusion

Assess Real Data

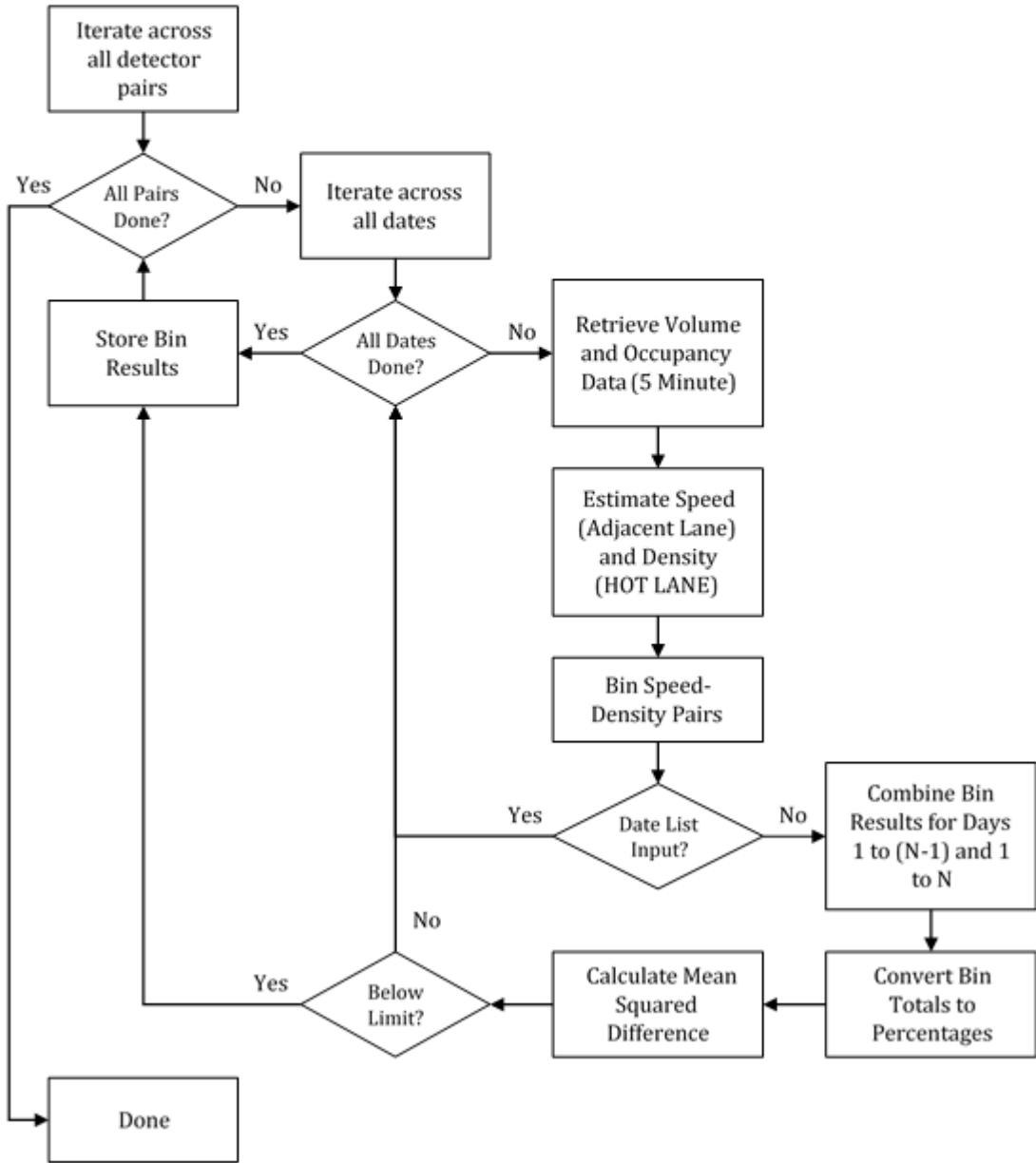


Figure 3.2 Part B of ZAR algorithm – assessing historical or simulated data.

### 3.3 PART C – PRODUCING CUMULATIVE SHOCKWAVE DISTRIBUTIONS

At a single location, historical data and characteristic distributions are cross-referenced to compile what will be referred to as a “comprehensive shockwave distribution”. Essentially, the characteristic distributions are weighted based on the historical data for the location and the relative frequency with which each of the characteristic distribution conditions occurs on the roadways. Two calculations are made for each location: the weights are applied to the characteristic distributions to assemble the comprehensive shockwave distribution and the percentages of all data falling into certain larger regions of the density/speed plot are found.

The first of these calculations is essentially self-explanatory. The percentages describing the frequency of occurrence of any of the density-speed conditions in the historical data are multiplied directly against the characteristic distributions for the corresponding conditions. Thus, for a density/speed pair that represented 5% of historical measurements, the histogram values for the related speed-density characteristic distribution would each be multiplied by 0.05. If 100 of the sampled shockwaves were of length 3, this would transform into 5 shockwaves of length three.

Following this multiplication, the resulting shockwave counts for each shockwave length are combined in the comprehensive shockwave distribution for the given location. For example, the 5 shockwaves of length 3 already found, which represent the contribution of one particular density/speed pair, would be added to the 10 shockwaves of length 3 found for an adjacent density/speed pair (perhaps coming from a characteristic distribution containing 40 shockwaves of length 3, but with a historical representation of 25% --  $40 * 0.25 = 10$ ). This same approach is repeated across all shockwave lengths for all density/speed pairs, ultimately yielding a single combined shockwave length distribution that encapsulates both the simulated behavior of the corridor under arbitrary conditions and the historical data of the corridor that describes how the location actually performs.

### Part C – Produce Cumulative Shockwave Distributions

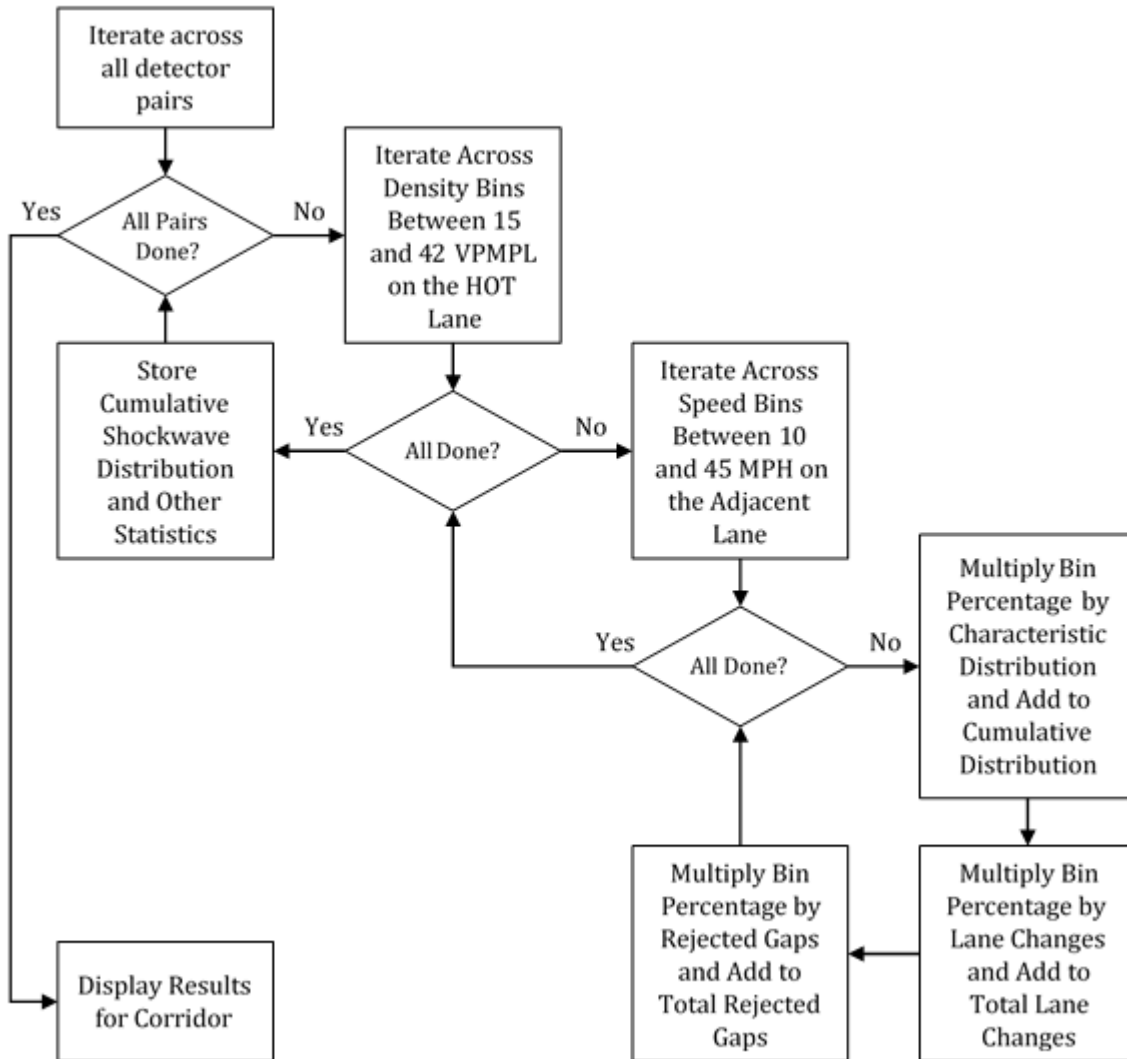
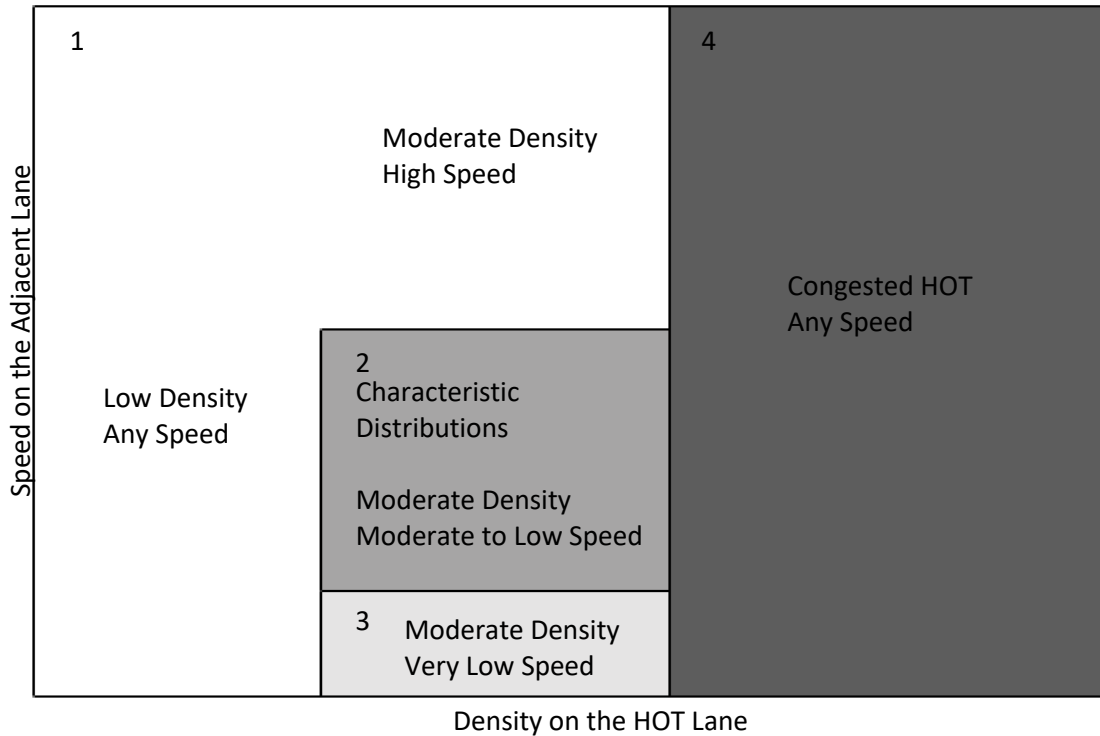


Figure 3.3 Part C of ZAR algorithm - producing cumulative shockwave distributions.

### 3.4 CORRIDOR-LEVEL ASSESSMENT

The ultimate goal of the developed tool is to examine the entirety of a corridor within one framework and produce a comprehensive assessment of the shockwave behavior of the complete HOT facility. This is achieved by combining the characteristic shockwave distributions produced by the Monte Carlo sampling methodology for each of the density/speed pairs of interest with the historical assessment distributions for each location along the corridor to generate a single mapping of shockwave activity throughout. These corridor maps can then be assessed holistically to identify locations where shockwaves of notable length occur frequently and thus which locations may require treatment to improve safety within the corridor. Because no direct relationship between shockwaves and crashes has been developed, only trend correlation, this tool serves to inform the designers or operators of a HOT facility and to aid in their assessment of the safety of the corridor.

To continue the discussion the ranges of density/speed pairs not covered by the characteristic distributions, Figure 3.4 shows the full ranges of speed and density broken down into four regions. The four regions illustrated represent major regimes that can be considered separately. The white area (Region 1) includes both the area above the characteristic distribution, where speeds on the adjacent GP lanes are higher than 45 mph but the density on the HOT lane is between 15 and 42 vpm, and the area covering densities from 0 to 15 vpm at any speed on the adjacent lane. Under the conditions in Region 1, shockwaves on the HOT lane are either unlikely or involve a small number of vehicles and an speed drop. Historical data that falls into the white area can be considered as “safe” for the purposes of this analysis.



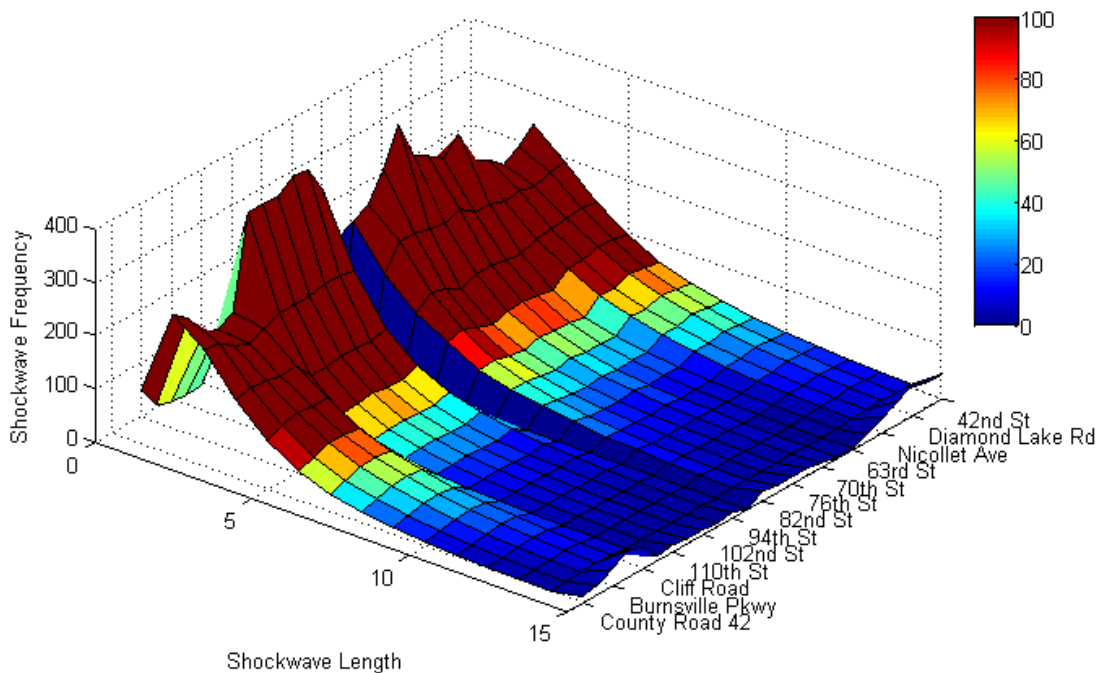
**Figure 3.4. Important speed-density regions.**

The next region, Region 2, is located in the center of the density/speed plot and is the characteristic distribution range of densities (15 to 42 vpm) and speeds (10 to 45 mph). Data falling within Region 2 is already well represented by this methodology. Underneath the characteristic distribution is Region 3, which represents nearly stopped traffic on the general purpose lane and a moderate density on the HOT lane. This third region has the potential to be extremely dangerous for drivers attempting to transition between lanes due to the severity of the speed drop. Any significant representation of Region 3 in the historical data for a corridor may suggest a need for lane change prohibitions.

