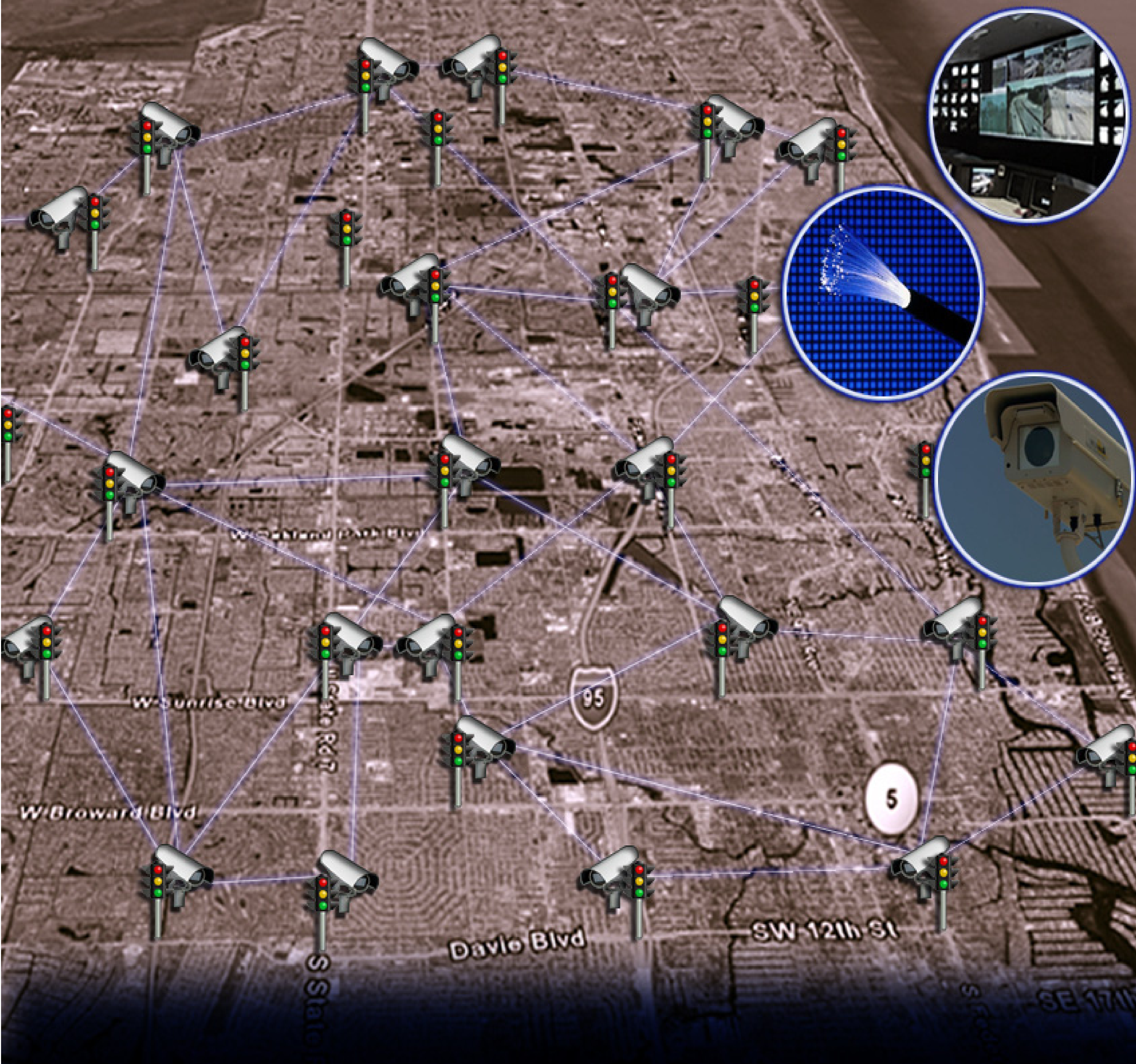



# Impact of Communication/Detection Degradation on Advanced Traffic Management Systems Operations

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

USF UNIVERSITY OF SOUTH FLORIDA

CUTR

# Impact of Communication/Detection Degradation on Advanced Traffic Management Systems Operations

## Final Report

Prepared for

**Florida Department of Transportation**
**Procurement Office**
**605 Suwannee Street, MS 20**
**Tallahassee FL 32399-0450**

Prepared by

**Pei-Sung Lin, Ph.D., P.E., PTOE**
**Aldo Fabregas**
**Hongyun Chen**
**Sachin Rai**

**Center for Urban Transportation Research (CUTR)**
**University of South Florida**
**4202 E. Fowler Ave. CUT100**
**Tampa, Florida 33620-5375**

With Assistance from

**Control Technologies & Cardno TBE**

July 2009

# DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

# ACKNOWLEDGEMENTS

Many people contributed to this research project both technically and spiritually; this final report could not be completed without their assistance and support. The authors would like to express our gratitude to the FDOT project manager, Mr. Carl Morse, and the former project manager, Mr. Liang Hsia, as well as FDOT project panels for their full support and coordination of this project. We would like to especially thank Mr. Mark Plass, District Traffic Operations Engineer, FDOT District 4, for his time and valuable technical input and comments on each technical report. Thanks to Ms. Patti Brannon and Ms. Sandra Bell of FDOT for providing needed assistance on the project contract, budget, and reporting matters. Thanks to Ms. Melissa Ackert Transportation System Management & Operations Manager, FDOT District 4, for her technical review and support in disseminating the project results.

The CUTR project team also would like to thank Mr. Gene Riggs, Mr. Efrain Duque, Mr. Fred Bibber, Mr. Phuoc Hoang, Mr. Mark Richmond, Ms. Harrison, and Mr. Nick Cliff of Sarasota County; Mr. David Hegel of the City of Sarasota, Mr. Jihad El Eid, Mr. Henk Koornstra, Mr. Scott Brunner, and Mr. John Kleinedler of Broward County; Mr. Kenneth Jacobs and Mr. Glenn Weaver of Pinellas County; Mr. Peter Brett of Hillsborough County; Mr. Robert Reck of Pasco County; Mr. Giri Jeedigunta from Palm Beach County; and Don Fullerton from the City of Jacksonville for their time and input during detailed traffic agency interviews and/or traffic data sharing for this research project.

Our subconsultants, Mr. Mike Day and Mr. Mike Travers with Control Technologies and Mr. Mark Modjeski and Mr. David Allen with Cardno TBE, who provided their expertise and experience on traffic signal operations and signal system equipment, are greatly appreciated for their technical reports, which contributed to this final report.

Finally, we would like to thank the transportation professionals and their agencies in Florida listed on the next page for their active participation in the traffic agency survey, which provided a valuable assessment of current traffic signal operations and maintenance practices in Florida and useful information and recommendations for this research project.

| Name | Title | Agency |
| --- | --- | --- |
| Denis Dietz | Traffic Operations Supervisor | Lake County Board of County Commissioners |
| Keith Pittman | Traffic Signal Supervisor | Polk County Traffic Engineering & Operations |
| Matthew Weisman | ITS Operations Engineer | City of Gainesville |
| John Ankeny | Traffic Signal Coordinator | Indian River County |
| Damian Bono | Traffic Signal Coordinator | Martin County Traffic Engineering |
| Wayne Little | Traffic Engineer II | City of Ocala |
| Ronnie Cotton | Public Works/Utilities Director | City of Haines City |
| Jon Cheney | Volusia County Traffic Engineer | Volusia County |
| Michael Mims | Foreman, Traffic Signals Signs and Markings | City of Panama City |
| Dennis Moxley | Engineering Program Manager | Traffic Operations - Escambia County |
| Mike Jammes | Division Coordinator | Clay County Public Works Traffic Division |
| Larry Turner | System Coordinator | City of Plant City |
| Michael L. Marcum | Traffic Division Administrator | City of Daytona Beach |
| William Pickard | Public Works Director | City of Bartow |
| John Kleinedler | Engineer III | Broward County Traffic Engineering |
| Kris McCoy | Traffic Systems Supervisor | Brevard County |
| Edward Albritton | Acting ITS Manger | Hillsborough County |
| Bill Foster | Traffic Signal Coordinator | City of St. Petersburg |
| Robert W. Reck | Traffic Operations Manager | Pasco County Traffic Operations Division |
| Red Childs, P.E. | Traffic Engineering Division Manager | Manatee County Transportation Management |
| David Hegel | Traffic Control Systems Analyst | City of Sarasota |
| Emmanuel Posadas | Traffic Operations Engineer | City of Boca Raton |
| Sheila Convery | Signal System Network Engineer | Collier County Traffic Operations |
| Paul Bertels | Traffic Operations Manager | City of Clearwater |
| Don Fullerton | Traffic Signal Engineer | City of Jacksonville |
| Robert Williams | Traffic Control Center Engineer | Miami-Dade Public Works |
| Reva White | Incident Management Specialist | Pinellas County Traffic Management |
| George Archibald | Staff Engineer | City of Naples |
| Alan C. Otley, P.E., CPM | City Signal Timing Engineer | City of Tallahassee Public Works, Traffic Engineering Division |
| Giri Jeedigunta, P.E. | Signal System Manager | Palm Beach County - Traffic Division |
| Robert W. Frank | Traffic Engineer | City of Fort Pierce |
| Christopher E. Kibler | Signal Systems Engineer | City of Orlando |
| Mike Scanlon | Traffic Design Engineer | City of Tampa – Public Works |
| Don Nix | Manager of Traffic Operations | City of Lakeland |

# Technical Report Documentation Page

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. | |
|---|---|---|---|
| 4. Title and Subtitle<br>Impact of Communication/Detection Degradation on Advanced Traffic Management Systems Operations | | 5. Report Date<br>July 2009<br>6. Performing Organization Code | |
| 7. Author(s)<br>Pei-Sung Lin, Aldo Fabregas, Hongyun Chen, Sachin Rai | | 8. Performing Organization Report No. | |
| 9. Performing Organization Name and Address<br>Center for Urban Transportation Research<br>4202 E. Fowler Avenue, CUT100<br>Tampa, FL 33620-57350 | | 10. Work Unit No.<br>11. Contract or Grant No.<br>BDH 29 | |
| 12. Sponsoring Agency Name and Address<br>Research Center<br>Florida Dept. of Transportation<br>605 Suwannee St. MS 30<br>Tallahassee, FL 32399-0450 | | 13. Type of Report and Period Covered<br>Draft Final Report<br>14. Sponsoring Agency Code | |
| 15. Supplementary Notes | | | |

16. Abstract

Substantial capital investment has been made by the Florida Department of Transportation (FDOT) and many local transportation agencies throughout the state in Advanced Traffic Management Systems (ATMS). This investment has not been consistently protected by effective maintenance, particularly in ATMS related communication, which facilitates traffic signal coordination, status reporting, etc., and detection, which directly impacts efficiency. It is important to recognize that robust communication and detection systems are keys to ensuring the benefits of ATMS.

The objective of this project is to understand and simulate the impact of communication and detection failure propagation through a typical ATMS architecture. This can lead to the development of more effective maintenance planning that targets cost-effective resources to critical portions of FDOT and local transportation agencies' advanced Traffic Management Systems communication and detection infrastructure.

The research team first performed a thorough literature review of major traffic signal system architectures and conducted a comprehensive traffic agency survey throughout Florida to understand the signal operations and maintenance practice. To effectively measure the performance of a traffic signal system itself, a practical signal system performance concept and measures were established. A traffic signal system degradation index and performance index were developed. Sensitivity analyses were performed through traffic simulations to assess the impact of communication and detection degradation as well as traffic signal timings on ATMS operations.

Based on analysis of a large amount of data obtained from the sensitivity analysis, traffic signal degradation and performance models were developed to assist traffic agencies to effectively assess the performance of their traffic signal systems. Furthermore, the research team and project contractors developed a set of improvement strategies that can be combined to provide a general overview of the most significant resource allocation strategies. A From-To matrix was developed to allow traffic agencies to select proper improvement actions based on their available resources. Finally, recommendations for operations and maintenance resource allocation strategies were provided. Future research direction was also recommended based on the results and findings of this project.

| 17. Key Word<br>ATMS, Detection, Communication, Signal, Degradation, Travel Time, Control Section, Index, Performance | | 18. Distribution Statement | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>159 | 22. Price |

# TABLE OF CONTENTS


**1. INTRODUCTION ..... 13**

**2. REVIEW OF SIGNAL SYSTEM ARCHITECTURES ..... 14**

2.1 COORDINATED SIGNAL SYSTEM ..... 14
2.1.1 Time-Based Coordination ..... 14
2.1.2 Interconnected Coordination ..... 15
2.2 TYPES OF SIGNAL SYSTEM ARCHITECTURES ..... 15
2.2.1 Time-Based System ..... 15
2.2.2 Centralized System ..... 15
2.2.3 Distributed System without Field Masters (Two-Level Distributed System) ..... 16
2.2.4 Distributed System with Field Masters (Three-Level Distributed System) ..... 17
2.3 PROS AND CONS OF DIFFERENT SIGNAL SYSTEM ARCHITECTURES ..... 18
2.3.1 Time-Based Systems ..... 18
2.3.2 Centralized Systems ..... 20
2.3.3 Distributed Systems without Local Masters ..... 21
2.3.4 Distributed Systems with Local Masters ..... 23

**3. SIGNAL OPERATIONS AND MAINTENANCE PRACTICES IN FLORIDA ..... 25**

3.1 DETECTION ..... 26
3.2 COMMUNICATION ..... 26
3.3 OBSERVATIONS FROM AGENCY SURVEY ..... 27
3.4 REMARKS ON SURVEY RESULTS ..... 28

**4. ESTABLISHMENT OF SIGNAL SYSTEM PERFORMANCE CONCEPT AND MEASURES ..... 29**

4.1 OBSERVED TRAFFIC SIGNAL SYSTEM PERFORMANCE ..... 30
4.2 RELATIONSHIP AMONG MAINTENANCE, PHYSICAL, AND OPERATIONAL SYSTEMS ..... 31
4.3 DEGRADATION OF TRAFFIC SIGNAL SYSTEM COMPONENTS ..... 32
4.4 TRAFFIC SIGNAL SYSTEMS DEGRADATION INDEX AND PERFORMANCE INDEX ..... 34
4.5 ANALYSIS OF TRAFFIC SIGNAL SYSTEMS ..... 36
4.6 EXISTING MEASURES OF SYSTEM PERFORMANCE ..... 37
4.6.1 Maintenance Performance Measures ..... 38
4.6.2 Operational System Performance Measures ..... 40
4.6.3 Functional Performance Measures ..... 41

**5. RELATIONSHIP AMONG SIGNAL SYSTEM ARCHITECTURES ..... 42**

**6. GENERIC TRAFFIC SIGNAL SYSTEM AND TEST SITES ........ 44**

6.1 ANALYSIS FOR DISTRIBUTED ARCHITECTURE WITH LOCAL MASTERS ........ 45
6.2 ANALYSIS FOR DISTRIBUTED ARCHITECTURE WITHOUT LOCAL MASTERS ........ 47
6.3 ANALYSIS FOR CENTRALIZED ARCHITECTURE ........ 47
6.4 TEST SITE MODELS ........ 49

**7. SENSITIVITY ANALYSIS OF SIGNAL SYSTEMS DUE TO DEGRADATION ........ 53**

7.1 DEGRADATION DUE TO DETECTION FAILURES ........ 53
7.1.1 Simulation Methodology ........ 53
7.1.2 Simulation Results and Sensitivity Ranges ........ 55
7.2 DEGRADATION DUE TO COMMUNICATION FAILURES ........ 61
7.2.1 Simulation Methodology ........ 61
7.2.2 Simulation Results and Sensitivity Ranges ........ 61
7.3 DEGRADATION DUE TO COMMUNICATION AND DETECTION FAILURES COMBINED ........ 65
7.4 DEGRADATION DUE TO CHANGE IN TRAFFIC PATTERNS ........ 67

**8. DEVELOPMENT OF SIGNAL SYSTEM PERFORMANCE ........ 71**

8.1 SYSTEM PERFORMANCE MODEL FOR DETECTION AND COMMUNICATION DEGRADATION ........ 71
8.1.1 Detection System Status ........ 71
8.1.2 Communication System Status ........ 72
8.1.3 Prevailing Conditions ........ 73
8.1.4 Performance Model for Detection ........ 73
8.1.5 Performance Model for Communication Degradation ........ 76
8.1.6 Performance Model for Communication and Detection Degradation ........ 77
8.2 SYSTEM PERFORMANCE MODEL FOR SIGNAL TIMING DEGRADATION ........ 81

**9. DEVELOPMENT OF RESOURCE ALLOCATION MODEL ........ 84**

9.1 RESOURCE ALLOCATION PERFORMANCE MODEL ........ 84
9.1.1 Overview of the Effect of Resource Allocation on System Performance ........ 84
9.1.2 Evaluation of Improvement Actions ........ 86
9.2 STRATEGIES TO IMPROVE DETECTION ........ 87
9.2.1 Upgrade Detection Technology ........ 87
9.2.2 Reduction in Detector Downtime by Improving Responsiveness of Contractors ........ 91
9.2.3 Increase the Detector Uptime by Providing Adequate Training and Procedures for Installation of Detectors ........ 93
9.3 ACTIONS TO IMPROVE COMMUNICATION ........ 95

9.3.1 Increase Responsiveness in Repair Time ........ 95
9.3.2 Increase Frequency of Inspection ........ 96
9.3.3 Install Time-of-Day Receivers (GPS clock) ........ 97
9.4 RECOMMENDATIONS FOR OPTIMAL ALLOCATION OF MAINTENANCE RESOURCES ........ 98
9.5 RESOURCE ALLOCATION MODEL ........ 99
9.6 RECOMMENDATIONS FOR OPERATIONS AND MAINTENANCE RESOURCE ALLOCATION STRATEGIES ........ 99
9.7 SHORT-TERM STRATEGIES TO IMPROVE DETECTION AND COMMUNICATIONS INFRASTRUCTURE PERFORMANCE ........ 101
9.7.1 Improvement of Detection Subsystem Performance ........ 100
9.8 IMPROVEMENT OF COMMUNICATIONS SYSTEMS PERFORMANCE ........ 105

**10. CONCLUSIONS AND RESEARCH RECOMMENDATIONS ........ 106**

10.1 CONCLUSIONS ........ 106
10.2 RESEARCH RECOMMENDATIONS ........ 108

**11. REFERENCES ........ 110**

**APPENDIX A ........ 111**

# LIST OF FIGURES

Figure 1 Schematic for a Centralized System ........ 16

Figure 2 Schematic for a Distributed System with Field Masters ........ 17

Figure 3 Ratings of Status of Traffic Signal System Components ........ 25

Figure 4 Basic Concept of Observed Traffic Signal System Performance ........ 30

Figure 5 Relationship among Maintenance, Physical, and Operational Systems ........ 32

Figure 6 Concept of Traffic Signal System Performance Considering Degradation of the Physical System and Traffic Signal Timing ........ 34

Figure 7 Degradation Index with Respect to Travel Time ........ 35

Figure 8 Highlighted Path of Research Project to Allocate Maintenance Resources to Improve Traffic Signal System Performance ........ 37

Figure 9 Relationships among System Architectures ........ 42

Figure 10 Adaptation of the HCM 2000 Urban Street Classification Criteria ........ 45

Figure 11 Selected Control Section on US 41 ........ 50

Figure 12 Selected Control Section on Fruitville Road ........ 51

Figure 13 Selected Control Section on W Broward Boulevard ........ 52

Figure 14 Standard NEMA Phasing for a Major Intersection ........ 54

Figure 15 Detection Failure Sensitivity Range on Fruitville Road Westbound during AM Peak Period ........ 56

Figure 16 Detection Failure on Fruitville Road Eastbound during AM Peak Period ........ 57

Figure 17 Detection Failures on Fruitville Road Westbound-Eastbound during PM Peak Hour ........ 58

