

2016

**STRIDE** | Southeastern Transportation Research,  
Innovation, Development and Education Center

# Final Report

Dynamic Traffic Control  
Interventions for Enhanced  
Mobility and Economic  
Competitiveness  
(Project #2013-009S)



Authors: Nagui M. Roupail, Ph.D., NCSU; Mohammed Hadi, Ph.D., FIU; Behzad Aghdashi, Ph.D. NCSU; Graduate Students: Samaneh Khazraeian, Joseph L. Trask and Yan Xiao

July 2016



## **DISCLAIMER**

*“The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation’s University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.”*

## **AUTHORS**

**Nagui M. Rouphail, Behzad Aghdashi, Joseph L Trask**

*Institute for Transportation Research and Education*

*North Carolina State University*

*Raleigh, NC, 27606*

**Mohammed Hadi, Yan Xiao, Samaneh Khazraeian**

*Lehman Center for Transportation Research*

*Florida International University*

*Miami, FL, 33199*

## TABLE OF CONTENTS

DISCLAIMER .....	i
AUTHORS.....	ii
TABLE OF CONTENTS.....	iii
LIST OF TABLES .....	vi
LIST OF FIGURES .....	vii
ACKNOWLEDGMENTS .....	xi
EXECUTIVE SUMMARY .....	xii
CHAPTER 1 INTRODUCTION AND BACKGROUND.....	14
BACKGROUND.....	15
RESEARCH OBJECTIVES .....	16
ORGANIZATION OF THE REPORT .....	16
CHAPTER 2 LITERATURE REVIEW.....	18
HARD SHOULDER RUNNING.....	19
Hard Shoulder Running Experience in Paris, France (A3-A86 Junction).....	19
Hard Shoulder Running Experience in Germany.....	20
Hard Shoulder Experience in United Kingdom (M42) .....	22
Hard shoulder Experience in the Netherlands .....	24
Hard Shoulder Experiences in the USA .....	25
Summary of Hard Shoulder Running Studies .....	26
RAMP METERING.....	27
Local Metering Strategies.....	28
System-Wide Algorithms .....	32
Ramp Metering Field Implementations.....	35
TRAFFIC DIVERSION.....	35
INCIDENT MANAGEMENT .....	36
CHAPTER 3 MODELING FRAMEWORK.....	39
FRAMEWORK OVERVIEW .....	39
	iii

Phase 1: Administrator Scenario Generation and Strategy Configuration .....	41
Phase 2: End User Interventions and ATM Selection .....	42
Phase 3: Multi-Run and Comparison.....	44
Detailed Process Flow Steps for the Framework .....	45
Step 1: Create Base Facility or Seed File .....	45
Step 2: Scenario Generation .....	45
Step 3: ATM Strategy Availability Configuration. ....	51
Step 4: Specify Output Display Options and Facility Event Information. ....	56
Step 5: Perform HCM Analysis for Current Analysis Period (AP) and Show Partial Results .....	59
Step 6: Check if the Current AP is the Last AP.....	61
Step 7: Select a Set of ATM Strategies to Be Incorporated in the Next AP .....	62
Step 8: View Run Analysis Summary .....	63
Step 9: Perform Another Analysis Run? .....	64
Step 10: Report Generator .....	65
CHAPTER 4 MODELING ATM STRATEGIES.....	67
TRAFFIC DIVERSION.....	67
INCIDENT MANAGEMENT .....	68
HARD SHOULDER RUNNING (HSR) .....	68
RAMP METERING.....	69
Objectives .....	69
Available Performance Measures for Ramp Metering .....	70
Calculating Necessary Performance Measures for Adaptive Ramp Metering .....	71
Challenges and Deviations from HCM Oversaturated Methodology .....	74
Illustrative Example 1 .....	76
Illustrative Example # 2.....	79
CHAPTER 5 CASE STUDIES .....	89
I-40 in NC CASE STUDY .....	89
Use Case 1: Ramp Metering with a Weather Event .....	90

Use Case 2: Incident Event with Hard Shoulder Running .....	95
Use Case 3: Incident Event with Diversion due to DMS .....	98
Use Case 4: Incident Event with Incident Management.....	101
Use Case 5: Incident Event with DMS Induced Diversion and Incident Management .....	104
Use Case 6: Work Zone.....	108
Summary of Use Cases.....	112
I-95 Case Study .....	114
Use case 1: Ramp Metering with a Weather Event .....	114
Use case 2: Incident Event with Hard Shoulder Running .....	117
Use case 3: Incident Event with the DMS Induced Diversion .....	118
Use case 4: Incident Event with Incident Management .....	120
Use case 5: Incident and Rain Events with DMS Induced Diversion and Incident Management .....	122
Use case 6: Work Zone.....	124
Summary of Use Cases.....	128
CHAPTER 6 SUMMARY AND NEXT STEPS .....	129
REFERENCES .....	132
APPENDIX A.....	1
APPENDIX B .....	1

## LIST OF TABLES

Table 2-1. Before and After Study for Hard Shoulder Use in France [1].....	19
Table 2-2. Sections with Dynamic Hard Shoulder in Germany [4].....	20
Table 2-3. Summary of Hard Shoulder Experiences .....	27
Table 2-4. Ramp Metering Benefits-Real World Experiences .....	35
Table 3-1. List of ATM strategies included in the framework. ....	42
Table 4-1. Hard shoulder Running Recommended CAFs to be implemented in the FREEVAL-DSS tool.....	68
Table 4-2. – Demand Data for Illustrative Example #1 .....	77
Table 4-3. Facility Leve Performance Measures With and Without Ramp Metering .....	78
Table 4-4. Selected Ramp and Mainlines Demands for the Four Regimes .....	81
Table 4-5. Fuzzy Logic Output Parameters Used in Illustrative Example # 2 .....	82
Table 4-6 ramp metering results summary for Regime II.....	82
Table 4-7. Average Generated Metering Rates - Regime II .....	84
Table 4-8. Illustrative Example 2 Ramp Metering Analysis- Regime III.....	85
Table 4-9. Average Generated Metering Rates – Regime III .....	85
Table 4-10. Illustrative Example 2 Ramp Metering Analysis- Regime IV .....	86
Table 4-11. Average Generated Metering Rates - Regime IV.....	86
Table 4-12. Illustrative Example 2. Ramp Metering Analysis- Regime V.....	87
Table 4-13. Average Generated Metering Rates - Regime V .....	87
Table 5-1: Summary of the use cases for the I-40 case study.....	113
Table 5-2: Summary of the use cases for the I-95 case study.....	128

## LIST OF FIGURES

Figure 2-1. Flow-speed curve for A3 and A4 motorways after implementation of HSR [21] .....	21
Figure 2-2. Speed-volume relationship of hard shoulder use in Germany [22].....	22
Figure 2-3. Hard shoulder use signs in Germany [22].....	22
Figure 2-4. Active Traffic management on M42 motorway, UK [24] .....	23
Figure 2-5. Crash reduction using hard shoulder in Netherlands (14).....	24
Figure 2-6. I-66 HOV and hard shoulder in Virginia [31].....	25
Figure 2-7. Shoulder use in Washington US 2 section [33] .....	26
Figure 2-8. Demand-capacity strategy [37] .....	28
Figure 2-9. ALINEA structure [5] .....	29
Figure 2-10. MPC structure .....	31
Figure 3-1. General process flow of the framework. ....	40
Figure 3-2. Example of the Phase 2 End User intervention window.....	44
Figure 3-3. Scenario Event Generation Panel.....	46
Figure 3-4. Stochastic Generation of a Weather Event.....	47
Figure 3-5. Deterministic Generation of a Weather Event. ....	47
Figure 3-6. Weather Event List Entry for a Stochastically Generated Heavy Rain Event. ....	48
Figure 3-7. Facility Preview Graphic with an Active Heavy Rain Event.....	48
Figure 3-8. A One-lane Closure Modeled in the Incident Event Generator. ....	49
Figure 3-9. Incident list entry for a one-lane closure event. ....	49
Figure 3-10. One-lane closure displayed on the facility preview graphic. ....	50
Figure 3-11. One-lane Closure Work Zone Scheduled for the Entire Study Period.....	50
Figure 3-12. One-lane closure work zone displayed on the facility preview graphic. ....	51
Figure 3-13. ATM Strategy Parameter and Availability Tab in the DSS Main Panel.....	52
Figure 3-14. Hard shoulder running and ramp metering configuration options. ....	53
Figure 3-15. “On Facility” diversion configuration options. ....	54
Figure 3-16. Upstream diversion configuration options. ....	55
Figure 3-17. Facility wide ATM parameter panel. ....	56
Figure 3-18. Display options customization options. ....	57
Figure 3-19. Sensor display options.....	58
Figure 3-20. Dialog to select the custom set of performance measures made available to the End User. ....	59
Figure 3-21. Selected set of sensor performance measures provided to the End User. ....	60
Figure 3-22. Additional Facility Information window for the example facility. ....	61
Figure 3-23. Example menu of ATM strategies available to the End User. The “Proceed with No Action” and “Take Action and Proceed” options are also shown at the bottom of the panel. ....	61



Figure 3-24. Facility performance measures and output with a heavy rain weather event and a one-lane closure incident. .... 62

Figure 3-25. Hard shoulder running selected for segments 6-8 for the next 4 periods to alleviate the congestion that has appeared as seen in Figure 3-24. .... 63

Figure 3-26. Example summary output for an intervention analysis run. .... 64

Figure 3-27. Updated End User options once an analysis run has been completed. .... 65

Figure 3-28. Output summary report showing comparison for three intervention runs. .... 66

Figure 4-1. – High Level Process Flow of Oversaturated Methodology in the HCM..... 70

Figure 4-2. – Segment Density and Queue Length within a 15 Minutes Analysis Period ..... 76

Figure 4-3. Geometric Configuration of Illustrative Example # 1..... 77

Figure 4-4. – Density, Demand, and Metering Rates for Segment #2 in Example 1 ..... 78

Figure 4-5. Illustrative Example # 2 ..... 79

Figure 4-6. Ramp and Mainline Flow allocation using the CO5 method [83] ..... 80

Figure 5-1. Base facility for the I-40 Case Study. .... 89

Figure 5-2. Heavy rain displayed on the facility graphic from 4:00-4:15pm. .... 90

Figure 5-3. Worsening conditions of the facility from 4:15-4:30pm and the deployment of ramp metering at segments 14, 16, 17, and 22..... 91

Figure 5-4. Remaining slow speeds and congestion on freeway indicating extension of the ramp metering ATM intervention. .... 92

Figure 5-5. Second extension of the ATM intervention. .... 93

Figure 5-6. Summary output of the first ramp metering ATM intervention run. .... 94

Figure 5-7. Incident at segment 21 at 4:30 showing slow speeds at segment 20. The bottom table shows the hard shoulder intervention in place for the next analysis period. .... 95

Figure 5-8. Green bar indicating the shoulder has been opened for segments 20 to 23. .... 96

Figure 5-9. Summary output showing travel time performance measures for the hard shoulder ATM intervention. .... 97

Figure 5-10. Summary output showing delay performance measures for the hard shoulder ATM intervention. .... 98

Figure 5-11. Incident at segment 21 at 4:30 showing slow speeds at segment 20. The bottom table shows the DMS induced diversion intervention in place for the next analysis period. .... 99

Figure 5-12. Summary output showing delay performance measures for the DMS induced diversion ATM intervention. .... 100

Figure 5-13. Facility conditions during the first period in which the incident occurs. In the bottom table, the checkbox is marked indicating incident management is active. .... 102

Figure 5-14. Summary output showing delay performance measures for the incident management ATM intervention. .... 103

Figure 5-15. Incident on segment 21 at 4:30 showing slow speeds at segment 20. The bottom table shows DMS induced diversion in place for the next analysis period, as well as the checkbox indicating incident management is active. .... 104

Figure 5-16. Summary output showing travel time performance measures for the DMS diversion and incident management combination intervention. .... 106

Figure 5-17. Summary output showing the comparison of the three intervention strategies. .... 107

Figure 5-18. Facility conditions in the first AP with a slowdown occurring at the work zone. . 108

Figure 5-19. Heavy breakdown occurring around the work zone in AP 4. The bottom table shows the ramp metering ATM intervention configured to begin in the following AP ..... 109

Figure 5-20. Poor facility conditions still exist when the first ramp metering intervention is set to expire so the strategy is extended for an additional 5 analysis periods. .... 110

Figure 5-21. Steady improvement of facility conditions for periods 16 to 21 (5:45-7:15pm). .. 111

Figure 5-22. Summary output showing travel time performance measures for the ramp metering ATM intervention. .... 112

Figure 5-23. I-95 study corridor-base facility..... 114

Figure 5-24. I-95 network speed counter-Bottleneck locations are segments 12 and 8 ..... 114

Figure 5-25. Worsening condition in presence of a medium rain event. .... 115

Figure 5-26. Ramp metering ATM intervention from 17:15 to 18:15 PM..... 116

Figure 5-27. Freeway Conditions at the 18<sup>th</sup> analysis period (18:15 to 18:30 PM)..... 116

Figure 5-28. Summary output of the ramp metering ATM intervention ..... 116

Figure 5-29. Incident at segment 20 at 4:30 yields slow speeds at segment 19, 18, 17 and 16. The bottom table shows hard shoulder intervention in place for the next analysis period ..... 117

Figure 5-30. Network performance after four analysis period hard shoulder ATM intervention ..... 117

Figure 5-31. Summary output of the hard shoulder running ATM intervention ..... 118

Figure 5-32. Incident at segment 20 at 4:30; slow speeds at segment 19, 18, 17 and 16. The bottom table shows DMS induced diversion intervention in place for the next analysis period. 119

Figure 5-33. Network performance after four analysis period diversion ATM intervention ..... 119

Figure 5-34. Summary output of the diversion ATM intervention..... 120

Figure 5-35. Facility conditions during the first period in which the incident occurs. In the bottom table, it can be seen that the checkbox is marked indicating incident management is active. .... 121

Figure 5-36. Summary output of the incident management ATM intervention ..... 122

Figure 5-37. Facility conditions during the first period in which the incident occurs. In the bottom table, it can be seen that the checkbox is marked indicating incident management is active. .... 123

Figure 5-38. Rain and incident presence in the 13<sup>th</sup> AP ..... 123

Figure 5-39. Summary output of the incident management and DMS ATM interventions ..... 124

Figure 5-40. Facility conditions during the first time period of the work zone analysis..... 125

Figure 5-41. Poor facility conditions still exist when the first ramp metering intervention for 3 hours has expired ..... 125

Figure 5-42. Poor facility condition after two ramp metering interventions ..... 126

Figure 5-43. Poor facility condition after ramp metering and diversion interventions ..... 126

Figure 5-44. Summary output of ramp metering and DMS ATM interventions ..... 127

## **ACKNOWLEDGMENTS**

This work was sponsored by a grant from the Southeastern Transportation Research, Innovation, Development, and Education Center (STRIDE) at the University of Florida. The STRIDE center is funded through the U.S. Department of Transportation's University Transportation Centers Program. The authors would like to thank STRIDE for their support of university-based research in transportation, and especially for the funding provided in support of this project.

## EXECUTIVE SUMMARY

This project developed a tool that assesses and prioritizes alternative active traffic management (ATM) strategies on freeway facilities, emulating as much as possible how these strategies are expected to be implemented in the real-world. As such, the development of this project fills a major gap in currently available tools and evaluation methods that have focused on planning level assessments of such strategies. This allows the assessment of the impacts of strategies, considering the impacts and timing of their implementation decisions, as they are implemented in the real-world environment. In addition to allowing a better assessment of ATM strategies compared to planning level tools, the tool can be applied in training of TMC operators, allowing them to experience the consequences of their actions or the actions of other operators and responders in a dynamic real-world environment. The tool builds on the existing freeway facility methodology in the 2010 HCM.

The key to the developed capability is the incorporation of two type of players: the Administrator and the End User. The Administrator configures the facility, generates scenarios (including weather, incidents and work zones) and sets the menu of available ATM strategies. The Administrator can be a TMC manager, an agency operations engineer, their consultant, or a combination of the above. The Administrator should have knowledge of the HCM procedures and associated tools. The Administrator should also have traffic operation and management experience to configure the scenario generation and strategy menus. The End User executes the analysis and invokes the interventions, where ATM strategies can be deployed either individually or in bundles. Ideally, the End User should be a TMC operator or manager, but it could also be an analyst emulating the decision of TMC operator or manager. It is important to understand the above two types of players, as described above. The End User, as defined in this project, should be familiar with how to operate the system but does not have to understand the HCM procedures or even transportation engineering principals. This is different from a typical End User of transportation engineering software. ATM strategies that can be invoked each 15 minutes include hard shoulder running, ramp metering (operated utilizing time of day, ALINEA, or fuzzy logic algorithms), dynamic message messaging, incident management, GP to ML diversion, and mainline and on-ramp diversion. All strategies have default impacts on demand, capacity, free flow speed or incident duration. Those impacts can be adjusted and calibrated by the Administrator.

The tool was applied to two real world case studies representing interstate facilities in North Carolina (I-40) and Florida (I-95). Six use cases were tested with each of the two case studies

to highlight various features of the framework and software implementation. Each use case involved a different combination of a 45-minute one-lane closure incident, and a 2-hour heavy rain, and/or a 1.2 mile work zone. The use cases also involved ramp metering (ALINEA Adaptive), hard shoulder running, incident management, and DMS strategies. The I-40 facility results showed that ramp metering improved the 95% Travel Time Index (TTI) by 5%. In addition; hard shoulder running, incident management strategy, and incident management combined with diversion due to DMS in response to the incident event; improved the 95% TTI by 14%, 7%, and 9%, respectively. The 95% TTI was improved by 8.7% when ramp metering was activated to mitigate congestion due to work zones. The same six use cases and strategies were applied on the I-95 facility. The results showed that ramp metering improved the 95% TTI by 12%. Hard shoulder running, incident management strategy, and incident management combined with diversion due to DMS; in response to the incident event; improved the 95% TTI by 59%, 40%, and 63%, respectively. The 95% TTI was improved by 5% when ramp metering was activated to mitigate congestion due to work zones. It is clear that most of the introduced strategies had much more benefits when implemented on I-95 compared to implementing on I-40, reflecting the higher congestion level on I-95. It is recommended that the tool developed in this study be implemented in support of traffic management center operations. The research team has recently demonstrated at the 2015 ITS Florida and Institute of Transportation Engineers (ITE) Florida section meeting. The team will continue these outreach activities. Other ATDM strategies will possibly be included in the tool as it starts to be implemented and feedbacks are obtained from the implementing agencies.

## CHAPTER 1 INTRODUCTION AND BACKGROUND

According to the latest Urban Mobility Report, US urban motorists in 2015 traveled an additional 7 billion hours and purchased an extra 3 billion gallons of fuel as a result of congestion. The economic impact of degraded mobility has been estimated at \$160 billion which is quickly eroding the nation's economic competitiveness [1]. The Federal Highway Administration (FHWA) [2] estimates that about half of all congestion delays are caused by non-recurrent congestion events, including incidents, weather, work zones, special events, demand surges and inadequate base capacity. Several strategies and countermeasures for managing and controlling non-recurrent congestion sources have been proposed.

These strategies can be divided into two broad categories dealing with the traffic demand and operations. As an example of active traffic management strategies that aim at improving traffic operations, ramp metering has been widely used in the US and around the world for several decades to control the demand at the ramp entry but also affect the maximum possible throughput by reducing the probability of breakdown [3]. Another example is hard shoulder running that increases the capacity of the roadway temporarily to better serve the traffic demand in the peak hour [4]. Traffic management centers can divert traffic away from an incident location on a freeway to avoid congestion and long queues. Incident management strategies can be employed to shorten the time that a portion of freeway segment experience one or more lane closures. A vast amount of literature exists on the use of active traffic management (ATM) techniques. The methodologies controlling these countermeasures can derive the associated parameters off-line or in real-time. For example the ALINEA algorithm, which can propose near optimal ramp metering rates for each ramp entry on the freeway is a real-time traffic responsive approach [5]. Several other approaches for ramp metering, using for example Linear Programming, provide offline solutions [6]. ATM is a framework which dynamically tries to collect and analyze traffic measurements, ideally with the aid of some type of simulation and/or data analytics that propose the best set of strategies to be implemented [7]. ATM has to select from a set of scenarios and controlling strategies in a fast and real-time environment [7].

ATDM or Active Traffic Demand Management is a planning level approach to assess the prevailing conditions and evaluates a set of strategies and their effects [8] [9] [4]. The ATDM strategies generate insights to enable the manager to handle the situation at an operational level. Many of the methods for assessing the effectiveness of ATDM strategies are still rooted at the planning rather than the operational levels of implementation. As an example, the ATDM analysis framework introduced in the Highway Capacity Manual (HCM) generates multiple scenarios of different event occurrences (incidents, weather) on a freeway facility. It then attempts to select an appropriate set of countermeasures to reduce the average travel time and vehicle hours of delay (VHD), while increasing the Vehicle Miles Traveled (VMT) [10]. DTALite [11], Dynasmart [12], VISSIM [13] [14], AIMSUN [15], and CORSIM [16] [17] have also been applied for planning level evaluation. In essence, such applications of the tools assume perfect knowledge of all

recurring and non-recurring congestion events across the entire assessment time period, and then proceed to evaluate strategies based on that perfect knowledge and the known sequence of events.

In reality, operators who manage the freeway system, while typically familiar with the facility recurrent bottleneck locations and diurnal demand patterns, cannot predict short term demand changes, traffic breakdown times, the precise onset of a specific weather events, and incident occurrence and attributes a priori. Having a framework that mimics the incremental progression of facility operation, including receiving information at fixed time intervals from a surveillance system and allowing interventions in midstream to alter the system status, would be very valuable from a couple of perspectives. First, such a framework can serve as a training tool for TMC operators and transportation students alike to test and compare the effectiveness (or lack thereof) of various ATM strategies in a near real world context. Second, the framework can serve as a springboard to incorporate predictive models of recurring and non-recurring events in future releases, enabling a more pro-active approach to implementing ATM strategies. In summary, existing frameworks use a planning level approach to enable the analyst to deal with the current situation on the freeway; however it lacks the ability to generate a set of actions to improve the current system performance measures with no knowledge of future conditions.

## **BACKGROUND**

A major issue faced by a TMC operator is that the consequences of a strategy cannot be known without some predictive ability of future traffic states. This deficiency leads us to develop a dynamic and stepwise analysis framework to strengthen the capability of operating agencies to improve their decision making under real world conditions. The proposed methodology aims to satisfy the needs for a stepwise approach consistent with data availability from a surveillance system, in order to provide subsequent performance output based on the incorporated strategies at each time step. In the proposed approach, HCM procedures and tools will be extended and combined with data from multiple sources to support agency decisions at the planning for operations or the operation stage.

Agencies will be able to assess alternative strategies and associated parameters off-line and in the future during on-line operations. The results from these tools developed in this research is presented in a format that is useful to traffic management center managers and operators to make decisions regarding the system. The project dovetails nicely with the ongoing NCHRP project 3-114 entitled *Operational and Reliability Impacts of Active Traffic Management Strategies*. The objectives of the NCHRP project are to review existing ATM studies and validate and expand the current HCM analysis to incorporate more ATM strategies. It will focus primarily on calibrating and validating macroscale parameters describing ATM-based speed, demand and capacity adjustment factors that can be translated into operational benefits. In addition, a validated, planning



level computational engine should be developed to incorporate those validated effects. The main contribution of this study is providing a capability to (virtually) intervene and implement the strategy in midstream of the operation, something the NCHRP research is not addressing. In fact, the best way of assessing such benefits is to emulate how they will be invoked in a real time setting in a traffic control center, which is a primary motivation for this research. Thus, the combination of a validated assessment of the true impacts of an expanded suite of ATM strategies (NCHRP) coupled with an ability to model their impact in a near-real time setting (STRIDE) will generate a tool that has practical value to analysts and TMC operators alike.

## **RESEARCH OBJECTIVES**

The goal of this research is to develop and evaluate methods to support ATM strategies that can be applied off-line in planning for operations and in near real time to improve traffic performance of freeway facilities subject to all sources of congestion. The specific objectives are:

- 1) To develop tools to assist operators in determining the impacts of their actions on freeway system performance,
- 2) To create a prioritized list of feasible solutions that can remedy deficiencies based on the tools developed in objective 1,
- 3) To implement those tools in a macroscopic simulation model, at an appropriate time resolution, and
- 4) To test and validate the methodology on real world facilities in North Carolina and Florida

This research therefore proposes a framework that is intended to be an operational level macroscopic simulation environment based on the HCM concepts to evaluate the operations on a freeway facility when using ATM strategies. As a primary objective, it seeks to provide functionalities similar to those available in Traffic Management Centers (TMCs). Both the framework and methodology build on the core freeway facilities methodology.

## **ORGANIZATION OF THE REPORT**

This report is organized in six chapters. Following the introductory chapter, Chapter 2 provides a detailed literature review on the Active Traffic Management Strategies that are considered in this research project. Chapter 3 describes the modeling framework that allows the introduction of dynamic interventions within the analysis. Chapter 4 details how the ATM strategies are incorporated into the proposed framework, and their effect on various modeling parameters are accounted for. Chapter 5 discusses the application of the proposed modeling

paradigm in two freeway facilities case studies: I-95 in Florida and I-40 in North Carolina. Finally, Chapter 6 provides the summary, conclusions and recommendations for future research. An appendix is provided that contain the user guide for the computational tool developed in this project, named FREEVAL-DSS for **D**ynamic **S**trategy **S**election.

## CHAPTER 2 LITERATURE REVIEW

Nowadays the increase in car-ownership all over the world has burdened motorway networks with considerable congestion problems. This congestion not only reduces quality of life but also increases the likelihood of accidents. On the other hand, due to economic problems and lack of space in urban areas, it is not possible to construct new roads to increase the capacity of freeway facilities. Several strategies have been developed to improve the performance of freeway networks, among which control strategies such as ramp metering, and peak period shoulder use are recognized as some of the most effective ways for relieving freeway traffic congestion. These strategies are part of a larger pool of strategies called ATM. In this section, the literature review for the strategies that have been modeled in the FREEVAL-DSS tool are covered.

Ramp metering is an Intelligent Transportation System (ITS) strategy to manage traffic. It is known to be one of the most effective ways for avoiding breakdown or reducing its duration. This strategy improves highway traffic conditions by controlling on-ramp flow; therefore, it improves safety and reduces environmental pollution. The main objective of speed harmonization is prevention of the onset of congestion. Other objectives are safety improvements, homogenization of traffic speeds in space and time, and freeway throughput augmentation.

Hard shoulders are reserve lanes available for emergency situations. Hard shoulder running is the temporary operation of hard shoulders as running lanes for normal traffic during peak period. The main objective of using the shoulder is providing additional capacity when needed without much infrastructure expansion requirements.

Dynamic message signs (DMS) are devices that provide real time traffic information such as traffic condition, parking, public transportation and environmental information for drivers. One of the most important usages of DMS is providing information in presence of an incident. The disseminated information helps drivers in selecting the alternative routes to avoid the congestion created by the incident.

Incident management is a coordinated program to detect, respond to, and clear the incident as quickly as possible. The main goal of the incident management program is to restore the capacity as safely as possible. This section summarizes the literature review of the discussed ATM strategies that will be assessed by the developed tool. In the following section, an extensive literature review is conducted on the state of the art of the some of the existing ATM strategies including hard shoulder running, speed harmonization, ramp metering, traffic diversion according to DMS information, and incident management.

## HARD SHOULDER RUNNING

### Hard Shoulder Running Experience in Paris, France (A3-A86 Junction)

Hard shoulder running has been implemented on the A3-A86 section in Seine-Saint-Denis department north of Paris to reduce the congestion in this section. The implementation involved changing from 4 lanes with a hard shoulder to 5 lanes without a hard shoulder. So, the hard shoulder was used as the fifth lane. Initially the section was composed of a 0.7 meter left curb, four 3.5 standard lanes and 2 meter hard shoulder with the total width of 16.7 meter. After the change, the section has a 0.5 left curb, a 3 meter left lane (fast lane), four 3.2 meter lanes and a 0.6 curb with the total length of 16.9 meter. To compensate for possible safety problem due to hard shoulder removal, some dynamic message signs, emergency call boxes and cameras were installed at the upstream of the section. The results before and after hard shoulder usage are shown in Table 2-1.

**Table 2-1. Before and After Study for Hard Shoulder Use in France [1]**

lane	Capacity (veh/h)			
	Toward Paris		Toward Provence	
	before	after	before	after
<b>Right 1</b>	2020	1335	2265	1865
<b>Lane 2</b>	2100	1635	1645	1750
<b>Lane 3</b>	1840	2040	2005	2000
<b>Lane 4</b>	2220	1755	2500	2035
<b>Lane 5 (Shoulder)</b>		2390		2395
<b>Section</b>	7890	8550	8100	9170

As can be seen from Table 2-1, capacity toward Paris and Provence were improved by 7% and 16 % respectively. The capacity toward Paris is affected by a downstream bottleneck, consequently the observed improvement was less. It was also found that free flow speed did not

increase [18]. In another study, it was shown that using hard shoulder reduced traffic density and consequently the number of accidents due to more fluid traffic [19].

### Hard Shoulder Running Experience in Germany

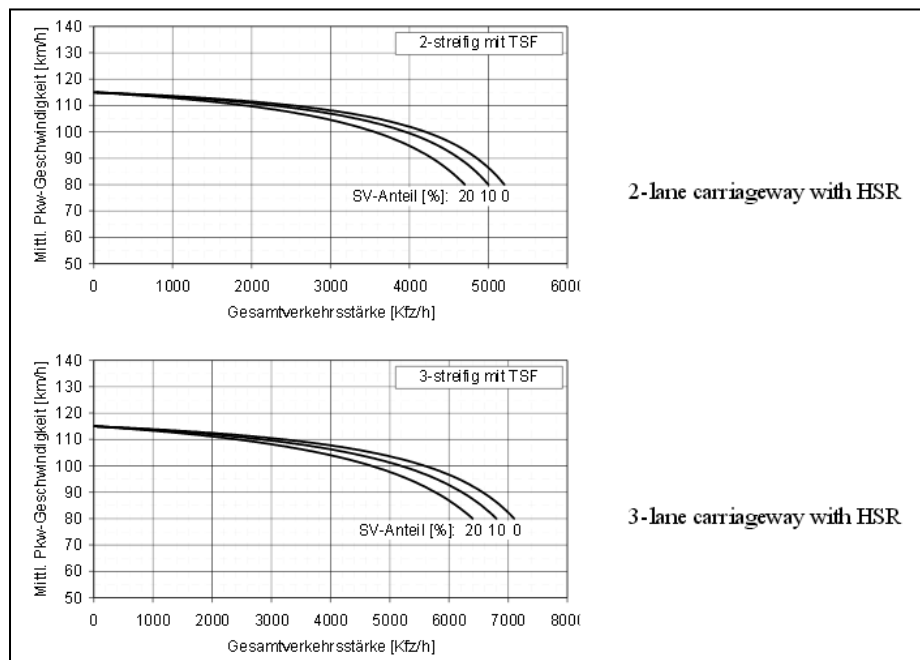
The first hard shoulder was implemented on A4 in 1996. Nowadays, hard shoulders have been used in various sections in Germany as shown in Table 2-2. For example, a hard shoulder lane was implemented by federal state of Hessen, Germany on the A5 motorway. It has three lanes and hard shoulder was used as the fourth lane. When traffic volume passes a certain threshold the shoulder lanes are activated. Following are the results of using hard shoulder on A5 [20]:

- Improving traffic flow
- Reducing congestion significantly
- Increasing capacity by 20 %

**Table 2-2. Sections with Dynamic Hard Shoulder in Germany [4]**

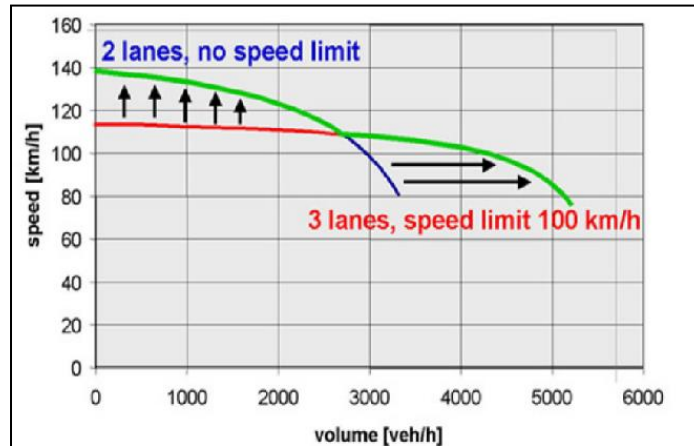
Freeway	Direction	Length (km)	Number of lanes
A 3	both	5.7+6	3+1
A 3	both	3.3+2	3+1
A 4	Koln	1.6	2+1
A 5	both	7.2+8.9	3+1
A 5	both	4.8+7.7	3+1
Freeway	Direction	Length (km)	Number of lanes
A 7	Flensburg	22.5	2+1
A 7	Flensburg	14	2+1
A 7	both	34.4+31.8	2+1
A 8	Salzburg	9.8+9.8	3+1
A 99	both	18+18	3+1

The results of a study on A4 and A3 motorways shows that the hard shoulder running increases the capacity of a 2 lane motorway (A4 motorway) by 30% and a 3 lane motorway (A3 motorway) by between 22% and 27% as shown in Figure 2-2. These curves will be included in German highway capacity manual (HBS) [21]. Furthermore, hard shoulder running increases throughput in a congested motorway as shown in Figure 2-2.



*Mittlere Pkw-Geschwindigkeit = speed in kilometers per hour; Gesamtverkehrsstärke = flow rate in vehicles per hour, SV-Anteil = portion of heavy vehicles, %)*

**Figure 2-1. Flow-speed curve for A3 and A4 motorways after implementation of HSR [21]**

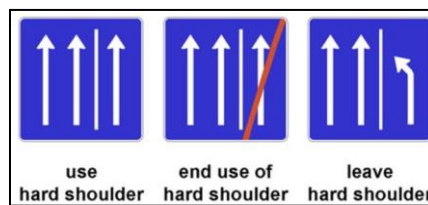


**Figure 2-2. Speed-volume relationship of hard shoulder use in Germany [22].**

Based on Kellermann study [23], in order to address any safety concerns regarding opening hard shoulders to regular traffic, the following actions are required:

1. Acceleration and deceleration lanes should be provided in the end of the hard shoulder
2. Emergency stopping areas
3. Drainage and slope requirements

Based on these results, opening hard shoulder decreased the congestion 68 to 82 percent and increased average speed by 9%, as well. Hard shoulder use is permitted using special signs as shown in Figure 2-3 along with using speed harmonization only [22].



**Figure 2-3. Hard shoulder use signs in Germany [22]**

### **Hard Shoulder Experience in United Kingdom (M42)**

The ATM (Active Traffic Management) project has been implemented on a 10-mi stretch of the M42 in the west Midlands as a pilot plan by highway Agency (HA) since 2006 as shown in Figure 2-4. One of the ATM strategies is using hard shoulder during peak periods. In order to

have more reliable travel times and less congestion, Dynamic speed limits are combined with hard shoulder running. Other ATM projects' components include [24]:

- Lane control signals
- Emergency refuge areas
- Closed circuit television (CCTV) cameras
- Enhanced lighting

After implementing ATM, traffic conditions on M42 became smoother. Capacity increased by 7 to 9 percent when the hard shoulder was opened to traffic. It is also found that travel times decreased by 24% northbound and 9% southbound [25]. What's more, after six months of implementing hard shoulder on M42, fuel consumption was estimated to have been reduced by 4% [26]. As a result of these findings, the transport secretary announced that the same plan would be implemented on other motorways [27].

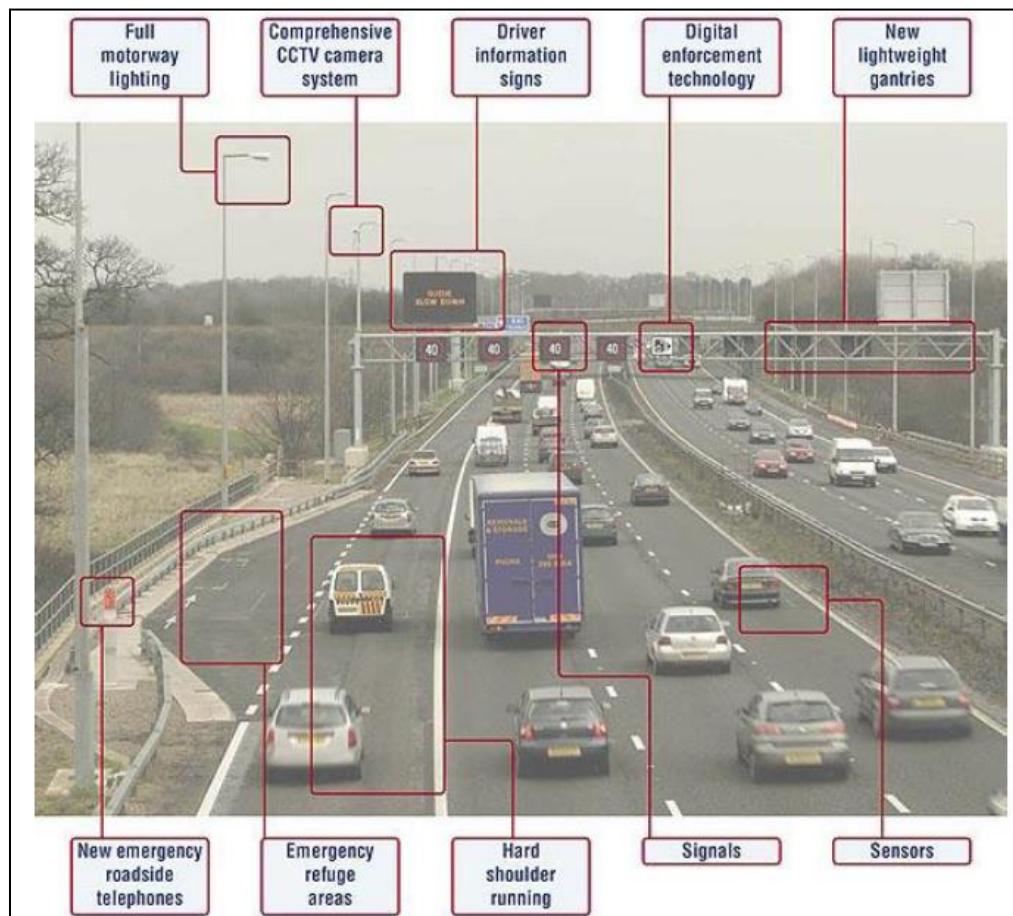


Figure 2-4. Active Traffic management on M42 motorway, UK [24]



## Hard shoulder Experience in the Netherlands

The National Traffic Control Center has operated temporary shoulder use and speed harmonization in various locations in the Netherlands. Right shoulder use was implemented in 2003 as part of a larger plan to increase the existing infrastructure usage [28]. Another kind of shoulder use implemented in the Netherlands was the temporary use of left lane (plus lane). In order to reduce the safety consequences due to using hard shoulder, some strategies were used along with hard shoulder running including overhead lane signs, emergency refuge areas, and CCTV surveillance [29]. Results suggest that depending on the usage levels capacity increased 7% to 22% and travel times decreased 1 to 3 minutes. The safety benefits of using hard shoulder are shown in Figure 2-5.

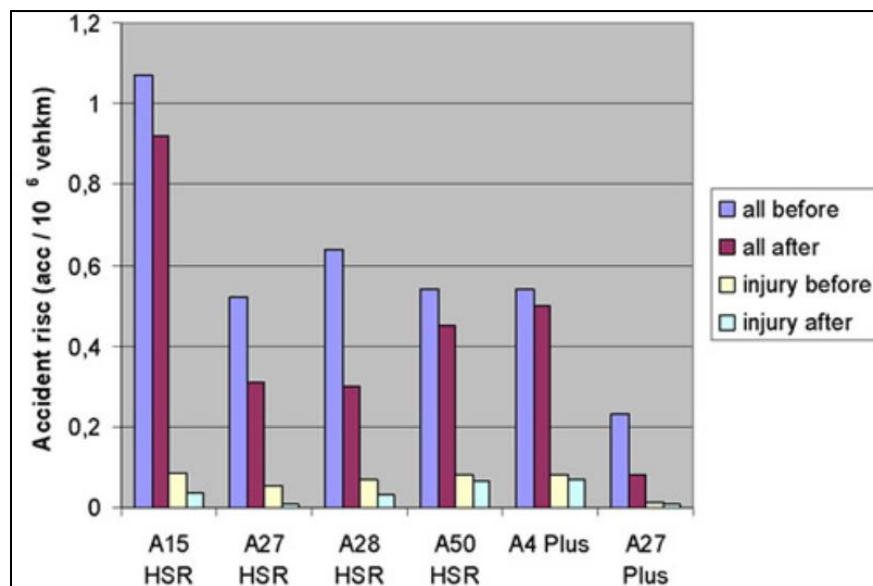
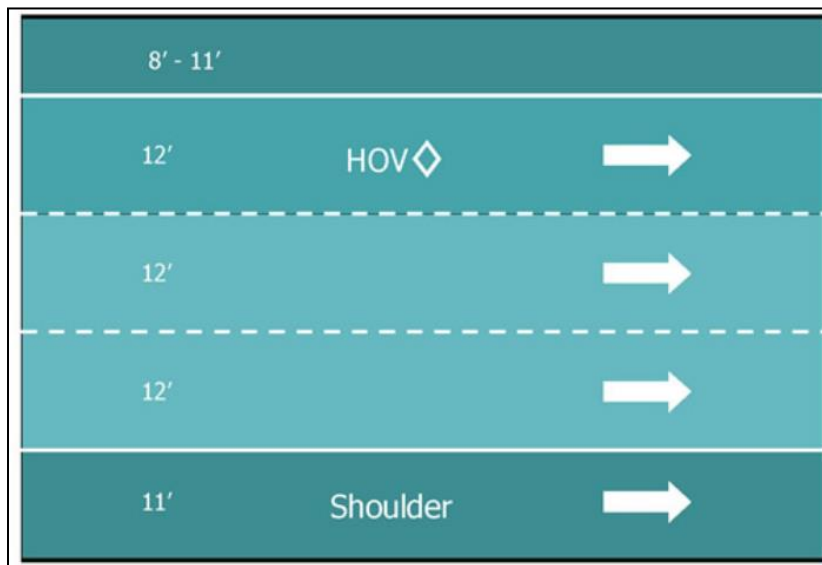


Figure 2-5. Crash reduction using hard shoulder in Netherlands (14)

Another study has been conducted in this regard in Netherlands. After using hard shoulder in 3 sections of a 2 lane motorway in Netherlands, It was found that capacity has been increased by about 50% [30].

## Hard Shoulder Experiences in the USA

A combination of hard shoulder and HOV lane was implemented on I-66 in Virginia in 1992. I-66 has three lanes in each direction [31]. The hard shoulder and HOV lane are the rightmost and leftmost lanes respectively as shown in Figure 2-6. The results showed that there was no safety improvement related to hard shoulder usage [32].