Finally, Region 4, the region defined by densities above 42 vpm corresponds to the case where traffic in the HOT lane has become congested and the tolling function on the lane has failed. Ideally, conditions in a well-managed lane never reach Region 4 and, in the cases where they do, the HOT lane operates as another lane within the freeway system and lane changing behavior between the HOT lane and the adjacent GP lanes is no different than lane changing behavior between GP lanes.



Finding the relative percentages of data that fall into each of the four regions can help define the operating condition of the HOT facility. Segments of a corridor with high percentages of conditions falling into Region 4 are evidence of a bad tolling algorithm or a location that simply cannot cope with the given demand. Segments with high percentages of conditions falling into Region 3 similarly suggest that the tolling system that is not functioning properly – by setting the toll too high, capacity is being wasted while the general purpose lanes are at a standstill. Iterating across a corridor creates a three-dimensional result dataset: along the x-axis is shockwave length in vehicles, along the y-axis is distance along the corridor marked by each station, and the z-axis represents the number of shockwaves in the comprehensive shockwave distribution for each location. Again, this z-axis value is the sum of the characteristic distribution shockwave lengths weighted by the historical data percentages. Figure 3.5 shows a sample surface rendering of the data for I-35W northbound.



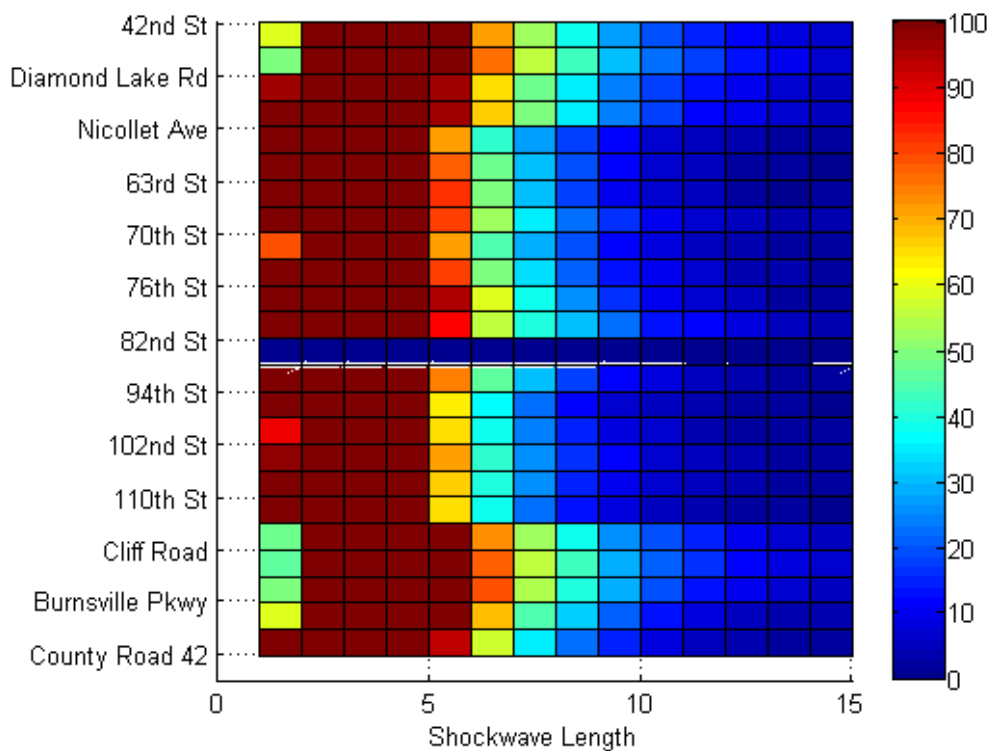
**Figure 3.5. Surface rendering of a sample comprehensive shockwave distribution.**

As shown in Figure 3.5, most of the shockwaves in the corridor are between two and five vehicles long (indicated in dark red). However, there are two locations within the corridor where longer shockwaves are more common. These cases are represented as slopes extending out towards the 10-vehicle mark on the x-axis between Burnsville Pkwy and Cliff Rd and between 42nd St to Diamond Lake Rd. At those locations, the height of the ridge corresponding to shockwave lengths of two to three vehicles is significantly lower than elsewhere in the corridor due to the higher relative frequency of long shockwaves. The gap in the middle of Figure 3.1Figure 3.5 at 82nd St is due to the fact that the detector station at this location did not have any data that fell in the characteristic distribution range of density and speed.

It is important to note that the results in Figure 3.5 are only useful when describing relative shockwave frequencies. The characteristic distributions that were used to create the figure included 1,000 shockwaves per density/speed pair. Those characteristic distributions were then multiplied by the

respective frequency rates calculated from the historical data and summed to calculate the total number of shockwaves per shockwave length per location. If only 100 shockwaves per density/speed pair had been used, the totals would have been exactly 1/10th of those shown. This would cause the z-axis in the figure to range from 0 to 40 shockwaves instead of 0 to 400 but would not change the relative heights of each of the peaks.

Although the surface rendering representation does illustrate the situation, it can be difficult to interpret because portions of the plot can be obscured. Alternately, a heat map version can display the same information by representing the shockwave frequencies with a color scale instead of a third dimension. Figure 3.6 shows the same data as Figure 3.5 but represents it with an “aerial view” and represents the z-axis with colors.



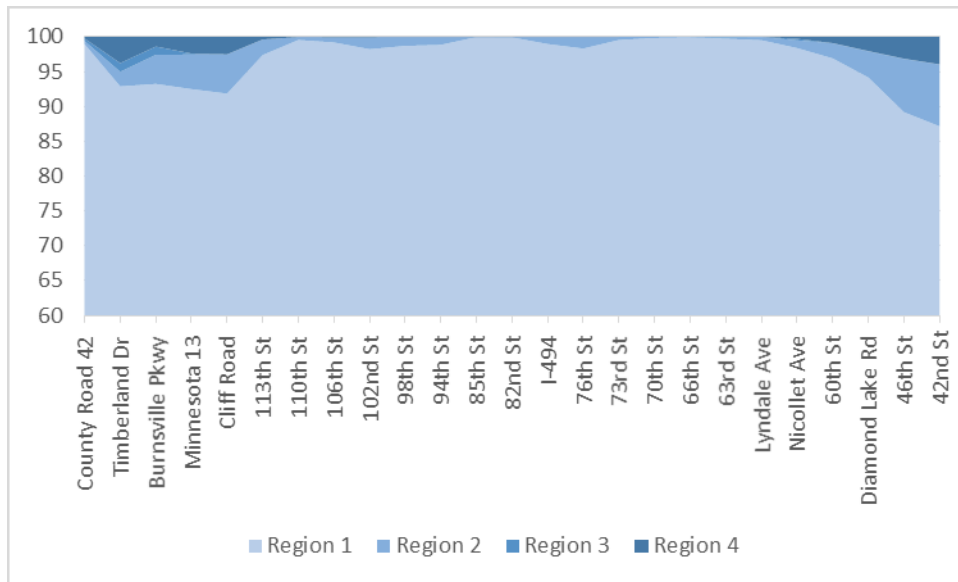
**Figure 3.6. Comprehensive shockwave distribution using full day historical data.**

In Figure 3.6, the dramatic difference in the heights of the peaks at Cliff Road and 110<sup>th</sup> St is not evident because the coloring truncates values above 100. This allows the viewer to distinguish smaller differences, such as the increased prevalence of longer shockwaves between Burnsville Pkwy and Cliff Rd and between 42nd St to Diamond Lake Rd where lighter blues extend beyond the 10-vehicle mark on the x-axis near Cliff Road and 46th Street (between DMD Lake and 42<sup>nd</sup>), with a weaker strength at the I-494 interchange near 82nd Street.

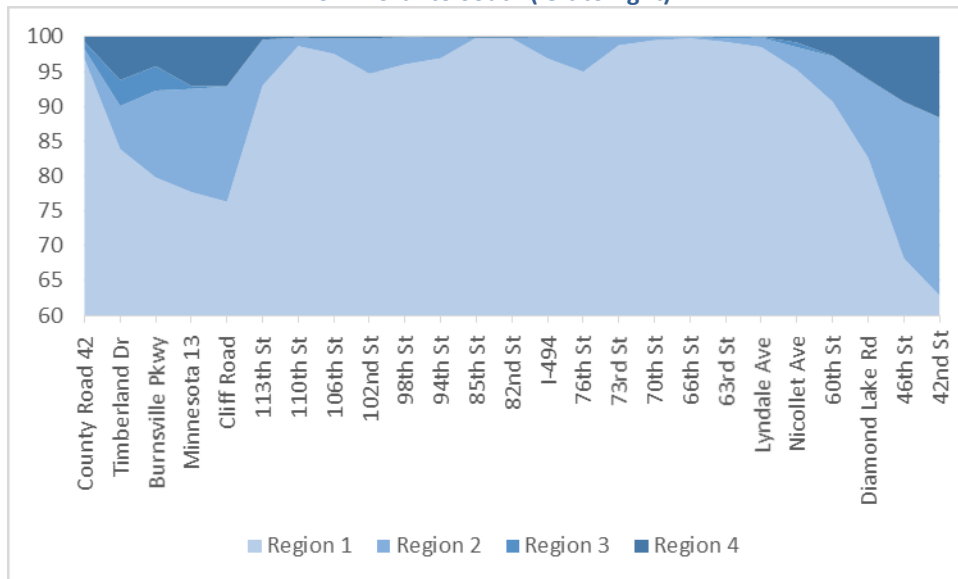
While neither of the two plots indicates a cutoff between safe and unsafe conditions, they provide a framework for how such a cutoff could be determined. For example, if a correlation between crashes and shockwaves of more than 10 vehicles long was established, a roadway manager could set a limit on the frequency of shockwaves of that length and find regions that conform to that rule. If the limit were set such that any location that is estimated to have 30 or more shockwaves more than 10 vehicles long

requires lane-change prohibitions, two small segments would be identified for consideration using Figure 3.6. Note that this is merely intended as an example of how a limit could be imposed.

Another visualization of the estimated or predicted performance of the HOT lane is a plot showing the portion of conditions falling into each of the four density/speed regions defined in Figure 3.4 during the entire, average day. For the I-35W example, Figure 3.7 shows the prevalence of data across each region when considering data across the entire day, while Figure 3.8 shows the prevalence of each region when only the peak periods are considered.



**Figure 3.7. Proportion of speed-density regions for full-day data. Traffic flows from North to South (left to right).**



**Figure 3.8. Proportion of speed-density regions for peak-periods-only data. Traffic flows from North to South (left to right).**

Recalling that Region 2 of the density/speed plot corresponds to the range of conditions that fall under the characteristic distributions, the plot of just data from the peak periods (Figure 3.8) reveals that vehicles at certain locations make significant use of the HOT lane. These are, unsurprisingly, also the locations that have the most concern with regard to shockwaves: Timberland Dr through Cliff Rd and Diamond Lake Rd through 42nd Street. The traffic in the region between Timberland Dr through Cliff Rd spends roughly 12 to 15 percent of the peak periods within the characteristic distribution range and traffic at the northern end of the corridor at 46<sup>th</sup> St and 42<sup>nd</sup> spends more than 20 percent of the peak hour in Region 2. Also of note, the area upstream of Highway 13 has a non-trivial wedge representing Region 3 – the region of the density/speed plot with the highest potential for danger. At both Timberland Drive and Burnsville Parkway, 3.5 to 4 percent of the peak periods have stopped traffic across the general purpose lanes while the HOT lane continues to operate at pre-congestion densities. This fits with anecdotal accounts of the corridor and data collected by Stanitsas that focused on the region around Highway 13 as a segment of particular concern.

The above discussions are offered as examples of interpretations and statements that can be made using the new analysis methodologies presented in this chapter and made available by the MnPASS Access Design Tool. The same results and visualizations can be produced for any demand increase scenarios that the user includes in the analysis.

## CHAPTER 4: CLOSED-ACCESS MODULE

Closed-access corridors restrict the movement of vehicles into and out of the high-occupancy toll (HOT) lane to specific regions along the corridor. This generally provides better service for vehicles traveling in the HOT lane, as there are fewer disruptions from the concentrated weaving that occurs in congested areas, however it can also pose a problem for those same vehicles when they attempt to enter or exit the HOT lane. Because access to the lane is only open in certain parts of the corridor, vehicles entering from nearby entrance ramps must have enough time to cross the general purpose (GP) lanes and reach the HOT lane before access is closed again. Similarly, vehicles exiting the corridor must be allowed to exit the HOT lane early enough to reach their intended exit. A driver's ability to do make these maneuvers is highly dependent on the traffic conditions on the GP lanes, as the time taken to traverse these lanes is influenced not only by the speed of the vehicle but also by the time it takes to successfully complete each lane change. This time can vary widely as conditions become increasingly congested because reduced vehicle headways and large speed differentials between the lanes make selecting a suitable gap considerably more difficult.

This variation means that the placement of access points to the HOT lane must be done carefully and with attention paid to the most frequently encountered traffic conditions in the corridor. To help designers with this process, a methodology was developed to model the process of vehicles moving to the HOT lane based on the traffic conditions and driver lane changing behavior. This model simulates traffic in a corridor segment where vehicles are travelling between the HOT lane and the nearby entrance or exit ramp by using a gap-acceptance model to determine the time required for each lane change. This produces a number of vehicle trajectories that are then used to assess the optimal location of the beginning and end points to the HOT lane based on the targeted percentage of vehicles served.

Given the strategy preference of open-access design in general unless there is a detrimental impact on safety and mobility of HOT lane users, the closed-access is implemented in the final software application as an add-on or next step following analysis with the open-access module. Regardless, the original design methodology to define access regions in a closed-access corridor segment was developed independently of the open-access module. For this reason, this chapter describes the closed-access module as an independent tool or function used by the general application.

The closed-access design methodology operates at the level of individual entrance or exit ramps, providing a solution for each freeway access point based on the results of the simulation at that location. Determining the optimal location of access points at the corridor level would require information that is outside the scope of this tool, therefore the results are only presented at the individual interchange level to avoid misleading the user. The following sections describe the methodology for computing the optimal location and length of access points at each entrance and exit, along with an example of how the methodology is implemented at a new location.