Figure 18 Detection Failures in US 41 SB during the PM Peak Hour ........ 59

Figure 19 Communication Failures on Fruitville Road during AM Peak Period ........ 62

Figure 20 Communication Failure on US 41 during PM Peak Period ........ 62

Figure 21 Communication Failures on Fruitville Road during Midday Period ........ 63

Figure 22 Communication Failures on US 41 during Midday Period ........ 63

Figure 23 Communication and Detection Failure on US 41 at Midday ........ 65

Figure 24 Combined Communication and Detection Failures on Fruitville Road during AM and Midday Periods ........ 66

Figure 25 Degradation Due to Changes in Traffic Patterns ........ 68

Figure 26 Weighted Degradation Index for Degradation Due to Changes in Traffic Patterns ........ 70

Figure 27 Detection Status Variables Example ........ 72

Figure 28 Degradation Index vs. Percentage of Detector Failure on Side Street by Different Traffic Volumes (VPHPL) ........ 75

Figure 29 Degradation Index vs. Percentage of Detector Failure of Left-Turn Phases on Major Street by Different Traffic Volumes (VPHPL) ........ 75

Figure 30 Degradation Index vs. Communication Failure (Clock Drifting) by Traffic Volume (VPHPL) ........ 77

Figure 31 Degradation Index vs. Detection Failure by Different Volume for 10% Clock Drifting ........ 79

Figure 32 Degradation Index vs. Detection Failure by Different Volume for 20% Clock Drifting ........ 79

Figure 33 Degradation Index vs. Detection Failure by Different Volume for 30% Clock Drifting ........ 80

Figure 34 Degradation Index vs. Detection Failure by Different Volume for 40% Clock Drifting ........ 80

Figure 35 Degradation Index vs. Detection Failure by Different Volume for 50% Clock Drifting ..... 81

Figure 36 Increase in Travel Time with Respect to the Vehicles per Hour per Lane ..... 83

Figure 37 Predicted DI with Respect to Volume per Hour per Lane ..... 83

Figure 38 Effect of Improvement Actions in System Status ..... 85

Figure 39 Decomposition of Downtime of Traffic Signal Component ..... 86

Figure 40 Performance Measure for Evaluation of Improvement Actions ..... 87

Figure 41 Repair Time for Broken Detectors for Inductive Loop Detectors ..... 88

Figure 42 Repair Time for Broken Detectors for Video Detectors ..... 88

Figure 43 Repair Time for Broken Detectors for Microwave Detectors ..... 88

Figure 44 Total Increased Travel Time per Minute of Observed Travel Time during Detection Breakdowns ..... 90

Figure 45 Comparison Between the Different Types of Detection Technologies Under Equivalent Conditions ..... 91

Figure 46 Reduction in the Total Increased Time per Minute of Observed Travel Time for Improving the Responsiveness on Loop Repair Work ..... 92

Figure 47 Expected Improvements if Repair Works are Completed BetweenThree and Seven Days ..... 92

Figure 48 Effect of Training and Inspection in the Total Increased Travel Time by Detection Technology ..... 94

Figure 49 Effect of Response Time to Communication Failures ..... 96

Figure 50 Effect of Response Time to Communication Failures in the Total Increased Travel Time ..... 97

# LIST OF TABLES


Table 1 Suggested Actions to Improve Traffic Signal System Performance .......................... 27

Table 2 Summary of the Relationship among Architectures ................................................ 43

Table 3 Classification of Agencies by Size ........................................................................ 44

Table 4 Classification of Urban Streets by Signal Density (HCM, 2000) .............................. 44

Table 5 Adaptation of the HCM 2000 Urban Street Classification Criteria ............................ 45

Table 6 Control Section Analysis for Distributed Architecture with Local Masters ............... 46

Table 7 Control Section Analysis for Distributed Architecture without Local Masters .......... 47

Table 8 Control Section Analysis for Centralized Architecture ............................................ 49

Table 9 Sensitivity Ranges for Degradation Index for Detection Failures in Fruitville Road Test Case ........................................................................ 60

Table 10 Sensitivity Ranges for Degradation Index for Detection Failures in US 41 Test Case ...................................................................................... 60

Table 11 Sensitivity Ranges for Degradation Index for Communication Failures in Fruitville Road Test Cases ...................................................................... 64

Table 12 Sensitivity Ranges for Degradation Index for Communication Failures in US 41 Test Cases .................................................................................... 64

Table 13 Sensitivity Ranges for Degradation Index for Combined Failures in Fruitville Road Test Cases ...................................................................... 67

Table 14 Sensitivity Ranges for Degradation Index for Combined Failures in US 41 Test Cases .................................................................................... 67

Table 15 Performance Model for Detection ...................................................................... 73

Table 16 Performance Model for Communication ... 76

Table 17 Performance Model for Detection and Communication ... 77

Table 18 Model for Predicting the Change in Travel Time Based on Traffic Growth ... 81

Table 19 Degradation Index for Detection Technologies Based on Agency Survey Information ... 89

Table 20 Percentage of Reduction on Increased Travel Time Due to Detection Failures Using Non-intrusive Detection ... 90

Table 21 Percentage of Reduction on Increased Travel Time Due to Detection Failures by Improving Responsiveness ... 93

Table 22 Percentage of Reduction on Increased Travel Time Due to Improvement in Training and Installation Inspection ... 94

Table 23 Percentage of Reduction on Increased Travel Time Due to Communication Failures by Improving Responsiveness ... 96

Table 24 Percentage of Reduction on Increased Travel Time Due to Communication Failures by Improving the Frequency of Inspection ... 97

Table 25 Resource Allocation Actions ... 100

# 1. INTRODUCTION

Substantial capital investment has been made by the Florida Department of Transportation (FDOT) and many local transportation agencies throughout the state in Advanced Traffic Management Systems (ATMS). This investment has not been consistently protected by effective maintenance, particularly in ATMS-related communication, which facilitates traffic signal coordination, status reporting, etc., and detection, which directly impacts efficiency. It is important to recognize that robust communication and detection systems are keys to ensuring the benefits of ATMS.

The objective of this project is to understand and simulate the impact of communication and detection failure propagation through a typical ATMS architecture. This can lead to the development of more effective maintenance planning that targets cost-effective resources to critical portions of FDOT and local transportation agencies' ATMS communication and detection infrastructures.

The research team first performed a thorough literature review of major traffic signal system architectures and conducted a comprehensive traffic agency survey throughout Florida to understand signal operations and maintenance practice. To effectively measure the performance of a traffic signal system itself, a practical signal system performance concept and measures were established. A traffic signal system degradation index and performance index were developed. Sensitivity analyses were performed through traffic simulations to assess the impact of communication and detection degradation as well as traffic signal timings on ATMS operations. Based on the analysis of large number data obtained from the sensitivity analysis, traffic signal degradation and performance models were developed to assist traffic agencies to effectively assess the performance of their traffic signal systems. Furthermore, the research team and project contractors developed a basic set of improvement actions that can be combined to provide a general overview of the most significant resource allocation strategies. A From-To matrix was developed to allow traffic agencies to select proper improvement actions based on their available resources. Finally, recommendations for operations and maintenance resource allocation strategies were provided. Future research direction was also recommended based on the results and findings of this project.

# 2. REVIEW OF SIGNAL SYSTEM ARCHITECTURES

Traffic signal systems consist of traffic signal controllers, a central computer, system software, signal timing plans/algorithms, and detection and communications components. These components can be configured into different system architectures to achieve specific goals of traffic signal operations and maintenance. Traffic signal systems under different system architectures provide different capabilities on traffic signal coordination, system monitoring, and data management. To understand the impact of communication and detection degradation on traffic signal system performance, it is necessary to learn the pros and cons of different signal system architectures with respect to the impact of detection and/or communication failures.

The subsequent sections contain information on a coordinated signal system, types of signal system architecture, and pros and cons of different signal system architectures with respect to impact of detection and/or communication failures.

## 2.1 Coordinated Signal System

Traffic signals on a roadway corridor are coordinated to maximize platoon progression and/or minimize delays and stops. Coordination among these intersections is achieved using either time-based coordination or interconnected coordination.

### 2.1.1 Time-Based Coordination

Traffic controllers have internal clocks that are synchronized such that the signals stay in proper coordination. The intersection controllers store the coordinated signal timings plans. Time-based coordination is used when a communications infrastructure is not available/required, or as backup for interconnected signals when the central computer or communication fails. These systems have low capital cost but provide limited capability. Such traffic signal systems with no interconnection and communication have the following major limitations [1]:

- Equipment failure cannot be automatically detected.
- Timing plans cannot be selected or changed remotely.
- Section-wide, traffic-responsive operation cannot be achieved.
- Records of equipment and traffic conditions are not collected.

These limitations may result in inefficient operation due to longer response time in detecting equipment failure and the ability of the control system to respond to the change in traffic demand. Time-based coordination is commonly used as backup for interconnected systems when the communication or central computer fails.

### 2.1.2 Interconnected Coordination

An interconnected system consists of communication networks that enable a field master controller or a central computer to communicate with local controllers in the network to implement coordinated signal timings. An advanced traffic signal system may use the traffic-responsive mode or implement adaptive traffic algorithms to adjust signal timing to traffic demand. The communication network provides the capability to monitor traffic conditions with vehicle detectors and prompt maintenance of equipment by monitoring for equipment failures. Interconnected systems have a higher capital cost than time-based systems. However, they enhance the capability of a traffic agency to remotely change traffic signal timings, monitor equipment for failure, conduct timely repairs, and provide the ability to implement traffic-responsive signal timings or adaptive signal systems algorithms.

Interconnected traffic signal systems can be configured as centralized, distributed, or hybrid (combination of centralized and distributed) systems. Furthermore, a distributed system can be a two-level distributed system (without field masters) or three-level distributed system (with field masters). These configurations provide traffic agencies with the ability to monitor the traffic flow, respond promptly to equipment failure, implement traffic-responsive or adaptive signal timings, and remotely conduct system-wide modifications to improve traffic flow.

## 2.2 Types of Signal System Architectures

### 2.2.1 Time-Based System

In a time-based system, signal coordination is based on the internal clocks in the controllers, as mentioned previously.

### 2.2.2 Centralized System

In a centralized system, the central computer transmits instructions to individual local controllers. The signal control is based on the background timing plans that reside in the central computer. The interval and phase changes are communicated to the local controllers. The detector and field equipment status are polled by the central computer at frequent intervals. The following are properties of a centralized control system [1, 2]:

- Requires reliable communication networks, as the real-time control information is transmitted from the central computer. In the case of communication failure, intersections revert to time-based coordination, which still requires a transition time.

- Requires a reliable central computer, as the central computer is responsible for adjusting the signal timing. In any case of central computer failure, all systems connected to the central computer revert to backup signal timings. Most agencies deploy fault-tolerant systems, which use two identical computers. When one computer fails, the system is operated by the other computer.
- Provides excellent surveillance response time.
- Allows centralized control adaptive algorithms (e.g., SCOOT).
- May not be easily expanded and has a limited maximum network size.

Figure 1 shows a schematic of a centralized system. If the budget allows, centralized systems can be considered for a robust linear communications infrastructure to each device, especially when a centralized adaptive control technology (e.g., SCOOT) is desired or when the system is expected to share infrastructure with other systems that require high reliability, such as emergency response.

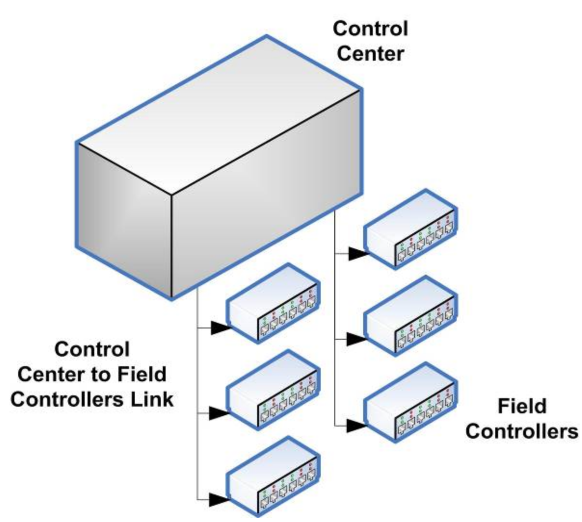



**Figure 1 Schematic for a Centralized System**

### 2.2.3 Distributed System without Field Masters (Two-Level Distributed System)

Distributed architecture without local masters is similar to the centralized architecture except the signal timings are downloaded to the intersection controller and stored there.

Data from detectors are processed at the intersection controller level and then uploaded to the central computer. These systems require lower communication capacity requirements, with a sampling rate of one per minute or less. The lower communication requirements offer the capability to connect more intersections to a communication facility.

### 2.2.4 Distributed System with Field Masters (Three-Level Distributed System)

In this system, a field master unit lies between the central computer and the local intersection controllers. Signal timing plans are transferred from the central computer to the intersection controller through the field master. Detector data are processed by the intersection controller and further by the field master. The processed data are then sent to the central computer. Field masters communicate with the central processor when a failure occurs or on a command from the central computer. Figure 2 shows a schematic of a distributed system with field masters. Such systems are representative of closed-loop systems.

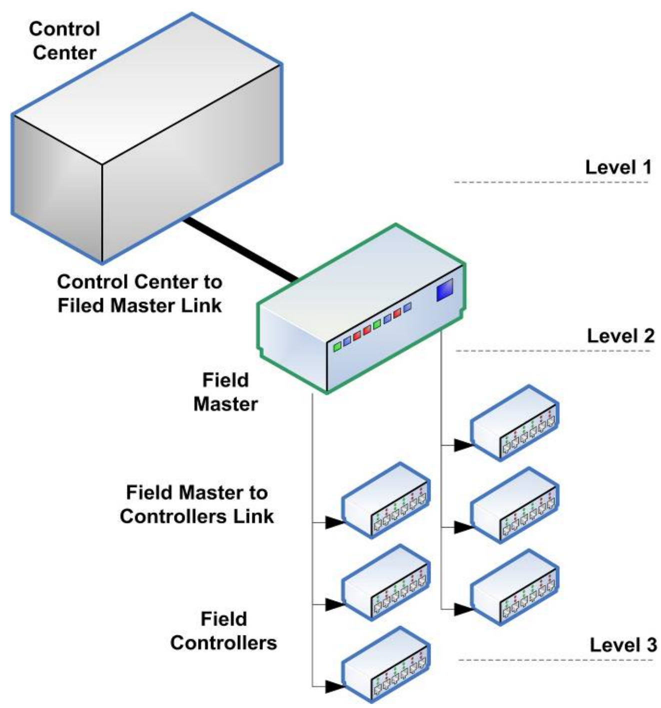



**Figure 2 Schematic for a Distributed System with Field Masters**

A closed-loop system is a distributed processor traffic signal system with control logic distributed among three levels: the local intersection controller, the on-street local master, and the central computer. There is a two-way communication network between the local intersection controllers and the field master(s), as well as between the field master(s) and the central computer. Control modes used by closed-loop systems include time-of-day mode, manual mode, traffic-responsive mode, controller unit parameter mode, and critical intersection control mode.

Distributed systems may be considered when powerful local controllers are desired, absolute real-time surveillance is not required, and the budget is limited, or when centralized adaptive technologies are not required.

## 2.3 Pros and Cons of Different Signal System Architectures

The pros and cons of different signal system architectures with respect to the impact of detection and/or communication failures are addressed in this section.

### 2.3.1 Time-Based Systems

It can be argued that time-based systems have no effective, reliable means within the system components to detect communications and detection failures. A time-based system can consist of stand-alone intersection controllers or controllers that are linked by a simplex (outbound) synchronization network. In stand-alone time-based systems, each intersection controller relies on its own time-of-day clock and internal scheduler to implement timing plans and to maintain coordination with other intersection controllers on the same arterial network. In simplex coordination schemes, two or three dial selection signals, along with a cycle clock synchronization (master cycle) reference signal, are broadcast from a central location or from a master controller to the controllers in a given subsystem. The signal is often transmitted via a hard-wire or radio circuit. Most modern controllers have the ability to respond to this type of coordination signal, which is often referred to as a "7-wire" system.

#### 2.3.1.1 Advantages

The major advantage of time-based systems is their low implementation cost relative to other systems. Stand-alone time-based coordination is supported as a base feature in all modern intersection controllers sold in the United States, requiring no communications infrastructure. Likewise, most NEMA controllers and 170/2070 software packages also have the ability to support "7-wire" coordination. However, a central timeclock or master controller is necessary to generate the synchronizing information, and an interconnect cable must connect all dependent controllers to the central timeclock or the various master controllers. The degree of coordination can be very precise for relatively little investment in the communications infrastructure as long as the time-of-day in the controllers is maintained within approximately 4-5 seconds at all times in the case of a stand-alone system, and as long as the interconnect is maintained in the case of a 7-wire interconnect system.

The last two caveats that were cited in the previous section form some of the principal weaknesses of time-based systems. As noted, in a time-based system where arterial coordination is a goal, the time of day that is maintained within each intersection controller must be within 4-5 seconds of some reference. This reference could be some external standard, such as the official time as calculated by the National Institute of Science and Technology (NIST), a master central clock, or a master controller clock. If the time of day is not maintained with this precision, the relative offsets of the controllers will begin to drift, causing a loss of coordination. Most modern intersection controllers calculate the time of day by counting the number of cycles on the incoming AC power. This is done with varying degrees of accuracy. It is not unusual for the time of day to drift 1 to 2 seconds per day from controller to controller under the best conditions. If malfunctions occur in the timekeeping hardware, the drift can be measured in terms of minutes per day or more. This effectively renders any coordination scheme useless within a matter of days without constant operator intervention. To remedy this, system technicians must check the individual locations every few days to make sure that the time of day is being properly maintained and must reset the time-of-day clocks as necessary. This constitutes a significant maintenance burden. To eliminate the need for constant technician checking of the time-of-day clocks in stand-alone systems, some vendors have supplied external electronic clocks that are installed in each intersection cabinet. Generally, the clocks receive time-of-day broadcasts from the NIST's WWV time service or from GPS satellites. The clocks generally output a pulse once per day to reset the controller's time-of-day clock to a specified time.

#### 2.3.1.2 Disadvantages

The major disadvantage of stand-alone and interconnected time-based systems is that there is no mechanism for reporting any failures contained within the system to a central location. Failures at each location must be detected by on-site observation at each location. This means that failure identification is relegated to a very informal and often unreliable public observation and feedback system. While routine maintenance by agency forces probably would identify problems at most intersections, in most agencies, periodic maintenance is performed at six-month intervals or longer, making it an ineffective tool.

The following failures can occur at intersections that significantly impact traffic flow:

- Detection failures
- Timing parameter alteration or corruption
- Time-of-day drift
- Field signal outages
- Other control device failures

While field signal outages may be readily noticed and reported by the public, the other items can have an equally significant impact on traffic flow in a coordinated network and yet may be difficult for the public to detect or attribute to a single intersection controller.

In conclusion, the almost total lack of timely feedback of any kind of system performance information severely impacts the overall effectiveness of time-based systems.

### 2.3.2 Centralized Systems

Centralized systems are characterized by a central computer that performs second-by-second surveillance and control of intersection controllers. Systems using the Urban Traffic Control System (UTCS) or its derivatives are typical examples.

#### 2.3.2.1 Advantages

As long as the communication links are maintained between the central computer and the intersections under its control, very precise control and coordination can be maintained. The systems provide immediate feedback of intersection status and support traffic-responsive operation.

#### 2.3.2.2 Disadvantages

Because of the need for second-by-second control and surveillance, centralized systems tend to have the highest cost in terms of central computer hardware and software and in communications infrastructure cost. Central systems also require significant numbers of additional detectors to support traffic-responsive and adaptive operations. Depending on the design of the system, this can result in an additional one to four detectors per intersection in the system. The traffic responsive and adaptive features are dependent on proper detector operation and can be severely compromised or disabled by detector failures. The requirement for additional detectors is reflected in significant increases in capital costs at system implementation and results in a significant maintenance requirement if the feature is to be supported throughout system life. In practice, the requirement often exceeds the ability of maintenance resources to keep up with the failures.