**Figure 2-6. I-66 HOV and hard shoulder in Virginia [31]**

Washington state of transportation has implemented hard shoulders on US 2 highway since 2009. In order to provide enough space for shoulder use the corridor was restriped as shown in Figure 2-7. Results shows that delay was reduced from 8-10 minute to 1-2 minutes and the average speed increased from 10 mph to 37 mph. [33]

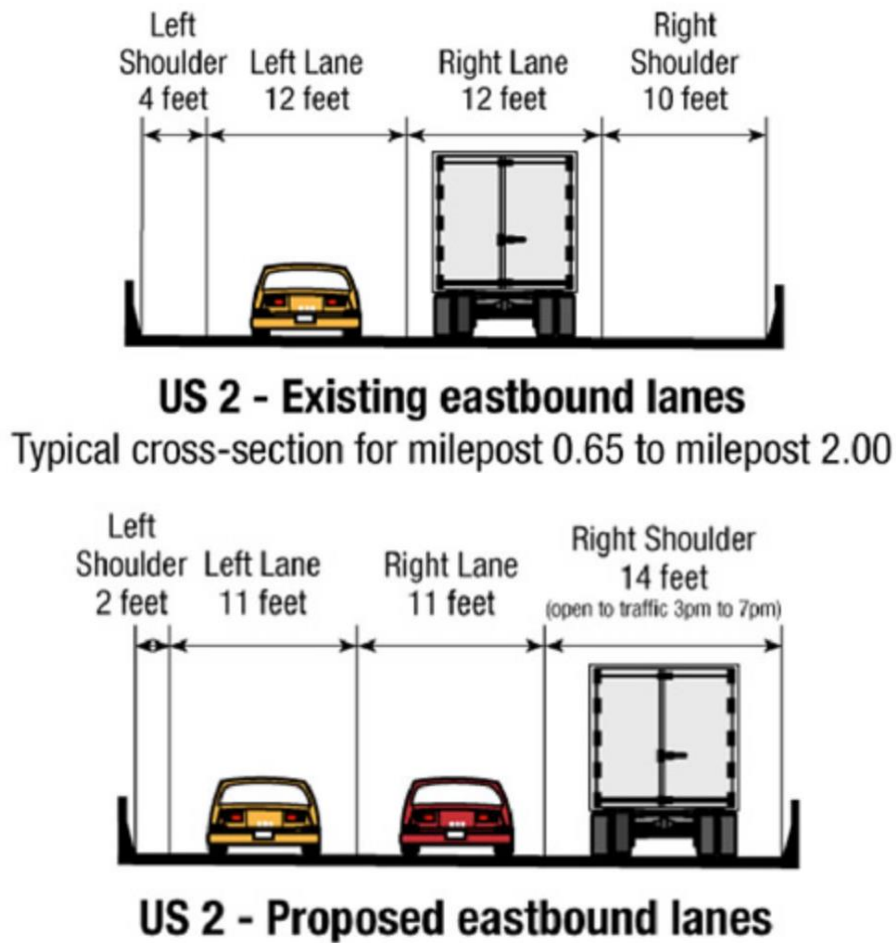


Figure 2-7. Shoulder use in Washington US 2 section [33]

### Summary of Hard Shoulder Running Studies

Hard shoulder running has been implemented in several countries especially in Europe. As it was shown in this section, it has safety and mobility benefits. Table 2-3 shows a summary of hard shoulder implementations' results across the world and the associated capacity adjustment factor (CAF) to be used in the HCM content.

**Table 2-3. Summary of Hard Shoulder Experiences**

Locations		Number of lanes	Results	CAF
Europe Experience	Germany	3+1 (A5)	20% increase in capacity	1.2
		3+1 (A3)	22% and 27% increase in capacity	1.22 and 1.27
		2+1 (A4)	30 % increase in capacity	1.3
	France	4+1	7% and 16% increase in capacity in different directions	1.07 and 1.16
	Netherlands	2+1	7% to 22% increase in capacity (based on level of usage)	1.07 to 1.22
	United Kingdom	3+1	7% to 9% increase in capacity 24% and 9% travel time reduction for different directions	1.07 to 1.09
US Experience	Virginia	3+1	Combination of HOV and HSR : improvement in safety	-
	Washington	2+1	Average speed increase from 10 mph to 37 mph	-

### **RAMP METERING**

Ramp metering was implemented on the Eisenhower freeway in Chicago for the first time in 1963 [34] . It is one of the most effective strategies to control traffic flow. Ramp meters are traffic signals at the entrance of freeways and are driven via a control strategy (controller). Ramp controller determines metering rates so that the mainline density remains below critical density, consequently the breakdown may be prevented. Basically ramp metering strategies are categorized into two general classes:

- Local strategies
- System-wide (coordinated) strategies

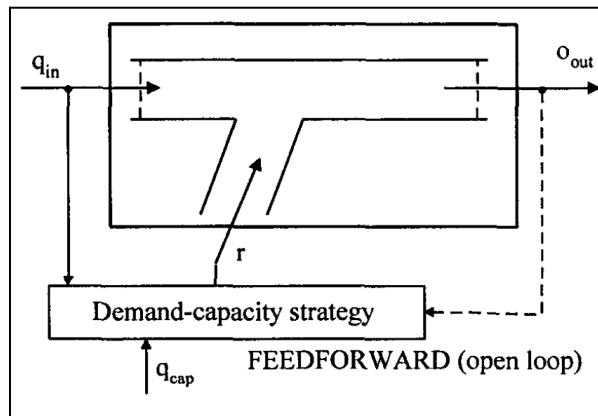
The local strategies adjust the metering rate based on existing traffic conditions near the ramp. This type of strategy controls only one meter and does not consider other ramps. System-wide strategies are designed to consider the traffic flow at a larger and wider level than local ramp meters and control several ramp meters simultaneously. Local and system-wide strategies can be

pre-timed or traffic responsive. In pre-timed strategies, metering rate is fixed during pre-defined time slots which usually contain the peak hour. In traffic responsive algorithms, the metering rate is generated based on real-time traffic measurements [35]. Hereunder some main local and system-wide strategies are described.

## Local Metering Strategies

### *Demand-capacity metering*

This method generates metering rates based on a comparison between downstream occupancy and critical occupancy (Figure 2-8). If the downstream occupancy is higher than the critical occupancy the metering rate is set to a minimum. Otherwise the metering rate is taken as the difference between upstream flow (in previous time step) and downstream capacity [36].



**Figure 2-8. Demand-capacity strategy [37]**

A typical equation used to calculate the metering rate is:

$$R(k) = \begin{cases} q_{cap} - q_{in}(k-1) & \text{if } O_{out}(k) \leq O_{cr} \\ r_{min} & \text{else} \end{cases} \quad (2-1)$$

Where:

$q_{cap}$  is the freeway capacity downstream of the ramp

$q_{in}$  is the freeway flow measurement just upstream of the ramp

$O_{out}$  is the freeway occupancy measurement downstream of the ramp

$O_{cr}$  is the critical occupancy

This strategy has been implemented in Paris. The results suggest that total travel time spent (TTS) decreased by 3.3% and mean speed (MS) decreased by 5.1% [38].

### ALINEA Algorithm

ALINEA is a closed loop, feedback control strategy proposed by Papageorgiou et al. in 1997. This strategy adjusts metering rate to keep the traffic occupancy on the merging segment (downstream of the on-ramp) at a desired occupancy, called  $\hat{O}$ . The desired occupancy is usually chosen smaller than or equal to the critical occupancy  $O_{cr}$ . The maximum flow on freeway can thus be estimated [5]. At each time step, the controller measures the density of the merging section and compares it to the critical value and if the density is higher than critical, it imposes more severe restriction upon the ramp flow as it is shown in Figure 2-9. ALINEA was implemented in Paris, Boulevard Peripherique for the first time. The results of a study show that ALINEA decreased TTS by 15.9% and increased MS by 23.1%. The second implementation of ALINEA was on the A10 motorway in Amsterdam. Based on the results TTS was decreased by 6.3% and MS increased by 8.2% [38].

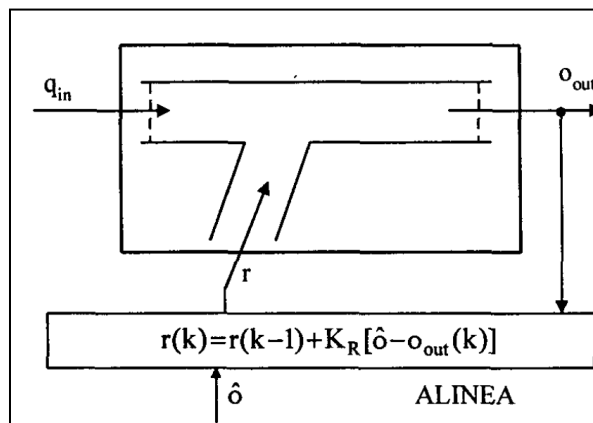


Figure 2-9. ALINEA structure [5]

The equation used to calculate the metering rate is as follows:

$$r(k) = r(k - 1) + K_R[\hat{O} - O_{out}(k)] \quad (2 - 2)$$

Where:

$r(k)$  is the metering rate at time step  $k$

$K_R$  is controller parameter

$O_{out}(k)$  is the occupancy of on-ramp downstream

$\hat{O}$  is the desired occupancy

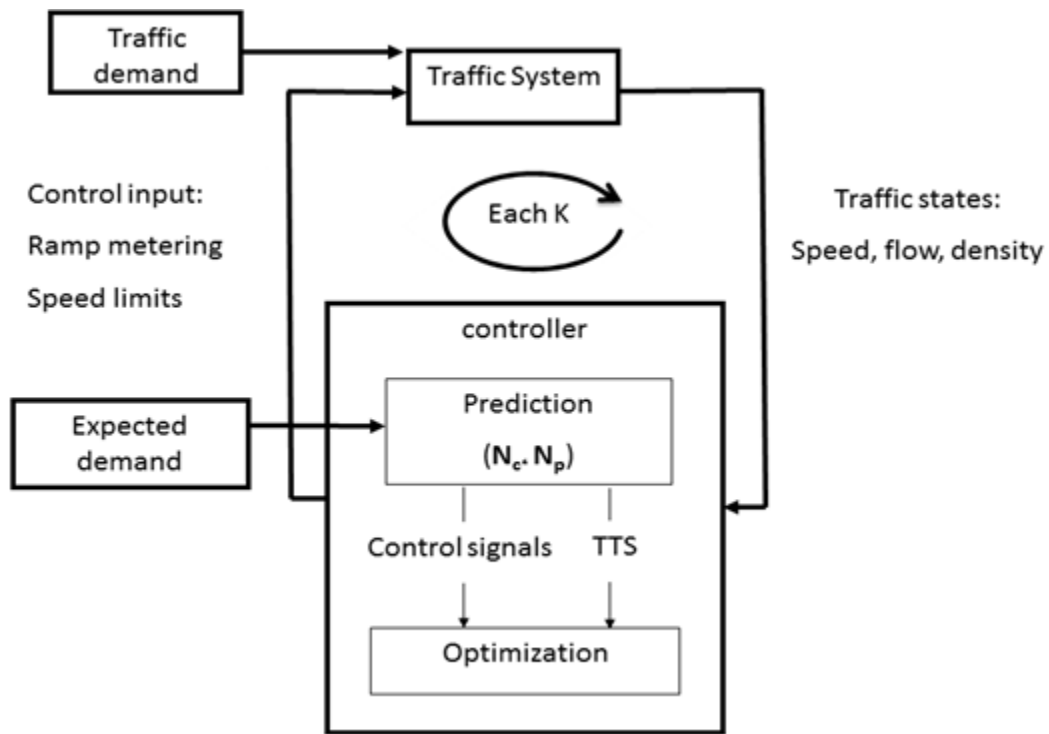
A modification of the ALINEA algorithm is implemented in the tool being developed in this study.

#### *Model predictive controller (MPC)*

Model predictive controller is an advanced control strategy which has been used since 1980. The general process of this controller is as follows [39]:

- Predicting future system behavior for a specific time horizon
- On-line calculation of future control signals in each time step by minimizing an objective function (i.e. Total Travel time Spent)
- Application of the first control signal to the system and repeating calculation of control signal for the next time-step

In each time step  $k$  an optimization process will be run for the  $[k, \dots, k + N_p - 1]$  horizon and only the first calculated control signal (control signal for time step  $k$ ) will be applied to the system (traffic system). There are 2 horizons in this controller:  $N_p$  and  $N_c$ .  $N_p$  is the prediction horizon and is equal to the number of time steps in which control signal will be predicted.  $N_c$  is the number of control signal which are calculated in each time step  $k$ . as it is shown in Figure 2-10 there are two loops in this controller. One is inside and one outside of the controller.



**Figure 2-10. MPC structure**

In each time step  $k$  the controller uses the model of the network to predict the future states of the network and by changing the future ramp meter rates, it finds the best sequence of rates that if applied to the ramp will produce the optimal result. The controller then applies the first prediction of the sequence to be implemented on the ramp meter [40].



## System-Wide Algorithms

### *Zone algorithm*

In this strategy, the freeway is subdivided into metering zones. Each zone may include several metered and unmetered ramps. The length of each zone can vary from three to six mile. Metering rates are calculated based on balancing the traffic volume entering and leaving each zone so that traffic density remains constant within the zone. The following equations are used to calculate zonal metering rates:

$$M = B + X + S - A - U \quad (2 - 3)$$

$$R_i = M * \frac{D_i}{D} \quad (2 - 4)$$

$$M = \sum_{i=1}^n R_i \quad (2 - 5)$$

Where:

- M is sum of metered entrances volumes
- A is upstream volume, U is sum of unmetered entrances volumes,
- S is the spare capacity within the zone,
- B is the downstream bottleneck capacity,
- X is sum of exit ramp volumes,
- R<sub>i</sub> and D<sub>i</sub> are the metering rates and demands for ramp I and n is number of metered ramps respectively.

This strategy was first implemented along I-35 (both east and west direction) in Minnesota in 1970. More than 300 ramp meters were installed until 1995. The results of one study shows that for 14 years of operation (EB direction), average peak hour speeds and peak period volumes increased by 16% and 25% respectively. Furthermore, the average number of peak period accidents decreased by 24%. For 10 years of ramp operations in the WB direction average peak period speeds and volumes increased 35% and 32% and the average number of peak period accidents reduced 27% [41].

A study on effectiveness of the ramp meters in the Twin Cities was conducted by Cambridge Systematic in 2000 [42]. The main goal of the study was to determine whether the ramp metering system benefits outperform the related costs. The data was collected during both “with” and “without” scenarios for five weeks. The with ramp meters data collection was done from September to October, 2000 and the ramp metering deactivation was performed from October to December, 2000. The study concluded that during the ramp metering deactivation the freeway

capacity decreased by 9%, speed dropped by 7%, travel times increased by 22% and crash rates increased by 26%.

### *Bottleneck algorithm*

In this strategy, the controller calculates 2 metering rates: local rate and bottleneck rate. Local metering rate is calculated for every on-ramp based on its upstream occupancy and bottleneck metering rate is calculated based on traffic volumes downstream of the ramp. For bottleneck rate calculation the number of upstream ramps are identified in order to reduce their entering volumes. This reduction is equal to number of vehicles stored in the segment. Each ramp has several bottlenecks metering rates among which the most restrictive one will be selected as final bottleneck metering rate. Then, the controller compares the local metering rate and the final metering rate and selects the more restrictive one. After queue adjustment for each ramp the metering rate is applied to each one [43].

This strategy was implemented in Seattle, Washington in 1981 on I-5 motorway. From 1981 to 1987, the main line peak period volumes increased 62% southbound and 86% northbound. Interestingly, travel time in an 11 km (6.8 mi) stretch decreased from 22 min to 11.5 min [41].

### *SWARM algorithm*

SWARM (System-Wide Area Ramp Metering) algorithm consists of two independent algorithms that operate separately. The more restrictive of the two is implemented each time step. SWARM1 is the predictive and system-wide part while SWARM2 is the local traffic responsive algorithm. SWARM1 aims to keep the real-time density below the saturation density for each segment of the network. It uses the Kalman filtering method to predict the density trend at each detector location and prevent the density excess. SWARM2 is a simple local metering algorithm that uses the upstream headway measurements (converted to density) and calculates the metering rate using a linear conversion from the calculated local density [44].

### *HELPER algorithm*

HELPER algorithm consists of a local traffic responsive algorithm with a centralized coordinated override system. Each ramp is controlled by the local algorithm unless the centralized system overrides the local controller. When a meter is operating at its most restrictive rate and/or the ramp queue exceeds the threshold, the ramp is considered critical and the upstream meters are overridden by the centralized controller [44].

### *Fuzzy controller*

Fuzzy logic algorithms are rule based and use linguistic knowledge and human expertise for fuzzy sets. Fuzzy controllers have 3 main steps: fuzzification, rule evaluation and defuzzification. Fuzzification is the process of converting each quantitative input to a fuzzy variable by means of membership functions. Each input has a certain number of classes (e.g., small, medium, and big) and each of these classes has a unique membership function. Rule evaluation is the process of calculating a fuzzy output based on fuzzified inputs. In this step each input will be evaluated against some IF-THEN rules to obtain the fuzzy output. Finally, the fuzzy output should be defuzzified to determine the control action (metering rate) [45].

In 1999, the Washington State Department of Transportation (WSDOT) implemented a fuzzy controller on I-405 in order to overcome the bottleneck algorithm shortcomings, previously implemented in the region. The fuzzy algorithm improved the freeway operations in comparison with the traditional algorithms [46]. In Holland, a fuzzy controller was implemented in 1989 on the A12 freeway. The evaluation results showed that in comparison with two other algorithms (ALINEA and Demand – capacity), the fuzzy controller increased bottleneck capacity 5-6% more and also produced 35% faster travel times [47]. Since the fuzzy logic algorithm ramp metering will be implemented in the developed tool (along with ALINEA algorithm), the details of a typical ramp metering algorithm are included as Appendix A in this report.

## Ramp Metering Field Implementations

Some of the real world experiences of ramp metering implementations are summarized in Table 2-4.

**Table 2-4. Ramp Metering Benefits-Real World Experiences**

Benefit Category		City	Outcome
Safety		Long Island, NY [48]	15% drop in collision rate
		Portland, OR [48]	43% Drop in collision rate
		Seattle, Washington [49]	Reduction in number of accidents by 20% to 58%
		Minnesota [50]	Reduction in crash rate by 24%
Mobility	speed	Miami (I-95) [51] [52]	Increase in travel speed in SB and NB by 45% and 11% respectively
	Throughput	Seattle, Washington [53]	Increase in throughput by 12% to 14%
Environment	Emission	Long Island [54]	17.4% reduction in Carbon monoxide and 13.1% reduction in hydrocarbons

## TRAFFIC DIVERSION

Dynamic message signs (DMS) are devices that provide real time traffic information such as traffic conditions, parking, public transportation, and environmental information to drivers. One of the most important usages of DMS is the provision information in the presence of an incident. The disseminated information helps drivers in deciding to divert to avoid the congestion created by the incident. An important and challenging parameter that needs to be identified is the percentage of drivers changing routes due to DMS information dissemination.

DMS message impacts on driver's diversion behavior can be found utilizing questionnaire stated and revealed preference surveys, network monitoring, and traffic network modeling [55].

Based on one study in France, 62% of drivers understood the DMS messages and 46% of them had at least one diversion in response to the information presented on DMS [56]. A survey conducted in Scotland found that 16% of drivers using inter-urban road network change their routes, when receiving messages through the DMS messages [57]. Tarry and Graham [58] conducted a study to assess the impacts of DMSs in the United Kingdom. The results showed that when a message with an alternative route instruction was given about an incident occurrence, 27-40% of drivers diverted. However, when the message reported the congestion without any instructions about the alternate route, only 2-5% of drivers diverted. A field study in Oslo showed that 20% of the vehicles changed route due to the information provided by DMS. Cumming [59] reported that only 4% of drivers change their routes. Davidson and Taylor [60] reported 41% diversion. Another study in London showed that only one fifth of the interviewed drivers changed their routes due the presented information by DSM. Based on a recent study in Saudi Arabia, only 5.9% of drivers changed their routes in response to DMS messages. This percentage was 0.07 of the percentage of the interviewed drivers who claimed they would comply with the DMS after its implementation. One of the reasons found for the difference between the observed and the expected value of diversion was that the DMS was newly introduced to that area and drivers were not familiar with the DMS concept [61].

An Enterprise Pooled Fund Study [62] found an increase in diversion rate that ranges from 0% to 12%. There was some evidence that this increase is a function of the incident delay as expected. A study in Maryland [63] analyzed case studies and found that the diversion was between 5% and 18%, depending on the case study.

## **INCIDENT MANAGEMENT**

Incident management is one of the most important components of the Transportation system management and operations (TSMO) Its primary goals are: 1) coordinating the activities of transportation agencies, police, and emergency services; 2) facilitating incident detection, verification, response, and clearance; and therefore 3) reducing the incident duration and minimizing the negative impacts of incidents. Below are summary of previous evaluation studies of incident management systems:

With the implementation of the Atlanta's NAVIGATOR system, the time needed to dispatch a service patrol truck to the incident site was reduced from 21 to 10 minutes (52 percent) and the average clearance time dropped from 26 to 20 minutes (23 percent) [64]. On San Francisco's I-880 corridor, the implementation of a freeway service patrol reduced the average response time from 28.9 to 18.4 minutes (36 percent) and decreased clearance time from 9.6 to 8.1 minutes (16 percent) [65]. A study in Colorado reported a reduction in response and clearance time

of 10.5 minutes for lane blockage incidents and 8.6 minutes for non-lane blockage incidents due to the implementation of a service patrol program [66]. A study in Houston reported that service patrol vehicles reduced total incident duration by 16.5 minutes [67]. In Minnesota, an evaluation of a service patrol program indicated a reduction in stall vehicle incident duration of eight minutes [68]. Based on a review of a number of studies, Khattak [69] found that service patrol vehicles reduces incident response time by 19 percent to 77 percent and incident clearance time by 8 minutes. A study in the Puget Sound region, WA, found that the service patrol vehicles reduced incident response time for lane blocking incidents from 7.5 minutes to 3.5 minutes [70]. In Houston, incident response duration was reduced by 20 percent due to the implementation of the TransGuide traffic management system. The evaluated phase of the TransGuide system included dynamic message signs, lane control signs, loop detectors, video surveillance cameras, and a communication network covering 26 instrumented miles [71]. An evaluation of the CHART program conducted in the year 2000 estimated that the average incident duration was about 33 minutes with CHART and 77 minutes without it. In 1999, the average incident duration was estimated to be about 42 minutes with CHART and 93 minutes without it [72].

A study in Virginia found that the average duration of incidents with service patrol in Northern Virginia was 17.3 percent shorter than for those without service patrol. The average duration with service patrol assist was 25 percent, 17.2, and 15.6 shorter than for those without assist for debris incidents, breakdowns, and crashes, respectively [73]. In Hampton Roads, the service patrol assist incidents had a 70.7 percent reduction in duration compared to police-assist only incidents in Hampton Roads, VA [74]. A case study of the traffic incident management program in Atlanta, GA reported a reduction in the average incident durations from 67 to 21 minutes and reduction in secondary crashes of 69 percent (from 676 to 210 in one year) [75]. A summary of the aforementioned incident management programs the associated results is shown in table 2-11.

Table 2-11. Summary of Incident Management Program Results

State/System	Results
Atlanta's NAVIGATOR System	-Dispatch time was reduced from 21 to 10 minutes (52%) -Average clearance time dropped from 26 to 20 minutes (23%)
San Francisco's Service Patrol Program	-Reduced the average response time from 28.9 to 18.4 minutes (36%) -Decreased clearance time from 9.6 to 8.1 minutes (16%)
Colorado Service Patrol Program	-Reduction in response and clearance time of 10.5 minutes for lane blockage incidents and 8.6 minutes for non-lane blockage incidents
Houston Service Patrol Program	-Reduced total incident duration by 16.5 minutes
Minnesota Service Patrol Program	-Reduction in stall vehicle incident duration of 8 minutes
Puget Sound region, WA, Service Patrol Program	-Reduced incident response time for lane blocking incidents from 7.5 minutes to 3.5 minutes
Houston TransGuide System	-Reduced incident response time by 20 percent
Maryland CHART Program	-Reduced incident duration from 77 minutes to 33 minutes
Virginia Service Patrol Program	-Average duration with service patrol assist was 25 percent, 17.2, and 15.6 shorter than for those without assist for debris incidents, breakdowns, and crashes, respectively
Hampton Roads Service Patrol Program	- Reduction in incident duration by 70.7 %
Atlanta, GA Incident Management System	-Reduction in the average incident durations from 67 to 21 minutes and reduction in secondary crashes of 69%

## CHAPTER 3 MODELING FRAMEWORK

In conducting an ATM analysis, the framework accounts for two types of operators: an *Administrator* and an *End User*. The initial responsibilities of the framework lie in the hands of the Administrator, who must first define and configure a congestion scenario using the HCM freeway facilities methodology. In other words, the Administrator knows the entirety of the conditions and performance on the facility.

The Administrator can be a TMC manager, an agency operations engineer, their consultant, or a combination of the above. The Administrator should have knowledge of the HCM procedures and associated tools. The Administrator should also have traffic operation and management experience to configure the scenario generation and strategy menus.

The scenario is then presented to the End User, who performs a period by period analysis HCM analysis, and when appropriate, invokes interventions by deploying any of the *available* ATM strategies based on an assessment of current and past freeway performance.

The End User executes the analysis and invokes the interventions, where ATM strategies can be deployed either individually or in bundles. Ideally, the End User should be a TMC operator or manager, but it could also be an analyst emulating the decision of TMC operator or manager. It is important to understand the above two types of players, as described above. The End User, as defined in this project, should be familiar with how to operate the system but does not have to understand the HCM procedures or even transportation engineering principals. This is different from a typical End User of transportation engineering software.

This categorization of the two distinct users is needed to simulate a TMC environment where the TMC operator does not necessarily have any prior knowledge of the non-recurring events that might appear on the facility any time in the future. The framework emulates this by having the Administrator fully define what information is available about the emulated real-time operations, while the End User only has access to the intervention simulation portion of the framework.

### FRAMEWORK OVERVIEW

There are three phases in the framework. The first phase is solely the Administrator's responsibility and is where the facility configuration, scenario generation, and ATM strategy menu availability take place. From there, the framework shifts to the End User in the next two phases. The second phase consists of executing the analysis and invoking the interventions, where several ATM strategies can be deployed either individually or in bundles. Strategies such as ramp



metering, DMS, hard shoulder running, and incident management may be available for selection by the End User based on the Administrator’s configuration of that facility. The framework enters the third phase upon completion of an ATM analysis run. Here, summary performance measures comparing the “before ATM” and “after ATM” scenarios are presented to the End User. At this point, the End User is presented with two options: the analysis can either be concluded, or if he/she wishes to explore other potential courses of action, the framework returns to the second phase to carry out additional or alternative ATM interventions. Figure 3-1 depicts the high level process flow of the proposed framework, showing the three distinct phases of the framework.

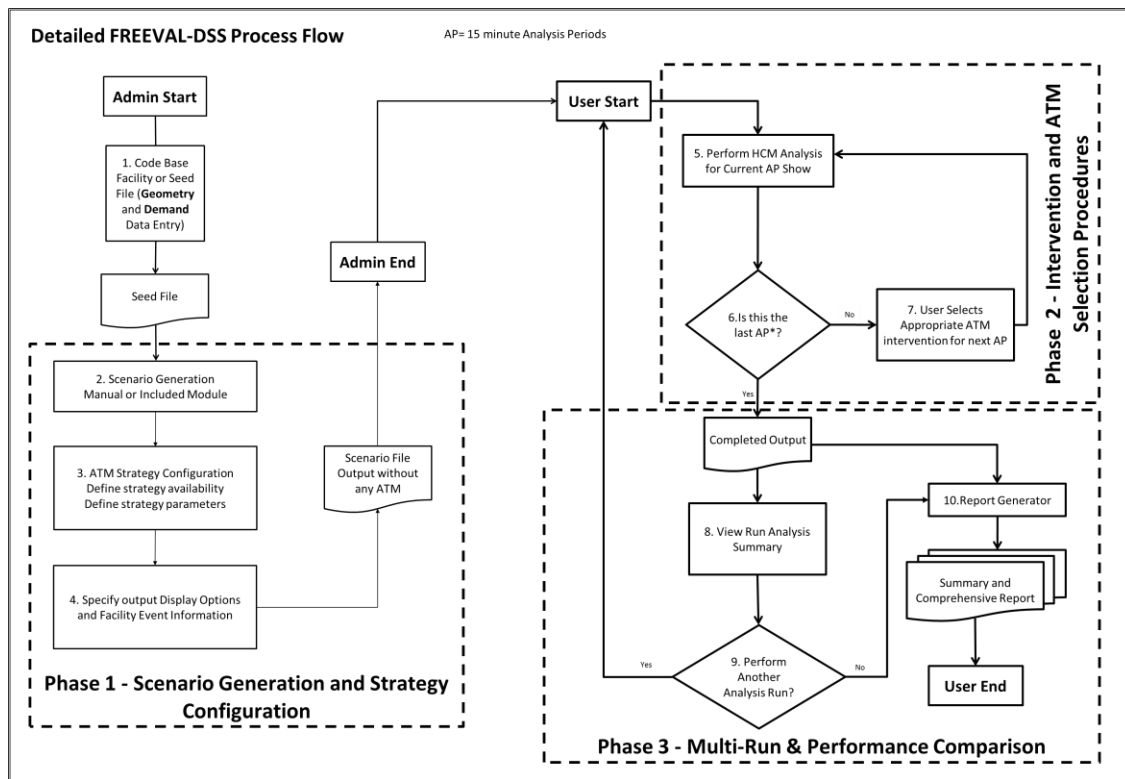


Figure 3-1. General process flow of the framework.

An important added value of this framework is that it makes use of the HCM’s oversaturated methodology for freeway facilities analysis. In the oversaturated methodology, the computational resolution is increased instantaneously from 15 minutes to 15-second time steps, enabling the freeway conditions to be updated at short time intervals. This allows for much finer implementation of queue progression and dissipation and improves the analysis of adaptive

strategies (e.g. ramp metering), as updated information and feedback on congestion are available in a near continuous manner.

### **Phase 1: Administrator Scenario Generation and Strategy Configuration**

In this phase, a seed file representing a base facility modeled using the HCM freeway facilities methodology is supplemented with a scenario that is characterized with certain non-recurring congestion sources. The Administrator then specifies the spatial and temporal availability of ATM strategies in addition to configuring the strategy parameters (capacity, demand, or duration effects). Lastly, the Administrator selects which performance measure outputs, facility information, and event information are available to the End User during the intervention phase.

The Administrator's first responsibility is to configure the base facility. This process requires the specification of both the facility geometry and demand inputs. Once the facility has been created, the Administrator can then choose to generate a specific "scenario" on top of the base conditions. The scenario serves as a means to simulate real world occurrences and variability of conditions. An internal scenario generation module allows the Administrator to schedule non-recurring events such as weather (rain, snow) and incidents (lane or shoulder closures). The module provides the ability to stochastically schedule some events based on a user specified probability of occurrence (e.g. specify probability of precipitation). The Administrator can also schedule planned work zones, though unlike weather and incident events, the presence of work zones will always be available to the End User. Default adjustment factors for capacity and free flow speed have been developed for all 3 types of events (work zones, weather, and incidents) and are provided to the Administrator as starting guidance [76].

After the scenario has been created, the Administrator is then responsible for configuring the ATM strategies that will be available to the End User during his or her analysis. A list of the strategies implemented in the framework can be found in Table 3-1. The Administrator is given the capability to fully customize the spatial and, when feasible, the temporal availability of the strategies. Further, the Administrator can configure any relevant strategy parameters at this step. Examples of parameters that can be specified for a strategy such as hard shoulder running are the segments of the facility where the shoulder can be opened, as well as the capacity of the open shoulder for the segments. Alternatively, for ramp metering the Administrator can specify the ramps at which it is implemented and can configure the metering schemes from the available options (both user specified and two different adaptive algorithms) that can be deployed. Many default values are provided in the framework for ATM strategy parameters. This gives the Administrator a starting point when specifying the scenarios, but the flexibility to enter locally calibrated parameter values is always available.

**Table 3-1. List of ATM strategies included in the framework.**

<b>Strategy</b>	<b>Description</b>
Hard Shoulder Running	Opens the hard shoulder as an additional lane with a reduced capacity.
Ramp Metering	User Specified and Adaptive strategies reducing on-ramp demand, which may result in increase in throughput, if breakdown is prevented.
Dynamic Message Signing	Traffic demand diverted to off-ramps between DMS location and downstream incident.
Incident Management	Facility wide reduction of incident duration.
GP to ML Diversion	Demand diversion from general purpose (GP) lanes to managed lanes (ML).
On-ramp Diversion	Administrator specified demand reduction of incoming on-ramp demand.

The final responsibility of the Administrator is to configure the End User display options. These options allow the Administrator to control the outputs that are made available during the End User analysis in order to more accurately represent real world facility situations. As an example, active traffic incidents and weather events can either be specifically displayed on the facility graphic, or hidden from view, requiring the End User to make decisions based only on the resulting congestion. Additional information, such as a weather forecast, can also be made available. The freeway performance measures and outputs given to the End User can be tailored to reflect each specific scenario, with options ranging from those as simple as speed, occupancy, and/or volume counts, up to the full slate of HCM performance measures on a segment-by-segment basis. Further, the Administrator can designate whether these outputs are available for each HCM segment or only available at a limited number of sensor locations across the facility.

### **Phase 2: End User Interventions and ATM Selection**

In the second phase, the Administrator passes control of the facility to the End User. Beginning with the first analysis period, the End User is presented with the Administrator selected set of facility performance measures, and based on the facility conditions observed from this information, the End User can choose to let the scenario play out naturally, or choose to make an

“intervention.” The performance measures that are presented are come from the underlying HCM methodology, and give an average of the conditions across all lanes of a segment. Each intervention is made by deploying one or more ATM strategies, and is allowed to take place at the conclusion of every 15-minute analysis period. The strategies are chosen from a menu of available ATM strategy options and can be implemented for just the following analysis period, or for any number of subsequent analysis periods. At the end of any 15-minute analysis period, an intervention can be stopped or extended, or new ones can be added. In this way, the freeway performance conditions in the next analysis periods are dependent on the selected ATM treatments. Further, the framework provides immediate feedback on the effectiveness of the strategies employed to guide further actions by the management system and/or analysts in the next 15 minutes. Figure 3-2 shows an example of the information and strategy menu presented to the End User during this phase.

At this intervention stage, several ATM strategies can be deployed either individually or in bundles. Ramp metering rates can be entered manually or automatically computed using dynamic metering strategies such as ALINEA [5] or Fuzzy Logic [46]. DMS can be selected to enable traffic diversions. For this strategy, diversion starts just downstream of the DMS sign location and continues through all downstream off-ramps. Incident management strategies can also be employed to enable a reduction in the duration of incident events. Other strategies made available in the framework include hard shoulder running and diversion of traffic from general-purpose lanes to managed lanes (when present).

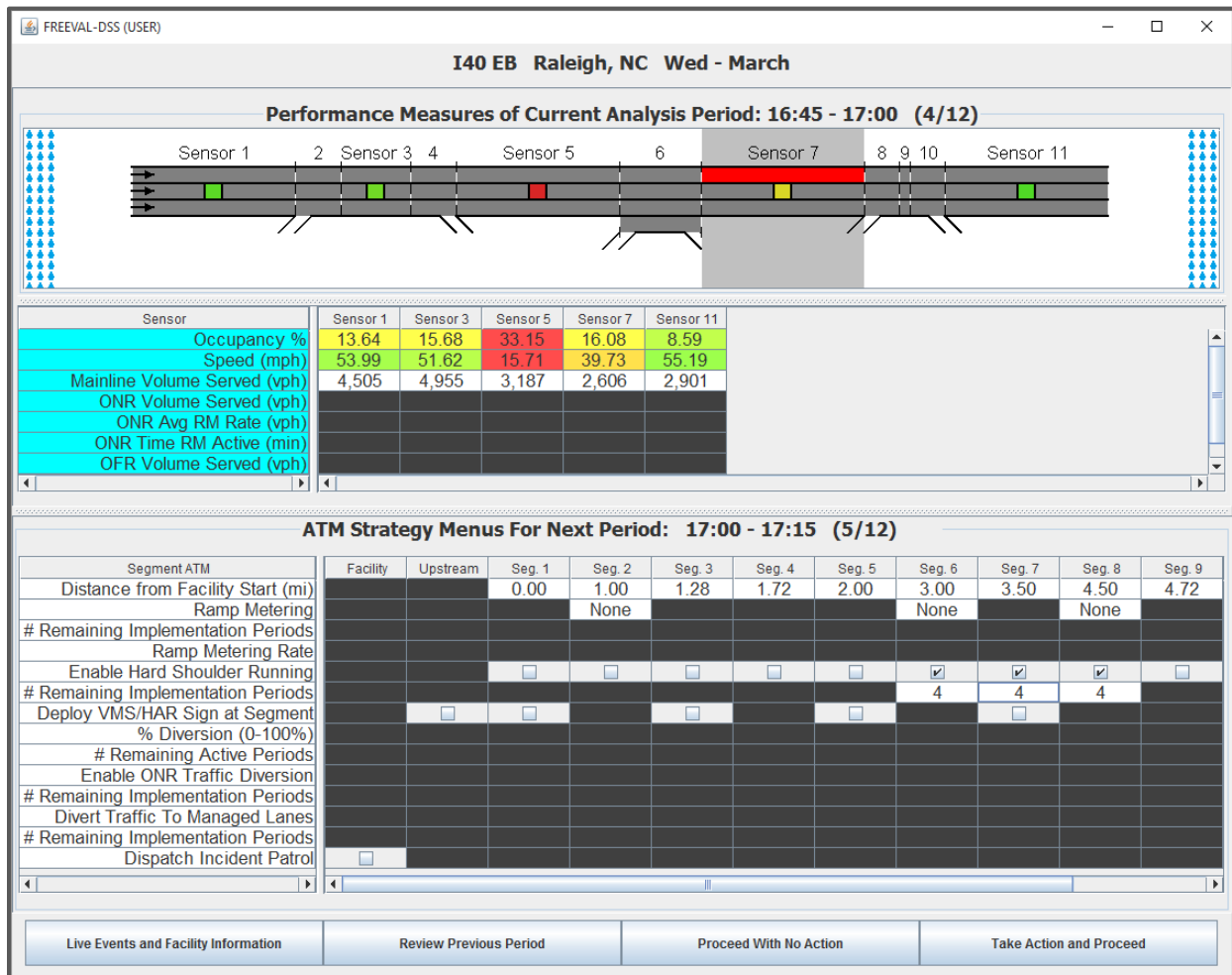


Figure 3-2. Example of the Phase 2 End User intervention window.

### Phase 3: Multi-Run and Comparison

This phase enables the End User to perform an ATM strategy intervention run any number of additional times. At the conclusion of each run, travel time and delay outputs for the current set of ATM interventions are presented to the End User. Additionally, the summary output provides comparisons between the base scenario performance and each successive intervention run for easy assessment and learning. Since a core purpose of the framework is to simulate the conditions of a TMC in order to test and train the TMC users, the End User may choose to execute multiple intervention runs and compare the effects of different courses of action until he or she is satisfied with the performance.

## Detailed Process Flow Steps for the Framework

This section details the description of each process as shown in Figure 3-1.

### Step 1: Create Base Facility or Seed File

In this step, the Administrator codes the core facility. To create a new project, the “New DSS Project” option should be selected in the “Project” dropdown menu. The analyst will then be prompted whether they wish to create a brand new facility, or import a facility from an existing core FREEVAL-2015e project. If a completely new facility is being created, the geometric and demand information of the subject facility needs to be fully characterized in this step for all 15-minute analysis periods in the study period. Once the initial inputs have been coded, it is necessary to calibrate the coded facility at this step. The Administrator will need to verify the reported performance measures of the coded facility and adjust input data as needed until the desired performance matches empirical observations or local knowledge of its operations

### Step 2: Scenario Generation

The Administrator has access to an internal scenario generation module to schedule weather events, incidents, and work zones. All three types of events can be scheduled deterministically, in which case the Administrator is required to provide the time periods in which the event will occur, as well as the location for both incidents and work zones. Weather events can also be generated stochastically based on a probability of occurrence and a specified expected duration. With each event type, its severity can be specified and the Administrator will be provided with default associated capacity, free flow speed, and demand adjustment factors. If desired, these values can be replaced with locally calibrated values according to the facility. The generated events are shown to the Administrator, who can override any attributes related to the events and/or their impacts. The scenario event generation process is conducted entirely within one of the three FREEVAL-DSS Administrator panels as shown in Figure 3-3.

The screenshot displays the 'Scenario Event Generation Panel' with three main sections: Weather, Incident, and Work Zone. Each section includes configuration fields and a list of generated events.

**Weather Section:**

- Buttons: Create/Edit Scenario Events, Configure ATM Strategy Parameters and Availability, Configure Display Options
- Facility Preview Analysis Period (A.P.) Control: A.P. 1/5, 17:00 - 17:15, First, Last, Jump To
- Weather:  Deterministic,  Stochastic, Event Probability: 70%
- Buttons: Generate Event, Edit Event, Delete Event
- Fields: Weather Type: <Select Type>, Event CAF: 1.0, Starting in Period: 1, Event SAF: 1.0, Duration (AP's): 1, Event DAF: 1.0
- List: Generated Weather Events

**Incident Section:**

- Buttons: Generate Event, Edit Event, Delete Event
- Fields: Occuring in Segment: <Select Segment>, Enter CAF: 1.0, Incident Severity: <Select Type>, Enter SAF: 1.0, Starting in Period: 1 (17:00), Ending in Period: 1 (17:15), Enter DAF: 1.0
- List: Generated Incidents

**Work Zone Section:**

- Buttons: Generate Work Zone, Edit Event, Delete Event
- Fields: Starting in Segment: <Select Segment>, Enter CAF: 1.0, Ending in Segment: <Select Segment>, Starting in Period: 1 (17:00), Enter SAF: 1.0, Ending in Period: 1 (17:15), Work Zone Type: <Select Type>, Enter DAF: 1.0
- List: Work Zones

**Figure 3-3. Scenario Event Generation Panel.**

*Generating a Weather Event*

Weather events can be generated in two ways: stochastically or deterministically. When choosing to generate an event stochastically, the analyst specifies a percent chance of the event occurring as opposed to specifying a specific time interval for the event. This can be used to emulate real world circumstances of weather forecasts, especially if information regarding the percentage chance of the event occurring is later made available to the End User (as will be discussed in Step 4). Given the specified probability, the event generator will randomly determine whether or not the event is generated based on the percentage chance. Further, a random starting time within the study period will be assigned to the event. If the generated starting time for the event occurs late in the study period, the desired duration of the event may be truncated by the ending of the study period. An example of a 45-minute heavy rain event with a 70% chance of occurring is shown in Figure 3-4.

The screenshot shows a software interface titled "Weather". At the top, there are two radio buttons: "Deterministic" (unselected) and "Stochastic" (selected). To the right of these is a text field for "Event Probability" set to "70%". A "Generate Event" button is located to the right of the probability field. Below this, there are three rows of input fields: "Weather Type" is a dropdown menu set to "Heavy Rain"; "Starting in Period" is a dropdown menu set to "3"; and "Duration (AP's)" is a dropdown menu set to "3". To the right of these are three text input fields: "Event CAF" with the value "0.8587", "Event SAF" with the value "0.92", and "Event DAF" with the value "1.0". On the far right, there is a vertical list box titled "Generated Weather Events" which is currently empty.

**Figure 3-4. Stochastic Generation of a Weather Event.**

Alternatively, an event can be generated in a deterministic manner where the analyst is responsible for specifying the exact start and end times for the event. As a note, deterministic events are considered to have a 100% chance of occurring. Figure 3-5 shows an example of the same 45-minute heavy rain event being deterministically generated with specified start and end times.