### 4.1 OPTIMAL LANE CHANGING REGION (OLCR) MODEL

This methodology for determining the optimal lane-changing region (OLCR) is based on the work of Stanitsas (2013) involving the analysis of vehicle lane changes associated with HOT lane usage at several points along I-35W between MN-13 and I-94. Most notably, this study produced a set of trajectories for vehicles merging to the HOT lane after merging to the freeway from the upstream entrance ramp (at 46th Street in Minneapolis) including measurements of speed, accepted and rejected gap sizes, and time spent in each lane and between lanes. Using this data, a methodology emulating the process used by drivers to move through the GP lanes to get to the HOT lane was developed. The goal of this

methodology was to reproduce the observed distances covered by drivers during their movement between the entrance ramp and the HOT lane and vice versa. In this model, demand for all lanes is considered to be equivalent to the observed traffic density. In addition to this, it is also assumed that lane changing is the same whether drivers move to the left or right, allowing the process to be used to account for vehicles as they leave the managed lane to exit the freeway at the following exit ramp.

This methodology uses Monte Carlo simulation techniques to model the movement of vehicles from an entrance ramp to the HOT lane. This involves the reconstruction of traffic flow for all of the GP lanes using headways sampled from the result of a Fundamental Diagram investigation for each lane. This investigation is conducted as a preparatory step to define the capacity of each lane, which allows the user to then model a number of traffic conditions as represented by a time series of density values in each lane. In addition, there is a gap-acceptance model that shapes the time increments that vehicles spend in each lane and the time drivers spent between lanes after accepting a gap is replicated by drawing random numbers from a lognormal distribution fitted to the corresponding measurements. Finally, an additional behavioral parameter describing the time that drivers spend on the originating lane before looking for an appropriate gap is also taken into account and represented by a user defined normal distribution. The final outcomes of this methodology are advisory positions and lengths for merging areas in HOT facilities.

#### 4.1.1 Traffic Flow Reconstruction

The process for reconstructing traffic flow in the GP lanes is based on the findings of a Fundamental Diagram investigation by Stanitsas (2013). This investigation found that at densities below capacity, headways most closely matched the lognormal distribution. This allowed for the creation of a methodology for reconstructing a traffic stream at a given point in time from a density value and the Fundamental Diagram parameters that describe the capacity of the lane. While this model only captures conditions below the critical density, the harvested trajectory measurements were also used to show that working with densities below this level does not significantly alter the results. For traffic conditions above the critical density, it was observed that vehicles reached the HOT lane before the proposed position of the gate for traffic conditions above the critical density. This can be seen in the box plots in Figure 4.1 where the maximum trajectory length for conditions above the critical density is smaller than the maximum trajectory length below the critical density.

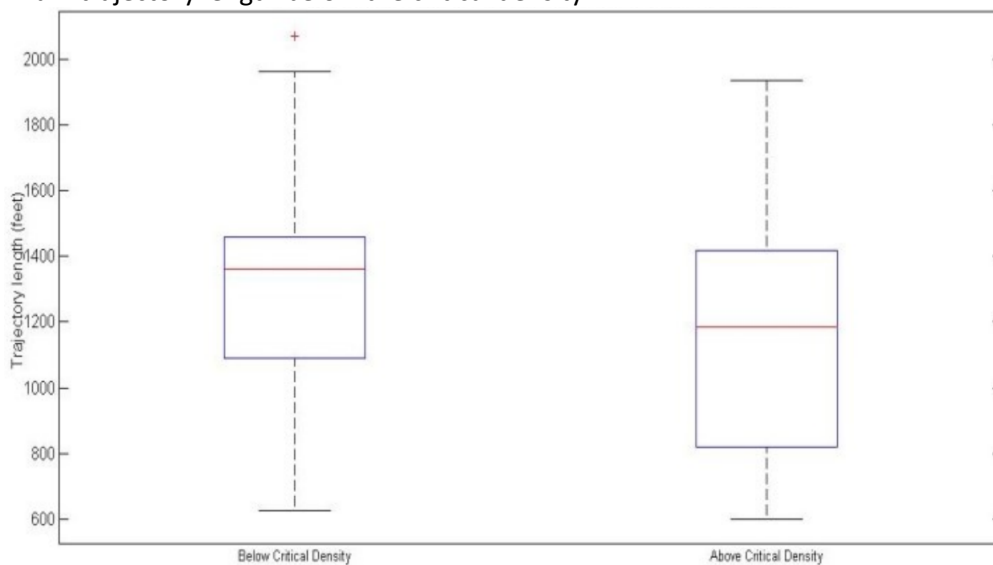
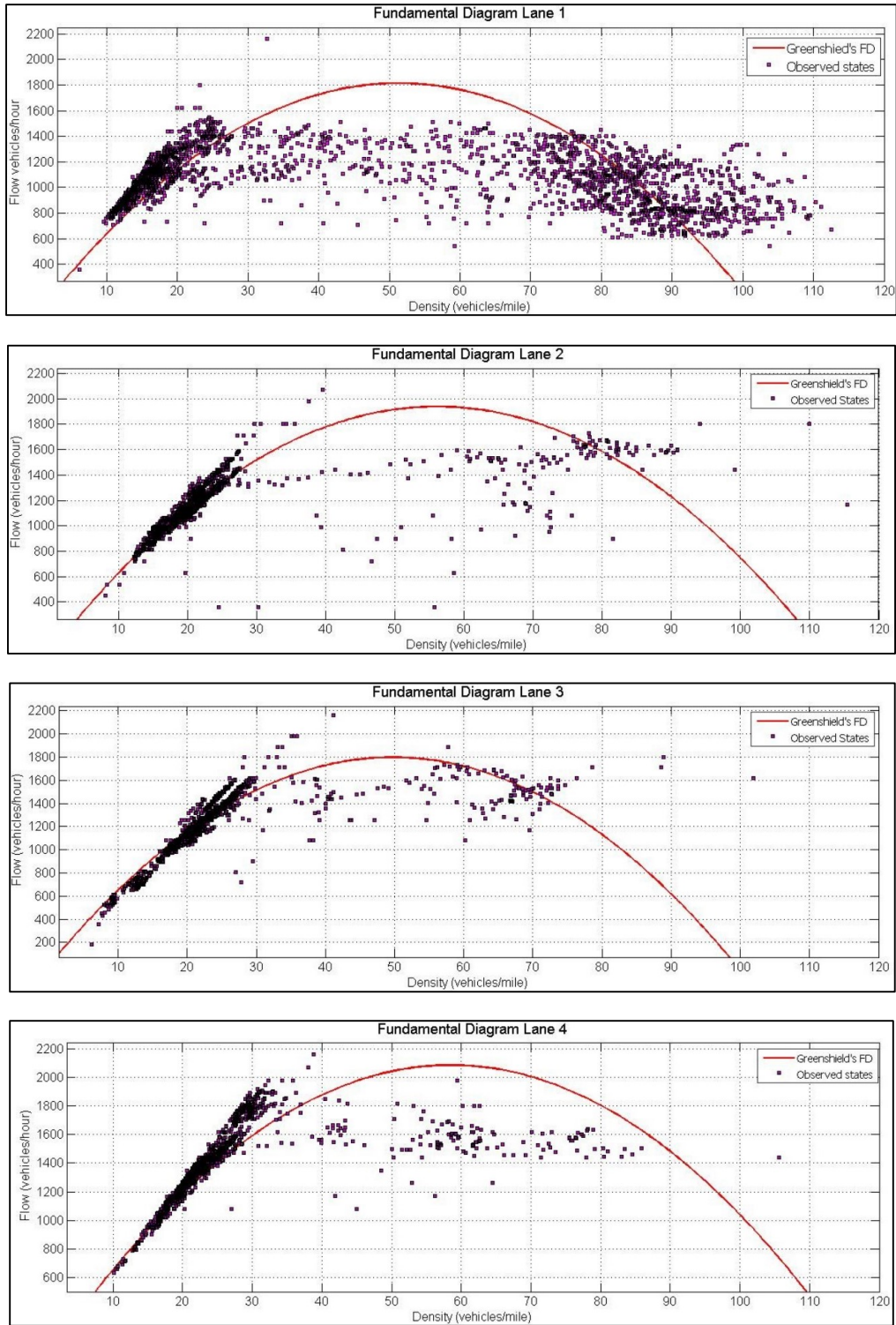


Figure 4.1 Comparison of trajectory lengths for cases above and below capacity.



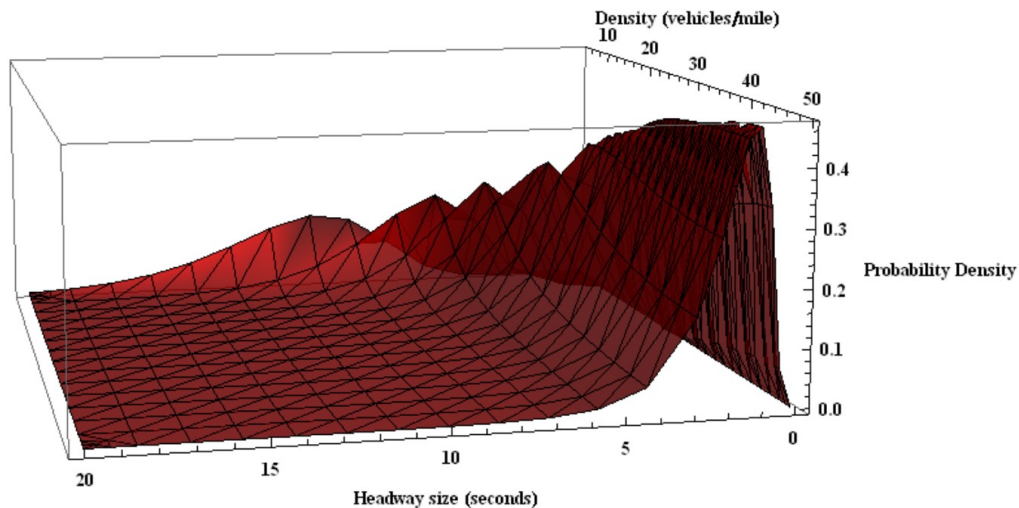
**Figure 4.2 Fitted Fundamental Diagrams for Lanes 1-4 at the I-35W Test Site.**

Reconstruction of the traffic stream is conducted separately for each lane. Before any simulation can occur, the parabolic fundamental diagram proposed by Greenshields, et al. (1935) is fitted to historical

data extracted for each lane of the examined freeway segment, according to the methodology used by Stanitsas (2013). This provides a means for relating density, flow, and speed in each lane, thereby allowing the algorithm to model a range of traffic states. An example of this relationship for the I-35W site can be seen in Figure 4.2.

The traffic state for a single simulation is represented by a time series of density in each lane which is then used as an input to the model that facilitates exploration of the recommended solutions under various conditions. When a run begins, the density evolution provided is used to sample headways from a distribution that corresponds to the density level at each point in time. The speed in each lane is initialized based on the density at that point in time and the relationship described by the Fundamental Diagram parameters. This produces a traffic stream that is representative of the macroscopic conditions of each lane over the course of the simulation.

Once the headway sequence and lane speeds have been initialized, a simple, rule-based car following model is employed to generate individual vehicle trajectories. The headway sequence is used to separate vehicles into platoon leaders and followers based on either a space threshold of 280 feet or a time threshold of 3.1 seconds, whichever is greater. To replicate drivers' willingness to approach their leader, a stochastic threshold is used for each driver of the simulated stream. In particular, the 25th percentile of the followers' headways is taken as the mean of a lognormal distribution that is sampled for each vehicle to vary the following distance. An example of the surface of distributions that is used to generate the headways can be seen in Figure 4.3.



**Figure 4.3 Surface of Distributions used for generating vehicle headways.**

Individual vehicle speeds are then derived by sampling from a normal distribution with a mean equal to the prevailing speed of the GP lane and a standard deviation equal to 3 feet per second. If followers are moving at a higher speed than their leaders and the headway threshold is violated, they match the speed of the vehicle ahead of them. This introduces variation to the gaps in the traffic stream that is necessary to accurately model lane changes.



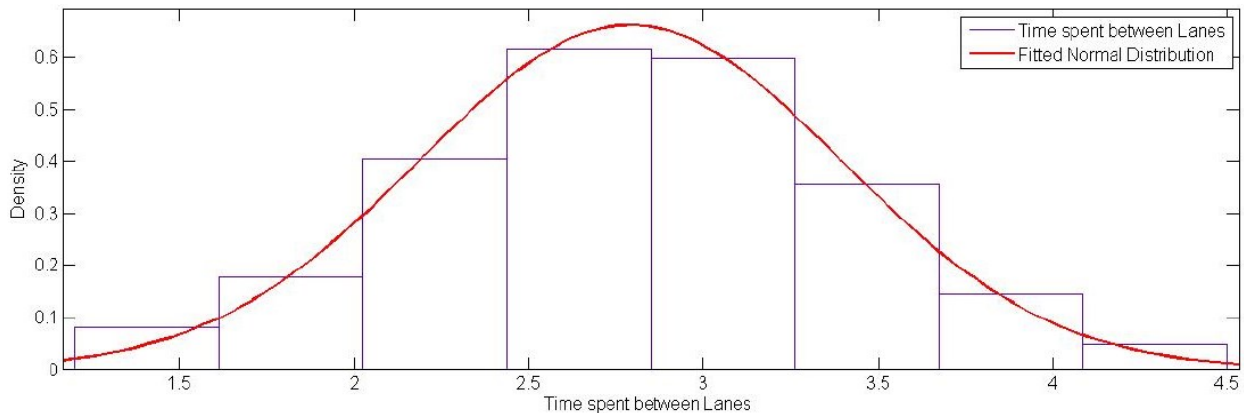
### 4.1.2 Modeling Lane Changes

The time spent in each lane is primarily influenced by the gap-acceptance model developed by Stanitsas. This is a logit model that derives the probability of accepting a gap based on the speed of the subject vehicle, the prevailing speed in the target lane, the size of the vehicle in front of the subject vehicle, and lagging (behind the subject vehicle) gaps, and the gaps rejected so far. Table 4.1 shows the parameters as calibrated by Stanitsas. Generally speaking, the probability that a vehicle accepts a gap increases as the size of the gap increases with the size of the lag gap carrying the greatest influence. The probability of a gap being accepted decreases as the speed of the target lane increases because merging from a slow-moving lane to a fast-moving lane is more challenging due to this speed differential. The coefficients of this model were fitted by Stanitsas using the collected trajectory data to describe the behavior that was observed.