Because of the need to issue commands and receive basic operational status information every second from each controller, little communication bandwidth remains for performing other remote functions such as database upload and download and detailed failure analysis. In traffic-responsive systems, there may be detailed reporting on system detector failures; however, reporting on actuation detectors at individual intersections is often limited or non-existent. With traffic adaptive systems, failure of actuation detectors may be reported; however, the particular detector that has failed or the reason for the failure usually is not.

When communication malfunctions occur with individual intersections, the impact on coordination can be severe, as there is no means to keep the offline intersections in synchronization with the intersections that remain online. Many centralized systems use a star or daisy-chain communications topology. If there is a communications failure that occurs in a central modem or in the transport links that are closest to the control center, the coordination and split control can be completely lost among the intersections in that communications channel. When this occurs at several intersections in the same control group, the impact on traffic capacity can be severe.

In general, while centralized systems offer the advantages of supporting robust traffic-responsive and traffic-adaptive operations, their operation also tends to be most severely impacted by communications and detector failures. While central systems can report timing and some equipment failures, the ability to provide detailed equipment failure information is often limited relative to the capabilities of distributed systems.

### 2.3.3 Distributed Systems without Local Masters

Distributed systems are characterized by local controllers with significant intelligence at each local intersection. Each intersection is monitored, usually on a second-by-second basis by a central computer. In most modern NEMA and 170 systems, local controllers are capable of time-based coordination and have time-of-day coordination schedules and multiple coordinated timing plans resident in the local controller. In addition, each local controller is capable of collecting system detector information and reporting it to the central computer to support traffic-responsive and historic data collection features. While individual intersections in distributed systems are monitored on a second-by-second basis, the central computer does not assert second-by-second control. This results in significantly reduced communications bandwidth requirements relative to a similar centralized system topology. This allows the system to accommodate more intersections on each communications channel or to return more detailed information about intersection operation. As an example, many distributed systems support a detailed display of controller inputs and outputs. Many distributed systems feature detector monitoring at the intersection level. The local intersection can often identify the type of failure, such as stuck on, stuck off, and chatter, and report the individual failure to the central computer.

#### 2.3.3.1 Advantages

In general, distributed systems are less sensitive to communications failures than are centralized systems. Unlike central systems, the coordinated operation of distributed systems can be immune to short-period communications interruptions (less than one minute). Because there is considerable intelligence at the intersection level, the controller can be programmed to run the usual time-of-day coordination plan when communications are lost. If the central computer is requesting the usual time-of-day plan when communications are lost, there may be no discernable impact on coordination for several days. Even when the central system is requesting a traffic-responsive plan, the impact of an offline intersection in a distributed system is frequently less than a similar failure in a centralized system. Because of second-by-second monitoring, failures are reported quickly. In addition, because of reduced bandwidth requirements to support routine intersection command and control, many distributed systems support on-demand diagnostics that can provide significant information on the nature of the any detected failures. For example, in some systems, the operator can observe the operation of individual vehicle and pedestrian detector inputs as well as other cabinet conditions (flash sense, stop time, door open, local data entry, etc.).

Many distributed systems also are capable of producing on-demand reports of individual detector status and failures. In most distributed systems, it is possible to upload, download, and verify the entire controller database. This function is not available in time-based systems and is non-existent or limited in fully-centralized systems. Some distributed systems even support automatic background comparison of the local controller's database to a recorded copy in the central computer's database. Compared to a central system with similar capabilities, communications and central computer requirements are less for distributed systems. Some distributed systems can support expanded status and event reporting features. Examples are detailed preemption event recording, including vehicle ID, duration, approach, and detailed conflict monitoring, including the status of all field outputs and detailed conflict monitor alarm information.

Distributed systems also tend to be more flexible in terms of communications media support, relative to centralized systems. While many central systems require a fairly homogeneous communications scheme, generally with little delay or equivalent delay characteristics in all communications channels, typical distributed systems tend to be able to support a variety of communications methods with varying transmission speeds and delay characteristics. For example, a distributed system can support a mix of fiber optic, radio, and hard-wire interconnects on the same system. This can allow for a more economical infrastructure to be designed. In addition, as agencies upgrade their infrastructure, it allows accommodation of multiple communications media as the upgrade proceeds.

#### 2.3.3.2 Disadvantages

To maintain the redundant capabilities of distributed systems, it is necessary to maintain both a central database and local copies of back-up timing plans in each intersection controller. However, this is often offset by the convenience of being able to view and modify the local timing information from the central site. Most distributed systems do not support traffic-adaptive or support a very limited traffic-adaptive operation. In addition, most distributed systems are vendor-specific. The selection of a central system is often governed by the controllers in use. Implementation of a central system that is compatible with the controllers in use often "locks in" a specific vendor.

### 2.3.4 Distributed Systems with Local Masters

Distributed systems with local masters are similar to distributed systems without local masters. The difference is that each control section has a local master or field master between the central computer and the local intersection controllers. Most field masters supervise the intersection controllers on a second-by-second basis and issue periodic plan commands. The central computer can communicate with the field master using a dedicated circuit on a second-by-second basis. However, most distributed systems with field masters support dial-up communications between the central computer and the field master.

#### 2.3.4.1 Advantages

Distributed systems with local masters have many of the same advantages of distributed systems without local masters. In addition, the support of dial-up communications between the local master and the central computer allows remote systems to be integrated the central system. This can allow relatively distant systems to be incorporated into a central system where the cost of providing a direct, dedicated connection would be cost-prohibitive or not feasible for some other reason. In operation, the field master maintains a time-of-day timing plan schedule and can command the local controllers and monitor for failures. The local master also transmits periodic time-of-day updates to maintain time-based coordination among the local intersection controllers under its supervision. Through periodic or on-demand communications between the local master and the central system, the field master can report accumulated data and recent failures. If the local master is connected to the central computer via a dedicated circuit, central monitoring of the field master and the local controllers on a second-by-second basis is possible at all times. On dial-up circuits, second-by-second observation is possible on demand.

In addition, most local masters have the ability to dial in to the central computer when failures or other reportable events occur. Most local masters have the ability to accumulate alarm and system detector information when they are not connected to the central computer and to automatically upload the information to the central computer when dialing in. In a dedicated circuit, the field master can accumulate system detector and alarm data when the link between the central computer and the local master is severed and report that information once the communications link is restored. In most distributed systems, the local master can support traffic-responsive operation for the local controllers under its supervision, even in the absence of communications with the central computer.

Distributed systems with local masters often can support a mix of local controllers without field masters, local controllers with field masters connected via a dedicated circuit, and local controllers with field masters connected via a dial-up circuit. This often provides considerable flexibility in the design of the communications infrastructure.

#### 2.3.4.2 Disadvantages

In general, the addition of a field master is advantageous where local systems are relatively distant from the central computer or where connection of dedicated circuit between the first local controller and the central system is not feasible. Field masters are most advantageous where a dial-up circuit is used between the central computers and the local intersections. It provides an intermediate supervisory controller in lieu of constant communications between the central computer and the local intersections. However, in practice, the use of dial-up circuits can be problematic. First, the dial-up circuits rely on a third party (the local telephone utility) for their maintenance. Depending on the effectiveness of the utility in responding to reported failures, significant downtime can result. In addition, the use of dial-up circuits results in a recurring monthly charge for the central computer and each dial-up field master.

Dial-up connection circuits, even though generally adequate for voice communications, may support limited or variable communications speeds, depending on individual circuit conditions. This can result in slow data throughput or even connection failures. The result is that the reliability of dial-up circuits is often less than that for dedicated lines.

Finally, because of the need to relay intersection data through the field master, even under the best of conditions, data throughput through field masters is less than in distributed systems that use direct connection to the central system. The reduction can be by a factor of 50 percent or more when uploading or downloading data to the intersection controllers. This is most noticeable when uploading and downloading the timing database for local controllers.

# 3. SIGNAL OPERATIONS AND MAINTENANCE PRACTICES IN FLORIDA

CUTR conducted an agency survey in January 2008 among 57 traffic/transportation agencies in Florida, with responses from 34 agencies that maintain approximately 12,000 signals. The objective of the survey was to gain insight regarding traffic signal system architectures, maintenance practices, and resource allocations. The detailed survey results can be found in Appendix A.

The survey collected information on the general practices for traffic signal system maintenance, budget allocation, performance measures, and ATMS operations. It focused primarily on communication and detection components, and it was not surprising that in addition to detection and communications, signal timing was also one of the major concerns among the responding agencies in the survey. In one question, the agencies were asked to rank their system components from 1 (worst) to 5 (best). Survey results for this question can be observed in Figure 3. The number of agencies rating signal timing at 1 or 2 is larger than for any other system component.

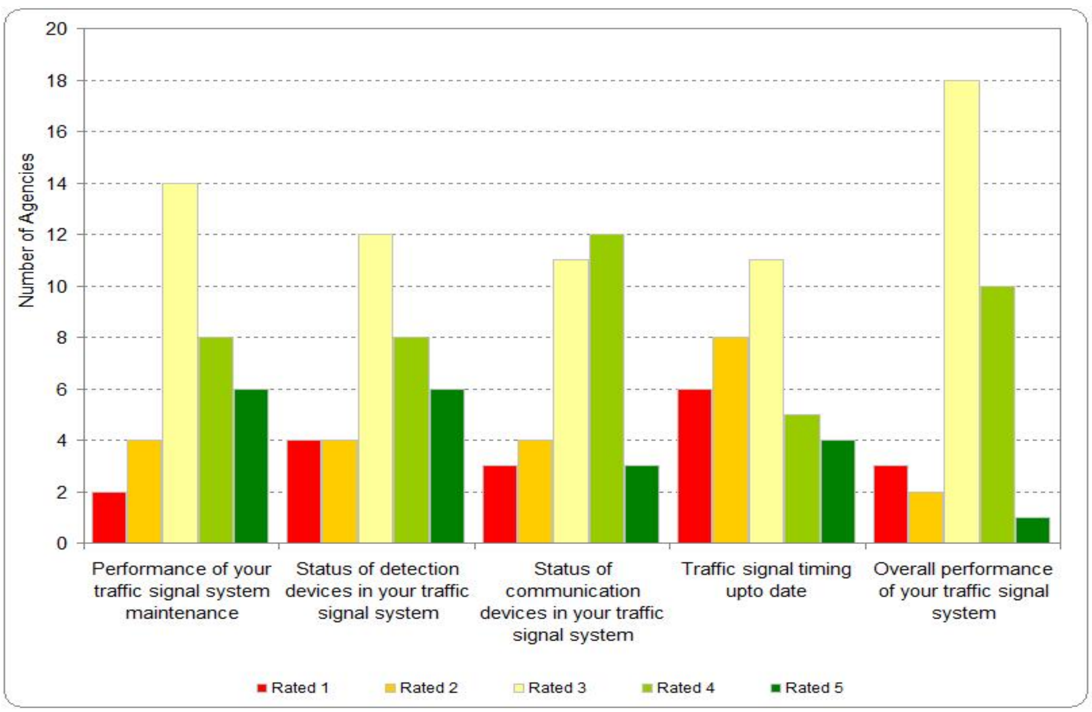



**Figure 3 Ratings of Status of Traffic Signal System Components**

The performance of communication and detection components was rated higher than timing. It is likely communication and detection systems were better maintained with fewer complaints, and signal retiming required more resources and attention. Perhaps one reason for this result is that failures in detection and communication components affect the way signal timing is displayed and perceived as a signal timing problem. The final ranking from the best performance to the worst among the five categories in this question was 1) performance of your traffic signal system maintenance, 2) status of detection devices in your traffic signal system, 3) status of communication devices in your traffic signal system, 4) overall performance of your traffic signal system, and 5) traffic signal timing to date. The following subsections provide a more detailed description of the survey results.

## 3.1 Detection

The survey revealed that the majority of detection equipment currently in use is inductive loop (92%) followed by video detection which is slowly positioning as the preferred technology due to easier maintenance without blocking traffic. Another benefit of video detection is that there are no loop replacements needed during resurfacing projects. Survey results indicate that one of the major issues raised with loop detector maintenance is from an outsourcing contract. The survey shows 71 percent of the agencies contract out 50 percent or more of detection maintenance work. The loop repair schedule was not fully controlled by the agency for timely repair due to trying to reduce the cost of repairing just a single or a few loops through contractors each time. Some agencies plan to put a timely repair schedule in their contracts to minimize the delay for repair. Based on the responses of agencies using ATMS, 10 to 20 percent of intersections have at least one detection malfunction or a broken loop at any given point in time.

## 3.2 Communication

The dominant communication architecture is centralized, followed by distributed without local masters (52% and 20%, respectively). Fiber optic and twisted pairs are the preferred technologies for communication between signals (39% and 37%, respectively), followed by leased lines (18%). For communication between signals and central computer, fiber, twisted pair, and leased lines are equally likely (31%, 35%, and 32%, respectively). The major causes of communication failures are device failure, cable cut, and lightning. About 52 percent of the agencies contract out 76 percent of communication repair work. Based on the responses of agencies using ATMS, on average, 5 to 15 percent of signals cannot be reached due to some forms of communication failures.

Agencies were asked to suggest actions aimed at improving traffic signal system performance. As shown in Table 1, staff (well-trained engineers and technicians), budget, and signal timing were the top three major actions preferred by the surveyed transportation agencies in Florida. Adding communication and detection in one category places them second on the list, just below well-trained engineers.

**Table 1 Suggested Actions to Improve Traffic Signal System Performance**

| Action | Number of Agencies |
|---|---|
| Well-trained engineers | 13 |
| Well-trained technicians, improve signals/technician ratio | 10 |
| Increased budgets | 10 |
| Improved signal timing and coordination | 8 |
| Preventive maintenance | 7 |
| Ensure detection is functional | 6 |
| Ensure communication is functional | 5 |

## 3.3 Observations from Agency Survey

The results observed from the agency survey were consistent with those of the 2007 National Traffic Signal Report Card (NTSRC) [3]. Signal timing is a preferred action for improving the operation of traffic signal systems because of its cost-benefit ratio. The NTSRC recommend that timing plans should be revised every three years. This led the research team to consider three primary sources of degradation of traffic signal system performance:

- Degradation due to malfunction of detection equipment
- Degradation due to malfunction of communication equipment
- Degradation due to obsolescence of timing plan (or increased traffic growth)

The NTSRC also revealed that small agencies (<50 signals) tend to perform worse than mid-size agencies (150-450 signals), primarily because they are not properly staffed. Mid-size agencies have the right balance between complexity and resources.

The NTSRC also recommends as good practice for maintenance operations keeping 90 percent or more of the detection system operational. One of the goals for this project was to determine what resource allocation and strategies are the most suitable to keep performance degradation from reaching predetermined lower-bound values. Resource allocation by itself can help to improve maintenance. According to one of the case studies in the 2007 NTSRC, the City of Austin (Texas) made signal improvements simply by reallocating existing funds to invest in more preventive maintenance. In another case study, the implementation of a central system with real-time monitoring and alarm-logging capabilities helped the engineers in the City of Plano (Texas) to focus their maintenance efforts. In this way, improving the architecture (communication) can help improve system maintenance by detecting failures in a timely manner.

## 3.4 Remarks on Survey Results

Detection and communication components guarantee the successful execution of a signal timing plan in the field. There are many studies on signal timing improvements, whereas studies assessing the impact of detection or communication failures are scarce. FDOT, in conjunction with the USF Center for Urban Transportation Research (CUTR), undertook the task of quantifying the effects of the degradation of communication and detection on the operation of traffic signal systems. The agency survey provided the opportunity for agencies to express their suggestions to improve the performance of traffic signal systems. The top two individual suggestions were related to staffing. Adding communication and detection improvements in one category places it second on the list, just below well-trained engineers. The importance of signal timing was also highlighted in the traffic agency survey. More trained staff and a better budget as well as improved resource allocation are needed to effectively improve and enhance our traffic signal systems.

# 4. ESTABLISHMENT OF SIGNAL SYSTEM PERFORMANCE CONCEPT AND MEASURES

A practical concept for effectively evaluating traffic signal system performance and assessing the impact of detection and communication degradation was developed in this research project. The concept focuses on the evaluation of the impact of degradations from major signal system components as well as the measurement of performance indicators such as travel time and delay, which may be significantly affected by traffic demand and roadway capacity. The proposed concept is based on the literature review, agency survey, and practical field operation and maintenance experience on the traffic signal system.

Several studies are especially beneficial for the development of the concept for traffic signal system evaluation. The models presented in the report "Elements of a Comprehensive Signal Asset Management System" [4] are specific to the development of traffic signal systems. "Traffic Control Systems Operations: Installation, Management and Maintenance" [5] presents models specific to traffic signal system maintenance agencies. Models integrating timing plan design, maintenance and performance measures for traffic signal system were published in "NCHRP Synthesis of Highway Practice 307: Systems Engineering Processes for Developing Traffic Signal Systems" [1].

The concept developed through this research project for evaluating a traffic signal system performance achieves the following major objectives:

- Addresses the process of integrating major traffic signal system components
- Considers different signal system architectures
- Establishes a traffic signal system performance index
- Incorporates the degradation of major signal system components in the system performance measures

In this chapter, a basic concept of measuring observed traffic signal system performance is presented first, followed by the relationship among maintenance, physical and operational systems. Then the degradation process of traffic signal system components is described. Based on the above-mentioned concept, relationship and process, the project team defines the traffic signal system degradation index and performance index. A detailed description of the systematic approach concept adopted for this study is then provided to evaluate a traffic signal system. The last part of this section lists the performance measures identified in literatures and traffic agencies for measuring the performance of the system.

## 4.1 Observed Traffic Signal System Performance

A traffic signal system consists of an operational system and a physical system as shown in Figure 4. The operational system receives the existing timing plans and executes them by means of the physical system. Two functions are involved in the generation and continuous revision of timing plans: signal timing design and signal timing management. The signal timing design function is carried out when a large-scale timing plan is necessary to improve traffic performance on a given roadway section. The signal timing management function consists of modification of the originally-designed timing to accommodate minor changes in traffic patterns. The interaction between these two functions gives origin to the existing timing residing in the local controller of the traffic signals. This interaction depends on staffing, software, and available funds (signal timing resources). When ATMS execute an adaptive traffic control strategy, the design and the management of timing plans are performed simultaneously and continuously through specialized control software. On the other hand, in a closed-loop traffic signal system, these two functions are separate processes that rely on available staffing and/or signal retiming contracts. The feedback arrow from the management function to the design function in Figure 4 represents major changes in the timing plans that require a signal timing design process.