The screenshot shows the same "Weather" software interface, but with the "Deterministic" radio button selected. The "Event Probability" field is now set to "100%". The "Starting in Period" dropdown is now set to "1 (17:00)" and the "Ending in Period" dropdown is set to "3 (17:45)". The "Event CAF", "Event SAF", and "Event DAF" values remain the same as in Figure 3-4. The "Generated Weather Events" list box is still empty.

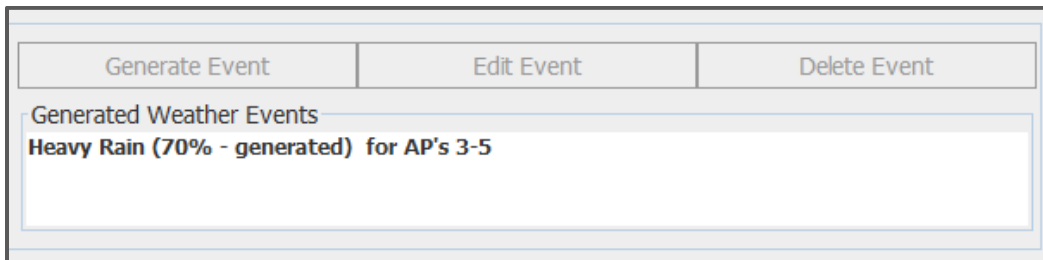
**Figure 3-5. Deterministic Generation of a Weather Event.**

For each event the analyst must specify a weather type, which is chosen from a list of eleven different categories. Each category contains default adjustment factors for capacity and speed, which will automatically be inserted into the event CAF and SAF text fields. As shown in Figure 3-4 and Figure 3-5, the ‘heavy rain’ rain weather type has a default CAF of 0.8587 and a default SAF of 0.92. The analyst can choose to override these and specify custom adjustment factors if facility specific data is available for weather.

After the analyst has specified all of the event parameters, the “Generate Event” button will be enabled and is used to formally create the event and assign it to the DSS scenario. It is at this point that the probabilistic “coin flip” will occur if the event is stochastic. Once this process is complete, the event will be shown in the “Generated Weather Events” list. The entry in the list will display the event type, the probability of the event, whether or not the event was generated,

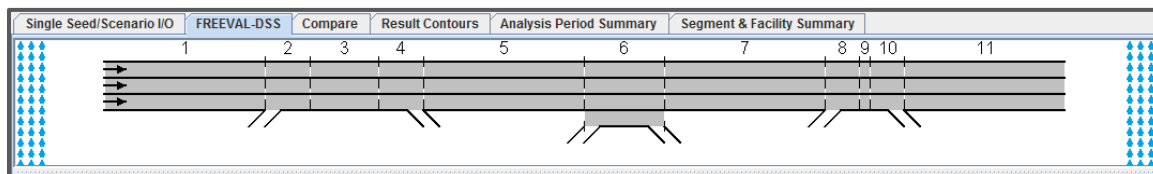


and the analysis periods (AP's) during which the event occurs (termed “generated” or “not generated”). Figure 3-6 gives an example of how the stochastically generated “heavy rain” event of Figure 3-4 is listed.



**Figure 3-6. Weather Event List Entry for a Stochastically Generated Heavy Rain Event.**

Each scenario can contain at most one weather event. Once generated, events can be deleted or edited using the respective buttons in the panel. The *Facility Preview Analysis Period Control* panel can be used to scroll through the analysis periods and view any weather events that occur on the facility graphic. Figure 3-7 shows the facility preview with the heavy rain graphic displayed on each side, indicating that the weather event is active during the selected period.



**Figure 3-7. Facility Preview Graphic with an Active Heavy Rain Event.**

### *Generating an Incident*

Overall, incidents are generated in a very similar manner to weather events. However, all incidents must be generated deterministically. The Administrator must first specify the segment in which the incident occurs. Next, the severity of the incident must be selected, ranging from a shoulder closure, to a one or multi-lane closure. As a note, the number of lanes closed cannot exceed one less than the number of lanes of the segment since a minimum of one lane must always remain open. Selecting a severity will populate the CAF, SAF, and DAF text fields with default values, but as with weather events, the analyst can always choose to enter their own values if the

data is available. Figure 3-8 shows how a one-lane closure that last for 45 minutes would be modeled for the incident event generator.

Incident			
Occuring in Segment:	7	Enter CAF:	0.74
Incident Severity:	1 Lane Closure	Enter SAF:	1.0
Starting in Period:	3 (17:30)	Enter DAF:	1.0
Ending in Period:	5 (18:15)		

Generate Event

Generated Incidents

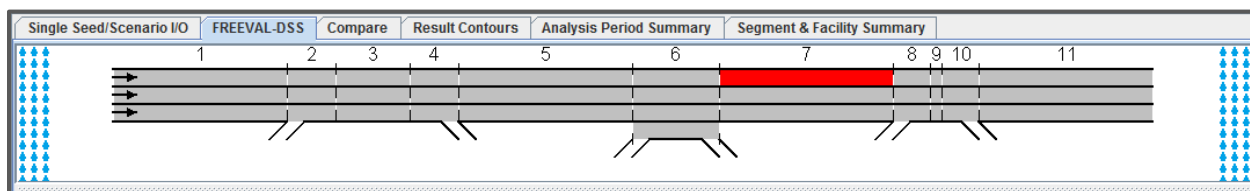
**Figure 3-8. A One-lane Closure Modeled in the Incident Event Generator.**

Once an incident has been generated, it is shown in the list of generated incidents. The list entry displays the severity of the incident, the segment location of the incident, and the analysis periods during which it is active. There is no limit on the number of incidents that can be included in a scenario, but the program will not allow incidents to overlap at a location during the same time periods. Any generated incident can be edited or deleted at any time using the “Edit Event” or “Delete Event” buttons. Figure 3-9 shows the list entry for the one-lane closure specified in Figure 3-8.

Generate Event	Edit Event	Delete Event
Generated Incidents		
1 Lane Closure at segment 7 for AP's 3-5		

**Figure 3-9. Incident list entry for a one-lane closure event.**

Incidents can be viewed on the facility preview graphic, and will be displayed as red bars indicating the number of lanes affected by the incident. The Administrator can view incidents in the scenario using the buttons in the *Facility Preview Analysis Period Control* panel to move to a period in which an incident is active. Figure 3-10 shows the one-lane closure of the previous two figures displayed during an active analysis period.



**Figure 3-10. One-lane closure displayed on the facility preview graphic.**

### *Specifying a Facility Work Zone*

The final type of non-recurring congestion event that the Administrator can choose to add to a scenario is a scheduled work zone. A work zone can span one or more segments, and can consist of shoulder work or a one or multi-lane closure. For each work zone, the Administrator is required to specify the starting and ending segments (this will be the same if the work zone is contained within a single segment), the starting and ending periods, and the work zone type. As with the other event types, selecting a work zone type will populate the CAF, SAF, and DAF text fields with default values. These values are computed utilizing the 3-107 work zone methodology [77] but the analyst is free to override these values if better data is available. Figure 3-11 shows how an Administrator might model a single segment one-lane closure work zone that lasts for the entire study period – in this case, 3 hours.

Work Zone			
Starting in Segment:	7	Enter CAF:	0.949765
Ending in Segment:	7	Enter SAF:	0.92415273
Starting in Period:	1 (16:00)	Enter DAF:	1.0
Ending in Period:	12 (19:00)		
Work Zone Type:	1 Lane Closure		

Generate Wor... Save Changes Discard Cha

Work Zones

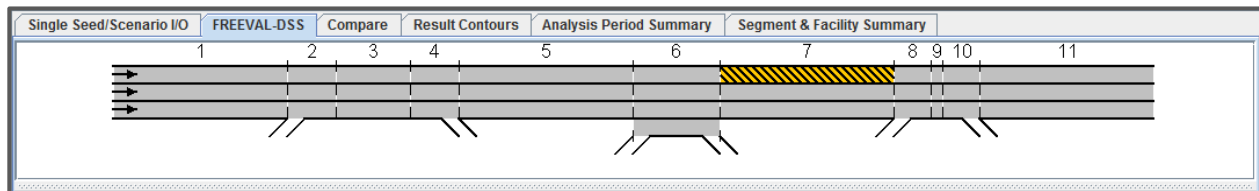
1 Lane Closure: Jan 1 Sat - Jan 1 Sat (Seg. 7 - 7) (Per. 1 - 12)

**Figure 3-11. One-lane Closure Work Zone Scheduled for the Entire Study Period.**

Once a work zone has been generated, it will appear in the list of work zones. The entry will display information about the work zone type, as well as the location and the time periods for which it is active. Any work zone that has been generated can be edited or deleted using the respective button, and there is no limit on the number of work zones that can be included in the scenario. Breaking up a work zone into multiple work zone events can be used to model more complex work zones such as one that has varying lane closure for different segments of the facility.

The only restriction is that work zones cannot overlap in the same segments during the same time periods.

Work zones are displayed on the facility graphic in yellow and black bars that reflect the type (i.e. shoulder work or a lane closure). The Administrator can view any scheduled work on the preview graphic by using the buttons in the *Facility Preview Analysis Period Control* panel to move to a period in which a work zone is active. Figure 3-12 shows the one-lane closure work zone of Figure 3-11 displayed during an active analysis period.



**Figure 3-12. One-lane closure work zone displayed on the facility preview graphic.**

### Step 3: ATM Strategy Availability Configuration.

Once the Administrator has coded the scenario, the next step is to configure the menu of ATM strategies that will be made available to the End User at each intervention. This process takes place in the second tab of the FREEVAL-DSS main panel (as shown in Figure 3-13). The panel is broken down into two separate parts. The top portion of the panel, labeled “Segment and Period ATM Strategy Availability,” is used to configure the availability and parameters of ATM strategies that can vary by segment and by period. This includes hard shoulder running (availability only), ramp metering, and diversion. The bottom portion of the panel, labeled “Facility Wide ATM Parameters,” is used to specify parameters that will be constant across the whole facility. This includes hard shoulder capacities, incident management parameters, and general purpose to managed lane diversion (where available).

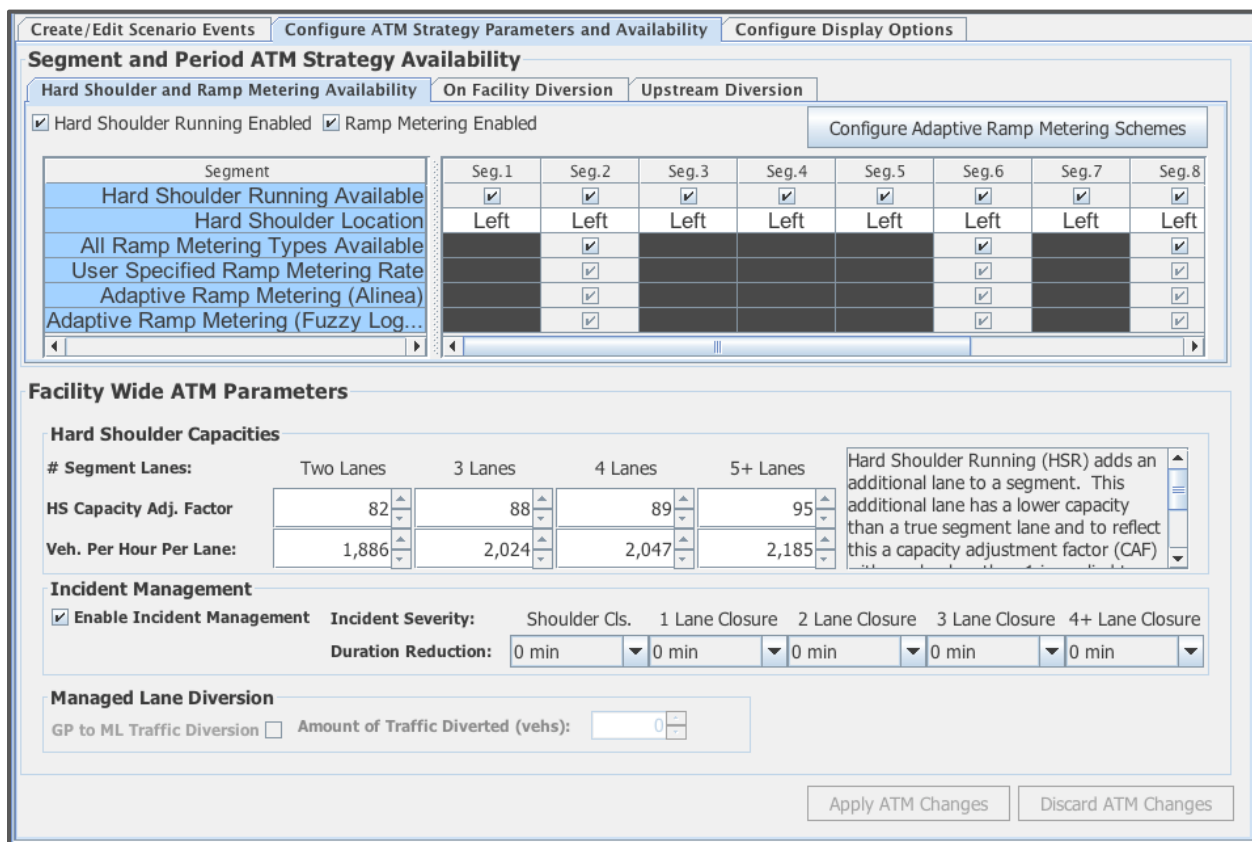
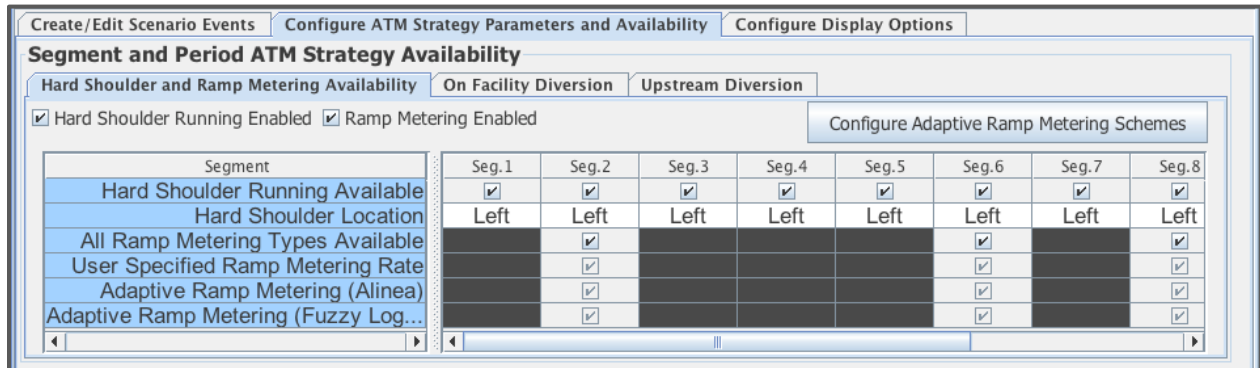


Figure 3-13. ATM Strategy Parameter and Availability Tab in the DSS Main Panel.

The “Segment and Period ATM Strategy Availability” panel consists of a set of three tabs that correspond to different strategies. The first tab allows the Administrator to configure both hard shoulder running and ramp metering properties, and is shown in Figure 3-14. The availability of hard shoulder running can be turned on or off for each segment using the checkboxes in the table, or the strategy as a whole can be toggled on or off using the checkbox above the table. Ramp metering schemes can be customized using the button in the top right of the panel, and ramp metering can be turned on or off for each ramp segment using the checkboxes in the table. There are three types of ramp metering implemented in the DSS framework: user specified, adaptive ALINEA, and an adaptive fuzzy logic approach. The table in this panel allows the Administrator to specify which (if any) of these three types is available at each ramp.



**Figure 3-14. Hard shoulder running and ramp metering configuration options.**

The second tab (shown in Figure 3-15) allows the Administrator to configure “On-facility” diversion. This type of diversion is either induced by deploying DMS on the mainline, or by enabling diversion at on-ramps. Enabling a DMS location at a segment will allow the End User to assess the benefits of DMS. In the context of this framework, DMS signs are used to divert traffic to ease congestion when incidents arise. When the End User deploys a DMS at a segment, he or she will specify an additional percentage of traffic that will be diverted. This percentage will be equally divided among all downstream off-ramp and weave segments up to and including the most down-stream segment in which an incident is occurring. However, it is important to note that if no incident occurs in the period a DMS has been deployed, there will be no effect.

The first two rows in the table shown in the panel give information that the Administrator will likely need to reference when configuring the on facility diversion parameters. The top row gives the number of incidents that occur in each segment of the facility, and the second row lists the maximum Vehicle hour delayed (VHD) that occurs at each segment during the study period. The third row of the table is used to enable the deployment of a DMS sign at a specific segment of the facility. If deployment of a DMS sign is enabled for a particular segment, this does not mean that a DMS will be deployed, rather it indicates that the End User will be able to deploy a sign there in the event that he or she deems it necessary.

The screenshot shows a software window titled "Segment and Period ATM Strategy Availability" with three tabs: "Create/Edit Scenario Events", "Configure ATM Strategy Parameters and Availability", and "Configure Display Options". The "Configure ATM Strategy Parameters and Availability" tab is active, showing sub-tabs for "Hard Shoulder and Ramp Metering Availability", "On Facility Diversion", and "Upstream Diversion". The "On Facility Diversion" sub-tab is selected, displaying a table with the following data:

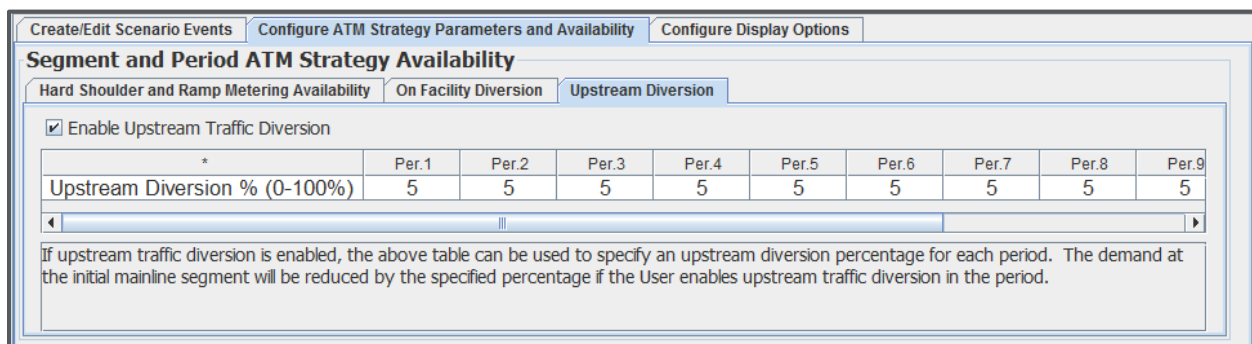
Segment	Seg 1	Seg 2	Seg 3	Seg 4	Seg 5	Seg 6	Seg 7	Seg 8
Number of Incidents in Segment	0	0	0	0	0	0	1	0
Maximum VHD at Segment	888.82	36.05	35.50	24.13	89.85	59.04	5.84	1.09
Enable VMS/HAR Sign Location	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Allow ONR Diversion Sign at Segment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
% Entering Dem. Reduction (0 - 100%)								

Below the table, a text box explains: "Enabling VMS/HAR sign locations at segments will allow the User to deploy a sign at the segment in their ATM analysis. In this analysis, VMS/HAR signs are used to divert traffic to ease congestion when incidents arise. If no incident is occurring in the period a VMS/HAR is deployed, there will be NO effect. When the User deploys a VMS/HAR at a segment, they will specify an additional % diversion will be equally divided among all downstream off-ramp and weave segments up to and including the most down-stream segment in which an incident is occurring."

Figure 3-15. “On Facility” diversion configuration options.

The final two rows of the table are used to configure on-ramp diversion. Enabling diversion at on-ramps is used to simulate factors that may occur outside of the facility such that the incoming demand via on-ramps is reduced. This could include information provided by arterial street’s DMS, the media, smartphone apps, social media, or web sites. Similar to DMS, the Administrator uses the checkboxes in the table to enable the availability of diversion for each on-ramp, but it will be up to the End User to decide if it is actually used in the intervention stage. Since this is simulating factors outside of the facility, it is left to the Administrator to decide the percentage of entering demand that will be diverted by each DMS.

The final tab of the “Segment and Period ATM Strategy Availability” section allows the Administrator to configure the availability of diversion that may occur due to circumstances upstream of the facility. If upstream traffic diversion is enabled, the above table can be used to specify an upstream diversion percentage for each period. The demand at the initial mainline segment of the facility will be reduced by the specified percentage if the End User enables upstream diversion during the period. Figure 3-16 shows the upstream diversion configuration table for an example facility with twelve analysis periods.



**Figure 3-16. Upstream diversion configuration options.**

Since not all ATM strategy parameters need to be configured individually for each segment, the bottom portion of the strategy parameter and availability tab is devoted to those parameters that can be specified for the facility as a whole. This primarily includes the specification of hard shoulder capacities, which can be given in terms of an HCM capacity adjustment factor or in vehicles per hour per lane. In the context of the HCM, hard shoulder running is implemented by adding an additional lane to a segment. The additional lane has a lower capacity than a true segment lane, which is reflected through the use of a capacity adjustment factor with a value less than 1. Alternatively, if the analyst has access to facility specific data in terms of vehicles, this can also be used to determine the capacity of the shoulder.

Incident management can also be enabled and configured in this section. For the DSS framework, the End User must decide in the first analysis period if incident management will be deployed. If it is, any incident that occurs during the study period will have its duration shortened by the amount specified in this step by the Administrator. The checkbox at the left of the panel toggles the availability on and off for incident management, and the drop down boxes can be used to specify the reduction amount (up to 90 minutes) for each incident severity. Figure 3-17 shows a more detailed view of the facility wide ATM parameter panel.



**Facility Wide ATM Parameters**

**Hard Shoulder Capacities**

# Segment Lanes:	Two Lanes	3 Lanes	4 Lanes	5+ Lanes
HS Capacity Adj. Factor	82	88	89	95
Veh. Per Hour Per Lane:	1,886	2,024	2,047	2,185

Hard Shoulder Running (HSR) adds an additional lane to a segment. This additional lane has a lower capacity than a true segment lane and to reflect this a capacity adjustment factor (CAF) with a value less than 1 is applied to the segment as a whole. For example, employing HSR on a 3

**Incident Management**

Enable Incident Management    Incident Severity:    Shoulder Cls.    1 Lane Closure    2 Lane Closure    3 Lane Closure    4+ Lane Closure

Duration Reduction:    0 min    0 min    0 min    0 min    0 min

**Managed Lane Diversion**

GP to ML Traffic Diversion     Amount of Traffic Diverted (vehs):    0

Apply ATM Changes    Discard ATM Changes

**Figure 3-17. Facility wide ATM parameter panel.**

**Step 4: Specify Output Display Options and Facility Event Information.**

In the final portion of the first phase, the Administrator has the opportunity to customize both what information is available to the End User, and how it is presented. This process takes place in the third tab of the main DSS Administrator panel. The top portion of the panel allows the Administrator to specify general information about the project and facility. The facility name, location, day of week, and month of year can all be specified. Figure 3-18 shows an example of the End User Display Options panel.

**Facility Information**

Available to User:

Facility Name

Facility Location

Day Of Week

Month of Year

**Display Options**

Color By Level of Service  Color by Segment Speed

Output by HCM Segment  Output by Sensor Location

HCM Style Table Output  Sensor Style Table Output  Custom Table Output

Show Incident Lane Closures  Show Weather Preview

**Sensor Location Configuration Table**

Sensor	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11
Sensor Name											
Located in Segment											
Ramp Sensor Data Avail...											
Distance From Start (mi)											

**Figure 3-18. Display options customization options.**

In the middle section of the panel, the display options for the End User can be customized. First, the color outputs shown on the facility preview graphic can be configured to either reflect the HCM Level of Service (LOS) segment performance measure, or the computed speed in the segment for the active time period. Next, the Administrator can specify if outputs will be given for each segment of the facility, or if outputs will be limited to those coming from “sensors” located along the facility. If the Administrator chooses the sensor outputs options, the table beneath the panel must be used to specify the location of each sensor. The table can also be used to give a name to each sensor, as well as indicate whether there is sensor data available for any on-ramps of the facility. Figure 3-19 shows an example of a sensor output configuration.

**Display Options**

Color By Level of Service       Color by Segment Speed  
 Output by HCM Segment       Output by Sensor Location  
 HCM Style Table Output       Sensor Style Table Output       Custom Table Output  
 Show Incident Lane Closures       Show Weather Preview     

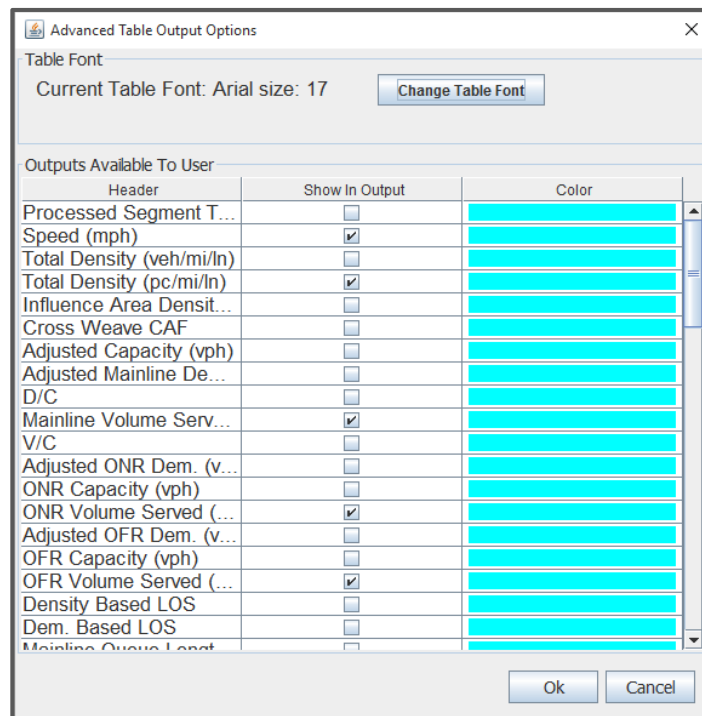
**Sensor Location Configuration Table**

Sensor	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11
Sensor Name	Sensor 1		Sensor 3		Sensor 5		Sensor 7				Sensor ...
Located in Segment	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Ramp Sensor Data Ava...	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Distance From Start (mi)	0.00	1.00	1.28	1.72	2.00	3.00	3.50	4.50	4.72	4.78	5.00

**Figure 3-19. Sensor display options.**

The Administrator can also choose which outputs and performance measures will be given to the End User at the end of each 15-minute analysis period. The framework provides two default choices, HCM style output or sensor style output, in addition to allowing the set of outputs to be fully customized. HCM style outputs provide speed, total density, mainline and ramp volume served, and information regarding ramp metering activity and metering rates. Sensor style outputs provide all of these outputs, plus an additional occupancy percent measure. As its name suggests, the sensor style output option can only be chosen when the outputs are already configured by sensor location as opposed to HCM segment. If neither of these is acceptable, the Administrator can choose to use custom table outputs and select any (or all) of the available performance measures using the “Configure Advanced Table Options” button. Figure 3-20 shows the advanced table options available for customization.

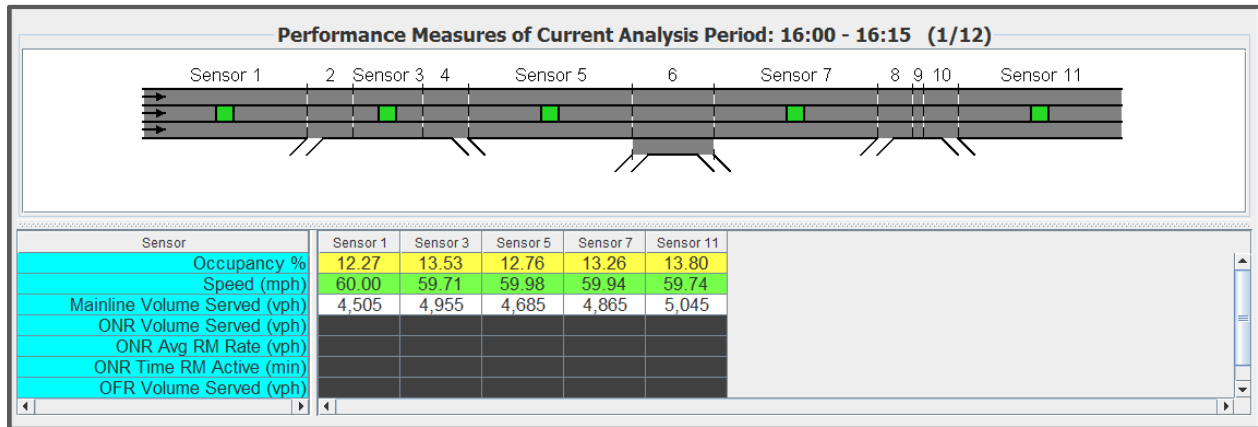


**Figure 3-20. Dialog to select the custom set of performance measures made available to the End User.**

Lastly, the Administrator can choose whether or not active incident or weather information will be given to the End User. If this information is made available, the facility graphic will display incidents and weather events during the periods in which they are active. Further, more information such as weather forecasts will be shown in the “Additional Facility Information” dialog available to the End User. At the end of this step the related processes for the Administrator are completed, and the coded facility with defined weather and incident events are ready to be simulated by the End User.

### **Step 5: Perform HCM Analysis for Current Analysis Period (AP) and Show Partial Results**

This is the first step for the End User to proceed with the analysis. The framework will perform the HCM freeway facilities methodology for only the current 15 minute analysis period (AP) at the end of which it will report the (available) freeway performance measures. In performing the freeway facilities methodology in the current AP, the limited output is shown to the user. The demonstration of limited results to the user is based on the level of data to which a TMC operator would have access.



**Figure 3-21. Selected set of sensor performance measures provided to the End User.**

As seen in Figure 3-21, the End User can view facility conditions in two places. First, the color of the sensors in the facility graphic reflect the speed (or LOS) of the facility at that segment. For the example in the figure, the speed at each segment is very close to the free flow speed of 60mph, so all sensors are green. However, as speed drops in a segment, the color of the sensor will transition from green to yellow to red accordingly. Second, in the table below the facility graphic, the Administrator specified performance measures are given to the End User. For the example in the figure, sensor-style table output was chosen. The rows giving occupancy percent and speed are colored according to the value to help easily identify problem areas. The color will scale from green to red indicating “good” and “bad” values, respectively. The table also displays values for mainline and ramp volume served, and if ramp metering is activated by the End User, average metering rates and time active will also be given (provided the sensor is located in a ramp segment). The End User can access additional facility information including weather forecasts and live events at the end of any analysis period. By using the “Live Events and Facility Information” button at the bottom of the End User screen (see Figure 3-2 for reference), a small dialog window will appear. Figure 3-22 shows this window for first analysis period of the example facility. There are no events currently active on the facility, but the weather forecast is given, indicating a 70% chance of rain during the study period.

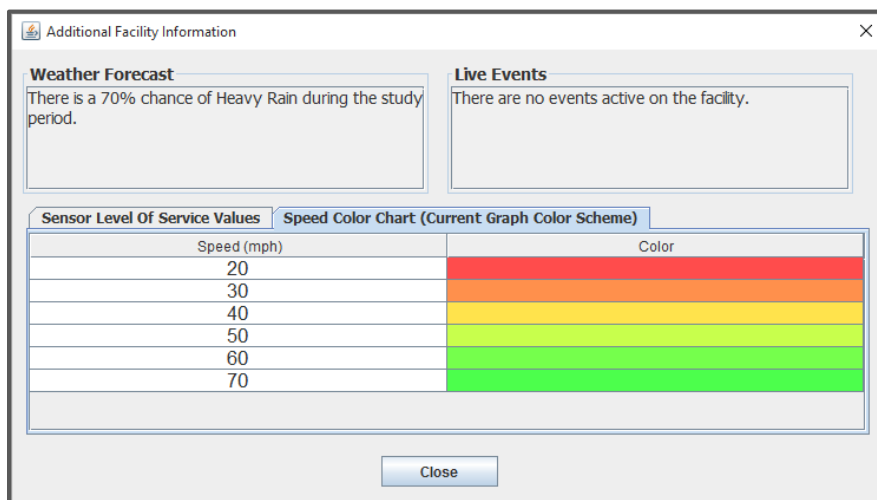


Figure 3-22. Additional Facility Information window for the example facility.

**Step 6: Check if the Current AP is the Last AP**

This step checks to see whether the analyzed AP is the last AP of the study period. If the current analyzed AP is the last one, then the process flow proceeds to Step 8. Otherwise, a menu of ATM strategies is presented to the End User from which the appropriate strategies (if any) are selected for implementation in the next AP in Step 7. Of course, at every AP the user may decide to “do nothing,” and will therefore mirror the base scenario generated by the Administrator. Figure 3-23 shows an example menu of ATM strategies that the End User would see in this step.

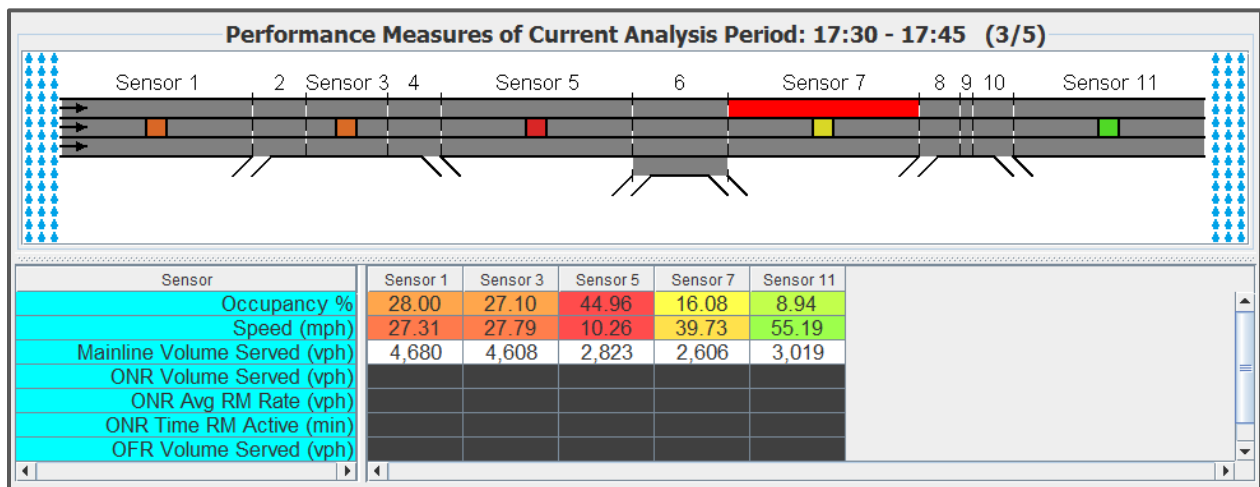
ATM Strategy Menus For Next Period: 16:15 - 16:30 (2/12)											
Segment ATM	Facility	Upstream	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9
Distance from Facility Start (mi)			0.00	1.00	1.28	1.72	2.00	3.00	3.50	4.50	4.72
Ramp Metering				None				None		None	
# Remaining Implementation Periods											
Ramp Metering Rate											
Enable Hard Shoulder Running			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
# Remaining Implementation Periods											
Deploy VMS/HAR Sign at Segment		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>		<input type="checkbox"/>		<input type="checkbox"/>		
% Diversion (0-100%)											
# Remaining Active Periods											
Enable ONR Traffic Diversion											
# Remaining Implementation Periods											
Divert Traffic To Managed Lanes											
# Remaining Implementation Periods											
Dispatch Incident Patrol	<input type="checkbox"/>										

Figure 3-23. Example menu of ATM strategies available to the End User. The “Proceed with No Action” and “Take Action and Proceed” options are also shown at the bottom of the panel.

**Step 7: Select a Set of ATM Strategies to Be Incorporated in the Next AP**

Based on the available performance measures and system outputs, the End User chooses any combination of the available ATM strategies to apply to the next analysis period. Once an appropriate course of action is chosen, the End User then proceeds to the next AP and returns to Step 6. It should be noted that from this point on, the performance measures, facility graphic, and other outputs will serve to provide immediate feedback on the effectiveness of the course of action taken thus far and will guide future deployment of ATM strategies.

For the example that was developed in the previous steps, assume we have progressed to the third analysis period. Figure 3-24 shows the performance measures indicating to the End User that the conditions on the facility have broken down considerably due to both a heavy rain weather event and a one-lane closure incident.



**Figure 3-24. Facility performance measures and output with a heavy rain weather event and a one-lane closure incident.**

Upon viewing these conditions, the End User will wish to make an ATM intervention. He or she will consult the menu of available strategies and choose one or more in order to help address the congestion that has formed on the facility. To keep things simple for this example, let us assume that the user chooses to open the Hard Shoulder from segments 6 to 8 to allow traffic to flow more easily around the active traffic incident. Figure 3-25 shows the selection of this strategy in the lower portion of the End User screen.

ATM Strategy Menus For Next Period: 17:00 - 17:15 (5/12)											
Segment ATM	Facility	Upstream	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9
Distance from Facility Start (mi)			0.00	1.00	1.28	1.72	2.00	3.00	3.50	4.50	4.72
Ramp Metering				None				None		None	
# Remaining Implementation Periods											
Ramp Metering Rate											
Enable Hard Shoulder Running			<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
# Remaining Implementation Periods								4	4	4	
Deploy VMS/HAR Sign at Segment		<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>		<input type="checkbox"/>		<input type="checkbox"/>		
% Diversion (0-100%)											
# Remaining Active Periods											
Enable ONR Traffic Diversion											
# Remaining Implementation Periods											
Divert Traffic To Managed Lanes											
# Remaining Implementation Periods											
Dispatch Incident Patrol	<input type="checkbox"/>										

Figure 3-25. Hard shoulder running selected for segments 6-8 for the next 4 periods to alleviate the congestion that has appeared as seen in Figure 3-24.

### Step 8: View Run Analysis Summary

In this step, the End User is presented with an analysis summary comparing the “before” and “after” scenarios to gauge the quality of the interventions performed. The summary contains statistics of various performance measures for the run so that the End User can readily evaluate the effectiveness of the ATM decision made during the study period.

The top section of the analysis run comparison window provides a summary of the general information for the project and states the number of intervention runs that have currently been conducted. The section below, titled “Facility Reliability Performance Measures For Base Scenario,” contains the reliability statistics for the underlying scenario before any ATM interventions are made. Finally, the bottom section, titled “Reliability Performance Measures After ATDM,” contains the reliability statistics for the most recent ATM intervention run. In addition to these statistics, the window contains a panel with two output graphs for the facility. The left graph gives the facility travel time for of the facility either by period or by segment, and the right graph shows the cumulative distribution function (CDF) of facility TTI. Each chart shows the respective distribution for both the base scenario and each intervention run. All distributions are vehicle mile traveled (VMT)-weighted. Further, the End User can view a more detailed look at the TTI distributions of both sets by pressing the “Show TTI Percentile Detail” button. In addition to travel time statistics, an analogous set of statistics reporting delay on the facility can be accessed by selecting “Delay” in the dropdown box above the graphs.



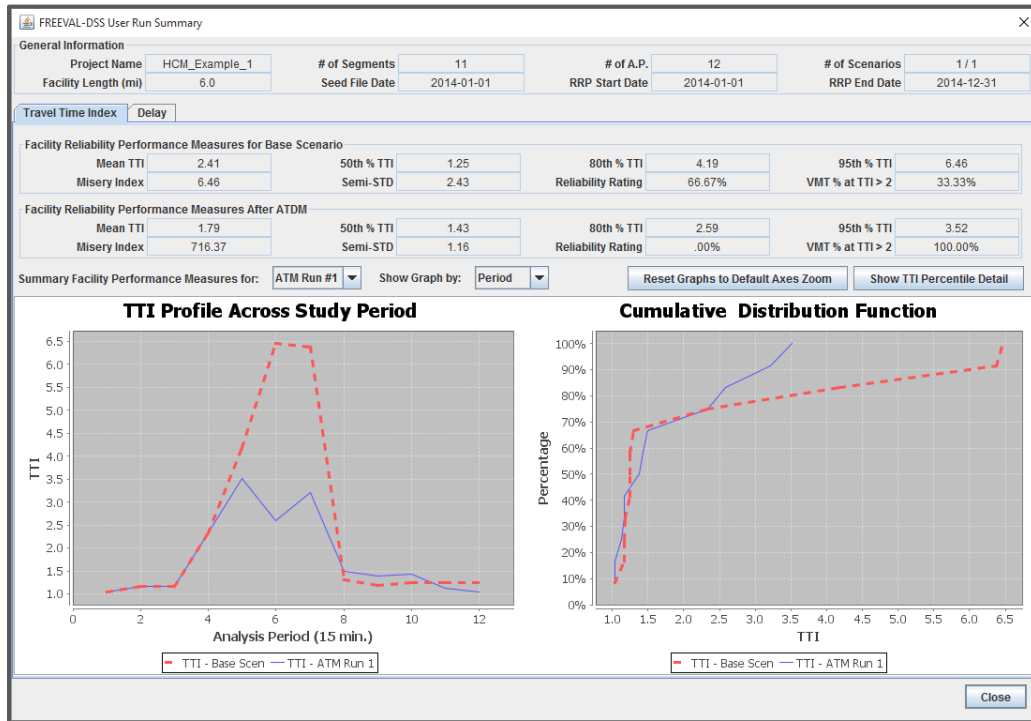


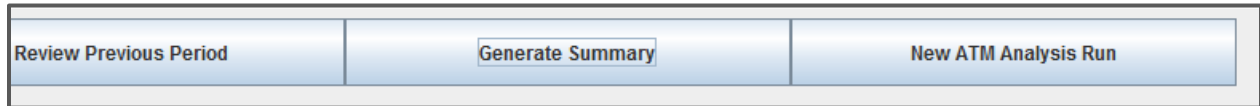
Figure 3-26. Example summary output for an intervention analysis run.

Returning to the example, if we assume that the only intervention made by the End User is the opening of the hard shoulder as discussed in the previous step, Figure 3-26 shows the summary output comparing the base conditions to those with the ATM intervention. The performance measures show significant improvement for both mean and 80<sup>th</sup> percentile TTI, which is supported by the graphs below. It is interesting to note that while the TTI profile shows a large drop in travel time during the worst periods, the travel time actually increases slightly for periods 8-10, which is likely due to some congestion arising due to merging traffic as the shoulder is closed. The End User may look at a result such as this and in a subsequent run choose to keep the shoulder open for another 15-30 minutes in order to avoid such a phenomenon.

### Step 9: Perform Another Analysis Run?

At this stage, the user is questioned whether he wants to re-run the analysis with a new set of strategies or not. If the End User chooses to rerun the analysis, then the process flow returns to Step 8 for a new run, otherwise it proceeds to Step 13. After a run summary has been viewed, the buttons at the bottom of the End User window will be updated to reflect the new options. Additionally, the End User is given the option at this point to review the interventions made during

the current run and can use the “Review Previous Period” button to toggle between analysis periods to view measures taken.



**Figure 3-27. Updated End User options once an analysis run has been completed.**

### **Step 10: Report Generator**

If the End User decides to not proceed with another intervention run, this step generates a report to show the performance across all runs by the End User in selecting the ATM strategies. Figure 3-28 shows the results of three runs conducted on the example that has been developed over the previous 9 steps. The first run opens the hard shoulder for an hour, the second makes use of DMS induced diversion upstream of the incident, and the last uses ramp metering and incident management. The graphs at the bottom clearly show the differences in performance of each.