**Table 4.1 Fitted parameters for the Gap Acceptance Model**

Fixed Effects Parameters	Value	Std. Error	z-value	Pr(> z )
$\beta_0$ (intercept)	-1.493	0.736	-2.027	0.043
$\beta_1$ (lag gap)	0.054	0.011	4.676	0.000
$\beta_2$ (subject vehicle speed)	0.119	0.043	2.748	0.006
$\beta_3$ (target lane speed)	-0.088	0.041	-2.163	0.031
AIC	168.71			
Random Effects Parameter		Variance	Std. Deviation	
$U_i$		$\approx 0$	$\approx 0$	

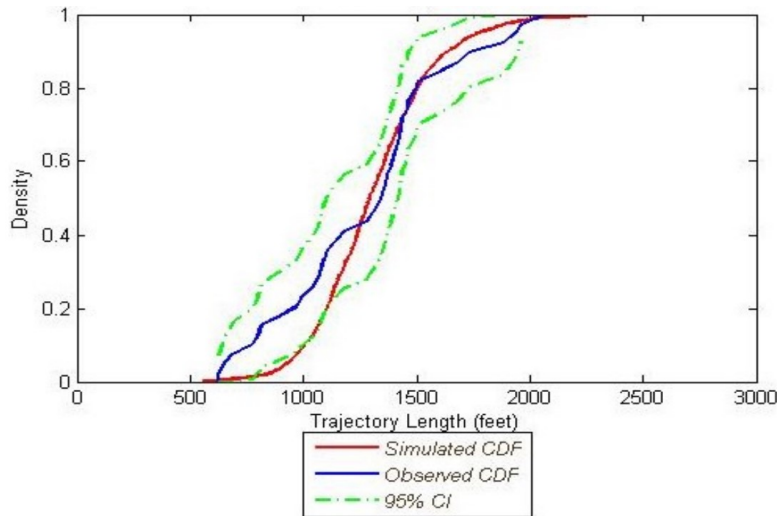
Another quantity used by the OLCR model is the time that drivers spend between lanes after they accept a gap in the target lane, essentially the duration of a lane change. The time that drivers take between making a decision and repositioning their vehicles in the middle of the target lane is quantified based on an analysis of the trajectory data performed as part of the Stanitsas study. This analysis produced a distribution of lane change durations that was normally-distributed with a mean equal to 2.79 seconds and a variance of 0.6 seconds<sup>2</sup>, shown in Figure 4.4. Figure 4.4 Distribution modeling the time drivers spend between lanes. (Stanitsas, 2013).



**Figure 4.4 Distribution modeling the time drivers spend between lanes.**

The last parameter required is used to account for the time drivers spend in each lane before they begin searching for a gap on the next lane. This is required due to the fact that drivers will take a short period of time after completing a lane change to evaluate the conditions of the lane they have just joined. This value, termed the Traffic Assessment Parameter (TAP), is sampled from a unimodal distribution – a

truncated normal distribution with mean equal to 0 seconds and standard deviation equal to 2.2 seconds. This method for selecting the TAP was determined by Stanitsas to provide the most realistic results, as seen in the comparison of the observed and simulated trajectory data in Figure 4.5.



**Figure 4.5 Comparison of cumulative distribution functions between observed and simulated trajectory lengths with unimodal TAP.**

#### 4.1.3 Simulation Process

The methodology developed to define advisory designs for OLCRs on freeway facilities uses the models described above to simulate traffic at the location of interest and determine a solution. Before the actual simulation can occur, the parameters of the Fundamental Diagram must be calibrated for each lane using historical data or data from a traffic simulator. This defines the capacity of each lane, which remains constant as individual simulation runs are used to generate a solution for a particular demand level.

To begin the run, trajectories for vehicles in the GP lanes are generated in five-minute intervals based on the parameters of the Fundamental Diagram and the desired demand level (density). Next, a numerical value is sampled for the TAP parameter for each driver and each lane change. When vehicles move from the acceleration lane to the lane on their left, the TAP is set equal to zero because there is no need for drivers to evaluate the conditions on the entrance ramp before start searching for an appropriate gap. The time increments that subject vehicles spend in each lane are shaped by the output of the gap-acceptance model and the time drivers spend between lanes. The same process is repeated for all of the lanes of interest. Given the speed of each lane involved in the process and the simulated time at which the subject vehicles travel, the total distance traveled between the entrance ramp and the HOT lane is computed. The percentage of drivers that should be served, which by default is set to 95%, is then used to provide a final recommendation of the location and size of the access point. Figure 4.6 shows a flow chart that describes this process.

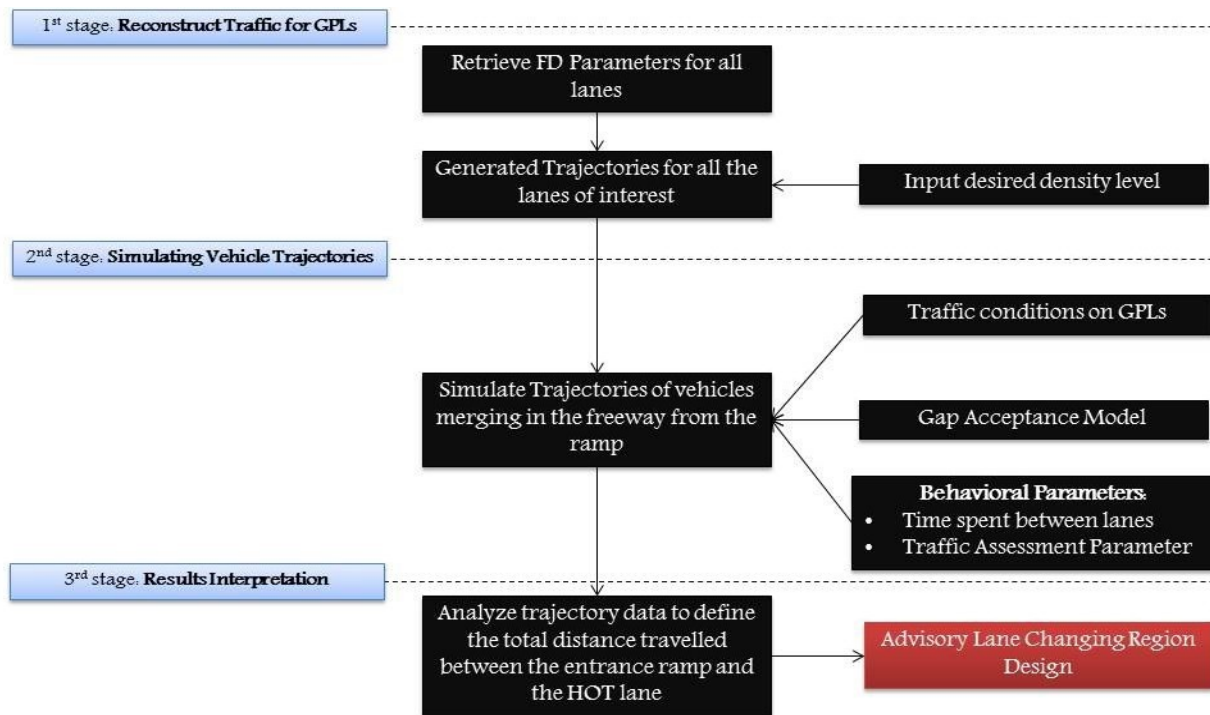


Figure 4.6 Schematic outlining the methodology for defining HOT access points at a location.

As mentioned previously, this process only provides a solution for each entrance/exit ramp. The results are therefore presented individually for each entrance/exit ramp. Once the program completes, the recommended location and size of the HOT access point is provided numerically relative to the location of the entrance ramp and a visualization is created to help the user see what the proposed access region will look like in the corridor (see Figure 4.7 for an example)



Figure 4.7 Visualizing the output of the Optimal Lane Changing Region model.

## 4.2 IMPLEMENTING THE PROPOSED METHODOLOGY ON I-394

To demonstrate how this model is applied to a corridor, a location on I-394 will be used as an example. Figure 4.8 presents the segment of interest that lies downstream of the entrance ramp from Louisiana Ave. The distance between the beginning of the gate and the entrance ramp to the freeway is approximately 2200 feet. In this particular example it is clear that the placement of the access point was primarily influenced by the entrance ramp from Louisiana Avenue, as Figure 4.9 shows that the access point is only 150 feet upstream of the next exit ramp.



Figure 4.8 Test Site on I-394 in relation to the upstream entrance ramp.



Figure 4.9 Test Site on I-394 in relation to the downstream exit ramp.

To demonstrate the potential of the proposed tool, Fundamental Diagram characteristics were identified for the examined location following the same procedure described for the validation experiments (shown in Table 4.2) Table 4.2 Fundamental Diagram Parameters GPLs on test site.. To define typical traffic conditions at this location, data for 10 typical weekdays were extracted, representing both winter and summer days. The density evolutions from five morning peak periods (7:00am - 9:30am) were used as the input to the experiment with the objective of capturing a large number of traffic patterns so that the design can accommodate a broad range of traffic conditions.

Table 4.2 Fundamental Diagram Parameters GPLs on test site.

Lane	Free-Flow Speed [miles/hour]	Jam Density [vehicles/mile]
1	63.78	130.9
2	71.52	112.2
3	71.29	134.3
4	69.48	111.6

Using these conditions as inputs to the methodology, the results suggests the starting point of the gate should be placed 750 feet downstream of the entrance ramp and be 1,100 feet long so that 95% of the users can successfully reach the HOT lane. As seen in Figure 4.10, this is significantly different compared to the existing design, which begins 1,450 feet downstream of the recommended location. Figure 4.11 Simulated trajectory lengths.presents the resulting histogram of the simulated distances that vehicles covered between the entrance ramp and the HOT lane. Based on this histogram, the actual location of the gate (2,200 feet downstream of the entrance ramp) is extremely generous, providing service to essentially 100% of entering users but significantly increasing the time they must wait before they are allowed to enter the HOT lane. Conversely, the location of the gate underserves users who wish to exit

the freeway at the downstream exit, as they are essentially unable to safely reach the exit ramp in the 150-foot space provided.



Figure 4.10 Proposed design.

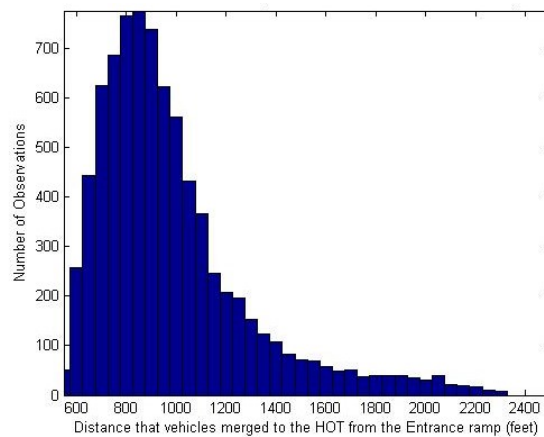
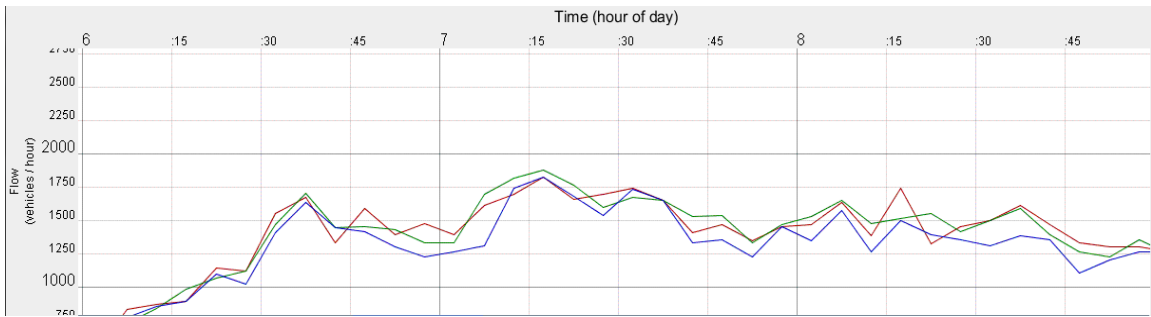


Figure 4.11 Simulated trajectory lengths.

Figure 4.12 Detector signal comparison - flow (vehicles/hour). presents the real flow evolution in vehicles per hour for a typical weekday for the detectors on the lane adjacent to the HOT lane at the examined segment – one upstream of the entrance ramp (red), one at the OLCR proposed beginning of the gate (green), and one at slightly downstream of the implemented beginning of the gate (blue). For most of the examined morning peak, flow at the OLCR-recommended beginning of the gate is consistently higher than the flow upstream of the entrance ramp. This can be attributed to vehicles merging onto the freeway from Louisiana Ave being forced to wait until access is permitted before merging into the HOT lane. Compared to the recommendation from the OLCR methodology, vehicles have to wait for up to 1,450 feet before the gate becomes available, placing additional traffic in the left-most GP lane that would otherwise use the HOT lane. In contrast, the OLCR recommendation would not result in this pattern as the additional vehicles would have already merged into the HOT lane as soon as they reached it.



**Figure 4.12 Detector signal comparison - flow (vehicles/hour).**

## CHAPTER 5: USER MANUAL

This section describes the interface developed for using the models discussed in previous chapters. The interface is a form-based web application that has a number of features to help organize the configuration of the system and simplify the process of generating results for a particular corridor. It also provides examples and descriptions of the inputs, outputs, and functions of the system to help walk the user through the process of using the tool.

The interface is organized around projects, which serve to encapsulate the configuration used for a particular investigation. The configuration consists of several pieces, some of which are modified by the user as part of regular operation of the tool and others that only need to be modified if the underlying assumptions of the model require changing. The things that are changed frequently are:

- the corridor segment being investigated
- the data used for informing the system of the common traffic conditions on the corridor
- predictions of changes in density on the HOT lane
- the network configuration, that maps corridor segments to detector IDs for retrieving data

The first three of these are set by the user for each project that they select. By default, the system uses the most recent network configuration (`metro_config.xml`) from IRIS, but the user may upload a specific file if they wish to investigate the conditions of a corridor at a specific point in time that no longer matches the current IRIS configuration.

The remaining configurable pieces only need to be changed when the underlying assumptions of the models must change. Because the models are statistical with a number of adjustable parameters that have been calibrated for a specific data set that represents the typical behaviors of drivers in the Twin Cities metro area, these parameters may need to change if there is a significant change in the behaviors of drivers or the traffic patterns in the region. These parameters are grouped into three main categories:

- parameters for modeling shockwave propagation, including platoon size distributions, headway distributions, and parameters that define driver car-following behavior
- the fundamental relationship between speed and density from traffic flow theory, i.e. the free-flow speed and jam density
- parameters that describe the way drivers change lanes, including gap acceptance probability and how long it takes drivers to make multiple successive lane changes

These first two groups combine to form “characteristic shockwave distributions,” which are distributions that model shockwave propagation over the range of hypothetical combinations of speed in the left-most GP lane and density in the HOT lane. These are used for identifying locations on a corridor where there are severe shockwaves that may require restricting access to the HOT lane. The last group is used when simulating lane changes in a small corridor segment to assess the impact of restricting access to drivers who may wish to enter the HOT lane from a nearby entrance ramp.

These pieces are organized in the web application in a way to emphasize the most commonly used features while still allowing the user to change them as needed without affecting other work. The following sections describe the layout of these features, how the features are used, and walks through an example of how to do so.

## 5.1 WEB INTERFACE IMPLEMENTATION

The backend for running the shockwave and lane change models is written in Python (2.7). The web interface is written in Python as well, using the Django web framework and Twitter Bootstrap to handle many of the web-specific features. Both the web application and the underlying models require a PostgreSQL database of version 9.5 or later. Additionally, the heavy computations are distributed to workers using Celery task queue (using RabbitMQ as the message queue and the PostgreSQL database for results) thereby allowing for a scalable computing environment that can easily be adjusted in response to demand for the tool. The development server produced by the University uses Apache HTTP Server to serve the files but other options could potentially be used.