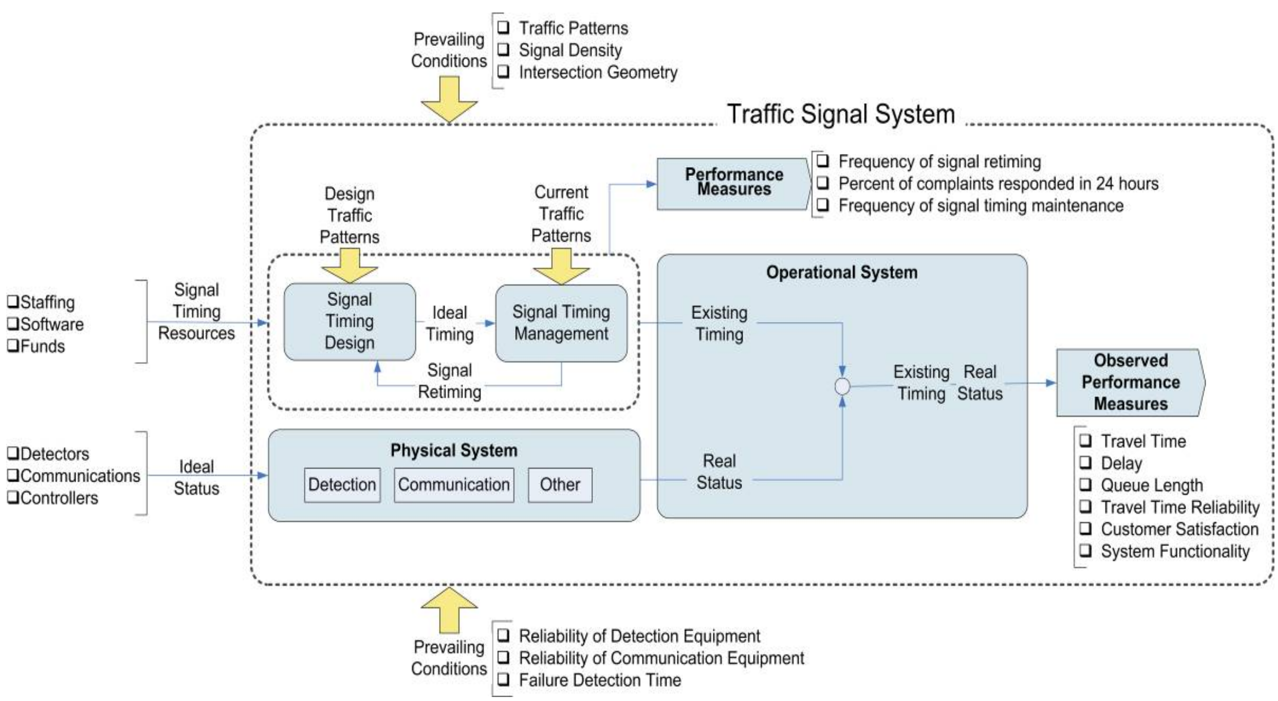



**Figure 4 Basic Concept of Observed Traffic Signal System Performance**

The physical system comprises the entire hardware inventory, including vehicle detection devices; communication, pedestrian, preemption, and priority calls equipment and infrastructure; signal heads; traffic controllers; signal cabinet; signal system computers in a traffic management center to provide vehicle detection; signal system communication; data collection and management; and signal display capabilities to support the functions of the operational system. As defined, the operational system is not a tangible system but comprises timing plans, signal control parameters, and commands that rely on the physical system for their execution. Among the components of the physical system, detection and communication play critical roles for a traffic signal system.

The signal timing plans are designed under the assumption that the traffic patterns are representative of traffic conditions and that intersection layouts for the design and the physical system are fully functional. With a fully-functional physical system, the intended signal timings can be completely executed by the traffic signal system. This is referred to as the "ideal status" of the physical system, as shown in the basic diagram of traffic signal systems in Figure 4.

The "prevailing conditions" are the typical conditions that can affect the performance of a traffic signal system, such as traffic patterns, signal density, intersection geometry, reliability of detection equipment, reliability of communications equipment, and failure detection time. The ideal traffic signal system performance for any given signal system architecture can be achieved through the most adequate signal timing under prevailing conditions (i.e., traffic pattern, pedestrian flow, signal density, intersection geometry) and a fully-functional physical system, including detection, communication and other related components (i.e., signal system layout, signal equipment, traffic management center). For this study, it was assumed that any degradation from the quality of a signal timing plan and any component of the physical system will negatively impact the performance of a traffic signal system. This assumption will be tested comprehensively through experimentation from traffic simulation and limited field data collection. The degradation of the components of the physical system will cause deviations from its ideal status. The degradation of the physical system in conjunction with the existing timing will result in signal performance observed in the field, as shown in Figure 4.

## 4.2 Relationship among Maintenance, Physical, and Operational Systems

The maintenance program or division of a traffic agency repairs and upgrades the degraded components and strives to maintain the real status of the physical system as close to the desired or ideal status as possible. As shown in Figure 5, the maintenance system has input parameters (resources) that can be used to achieve a desired status of the physical system. The "prevailing conditions" for the maintenance system consist of the inherent reliability features of the individual components of the traffic signal system and external conditions (e.g., uptime of detectors).

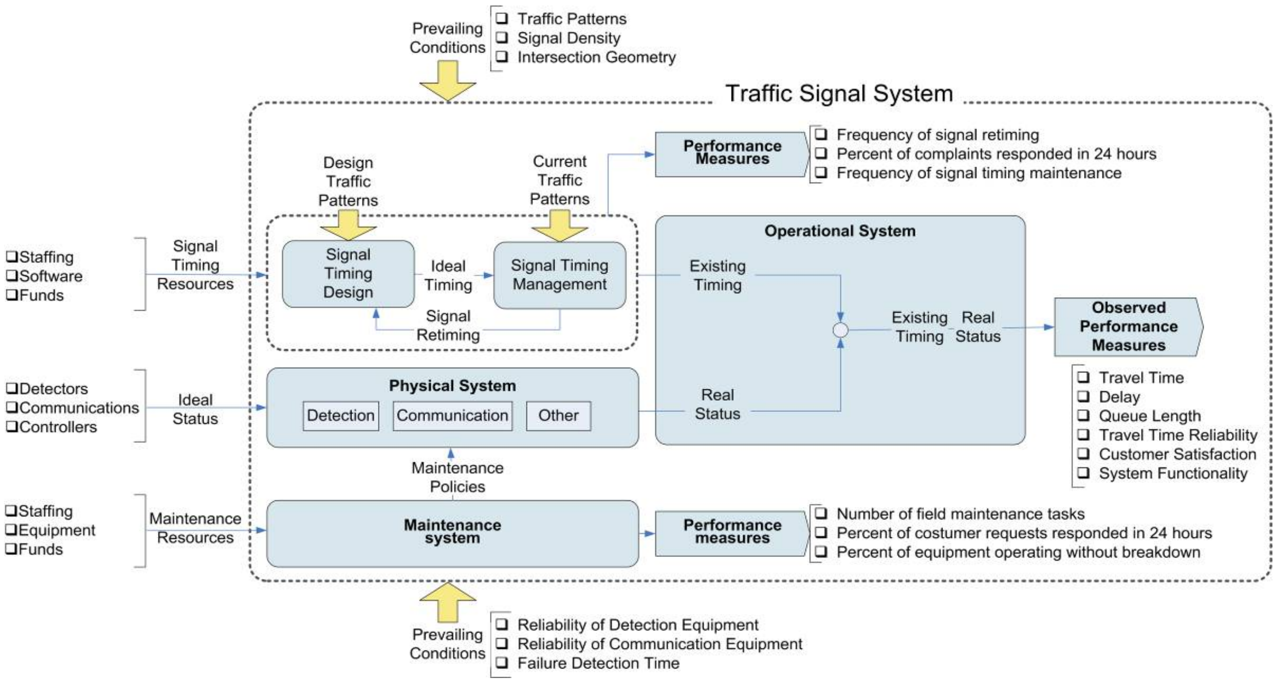



**Figure 5 Relationship among Maintenance, Physical, and Operational Systems**

For performance measure purposes, the maintenance program or division of a traffic agency usually keeps a record of the number of requests for signal equipment repair, repair jobs, and signals maintained, and/or the percentage of customer requests responded to within a specific time period. In addition to these system-specific performance measures, an assessment of the real status of the operational system from the maintenance efforts is necessary. Therefore, it is important for this study to relate the traffic signal maintenance performance measures and policies from a traffic agency to the real status of the physical system, and further to the performance measures of entire operational system, as shown in Figure 5.

## 4.3 Degradation of Traffic Signal System Components

One of the main objectives of this project is to assess the impact of degradation from detection and communication components on the intended (ideal) traffic signal system performance. Two major sources of degradation are considered:

- Degradation of the physical system, especially from detection and communication
- Degradation of the signal timing due to changes in traffic patterns over time

In this project, the degradation of the physical system focuses primarily on detection and communication devices. It is easily assumed that existing signal timing is proper for traffic patterns representing existing traffic conditions. However, in reality, most systems suffer natural degradation of signal timing plans due to expected growth over time and sudden degradation due to unpredicted changes in traffic patterns from incidents. These degradations of timing plans are present in most traffic signal systems in the field. Observed traffic signal performance measures such as travel time, delay, and queue length are the result of interaction among the physical system, signal timing, and traffic conditions.

The degradation of a traffic signal system's performance comes not only from the degradation of the physical system but also from traffic signal timing. It would be incomplete to evaluate traffic signal system performance by isolating the impact of traffic signal timing to the performance. Therefore, in addition to the physical system, the impact of the signal timing component on traffic signal system performance also was studied in this project.

Any failure in the physical system has an effect on the operational system and on the actual timing displayed in the field. Theoretically, for each status of the physical system there could be a corresponding timing plan on a fully-operational system that will have the same performance measures as the original system. An outdated timing plan may mask the effects of the degradation of the physical system, leading to further degradation of operational system performance measures (e.g., travel time).

Performance measures observed in the field contain the combined effect of physical system status and existing signal timing under prevailing conditions. Currently, only the numerical values of the observed performance measures of a traffic signal system under a specific prevailing traffic condition (e.g., PM peak hour traffic) are reported with no associated information on the signal system performance itself. The numerical values of the observed performance measures cannot reflect traffic signal system performance itself because the same observed performance, such as travel time or travel delay, can result from numerous combinations of physical system status, existing timing, and traffic conditions.

When both the status of the physical system and the signal timing are ideal, the traffic signal system can achieve its ideal performance. An ideal performance measure of the system can generally represent the best performance the system can achieve under a specific prevailing condition. The concept of traffic signal system performance considering the degradation of physical system and traffic signal timing is shown in Figure 6. Ideal performance generally cannot be easily observed in the field except for the most recent retimed signal systems with a fully-functional physical system or a fully-functional adaptive traffic signal system. However, ideal performance under specific prevailing traffic conditions can be obtained through carefully calibrated traffic simulations.

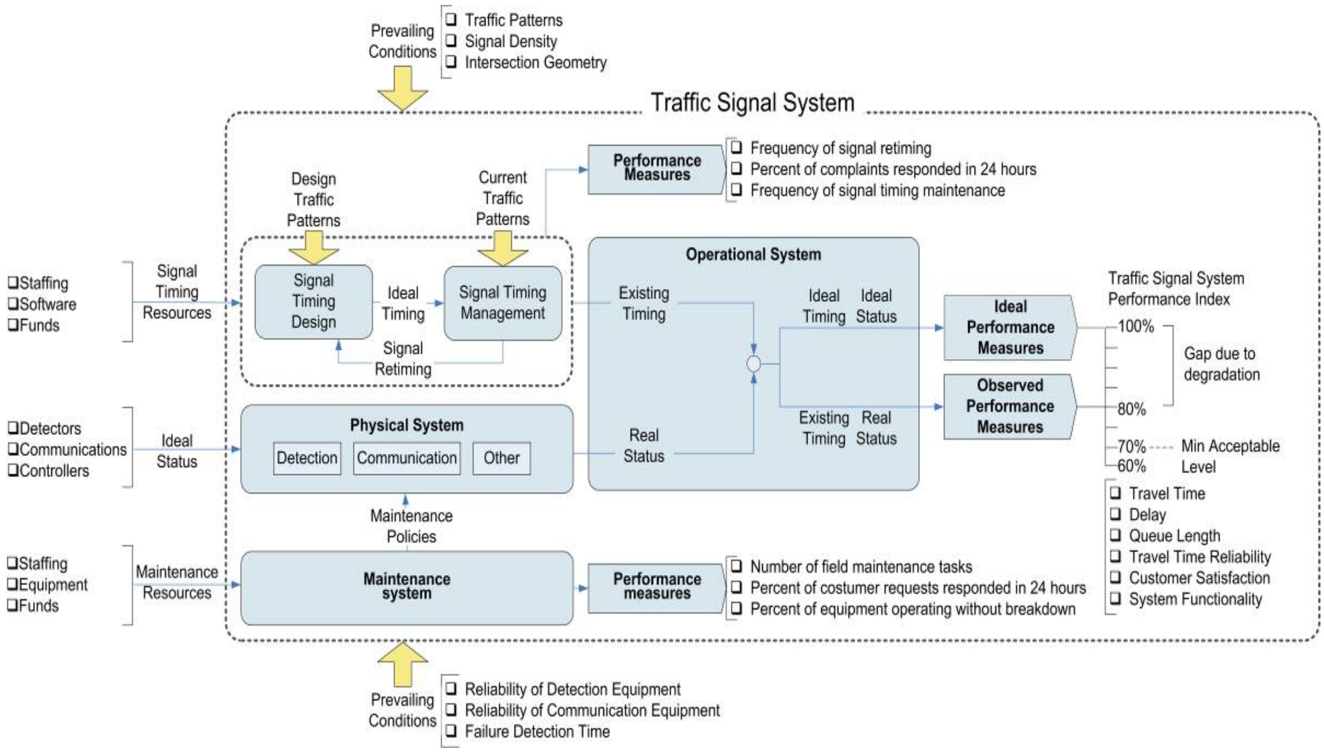



**Figure 6 Concept of Traffic Signal System Performance Considering Degradation of the Physical System and Traffic Signal Timing**

## 4.4 Traffic Signal Systems Degradation Index and Performance Index

Any departure from ideal conditions, whether due to degradation of the physical system (detection, communication, and/or others) or timing plans, will cause a gap in any performance measure between the full potential of the system and the current conditions as shown in Figure 6. Travel time is one of the most commonly-used performance measures for corridors. To adequately evaluate the performance of a traffic signal system itself, this research defines a Degradation Index (DI) of a traffic signal system as the percent of increased travel time due to system degradation relative to its observed travel time. The Performance Index (PI) is defined as the percent of ideal travel time relative to the observed travel time. The "ideal travel time" is the travel time the system can achieve under fully-functional detection and communication systems and ideal signal timing usually through signal retiming. The relationships among observed travel time, ideal travel time, and increased travel time are shown in Figure 7.

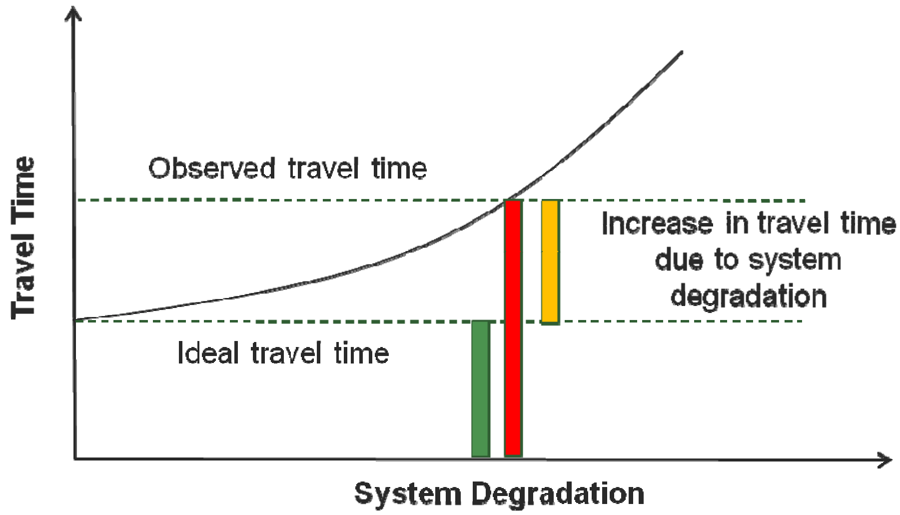



**Figure 7 Degradation Index with Respect to Travel Time**

The DI and PI can be expressed as follows:

$$DI = \frac{TT_{increased}}{TT_{Obsered}}$$

Where

| | |
|---|---|
| $DI$: | Degradation Index, in percent (%) |
| $TT_{increased}$: | Travel time increased due to system degradation |
| $TT_{observed}$: | Observed travel time under existing conditions |

$$PI = \frac{TT_{idea}}{TT_{Obsered}}$$

Where

| | |
|---|---|
| $PI$: | Performance Index, in percent (%) |
| $TT_{idea}$: | Travel time under fully functional detection and communication systems and ideal signal timing plan |
| $TT_{observed}$: | Observed travel time under existing conditions |

$$PI = 100\% - DI$$

Where

| | |
|---|---|
| $PI$: | Performance Index, in percent (%) |
| $DI$: | Degradation Index, in percent (%) |

This Performance Index may have a minimum limit, below which the system degradation becomes unacceptable. The resources and policies of the maintenance system can be better used to reach a target physical system real status that allows the traffic signal system to achieve the desired performance for the operational system.

### 4.5 Analysis of Traffic Signal Systems

This section describes the approach for developing potential measurements for a traffic signal system through the concept of traffic signal system performance evaluation and the factors that may influence traffic signal performance. These factors can be classified as controllable and uncontrollable factors [6]. Any factor of interest that can be modified is considered a controllable factor (e.g., a percentage of functional detectors in a control section). The factors that cannot be modified or considered are the uncontrollable factors (e.g., traffic volume). In this project, the controllable factors are referred to as "system parameters." In general, these parameters are associated with the decision variables that are to be optimized or improved through resource allocation. The uncontrollable factors are referred to as "prevailing conditions," since these factors describe the working conditions to which the system is exposed. In accordance with the proposed approach, any traffic signal system can be characterized by the specific prevailing conditions, analyzed by modifying the system parameters based on resource allocations, and evaluated using performance measures. The subsequent parts of this section present the proposed analysis of traffic signal systems followed by potential measures of signal system performance.

The concept of traffic signal performance measures considering degradation of the physical system and signal timing gives a broad view of the main elements of traffic signal systems and their interactions, as presented in Figure 6. The highlighted path represents one of the main objectives of this project, which is to properly allocate available resources to improve traffic signal system performance, as shown in Figure 8. The maintenance resources are allocated and input into the maintenance system, which will transfer them to the physical system through maintenance policies (e.g., frequency of inspections). Each resource allocation strategy will result in a maintenance policy that can be evaluated through the real status of the physical system (performance of physical system). The real status of the physical system will significantly affect the performance of the operational system. The performance measures of the operational system contain the combined effect of the physical systems (detection, communications, and others) and the quality of signal timings.

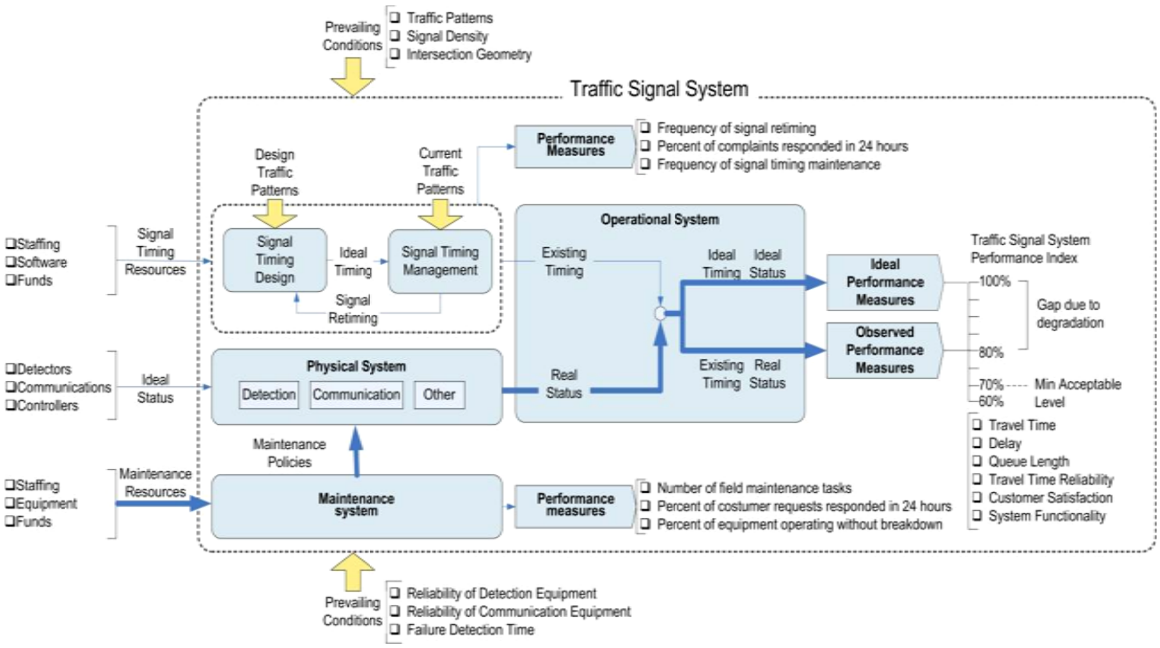



**Figure 8 Highlighted Path of Research Project to Allocate Maintenance Resources to Improve Traffic Signal System Performance**

The goal of this analysis was twofold: to understand the nature of the relationship among the maintenance system input parameters, and to determine the system parameters that have significant impact on the performance measures of the operational system. This project developed a practical process to assist transportation agencies to effectively allocate their maintenance resources, such as staffing, equipment, and funding, to achieve the goals of their intended traffic signal system performance, which will be presented later in this report.