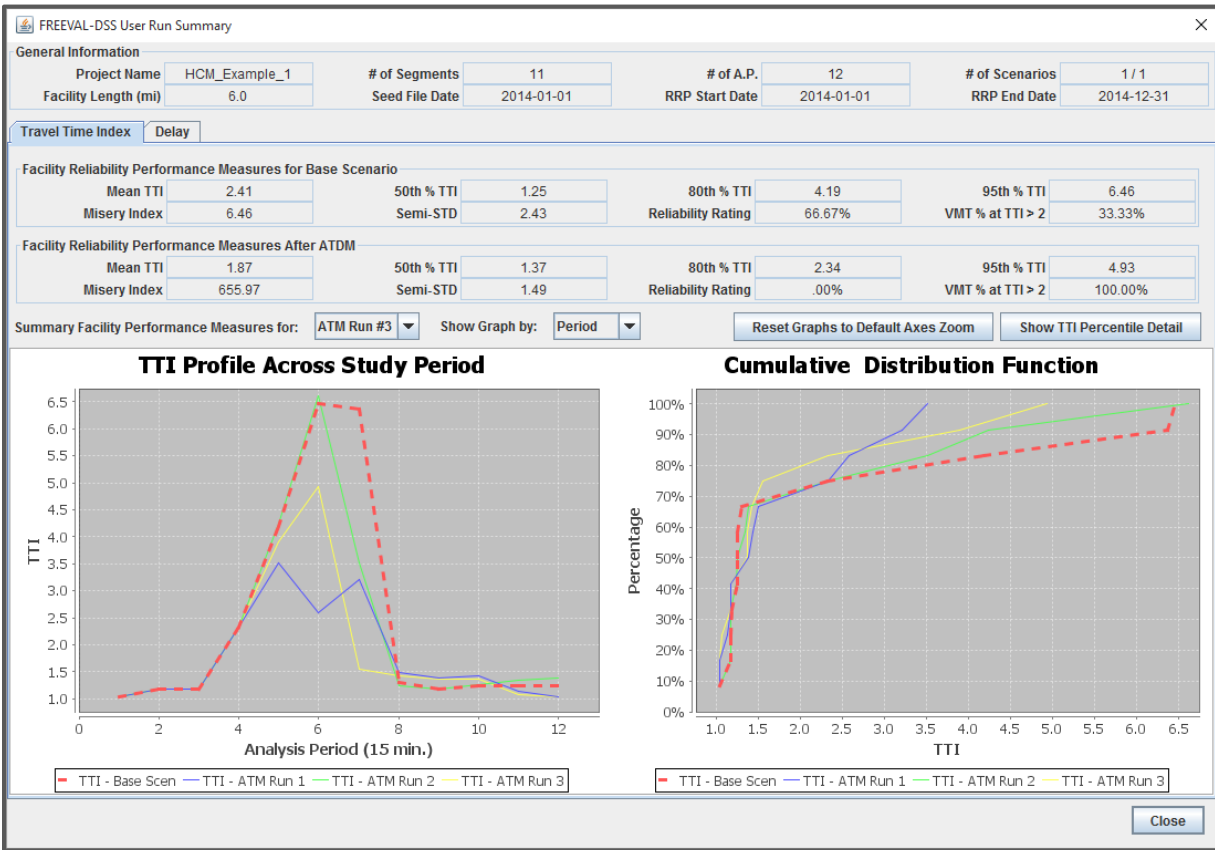


Figure 3-28. Output summary report showing comparison for three intervention runs.

## CHAPTER 4 MODELING ATM STRATEGIES

In this section, the incorporation of four ATM strategies in the FREEVAL-DSS context are discussed in details. These strategies are:

1. Traffic Diversion
2. Incident Management
3. Hard Shoulder Running
4. Ramp Metering

### TRAFFIC DIVERSION

There are three types of diversion available in the framework: dynamic message sign (DMS) induced diversion, on-ramp diversion, and “upstream” diversion. The three types differ both in how they are implemented as well as which parameters are configured by the Administrator and the End User. First, for DMS induced diversion, the framework models the deployment of message signs that are used to divert traffic when incidents arise. As a note, for the purposes of the DSS framework, the use of message signs to divert traffic arising due to congestion from other causes is not modeled, and message signs can only be deployed when there is an active incident. When a DMS is deployed at a segment, the analyst will specify a percentage of traffic that will be diverted from the mainline to off-ramps leading it outside of the facility. The diversion percentage will be equally divided amongst all off-ramps upstream of the incident and downstream of the DMS. However, it is important to note that if no incident occurs in the period a DMS has been activated, there will be no effect of the sign.

The second type of diversion that is modeled occurs at on-ramps and is used to simulate any factors occurring outside of the facility that may cause incoming demand via on-ramps to be reduced. Since this simulates factors outside of the facility, it is left to the Administrator to specify the percentage of entering demands that will be diverted at each ramp. The third and final type of diversion that is modeled in the methodology is used to account for any diversion that may occur upstream of the first segment of the facility. This allows demand at the initial mainline segment of the facility to be reduced by a specified percentage during each analysis period if the analyst knows that such a phenomenon may occur in real world situations.

## INCIDENT MANAGEMENT

Incident management is one of the global strategies that is implemented in the framework. For the DSS framework, the End User analyst must make a decision in the first analysis period whether or not incident management will be deployed for the entire study period. If it is activated, any incident that occurs during the study period will have its duration shortened by an amount previously specified by the Administrator. Different duration reductions can be specified for each incident severity type, with the reduction amounts being in 15-minute increments up to 90 minutes. If the reduction amount is greater than or equal to the length of an incident, then the incident will be treated as if it never occurs as the framework assumes that incident management has reduced its length enough such that the effects are not felt in the analysis period in which it occurs.

### HARD SHOULDER RUNNING (HSR)

As described previously, hard shoulders are reserve lanes available for emergency situations that can be on the right, left or both sides of the freeway. Hard shoulder running is the temporary operation of hard shoulders as running lanes for normal traffic during congested periods. The main objective of using the shoulder is providing additional capacity when needed without adding lanes.

Due to the fact that opening hard shoulders increases the freeway capacity, Capacity Adjustment Factors (CAF) are used to model the hard shoulder running operation in the FREEVAL-DSS software. For this reason, the capacity increase percentages were extracted from the real world hard shoulder running implementations (refer to Chapter 2 for more information). Table 4-1 shows the extracted CAFs from the literature and the recommended (default) values. The recommended values are the average of the increase percentages found in the literature. The increase percentages vary by the number of lanes. For example, if the freeway has 2 lanes and the shoulder is opened during the peak period, the overall capacity (2+1 lanes) is increased by 25% on average (CAF=1.25).

**Table 4-1. Hard shoulder Running Recommended CAFs to be implemented in the FREEVAL-DSS tool.**

Number of lanes	CAF Range based on Literatures	Default CAF
2	1.2 to 1.3	1.25
3	1.2 to 1.27	1.23
4	1.07 to 1.16	1.12

## RAMP METERING

### Objectives

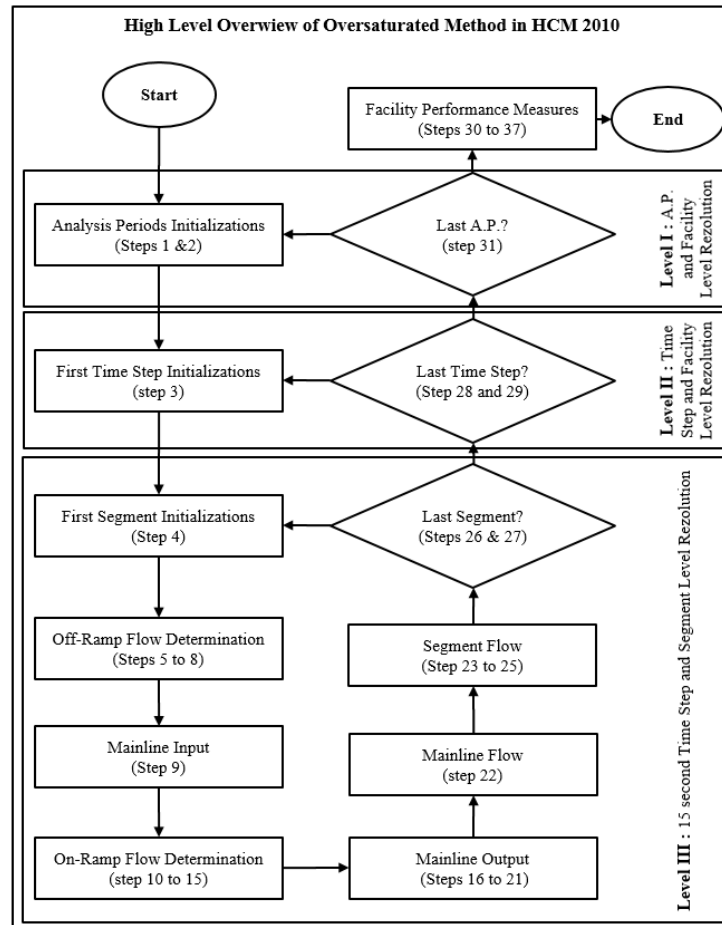
Along with the incorporation in DSS framework, the other objectives of this research concern the development of a methodology that incorporates adaptive ramp metering into the HCM 2010 freeway facilities methodologies in order to:

1. Enable the assessment of different adaptive ramp metering algorithms and as a result tune and optimize their parameters
2. Enable the analysis of travel time reliability on the facilities that are operating adaptive ramp metering
3. Enable the true and correct use of ramp metering as one of ATDM strategies under ATDM methodology in the HCM 2010

According to the oversaturated analysis, documented in Chapter 25 of 2010 HCM, the freeway facilities methodology changes its temporal and spatial units of analysis when oversaturated flow condition occur on the facility [78]. The spatial units become nodes and segments, and the temporal unit moves from a 15 minutes Analysis Periods (AP) to Time Steps that usually are between 15 seconds to 1 minute. A node is defined as the junction of two segments. There is always one more node than segments, with nodes added at the beginning and end of each segment [78]. Per the HCM's recommendation, the default time step unit used in freeway facilities analysis that maintains a certain accuracy for a short segments (up to 300 ft) is 15 seconds [78].

HCM also uses a modified Cell Transmission Model (CTM) that focuses on the number of vehicles that can travel between segments in a time step [79] [80]. Analysis of freeway segments depends on the relationships between segment speed, flow, and density. The calculations for oversaturated segments assume a simplified linear flow-density relationship in the congested regime. The HCM freeway facilities methodology overrides the speed and densities for undersaturated segments by utilizing more accurate speed flow regression models provided in Chapters 11, 12 and 13.

The high level oversaturated analysis process flow of the HCM freeway facilities methodology is depicted in Figure 4-1. The flowchart is divided into three major parts. There are three major loops of computations for each 15 minutes analysis period. Within each 15 minute analysis period, computations for 60 times steps are performed from the beginning node to the end. Each of these three major parts is associated with a certain resolution of parameters for the oversaturated analysis. HCM defines 37 steps for the oversaturated methodology that is documented comprehensively in Chapter 25 of 2010 HCM.



**Figure 4-1. – High Level Process Flow of Oversaturated Methodology in the HCM**

The procedure first calculates a number of flow variables starting at the first node during the first time step of oversaturation, followed by each downstream node and segment in that same time step. After performing all computations in the first time step, calculations are carried out at each node and segment during subsequent time steps for all remaining time intervals until the analysis is completed.

### Available Performance Measures for Ramp Metering

In spite of the fact that the smallest unit of computations is a time step, several performance measures are computed at the 15 minute analysis period aggregation level. In order to implement

adaptive ramp metering, all necessary performance measures needs to be available on a 15 second basis. Three major performance measures that are computed based on current methodology in HCM 2010 are Segment Flow, Number of Vehicles and Number of Unserved vehicles in each node. The segment flow  $SF(i - 1, t, p)$  for segment  $i$  (which corresponds with node  $i - 1$ ) in analysis period  $t$  and time step  $p$  is computed based on the mainline and off-ramp flow on node  $i$  per Equation 4-1:

$$SF(i - 1, t, p) = MF(i, t, p) + OFRF(i, t, p) \quad (4-1)$$

Where  $MF(i, t, p)$  and  $OFRF(i, t, p)$  are mainline flow and off-ramp flow in node  $i$  in analysis period  $t$  and time step  $p$ . Along with the segment flow, at the conclusion of each 15 second time step, the number of vehicles presented in each node  $NV(i - 1, t, p)$  is computed based on Equation 4-2:

$$\begin{aligned} NV(i - 1, t, p) & \quad (4-2) \\ & = NV(i - 1, t - 1, p) + MF(i - 1, t, p) + ONRF(i - 1, t, p) \\ & \quad - MF(i, t, p) - OFRF(i, t, p) \end{aligned}$$

Where  $ONRF(i - 1, t, p)$  is the on-ramp flow in node (i-1) for analysis period  $t$  and time step  $p$ . By knowing the number of vehicles in each node  $NV(i - 1, t, p)$ , the un-served vehicles  $UV(i - 1, t, p)$  are computed based on Equation 4-3:

$$UV(i - 1, t, p) = NV(i - 1, t, p) - [KB(i - 1, p) \times L(i - 1)] \quad (4-3)$$

Where  $KB(i - 1, p)$  and  $L(i - 1)$  are background density and segment length for node  $(i - 1)$  and time step  $p$ , respectively. These are three main variables that represent the operational status of the facilities segments in the oversaturated analysis. All other freeway performance measures are computed based on these variables. However, they are not characterized at the end of each 15 second time step. The next section provides further discussion on required modifications to the oversaturated method to estimate the remaining necessary performance measures for adaptive ramp metering.

### Calculating Necessary Performance Measures for Adaptive Ramp Metering

Ramp metering algorithms require more inputs from a freeway facility apart from segment flow, number of vehicles, and number of unserved vehicles to generate a metering rate. In this section, necessary modification and enhancements are discussed in order to generate these performance measures.



All of these computations need to be performed before step 10 of the oversaturated method, since the ramp metering rate needs to be available in step 10. Step 10 falls into the third level loop in the methodology, which implies that the three main variables are available for calculations for the previous 15 second time step.

#### *Mainline Density*

In order to compute the densities, first, the number of unserved vehicles needs to be determined. If the number of unserved vehicles is zero for a node (or a segment), then under-saturated equations according to Chapters 11, 12 and 13 of 2010 HCM are invoked to compute the segment density based on its type. If there are some queues available on the segment, the fundamental flow-density diagram will be used to compute density. The density will be computed based on Equation 4-4.

$$K(i - 1, t, p) = NV(i - 1, t, p) / [NL(i, t) \times L(i)] \quad (4-4)$$

Where  $NL(i, t)$  is the number of lanes on segment  $i$  or node  $(i - 1)$ .

#### *Mainline Speed*

If the analysis of the segment is performed in the under-saturated mode, then the speed should be computed based on equations provided in Chapters 11, 12 and 13 of the HCM. Otherwise, the speed of a segment is computed based on Equation 4-5.

$$S(i - 1, t, p) = SF(i - 1, t, p) / (K(i - 1, t, p)) \quad (4-5)$$

#### *Mainline Occupancy*

The freeway facilities methodology in the HCM does not compute the occupancy for any segments. However based on the estimation method provided by May [81] we can estimate the occupancy based on the reported density for each segment. For this purpose, we assume the average length of each vehicle is  $L_{veh}$  and the average length of sensor is  $L_{sen}$  in feet. Then, the occupancy can be estimated based on computed density per Equation 4-6.

$$O(i - 1, t, p) = \frac{L_{veh} + L_{sen}}{5,280} \times K(i - 1, t, p) \quad (4-6)$$

#### *On-Ramp Queue Length*

HCM only reports the number of unserved vehicles at the on-ramp, thus, by developing a relationship between the queue length at an on-ramp and the amount of unserved vehicles present

on the on ramp, we can incorporate the later variable for any ramp metering algorithm that requires queue length as an input. The unserved vehicles are converted to queue lengths in feet based on the jam density of the facility.

#### *On-Ramp Queue Occupancy*

HCM does not evaluate the density or occupancy of vehicles on the on-ramps. However, the number of vehicles stored on the on-ramp is known. If the relationship between the number of vehicles on the on-ramp and the ramp queuing capacity is provided by the analyst, then this variable can also be available for the adaptive ramp metering algorithm.

#### *Ramp Metering Algorithms Cycle Length*

As discussed earlier in this section, the oversaturated methodology in the HCM utilizes a 15 second time step for its computations. As a result, the smallest cycle length for a ramp metering algorithm will be 15 seconds. The ramp metering algorithm can be called in certain time steps to match with desired lengths, such as 30, 45 and 60 seconds with average performance measures.

In order to incorporate the adaptive ramp metering with the specifications described, five key performance measures of the facility need to be computed at step 11 of the oversaturated methodology the in HCM. For this purpose, Equations 4-1 through 4-6 are used in step 11 to make those facilities performance measures available for computations of ramp metering rates.

$$RM(i, t, p) = f(S, D, O, \dots) \quad (4-7)$$

By incorporation of Equations 4-1 through 4-6, any ramp metering logic (algorithm) can be modeled in the HCM context. To do this, the ramp metering rate at a given time step  $RM(i,t,p)$  needs to be defined as an equation based on the key performance measures of the facility. This variable will be used to compute the maximum flow allowed on the on-ramp per Equation 4-8:

$$\begin{aligned}
 & ONRO(i, t, p) \\
 = \min & \left\{ \begin{array}{l} \begin{array}{l} RM(i, t, p) \\ ONRC(i, t, p) \\ SC(i, t, p) \end{array} \\ \max \left\{ \begin{array}{l} \min \left\{ \begin{array}{l} MF(i + 1, t - 1, p) + ONRF(i, t - 1, p) \\ MO3(i, t - 1, p) + ONRF(i, t - 1, p) \end{array} \right\} - MI(i, t, p) \\ \min \left\{ \begin{array}{l} SC(i, t, p) \\ MF(i + 1, t - 1, p) + ONRF(i, t - 1, p) \\ MO3(i, t - 1, p) + ONRF(i, t - 1, p) \end{array} \right\} / 2N(i, p) \end{array} \right\} \end{array} \right\} \quad (4-8)
 \end{aligned}$$

With the incorporation of the proposed equations in the oversaturated methodology in the HCM, any adaptive and dynamic ramp metering algorithm can be modeled in the context of HCM.

### Challenges and Deviations from HCM Oversaturated Methodology

Since the freeway facilities methodology in the HCM employs a 15 minutes analysis period as its main temporal unit for analysis, computing some of the performance measures in the 15 seconds time steps could have potential biases. This is mainly caused by traversing analysis types between under-saturated and over-saturated within a 15 minutes analysis period. In other words, HCM evaluates the analysis status (oversaturated and under-saturated) at the conclusion of 15 minutes, however, the segment may have been partially operated on in two analysis types. For example, a freeway segment at the start of the AP may have some unserved vehicles that clear up in the next 5 minutes. For the next 10 minutes of the AP, the segment operates in under-saturated conditions. As a result, the speed estimation at the end of the AP is reported based on the under-saturated models for the entire 15 minute analysis period.

The proposed method to incorporate ramp metering evaluates the status of the facility in each 15 second time steps and presents the corresponding speed to the ramp metering function (or algorithm). As a result, the metering rate may not completely be consistent with the average 15 minute analysis period output from HCM methodology. This phenomena occurs only in the segments that are not experiencing severe congestion, since the congestion either starts or finishes at the middle of the 15 minute analysis period. As a result, the bias between under-saturated and oversaturated speed estimations is not significant. The vast amount of tests performed by the authors confirmed this negligible difference.

As an example, Figure 4-2 shows several performance measures for a segment where its density (or occupancy) is fed into the ramp metering equation (Equation 4-8) for one 15 minute analysis period.

At the beginning of the analysis period, the existence of queue from previous analysis periods will be cleared up by a lesser amount of traffic entering the segment. As shown, 5 minutes into the analysis period, the queue clears (time step 20). The analysis continues until the entry and exit traffic flow stabilizes, which happens in time step 36. Since the segment is already operating in an oversaturated mode (considering the presence of the queue at the beginning of the analysis period), it will be processed by oversaturated analysis in the HCM. However, HCM checks for existence of the queue at the conclusion of the 15 minute analysis period. Since there is no queue left at the end of the 15 minute analysis period, HCM uses the undersaturated models described in Chapters 11, 12 and 13 to estimate the density of the segment. In this example, the density of the segment reported by HCM is 40 pcpmpl (shown by the dotted curve). On the other hand, the ramp-metering algorithm reads the densities computed in each 15 second time step, which is shown by a solid black curve in Figure 4-2. Although the ramp metering reads instantaneous densities, however, the average density readings for the ramp metering equation will be reported as 44 pcpmpl. In other words, the average density used by adaptive ramp metering (44 pcpmpl) is not equal to the average density reported by the HCM (30 pcpmpl). It should be noted that the adaptive ramp metering algorithm uses more correct simulation of densities vs. the HCM procedure and better predicts the metering rates based on the predetermined ramp metering algorithm.

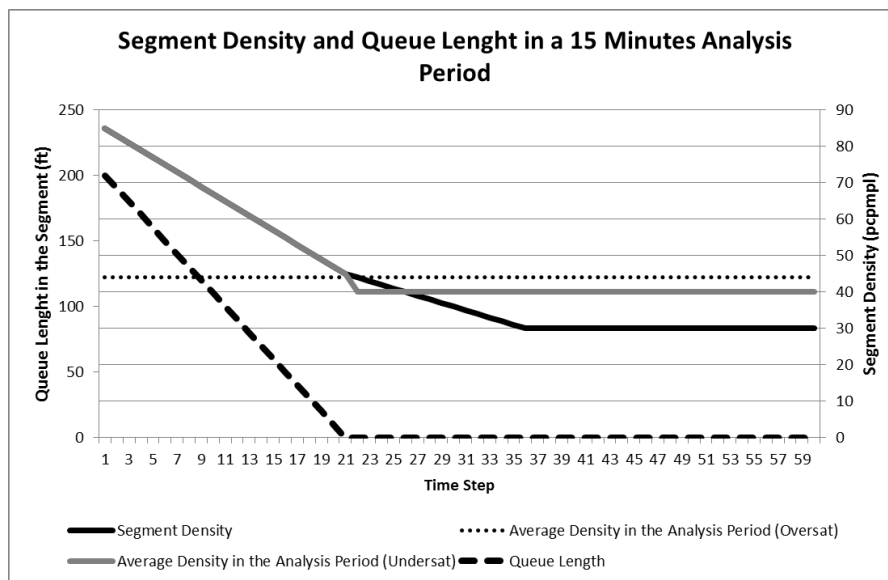


Figure 4-2. – Segment Density and Queue Length within a 15 Minutes Analysis Period

### Illustrative Example 1

In this section, a simple hypothetical example is provided to demonstrate the operation of adaptive ramp metering. This example includes a simple facility with only one on ramp that uses ALINEA ramp metering (Figure 4-3). The facility is aimed to be simple in demonstrating the true and correct dynamics of ramp metering in terms of key characteristics of the traffic flow, such as occupancies, speeds, flow rates, and etc. The facility consists of three mainline lanes and three HCM segments that are Basic, On-Ramp, and Basic for an hour and a half study period (six 15 minute analysis periods (AP's)). In the ALINEA ramp metering algorithm a target density of 42 pcpmpl is chosen. All vehicles are passenger cars and capacity for each segment is 7,200 pcph. Table 4-2 shows the demand information for all segments and periods of the analysis. As shown with bold font, the second and third segment in the analysis period 3 became oversaturated.

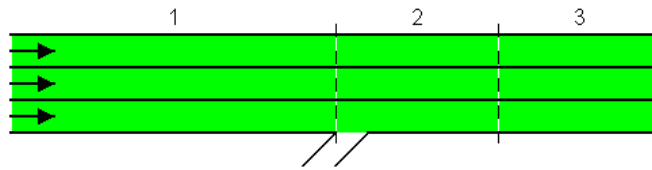


Figure 4-3. Geometric Configuration of Illustrative Example # 1

Table 4-2. – Demand Data for Illustrative Example #1

AP #	Segment #1 Demand (pc/h)	Segment #2 Demand (On-Ramp Demand) (pc/h)	Segment #3 Demand (pc/h)
1	6,000	6,500 (500)	6,500
2	6,200	6,950 (750)	6,950
3	6,400	<b>7,400 (1,000)</b>	<b>7,400</b>
4	6,200	6,950 (750)	6,950
5	6,000	6,500 (500)	6,500
6	5,800	6,300( 500)	6,300

Figure 4-4 shows the outcome of implementing the ALINEA ramp metering algorithm. As shown, in the analysis period 3, ramp metering lowers the entry traffic from the on-ramp onto the freeway. There are jumps in the density of the segment at the beginning of each 15 minute time period which is caused by a sudden increase and decrease on the traffic demand level. There are also variations in the density and metering rates which is caused by the nature of ALINEA ramp metering algorithm, which linearly seeks to achieve the target density, which in this case is 42 pcpmpl.

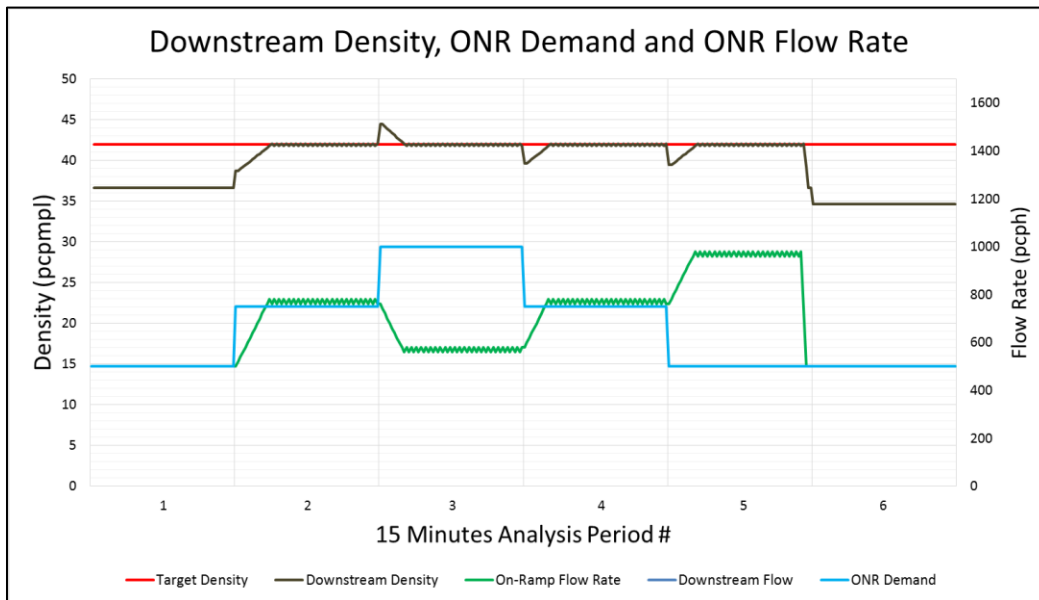


Figure 4-4. – Density, Demand, and Metering Rates for Segment #2 in Example 1

Table 4-3. Facility Leve Performance Measures With and Without Ramp Metering

Facility Performance Measure	With Ramp Metering	Without Ramp Metering	Percent Change
Average Travel Time (min)	2.13	2.15	-0.93%
VHD (delay / interval (hrs))	79.28	69.56	+14%
Space Mean Speed (mph)	56.38	55.90	+0.86%
Max D/C	1.03	1.03	0
Max V/C	1.00	1.00	0

As shown in Figure 4-4, the implemented ALINEA ramp metering algorithm performs as expected and is consistent with the fundamentals of freeway analysis and also the metering equation. Table 4-3 presents the facility level performance measures of the subject facility. As shown, the travel time reduces by the incorporation of ramp metering while the VHD increases. The increase in VHD is due to delay of the vehicles waiting on the on-ramp.

### Illustrative Example # 2

A second hypothetical example shown in Figure 4-5 is composed of one on-ramp and ten basic segments, which were coded in the FREEVAL-DSS software to validate the tool assessment of the effect of different ramp metering strategies on the performance measures. The mainline has three lanes and the on-ramp has one lane. The average speed (mph), mainline delay (hrs) and on-ramp delay (hrs) were selected as the performance measures.

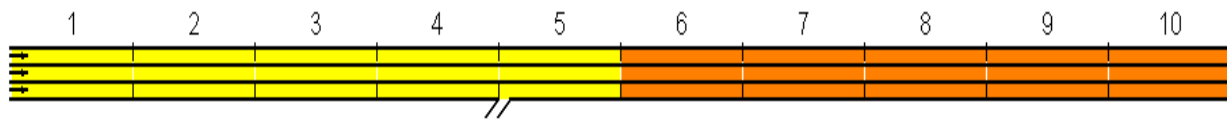


Figure 4-5. Illustrative Example # 2

To test the ramp metering performance with different ramp and mainline demand combinations, six different regimes, defined in the SHRP 2 CO5 project were used [82] [83]. The SHRP-2, CO5 approach uses the concept of multiple regimes based on the mainline and ramp demands to designate the flow allocation to the two competing flows. The rationale for using multiple regimes where the flow allocation progressively works in favor of mainline traffic is explained in details in [83]. These regimes are depicted in Figure 4-6. The designation of the upstream demand in each of the regimes is indicated by the dashed lines connecting them to the diagonal line defined by the downstream flow rate  $F_D$ . The external shaded area is considered to be infeasible either because the ramp demand exceeds the ramp roadway capacity (Regime I), or the mainline demand exceeds the mainline capacity (Regime VI). Of particular interest are Regimes II, III and IV, where the allocation of available downstream flow varies significantly. In regime II, the method stipulates that the mainline demand is fully served, with queuing occurring strictly on the ramp approach. In regime III, the method assumes a fixed allocation where the ramp flow that is served is strictly limited to  $1/2$  of the downstream lane flow. The remaining lanes serve mainline traffic. Finally in regime IV, queuing occurs exclusively on the mainline, with ramp demand fully served. Based on the above definitions, each of the six regimes is defined below.

- Regime I:  $D_R > C_R$  is an infeasible region since the ramp roadway cannot deliver the full ramp demand. The maximum ramp flow that can be delivered to the gore area is limited the ramp roadway capacity  $C_R$ .
- Regime II:  $D_R > \frac{F_D}{2NL}$  and  $(F_D - C_R) < D_M < F_D(1 - \frac{1}{2NL})$



- Regime III:  $D_R > \frac{F_D}{2NL}$  and  $F_D(1 - \frac{1}{2NL}) < D_M < C_M$
- Regime IV:  $D_R < \frac{F_D}{2NL}$  and  $F_D(1 - \frac{1}{2NL}) < D_M < C_M$
- Regime V:  $D_M + D_R \leq F_D$  represents under-saturated flow conditions which are outside the scope of this research since ramp metering strategies are not beneficial under these conditions. Regime VI is also infeasible as the mainline demand exceeds capacity, so the maximum presented flow cannot exceed the mainline capacity  $C_M$ , where:
- NL = Number of Mainline Lanes upstream or downstream of merge point
- $F_D$  = Downstream Freeway Flow Rate (or capacity) in vph
- $D_M$  = Upstream Freeway Mainline Demand Flow Rate (vph)
- $D_R$  = Ramp Demand Flow Rate (vph)
- $C_R$  = Ramp roadway capacity (vph)

As stated earlier, Regimes I and VI are infeasible regimes; so, regimes II, III, IV and V were selected for further analysis.

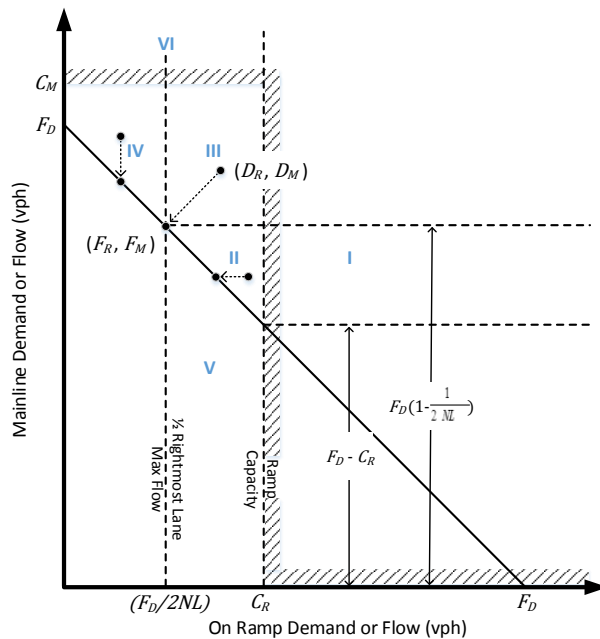


Figure 4-6. Ramp and Mainline Flow allocation using the CO5 method [83]

Table 4-4 shows the selected on-ramp and main line demands for each of the four regimes.

**Table 4-4. Selected Ramp and Mainlines Demands for the Four Regimes**

Regimes	Regime Characteristics	Ramp Demand ( $D_R$ ) vph	Mainline Demand ( $D_M$ ) vph
II	Ramp demand high, mainline average	1200	5,500
III	Ramp demand high, mainline high	1200	6,500
IV	Ramp demand average, mainline high	750	6,500
V	Ramp demand average, mainline average	750	5,500

A fixed, ALINEA, and Fuzzy logic ramp metering algorithms were applied to the on-ramp under the four regimes presented in Table 4-4 and the results are shown in Table 4-5 to Table 4-13. The Fuzzy Logic ramp metering has several parameters to be tuned (refer to Appendix A for more information about the Fuzzy logic ramp metering). After conducting sensitivity analysis on the parameters, it was found out that the on-ramp queue length rule's weight and the output (Metering rate) membership function parameters have the highest effects on the performance measures in the ramp metering implementation in the FREEVAL-DSS. Therefore, three on ramp queue length weights (RQW) of 0, 3 and 6 and two sets of output parameters (Table 4-5) were tested in this analysis. When the ramp queue length weight is 0, the queued ramp vehicles are ignored and the ramp queue length does not have any effect on the generated metering rate. In this case, the ramp delay is expected to be the highest and mainline delay is expected to be the lowest. As the ramp queue rule weight increases the metering rate also increases in order to serve more vehicles from the on-ramp queue. Table 4-5 shows two sets of output parameters used in this study. These values were taken from the I-95 Fuzzy ramp metering system. However, these values are not optimized and better results can be gotten by fine tuning the parameters.

**Table 4-5. Fuzzy Logic Output Parameters Used in Illustrative Example # 2**

Fuzzy Logic Output Parameters	Output membership function thresholds when ramp demand=1200vph	Output membership function thresholds when ramp demand=750vph
Very Small-Center	12	6
Very Small -Upper	14	8
Small-Lower	13.5	6
Small-Upper	16	10
Medium-Lower	15.5	8
Medium-Upper	17.5	12
Big-Lower	17	10
Big-Upper	19.5	14
Very Big-Lower	18.5	18.5
Very Big-Upper	21	21

**Ramp Metering Rate for Uncongested Conditions (Regime II)**

Table 4-6 shows the ramp metering results summary for Regime II. As can be seen from the table, the network average speed before applying the ramp metering is 56-60 mph. So, there is no congestion under this regime and the ramp metering does have significant effects on the performance measures mainline. Ramp metering is not expected to be beneficial under these conditions. Table 4-6 shows that some metering strategies result in some improvements in mainline speeds with an increase in ramp delays, depending on the strategy. The generated metering rates are shown in Table 4-7. As can be seen from the table, there is no average metering rate reported for the ALINEA strategy. The reason is that the facility is not oversaturated in the time period, thus there is enough capacity on the mainline for all of the on-ramp demand to be met and ramp metering is not invoked.

Table 4-6 ramp metering results summary for Regime II

Metering Type	Performance measures	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Total	
Fuzzy Logic	(RQW) <sup>c</sup>	Average Spd	65.36	65.36	65.36	65.36	58.19	60.46	60.46	60.46	60.46	60.46	<b>62.19</b>
		VHD-M	1.40	1.40	1.40	1.40	4.59	3.56	3.56	3.56	3.56	3.56	<b>27.98</b>
		VHD-R	N/A	N/A	N/A	N/A	11.75	N/A	N/A	N/A	N/A	N/A	<b>11.75</b>
	RQW=3	Average Spd	65.36	65.36	65.36	65.36	57.49	59.50	59.50	59.50	59.50	59.50	<b>61.64</b>
		VHD-M	1.40	1.40	1.40	1.40	5.02	4.07	4.07	4.07	4.07	4.07	<b>30.94</b>
		VHD-R	N/A	N/A	N/A	N/A	8.54	N/A	N/A	N/A	N/A	N/A	<b>8.54</b>
	RQW=6	Average Spd	65.36	65.36	65.36	65.36	57.22	59.15	59.15	59.15	59.15	59.15	<b>61.44</b>
		VHD-M	1.40	1.40	1.40	1.40	5.19	4.26	4.26	4.26	4.26	4.26	<b>32.08</b>
		VHD-R	N/A	N/A	N/A	N/A	7.15	N/A	N/A	N/A	N/A	N/A	<b>7.15</b>
None	Average Spd	65.36	65.36	65.36	65.36	55.94	57.64	57.64	57.64	57.64	57.64	<b>60.56</b>	
	(VHD-M) <sup>a</sup>	1.40	1.40	1.40	1.40	6.01	5.13	5.13	5.13	5.13	5.13	<b>37.25</b>	
	(VHD-R) <sup>b</sup>	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>	
Fixed (500 vph)	Average Spd	65.36	65.36	65.36	65.36	59.51	62.59	62.59	62.59	62.59	62.59	<b>63.39</b>	
	VHD-M	1.40	1.40	1.40	1.40	3.78	2.54	2.54	2.54	2.54	2.54	<b>22.04</b>	
	VHD-R	N/A	N/A	N/A	N/A	22.24	N/A	N/A	N/A	N/A	N/A	<b>22.24</b>	
Fixed (800 vph)	Average Spd	65.36	65.36	65.36	65.36	58.30	60.62	60.62	60.62	60.62	60.62	<b>62.29</b>	
	VHD-M	1.40	1.40	1.40	1.40	4.52	3.48	3.48	3.48	3.48	3.48	<b>27.49</b>	
	VHD-R	N/A	N/A	N/A	N/A	12.71	N/A	N/A	N/A	N/A	N/A	<b>12.71</b>	
ALIN EA	Average Spd	65.36	65.36	65.36	65.36	55.94	57.64	57.64	57.64	57.64	57.64	<b>60.56</b>	
	VHD-M	1.40	1.40	1.40	1.40	6.01	5.13	5.13	5.13	5.13	5.13	<b>37.25</b>	
	VHD-R	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>	

<sup>a</sup>Mainline delay <sup>b</sup>On-ramp delay <sup>c</sup>Ramp Queue Weight

**Table 4-7. Average Generated Metering Rates - Regime II**

RM type		Average metering rate (vph)
Fixed	500 vph	500
	800 vph	800
ALINEA		No Average reported since no metering invoked
Fuzzy Logic	0	817
	3	953
	6	1001

**Ramp Metering Rate for Congested Conditions (Regimes III and IV)**

Regime III is the most congested regime among the others. Segment 4 which is the segment before the on-ramp is operates at a speed of 28 mph under the no ramp metering scenario. It can be seen from Table 4-8 that when fixed ramp metering rate of 500 vph is applied to the on-ramp, segment four’s speed increases to 60 mph but the on-ramp delay increases to 22.24 hours, as well. In the case of a fixed metering rate of 800 vph, segment four’ speed improves slightly to 33 mph with onramp delay of 12.71 hours. The fuzzy logic algorithm (up to 6 appears to produce a higher rate to prevent ramp delays. The generated metering rate is also shown in Table 4-9.

**Table 4-8. Illustrative Example 2 Ramp Metering Analysis- Regime III**

Metering Type	Performance measures	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Total	
No RM	Average Spd	59.18	59.18	45.11	27.93	56.14	57.61	57.61	57.61	57.61	57.61	53.56	
	VHD-M	4.24	4.24	11.98	30.06	5.91	5.15	5.15	5.15	5.15	5.15	82.19	
	VHD-R	N/A	N/A	N/A	N/A	2.58	N/A	N/A	N/A	N/A	N/A	2.58	
Fixed (500 vph)	Average Spd	59.18	59.18	59.18	59.18	55.13	55.13	55.13	55.13	55.13	55.13	55.06	
	VHD-M	4.24	4.24	4.24	4.24	6.74	6.74	6.74	6.74	6.74	6.74	69.68	
	VHD-R	N/A	N/A	N/A	N/A	22.24	N/A	N/A	N/A	N/A	N/A	12.71	
Fixed (800 vph)	Average Spd	59.18	59.18	54.07	33.28	56.88	57.61	57.61	57.61	57.61	57.61	56.75	
	VHD-M	4.24	4.24	6.65	23.27	5.52	5.15	5.15	5.15	5.15	5.15	57.41	
	VHD-R	N/A	N/A	N/A	N/A	12.71	N/A	N/A	N/A	N/A	N/A	22.24	
ALIN EA	Average Spd	59.18	59.18	59.18	39.17	57.47	57.61	57.61	57.61	57.61	57.61	56.22	
	VHD-M	4.24	4.24	4.24	17.57	5.22	5.15	5.15	5.15	5.15	5.15	61.27	
	VHD-R	N/A	N/A	N/A	N/A	18.94	N/A	N/A	N/A	N/A	N/A	18.94	
Fuzzy Logic	RQW = 0	Average Spd	59.18	59.18	54.05	33.23	56.89	57.61	57.61	57.61	57.61	57.61	55.06
		VHD-M	4.24	4.24	6.66	23.36	5.52	5.15	5.15	5.15	5.15	5.15	69.78
		VHD-R	N/A	N/A	N/A	N/A	12.57	N/A	N/A	N/A	N/A	N/A	12.57
	RQW = 3	Average Spd	59.18	59.18	53.09	32.40	56.79	57.61	57.61	57.61	57.61	57.61	54.87
		VHD-M	4.24	4.24	7.16	24.30	5.57	5.15	5.15	5.15	5.15	5.15	71.27
		VHD-R	N/A	N/A	N/A	N/A	11.41	N/A	N/A	N/A	N/A	N/A	11.41
	RQW = 6	Average Spd	59.18	59.18	52.38	31.86	56.72	57.61	57.61	57.61	57.61	57.61	54.74
		VHD-M	4.24	4.24	7.53	24.93	5.61	5.15	5.15	5.15	5.15	5.15	72.31
		VHD-R	N/A	N/A	N/A	N/A	10.60	N/A	N/A	N/A	N/A	N/A	10.60

Table 4-10 and Table 4-11 present the results for Regime IV. This regime is also congested. The obtained results have the same trends as those obtained for Regime III, discussed earlier.