## 5.2 SITE LAYOUT

To keep users' work organized, the application requires the user to log in before they can use it. Once logged in, the user is taken to their Dashboard, an example of which is shown in Figure 5.1. This page contains an overview of the user's work, including the number of projects they have created, the number of each type of configuration profiles available (including the defaults), and links to an overview pages for each of these.

Object	# Objects
Projects	9
Network Configurations	3
Characteristic Shockwave Distributions	1
Shockwave Model Parameter Profiles	1
Fundamental Relationship Models	1
Lane Change Models	1
Density Predictions	5
Trash	0

**Figure 5.1** User dashboard page, providing a broad overview of the user's work.

This figure also shows the static navigation elements of the site. The top bar provides a link to the user's dashboard (accessed by clicking on the "MnPASS Access Design Tool" page title), a link to a help section containing examples, and a link that logs the user out. The side bar provides access to the overview pages for projects, each of the configuration types, and a trash bin where objects are initially sent after they are deleted. It also highlights the section of the site where the user is currently located.

The project overview page (Figure 5.2) lists all of the projects that have been created by the user in a table, displaying the project name, the corridor segment with a plot highlighting the segment on the network map, the parameters of the data used, the owner, and the modified time. Initially the projects are sorted by their modification time in descending order, so that the most recently modified project appears first. This sorting can be changed by clicking on the respective column header.



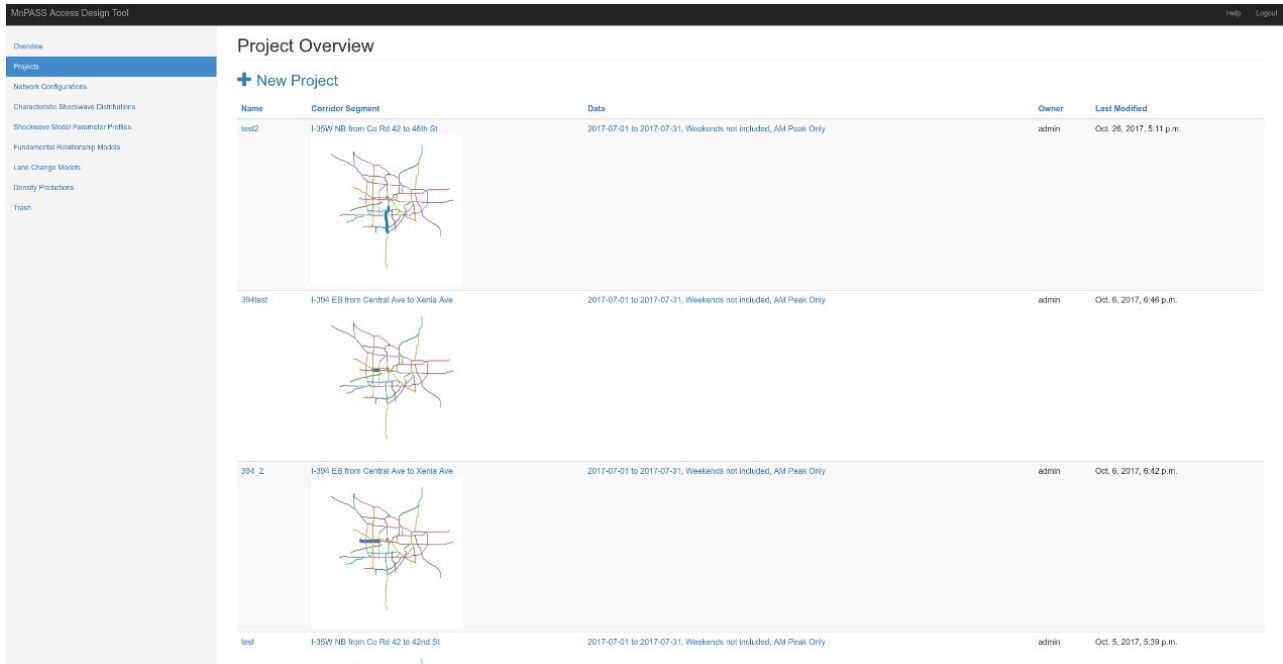


Figure 5.2 Project overview page, showing information about all of the user's projects.

The network configuration overview page (Figure 5.3) lists all of the network configurations that have been uploaded by the user, including their name, the timestamp in the metro\_config.xml file used for that profile, the owner of the configuration profile, and the modification time. The remaining overview pages (Figures 5.4-8) list the respective objects, including the owner of the object and the modification time. The final item in the navigation bar, the trash (Figure 5.9), lists all objects that have been sent to the trash by the user, along with buttons to restore the object or delete it forever.

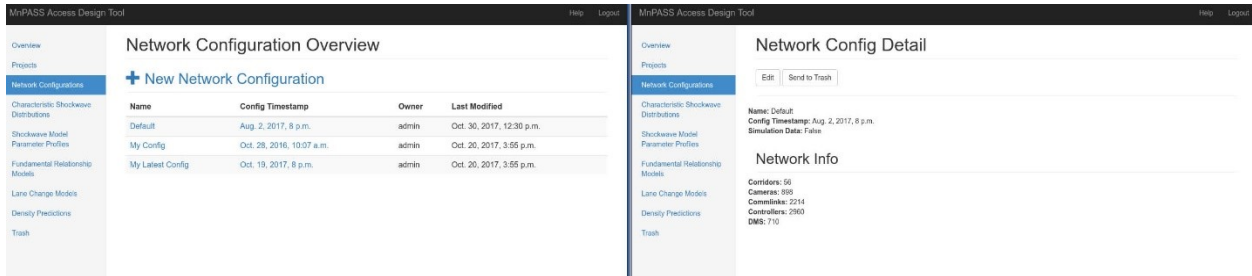


Figure 5.3 Network configuration overview page (left) and detail page (right).

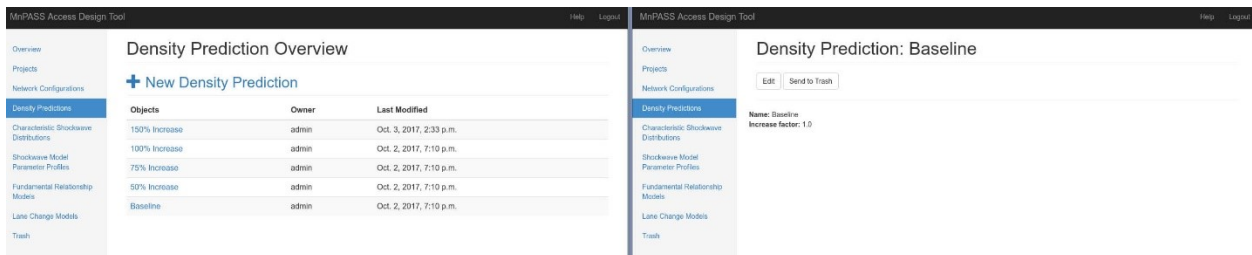


Figure 5.4 Density prediction overview page (left) and detail page (right).

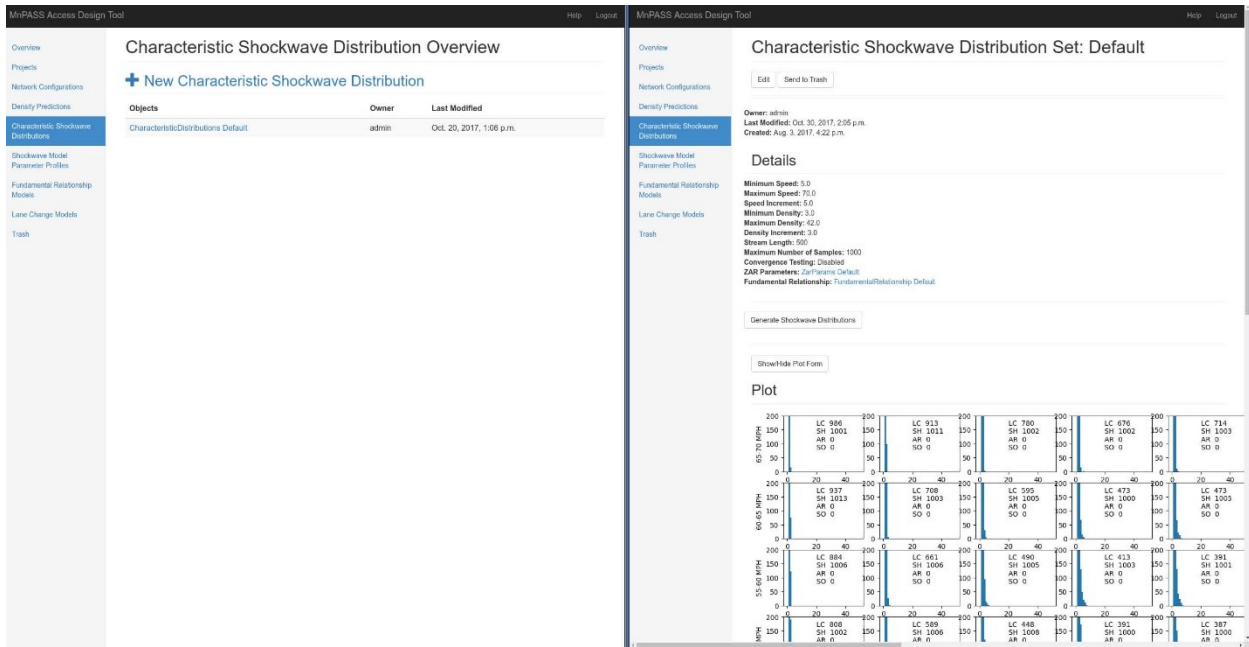


Figure 5.5 Characteristic shockwave distribution overview page (left) and detail page (right).

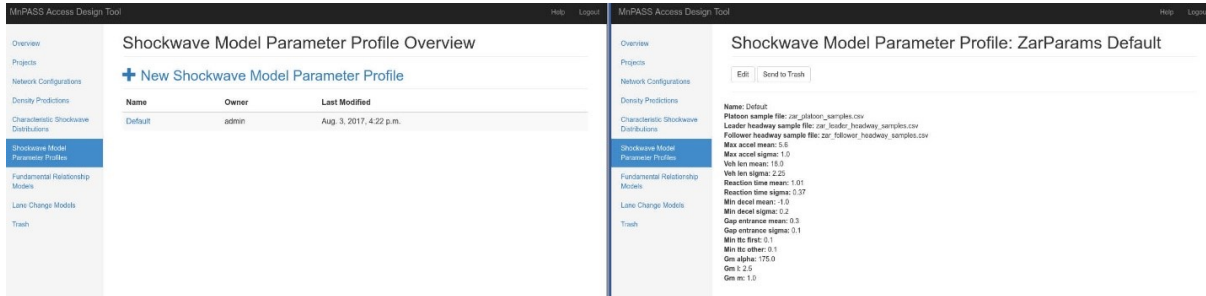


Figure 5.6 Shockwave model parameter profile overview page (left) and detail page (right).

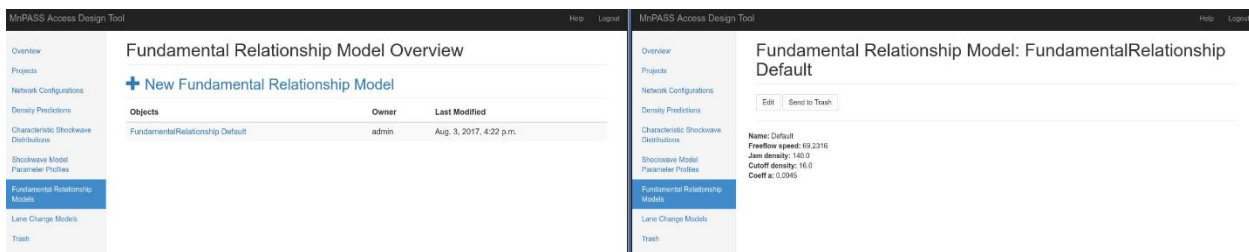


Figure 5.7 Fundamental relationship profile overview page (left) and detail page (right).

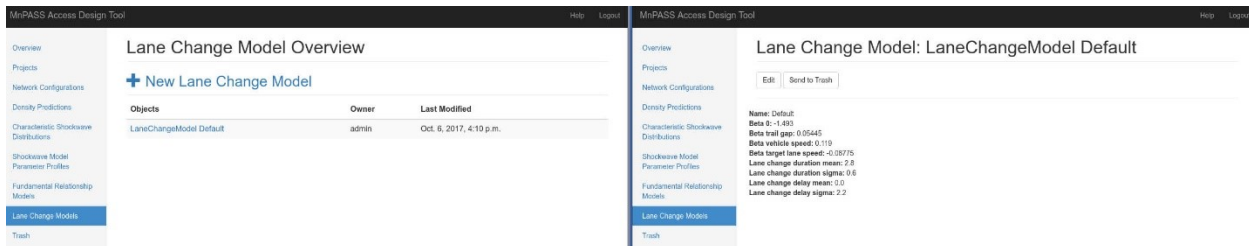


Figure 5.8 Lane change model profile overview page (left) and detail page (right).

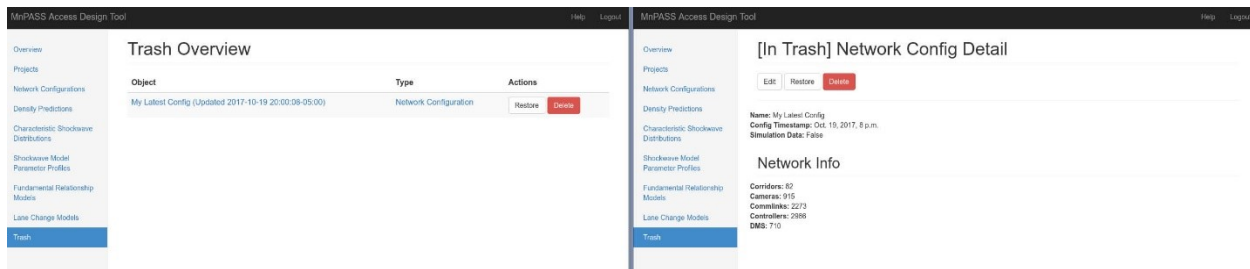


Figure 5.9 Trash overview page (left) and example of trashed object detail page (right).

From each overview page, the user can click on any item in the list to be directed to a page containing details of the selected item (Figures 5.3-9). In most cases the details consist only of a list of numerical parameters, but in some cases, such as for characteristic shockwave distributions (Figure 5.4), can include a visualization of the item’s data. In addition to this, the detail page contains buttons that can be used to edit the object or, if it is owned by the user (i.e. not one of the defaults), to send the object to the trash. For objects that are already in the trash (Figure 5.9), buttons to restore the object or delete it forever are displayed instead.

### 5.3 USING THE WEB INTERFACE

The main functionality of the MnPASS Access Design Tool is handled via projects, which allow the user to investigate the shockwave formation on a specific corridor segment using data from a specific period of time, and to investigate the impact of restricting access in a location on traffic entering the corridor. By default, the interface contains the necessary configurations to do this for the majority of situations without requiring any inputs from the user beyond the corridor of interest and the range of traffic data to use. To allow flexibility though, the interface also provides the user with the ability to generate additional configuration profiles to model the network as it was at a different point in time (via “network configurations”), model the effect of changes in HOT density (via “density predictions”), adjust how shockwave formation is modeled (via “characteristic shockwave distributions,” “shockwave model parameter profiles,” and “fundamental relationship models”), and adjust how lane changes are modeled (via “lane change models”). The following sections provide examples to show how these features are used and how they relate to each other. This information can also be accessed from within the web interface by clicking on the “Help” link in the top navigation bar.