## 4.6 Existing Measures of System Performance

In general, performance measures for the maintenance of a traffic signal physical system are reported from a managerial standpoint and isolated from the traffic operations performance measures. However, the performance on maintenance of a traffic signal physical system directly affects the operational performance of a traffic signal system. In this section, the performance measures focus on three parts:

- Maintenance performance measures
- Operational performance measures
- Functional performance measures

The maintenance performance measures are those reported by agencies on a monthly, quarterly, and/or annual basis. They provide the maintenance output and/or performance indices of a maintenance system. The operational performance measures are directly related to traffic signal system performance experienced by motorists. They can show the results of operational performance of a traffic signal system from the effort of a traffic signal maintenance agency. The functional performance measures are based on the perspective of the management center on the effects of the degradation of the physical system.

### 4.6.1 Maintenance Performance Measures

A document search was performed on several public works department internet sites throughout Florida [7, 8]. The objective was to gain insight into the performance measures used and reported in practice. It is important to note that the reported performance measures are related to managerial objectives and provide a general overview of the system. The most relevant information on maintenance performance measures used and reported in practice is output performance measures and associated indices, which measures production achieved by the traffic signal maintenance agencies. These maintenance-related output performance measures and associated indices are as follows:

- Number of signalized locations and school flasher locations maintained
- Number of video imaging detector systems maintained
- Customer satisfaction (%) with traffic signal coordination during peak congestion time
- Customer satisfaction (%) with management of traffic flow on county streets
- Number of signalized intersections retimed or evaluated
- Number of arterials retimed/evaluated
- Number of traffic signal plans designed
- Customer timing requests
- Percentage of traffic signals on-line (coordinated) compared to total number of signals scheduled for coordination
- Percentage of signal timing plans evaluated/developed for signals operating on computerized traffic signal system
- Average emergency traffic signal response time
- Percentage of system traffic signals operating online
- Number of signalized field maintenance tasks
- Number of repairs to controllers and peripherals

- Percentage of equipment operating without breakdown
- Percentage of emergencies responded to within 1 hour
- Percentage of detection malfunctions repaired within 10 days
- Percentage of street light problems responded within 48 hours
- Percentage of "knock down" signals repaired within 24 hours
- Percentage of customer requests initially responded within 24 hours

Several maintenance performance indices can be derived from their output performance measures and represent the real status of the physical system. These performance indices can be divided into effectiveness performance measures and efficiency performance measures.

#### 4.6.1.1 Effectiveness performance measures

Effectiveness performance measures indicate the relative coverage of the maintenance system with respect to the totality of the equipment under supervision. These performance measures are further divided into detection- and communication-specific performance measures.

##### *4.6.1.1.1 Detection-specific performance measures*

- Percentage of functional stop bar detectors operating in the control section

##### *4.6.1.1.2 Communication-specific performance measures*

- Percentage of failures on the link between central computer and local controller
- Percentage of failures on the link between local controller and field master

#### 4.6.1.2 Efficiency performance measures

The efficiency performance measures indicate the amount of malfunctioned or broken equipment that can be repaired or replaced during a predetermined time interval. These performance measures are divided into detection- and communication-specific performance measures.

##### *4.6.1.2.1 Detection-Specific Performance Measures*

- Percentage of stop bar detectors operating in the control section repaired within 15 days

#### *4.6.1.2.2 Communication-Specific Performance Measures*

- Percentage of central computer to local controller link failure repaired within 48 hours
- Percentage of local controller to field master link failure within 48 hours

### 4.6.2 Operational System Performance Measures

To better assess the impact of maintenance policies or the actual status of the physical system on the operation of traffic signal systems, specific operational performance experienced by motorists is required. A list of the potential operational performance measures for a control section and an intersection is presented below:

#### 4.6.2.1 Control section

- Travel time
- Travel time reliability
- Average delay
- Average speed
- Directional delay
- Directional speed
- Throughput
- Percentage of system congested (% of miles with LOS E or F ) [1]
- Traffic signal system performance index
- Customer satisfaction
- Improvement in mobility

#### 4.6.2.2 Intersection

- Delay
- Speed
- Number of stops
- Queue length
- Throughput
- Phase failure rate (fail to clear the queue) [9]
- Customer satisfaction

It is necessary to note that the concept of signal degradation index and performance index on travel time can be applied to other existing operational measures to actually measure the performance of a traffic signal system itself.

### 4.6.3 Functional Performance Measures

In advanced traffic management, downloading timing plans, retrieval of existing timing plans, video monitoring, and live traffic counts of remote traffic signals are functions that may be interrupted due to the degradation of the detection and communication equipment. The functional performance measures assess the impact of the degradation of the physical system on the operations of advanced traffic management systems from the perspectives of a traffic engineer and a traffic management center. These performance measures are:

- Percentage of signals with video monitoring capability on line
- Percentage of signals with timing plan uploading capability on line
- Percentage of signals with timing plan downloading capability on line

# 5. RELATIONSHIPS AMONG SIGNAL SYSTEM ARCHITECTURES

Based on the literature review, simulation experiments, interviews with agencies, and the input from the project contractor, a general view of communication failures between architectures was developed. The relationship between architectures can be explained by the operational behavior of the control section based on the type of component failure. Figure 9 presents the communication flows between a traffic management center and the local controllers for the main architecture types. It can be observed that the synchronization of timing clocks in local controllers is a critical piece of information shared by all the architecture types.

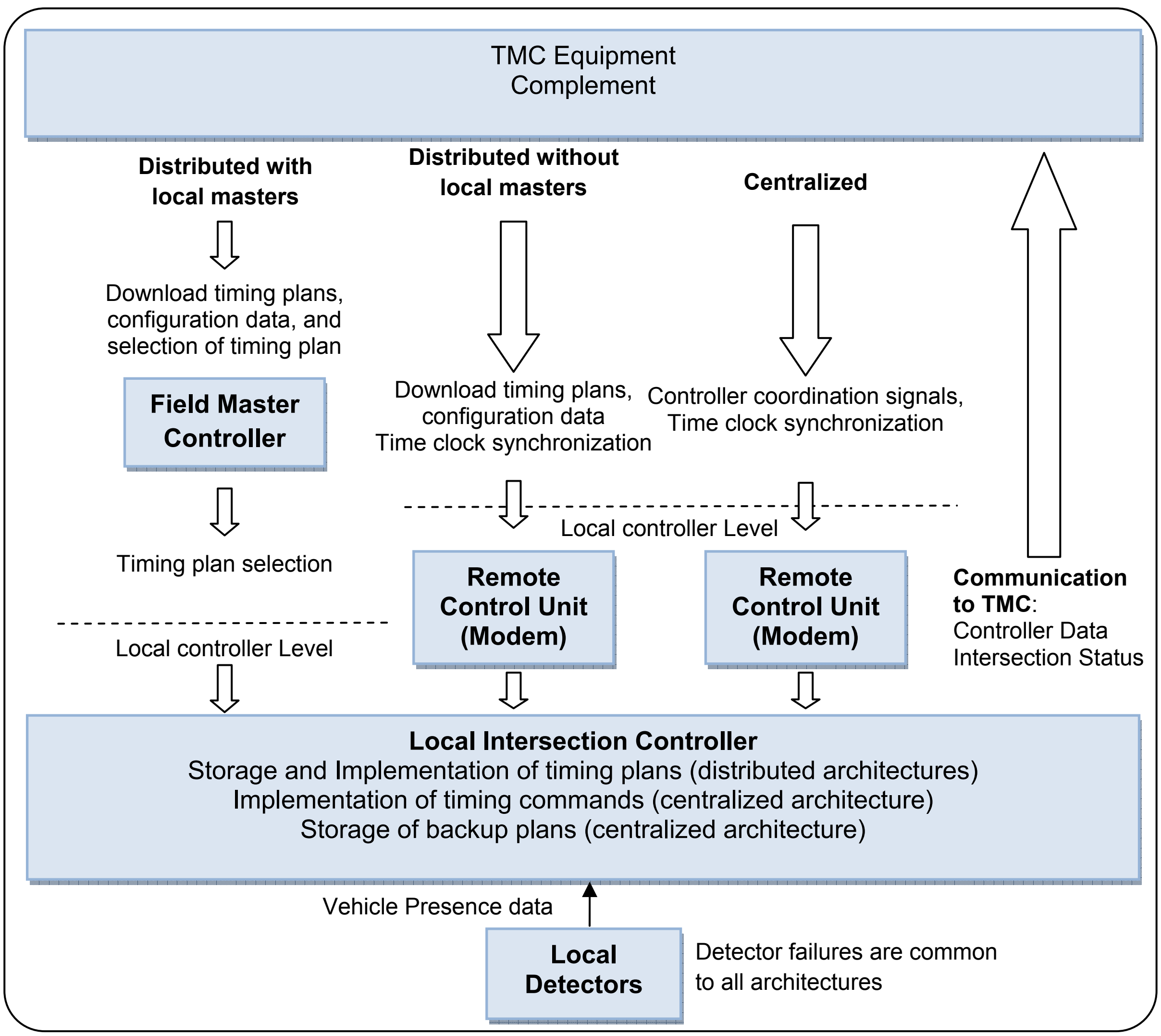



**Figure 9 Relationships among System Architectures**

The common effect of detection degradation can be observed in Figure 9. The effect of this type of degradation is translated in a modified green phase display and an incorrect allocation of the available capacity.

Communication failures are less frequent than detection failures and are easily detected by the maintenance personnel or TMC operators. In the majority of modern traffic signal control systems, communication failures are not noticeable to the public until the first few days of the failure. The effect of communication failures could surpass that of communication failures itself if they are not repaired within the first couple of weeks of its occurrence. The summary of the effect of communication failures by signal system architectures is presented in Table 2. The operational behavior describes in terms of timing plan display. The functional behavior is related to reporting function of the TMC.

**Table 2 Summary of the Relationship among Architectures**

| Architecture | Failure | Operational Behavior | Functional Behavior |
|---|---|---|---|
| Time-Based | Detection | Extended green phases and incorrect allocation of capacity | Not applicable |
| | Communication | Not applicable | Not applicable |
| Centralized | Detection | Extended green phases and incorrect allocation of capacity | Status of detection equipment downgraded |
| | Communication | Execution of backup timing plan, clock drifting, and progression affected. In some cases, controller will run in free operation | One or more intersections off-line, depending on network topology |
| Distributed with Masters | Detection | Extended green phases and incorrect allocation of capacity | Status of detection equipment downgraded |
| | Communication Master-TMC | Execution of stored timing plans by local controllers | Entire control section off-line |
| | Communication Master-Local Controllers | Execution of backup timing plan, clock drifting, and progression affected | One or more intersections off-line |
| Distributed without Masters | Detection | Extended green phases and incorrect allocation of capacity | Status of detection equipment downgraded |
| | Communication to TMC | Execution of backup timing plan, clock drifting, and progression affected | One or more intersections off-line, depending on network topology |

# 6. GENERIC TRAFFIC SIGNAL SYSTEM AND TEST SITES

The experiments and tests required to conduct the study were performed on selected control sections matching the majority of the characteristics of the control section described in the agency survey. The characteristics of the generic control section were derived based on information collected through the agency survey. There are a significant number of variables that can be taken into consideration in the determination of the generic control section. For simplicity, architecture, control section size, and urban street class were considered.

The size of the traffic signal system was defined as the number of coordinated signals, which were divided into five categories (similar to the categories used by the National Transportation Operations Coalition, 2007). These categories are listed below in Table 3.

**Table 3  Classification of Agencies by Size**

| Category | Number of Signals |
|---|---|
| 1 | Less than 50 |
| 2 | 50 to 150 |
| 3 | 150-450 |
| 4 | 450-1,000 |
| 5 | More than 1,000 |

In addition to the size of the traffic signal system, an approximate measure of the signal density for interconnected signals was derived from the survey. This approximate signal density was obtained by dividing the number of coordinated signals by the miles of interconnected signals for each responding agency. This density was classified according to the *Highway Capacity Manual* (HCM, 2000) classification of urban streets in Table 4.

**Table 4 Classification of Urban Streets by Signal Density (HCM, 2000)**

| Urban Street Class | Default (signals/mi) |
|---|---|
| I | 0.8 |
| II | 3 |
| III | 6 |
| IV | 10 |

The default values were assumed to be the middle point of an interval containing density values that can be represented by such a default value. This adaptation of the urban street classification of the HCM is presented in Figure 10.

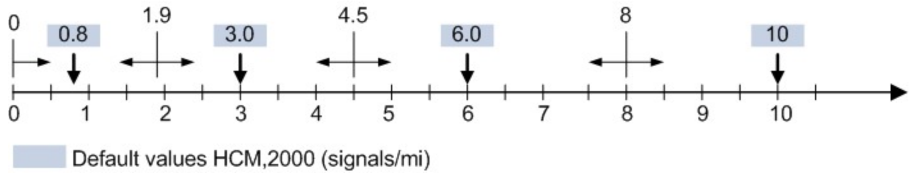



**Figure 10 Adaptation of the HCM 2000 Urban Street Classification Criteria**

The intervals used for classifying the agencies by signal density are presented in Table 5. This approximate measure of density is used to establish the average signal spacing for the simulation experiments that will be performed in later stages of this research project.

**Table 5 Adaptation of the HCM 2000 Urban Street Classification Criteria**

| Urban Street Class | Default (signals/mi) | Interval (signals/mi) |
|---|---|---|
| I | Less than 0.8 | 1.9 or less |
| II | 3 | 1.9-4.5 |
| III | 6 | 4.5-8 |
| IV | 10 | 8 or more |

## 6.1 Analysis for Distributed Architecture with Local Masters

The analysis of the control section for surveyed traffic signal system under a distributed architecture with local masters is shown in Table 6. Distributed architecture with local masters accounted for 15 percent of all the coordinated signals from the surveyed agencies. The top two types of control sections (when sorted by percentage of coordinated signals) accounted for 12.5 percent of all the coordinated signals from the surveyed agencies.

The characteristics of a typical control section for distributed architecture with local masters could be a type-III urban street with 6 to 10 signals and located in an agency with 450 to 1,000 coordinated signals. The second most frequent control section may have 6 to 10 signals and is usually located in a traffic signal system with between 50 and 150 coordinated signals. Of the 7 agencies with these characteristics, 3 are equivalent to a type-I urban street, 2 to a type II urban street, and 2 to a type III urban street.

**Table 6 Control Section Analysis for Distributed Architecture with Local Masters**

| Architecture | System Size (number of signals) | Control Section Size | Percent of Coordinated Signals* | Number of Agencies | Urban Street Class |
|---|---|---|---|---|---|
| Distributed with Local Masters | 50 or less | 5 or less | 0.0% | - | - |
| | | 6-10 | 0.0% | - | - |
| | | 11-15 | 0.2% | 1 | I |
| | | 16 or more | 0.0% | - | - |
| | **50-150** | 5 or less | 0.0% | - | - |
| | | **6-10** | **3.8%** | **7** | **I(3), II(2), III(2)** |
| | | 11-15 | 1.3% | 2 | I,II |
| | | 16 or more | 0.0% | - | - |
| | 150-450 | 5 or less | 0.0% | - | - |
| | | 6-10 | 0.0% | - | - |
| | | 11-15 | 0.0% | - | - |
| | | 16 or more | 0.0% | - | - |
| | **450-1,000** | 5 or less | 0.0% | - | - |
| | | **6-10** | **8.7%** | **1** | **III** |
| | | 11-15 | 0.0% | - | - |
| | | 16 or more | 0.8% | 1 | II |
| | More than 1,000 | 5 or less | 0.0% | - | - |
| | | 6-10 | 0.0% | - | - |
| | | 11-15 | 0.0% | - | - |
| | | 16 or more | 0.0% | - | - |

*The percentages were calculated based on the number of coordinated signals for all types of architecture; therefore, the percentages will not add up to 100.

The distribution of detection technology used in the top two types of control sections is 88 percent inductive loop, 11 percent video, and 1 percent microwave. The types of technologies used for communication between such signals are 72 percent fiber optic, 19 percent twisted pair, and 9 percent wireless. The types of technologies used by the surveyed agencies for communication between signals and traffic management center (TMC) are 73 percent leased lines, 21 percent fiber optic, 5 percent twisted pair, and 1 percent wireless.

## 6.2 Analysis for Distributed Architecture without Local Masters

The analysis of the control section for traffic signal systems under a distributed architecture without local masters is presented in Table 7 In this table, the number of signals and the agency count indicate that the typical control section is in an agency with 450 to 1,000 coordinated signals, having 6-10 signals per section, and with type II or III signal density.

The distribution of detection technology used in the top two types of control sections for distributed without local master type of architecture is 98 percent inductive loop, 1 percent video, and 1 percent microwave. The types of technologies used for communication between such signals are 99 percent fiber optic and 1 percent twisted pair. The types of technologies used by the surveyed agencies for communication between signals and traffic management center (TMC) are 52 percent fiber optic, 33 leased lines, 14 percent twisted pair, and 1 percent wireless.

## 6.3 Analysis for Centralized Architecture

The tabulated data for traffic signal system under a centralized architecture are presented in Table 8. Coordinated signals with centralized architecture accounted for 52 percent of all the coordinated signals from the surveyed agencies. The top two types of control sections for this architecture account for 38.4 percent of all the coordinated signals of the surveyed agencies. For different agency sizes, the most typical characteristics for a control section are 6 to 10 signals with a density equivalent to a type-II urban street. This result is the same for both agencies with more than 1,000 signals as well as those with 150 signals or less.

**Table 7 Control Section Analysis for Distributed Architecture without Local Masters**

| Architecture | System Size (number of signals) | Control Section Size | Percent of Coordinated Signals* | Number of Agencies | Urban Street Class |
|---|---|---|---|---|---|
| Distributed Without Local Masters | 50 or less | 5 or less | 0.0% | - | - |
| Distributed Without Local Masters | 50 or less | 6-10 | 0.3% | 1 | II |
| Distributed Without Local Masters | 50 or less | 11-15 | 0.0% | - | - |
| Distributed Without Local Masters | 50 or less | 16 or more | 0.0% | - | - |
| Distributed Without Local Masters | 50-150 | 5 or less | 0.9% | 1 | II |
| Distributed Without Local Masters | 50-150 | 6-10 | 0.0% | - | - |
| Distributed Without Local Masters | 50-150 | 11-15 | 0.0% | - | - |
| Distributed Without Local Masters | 50-150 | 16 or more | 0.0% | - | - |
| Distributed Without Local Masters | **150-450** | 5 or less | 0.0% | - | - |
| Distributed Without Local Masters | **150-450** | 6-10 | 0.2% | 1 | II |
| Distributed Without Local Masters | **150-450** | **11-15** | **3.5%** | **1** | **IV** |
| Distributed Without Local Masters | **150-450** | 16 or more | 2.5% | 1 | I |
| Distributed Without Local Masters | **450-1,000** | 5 or less | 0.0% | - | - |
| Distributed Without Local Masters | **450-1,000** | **6-10** | **10.8%** | **2** | **II,III** |
| Distributed Without Local Masters | **450-1,000** | 11-15 | 0.0% | - | - |
| Distributed Without Local Masters | **450-1,000** | 16 or more | 0.0% | - | - |
| Distributed Without Local Masters | More than 1,000 | 5 or less | 0.0% | - | - |
| Distributed Without Local Masters | More than 1,000 | 6-10 | 0.0% | - | - |
| Distributed Without Local Masters | More than 1,000 | 11-15 | 0.0% | - | - |
| Distributed Without Local Masters | More than 1,000 | 16 or more | 0.0% | - | - |

*The percentages were calculated based on the number of coordinated signals for all types of architecture , therefore, the percentages will not add up to 100.