**Table 4-9. Average Generated Metering Rates – Regime III**

RM type	Average Metering Rate (vph)	
Fixed	500 vph	500
	800 vph	800
ALINEA	405	
Fuzzy Logic	0	786
	3	836
	6	869

**Table 4-10. Illustrative Example 2 Ramp Metering Analysis- Regime IV**

Metering Type	Performance measures	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Total	
No RM	Average Spd	59.2	59.2	55.4	34.4	57.0	57.6	57.6	57.6	57.6	57.6	55.32	
	VHD-M	4.2	4.2	6.0	22.1	5.5	5.2	5.2	5.2	5.2	5.2	67.73	
	VHD-R	N/A	N/A	N/A	N/A	0.0	N/A	N/A	N/A	N/A	N/A	0.00	
Fixed (200 vph)	Average Spd	59.2	59.2	59.2	59.2	57.6	57.6	57.6	57.6	57.6	57.6	58.26	
	VHD-M	4.2	4.2	4.2	4.2	5.1	5.1	5.1	5.1	5.1	5.1	47.75	
	VHD-R	N/A	N/A	N/A	N/A	17.5	N/A	N/A	N/A	N/A	N/A	17.47	
Fixed (500 vph)	Average Spd	59.2	59.2	59.2	59.2	55.1	55.1	55.1	55.1	55.1	55.1	56.75	
	VHD-M	4.2	4.2	4.2	4.2	6.7	6.7	6.7	6.7	6.7	6.7	57.41	
	VHD-R	N/A	N/A	N/A	N/A	7.9	N/A	N/A	N/A	N/A	N/A	7.94	
ALINEA	Average Spd	59.2	59.2	59.2	49.6	57.6	57.6	57.6	57.6	57.6	57.6	57.28	
	VHD-M	4.2	4.2	4.2	9.4	5.2	5.2	5.2	5.2	5.2	5.2	53.00	
	VHD-R	N/A	N/A	N/A	N/A	12.3	N/A	N/A	N/A	N/A	N/A	12.32	
Fuzzy Logic	RQW=0	Average Spd	59.2	59.2	59.2	45.1	57.5	57.6	57.6	57.6	57.6	57.6	56.82
		VHD-M	4.2	4.2	4.2	12.3	5.2	5.2	5.2	5.2	5.2	5.2	56.02
		VHD-R	N/A	N/A	N/A	N/A	9.8	N/A	N/A	N/A	N/A	N/A	9.80
	RQW=3	Average Spd	59.2	59.2	59.2	41.9	57.4	57.6	57.6	57.6	57.6	57.6	56.48
		VHD-M	4.2	4.2	4.2	14.8	5.3	5.2	5.2	5.2	5.2	5.2	58.59
		VHD-R	N/A	N/A	N/A	N/A	7.6	N/A	N/A	N/A	N/A	N/A	7.61
	RQW=6	Average Spd	59.2	59.2	59.2	40.5	57.3	57.6	57.6	57.6	57.6	57.6	56.34
		VHD-M	4.2	4.2	4.2	16.0	5.3	5.2	5.2	5.2	5.2	5.2	59.79
		VHD-R	N/A	N/A	N/A	N/A	6.6	N/A	N/A	N/A	N/A	N/A	6.57

**Table 4-11. Average Generated Metering Rates - Regime IV**

RM type	Average Metering Rate(vph)	
Fixed	200 vph	200
	500 vph	500
ALINEA	300	
Fuzzy	0	425
	3	516
	6	554

Regime V represents under-saturated flow conditions. So, as can be seen from Table 4-12, ramp metering does not have a significant effect on the network performance. Table 4-13 shows the associated ramp metering rates. For the ALINEA, no average metering rate is reported since there is no congestion and the on-ramp is not metered.

**Table 4-12. Illustrative Example 2. Ramp Metering Analysis- Regime V**

Metering Type	Performance measures	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Total	
No RM	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	58.5 3	60.9 7	60.9 7	60.9 7	60.9 7	60.97	<b>62.48</b>	
	VHD-M	1.40	1.40	1.40	1.40	4.38	3.31	3.31	3.31	3.31	3.31	<b>26.49</b>	
	VHD-R	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>	
Fixed (200 vph)	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	60.3 9	64.3 3	64.3 3	64.3 3	64.3 3	64.33	<b>64.35</b>	
	VHD-M	1.40	1.40	1.40	1.40	3.24	1.79	1.79	1.79	1.79	1.79	<b>17.80</b>	
	VHD-R	N/A	N/A	N/A	N/A	17.4 7	N/A	N/A	N/A	N/A	N/A	<b>17.47</b>	
Fixed (500 vph)	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	59.5 1	62.5 9	62.5 9	62.5 9	62.5 9	62.59	<b>63.39</b>	
	VHD-M	1.40	1.40	1.40	1.40	3.78	2.54	2.54	2.54	2.54	2.54	<b>22.04</b>	
	VHD-R	N/A	N/A	N/A	N/A	7.94	N/A	N/A	N/A	N/A	N/A	<b>7.94</b>	
ALINEA	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	58.5 3	60.9 7	60.9 7	60.9 7	60.9 7	60.97	<b>62.48</b>	
	VHD-M	1.40	1.40	1.40	1.40	4.38	3.31	3.31	3.31	3.31	3.31	<b>26.49</b>	
	VHD-R	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>	
Fuzzy Logic	RQW =0	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	58.5 3	60.9 7	60.9 7	60.9 7	60.9 7	60.97	<b>62.48</b>
		VHD-M	1.40	1.40	1.40	1.40	4.38	3.31	3.31	3.31	3.31	3.31	<b>26.49</b>
		VHD-R	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>
	RQW =3	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	57.4 9	59.5 0	59.5 0	59.5 0	59.5 0	59.50	<b>61.64</b>
		VHD-M	1.40	1.40	1.40	1.40	4.38	3.31	3.31	3.31	3.31	3.31	<b>26.49</b>
		VHD-R	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>
	RQW =6	Average Spd	65.3 6	65.3 6	65.3 6	65.3 6	57.2 2	59.1 5	59.1 5	59.1 5	59.1 5	59.15	<b>61.44</b>
		VHD-M	1.40	1.40	1.40	1.40	4.38	3.31	3.31	3.31	3.31	3.31	<b>26.49</b>
		VHD-R	N/A	N/A	N/A	N/A	0.00	N/A	N/A	N/A	N/A	N/A	<b>0.00</b>

**Table 4-13. Average Generated Metering Rates - Regime V**

RM type		Average metering rate (vph)
Fixed	200 vph	200
	500 vph	500
ALINEA		No Average reported
Fuzzy	0	870
	3	870
	6	870

From the results presented in this section, it can be concluded that the ramp metering implementation in FREEVAL-DSS shows that ramp metering has significant effects on the network performance when there is congestion in the network. Fixed ramp metering has no feedback from the mainline and on-ramp detection. ALINEA ramp metering receives feedback from the mainline and calculates the on-ramp metering based on this feedback. The Fuzzy logic



algorithm gets feedback from both mainline and on the ramp and tries to create a balance between the mainline delay and on-ramp delay depending on the rules weights. However, the Fuzzy controller parameters need to be fine-tuned to produce the best performance. The developed adaptive ramp metering toolbox can help analysts model any adaptive ramp metering in the HCM context. This can help practitioners to fine-tune the ramp metering algorithm parameters to improve the freeway performance. Also, it will provide a platform for assessing other emerging ramp metering algorithms.

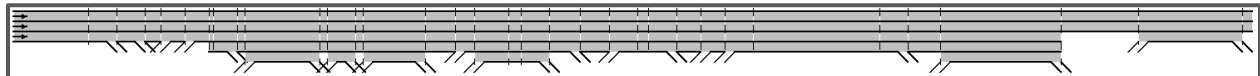
## CHAPTER 5 CASE STUDIES

This chapter covers the application of the methodology described in Chapters 3 and 4 to two real world case studies on interstate facilities in North Carolina and Florida. Each case study will include several use cases intended to highlight the impacts of a selected set of strategies on the facility performance. Appendix B contains hyperlinks to the FREEVAL-DSS users guide.

### I-40 in NC CASE STUDY

This section presents six use cases designed to highlight various features of the framework and software implementation. To keep the examples relatively simple, most cases only make use of a single ATM strategy, even in the event that employing more strategies could yield better results. This simulates potentially limited facility resources or budgets that may be available in many situations. Additionally, some of the examples may show little improvement due to the ATM interventions made. This serves as reinforcement that not every strategy is always the best choice and some can in fact do more harm than good when used incorrectly.

The base facility used for this case study is a 12.5 mile section of I-40 eastbound outside of Raleigh, NC. The study period consists of 6 hours from 2:00pm to 8:00pm. The base facility is shown in Figure 5-1. Under base conditions there is no breakdown due to congestion (i.e. no segments with LOS F) on the facility, but a mild bottleneck does naturally occur during the peak hours on segment 32 due to a lane drop.



**Figure 5-1. Base facility for the I-40 Case Study.**

The first five use cases make use of two different scenario events: a 45-minute one-lane closure incident occurring in segment 21, and a 2-hour heavy rain event from 4-6 pm. Each of the five use cases contains one of these events, and varying approaches through ATM interventions to alleviate the resulting congestion are explored. The final use case examines the conditions surrounding a work zone closing one lane over a 1.2 mile stretch for the entire study period.

Most of the ATM availability options are configured the same way for each of the 6 use cases. Ramp metering (ALINEA Adaptive) is available at every on-ramp segment, and hard shoulder running is enabled at all segments with the shoulder having the default capacity. The default parameters for ALINEA ramp metering can be found in Table A-5 in Appendix A. The default capacities of the hard shoulder are those given in Table 4-1. Dynamic Message Sign

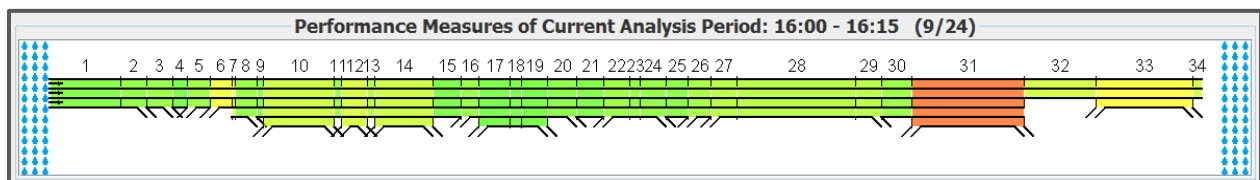
(DMS) locations are available at segments 4, 11, 15, 21, and 28. The only difference in strategy availability is that the preemptive activation of incident management is available for the facility only for cases 4 and 5. Incident management for these examples leads to a 15-minute reduction of incidents for shoulder and one-lane closures.

For each use case, the display options are coded to be the same. Output on the facility preview graphic is colored by speed and is available for each HCM segment. The performance measure table displays “HCM Style” outputs, listing speed, total density, mainline and ramp volumes served, and ramp metering rates and time active. Lastly, both the weather event and incident information is made available to the End User.

### Use Case 1: Ramp Metering with a Weather Event

For the first use case, a heavy rain weather event was deterministically generated to occur between 4 and 6 pm and all base conditions were used otherwise.

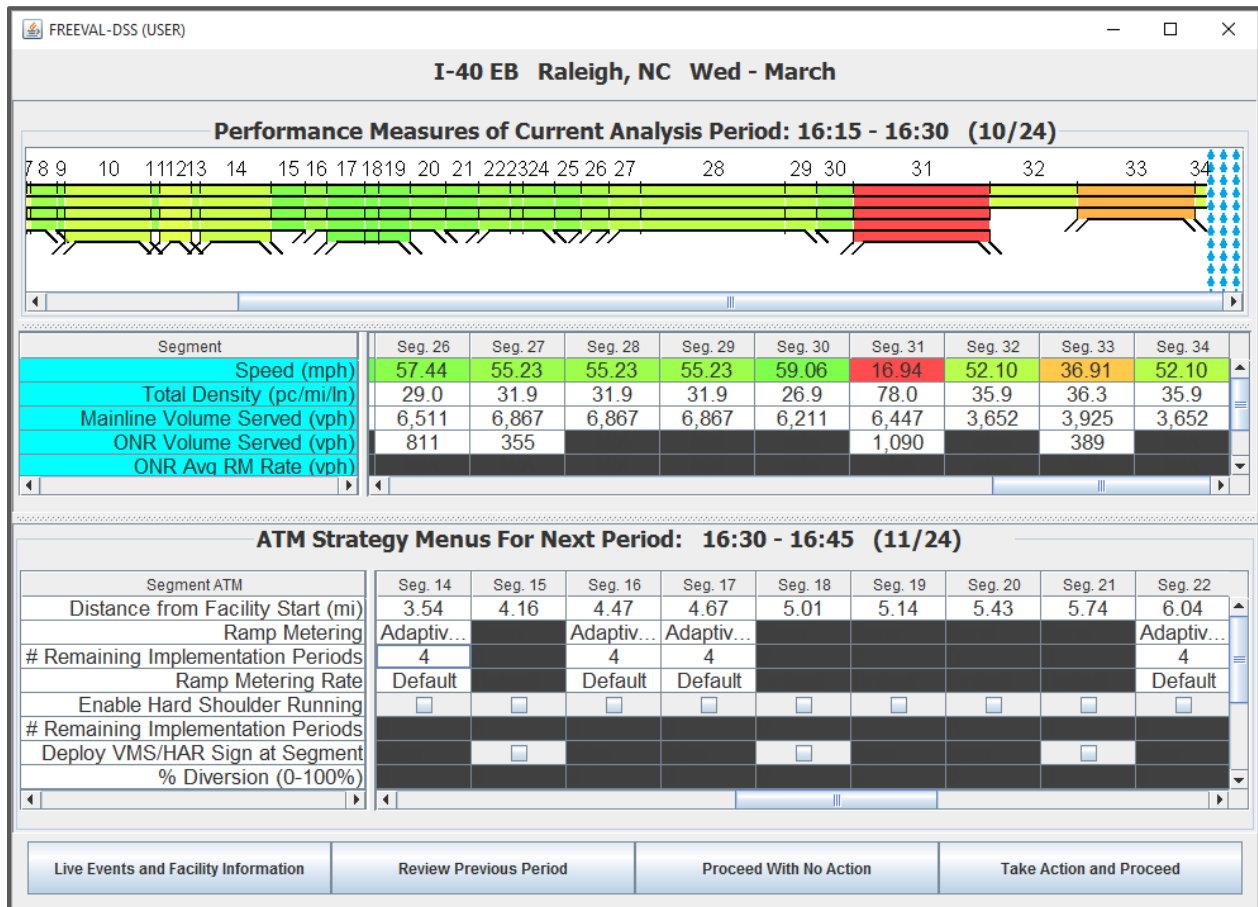
For the first analysis period, the conditions on the facility are very good. Both the facility graphic and performance measure table show speeds for all segments that are close to those under free flow conditions. As no ATM intervention is needed when the facility is operating at this level, the End User will choose to “Proceed With No Action” for the first 8 periods (2 hours) of the study period as conditions remain excellent. At 4 pm, the heavy rain event starts and the End User observes this on the facility preview graphic (as seen in Figure 5-2). The End User should also notice that speeds are beginning drop at the downstream end of the facility, especially at segment 31 where speeds have dropped to 31 mph. However, a breakdown has not yet occurred, so in this example, the End User chooses not to make an intervention.



**Figure 5-2. Heavy rain displayed on the facility graphic from 4:00-4:15pm.**

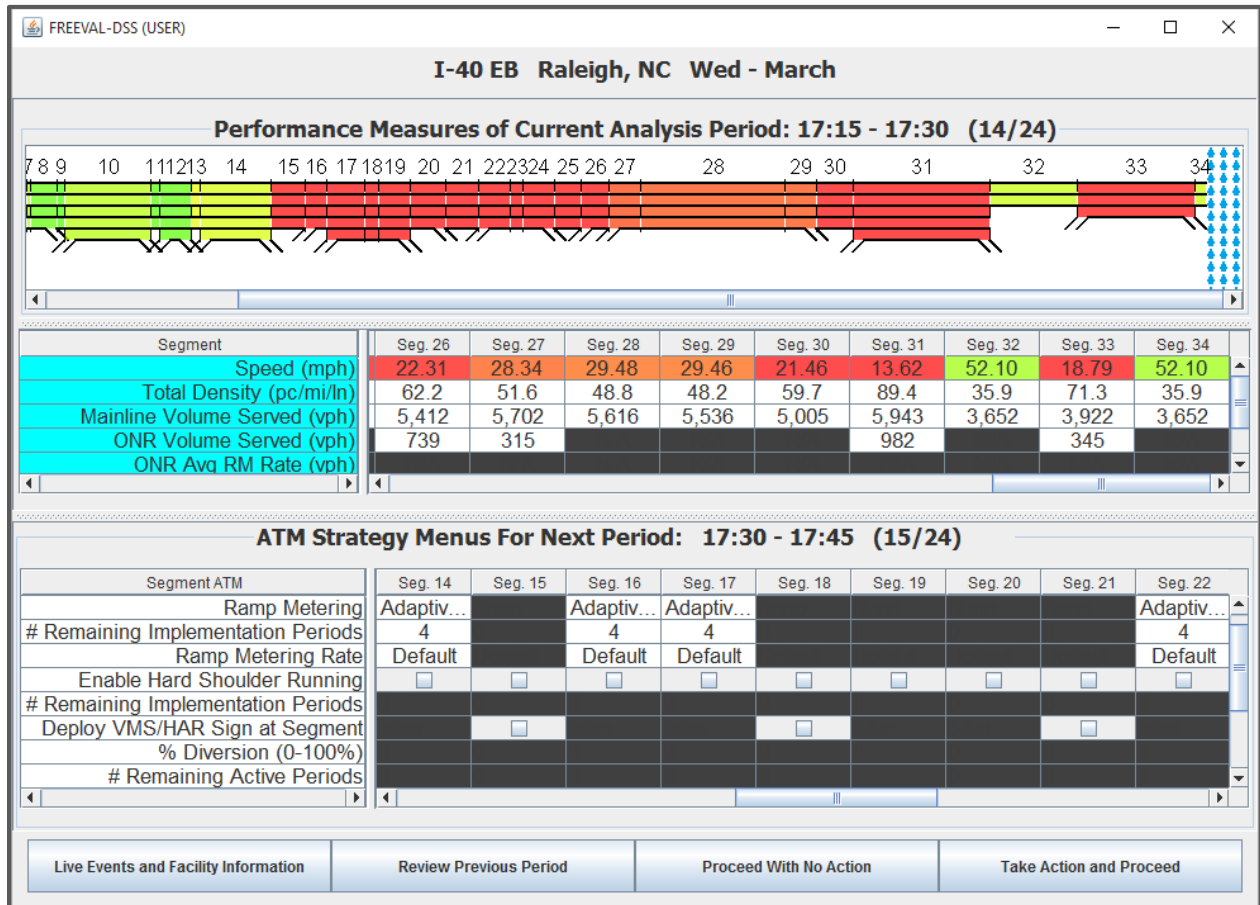
Proceeding to the next period, it is observed from the graphic and table outputs that the speeds are continuing to drop across the facility, and a major slowdown has occurred at segment 31 (as seen at the top of Figure 5-3). It is at this point that the End User decides an ATM intervention as necessary. The End User comes to the conclusion that reducing the traffic coming

into the facility via on-ramps is the appropriate course of action, and chooses to employ ramp metering at on-ramps upstream of the breakdown in segment 31. Specifically, the End User activates the ALINEA adaptive ramp metering at segments 14, 16, 17, and 22 and sets the remaining implementation periods as 4 so the metering will be in effect for at least the next hour.



**Figure 5-3. Worsening conditions of the facility from 4:15-4:30pm and the deployment of ramp metering at segments 14, 16, 17, and 22.**

The End User uses the “Take Action and Proceed” option to move through the next 4 analysis periods as the ramp metering takes effect. At the end of the 4 periods, the End User observes that speeds are still slow and there is significant congestion remaining on the facility. In order to continue to attempt to improve conditions on the facility, the End User then chooses to extend the ramp metering intervention for another hour before a reassessment will be made. The extension of the ATM intervention is shown in Figure 5-4.



**Figure 5-4. Remaining slow speeds and congestion on freeway indicating extension of the ramp metering ATM intervention.**

The End User proceeds with ramp metering active for 4 more analysis periods until the ramp metering is set to come to an end. However, upon viewing the conditions of the facility in the 18<sup>th</sup> analysis period (6:15-6:30 pm), the End User observes that while the rain has stopped, some congestion still remains and slow speeds exist in segments 30, 31, and 33. Consequently, the End User chooses to once again extend the currently active ramp metering intervention, this time adding 2 more analysis periods (as shown Figure 5-5).

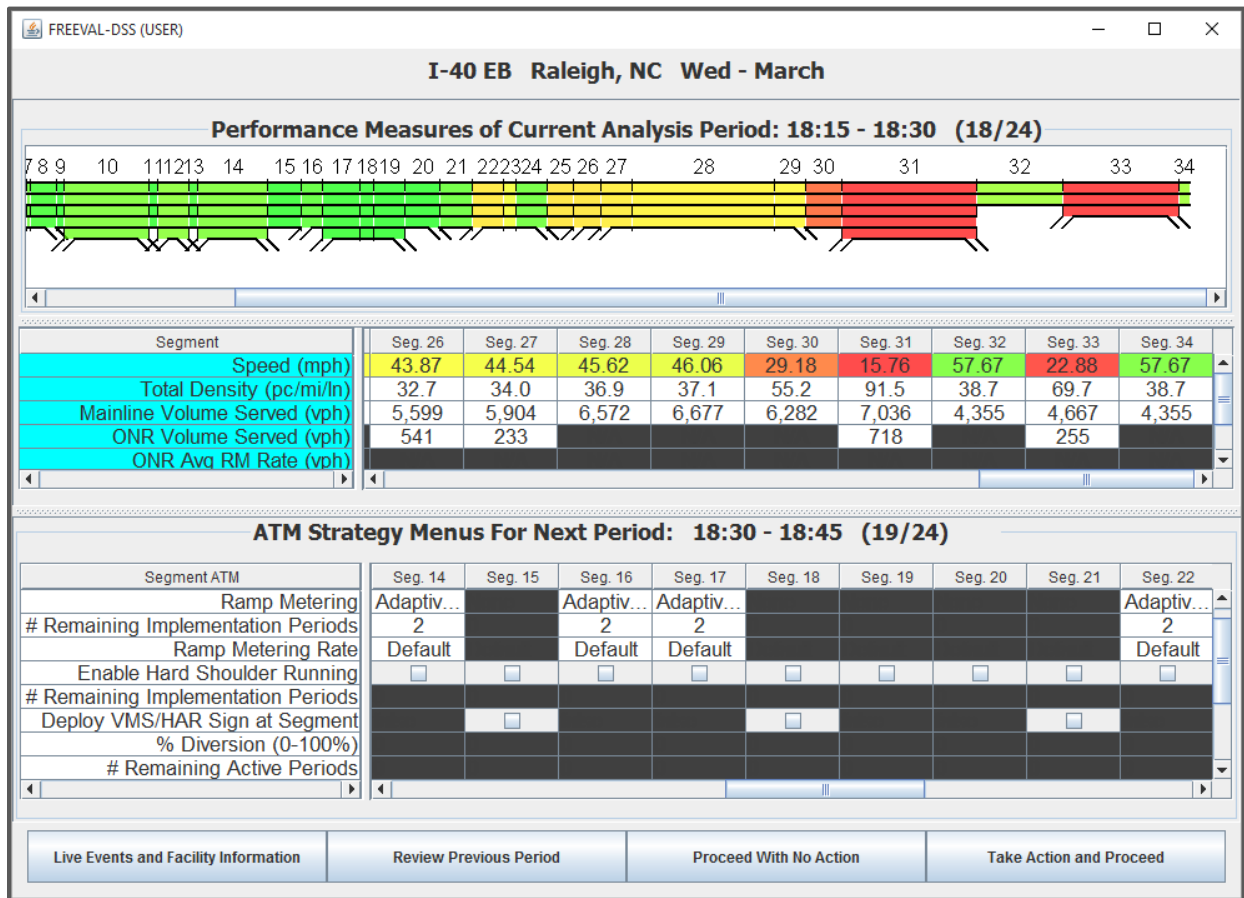


Figure 5-5. Second extension of the ATM intervention.

As the final extension of the ramp metering intervention expires, the End User can view that speeds have returned to normal and no more congestion exists on the facility. In fact, the performance measures of the facility graphic and output table indicate that the facility has returned to free flow conditions almost completely across the board. At this point, the End User concludes that the current ramp metering intervention does not need to be extended, and that no ATM intervention at all should be made. The End User uses the “Proceed With No Action” button to move through the following periods, and with no more congestion arising, concludes the current analysis run and generates the performance summary.

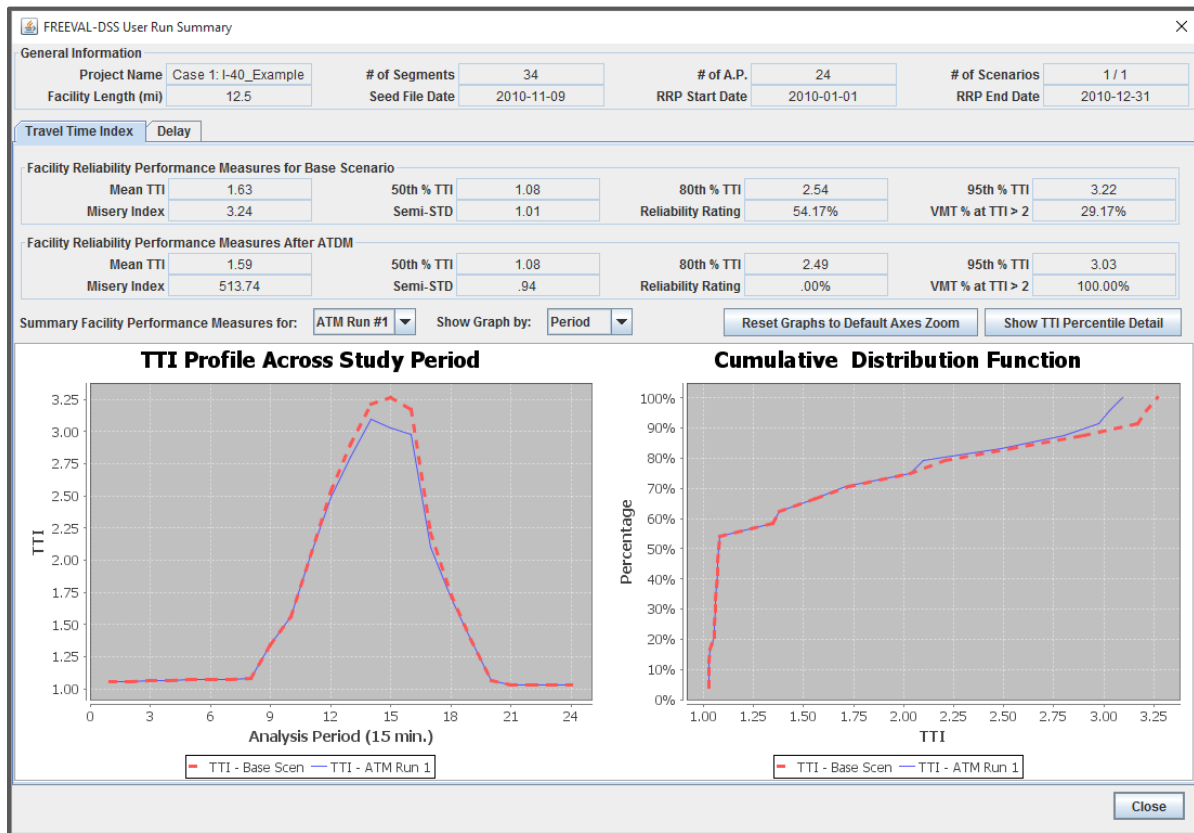
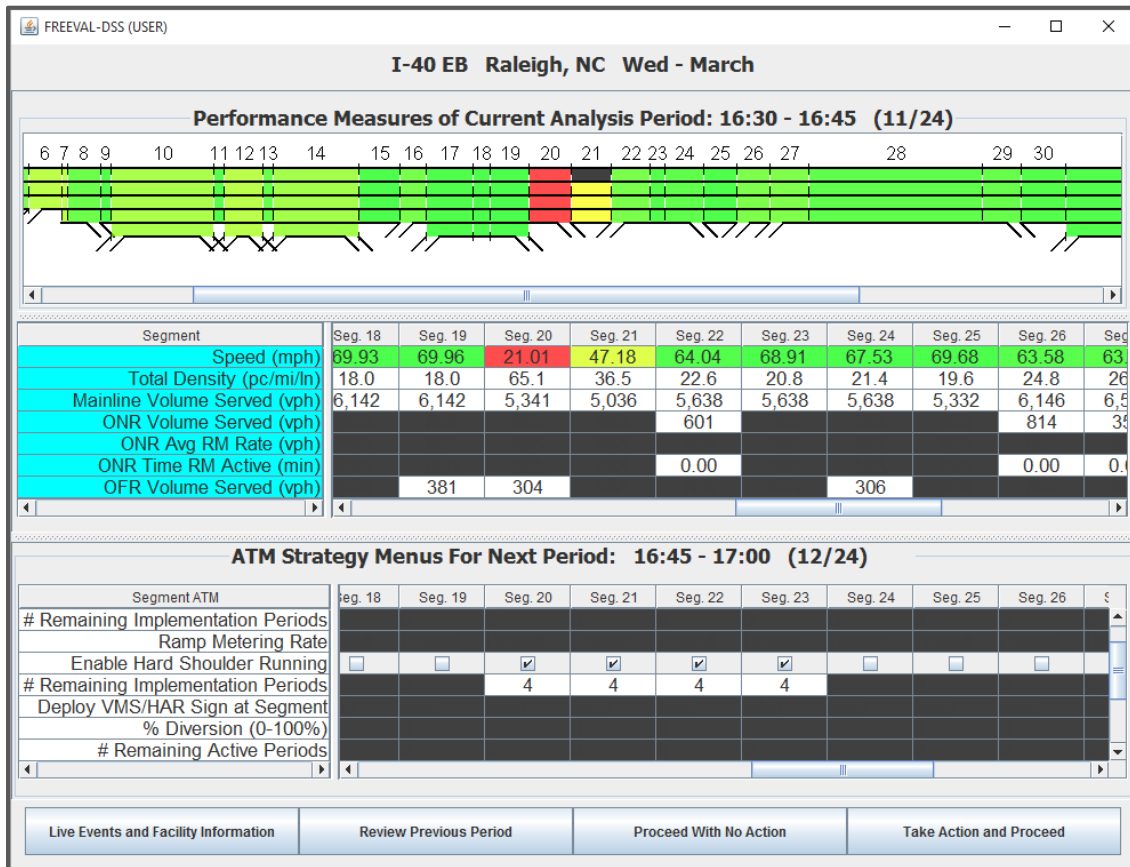


Figure 5-6. Summary output of the first ramp metering ATM intervention run.

The performance measures of the summary output window show that the intervention strategy employed in this example led to moderate improvement of the facility conditions during the study period. From Figure 5-6, it can be seen that the mainline’s mean TTI dropped from 1.63 to 1.59. More significant improvement is shown of the 95<sup>th</sup> percentile TTI measure, where the TTI dropped from 3.22 to 3.03, a 5% improvement. The TTI profile and cumulative distribution graphs also reinforce the notion that moderate improvement was gained through the ramp metering intervention. Starting at the 12<sup>th</sup> analysis period (5:00 pm), the End User can see improvement in the facility travel time. This improvement remains slight until the 14<sup>th</sup> analysis period (5:30 pm), where a more significant improvement can be seen for the peak half hour until the 16<sup>th</sup> period (5:30-6:00pm). As the facility stabilizes beyond this time period due to the rain stopping, the facility performance of the ATM intervention run and the base scenario converge while the facility returns to free flow conditions.

### Use Case 2: Incident Event with Hard Shoulder Running

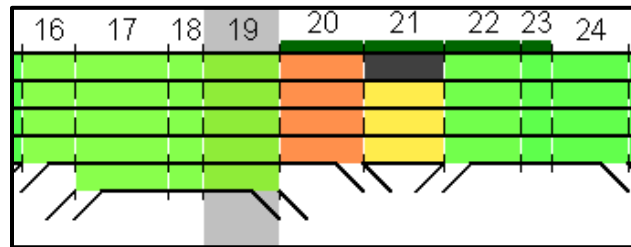
For the second use case, a 45-minute incident event resulting in a one-lane closure at segment 21 was generated to occur between 4:30 and 5:15 pm and all base conditions were used otherwise. For the first analysis period, the conditions on the facility are very good. Both the facility graphic and performance measure table show speeds for all segments that are close to those under free flow conditions. Moving forward, the End User should choose to “Proceed With No Action” for the first 10 periods (2 hours 30 minutes) of the study period as conditions remain excellent. At 4:30 pm, the one-lane closure incident starts and the End User can observe this on the facility preview graphic, as shown in Figure 5-7. The End User should also notice that speed drops drastically at the segment immediately upstream of the incident (segment 20), plunging all the way to 21 mph. In this case, it is clear a breakdown has occurred because of the incident and the End User chooses to make an ATM intervention.



**Figure 5-7. Incident at segment 21 at 4:30 showing slow speeds at segment 20. The bottom table shows the hard shoulder intervention in place for the next analysis period.**



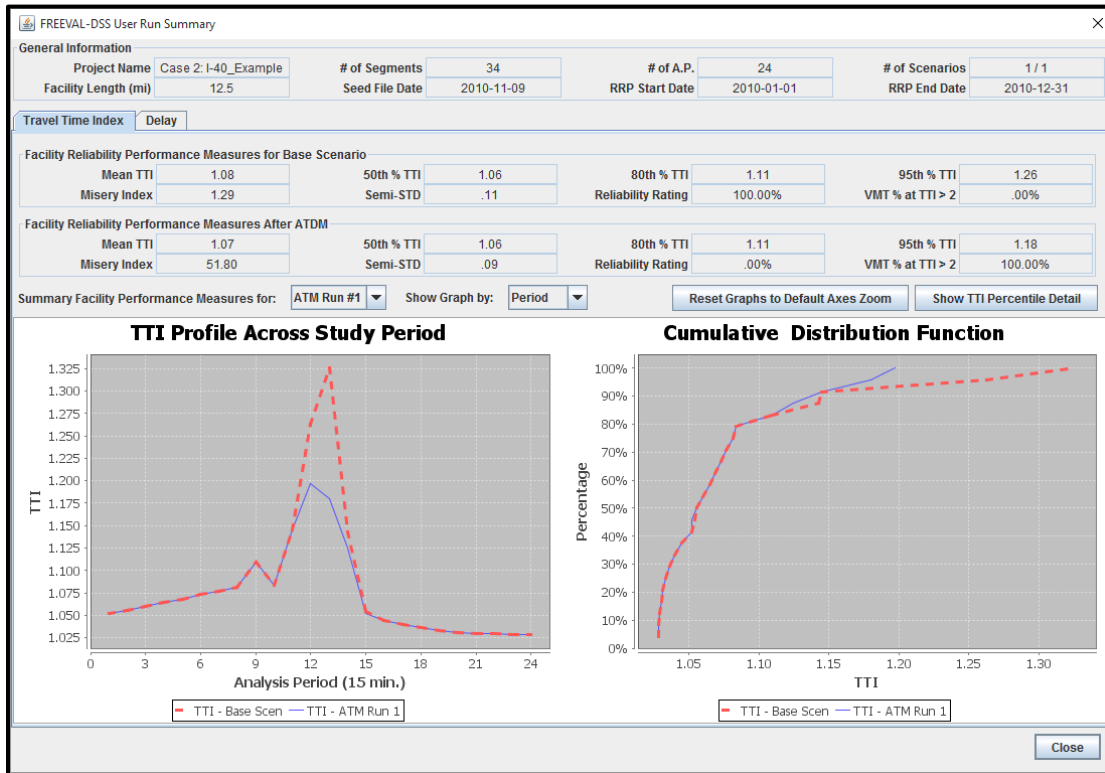
For these conditions, the End User comes to the conclusion that opening the hard shoulder around the incident is the most desirable course of action. Specifically, the End User chooses to open the hard shoulder from segments 20-23 for one hour, checking the Hard Shoulder Running boxes in the ATM selection table and setting the remaining implementation periods at 4 for each of the segments.



**Figure 5-8. Green bar indicating the shoulder has been opened for segments 20 to 23.**

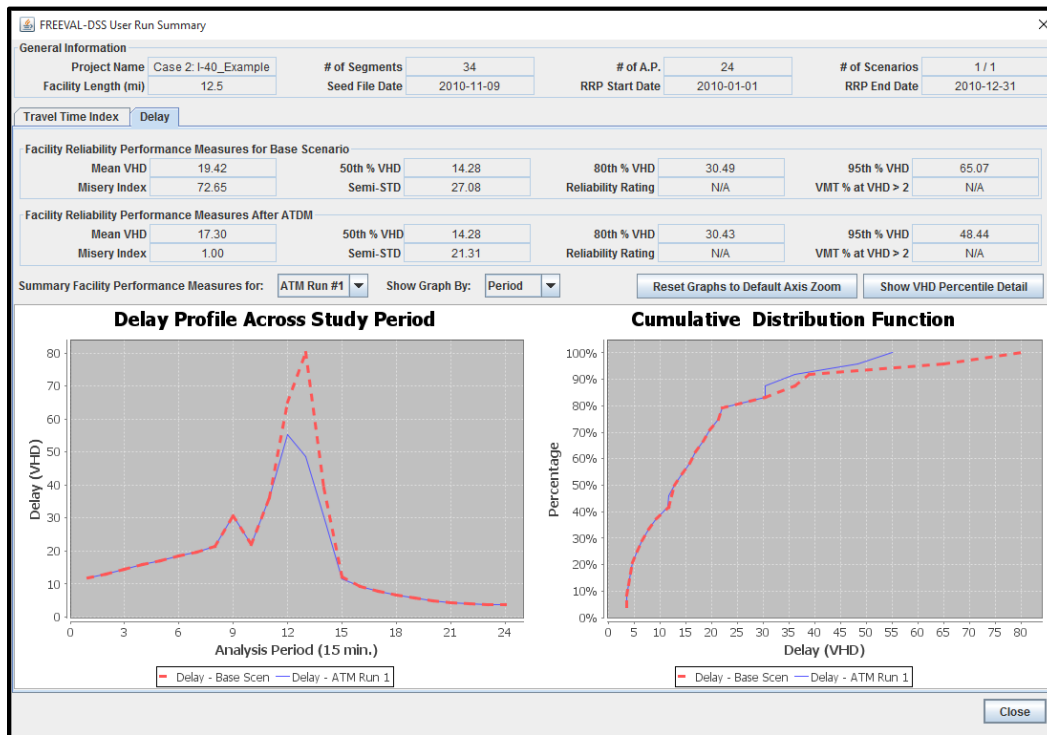
The End User uses the “Take Action and Proceed” option to move through the next analysis periods as the shoulder is opened (see Figure 5-8). After three periods, the End User observes that the incident has ended, and the resulting congestion has cleared. Thus the End User concludes that while under the initial intervention the hard shoulder remains open for one more period, there is no need to do so, and the number of remaining implementation periods is changed to 0. Alternatively, the End User could use the “Proceed With No Action Button” which automatically clears any ATM strategies currently being deployed.

With the incident cleared and the ATM intervention complete, the End User can view that speeds have returned to normal and no more congestion exists on the facility. As a whole, the performance measures shown on the facility graphic and in the output table indicate that the facility has returned to free flow conditions across the board. The End User uses the “Proceed With No Action” button to move through the following periods, and with no more congestion arising, proceeds to the end of the study period without making any more interventions. Next, the End User concludes the current analysis run and generates the performance summary.



**Figure 5-9. Summary output showing travel time performance measures for the hard shoulder ATM intervention.**

The performance measures of the summary output window show that the intervention strategy employed in this example led to noticeable improvement of the worst facility conditions during the study period. From Figure 5-9, it can be seen that while the mean TTI barely changed, significant improvement is shown at 95<sup>th</sup> percentile TTI, where the value dropped from 1.26 to 1.08, a 14% improvement. The TTI profile and cumulative distribution graphs also reinforce the notion that there was improvement gained through the opening of the hard shoulder. Starting at the 11<sup>th</sup> analysis period (4:45pm), the End User can see improvement in the facility travel time. From this point until the 15<sup>th</sup> analysis period (5:45pm), improvement can be seen in TTI, with the peak increase in travel time being significantly reduced from analysis periods 12-14 (5:00-5:30pm). The improvement can perhaps be observed more easily by looking at the delay performance measures of the summary output. As show in Figure 5-10, the mean vehicle hours delay (VHD) dropped from 19.4 to 17.3 hours, and the 95<sup>th</sup> percentile VHD dropped from 65.1 to 48.5 hours. It is also clear from the delay profile graph across the study period that the worst delay occurring at period 13 (5:15pm) was almost cut in half.



**Figure 5-10. Summary output showing delay performance measures for the hard shoulder ATM intervention.**

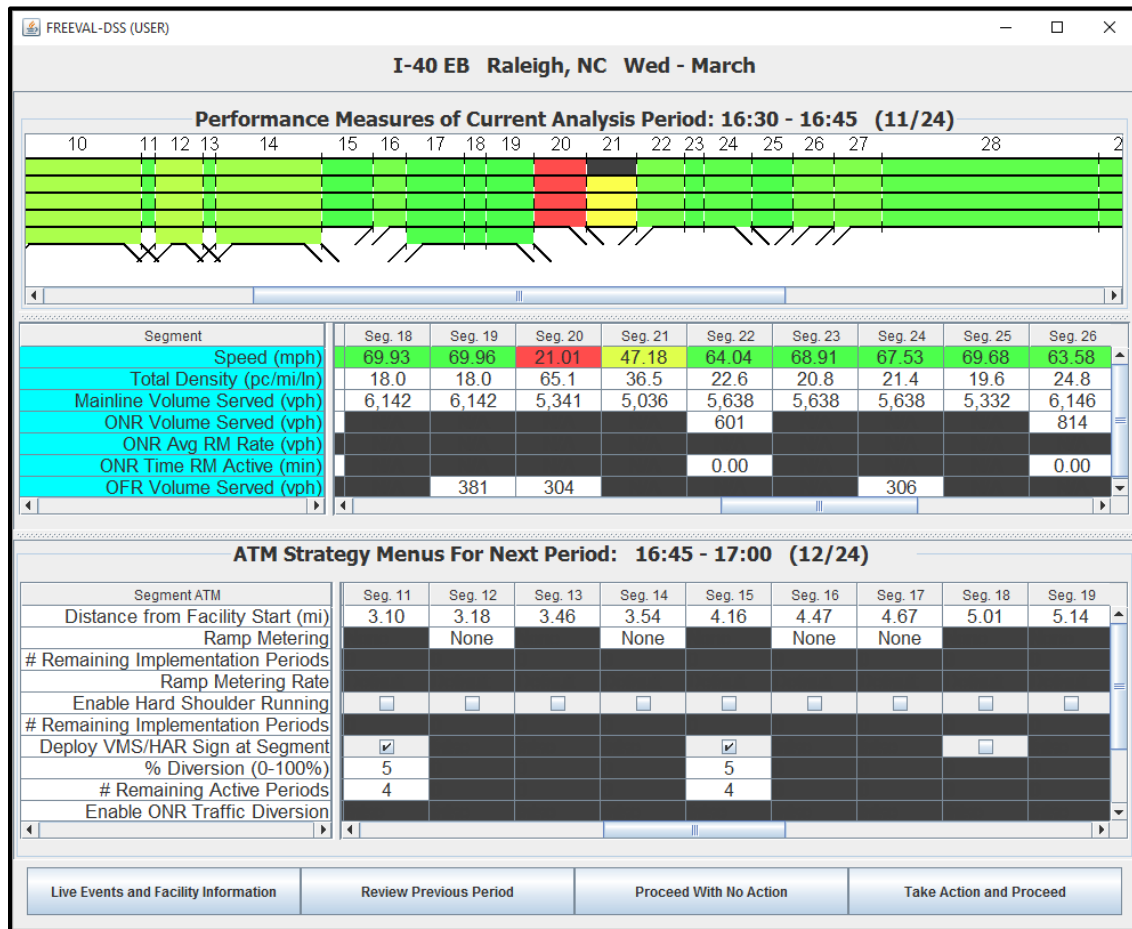
**Use Case 3: Incident Event with Diversion due to DMS**

For the third use case, a 45-minute incident event resulting in a one-lane closure at segment 21 was generated to occur between 4:30 and 5:15 pm and all base conditions were used otherwise.