#### 5.3.1 Working with Projects

To investigate a corridor segment, the user will need to create a new project. Start by clicking the "Projects" link in the site navigation pane to the left, then click the "New Project" link at the top of the page (Figure 5.10). Give the project a name, then select a network configuration to use. The default will automatically update each time it is used, otherwise the user can create your own (Figure 5.11). If the user would like to explore corridors that don't have an HOT lane, uncheck the box next to "Require HOT Detectors". Note that the results generated in this case may not be representative of conditions with a real HOT lane (Figure 5.12). Select a characteristic shockwave distributions set to use for generating results. In most cases the default will be OK, but the user may need to generate new sets if the user wants to model different driver behaviors or otherwise change the shockwave propagation modeling. After the user have selected one, click "Save" (Figure 5.13).

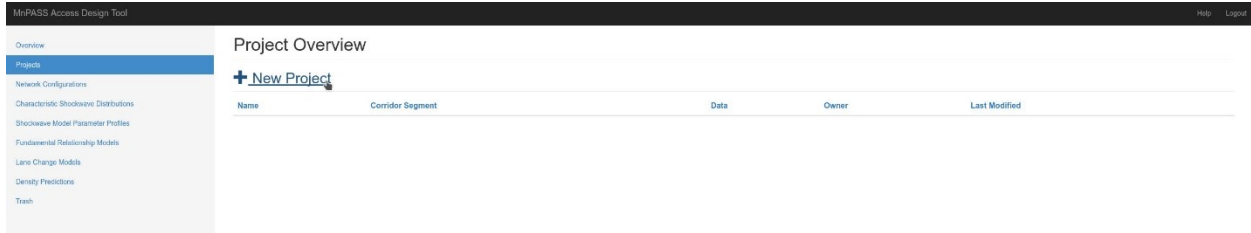


Figure 5.10 Link to create a new project.

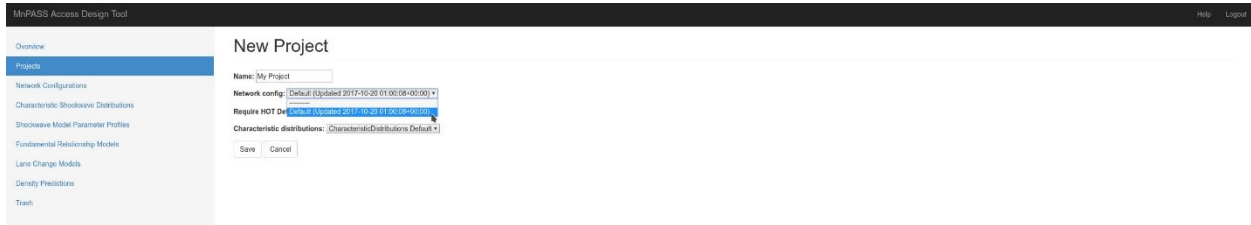


Figure 5.11 Selecting a network configuration for a project.



Figure 5.12 Checkbox to enable/disable HOT detector requirement for data retrieval.

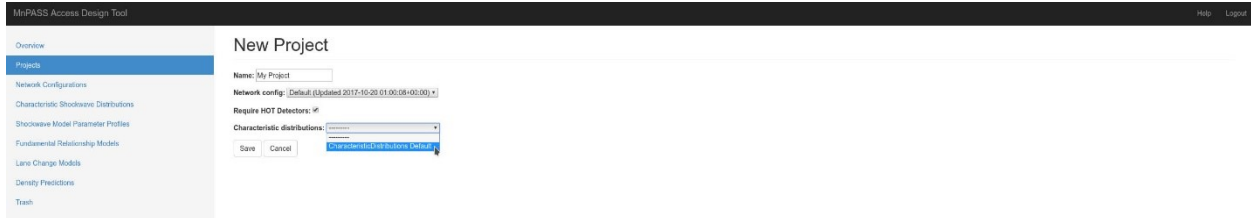


Figure 5.13 Selecting a characteristic shockwave distribution set for a project.

The user will be redirected to the newly-created project page. Now the user must select a corridor segment to investigate. To do this, click on the "Select..." link next to "Corridor segment" (Figure 5.14). The user will be directed to a new page to perform the selection. Select a corridor segment using the drop down menus. The menus will automatically populate with options from the selected network configuration. Once the user have selected the route, direction, start, and end points, click "Save" to be directed back to the project page (Figure 5.15). Now the user must select the data that will be used to generate results. To do this, click on the "Select..." link next to "Traffic Data" (Figure 5.16) and the user will be directed to a new page. Use the date pickers to select a start and end date (Figure 5.17). Leave the box next to "Use weekends" unchecked unless the user would like weekends to be included in the data retrieved. Select the period from each day that will be used: AM Peak (6:00am – 10:00am), PM Peak (3:00pm – 7:00pm), both peak periods ("Peak Periods Only"), or the full day (Figure 5.17). Then click "Save" to be directed back to the project page again.

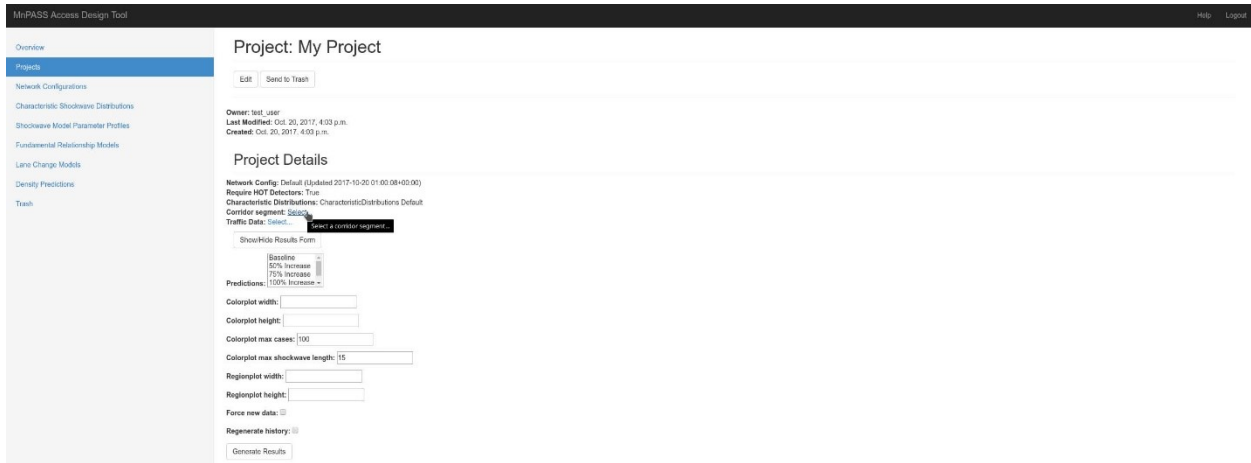


Figure 5.14 Link to select corridor segment for a project.



Figure 5.15 Corridor segment selection page.

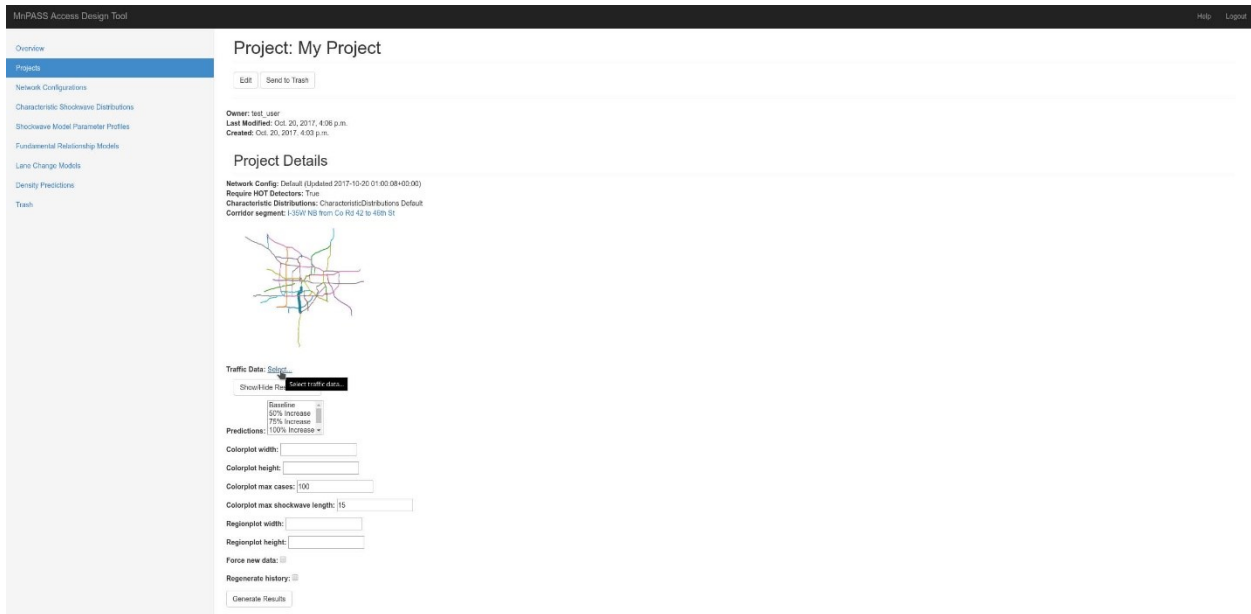


Figure 5.16 Link to select traffic data for a project.

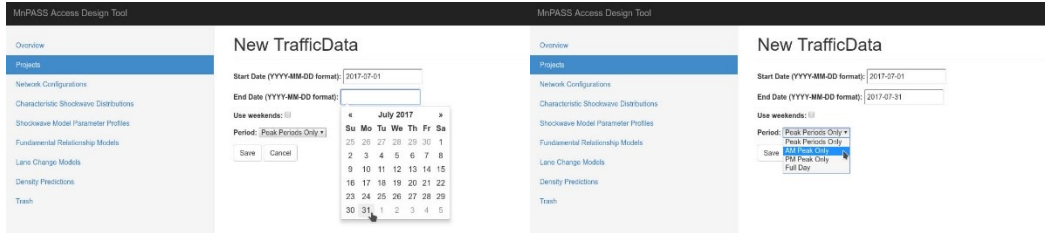


Figure 5.17 Traffic data selection form.

The user is now ready to generate results. To do this, select one or more predictions to use for generating results (select multiples by holding down Ctrl or Shift), adjust any of the fields if the user like (descriptions of them will appear as the user hover over them), then click "Generate Results" (Figure 5.18). The application will then begin fetching results. The progress will be shown as a percentage and the page will periodically refresh until the results are ready. Once they are, the user will see plots on the page (Figure 5.19). The color plot on the left shows the distribution of shockwaves along the corridor, with the Y-axis showing the station, the X-axis showing the shockwave length, and the color intensity showing the number of shockwaves of that length at that station (capped at 100 by default). The shockwave length and maximum number of shockwaves can be adjusted by changing the corresponding values in the form and regenerating results. The data that is retrieved is stored in a database so regenerating will not take as much time as the first generation. The plot on the right shows the frequency of speed and density conditions on the corridor, split into four regions (described in the legend). This is to give the user an idea of the traffic conditions in this corridor that were used to generate the color plot.

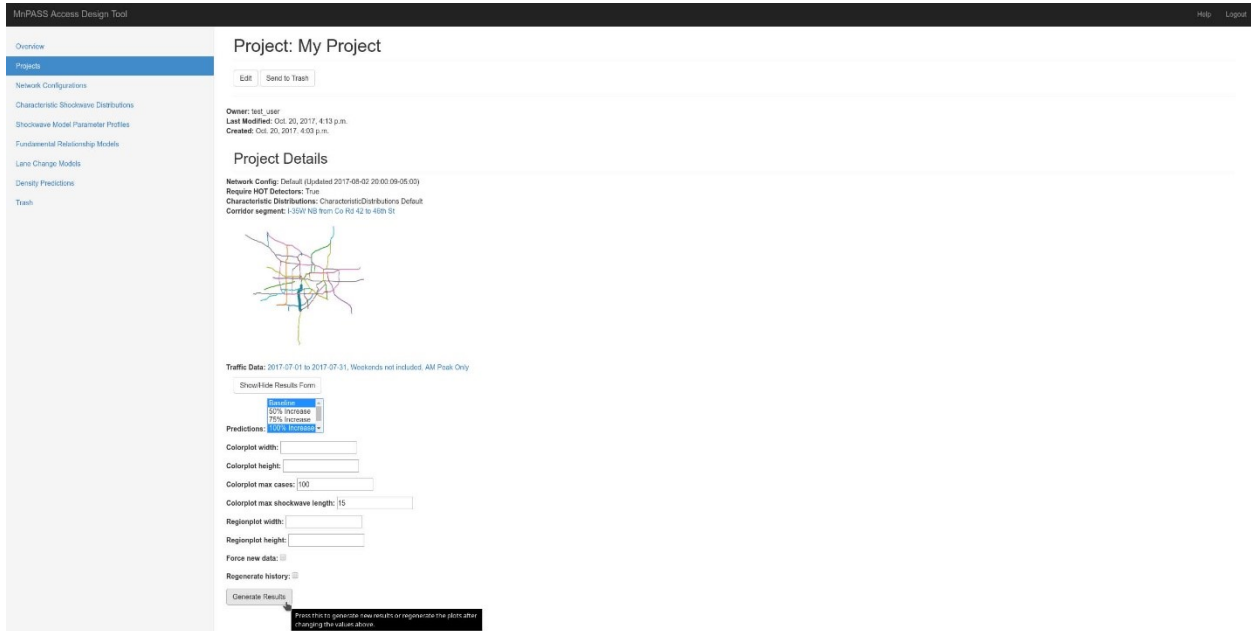


Figure 5.18 Form for generating shockwave propagation results

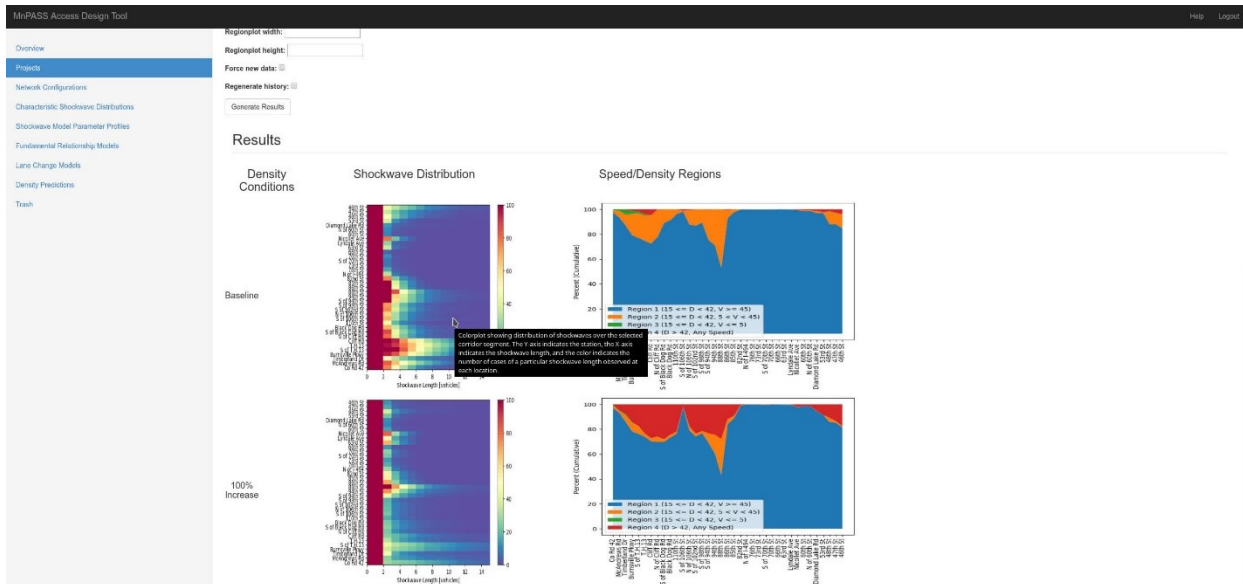


Figure 5.19 Project page after results are generated, including color plots showing shockwave severity (left column) and plots showing a visualization of the traffic data used to generate the color plot.