**Table 8 Control Section Analysis for Centralized Architecture**

| Architecture | System Size (number of signals) | Control Section Size | Percent of Coordinated Signals* | Number of Agencies | Urban Street Class |
|---|---|---|---|---|---|
| Centralized | 50 or less | 5 or less | 0.0% | - | - |
| | | 6-10 | 0.0% | - | - |
| | | 11-15 | 0.0% | - | - |
| | | 16 or more | 0.0% | - | - |
| | 50-150 | 5 or less | 1.8% | 1 | I |
| | | 6-10 | 2.6% | 2 | I,II |
| | | 11-15 | 0.1% | 1 | II |
| | | 16 or more | 0.0% | - | - |
| | 150-450 | 5 or less | 0.0% | - | - |
| | | 6-10 | 3.5% | 1 | II |
| | | 11-15 | 2.3% | 1 | I |
| | | 16 or more | 0.0% | - | - |
| | 450-1,000 | 5 or less | 0.0% | - | - |
| | | **6-10** | **11.8%** | **1** | **II** |
| | | 11-15 | 0.0% | - | - |
| | | 16 or more | 6.2% | 1 | II |
| | More than 1,000 | 5 or less | 0.0% | - | - |
| | | **6-10** | **26.6%** | **1** | **II** |
| | | 11-15 | 0.0% | - | - |
| | | 16 or more | 0.0% | - | - |

*Percentages were calculated based on the number of coordinated signals for all types of architecture, therefore, the percentages will not add up to 100.

The distribution of detection technology used by the agencies with this typical control section is 89 percent inductive loop, 10.7 percent video, and 0.4 percent microwave. The types of technologies used for communication between signals are 57 percent twisted pair, 34 percent leased lines, and 9 percent fiber optic. The types of technologies used for communication between signals and traffic management center (TMC) are 54 twisted pair, 37 leased lines, and 9 percent fiber optic.

## 6.4 Test Site Models

The generic control sections were used to analyze the degradation performance of signal traffic timing. Based on data availability and retiming date three control sections were selected, two in FDOT District One and one in FDOT District Four. The first control section comprises 10 intersections on US 41, as presented in Figure 11. It is a six-lane divided highway with a speed limit of 45 mph. It is observed that the signal spacing ranges from 0.3 to 0.5 miles. The selected road segment was retimed during 2008 and turning movement counts were available.

- Number of signalized intersections: 10
- Length of control section: 2.7 miles
- Signal spacing between intersections: 0.3 and 0.5 miles
- Speed limit: 45 mph on a six-lane divided highway
- PM peak hour traffic
- SB traffic was heavier than NB
- SB has a large progression band, NB has a small one

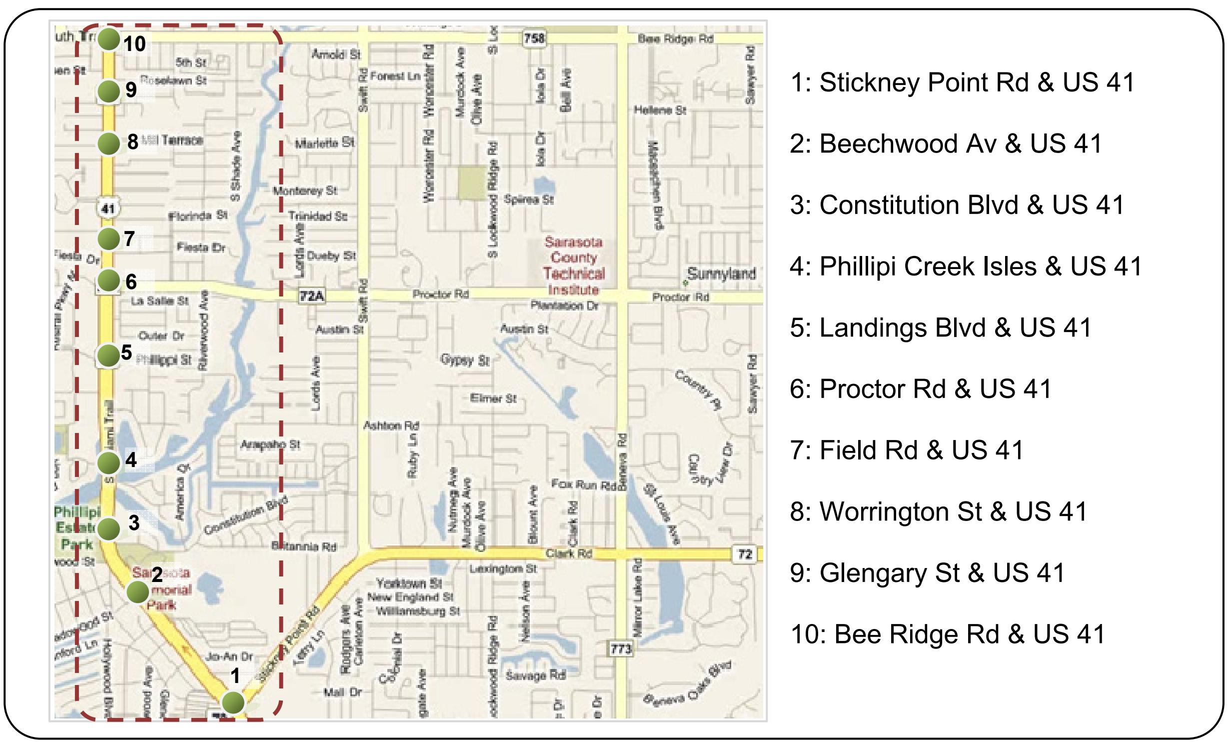



**Figure 11  Selected Control Section on US 41**

The second control section is located in the jurisdiction of City of Sarasota in FDOT District 1. The main directions are along Fruitville Road consisting of nine intersections communicating between US 301 and US 41. Figure 12 illustrates the selected roadway segment. All the intersections in the corridor are actuated-coordinated, and the speed limit for the section is 35 mph. The traffic volume and turning movements are available and were counted in 2008. The distances between the intersections range from 0.08 mile to 0.15 mile, which meet the typical control section requirement based on the survey information.

- Number of signalized intersections: 9
- Length of control section: 1 mile
- Average spacing between intersections: 0.12 mi
- Speed limit: 35 mph (most of the segment)
- PM  peak hour traffic
- EB volume is heavier than WB
- EB has a larger progress band

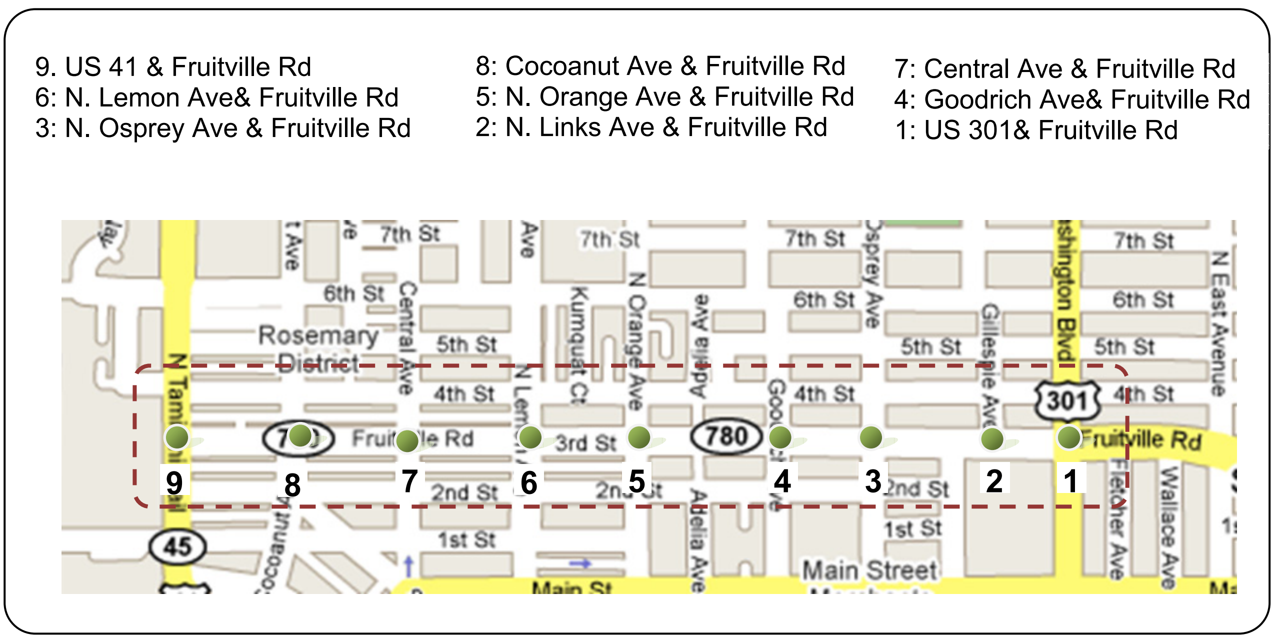



**Figure 12  Selected Control Section on Fruitville Road**

The third control section comprises eight intersections on W. Broward Boulevard, as presented in Figure 13. The speed limit for the section is 35 mph. It is observed that the average spacing between intersections is 0.17 mile.

- Number of signalized intersections: 8
- Length of control section: 1.2 miles
- Average spacing between intersections: 0.17 mi
- Speed limit: 35 mph (most of the segment)
- Midday peak hour traffic
- EB volume is heavier than WB

1. NW 11th Av & W Broward Blvd
2. NW 9th Av & W Broward Blvd
3. NW 7th Av & W Broward Blvd
4. NW 5th Av & W Broward Blvd
5. NW 1st Av & W Broward Blvd
6. N Andrews Av & W Broward Blvd
7. NE 3rd Av & W Broward Blvd
8. N Federal Hwy & W Broward Blvd

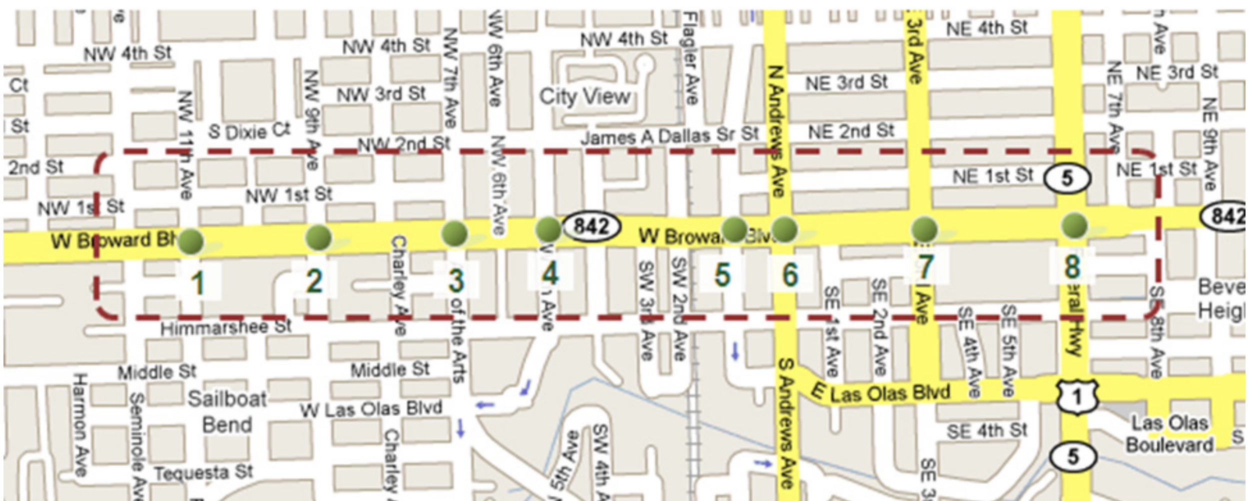



**Figure 13 Selected Control Section on W Broward Blvd**

# 7. SENSITIVITY ANALYSIS OF SIGNAL SYSTEMS DUE TO DEGRADATION

Based on the proposed approach, traffic signal system degradation is defined as the difference between the best performance that can be achieved by a system if all its components are operative and the observed performance when some communication and detection failures occur. Moreover, the proposed approach extends the concept of degradation to signal timing obsolescence due to changes in traffic patterns. These three concepts are interrelated and constitute the main degradation sources considered in this project.

## 7.1 Degradation Due to Detection Failures

In urbanized areas, traffic signals are organized into control sections and coordinated to provide progression to major vehicular flows. Usually, the priority of the traffic signal system manager is to favor the direction with the greatest demand. The detection system plays an important role in this aspect by providing the information of unused green time such that the controller can properly reallocate it during a given signal cycle.

An adequate detection infrastructure is necessary to ensure proper green time utilization and an adequate signal timing display. A detection failure can cause deterioration of the detection system, and this will cause modifications to the signal timing display in the field such as extending the green time when no vehicle is present. Traffic microsimulation was used to test several degradation scenarios of detection components. The methodological approach and results are presented in the following subsections

### 7.1.1 Simulation Methodology

Vehicle detectors are used to generate information specifying the presence of a vehicle at a particular location. Traffic signal systems use detectors to actuate or terminate a signal phase or measure traffic conditions in the network. Traffic detectors can be placed at the stop line of an intersection, upstream of an intersection, or downstream of an intersection, depending on the purpose of detection. Based on the results of the agency survey, most agencies responded that 76-100 percent of the detectors are used as presence detectors. This characteristic also is reflected in the typical control section determination.

Most of the detectors currently in use are loop detectors, followed by video detection. Detector failure may result in inefficient operation of traffic signal systems, which may cause the controller to display inadequate traffic signal timings.  As in many electronic components, detectors have a fail-safe mode, which consists of placing a continuous call on the controller for the movement associated with the failed detector. For an intersection either isolated or coordinated, the phase with failed detectors will display and extend the green until its maximum allowed settings in every cycle to avoid gap-out and phase-skipping, which can be referred as maximum recall.

A phase may be terminated by one of three possible mechanisms: when maximum green is reached (max-out), when corresponding force-off time is reached (force-off), or when the phase is terminated because there are no more vehicles to serve (gap-out). During coordination, the maximum green usually is not enabled or is set such that the phase will reach its force-off point before its maximum green. Under such circumstances, a detector failure will prevent the early termination of a phase due to gap-out. The unused green time of the phase will not be allocated to the major direction; instead, it will be consumed by the phase with a failed detector, which will cause a max recall.

For sensitivity analysis, a standard NEMA phasing was adopted. For example, for an east-west arterial intersecting with minor roads, the following standard NEMA phasing, as shown in Figure 14, is generally used.

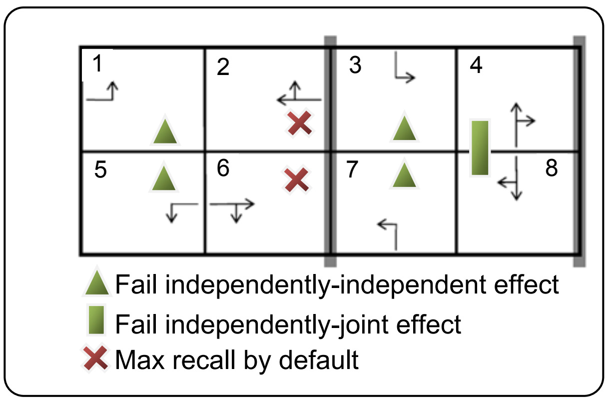



**Figure 14  Standard NEMA Phasing for a Major Intersection**

In Figure 14, the green triangles mean that the phases can fail independently. For instance, the detectors of phases 1 and 5 can fail individually and consume more green time than expected, preventing the major direction to take advantage of the unused green time. The detectors of Phases 4 and 8 may fail independently, but since these two phases have to cross the barrier at the same time, both phases will terminate simultaneously. If one of them has failed detectors, the other one will be on hold until both can cross the barrier at the same time.

Simulating detector failures by complete enumeration may result in a large number of experiments. For example, for an intersection with five phases, 32 (= $2^5$) simulation models are required to cover all the possible combinations of detector failures. The sensitivity analysis was carried out by following some simple rules to create significant data:

- All detection functional
- All detection failed
- One phase at a time
- One approach at a time
- One intersection at a time
- All left turns
- All left turns in both main directions
- All left turns by main direction
- All left turns in side streets
- All through movement in side streets
- Random scenarios

A total of 1,209 traffic microsimulation modes were generated using CORSIM. Each model had five runs. The results were collected automatically and stored in a database for further analysis. The results of the simulation models are presented in the following section.

### 7.1.2 Simulation Results and Sensitivity Ranges

The following figures provide an overview of the degradation caused by detection failures. It can account for up to 40 percent increase in the travel time. In Figure 15, the green line (lower part of the band) represents the travel time for westbound Fruitville Road during the AM peak hour when all the detection is operational. The red line indicates the travel time in the corridor when all of the detection is down. The gray or shaded area represents the different simulation runs (over 120 simulation models), with random scenarios in the middle of these two extreme situations. The degradation index for this case can be as high as 23 percent if the detection components are inoperative. Under these circumstances, the observed travel time on westbound Fruitville Road could be reduced by up to 23 percent by bringing all of the detectors back to the operation.

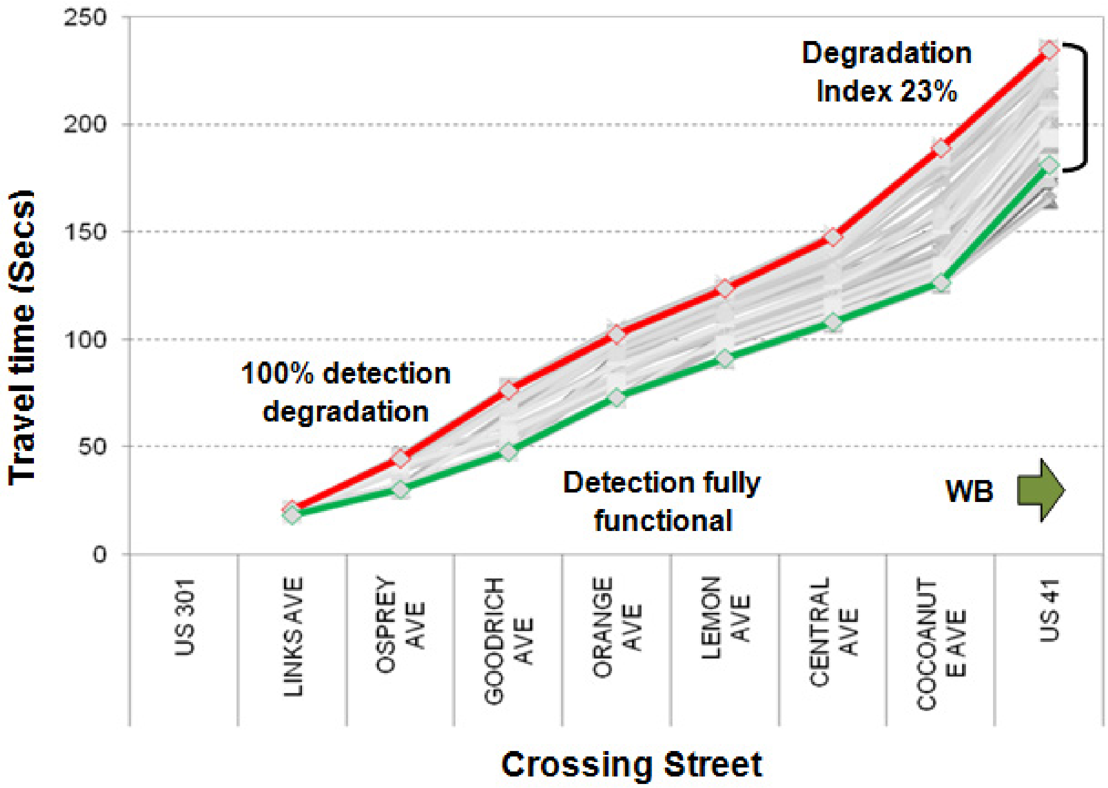



**Figure 15 Detection Failure Sensitivity Range on Fruitville Road Westbound during AM Peak Period**

Figure 16 shows the eastbound direction of the AM peak period for the test case of Fruitville Road. It can be observed that detection is critical at one particular intersection (Orange Avenue). If all detections are operational at this location, the intersection does not interrupt eastbound progression in the corridor, as indicated by dash lines in Figure 15. When detection failures occur, the queue at the eastbound approach will quickly accumulate due to the short link to its upstream intersection, which will significantly affect the eastbound coordination. The degradation on detection at the Orange Avenue intersection causes a major increase in travel time for the eastbound direction.