As with the previous examples, it is clear that freeway conditions are very good at the start of the study period. Moving forward, the End User chooses to “Proceed With No Action” for the first 10 periods (2 hours 30 minutes) of the study period, as conditions remain excellent. At 4:30 pm, the one-lane closure incident starts and the End User can observe this on the facility preview graphic, as shown in Figure 5-11. The End User should also notice that speed drops drastically at the segment immediately upstream of the incident (segment 20), plunging all the way to 21 mph. In this case, it is clear a breakdown has occurred because of the incident and the End User chooses to make an ATM intervention.

The End User comes to the conclusion that the most desirable course of action is to use dynamic message signs (DMS) at segments upstream of the slowdown. Specifically, the End User

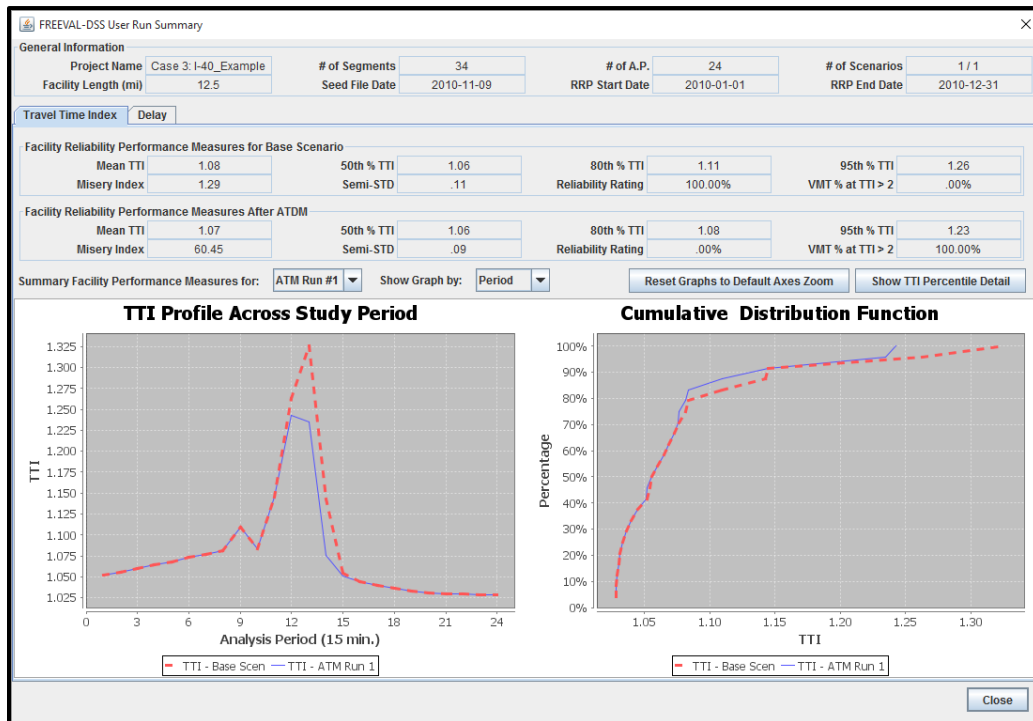
deploys DMS at segments 4, 11, and 15. The End User estimates that each sign will result in 5% of the traffic being diverted off of the facility via a downstream off-ramp. For this initial intervention, the End User chooses to deploy the signs for 4 analysis periods (1 hour) to see how conditions on the facility evolve. The bottom table of Figure 5-11 shows the DMS deployment intervention configured to begin in the 12<sup>th</sup> period (4:45-5:00pm).



**Figure 5-11. Incident at segment 21 at 4:30 showing slow speeds at segment 20. The bottom table shows the DMS induced diversion intervention in place for the next analysis period.**

The End User uses the “Take Action and Proceed” option to move through the next analysis periods as the signs are deployed and a portion of the traffic is diverted. After three periods, the End User observes that the incident has ended, and the resulting congestion has cleared. Thus the End User concludes that while under the initial intervention the DMS signs remain active for one

more period, there is no need to do so, and they in fact will have no effect once the incident has cleared, so the number of remaining implementation periods is changed to 0. Alternatively, the End User could use the “Proceed With No Action Button” which clears all ATM strategies currently being deployed. With the incident cleared and the ATM intervention complete, the End User can view that speeds have returned to normal and no more congestion exists on the facility. As a whole, the performance measures shown on the facility graphic and in the output table indicate that the facility has returned to free flow conditions across the board. The End User uses the “Proceed With No Action” button to move through the following periods, and with no more congestion arising, proceeds to the end of the study period without making any more interventions. Next, the End User concludes the current analysis run and generates the performance summary.



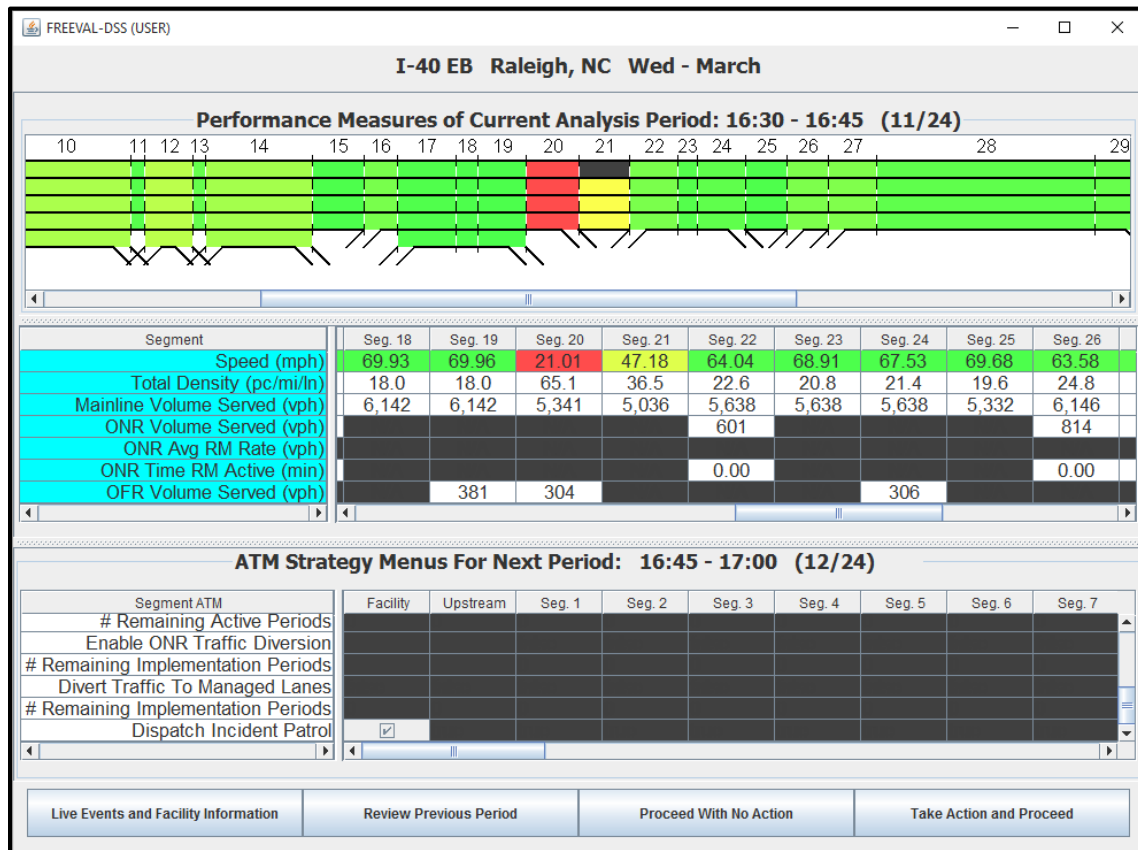
**Figure 5-12. Summary output showing delay performance measures for the DMS induced diversion ATM intervention.**

The performance measures of the summary output window show that the intervention strategy employed in this example led only to improvement of the worst facility conditions during the study period. From Figure 5-12, it can be seen that the TTI barely improves for the majority

of the distribution. However, the TTI profile and cumulative distribution graphs show that there was improvement gained through the use of the DMS induced diversion. Starting at the 11<sup>th</sup> analysis period (4:45pm), the End User can see improvement in the facility travel time. From this point until the 15<sup>th</sup> analysis period (5:45pm), improvement can be seen in TTI, with the peak increase in travel time being significantly reduced from analysis periods 12-14 (5:00-5:30pm).

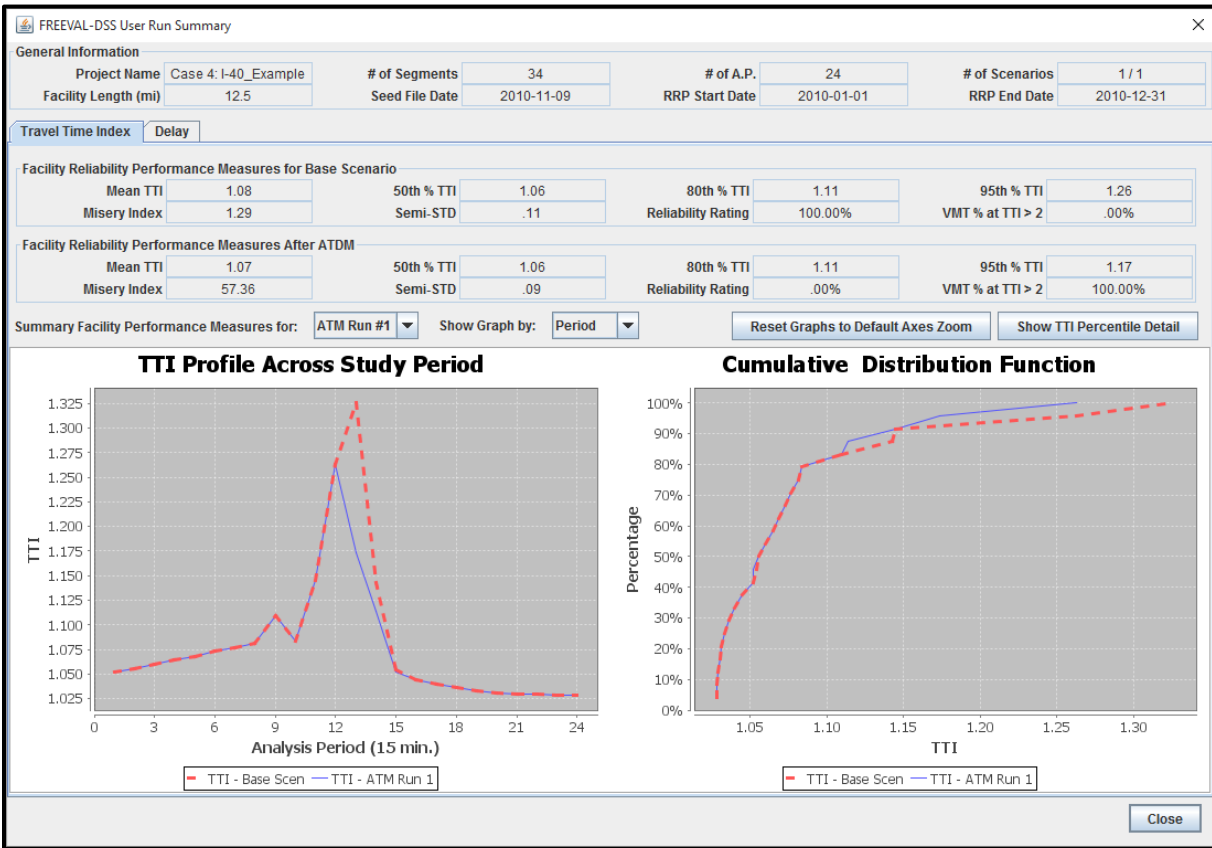
#### **Use Case 4: Incident Event with Incident Management**

For the fourth use case, a 45-minute incident event resulting in a one-lane closure at segment 21 was generated to occur between 4:30 and 5:15 pm and all base conditions were used otherwise. As with the previous examples, it is clear that freeway conditions are very good at the start of the study period. However, for this example the End User knows that incident management is available for the facility and consequently decides to enable it as a precautionary measure. To activate incident management, the End User marks the checkbox in the first analysis period (regardless of facility conditions), and then chooses the “Take Action and Proceed” option. This enables incident management for the entirety of the study period. Proceeding through the first 10 periods (2 hours 30 minutes), the facility conditions remain excellent. At 4:30 pm, the one-lane closure incident starts and the End User observes this on the facility graphic, as shown in Figure 5-13. The End User also notices that speed drops drastically at the segment immediately upstream of the incident (segment 20), falling to 21 mph. In this case, it is clear a breakdown has occurred due to the incident. While in previous examples the End User comes to the conclusion that an ATM intervention should be made at this point, the End User for this example has already enabled incident management. Believing the 15-minute reduction will be enough, or facing some resource restriction, the End User chooses not to make any additional intervention. The End User uses the “Take Action and Proceed” option to move through the next analysis periods. After two periods (30 minutes), the End User observes that the incident has ended, and the resulting congestion has cleared.



**Figure 5-13. Facility conditions during the first period in which the incident occurs. In the bottom table, the checkbox is marked indicating incident management is active.**

With the incident cleared and the ATM intervention complete, the End User can view that speeds have returned to normal and no more congestion exists on the facility. As a whole, the performance measures shown on the facility graphic and in the output table indicate that the facility has returned to free flow conditions across the board. The End User uses the “Proceed With No Action” button to move through the following periods, and with no more congestion arising, proceeds to the end of the study period without making any more interventions. Next, the End User concludes the current analysis run and generates the performance summary.



**Figure 5-14. Summary output showing delay performance measures for the incident management ATM intervention.**

The performance measures of the summary output window show that the intervention strategy employed in this example led only to improvement of the worst facility conditions during the study period. The mean TTI only drops from 1.08 to 1.07, but the 95<sup>th</sup> percentile TTI drops from 1.26 to 1.17, a 7% improvement. This matches intuition as the incident occurs during the peak traffic hour, and since the ATM intervention only served to reduce the length of the incident, the majority of the facility conditions remain unchanged. From Figure 5-14, it can be seen that the TTI barely improves for the majority of the distribution. However, the TTI profile and cumulative distribution graphs show that there was improvement gained through the deployment of incident management for the study period. Starting at the 12<sup>th</sup> analysis period (5:00pm), the End User can see improvement in the facility travel time. From this point until the 15<sup>th</sup> analysis period (5:45pm), improvement can be seen in TTI, with the peak increase in travel time being significantly reduced from analysis periods 12-14 (5:00-5:30 pm).



### Use Case 5: Incident Event with DMS Induced Diversion and Incident Management

For the fifth use case, a 45-minute incident event resulting in a one-lane closure at segment 21 was generated to occur between 4:30 and 5:15 pm and all base conditions were used otherwise.

At the start of the study period, the freeway conditions are observed to be very good, with speeds being close to free flow speeds across the facility. As with the previous example, the End User knows that incident management is available for the facility and decides to enable it as a precautionary measure. The End User chooses to “Take Action and Proceed” activating incident management for the entirety of the study period. Proceeding through the first 10 periods (2 hours 30 minutes), the facility conditions remain excellent. At 4:30 pm, the one-lane closure incident starts and the End User observes this on the facility graphic. The End User also notices that speed drops drastically at the segment immediately upstream of the incident (segment 20), falling to 21mph. In this case, it is clear a breakdown has occurred due to the incident.

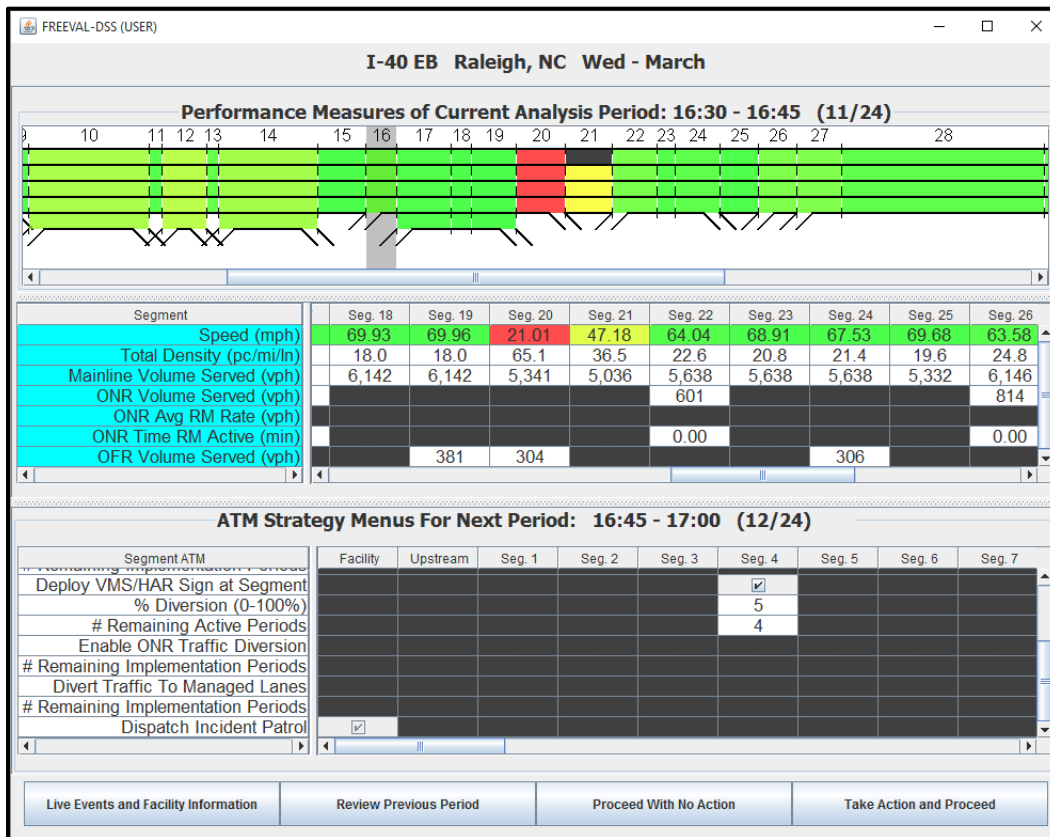
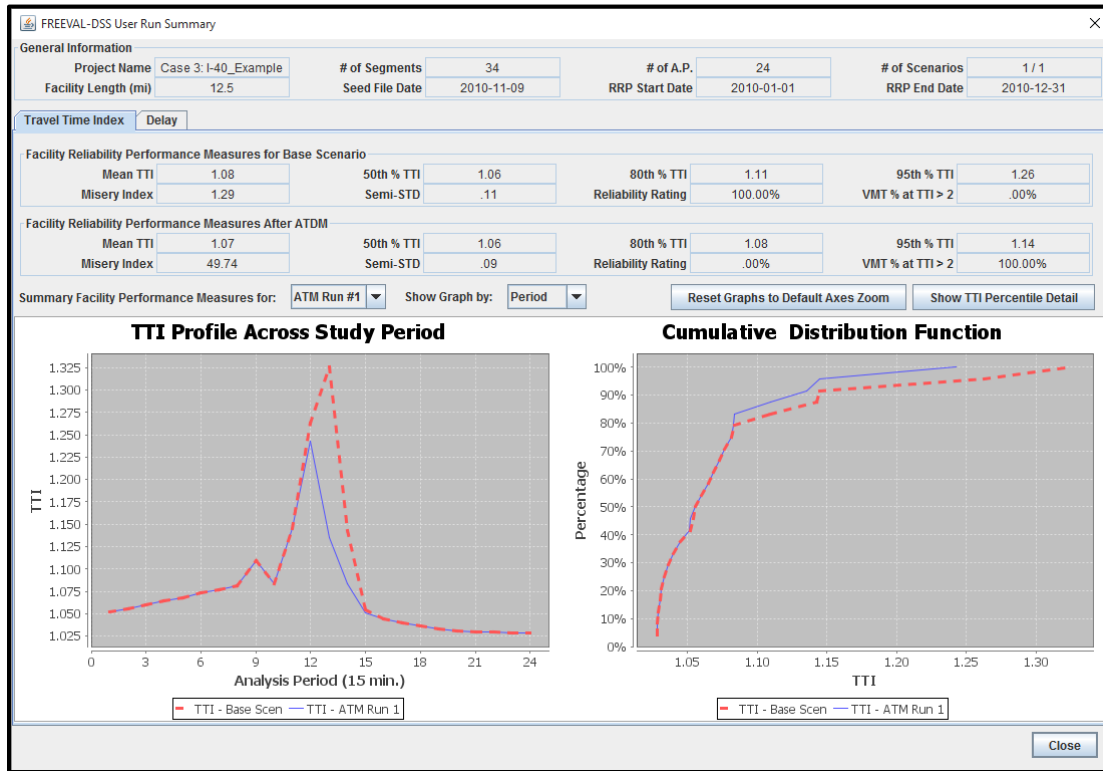


Figure 5-15. Incident on segment 21 at 4:30 showing slow speeds at segment 20. The bottom table shows DMS induced diversion in place for the next analysis period, as well as the checkbox indicating incident management is active.

While incident management is currently deployed and the duration of the incident will be reduced by 15-minutes, the End User comes to the conclusion that an additional ATM intervention should be made. Unlike the previous example, the End User in this case does not believe the 15-minute reduction will be enough, and has the resources to make use of a second ATM strategy. The End User decides that the most desirable course of action is to use DMS, in addition to the incident management. Specifically, the End User deploys DMS at segments 4, 11, and 15, and it is estimated that each sign will result in 5% of the mainline traffic being diverted off of the facility via a downstream off-ramp. For this initial diversion intervention, the End User chooses to deploy the signs for 4 analysis periods (1 hour) to see how conditions on the facility evolve. The End User uses the “Take Action and Proceed” option to move through the next analysis periods. After two periods (30 minutes), the End User observes that the incident has ended, and the resulting congestion has cleared. The End User concludes that while under the initial intervention the DMS signs remain active for two more periods, there is no longer any need for them as they will have no effect once the incident has cleared, so the number of remaining implementation periods is changed to 0. With the incident cleared and the ATM intervention complete, the End User can view that speeds have returned to normal and no more congestion exists on the facility. As a whole, the performance measures shown on the facility graphic and in the output table indicate that the facility has returned to free flow conditions across the board. The End User uses the “Proceed With No Action” button to move through the following periods, and with no more congestion arising, proceeds to the end of the study period without making any more interventions. Finally, the End User concludes the current analysis run and generates the performance summary.

The performance measures of the summary output window (see Figure 5-16) show that the intervention strategy employed in this example led significant improvement of the worst facility conditions during the study period. While the mean TTI only drops from 1.08 to 1.07, the 95<sup>th</sup> percentile TTI drops from 1.26 to 1.14, a 9% improvement. This provides an interesting comparison with the previous two use cases. In use case 3, just the DMS portion of the intervention was used, and the improvement was not significant other than at the worst period (i.e. at the maximum TTI). Alternatively, in use case 4, just the incident management portion of the ATM intervention was used, and the improvement at the 95<sup>th</sup> percentile TTI was only 7%.



**Figure 5-16. Summary output showing travel time performance measures for the DMS diversion and incident management combination intervention.**

Additionally, from Figure 5-16 it can be seen that while the TTI remains mostly the same for a large portion of the distribution, the TTI profile and cumulative distribution graphs show that there was in fact significant improvement during the peak periods. Starting at the 12<sup>th</sup> analysis period (5:00pm), there is a major improvement in the facility travel time. From this point until the 15<sup>th</sup> analysis period (5:45pm), improvement of the TTI over the base scenario is maintained.

Multi-run comparison of Use Cases 3-5

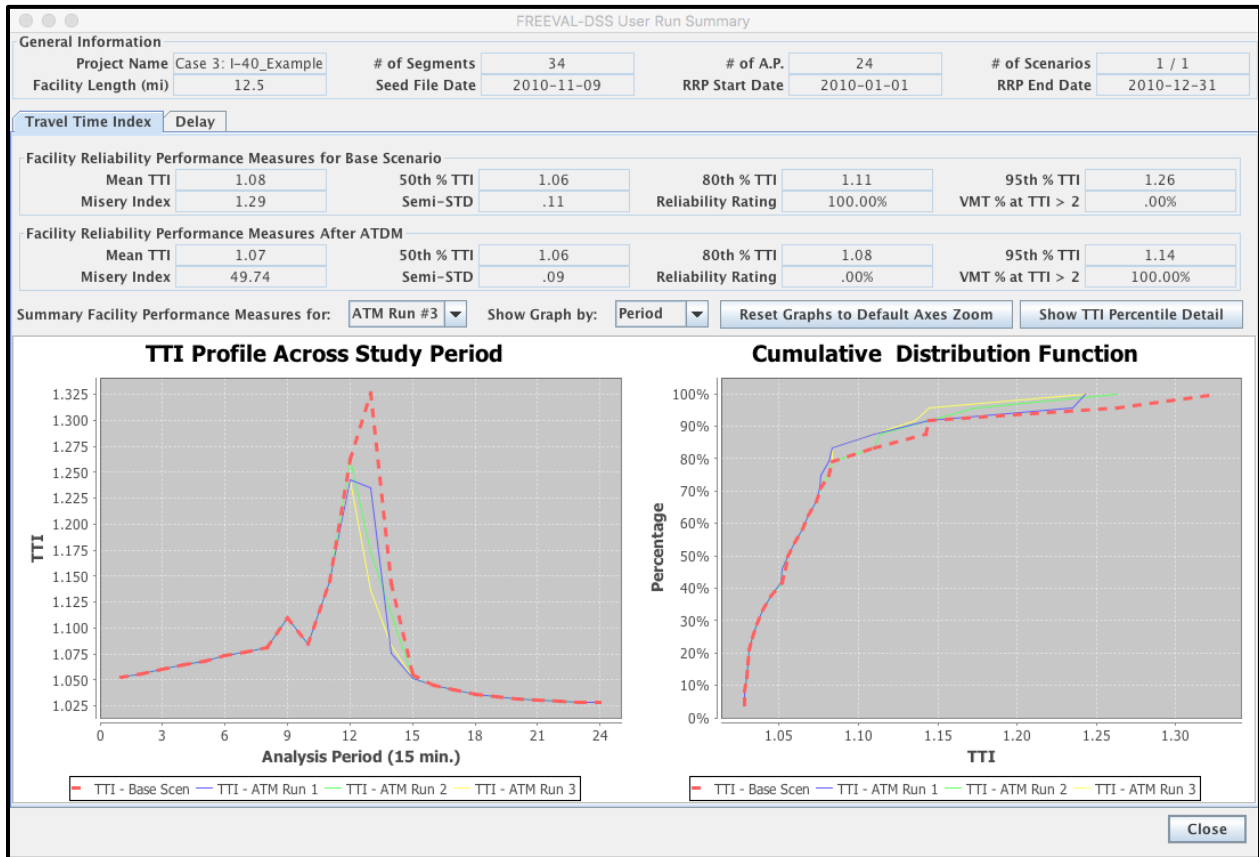


Figure 5-17. Summary output showing the comparison of the three intervention strategies.

To demonstrate the multi-run comparison ability of the framework, the interventions selected in use cases 3, 4, and 5 can be combined into a single use of the methodology. Each of the three analysis runs was conducted on the same scenario, and each took a different approach when making ATM interventions. As noted in the previous section, use case 5 is actually a combination of use cases 3 and 4. Figure 5-17 shows an example of the multi-run summary report of the three intervention runs. Conducting the analysis in this way often allows for an easier access and comparison between intervention strategies.

### Use Case 6: Work Zone

For the sixth and final use case, it is assumed that the facility has a work zone spanning a 1.2 mile stretch from segments 22 to 26. The work zone closes one lane of the facility in each of the five segments and is active for the entire study period.

For the first time during these use cases, the conditions during the first analysis period of the study period are not completely congestion free (see Figure 5-18). There is an obvious drop in speed in the segments in which the work zone is active. From the output table, the End User can observe that speeds in these segments are hovering just above 40 mph, which is well below free flow speed. However, since a slowdown such as this is normal for a work zone of this size and the congestion has not spread outside of the work zone, for our example the End User will choose to “Proceed With No Action” for the time being. Proceeding to the 3<sup>rd</sup> analysis period (2:45-3:00pm), the facility graphic and performance measure table both indicate that conditions are mostly stable within the work zone, and since the congestion continues to be contained within the work zone, the End User chooses not to make an intervention at this point.

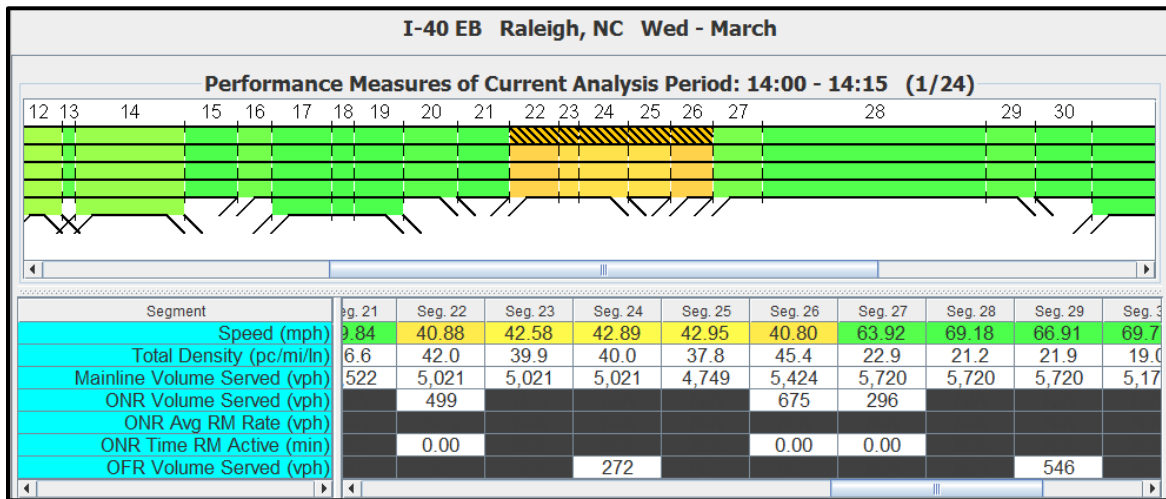
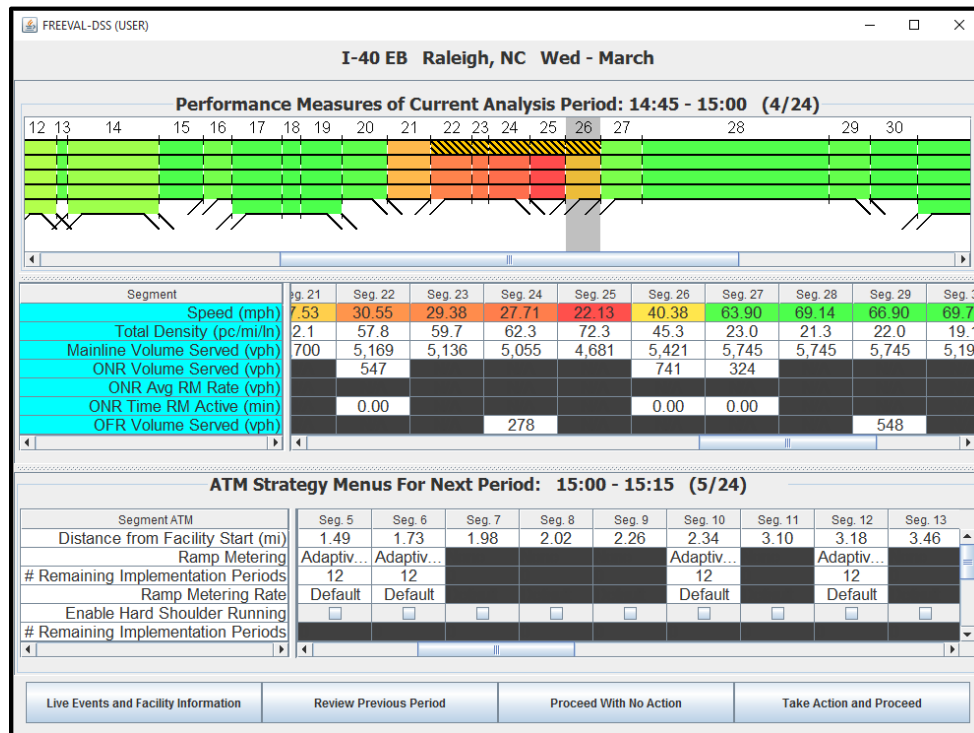


Figure 5-18. Facility conditions in the first AP with a slowdown occurring at the work zone.

Moving to the next analysis period, the End User notes that the facility conditions have started to worsen, as shown in Figure 5-19. The slow speeds in the work zone have now caused congestion to spread immediately upstream of the work zone. The speed in segment 21 has now been reduced greatly, and the End User concludes that it is now time to make an ATM intervention.



**Figure 5-19. Heavy breakdown occurring around the work zone in AP 4. The bottom table shows the ramp metering ATM intervention configured to begin in the following AP**

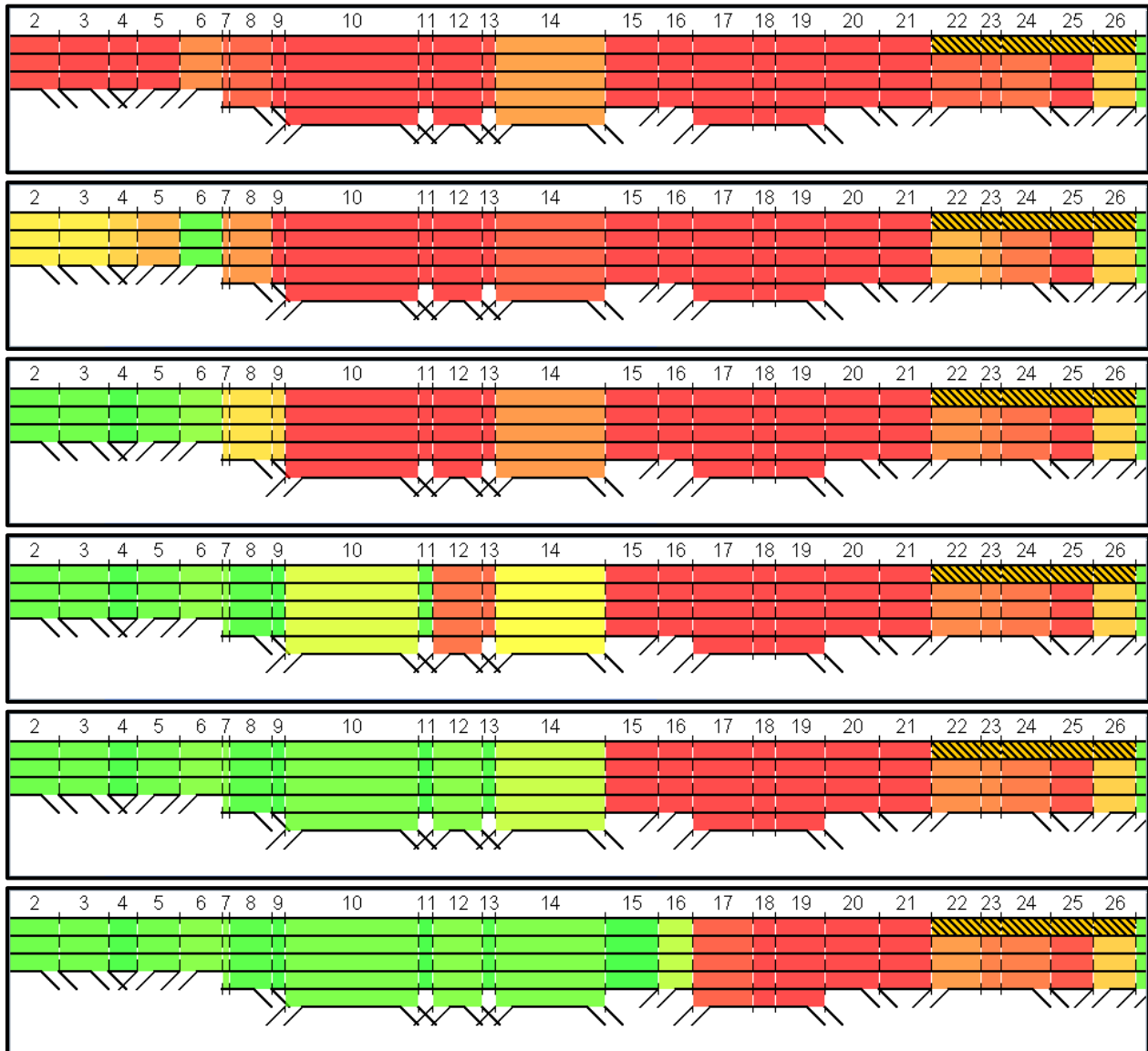
For this example, the End User comes to the conclusion that reducing the traffic coming into the facility via on-ramps is the appropriate course of action. The End User chooses to employ ramp metering at all on-ramps upstream of the work zone as well as at those on-ramps within the work zone. Specifically, the End User activates ALINEA adaptive ramp metering at segments 5, 6, 10, 12, 14, 16, 17, 22, and 26, and sets the remaining implementation periods as 12 so the metering will be in effect for at least the next three hours. While the widespread activation of ramp metering in this scenario may seem a significantly more drastic ATM intervention than in previous examples (i.e. the ramp metering used in use case 1), there are two main reasons leading to this thought process. First, the End User knows the work zone will last for the entire study period, and second, the End User knows that traffic will only increase over the next 2-3 hours as the afternoon weekday rush hour comes and goes. With this knowledge in hand, the End User knows the conditions on the freeway are likely to continue to deteriorate drastically until demand begins to subside around 6:00pm. The End User uses the “Take Action and Proceed” option to move through the next 12 analysis periods as the ramp metering takes effect. As suspected, the facility conditions worsened severely, and the congestion spreads upstream throughout the facility. At this point, the

End User observes that the ramp metering intervention should be extended, and chooses to add 1 hour and 15 minutes (5 analysis periods) to each ramp in which metering has been deployed so that the strategy will last until 7:15pm.



**Figure 5-20. Poor facility conditions still exist when the first ramp metering intervention is set to expire so the strategy is extended for an additional 5 analysis periods.**

The End User proceeds with ramp metering active for the additional 5 analysis periods until the ramp metering is set to come to an end. Viewing the conditions of the facility in the 21<sup>st</sup> analysis period (7:00-7:15pm), the amount of congestion on the facility has decreased significantly. Further, using the “Review Previous Period” and “Review Next Period” buttons at the bottom of the window, the End User notes that the congestion has been improving steadily since the 16<sup>th</sup> period (see Figure 5-21). Consequently, the End User decides to let the ramp metering expire as the congestion should resolve itself naturally from this time period until the end of the study period without the aid of an ATM intervention. The End User uses the “Proceed With No Action” button to move through the following periods, and with no more congestion arising, concludes the current analysis run and generates the performance summary.



**Figure 5-21. Steady improvement of facility conditions for periods 16 to 21 (5:45-7:15pm).**

The performance measures of the summary output window show that the intervention strategy employed in this example led to moderate improvement of the facility conditions during the study period. From Figure 5-22, it can be seen that the mean TTI dropped from 2.27 to 2.12. A more significant improvement is shown at 80<sup>th</sup> percentile measure, where the TTI dropped from 3.63 to 3.21, an 11.5% improvement. The TTI profile and cumulative distribution graphs also reinforce the notion that there was moderate improvement gained throughout the ramp metering intervention. Starting from the 4<sup>th</sup> analysis period (3:00pm), the End User can see improvement



in the facility travel time. This improvement remains until the facility conditions begin to naturally stabilize and clear from the 19<sup>th</sup> period (6:45pm) to the end of the study period. An interesting unintended consequence of the ATM intervention can also be seen in the TTI profile. As the ramp metering processes end, the amount of demand entering through the on-ramps increases as the delayed vehicles are let through unimpeded. This causes a slight slowdown at the ramps and actually increases the travel time slightly for periods 21-23 (7:15-7:45pm). However, this does not alter the preceding analysis, as the End User will likely view this as a worthwhile tradeoff for the larger improvement seen in travel time over the course of the entire study period.

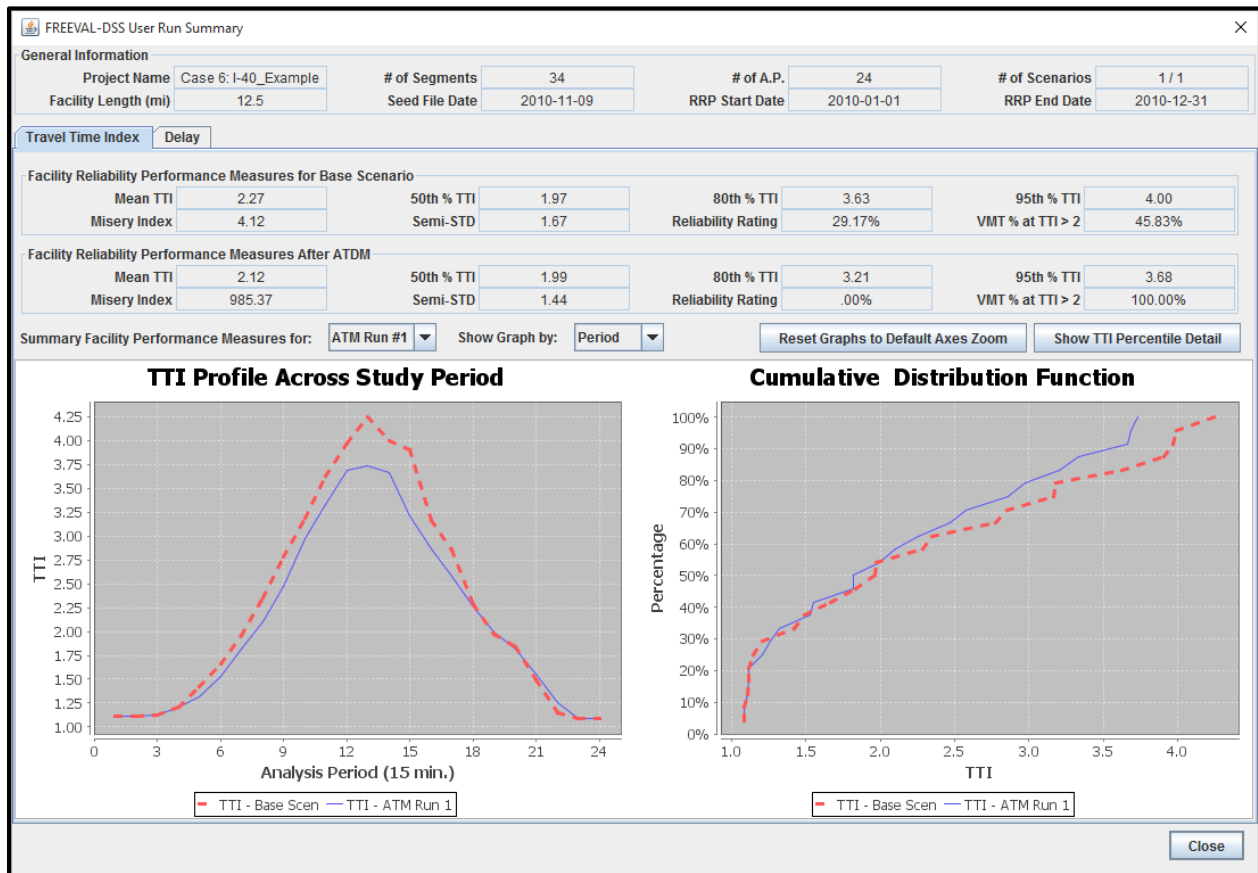


Figure 5-22. Summary output showing travel time performance measures for the ramp metering ATM intervention.