Once the user have generated the shockwave plots, the user can explore closing access at a particular station on the corridor by running lane change simulations. To do this, first select one of the stations from the drop down list (Figure 5.20). Adjust any of the options if the user like, then click "Check Data" (Figure 5.21). This will fetch additional data for the other traffic lanes to allow the lane change simulation. It will also check to see if the data is suitable for the model that is used. If it isn't a warning will be shown advising the user to select another station; if the user don't the results may be misleading.

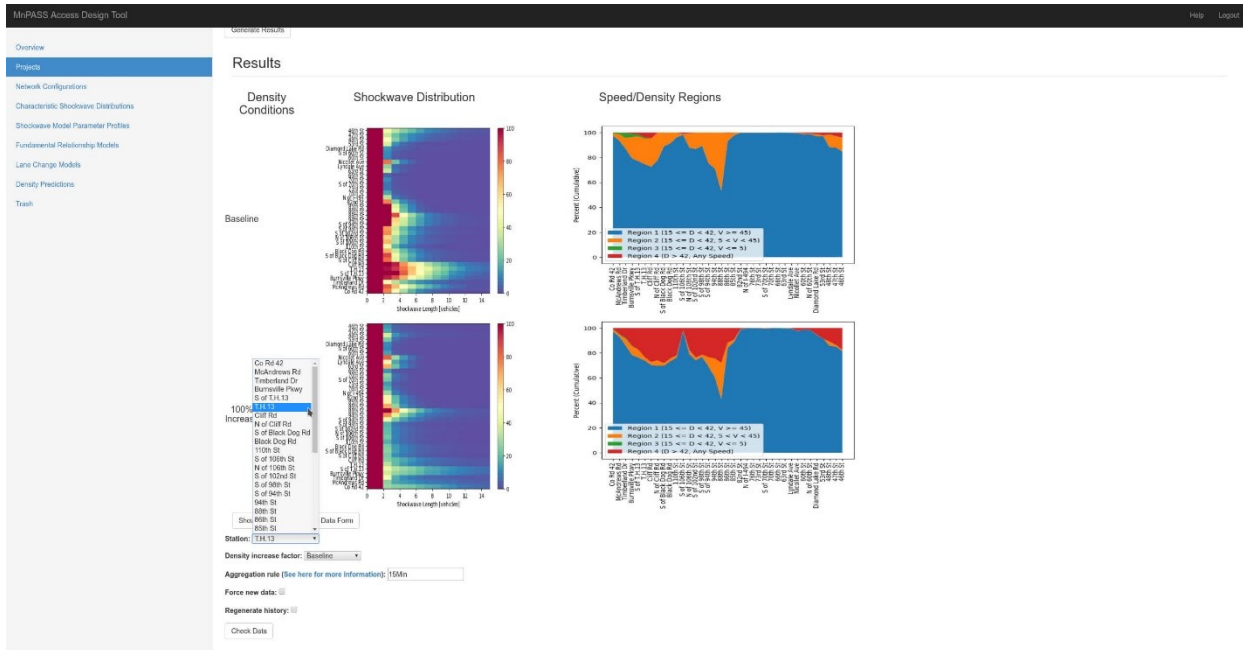


Figure 5.20 Dropdown menu for selecting a station for exploring access restriction in high-shockwave areas.

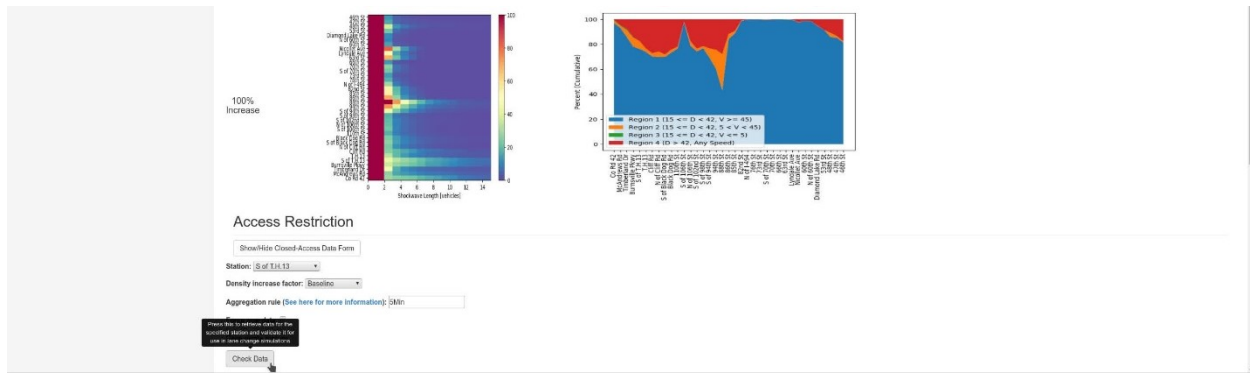


Figure 5.21 Button for starting data retrieval for running lane change simulations.

Once the data is ready, another form will appear, along with a diagram showing how the inputs correspond to a design solution. The user can use the "Distance to ramp gore" parameter to design an access gate for the case of a station upstream of an entrance ramp (blue on the diagram) OR the case of a station downstream of an entrance ramp (red on the diagram). Note that only one of these cases can be modeled at a time. Inputting a value for the "Distance to ramp gore" parameter will cause the resulting lane change and gate distances to be relative to the station the user selected. Once the user have input a distance value, change any of the other options if the user like, then click "Run Simulation" (Figure 5.22).

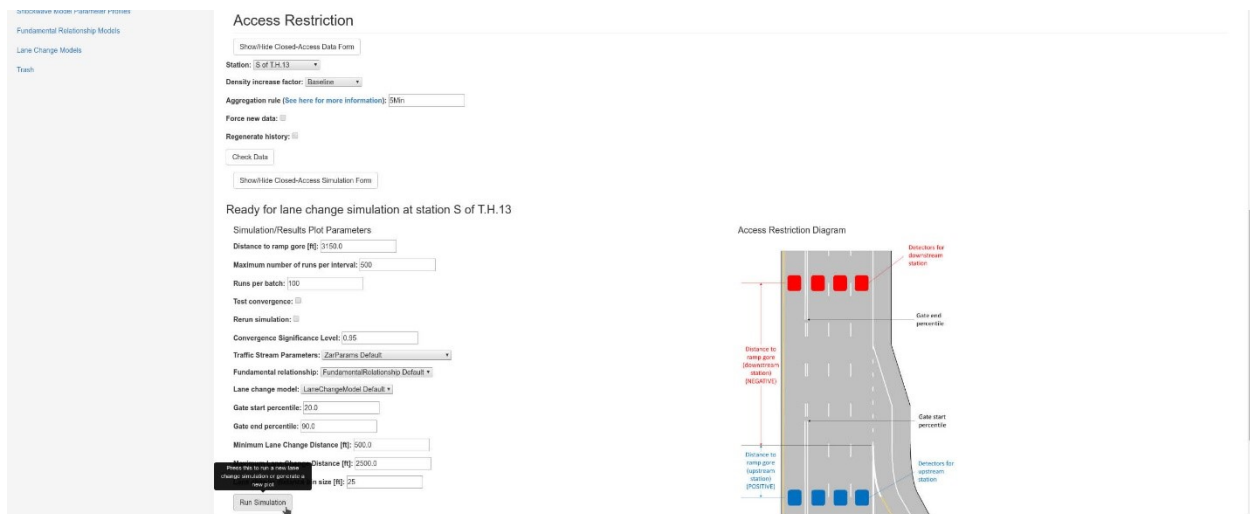


Figure 5.22 Form for running lane change simulations and diagram to help the user.

The simulation will then run, with the progress indicated by a percentage, and the page will periodically refresh. Once it is done, the user will be shown a histogram showing the distribution of the distances traversed by vehicles attempting to reach the HOT lane from an upstream entrance ramp, along with design recommendations to accommodate a certain percentage of drivers (Figure 5.23). If the user entered a value for the "Distance to ramp gore parameter," these distances are measured relative to the station the user selected. Otherwise they are measured from the first point vehicles can merge onto the right-most lane, i.e. the gore of a theoretical entrance ramp. This can help the user understand the implications of closing access in a particular location on service for vehicles entering from an upstream ramp.



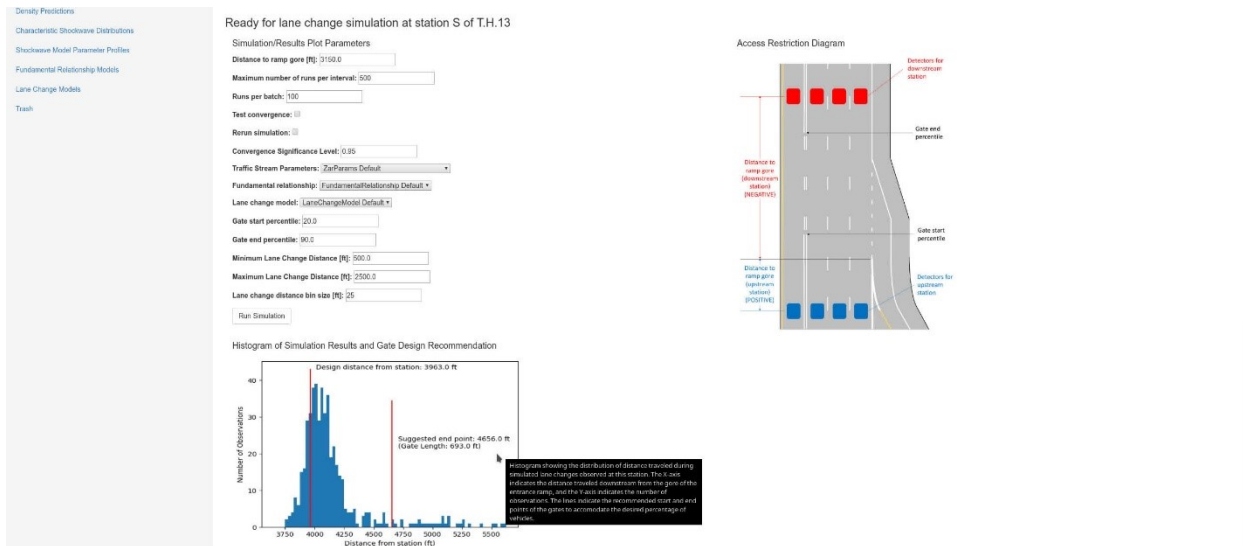


Figure 5.23 Plot with histogram of simulated lane changes and recommended gate position.

### 5.3.2 Defining a New Network Configuration

A network configuration is made using a metro\_config.xml file from IRIS. By default, the default configuration will always retrieve the latest file from IRIS, but the user can create new configurations to use a specific file, or to freeze it at the current point in time.

To define a new network configuration from a metro\_config.xml file, start by clicking the "Network Configurations" link in the site navigation pane to the left, then click the "New Network Configuration" link at the top of the page (Figure 5.24). Give the configuration a name, then upload your metro\_config.xml file (Figure 5.25). The user will be redirected to a page showing details about the configuration file uploaded. The user will now see the option in your list of available Network Configurations (Figure 5.27).

To define a new network configuration using the latest XML file, start again by clicking the "Network Configurations" link in the site navigation pane to the left, then click the "New Network Configuration" link at the top of the page (Figure 5.24). Give the configuration a name, but this time don't upload a file. The latest file will automatically be retrieved (Figure 5.26). The user will be redirected to a page showing details about the configuration file uploaded. The user will now see the option in your list of available Network Configurations (Figure 5.27). This configuration, unlike the default configuration, will be fixed with this file and will not update automatically.



Figure 5.24 Link to create a new network configuration.

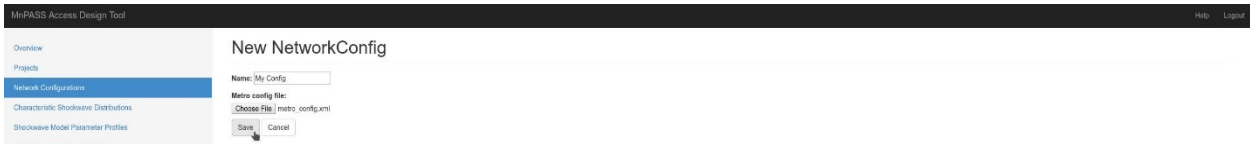


Figure 5.25 Form for creating a new network configuration, with a file uploaded.

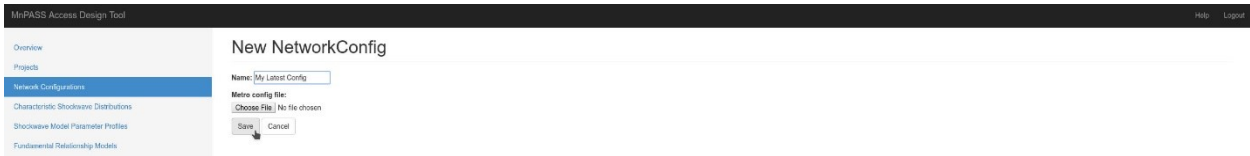


Figure 5.26 Form for creating a new network configuration, without a file uploaded (will retrieve the latest).



Figure 5.27 List of network configurations showing user-created options along with default. Note the values in the "Config Timestamp" column, which indicate the date that the corresponding metro\_config.xml file was updated.

### 5.3.3 Creating a New Characteristic Shockwave Distribution Set

The Characteristic Shockwave Distributions are used to generate the shockwave severity data given the traffic data on the selected corridor. The distributions are general and encompass conditions over the entire range of realistic left GP lane speed/HOT lane density conditions, but are tied to a particular set of parameters that describe the shockwave propagation process (such as car following parameters and platoon sizes, among others). In order to change these parameters for an investigation, the user must generate a new Characteristic Shockwave Distribution set and use it for a project.

To create a new Characteristic Shockwave Distribution set, start by clicking the "Characteristic Shockwave Distributions" link in the site navigation pane to the left, then click the "New Characteristic Shockwave Distribution" link at the top of the page (Figure 5.28). Give the new distribution set a name and change any parameters the user would like, such as the minimum/maximum HOT density/left GP lane speed. Select one of the available shockwave parameter profiles and fundamental relationship models. If the user wish to use adjust the shockwave generation parameters or the fundamental relationship between speed and density, the user must do that first by creating a new profile (Section 5.2.4). Once the user are done, click the save button (Figure 5.29).