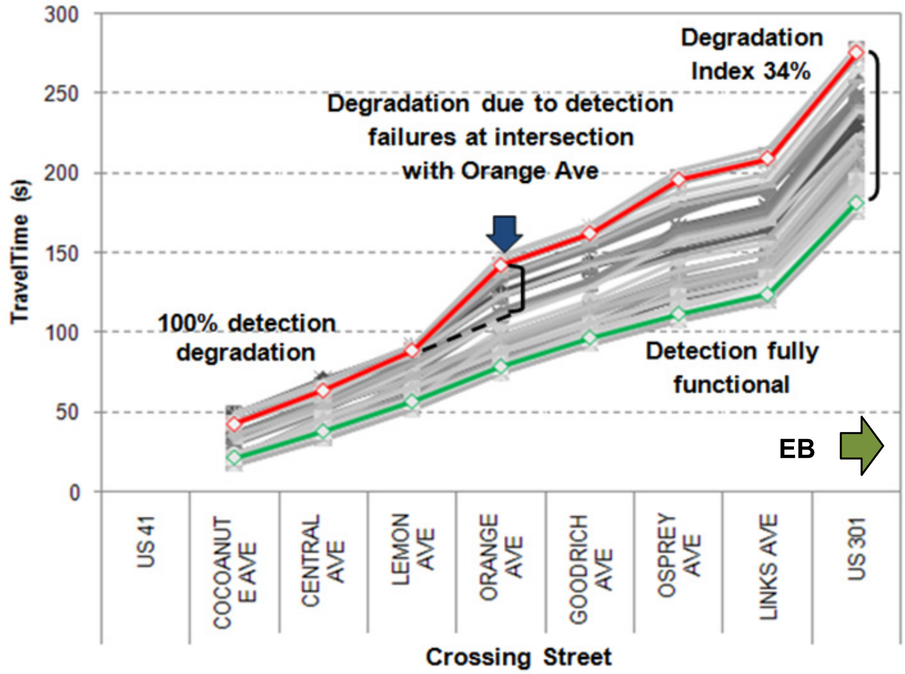



**Figure 16 Detection Failure on Fruitville Road Eastbound during AM Peak Period**

Figure 17 shows both the eastbound (EB) and westbound (WB) directions of the Fruitville Road corridor during the PM peak hour. The WB direction is heavily affected by the failure of its detection components. The failures of detections at Orange Avenue have more significant effects on westbound progression than that of eastbound and cause a significant degradation. A particular feature of the PM peak hour case is that the degradation consistently increases in the WB direction as it approaches US 41. This situation can be explained in part by the traffic distribution of the left-turn movement in the opposite direction (EB). The opposing EB left-turn volumes decrease towards the US 41; this implies that there is a high probability of phase-skipping or early termination of the EB left-turn phases by gapping-out during normal conditions. When detection is operational, the unused green time can go to the coordinated direction, contributing to the efficiency of the operation of the corridor. When these EB left-turn detectors fail, they significantly increase the travel time in the WB direction.

The EB direction, in this case, is not as sensitive to detection failures as the WB. Close to the east end of the corridor is a T-intersection (Links Avenue) with a significant amount of traffic turning right and low traffic turning left from northbound of the Links Avenue. Detection malfunctions will cause an increase in the green phase display for the northbound left turns, allowing a significant proportion of vehicles from the side street to turn right into the Fruitville corridor in good traffic conditions and therefore improving the travel time in the subsequent corridor segments. This can be observed in Figure 17

(EB) in the shaded gray area below the green line representing the ideal case performance.

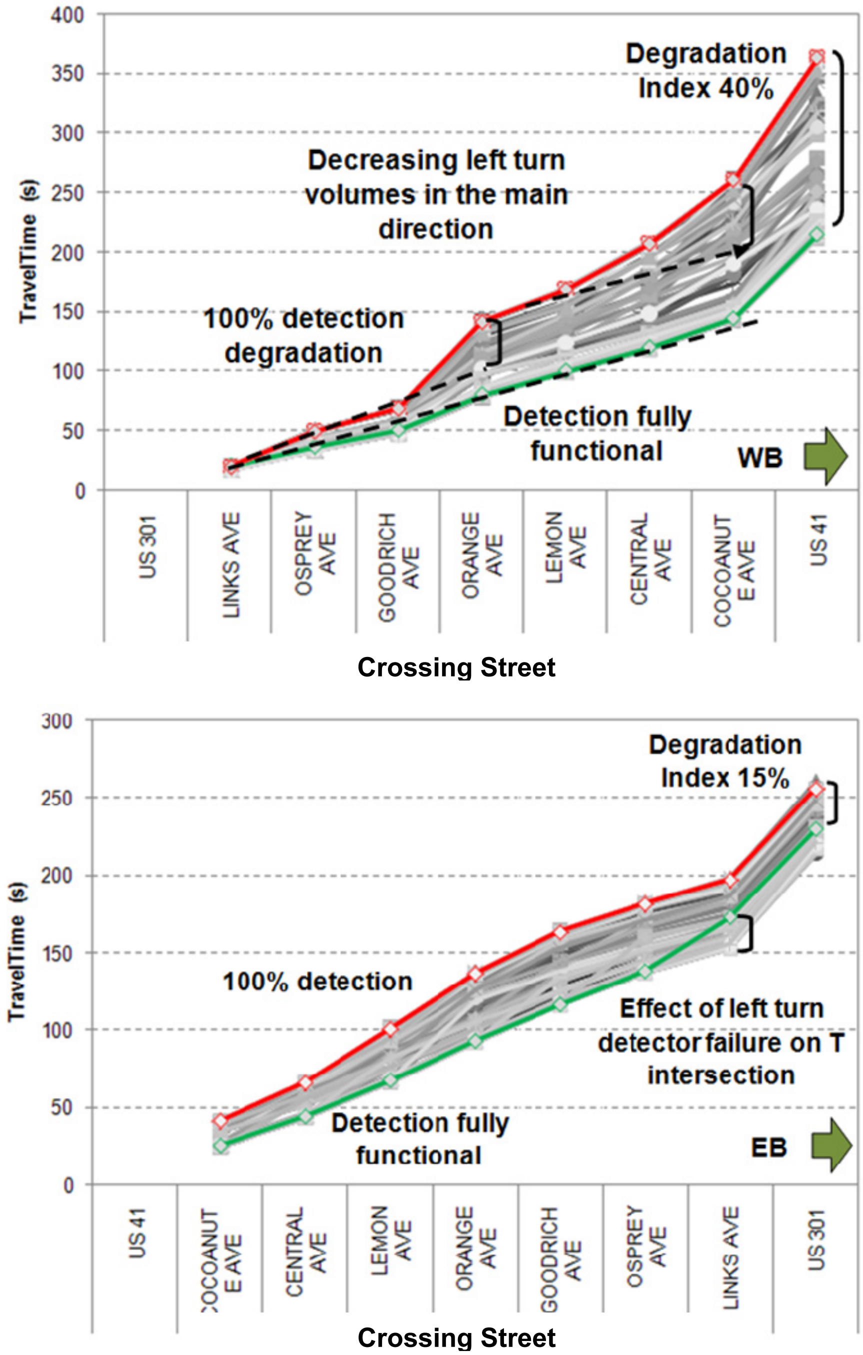



**Figure 17 Detection Failures on Fruitville Road Westbound-Eastbound during PM Peak Hour**

Additional cases of degradation for US 41 corridor are presented in Figure 18. Failures in the left turn detectors in the main direction significantly impact the performance of the corridor.

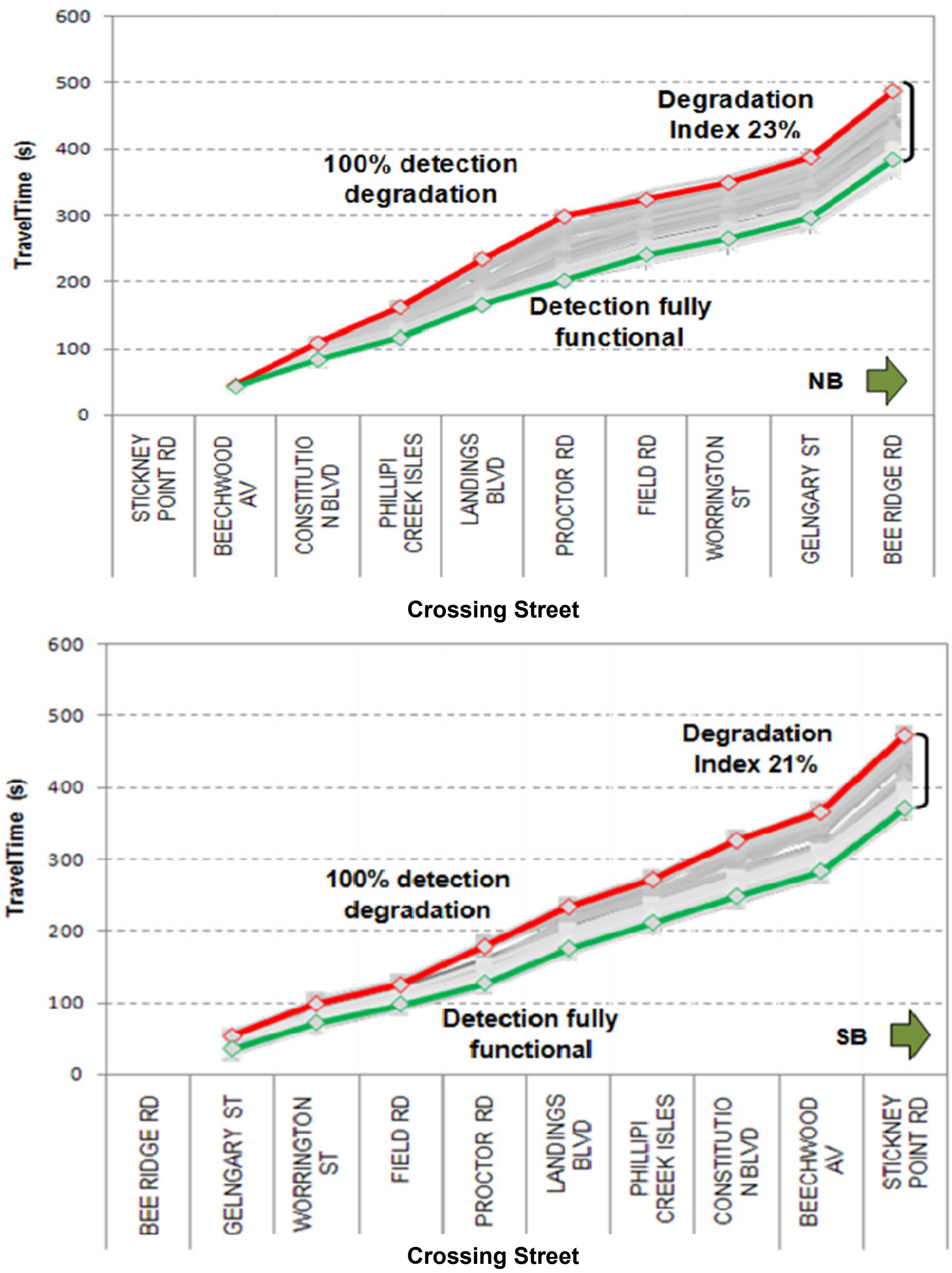



**Figure 18 Detection Failures in US 41 SB during the PM Peak Hour**

It can be observed from the above figures that the case of the US 41 corridor has slightly less degradation of the travel time than the case of Fruitville Road. The main difference between these two corridors is the volume in the coordinated direction and the number of lanes. These differences were captured by using the average volume per hour per lane. As the corridor becomes more congested due to traffic demand, the impact of the degradation of detection systems decreases.

During the detection experiments, it was found that failures on detectors for left-turn movements in one direction (e.g., EBL) will affect negatively the opposite coordinate direction (WBT) and will favor their original coordinated direction (EBT). This will translate in cases where the travel time in one of the coordinated direction is improved at the expense of the performance of the opposite coordinated direction in the presence of detection failures. This situation is site-specific, and it may occur in a large amount of possible combinations. The degradation index starts with a value of zero when there is no degradation and can climb as high as 40 percent. The sensitivity ranges for the degradation index for all the test cases are presented in Tables 9 and 10.

**Table 9 Sensitivity Ranges for Degradation Index for Detection Failures in Fruitville Road Test Case**

| Model | Direction | Ideal Travel Time (sec) | Degraded Travel Time (sec) | Degradation Index (%) |
|---|---|---|---|---|
| Fruitville AM | WB | 234.50 | 180.88 | 23 |
| Fruitville AM | EB | 275.56 | 181.74 | 34 |
| Fruitville MID | WB | 205.94 | 182.30 | 11 |
| Fruitville MID | EB | 221.30 | 193.68 | 12 |
| Fruitville PM | WB | 363.68 | 216.42 | 40 |
| Fruitville PM | EB | 256.04 | 218.24 | 15 |
| | | | **Maximum** | 40 |

**Table 10 Sensitivity Ranges for Degradation Index for Detection Failures in US 41 Test Case**

| Model | Direction | Ideal Travel Time (sec) | Degraded Travel Time (sec) | Degradation Index (%) |
|---|---|---|---|---|
| US41 AM | SB | 455 | 340 | 25 |
| US41 AM | NB | 496 | 401 | 19 |
| US41 MID | SB | 460 | 346 | 25 |
| US41 MID | NB | 417 | 383 | 8 |
| US41 PM | SB | 472 | 371 | 21 |
| US41 PM | NB | 486 | 376 | 23 |
| | | | **Maximum** | 25 |

## 7.2 Degradation Due to Communication Failures

Communication failures are among the main distinctive factors between traffic control system architectures. As discussed in previous sections, centralized systems rely heavily on communication compared to distributed systems. Communication between the traffic management center and a control section serves two main purposes: monitoring and control. Monitoring includes system checks, failure reporting, controller performance reporting, camera feeds, and traffic counts, among others. Control features include running second-by-second green-time display, broadcasting backup timing plans, and time-clock synchronization. In the traffic operations setting, the major effect of communication failure is time-clock drifting. Drifting may occur in different directions between intersections (e.g., controller clock running much faster vs. much slower). Drifting can occur at rates of one second per day and, if not repaired within a certain period, the degradation of the system will increase significantly.

### 7.2.1 Simulation Methodology

The approach taken to simulate clock drifting was to randomly generate a clock drifting direction (e.g., -1, 0, and 1) and apply a factor up to half of the cycle length of the intersection (also generated randomly). This simulates a typical clock drifting scenario for up to 20 percent of the signals in the control section; longer repair times are simulated by increasing the applied factor up to its maximum. A total of 853 simulation models were run to assess the effect of communication failures in traffic signal system degradation. The simulated scenarios (each with four degrees of severity) included the following:

- All the intersections
- One intersection at a time
- A random number of intersections

### 7.2.2 Simulation Results and Sensitivity Ranges

In most cases, the operational effects of communication failures are loss of synchronization between intersections interrupting progression. One or more intersections may fail at the same time, causing a wide range of effects. It is important to note that although there can be a worst case of performance reduction due to clock drifting, this case might be rarely achieved and has to be specifically generated. Since clock drifting occurs randomly, the process was simulated rather than designed. Under these circumstances, a random direction for drifting was created, and a severity factor was applied ranging from 5 to 60 seconds. The sensitivity range was found by taking the maximum value produced by the simulated communication failures. Figure 19 shows the results of the simulation experiments for the case of the Fruitville corridor. The bold lines represent the base scenario where communication is operational and ideal for the control section. The shaded area corresponds to departures from the established offsets due to clock drifting produced by a series of simulation experiments Figures 19 to 22 show additional cases of communication degradation examples.