### Summary of Use Cases

The previous sections detail six use cases analyzed for the I-40 case study. Table 5-1 provides a summary of these six scenarios, giving the scenario event and intervention strategies

used, as well as a summary of the TTI performance measures for both before and after the interventions were made. The table shows that while there was improvement in each use case, the amount of improvement varied significantly based both on the scenario event and the type of intervention made. The analyses of use cases 3 – 5 demonstrate that it can be effective to combine multiple ATM strategies into a single intervention when that capability is available to the End User. Further, use cases 2 – 5 show how repeated runs comparing different interventions for the same scenario can inform an End User as to which strategies are most effective.

**Table 5-1: Summary of the use cases for the I-40 case study.**

Use Case	Scenario Event	Interventions Employed	Base Scenario TTI* (Free Flow TT= 11.4 min)			After Intervention TTI*		
			Mean	80 <sup>th</sup>	95 <sup>th</sup>	Mean	80 <sup>th</sup>	95 <sup>th</sup>
1	Weather: Heavy Rain	Ramp Metering – Adaptive ALINEA	1.63	2.54	3.22	1.56	2.49	3.03
2	Incident: One Lane Closure	Hard Shoulder Running	1.08	1.11	1.26	1.07	1.11	1.18
3	Incident: One Lane Closure	DMS Diversion	1.08	1.11	1.26	1.07	1.08	1.23
4	Incident :One Lane Closure	Incident Management	1.08	1.11	1.26	1.07	1.11	1.17
5	Incident: One Lane Closure	DMS Diversion and Incident Management	1.08	1.11	1.26	1.07	1.08	1.14
6	Work Zone	Ramp Metering – Adaptive ALINEA	2.27	3.63	4.00	2.12	3.21	3.68

### I-95 Case Study

As with the I-40 use cases, six simple use cases were designed to evaluate the effect of ATM interventions on network performance measures under rain and incident conditions (45 minute incident in segment 20 and 2 hours of heavy rain). The base corridor used for this case study is a 12-mile section of I-95 northbound in Miami, Florida, as shown in Figure 5-23. As it can be seen from Figure 5-24, segment 12 and 8 are bottleneck locations (Merge from SW 79<sup>th</sup> and SW 103<sup>rd</sup> Streets). The starting point of the network is located on the I-95 mainline at NW 8 Street, and the ending point is located on I-95 at NE 187 Street. The study period is from 2:00 PM to 7:00 PM.

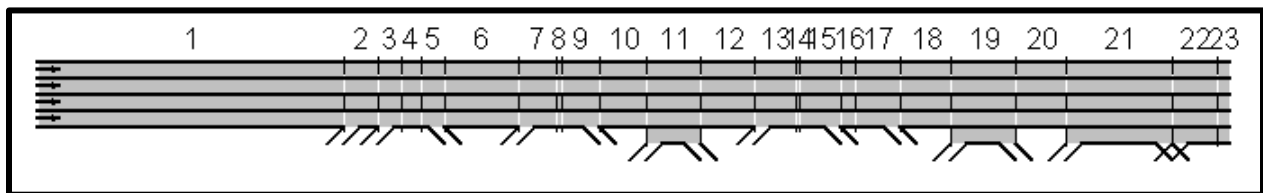


Figure 5-23. I-95 study corridor-base facility

Single Seed/Scenario I/O	FREEVAL-DSS		Compare	Result Contours	Analysis Period Summary			Segment & Facility Summary				
Analysis Period	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8	Seg. 9	Seg. 10	Seg. 11	Seg. 12	Seg. 13	
#1 14:00 - 14:15	55.7	55.7	55.7	55.8	52.1	52.1	52.1	54.5	46.5	52.4	48.2	
#2 14:15 - 14:30	54.9	54.9	54.9	55.3	51.1	51.1	51.1	53.8	46.4	51.6	47.1	
#3 14:30 - 14:45	52.0	52.0	52.0	53.8	48.6	48.6	48.6	52.0	45.4	50.2	45.7	
#4 14:45 - 15:00	53.9	53.9	53.9	55.1	51.7	51.7	51.7	54.3	45.2	52.4	47.9	
#5 15:00 - 15:15	52.6	52.6	52.6	54.3	50.3	50.3	50.3	53.3	45.7	51.7	47.4	
#6 15:15 - 15:30	49.8	49.8	49.8	52.3	46.4	46.4	46.4	49.2	44.6	46.9	41.8	
#7 15:30 - 15:45	48.4	48.4	48.4	51.0	44.4	44.4	56.8	40.4	25.7	24.3	46.6	
#8 15:45 - 16:00	50.8	50.8	50.8	35.6	31.5	31.5	34.4	23.1	17.9	24.8	46.7	
#9 16:00 - 16:15	34.5	34.5	37.5	27.0	24.9	24.9	46.0	43.4	21.8	25.5	46.7	
#10 16:15 - 16:30	40.2	40.2	45.6	27.1	28.7	28.7	52.1	47.5	20.5	23.9	46.7	
#11 16:30 - 16:45	54.0	54.0	57.7	35.7	36.0	36.0	54.3	26.2	19.5	24.6	46.7	
#12 16:45 - 17:00	51.9	38.0	38.0	23.3	42.2	42.2	45.4	41.3	22.5	25.6	46.7	
#13 17:00 - 17:15	53.5	53.5	53.5	29.7	47.6	47.6	47.6	57.5	27.0	25.3	46.7	
#14 17:15 - 17:30	51.8	51.8	51.8	53.1	48.9	48.9	48.9	52.1	28.5	23.4	46.7	
#15 17:30 - 17:45	55.3	55.3	55.3	55.4	52.6	52.6	52.6	54.8	50.2	35.9	48.6	
#16 17:45 - 18:00	55.5	55.5	55.5	55.7	53.9	53.9	53.9	55.9	47.9	55.6	53.9	
#17 18:00 - 18:15	55.9	55.9	55.9	56.1	55.0	55.0	55.0	56.8	47.8	55.9	54.3	
#18 18:15 - 18:30	54.5	54.5	54.5	55.6	53.7	53.7	53.7	55.9	48.0	54.9	52.7	
#19 18:30 - 18:45	57.0	57.0	57.0	56.8	56.1	56.1	56.1	57.6	48.1	56.4	54.3	
#20 18:45 - 19:00	58.3	58.3	59.4	57.8	57.3	57.3	58.8	59.2	49.0	57.5	54.8	

Figure 5-24. I-95 network speed counter-Bottleneck locations are segments 12 and 8

### Use case 1: Ramp Metering with a Weather Event

For this use case a medium rain event was generated to occur between 5 to 6 PM. Figure 5-25 shows that the speeds are continuing to drop for segments before segment 12 during the rain presence. ALINEA adaptive ramp metering was enabled at segments 2, 7, 11 and 13 from 5:15 to

6:15 PM to reduce the number of vehicles that can enter the freeway. Figure 5-26 shows the ramp metering intervention for 4 analysis periods. As the freeway is operating at free flow speed (Figure 5-27) in the 18<sup>th</sup> analysis period (6:15 to 6:30) no ramp metering extension is needed and the End user uses the "Proceed with no action" to go through the following periods.

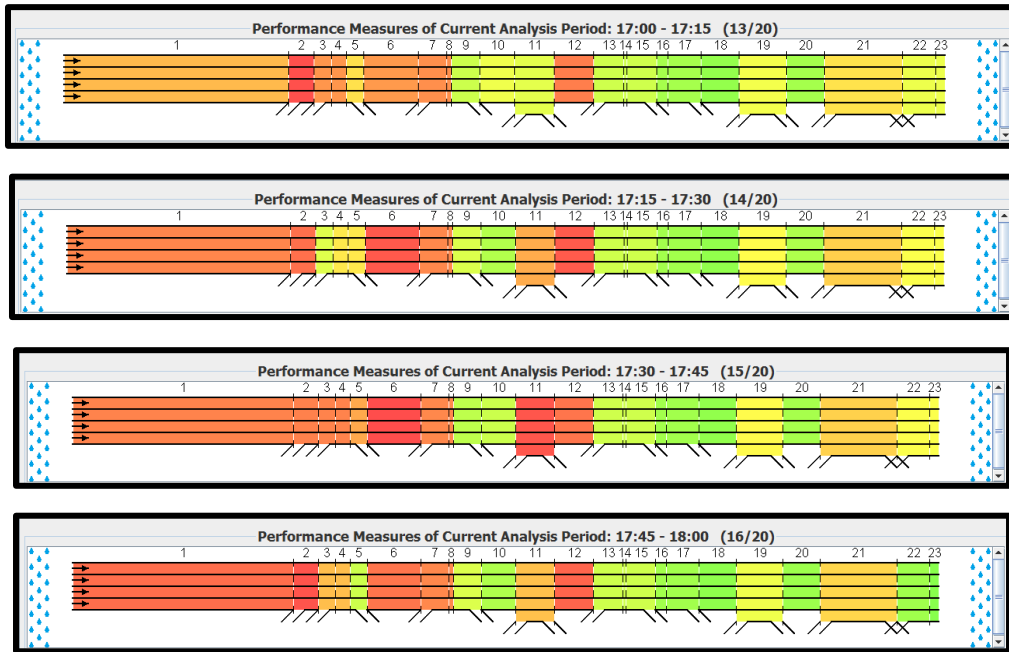
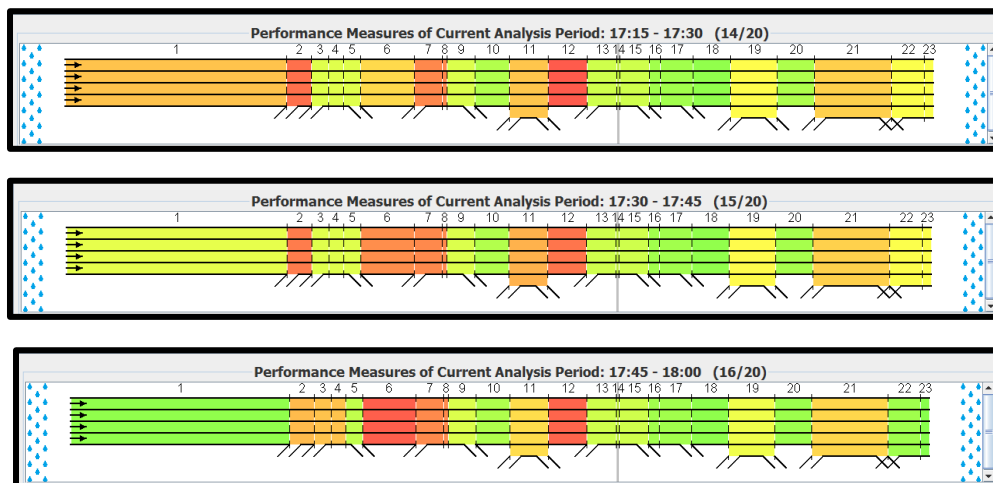


Figure 5-25. Worsening condition in presence of a medium rain event.



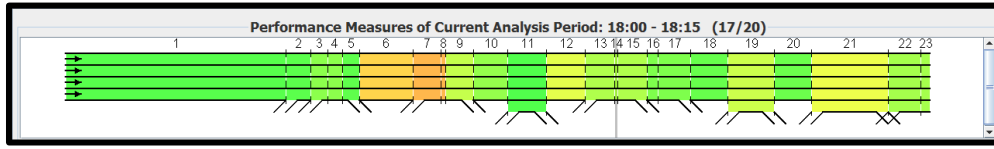


Figure 5-26. Ramp metering ATM intervention from 17:15 to 18:15 PM

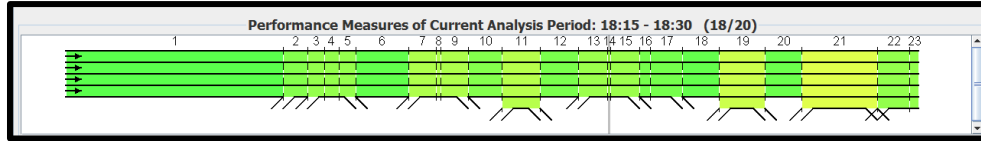


Figure 5-27. Freeway Conditions at the 18<sup>th</sup> analysis period (18:15 to 18:30 PM)

From Figure 5-28, it can be seen that the mean TTI dropped from 1.35 to 1.25, a 7 percent improvement. The improvement is started at analysis period 14 when the ramp metering is activated and ends at analysis period 18. After the 18<sup>th</sup> analysis period the performance of ATM intervention run as the base scenario converge as the facility returns to normal condition.



Figure 5-28. Summary output of the ramp metering ATM intervention

### Use case 2: Incident Event with Hard Shoulder Running

In this use case one incident resulting in one lane blockage was generated at segment 20 from 4:30 to 5:15 PM (AP 11 to 13). As it can be seen from Figure 5-29, once the incident happens in analysis period 11, segments 19 and 18' speed drops drastically. The user chooses to open the hard shoulder for segments 19, 20, 21 and 22 for 1 hour. Figure 5-30 shows the network performance after opening the hard shoulder for 4 analysis period (12, 13, 14 and 15<sup>th</sup>). The resulting congestion at segments 19, 18, 17 and 16 has cleared and the user continues proceeding with the “Proceed with no action”. However, the upstream section of the corridor remains congested due to the heavy queue back up from both the incident and the bottleneck at segment 12. Even if the ATM intervention continues until the end of the study, the queue is not cleared.

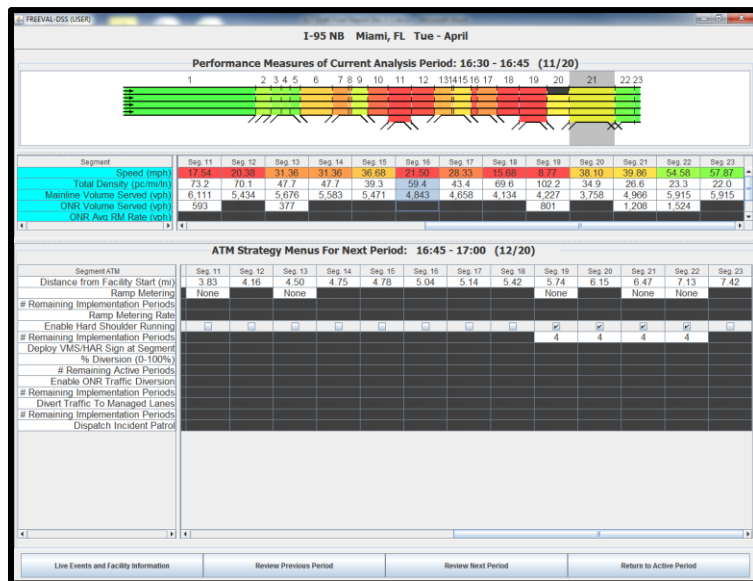


Figure 5-29. Incident at segment 20 at 4:30 yields slow speeds at segment 19, 18, 17 and 16. The bottom table shows hard shoulder intervention in place for the next analysis period

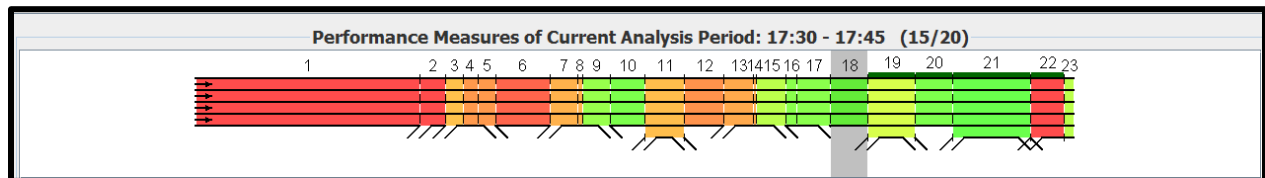


Figure 5-30. Network performance after four analysis period hard shoulder ATM intervention

Figure 5-31 shows that the mean TTI dropped significantly from 2.24 to 1.9, a 15% improvement due to the hard shoulder intervention. The improvement starts at the 12<sup>th</sup> analysis period and remains until the 16<sup>th</sup> analysis period.

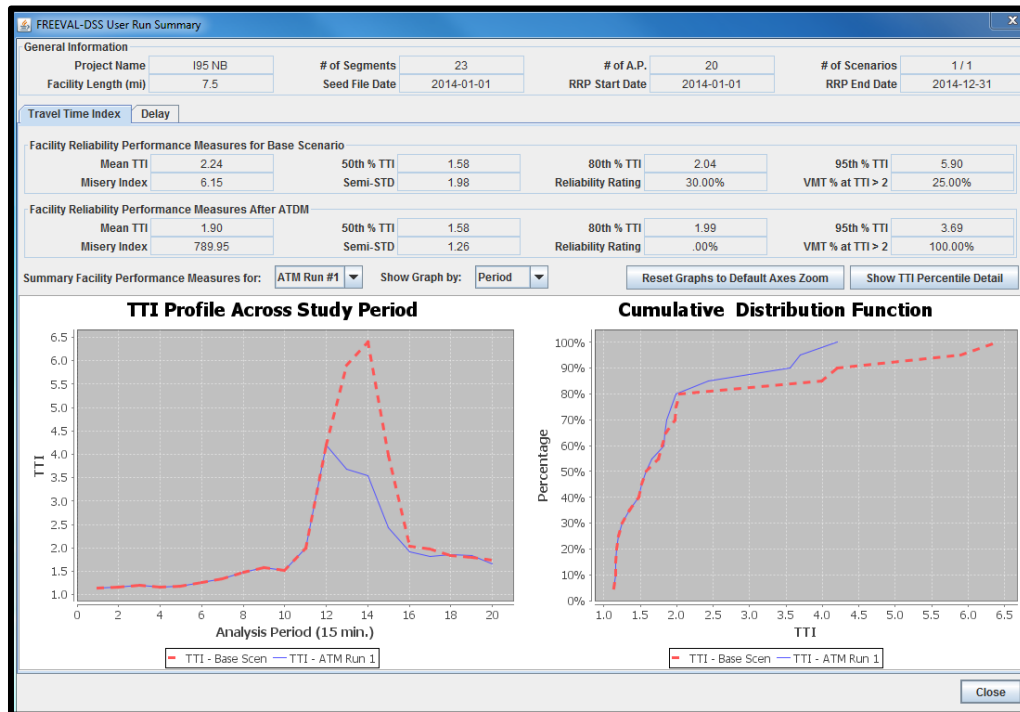


Figure 5-31. Summary output of the hard shoulder running ATM intervention

### Use case 3: Incident Event with the DMS Induced Diversion

For the third use case, a one lane blockage incident was generated at segment 20 from 4:30 to 5:15 PM. The upper part of Figure 5-32 shows the network condition at the 11<sup>th</sup> time step in which the incident occurs. Speed at segments 19, 18, 17 and 16 drop due to the incident occurrence. The user activates the DMS at the segments upstream of the incident for 4 analysis period to see how the network performance changes. It is assumed that 5% of the traffic divert according to the DMS information.

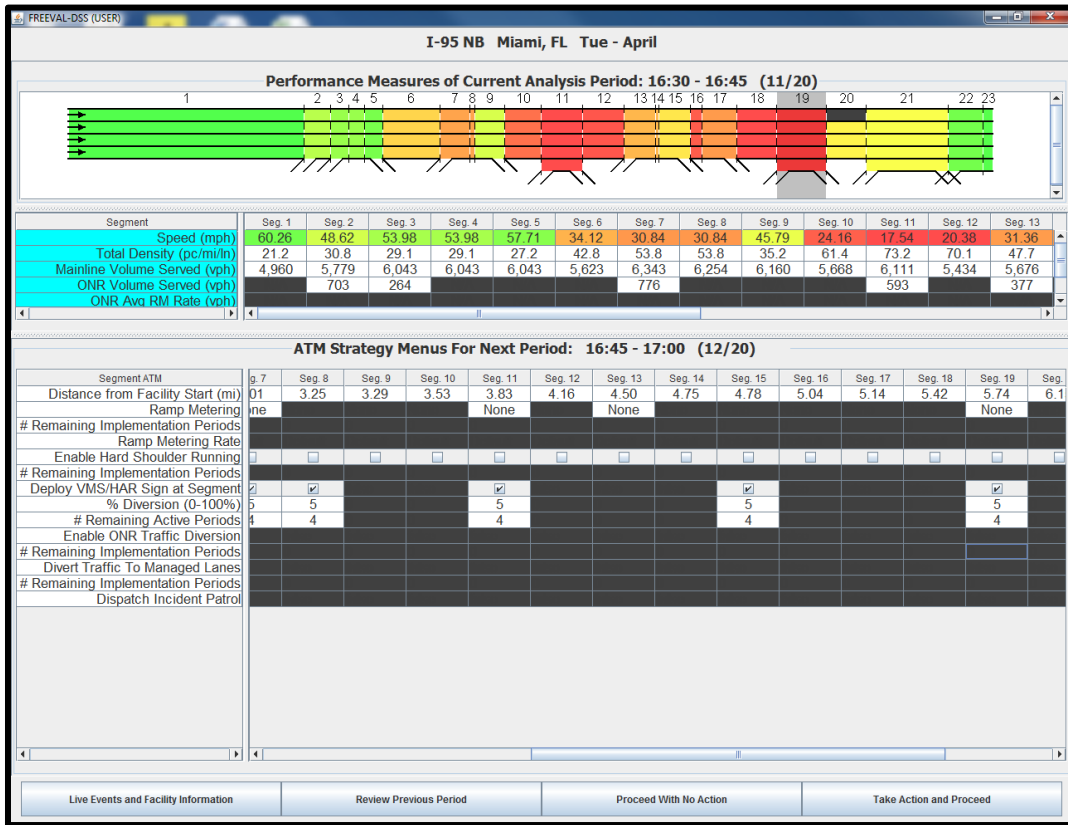


Figure 5-32. Incident at segment 20 at 4:30; slow speeds at segment 19, 18, 17 and 16. The bottom table shows DMS induced diversion intervention in place for the next analysis period.

As Figure 5-33 shows, four analysis periods intervention clear the congestion resulted from the incident at segments 19, 18, 17 and 16 and no extension is needed.

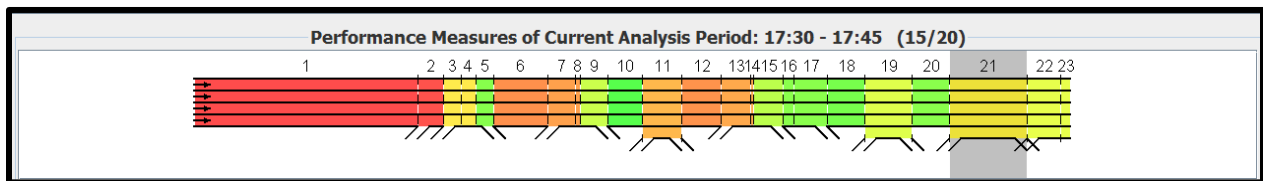


Figure 5-33. Network performance after four analysis period diversion ATM intervention



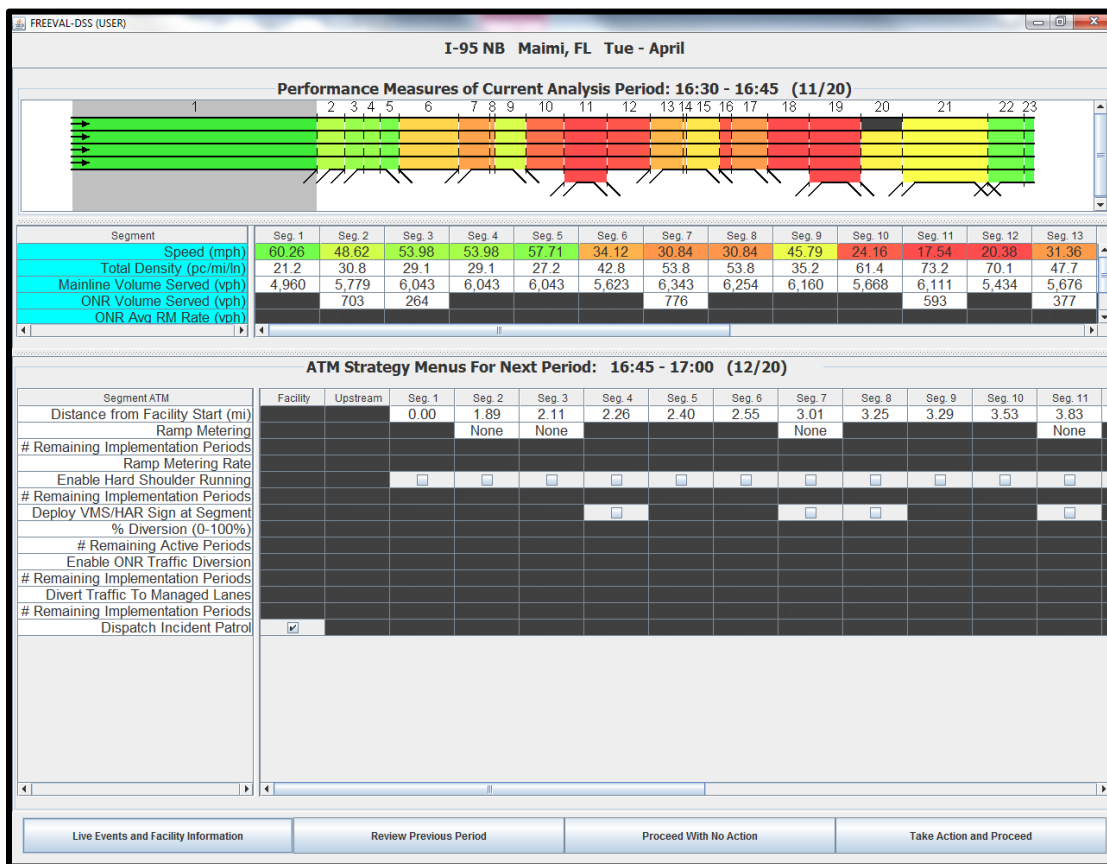
Figure 5-34 shows significant improvement due to the DMS activation intervention. The mean TTI drops from 2.24 to 1.79, a 20% improvement.



Figure 5-34. Summary output of the diversion ATM intervention

#### Use case 4: Incident Event with Incident Management

As with the use case 2 and 3, a one lane blockage incident was generated at segment 20 for 45 minutes. As Figure 5-35 shows, segments 19, 18, 17 and 16 are affected by the incident and the speed dropped drastically. The user then enables the incident management seeing the incident impact on these segments. It is assumed that incident management reduces the incident duration by 15 minutes.



**Figure 5-35. Facility conditions during the first period in which the incident occurs. In the bottom table, it can be seen that the checkbox is marked indicating incident management is active.**

The effect of the incident intervention is depicted in Figure 5-36. The performance measures of the summary output window show that the intervention strategy employed in this example led to significant improvement of the network. The mean TTI drops from 2.24 to 1.95, a 13% improvement, and the 95<sup>th</sup> percentile TTI drops from 5.9 to 4.2, a 28% improvement. The TTI profile and cumulative distribution graphs show that there was improvement gained through the deployment of incident management for the study period. Starting at the 12<sup>th</sup> analysis period (5:00pm), the End User can see improvement in the facility travel time. From this point until the 15<sup>th</sup> analysis period (5:45pm), improvement can be seen in TTI, with the peak increase in travel time being significantly reduced from analysis periods 12-14 (5:00-5:30pm).

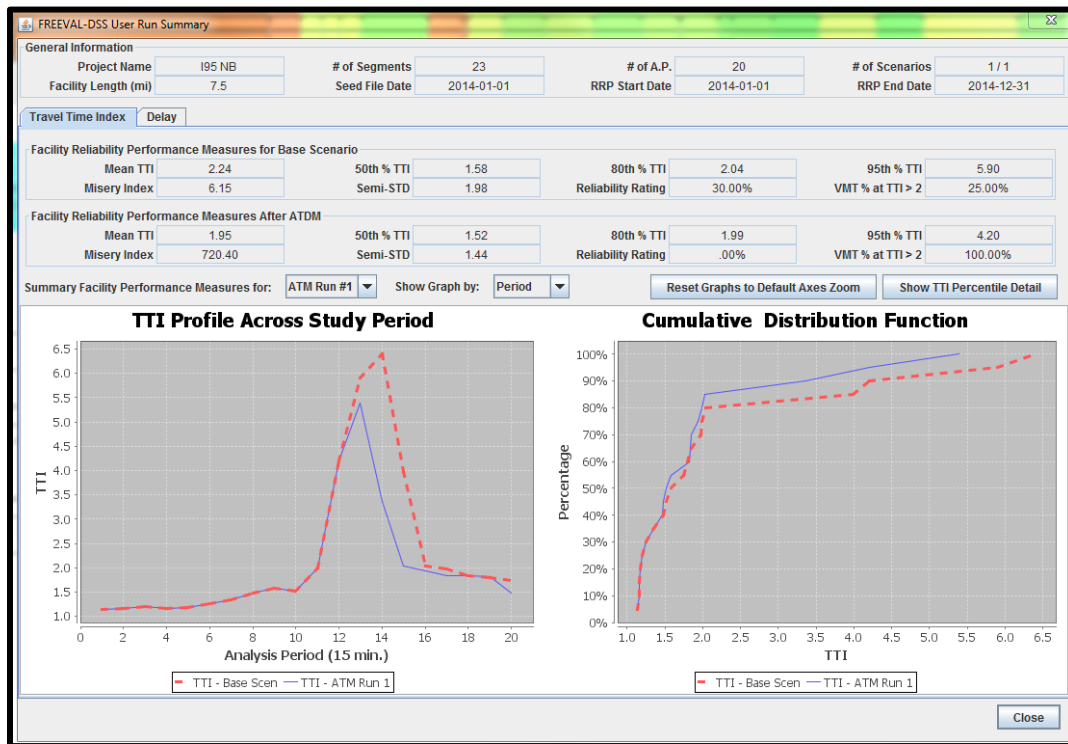


Figure 5-36. Summary output of the incident management ATM intervention

### Use case 5: Incident and Rain Events with DMS Induced Diversion and Incident Management

For the fifth use case one incident event from 4:30 to 5:15 PM (AP 11 to 13) and one rain event from 5 to 6 pm (AP 13 to 16) were generated. The user activates the incident management when seeing the incident occurrence at the 11<sup>th</sup> analysis period. Then, the user decides to go through the 12<sup>th</sup> AP with incident management being active only. But at the 13<sup>th</sup> AP the rain is started and speed drops drastically at the beginning part of the network (Figure 5-38) and the user decides to activate the DMSs for at least 1 hour at the upstream of the incident location. After the four analysis periods of DMS activation the network returns to normal condition and no more extension of DMS intervention is needed.

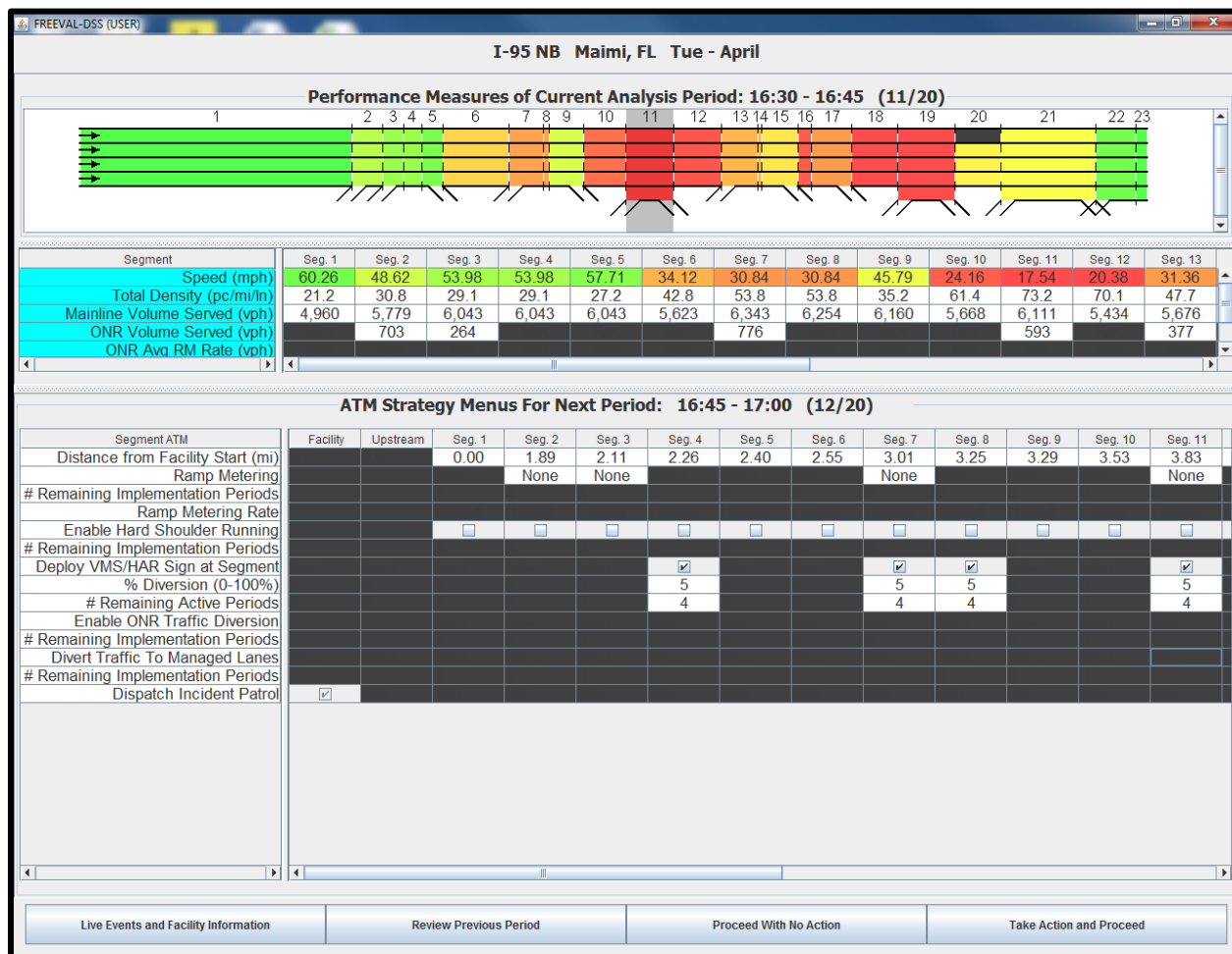


Figure 5-37. Facility conditions during the first period in which the incident occurs. In the bottom table, it can be seen that the checkbox is marked indicating incident management is active.

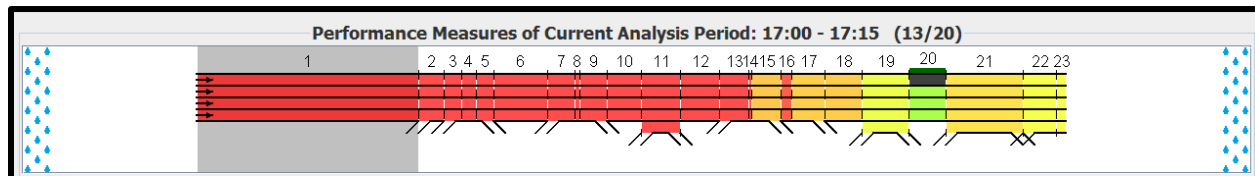


Figure 5-38. Rain and incident presence in the 13<sup>th</sup> AP

The performance measures of the summary output window (see Figure 5-16) show that the intervention strategies employed in this example led significant improvement of the worst facility conditions during the study period. While the mean TTI drops from 2.40 to 2.05, the 95<sup>th</sup> percentile TTI drops from 6.86 to 4.2, a 39% improvement.

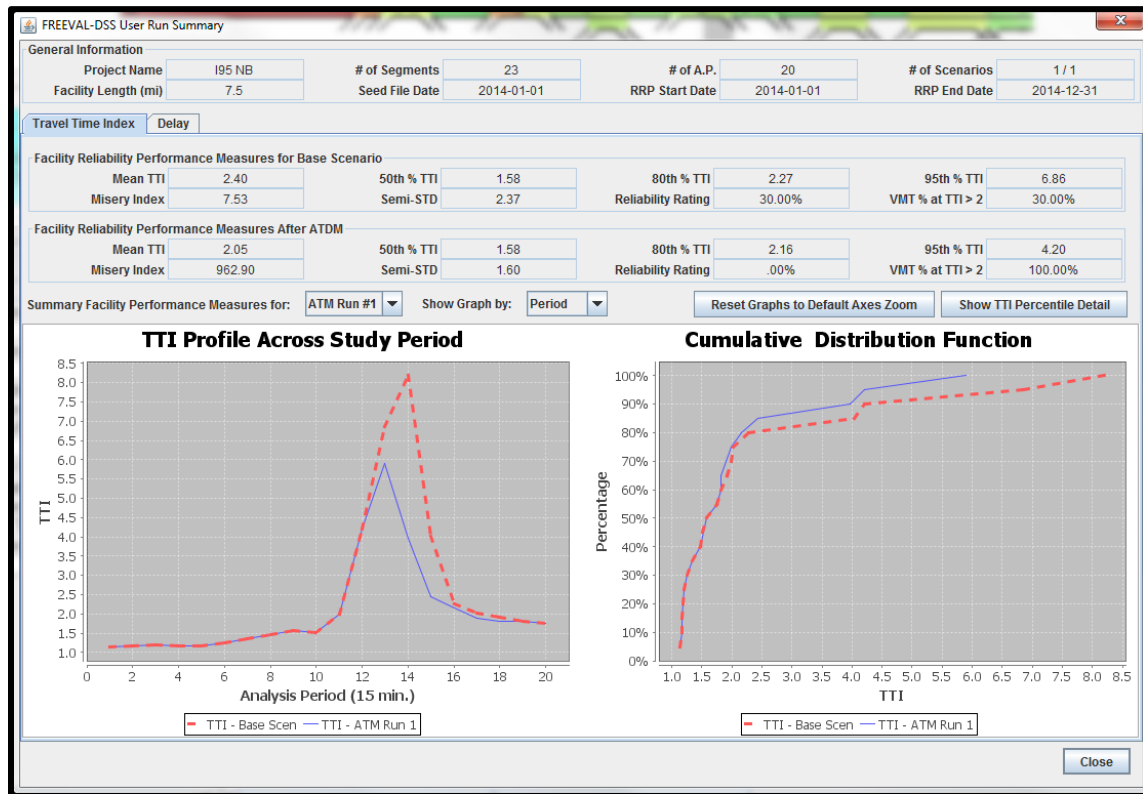


Figure 5-39. Summary output of the incident management and DMS ATM interventions

### Use case 6: Work Zone

For the final use case, a one lane closure work zone was generated from segment 12 to segment 22 for the entire study period. As it is observed from Figure 5-40, segments 13 to 16 get congested due to the work zone operation at the 1<sup>st</sup> analysis period. The user then decides to activate the ramp metering for the upstream on-ramps at least for 3 hours.

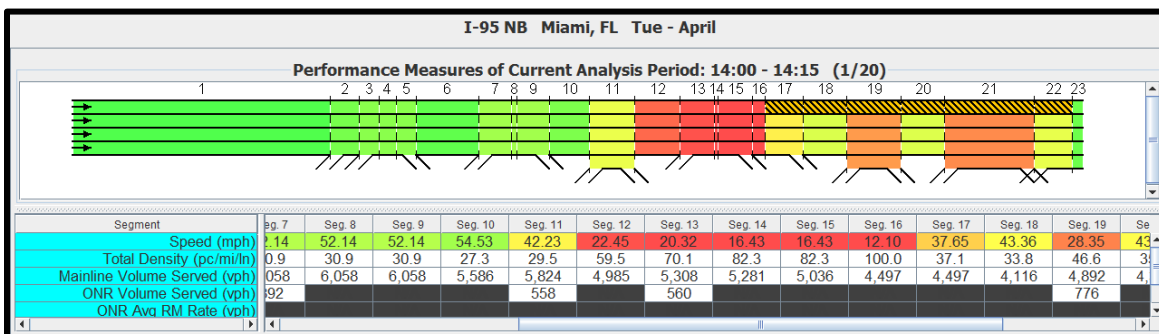


Figure 5-40. Facility conditions during the first time period of the work zone analysis.

The user uses the “take action and Proceed” option to move through the next 12 analysis periods as the ramp metering takes effect. At the 13<sup>th</sup> analysis period the user observe that the congestion spread upstream throughout the facility as shown in Figure 5-41. So the user decides to extend the ramp metering for 7 more periods until the end of the study (analysis period 20). But when the study ends the network is still very congested (Figure 5-42). So, the user decides to go back and used the “Review Previous Period” to activate the DMS as well in order to divert the vehicles from the congested path. Even when the DMSs are activated until the end of the study period (analysis period 20), the network remains congested as shown in Figure 5-43. The user concludes that the resulted congestion is too severe to be solved solely by ATM interventions.

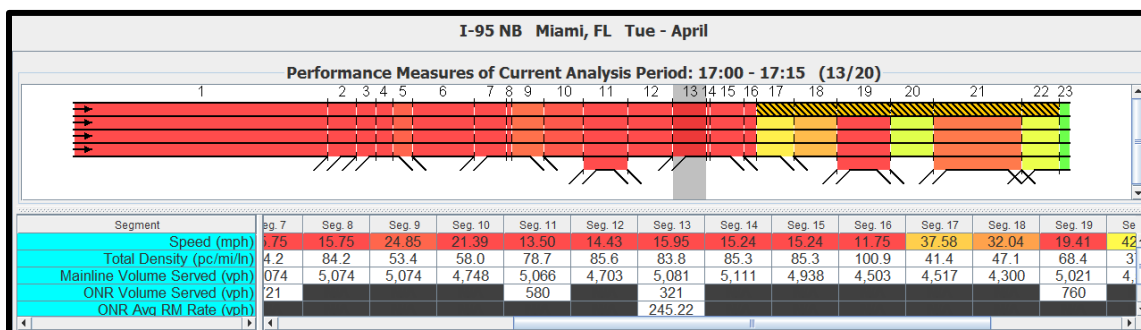


Figure 5-41. Poor facility conditions still exist when the first ramp metering intervention for 3 hours has expired

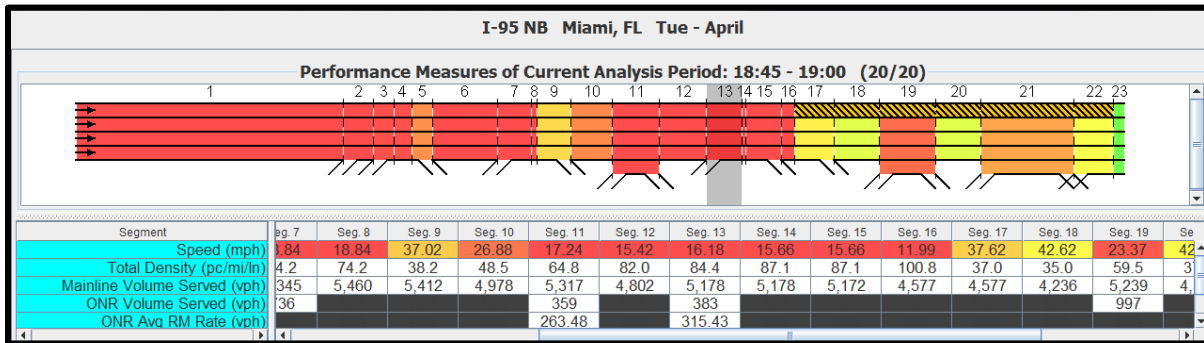


Figure 5-42. Poor facility condition after two ramp metering interventions

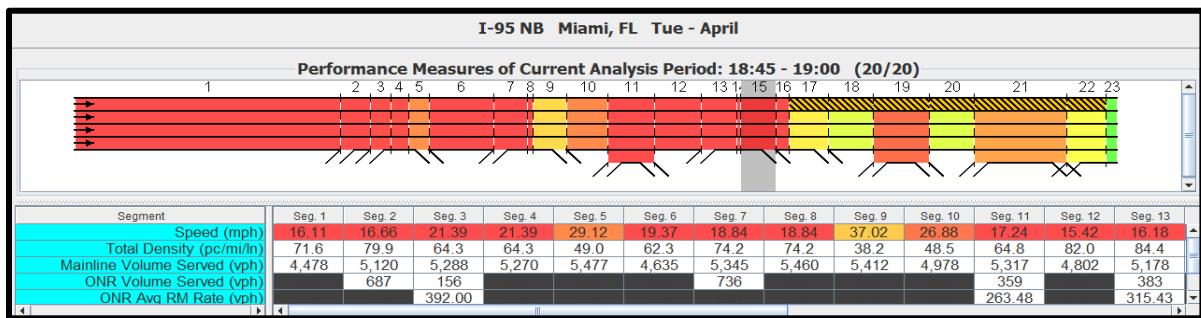


Figure 5-43. Poor facility condition after ramp metering and diversion interventions

From Figure 5-44 it can be seen that the mean TTI drops from 4.14 to 3.49, a 16% improvement. The improvement starts from the 1<sup>st</sup> AP and remains until the 11<sup>th</sup> analysis period. After the analysis period 11, travel time oscillates and in some cases it is worse than the base condition. One reason for this observation can be the presence of bottlenecks at segments 12 and 8 that worsen the situation and ATM intervention cannot help improving anymore.