Figure 5.28 Link to create a new Characteristic Shockwave Distribution set.

MiPASS Access Design Tool

Overview  
Projects  
Network Configurations  
Density Predictions  
**Characteristic Shockwave Distributions**  
Shockwave Model Parameter Profiles  
Fundamental Relationship Models  
Lane Change Models  
Trash

### New CharacteristicDistributions

Name: My Characteristic Distrib

Min speed: 10.0

Max speed: 70.0

Speed increment: 5.0

Min density: 15.0

Max density: 42.0

Density increment: 3.0

Stream length: 500

Maximum number of samples: 1000

Test convergence:

Significance: 0.95

Zar params: ZarParams Default

Fundamental relationship: FundamentalRelationship Default

Save Cancel

**Figure 5.29** Form for creating a new Characteristic Shockwave Distribution set.

The user will be redirected to a page showing details about the new distribution set, which has not been generated yet. To generate the shockwave distributions, which requires running computationally-intensive simulations that will take hours to days to finish running, click the "Generate Shockwave Distributions" button (Figure 5.30). The simulations will then begin running. The user can check on the progress of the generation by checking this page and looking at the percent complete value (Figure 5.31). If the user wishes to abort the run, press the "Cancel Run" button and the process will terminate within a few seconds.

MiPASS Access Design Tool

Overview  
Projects  
Network Configurations  
Density Predictions  
**Characteristic Shockwave Distributions**  
Shockwave Model Parameter Profiles  
Fundamental Relationship Models  
Lane Change Models  
Trash

### Characteristic Shockwave Distribution Set: My Characteristic Distributions

Edit Send to Trash

Owner: admin  
Last Modified: Oct 30, 2017, 2:15 p.m.  
Created: Oct 30, 2017, 2:15 p.m.

#### Details

Minimum Speed: 10.0  
Maximum Speed: 70.0  
Speed Increment: 5.0  
Minimum Density: 15.0  
Maximum Density: 42.0  
Density Increment: 3.0  
Stream Length: 500  
Maximum Number of Samples: 1000  
Convergence Testing: Disabled  
ZAR Parameters: ZarParams Default  
Fundamental Relationship: FundamentalRelationship Default

Generate Shockwave Distributions

Show/Hide Plot Form

Figure width:

Figure height:

Subplot width: 2.5

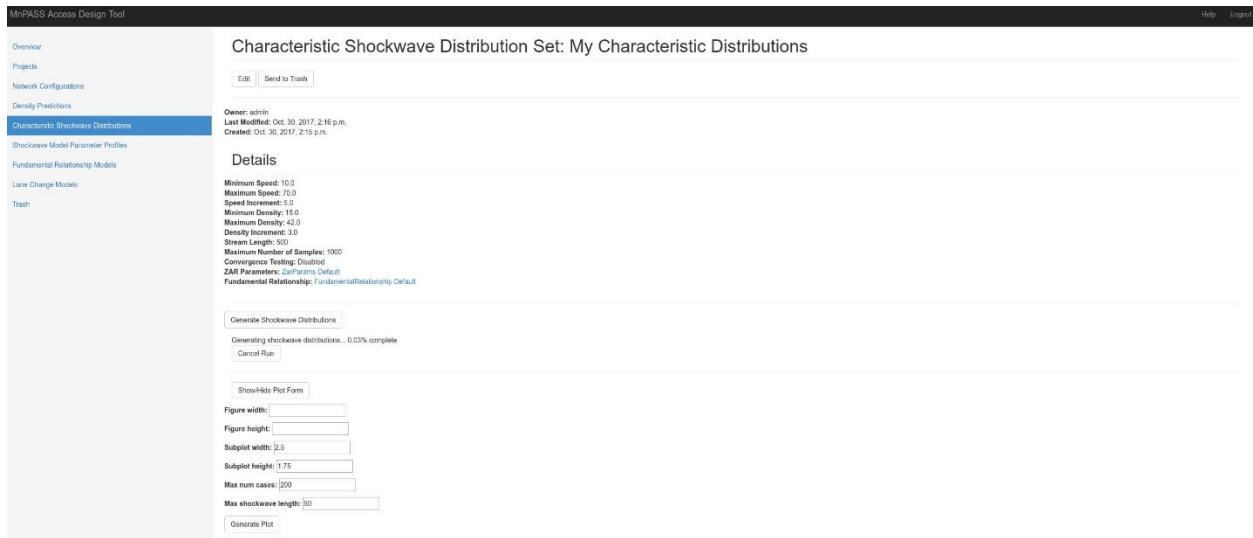
Subplot height: 1.75

Max num cases: 200

Max shockwave length: 50

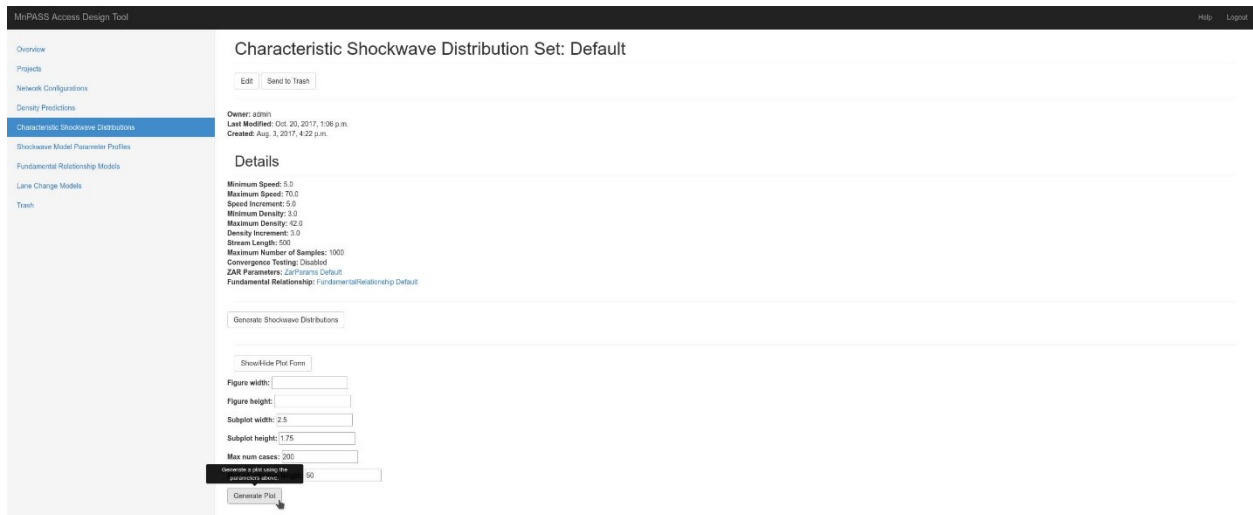
Generate Plot

**Figure 5.30** Characteristic Shockwave Distribution page before simulations are started.



**Figure 5.31 Characteristic Shockwave Distribution page during a running simulation, showing progress and a cancel button.**

Once the process has finished, the percent complete indicator will disappear. The distribution will now be available for selection in your projects. The user can also generate a plot showing all of the distributions by clicking the "Generate Plot" button at the bottom of the page (Figure 5.32). The user can adjust some of the plot parameters before doing so using the form if the user would like. This step is optional, but is recommended so the user can visualize the results of your changes to the model(s). The plot will then start to generate. There is no progress indicator for this, though it should take less than a minute. The page will auto-refresh until it is done, after which the user will see the plot at the bottom of the page (Figure 5.33). The plot consists of a number of subplots, each showing the distribution of shockwaves formed at a given HOT density and left GP lane speed based on the inputs the user specified. To allow the distributions to adequately model all traffic conditions the plot will be large, so the user may have to scroll to see all of them.



**Figure 5.32 Button to generate plots of the Characteristic Shockwave Distribution set.**

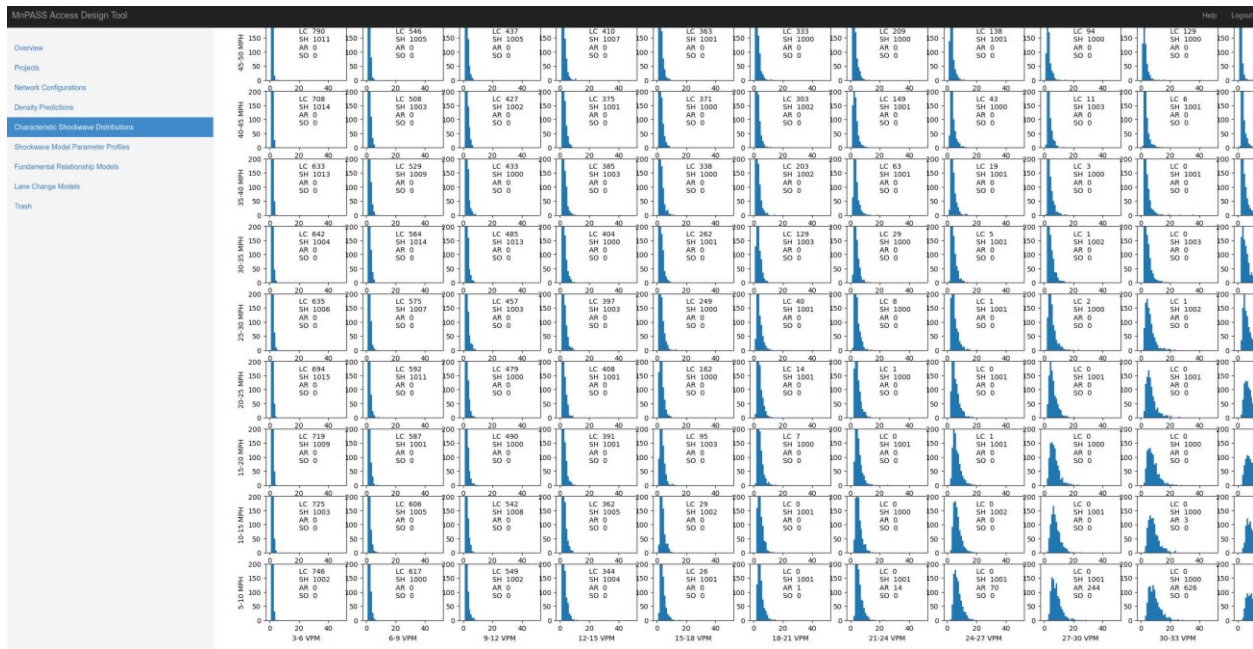


Figure 5.33 Section of the Characteristic Shockwave Distribution set plot.

### 5.3.4 Creating a New Parameter Profile

To create a new parameter profile (a Shockwave Model, Fundamental Relationship Model, or a Lane Change Model), click on the corresponding link in the navigation sidebar, then click on the "New..." link at the top of the page. This example looks at creating a new Shockwave Model Profile (Figure 5.34). Give the new model profile a name and change any parameters the user would like, such as the minimum/maximum vehicle acceleration, mean/standard deviation for vehicle length or reaction time distributions, or car following parameters, among others. The user can also upload new CSV files containing platoon size or vehicle headway distributions, otherwise the defaults will be used (note that this is not an option for other models). Once the user have made all the changes the user would like, click the save button (Figure 5.35). The user will be redirected to a page showing details about the new parameter profile. The user can edit the values if the user like by clicking on the "Edit" button near the top of the page. The model will now be available for selection when creating a new characteristic shockwave distribution set, as seen in Figure 5.36.



Figure 5.34 Link to create a new Shockwave Model Parameter Profile.

Figure 5.35 Form for editing Shockwave Model Parameter values.

Figure 5.36 New Shockwave Model available for selection when creating or editing a Characteristic Shockwave Distribution set.

## CHAPTER 6: CONCLUSIONS

The product of this project provides a tool for traffic managers and planners to examine the conditions within an existing or prospective corridor and the distribution of shockwave lengths which are expected. From the distribution of shockwave lengths, decisions can be made regarding access restriction on the HOT lane to ensure that drivers do not attempt to make lane changes at locations prone to dangerous conditions. This tool provides support for the managers and planners by aggregating the entire behavior of the HOT lane within the corridor into a framework for simplified consideration.

The final methodology is an improvement and expansion over previous efforts. Stream generation was reworked to ensure a good mix of target stream densities and speeds are created, and include perturbation and simulation in order to ensure that the vehicle streams used for simulation are realistic. Shockwave simulations were improved through the inclusion of a complete car following model and additional parameters and behaviors to capture the ability of drivers to observe beyond their immediate leader. The entire Monte Carlo sampling framework was also extended throughout a corridor by the inclusion of an assessment of historical data. Ultimately, the results produced by this project are more robust than previous approaches.

There are still several areas in which improvements could be made. At the core, this methodology is based on the data collected along the I-35W and I-394 HOT lanes. The extent of that data limited the scope of calibration and validation for the tool. Notably, no data was collected while the HOT was at densities approaching breakdown (33 to 42 vpm). Within that scope, it is possible that driver behavior changes significantly since gaps are much smaller. Regarding those underlying behaviors, two components were incorporated into the model through calibration in order to produce satisfactory results: a scaling sensitivity coefficient on the GM car following model, and a look ahead mechanism which also scales with density. In both cases, linear relationships between density and the parameter were introduced to shift driver behavior as density increases. However, lacking calibration data or specific measurements of how drivers perform (especially with regard to look ahead), these mechanisms are only estimations based on engineering judgement of reasonable behavior.

Regarding the car following model, although many different calibrations were attempted, it is possible that a more accurate set of calibration values exists. Again, a more robust dataset of real-world shockwave measurements would aid in producing a well-fitting car following model. Other car following models entirely may also fit the situation more accurately. This methodology utilized the GM model due to the simple inputs of position and speed and the relatively flexible framework of its calibration parameters. Other car following models were not fully considered and could replace the GM model within the methodology. Fortunately, the development of this tool proceeded in such a way that the car following model is isolated within the model, allowing for relatively straightforward replacement if the need arise.

When combining the resulting characteristic shockwave distributions with historical data to produce comprehensive shockwave distributions, two important assumptions are made regarding the corridor: that the lane change frequency between the GP and HOT is constant over time, and is also evenly distributed across the corridor. Both of these assumptions raise crucial issues regarding the management of the HOT, but the mechanisms necessary to resolve them are far from trivial. This methodology makes these assumptions to provide a simplified view of a corridor's behavior and allow traffic managers to gain insight into potential safety hazards without requiring the construction and calibration of a micro-simulation model. In the case that information regarding these two assumptions

is available, additional weighting could be introduced to this methodology to improve the resulting assessment.

Finally, this project explored the possibility of increased density scenarios with regard to the HOT. Those scenarios were constructed by scaling up the density on the HOT at all times of day while leaving the activity on the general purpose lanes unaltered. While interesting, these increase scenarios are not realistic in the sense that the HOT and GP lanes both change as demand across the corridor increases. A more robust mechanism for estimating future conditions would lead to more realistic estimates of future comprehensive distributions. Rather than the dramatic increase in congested HOT which was developed with the increase scenarios in the previous chapter, a larger component of characteristic distribution-range conditions would be expected given that the tolling mechanism on the HOT works to maintain operations on the lane. If demand across the corridor increases, the tolling mechanism pushes back to keep the HOT lane functioning, prolonging pre-congestion conditions as much as possible.



## REFERENCES

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