Figure 5-44. Summary output of ramp metering and DMS ATM interventions



### Summary of Use Cases

Table 5-2 shows the summary of the six use cases done for the I-95 network. The TTI performance measures were calculated for both before and after the ATM interventions. As can be seen from the table, the ATM intervention improvement of the TTI depends on the event type and the ATM strategy applied. The End User can observe the effect of applying different ATM strategies to mitigate the impacts of the same event type (for example incident). Looking at the use cases 2-4 which have the same event type, the user can conclude that DMS diversion intervention is the best strategy for the lane closures event since the mean TTI dropped from 2.24 to 1.79.

**Table 5-2: Summary of the use cases for the I-95 case study.**

Use Case	Scenario Event	Intervention Strategies Employed	Base Scenario TTI (Free Flow TT= 9.5 min)			After Intervention TTI		
			Mean	80 <sup>th</sup>	95 <sup>th</sup>	Mean	80 <sup>th</sup>	95 <sup>th</sup>
1	Weather: Heavy Rain	Ramp Metering – Adaptive ALINEA	1.4	1.58	1.88	1.34	1.52	1.66
2	Incident: One Lane Closure	Hard Shoulder Running	2.24	2.04	5.9	1.9	1.99	3.69
3	Incident: One Lane Closure	DMS Diversion	2.24	2.04	5.9	1.79	1.99	3.45
4	Incident :One Lane Closure	Incident Management	2.24	2.04	5.9	1.95	1.99	4.2
5	Incident: One Lane Closure	DMS Diversion and Incident Management	2.4	2.27	6.86	2.05	2.16	4.2
6	Work Zone	Ramp Metering – Adaptive ALINEA	4.14	4.95	5.56	3.94	4.96	5.3

## CHAPTER 6 SUMMARY AND NEXT STEPS

This project developed a tool that assess and prioritize alternative active traffic management strategies, emulating as much as possible how these strategies are expected to be implemented in the real-world. As such, the development of this project fills a major gap in currently available tools and evaluation methods that have focused on planning level assessments of such strategies. The develop tool can be differentiated from planning level tools, such as those that implement the HCM ATDM procedure in two aspects: 1) the level analysis details and 2) the introduction of operator decisions as part of modeling environment. Regarding the first point, the algorithms of the management strategies are implemented in details and as much as possible to replicate real-world implementations. To correctly implement these algorithms, the program makes use of the oversaturated methodology of the HCM's freeway facilities analysis, in which the computational resolution is at much more finer level of detail (15 seconds instead of 15 minutes). With regard to the second point (the introduction of operator decisions), performance measures similar to those available to traffic management centers' operators are presented to the End User at the end of each analysis period and the End User is allowed to change the selected strategies for implementation in the next 15 minutes. This allows the assessment of the impacts of strategies, considering the impacts of their implementation decisions, as they are implemented in the real-world environment. In addition to allowing a better assessment of ATDM strategies compared to planning level tools, the tool can be applied in training of TMC operators, allowing them to see the consequences of their actions or the actions of other operators and responders in a dynamic real-world environment.

The tool framework involves two type of players: the Administrator and the End User. The Administrator performs facility configuration, scenario generation, and ATM strategy menu availability identification. The Administrator can be a traffic management manager, an agency operations engineer, their consultants, or a combination of the above. The Administrator should have knowledge of the HCM procedures and associated tools to set the seed file. The Administrator should also have traffic operation and management experience to configure the scenario generation and strategy menu. The End User executes the analysis and invokes the interventions, where several ATM strategies can be deployed either individually or in bundles. Ideally, the End User should be a TMC operator or manager, but it could also be an analyst emulating the decision of TMC operator or manager.

In addition to recurrent congestion, the scenarios that can be modeled include non-recurrent events involving rain, incidents, work zones, or combinations thereof. The strategies that can be invoked by the End User, if allowed by the Administrator, include Hard shoulder running, ramp

metering (operated utilizing time of day, ALINEA, or fuzzy logic algorithms), dynamic message sign messaging, incident management, GP to ML diversion, and mainline and on-ramp diversion. Default values of the parameters associated with these strategy impacts are provided in the developed framework based on an extensive review of literature but the Administrator can change these parameters, if better values are available based on the knowledge of existing conditions. It is possible to introduce new strategies and/or additional algorithms associated with these strategies in the future. The End User can perform multiple runs for the same scenario with different ATM strategy interventions in different runs. The outputs for the different runs can be compared to assess their impacts in mitigating recurrent and non-recurrent congestion.

An important component in any software development is the validating that the associated methods and models have been implemented correctly and they are producing reasonable results. Before utilizing use cases to demonstrate the use of the developed tool, simple hypothetical networks were used to demonstrate that different strategies were modeled correctly. For example, such a hypothetical network was used to test the benefits of ramp metering with fixed metering rate, the ALINEA algorithm, and Fuzzy Logic Algorithm under different traffic congestion patterns. The results showed that the ramp metering algorithms responded logically to the various traffic patterns and produced benefits. Ramp metering had significant effects on the network performance when there was congestion in the network. The ALINEA ramp metering receives feedback from the mainline detectors only and calculates the on-ramp metering based on this feedback. The Fuzzy Logic algorithm gets information from both the mainline and on-ramp detectors and attempts to create a balance between the mainline delay and on-ramp delay depending on the rule's weights.

After validation as described above, the tool was applied to two real world case studies representing interstate facilities in North Carolina (the I-40 facility) and Florida (the I-95 facility). These applications provided a clear demonstration of the ability of the tool to assess the impacts of ATDM strategies on the performance of the system. Six use cases were used with each of the two case studies to highlight various features of the framework and software implementation. Each of the six use cases involves a different combination of a 45-minute one-lane closure incident, and a 2-hour heavy rain, and/or a 1.2 mile work zone. The use cases also involve implementing ramp metering (ALINEA Adaptive), hard shoulder running, incident management, and DMS strategies. The I-40 facility results showed that ramp metering improved the 95% TTI by 5%. In addition; hard shoulder running, incident management strategy, and incident management combined with diversion due to DMS; in response to the incident event; improved the 95% TTI by 14%, 7%, and 9%, respectively. The 95% TTI was improved by 8.7% when ramp metering was activated to mitigate congestion due to work zones.

The same six use cases and the same strategies used in the I-40 facility assessment were used in the I-95 assessment. The results showed that ramp metering improved the 95% TTI by 12%. Hard shoulder running, incident management strategy, and incident management combined with diversion due to DMS; in response to the incident event; improved the 95% TTI by 59%, 40%, and 63%, respectively. The 95% TTI was improved by 5% when ramp metering was activated to mitigate congestion due to work zones. It is clear that most of the introduced strategies had much more benefits when implemented on I-95 compared to implementing on I-40, reflecting the higher congestion level on I-95.

It is recommended that the tool developed in this study starts to be implemented in real-world applications to support traffic management center operations. The research team has conducted outreach activities to demonstrate the tool including a recent demonstration at an ITS Florida and Institute of Transportation Engineers (ITE) Florida section meeting. The team will continue these outreach activities. Other ATDM strategies will possibly be included in the tool as it starts to be implemented and feedbacks are obtained from the implementing agencies.

## REFERENCES

- [1] Texas A&M University Transportation Institute., "Urban Mobility Report 2015," [Online]. Available: <http://mobility.tamu.edu/ums/>. [Accessed 21 November 2015].
- [2] Federal Highway Administration Office of Operation. [Online]. Available: [http://ops.fhwa.dot.gov/program\\_areas/reduce-non-cong.htm](http://ops.fhwa.dot.gov/program_areas/reduce-non-cong.htm). [Accessed 13 March 2013].
- [3] Federal Highway Administration, "Ramp Management and Control," 2013. [Online]. Available: [http://ops.fhwa.dot.gov/publications/ramp\\_mgmt\\_handbook/manual/manual/pdf/rm\\_handbook.pdf](http://ops.fhwa.dot.gov/publications/ramp_mgmt_handbook/manual/manual/pdf/rm_handbook.pdf). [Accessed 5 June 2013].
- [4] Federal Highway Administration, "Synthesis of Active Traffic Management Experiences in Europe and the United States," [Online]. Available: <http://ops.fhwa.dot.gov/publications/fhwahop10031/sec3.htm>. [Accessed 5 June 2013].
- [5] M. Papageorgiou, H. Haj-Salem and J. Blosseville, "ALINEA: A local feedback control law for on-ramp metering," *Transport. Res. Record*, vol. 1320, pp. 58-64, 1991.
- [6] T. Yoshino, T. Sasaki and T. Hasegawa, "The Traffic Control System on the Hanshin Expressway," *Interfaces Magazine*, Jan/Feb 1995.
- [7] P. Varaiya and A. A. Kurzhanskiy, "Active Traffic Management".
- [8] "Development of Highway Capacity Manual Methodologies To Assess Advanced Traffic Management Strategies That Influence Traffic Demand," Dowling Associates Inc, 2009.
- [9] F. H. Administration, "Active Transportation and Demand Management-Active Traffic Management," [Online]. Available: <http://www.ops.fhwa.dot.gov/publications/fhwahop13003/fhwahop13003.pdf>.
- [10] R. Dowling, G. Karkee, V. Kiattikomol and S. Ashiabor, "HCM ATDM Work-Zone and Incident Capacity Reduction Models," Dowling Associates Inc..
- [11] "DTALite Website," [Online]. Available: <https://sites.google.com/site/dtalite/>. [Accessed 15 October 2013].

- [12] "DYNASMART-P," MCTrans Center, [Online]. Available: <http://mctrans.ce.ufl.edu/featured/dynasmart/>. [Accessed 31 July 2015].
- [13] "PTV Group website," [Online]. Available: <http://vision-traffic.ptvgroup.com/en-uk/products/ptv-vissim/functions/>. [Accessed 15 Oct 2013].
- [14] PTV Group, "What keeps traffic flowing?," [Online]. Available: [http://vision-traffic.ptvgroup.com/fileadmin/files\\_ptvvision/Downloads\\_N/0\\_General/2\\_Products/2\\_PTV\\_V\\_Vissim/EN-UK\\_PTV\\_Vissim\\_Brochure.pdf](http://vision-traffic.ptvgroup.com/fileadmin/files_ptvvision/Downloads_N/0_General/2_Products/2_PTV_V_Vissim/EN-UK_PTV_Vissim_Brochure.pdf). [Accessed 15 October 2013].
- [15] "AIMSUN 5.1 Microsimulator User's Manual Version 5.1," TSS-Transport Simulation Systems, 2008.
- [16] "TSIS User Guide, McTrans," University of Florida, 2011.
- [17] "CORSIM User Guide, McTrans," University of Florida, 2011.
- [18] S. Cohen, "Using the hard shoulder and narrowig lanes to reduce congestion. Some lessons from an experience on the Paris Motorway network," in *12th IEE conferance on Road transport Information and Control* , London,UK, 2004.
- [19] M. Aron, R. Seidowsky and S. Cohen, "Safety impact of using the hard shoulder during congested traffic. The case of a managed lane operation on a french urban motorway," *Transportation Research* , vol. Part C, pp. 168-180, 2010.
- [20] A. Pilz and G. Riegelhuth, "Temporary Hard Shoulder Use in Hessen: Experiences and Strategic Planning, Technical Session 3.3: ERP achievements," 2007. [Online]. Available: [http:// www.i2tern.info/doks/paper/paper92.pdf](http://www.i2tern.info/doks/paper/paper92.pdf).
- [21] K. Lemke, "Hard Shoulder Running as a Short-Term Measure to Reduce Congestion," 4th International Symposium on Highway Geometric Design, Bergisch Gladbach, Germany, 2010.
- [22] K. Tlemke and M. Irzik, "Temporary Use of Hard Shoulders-Experiences and Economic Assessment," Federal Highway Research Institute, Traffic Planning, Highway Design, and Safety Analyses Section, Bergisch Gladbach, Germany, 2006.
- [23] G. Kellermann, "Experience of using hard shoulder to improve traffic flow.," *Traffic Engineering and Control*, no. 41, pp. 412-414, 2000.

- [24] P. Chase and E. Avineri, "Maximizing motorway capacity through hard shoulder running : UK perspective," *The Open Transportation Journal*, pp. 7-18, 2008.
- [25] D. F. T. Highway Agency, "M42 Active Traffic management Results- First Six Months," Highway Agency Department of Transport, London, England, 2007.
- [26] "4-lane Variable Mandatory Speed Limits - 12 Month Report," Highways Agency, Department for Transport , London, England, 2008.
- [27] [Online]. Available: <http://www.roadtraffic-technology.com/projects/m42/>.
- [28] B. Helleman, "Hard Shoulder Running (HSR) in The Netherlands," Ministry of Transport, Public Works, and Water Management, Directorate-General of Public Workds and Water Managemen, Rotterdam, The Netherlands, 2006.
- [29] F. Middelham, "Dynamic Traffic Management," AVV Transport Research Center, Ministry of Transport, Public Works, and Water Management, Rotterdam, The Netherlands, 2006.
- [30] F. Middelham, "State of practice in dynamic traffic management in the Netherlands," in *Control in Transportation Systems*, ELSEVIER, 2003.
- [31] D. Ungemah and B. Kuhn, "Special use of shoulders for Managed Lanes: review of practice and research," Texas Transportation Institute, 2009.
- [32] J. Lee, R. Dittberner and H. Sripathi, "Safety Impacts of Freeway Managed-Lane Strategy: Inside Lane for High-Occupancy Vehicle Use and Right Shoulder Lane as Travel Lane During Peak Periods," *Transportation Research Record*, 2012.
- [33] M. Swires and e. al., "US 2 - Hard Shoulder Running Case STudy," Washington State Department of Transportation, Washington, 2009.
- [34] A. May, "Experimentation with manual and automatic ramp control," *Highway research record* 59, 1964.
- [35] M. Papageorgiou and L. Papamichail, Handbook of Ramp metering, 2007.
- [36] M. papageorgiou, "freeway ramp metering: an overview," *IEEE Transaction on intelligent transportation systems*, vol. 3, no. 8, pp. 271-281, 2001.

- [37] M. Papageorgiou, "freeway ramp metering: an overview," *IEEE Transaction on intelligent transportation systems*, vol. 3, no. 8, pp. 271-281, 2002.
- [38] M. Papageorgiou, H. Hadj-Salam and F. Middelham, "ALINEA local ramp metering-summary of field results," *Transportation Research Record*, no. 1603, pp. 90-98, 1997.
- [39] E. Camacho and C. Bordons, *Model predictive control*, London: Springer, 2004.
- [40] A. Hegyi, B. Schutter and H. Hellendoorn, "Model predictive control for optimal coordination of ramp metering and variable speed limits," *Transport.Res.C*, vol. 13, pp. 185-209, 2005.
- [41] G. Piotrowicz and J. Robinson, "Ramp metering status in North America," FHWA, 1995.
- [42] I. Cambridge Systematics, "Twin Cities Ramp Meter Evaluation," Cambridge Systematics, Inc, Oakland, California, 2001.
- [43] L. Jacobsen, K. Henry and O. Mahyar, "Real-time metering algorithm for centralized control," *Transportation Research Record*, vol. 1232, 1989.
- [44] A. D. May and K. Bogenberger, "Advanced Coordinated Traffic Responsive Ramp Metering Strategies," CALIFORNIA PATH PROGRAM, INSTITUTE OF TRANSPORTATION STUDIES, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIFORNIA, 1999.
- [45] T. Mathwork, "Fuzzy Logic Toolbox User's Guide," 2006.
- [46] C. Taylor and D. Meldrum, "Evaluation of A Fuzzy ramp metering algorithm: Comparative study between three ramp metering algorithms used in the greater Seattle area," Washington State Transportation Center (TRAC), Seattle, Washington, 2000.
- [47] H. Taale, J. Rosloot and J. Slager, "The Assessment of Ramp Metering Based on Fuzzy Logic," in *3rd ITS World Congress*, Orlando, 1996.
- [48] "NCHRP Project 03-114: Planning and Evaluating Active Traffic Management Strategies," Texas A&M Transportation Institute & Kimley-Horn and Associates, Inc., 2014.



- [49] K. Henry and O. Mehyar, "Six-Year FLOW Evaluation," Washington State Department of Transportation, District 1, 1989.
- [50] Cambridge systematics, Inc, "Mn/DOT Ramp Meter Evaluation," Minnesota Department of Transportation, 2002.
- [51] A. Gan and W. Wu, "Evaluation of Average Speeds and Travel Times Before and After Ramp Signaling I-95 in Miami-Dade County," District Six Florida Department of Transportation, 2009.
- [52] A. Gan and W. Wu, "Evaluation of Average Speeds and Travel Times Before and After Ramp Signaling on Southbound I-95 in Miami-Dade County," District Six Florida Department of Transportation, 2010.
- [53] E. Arnold, "Ramp Metering: A Review of the Literature," Virginia Transportation Research Council, 1998.
- [54] L. Jacobson, J. Stribiak, L. Nelson and D. Sallman, "Ramp Management and Control Handbook," FHWA-HOP-06-001, US Department of Transportation, Federal Highway Administration, 2006.
- [55] P. Bonsall, "Research methods for the study of driver response to in-vehicle and roadside guidance-methods," in *Sixth World Conference on Trsansport Research*, Lyon, France, 1992.
- [56] MV2, "Evaluation de la politigue d'affichage sur les panneaux a message variable," Direction Regionale de l'Equipment, 1997.
- [57] J. Swann, I. Routledge, J. Parker and S. Tarry , "Results of practical applications of variable message signs (VMS): A64/A1 accident reduction scheme and Fourth estuary Driver Information and Control System (FEDICS)," *Traffic Management and Road Safety*, pp. 149-167, 1995.
- [58] S. Tarry and A. Graham, "The role of evaluation in ATT developement.," *Traffic Engineering and Control*, vol. 12, no. 36, pp. 688-693, 1995.
- [59] M. Cummings, "Electronic signs strategies and their benefits.," in *Seventh International Conference on Road Traffic Monitoring and Control*, London, UK, 1994.

- [60] F. Davidsson and N. Taylor, "ITS modelling in Sweden using CONTRAM.," TRL Report, 2003.
- [61] N. T. Rarrout and Y. F. Issa, "Effectiveness of newly introduced variable message signs in Al-Khobar, Saudi Arabia," *Traffic & Transportation*, vol. 26, no. 2, pp. 169-177, 2014.
- [62] D. Deeter, "Impacts of Traveler Information on the Overall Network," ENTERPRISE Pooled Fund Study TPF-5(231), Michigan DOT, Lansing, MI, 2012.
- [63] A. Haghani, M. Hamed, R. Fish and A. Nouruzi, "Evaluation of Dynamic Message Signs and Their Potential Impact on Traffic Flow," University of Maryland, Baltimore, MD, 2013.
- [64] M. Presley and K. Wyrosdick, "Calculating Benefits for Navigator, Georgia's Intelligent Transportation System," Georgia Department of Transportation, Atlanta, GA, 1998.
- [65] A. Skabardonis, H. Noeimi, K. Petty, D. Rydzewski, P. Varaiya and H. Al-Deek, "Freeway Service Patrol Evaluation," California PATH Program Institute of Transportation Studies, University of California, Berkeley, CA, 1995.
- [66] P. Cuiciti and B. Janson, "Incident Management via Courtesy Patrol: Evaluation of Pilot Program in Colorado," *Transportation Research Record*, no. 1494, 1995.
- [67] P. Hawkins, "Evaluation of the Southwest Freeway Motorist Assistant Program in Houston," Texas Transportation Institute, College Station, TX, 1993.
- [68] "Highway Helper Summary Report - Twin Cities Metro Area," Minnesota Department of Transportation, 1994.
- [69] A. Khattak, N. Roupail and K. Monast, "A Method for Prioritizing and Expanding Freeway Service Patrols," in *Transportation Research Board 83rd Annual Meeting*, Washington, D.C., 2004.
- [70] J. Nee and M. Hallenbeck, "Evaluation of the Service Patrol Program in the Puget Sound Region," Washington State Transportation Commission, 2001.
- [71] R. Henk, R. Molina and P. Inwin, "Before-and-After Analysis of the San Antonio TransGuide System," in *The 76th Annual Meeting of the Transportation Research Board*, Washington, DC, 1997.

- [72] A. Petrov, P. Lin, N. Zou and G. Chang, "Evaluation of the Benefits of a Real-Time Incident Response System," in *The 9th World Congress Conference on ITS*, Chicago, Illinois, 2002.
- [73] L. Dougald and M. Demetsky, "Assessing Return on Investment of Freeway Safety Service Patrol Programs," *Transportation Research Record: Journal of the Transportation Research Board*, no. 2047, pp. 19-27, 2008.
- [74] L. E. Dougald, "A Return on Investment Study of the Hampton Roads Safety Service Patrol Program," Virginia Transportation Research Council, Charlottesville, VA, 2007.
- [75] J. L. Carson, "Traffic Incident Management Resource Management," Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 2009.
- [76] J. Zegeer, J. Bonneson, R. Dowling, P. Ryus, M. Vandehey, W. Kittelson, N. Roupail, B. Schroeder, A. Hajbabaie, B. Aghdashi, T. Chase, S. Sajjadi, R. Margiotta and L. Elefteriadou, "Incorporating Travel Time Reliability into the Highway Capacity Manual," SHRP 2 Reliability Project L08, 2013.
- [77] "NCHRP 03-107:Work Zone Capacity Methods for the Highway Capacity Manual," Kittelson & Associates, 2015.
- [78] Highway Capacity Manual, Washington, DC: Transportation Research Board, 2010.
- [79] C. F. Daganzo, "The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory," *Transportation Research Part B: Methodological*, vol. 28, no. 4, pp. 269-287, 1994.
- [80] C. F. Daganzo, "The cell transmission model, part II: network traffic," *Transportation Research Part B: Methodological*, vol. 29, no. 2, pp. 79-93, 1995.
- [81] A. May, Traffic Flow Fundamentals, Englewood, New jersey: Prentice-Hall, inc. A Division of Simon & Schuster, 1990.
- [82] N. Roupail, B. Aghdashi, K. Ko, M. Hadi and S. Khazraeian, "Flow Allocation at Congested Ramp Merges," in *Transportation Research Board Annual Meeting*, Washington DC, 2015.

- [83] Kittelson & Associates Inc., "Understanding the Contributions of Operations, Technology, and Design to Meeting Highway Capacity Needs," SHRP2 Project C05. Transportation Research Board of the National Academies, Washington DC, 2010.
- [84] N. Metz, H. Schlichter and H. Schellenberg, "Positive effects of a traffic control system on fuel consumption and exhaust emissions on the German A9 Autobahn," *Int.J.of Vehicle Design* 18, pp. 354-367, 1997.
- [85] H. Lenz and R. Sollacher, "Nonlinear speed-control for continuum theory of traffic flow," in *14th world congress of IFAC* , Beijing, China, 1999.
- [86] L. Elefteriadou , C. Letter and E. Mintsis, "Managed Lane Operation-Adjusted Time of Day Pricing vs. Near-Real Time Dynamic Pricing, Volume II:Ramp Signaling and Variable Speed Limits (VSL)," Transportation Research Center, University of Florida, 2012.
- [87] B. Harbord and J. Jones, "Camera Enforcement of Traffic Regulations," *IEE Colloquium*, vol. 18, pp. 51-54, 1996.
- [88] FHWA, "Efficient use of highway capacity summary report to congress," FHWA, 2008.
- [89] J. Sparmann, "Freeway operation in Germany: Experiences in Hessen," Hessian Ministry of Economy and Transport, Athens, Greece, 2006.
- [90] A. Hegyi, B. Schutter and J. Hellendoorn, "MPC-based Optimal Coordination of Variable Speed Limits to Suppress Shock Waves in Freeway," in *American Control Conference* , Denver, Colorado, 2003.
- [91] P. Lin, K. Kang and G. Chang, "Exploring Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operation," *Intelligent Transportation Systems*, vol. 8, pp. 1-14, 2004.
- [92] M. Abdel-Aty and A. Dhindsa, "Coordinated Use of Variable Speed Limits and Ramp Metering for Improving Traffic Safety on Congested Freeways," in *Transportation Research Board 86nd Annual Meeting*, Washington, D.C., 2007.
- [93] M. Papageorgiou, E. Kosmatopoulos and I. Papamichail, "Effect of Variable Speed Limits on Motorway Traffic Flow," *Transportation Research Record*, no. 2047, pp. 37-48, 2008.

- [94] A. Ghods, A. Rahimi Kian and M. Tabibi, "Adaptive Freeway Ramp Metering and Variable Speed Limit Control: A Genetic Fuzzy Approach," *IEEE Intelligent Transportation Systems Magazine*, pp. 27-36, 2009.
- [95] R. Carlson, M. Papamichail and M. Papageorgiou, "Variable Speed Limits as a Mainline Metering Device for Freeways," in *Transportation Research Board Annual Meeting*, Washington, D.C., 2010.
- [96] J. Paio and M. McDonald, "Safety Impacts of Variable Speed Limits-A Simulation Study," in *11th International IEEE*, 2008.
- [97] P. Allaby, B. Hellinga and M. Bullock, "Variable Speed Limits: safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications," *IEEE Transaction on Intelligent Transportation System*, vol. 8, no. 4, pp. 671-680, 2007.
- [98] S. Travis Waller, N. ManWo, E. Ferguson, N. Nezamuddin and D. Sun, "Speed Harmonization and Peak-period Shoulder Use to Manage Urban Freeway Congestion," Texas A&M University-Kingsville, FHWA/TX-10/0-5913-1, 2009.
- [99] P. Allaby, B. Hellinga and M. Bullock, "Variable Speed Limits: Safety and operational impacts of a Candidate Control Strategy for Freeway Application," *IEEE Transactions on Intelligent Transportation Systems*, vol. 4, no. 8, pp. 671-680, 2007.
- [100] A. Ghods, A. Rahimi Kian and M. Tabibi, "Adaptive freeway ramp metering and variable speed limit control:A Genetic - Fuzzy approach," *IEEE INTELLIGENT TRANSPORTATION SYSTEMS MAGAZINE*, pp. 27-36, 2009.
- [101] K. Chatterjee, N. Hounsell, N. Firmin and P. Bonsall, "Driver response to variable message sign information in London," *Transportation Research Part C*, vol. 10, no. 2, pp. 149-169, 2002.
- [102] "Evaluation of A Fuzzy ramp metering algorithm: Comparative study between three ramp metering algorithms used in the greater Seattle area".
- [103] FHWA, "Ramp Metering Presentation," FHWA, [Online]. Available: <http://www.ops.fhwa.dot.gov/bn/resources/rampmetering.htm>.
- [104] B. J. Schroeder, N. M. Roupail and S. Aghdashi, "Deterministic Framework and Methodology for Evaluating Travel Time Reliability on Freeway Facilities,"

*Transportation Research Record: Journal of the Transportation Research Board*, vol. 2396, no. 1, pp. 61-70, 2013.

- [105] W. Kittelson and M. Vendehey, "SHRP 2 – L08: Incorporation of Travel Time Reliability into the HCM," The Strategic Highway Research Program 2, Transportation Research Board of The National Academies, Portland, Oregon, 2013.
- [106] R. G. Dowling, "Final Report: Development of Highway Capacity Manual Methodologies To Assess Advanced Traffic Management Strategies That Influence Traffic Demand," Dowling and Associates, 2011.
- [107] "MAP 21," [Online]. Available: <https://www.fhwa.dot.gov/map21/>.

## APPENDIX A

Both Fuzzy and ALINEA controllers have been implemented in FREEVAL environment. This appendix focuses on the Fuzzy logic implementation in the HCM content. The implemented Fuzzy ramp metering in FREEVAL is based on the I-95 ramp metering deployment.

### OVERVIEW OF CURRENT I-95 FUZZY RAMP METERING MODEL

In February, 2009 the Florida Department of Transportation (FDOT) installed a ramp metering system on I-95 in Miami, FL. Eight meters were installed in the northbound direction from NW 62 Street to NW 2 Ave. In April, 2010 two more ramp meters were installed in the northbound direction, along with twelve new ramp meters in the southbound direction from Ives Dairy Rd to NW 62 Street. The northbound ramp meter system operates in the afternoon peak period from approximately 3:30 pm to 7:00 pm. All ramps employ a fuzzy logic metering algorithm that is based on an algorithm originally developed for ramp metering implementation in Washington State.

#### Fuzzy Controller Inputs

In the I-95 fuzzy ramp metering system, detector information is relayed every 20 seconds to a fuzzy logic controller for each metered ramp. This information is processed by the controller and serves as an input to the fuzzy logic algorithm. The metering rate is updated every 20 seconds using 1-minute averages of the previous three samples. The inputs to the metering algorithm and the detector associations are shown in Table A-1.

**TABLE A-1 Fuzzy Logic Ramp Metering Algorithm Inputs.**

Input	Detector Location
Local Occupancy	Just upstream of merge location
Local Speed	Just upstream of merge location
Downstream Occupancy	Downstream of merge location
Downstream Speed	Downstream of merge location
Queue Occupancy	Queue detector on the ramp near ramp signal
Advanced Queue Occupancy	Queue detector the end of on ramp

## Fuzzy Controller Steps

### Fuzzification

In this step each input is converted to a set of fuzzy values which are between 0 and 1. The user can define different fuzzy classes for each input. For example Local occupancy has five classes “VS”, “S”, “M”, “B” and “VB” which are very small, small, medium, big and very big respectively. In order to convert the input values to a fuzzy value we need a function that receives the input and generate the degree of its membership to each one of the classes (‘VS’, ‘M’, ‘B’ and etc). This function is called the input membership function. Triangular membership functions are used in the I-95 Fuzzy ramp metering model. Figure A-1 shows the default membership functions for the local occupancy, downstream occupancy, local and downstream speed, respectively. Figure A-2 shows the membership functions for the output which is ramp metering rate. The unit for ramp metering rate is vehicles per minute (VPM). Each ramp has a specific set of metering rate fuzzy classes. These differ slightly by the ranges of the fuzzy thresholds.

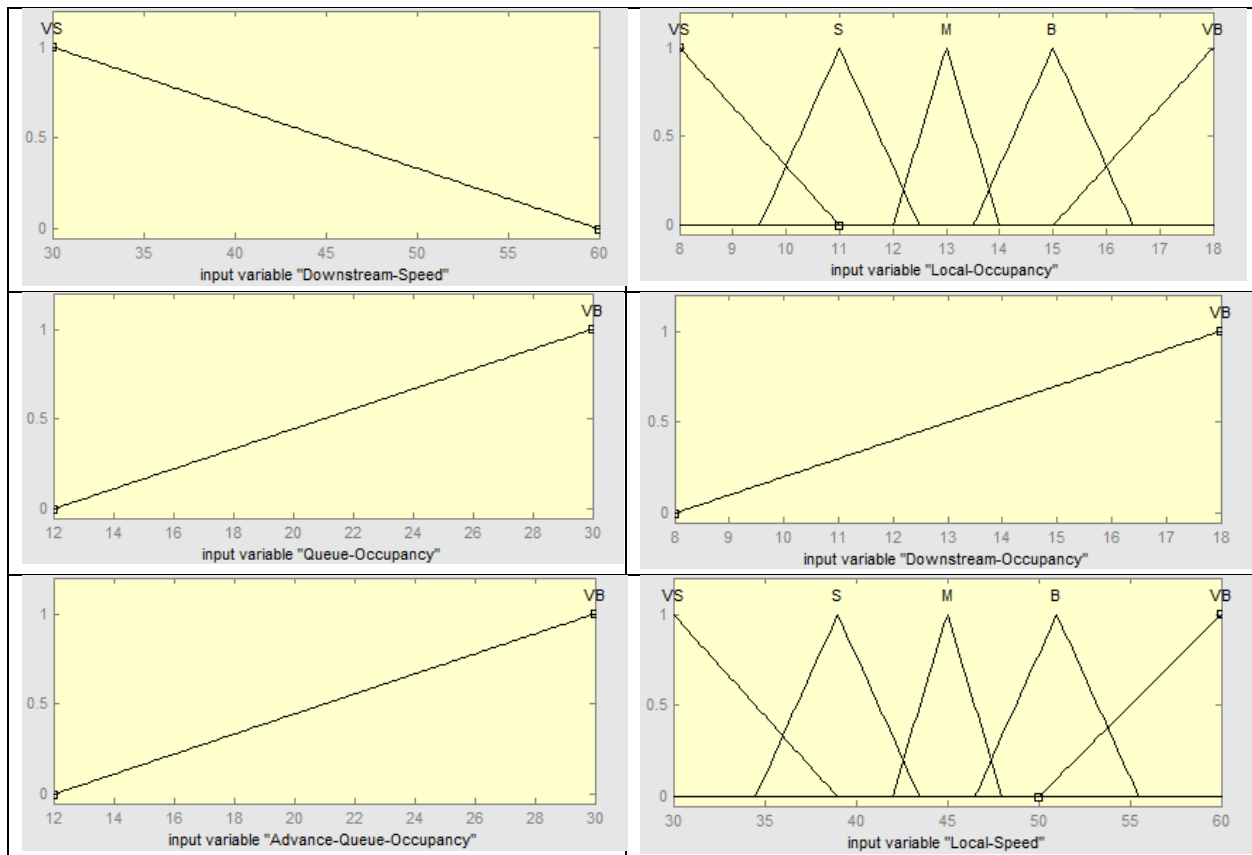
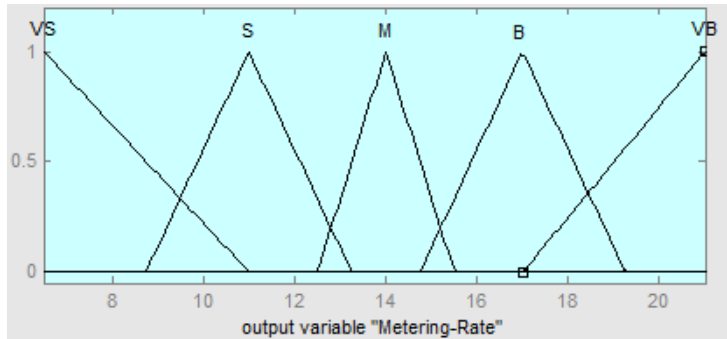


FIGURE A-1 Fuzzy Controller inputs membership functions.





**FIGURE A-2 Membership functions for Metering Rate.**

**Rule Evaluation**

In this step, the controller determines to which extent each of the rules is to be applied. The rules are “if-then” statements that control the system. The set of fuzzy rules is shown Table 2.

**TABLE A-2 I-95 Fuzzy Logic Rules**

Rule Number	Rule weight	Rule premise	Rule outcome
1	2.5	If local occupancy is VB	Metering Rate is VS
2	1	If local occupancy is B	Metering Rate is S
3	1	If local occupancy is M	Metering Rate is M
4	1	If local occupancy is S	Metering Rate is B
5	1	If local occupancy is VS	Metering Rate is VB
6	3	If local speed is VS AND local occupancy is VB	Metering Rate is VS
7	1	If local speed is S	Metering Rate is S
8	1	If local speed is B	Metering Rate is B
9	1	If local speed is VB AND local occupancy is VS	Metering Rate is VB
10	4	If downstream speed is VS AND downstream occupancy is VB	Metering Rate is VS
11	2	If queue occupancy is VB	Metering Rate is VB
12	4	If advance queue occupancy is VB	Metering Rate is VB

As it can be seen from Table A-2 each rule has a weight which shows the importance of the rule. All the rules are evaluated for every set of the inputs. Each rule has an outcome which is equal to rule premise's degree of activation. If there is "AND" between premise's statements, the premise's degree of activation is the minimum of the degree of memberships.

After determining the rule activation degree, the area of membership function below the activation degree should be multiplied by the center of this surface. This multiplication is the rule outcome. For all of the rules, their outcomes are averaged and the final result is the output of the controller. After this step the final output is defuzzified. The defuzzification is described in the following section.

### **Defuzzification**

Defuzzification is the process of averaging the outcome of the rules to find the final output of the controller. The output metering rate is determined by converting the set of metering rate fuzzy variables to a single quantitative metering rate. The output metering rate can be calculated by using the following equation:

$$\text{Metering Rate} = \frac{W_i C_i I_i}{W_i I_i}$$

where,

$W_i$ : Weight of ith rule

$C_i$ : Centroid of the output class

$I_i$ : The implicated area of the output class

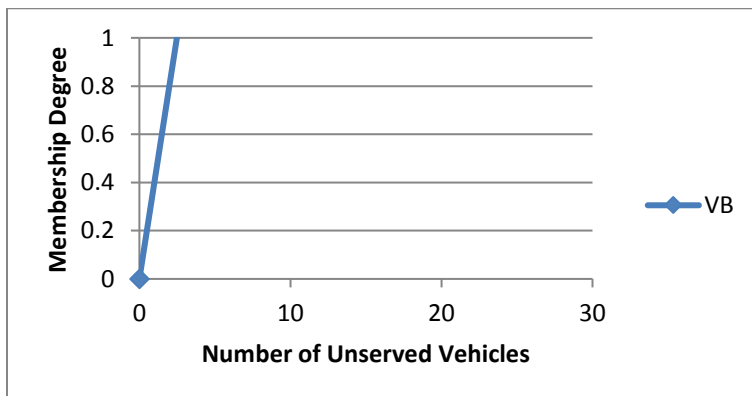
## FUZZY LOGIC IMPLEMENTATION IN FREEVAL

A modified version of Miami’s I-95 fuzzy ramp metering model was implemented in the FREEVAL environment. Since the FREEVAL model does not report on-ramp density and speed values, two of the inputs to the fuzzy controller (queue occupancy and advance queue occupancy) are not available. The only output related to the on-ramp is number of unserved vehicles in each 15 second interval. Thus, rule numbers 11 and 12 were combined and a new rule was utilized to consider on-ramp performance, as shown in Table A-3. Finally, a total of 11 rules was included in the fuzzy algorithm to be implemented in FREEVAL model.

**Table A-3 Rule modification to be implemented in FREEVAL-DSS**

Rule Number	Rule weight	Rule premise	Rule outcome
11	5	If number of on-ramp unserved vehicles is VB	Metering Rate is VB

Figure A-4 shows the proposed membership function for on-ramp unserved vehicles. As it can be seen from the figure, the maximum number of unserved vehicles is 30 vehicles. This value varies with the on-ramp length and can be easily calculated by dividing the on-ramp length by the average distance headway in the queue, which is assumed to be 20 feet in this study.



**FIGURE A-3 Membership function for number of on-ramp unserved vehicles**

After the fuzzy algorithm implementation in FREEVAL-DSS, an adaptive fuzzy ramp metering tool box was created in FREEVAL. The adaptive ramp metering tool box enables the user to change the default fuzzy parameters (shown in Table A-4) based on local conditions. Different schemes with different fuzzy parameters can be defined for each on ramp.

Table A-4 Default Fuzzy algorithm parameters implemented in the FREEVAL-DSS tool

Number	Variable	Default Value (based on Miami I-95 ramp controllers)
1	L_v	20
2	L_d	6
3	Output_VS_center_threshold	12.125
4	Output_VS_upper_threshold	14.75
5	Output_S_lower_threshold	13.438
6	Output_S_upper_threshold	16.063
7	Output_M_lower_threshold	15.625
8	Output_M_upper_threshold	17.375
9	Output_B_lower_threshold	16.938
10	Output_B_upper_threshold	19.563
11	Output_VB_lower_threshold	18.25
12	Output_VB_center_threshold	20.875
13	Up_OCC_VS_center_threshold	8
14	Up_OCC_VS_upper_threshold	11
15	Up_OCC_S_lower_threshold	9.5
16	Up_OCC_S_upper_threshold	12.5
17	Up_OCC_M_lower_threshold	12
18	Up_OCC_M_upper_threshold	14
19	Up_OCC_B_lower_threshold	13.5
20	Up_OCC_B_upper_threshold	16.5
21	Up_OCC_VB_lower_threshold	15
22	Up_OCC_VB_center_threshold	18
23	Down_OCC_VB_lower_threshold	8
24	Down_OCC_VB_center_threshold	18
25	Up_SPD_VS_center_threshold	30
26	Up_SPD_VS_upper_threshold	39
27	Up_SPD_S_lower_threshold	34.5
28	Up_SPD_S_upper_threshold	43.5
29	Up_SPD_M_lower_threshold	42
30	Up_SPD_M_upper_threshold	48
31	Up_SPD_B_lower_threshold	46.5
32	Up_SPD_B_upper_threshold	55.5
33	Up_SPD_VB_lower_threshold	51

34	Up_SPD_VB_center_threshold	60
35	Down_SPD_VS_center_threshold	30
36	Down_SPD_VS_upper_threshold	60
37	Min_queue_lenght	0
38	Max_queue_lenght	150
39	RW_ramp_queue	2

The default parameters for the ALINEA controller are shown in Table A-5.

Table A-5 Default ALINEA algorithm parameters implemented in the FREEVAL-DSS tool

Parameter	Default Value
Regulator parameter(veh/step)	40
Target density (pc/mi/ln)	42
Minumum Ramp Metering rate (vph)	240
Maximum Ramp Metering Rate (vph)	2100

## APPENDIX B

This appendix provides users with the hyperlink to the FREEVAL-DSS user's guide.

[https://www.youtube.com/watch?v=NpSt\\_rVq1-A](https://www.youtube.com/watch?v=NpSt_rVq1-A)

Further information regarding the installation of FREEVAL-DSS tool are provided in the following link:

[https://www.youtube.com/watch?v=jarNeS\\_yaak](https://www.youtube.com/watch?v=jarNeS_yaak)