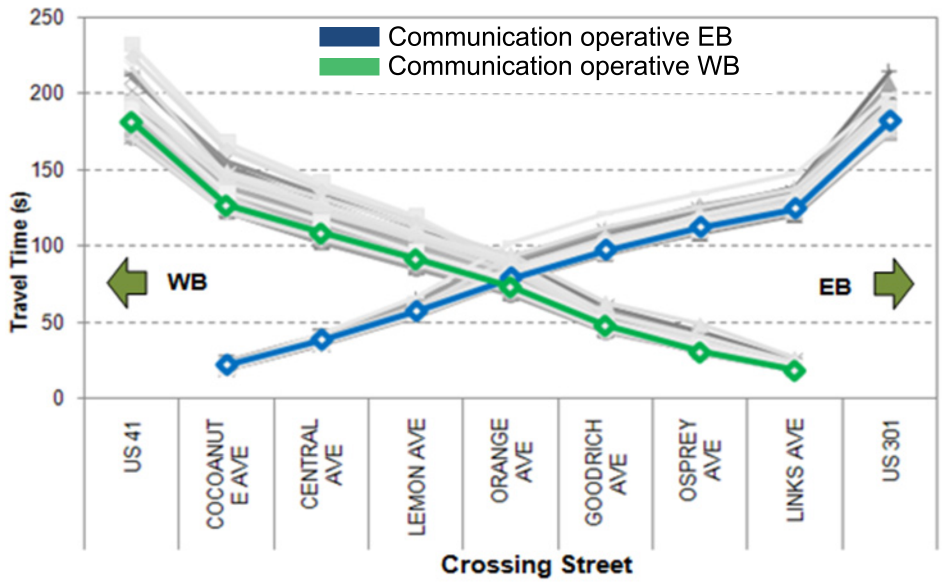



**Figure 19  Communication Failures on Fruitville Road during AM Peak Period**

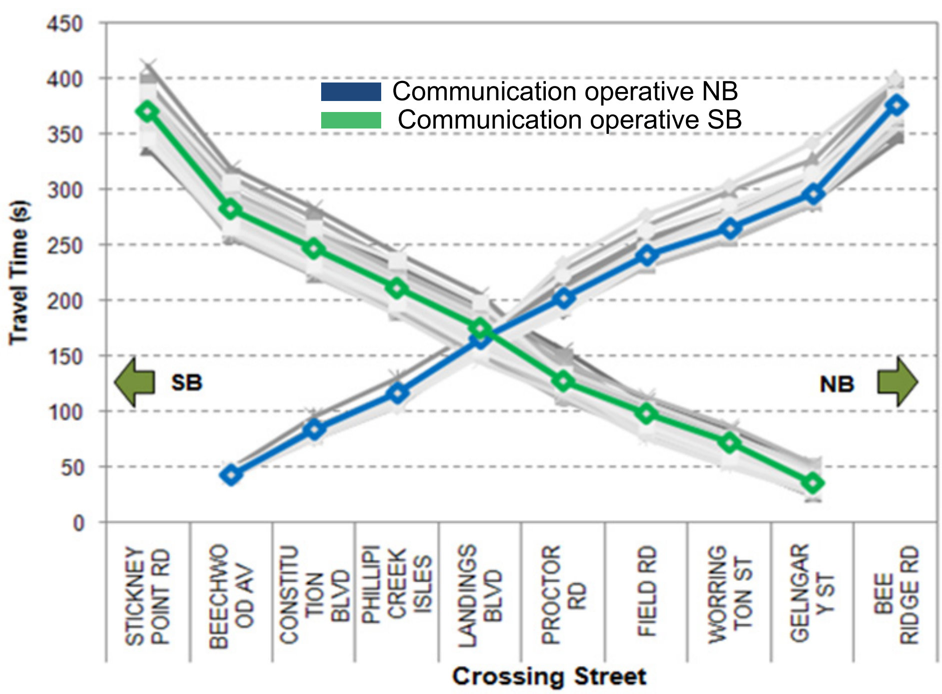



**Figure 20  Communication Failures on US 41 during PM Peak Period**

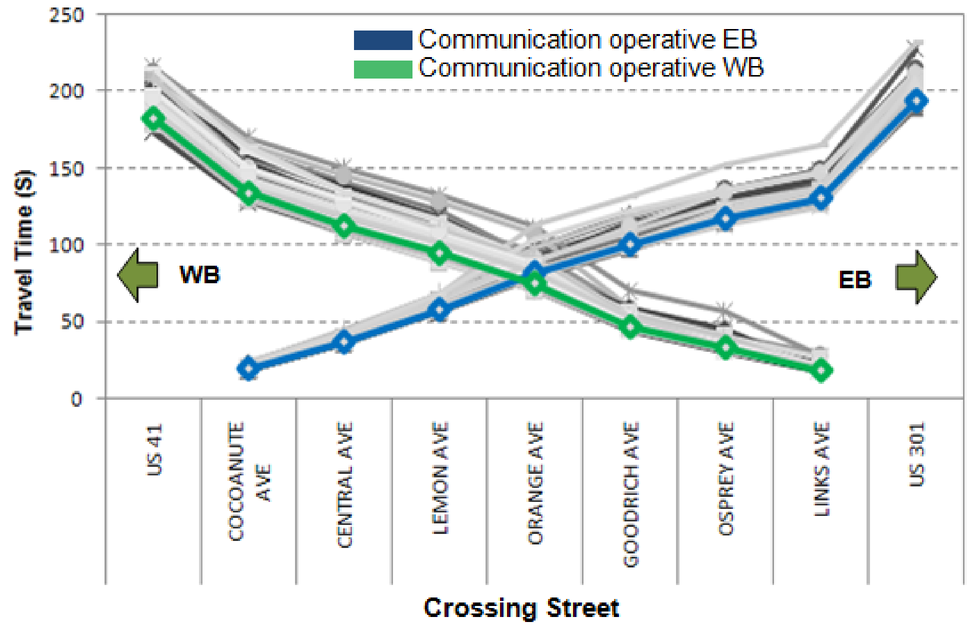



**Figure 21 Communication Failures on Fruitville Road during Midday Period**

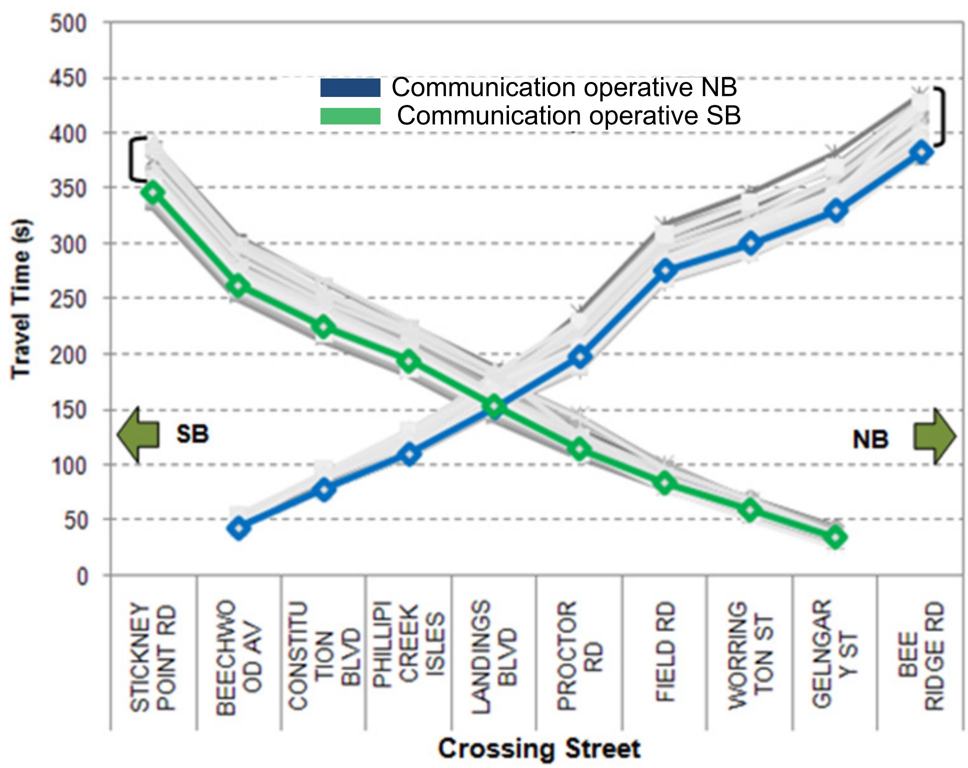



**Figure 22 Communication Failures on US 41 during Midday Period**

Since the communication failure simulation procedure produced a random variation pattern for the controller clocks, it was still possible to find signal parameters for a particular corridor that would produce better travel times than in the ideal situation. This was possible mainly since the timing parameters were adjusted to improve the traffic operations in the field, which may differ from the best configuration settings for a simulation model. Also, improvement in one direction can result in decreased performance in the opposite direction due to the shifting of the start of the green interval. A summary of the degradation indices for communication failures is presented in Tables 11 and 12.

**Table 11 Sensitivity Ranges for Degradation Index for Communication Failures in Fruitville Road Test Cases**

| Model | Direction | Ideal Travel Time (sec) | Degraded Travel Time (sec) | Degradation Index (%) |
|---|---|---|---|---|
| FRUITVILLE AM | WB | 181 | 231 | 22 |
| FRUITVILLE AM | EB | 181 | 214 | 15 |
| FRUITVILLE MID | WB | 182 | 215 | 15 |
| FRUITVILLE MID | EB | 193 | 231 | 16 |
| FRUITVILLE PM | WB | 216 | 259 | 17 |
| FRUITVILLE PM | EB | 218 | 244 | 11 |
| | | | **Maximum** | **22** |

**Table 12 Sensitivity Ranges for Degradation Index for Communication Failures in US 41 Test Cases**

| Model | Direction | Ideal Travel Time (sec) | Degraded Travel Time (sec) | Degradation Index (%) |
|---|---|---|---|---|
| US41 AM | SB | 340 | 374 | 9 |
| US41 AM | NB | 401 | 429 | 7 |
| US41 MID | SB | 346 | 393 | 12 |
| US41 MID | NB | 383 | 435 | 12 |
| US41 PM | SB | 371 | 411 | 10 |
| US41 PM | NB | 376 | 400 | 6 |
| | | | **Maximum** | **12** |

## 7.3 Degradation Due to Communication and Detection Failures Combined

A more realistic view of system degradation can be achieved when both types of failures (communication and detection) are considered. Experiments from both original data sets were sampled and combined to produce a set of simulation models comprising the combined effect of the detection and communication components on traffic operations. The sensitivity range was measured from the ideal condition to the maximum of the observed values of the simulated scenarios.

Figure 23 shows the degradation due to combined communication and degradation failures with respect to the best and worst cases of detection scenarios of one of the test cases during midday. It was observed that the combination of detection and communication failures caused a wider sensitivity range for the degradation index. In the US 41 Midday test case, the SB direction had more demand than the NB direction. In the presence of communication failures, this could lead to significant degradation, as shown in Figure 23. Additional degradation cases for the Fruitville test case are presented in Figure 24.

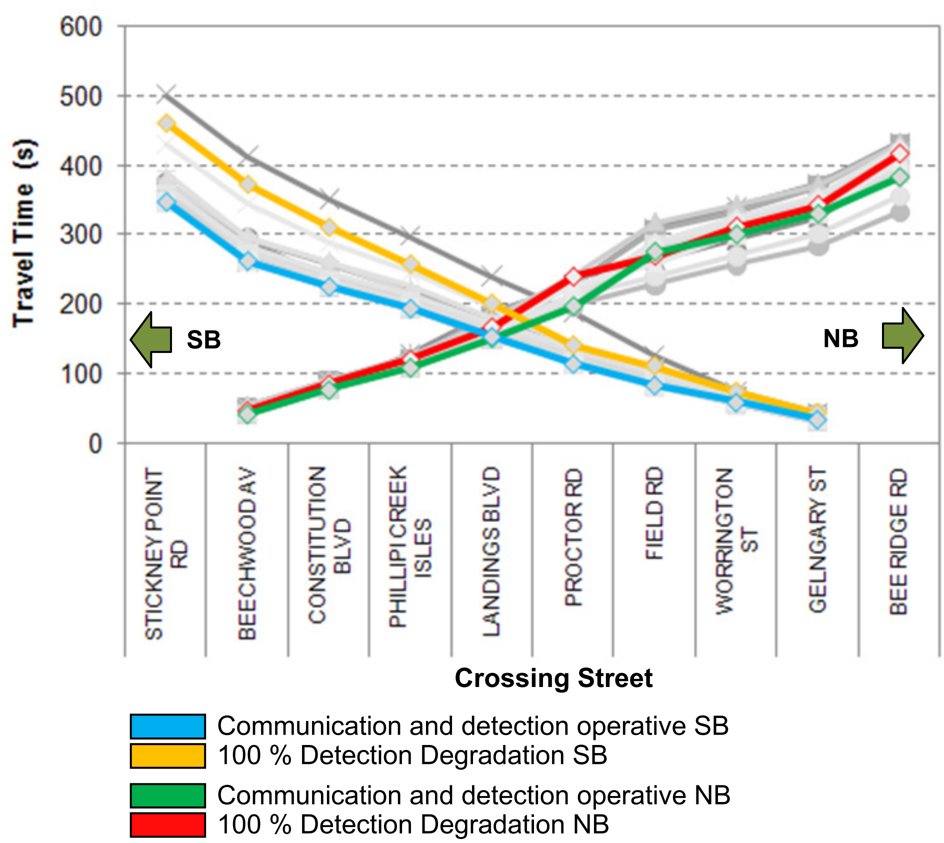



**Figure 23 Communication and Detection Failure on US 41 at Midday**

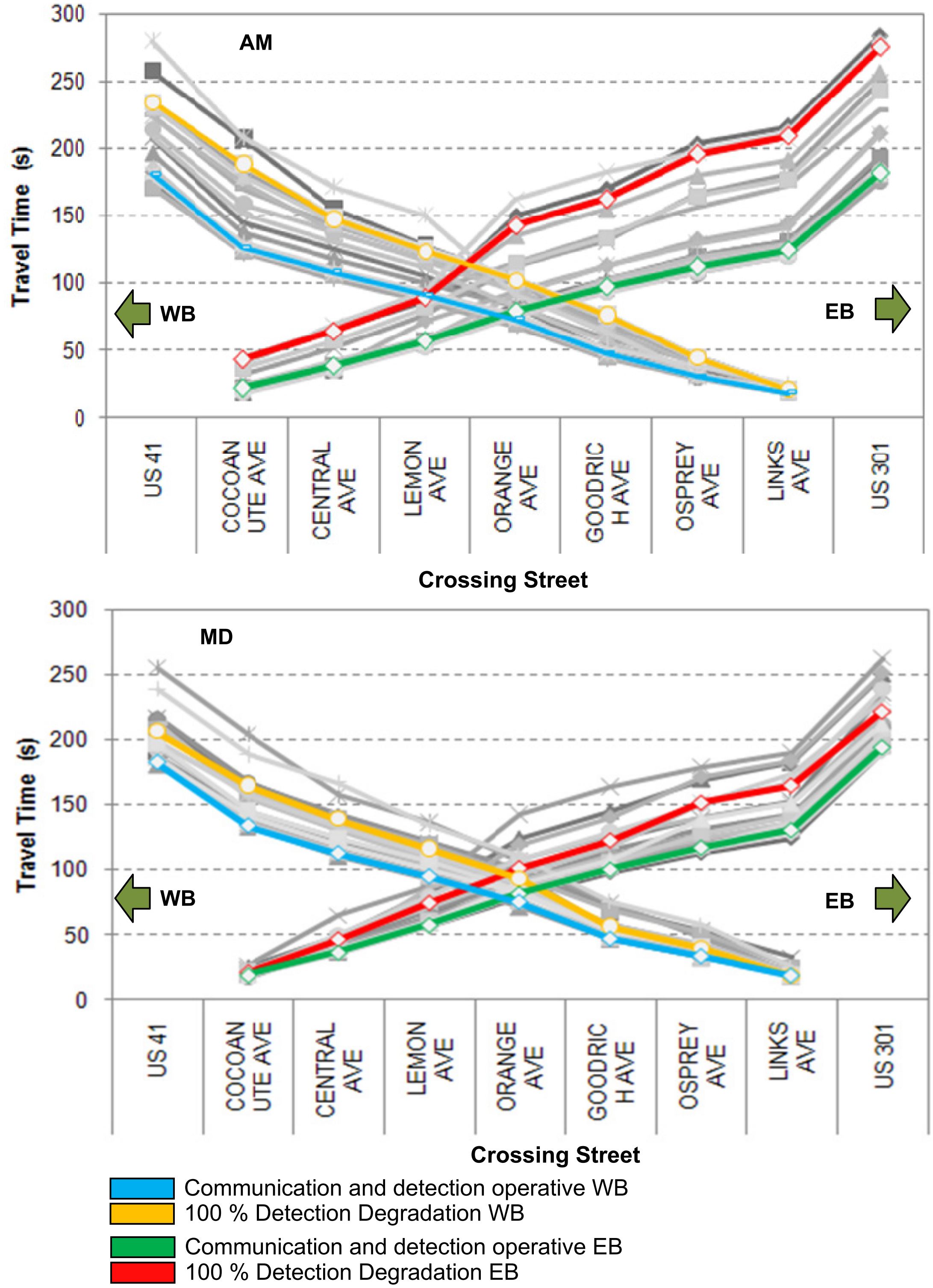



**Figure 24 Combined Communication and Detection Failures on Fruitville Road during AM and Midday Periods**

Figure 24 shows examples of combined degradation on the Fruitville corridor during an AM peak and midday conditions. In the critical case, 36 percent of the travel time in the corridor can be attributable to degradation of communication and detection components. Tables 13 and 14 summarize the results for the sensitivity ranges for the combined experiments.

**Table 13 Sensitivity Ranges for Degradation Index for Combined Failures in Fruitville Road Test Cases**

| Model | Direction | Ideal Travel Time (sec) | Degraded Travel Time (sec) | Degradation Index (%) |
|---|---|---|---|---|
| FRUITVILLE AM | WB | 181 | 280 | 35 |
| FRUITVILLE AM | EB | 182 | 284 | 36 |
| FRUITVILLE MID | WB | 182 | 255 | 28 |
| FRUITVILLE MID | EB | 194 | 262 | 26 |
| FRUITVILLE PM | WB | 216 | 364 | 40 |
| FRUITVILLE PM | EB | 218 | 277 | 21 |
| | | | **Maximum** | **40** |

**Table 14 Sensitivity Ranges for Degradation Index for Combined Failures in US 41 Test Cases**

| Model | Direction | Ideal Travel Time (sec) | Degraded Travel Time (sec) | Degradation Index (%) |
|---|---|---|---|---|
| US41 AM | SB | 341 | 481 | 29 |
| US41 AM | NB | 401 | 532 | 25 |
| US41 MID | SB | 347 | 501 | 31 |
| US41 MID | NB | 383 | 432 | 11 |
| US41 PM | SB | 371 | 473 | 21 |
| US41 PM | NB | 377 | 493 | 23 |
| | | | **Maximum** | **31** |

## 7.4 Degradation Due to Change in Traffic Patterns

Another effect that is present in real-world scenarios is degradation due to changes in traffic patterns mainly due to the growth of traffic volumes. Based on the agency survey, 48 percent of the agencies stated that they retime their signals every 1 – 3 years and another 15 percent every 3 – 5 years. This result indicates that there is an increased chance of encountering degradation due to changes in traffic patterns mixed with degradation due to detection and communication malfunctions.

The main difference between the degradation caused by the change of the traffic patterns and the degradation of communication and detection components is that when such components are repaired or replaced, the system has the ability to return to the original conditions. In the case of traffic signal timing, the prevailing conditions change, and the system will not return to its original conditions. The ideal scenario occurs after optimizing the signal timing to accommodate the new traffic.

As illustrated in Figure 25, three different signal conditions exist: current condition, degraded condition, and ideal condition. The current condition, at t=1, is the optimized signal timing for the prevailing volume conditions when the timing was implemented. The degraded condition, at t=2, represents the growth traffic demand with the original signal timing at t=1. Due to the increasing volume, the signal timing at t=1 did not meet the traffic demand at t=2. Therefore, the traffic signal timing is outdated, presenting a certain level of degradation. The ideal condition, at t=3, is the optimized signal timing after the volume increases. The degradation performance index is used to measure how the gap between the degraded condition and ideal condition.

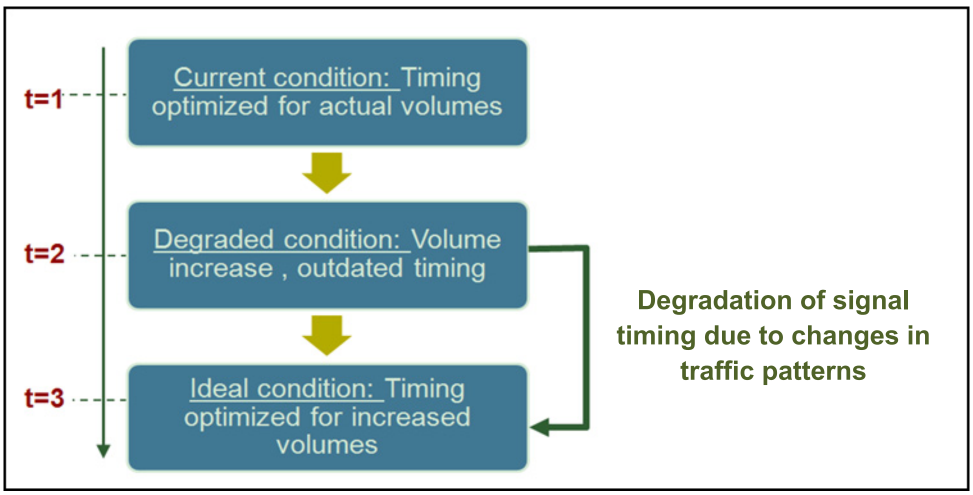



**Figure 25 Degradation Due to Changes in Traffic Patterns**

For signal timing, a weighted degradation index was calculated as a measure of the overall degradation in the control section. The weights are based on vehicles per hour per lane for each direction. The objective of this weighted degradation index is to give more importance to the direction of major volume and to have a single measure of degradation for the control section. Another reason to adopt this performance measure is to compensate for the interaction of the coordinated directions. It is common to encounter cases in which the improvement in one direction leads to major delays in the other.

$$WDI = \frac{WTT_D - WTT_I}{WTT_D}$$

Where,

*WDI*: Weighted Degradation Index, in percent

$WTT_D$: Weighted travel time in degraded conditions

$WTT_I$: Weighted travel time in ideal conditions

The weighted travel time is calculated using the following expression:

$$WTT = \frac{V_1 * TT_1 + V_2 * TT_2}{V_1 + V_2}$$

Where,

*WTT*: Weighted travel time

$V_1$: Average volume per hour per lane for direction 1 (EB, NB)

$V_2$: Average volume per hour per lane for direction 2 (WB, SB)

$TT_1$: Travel time for direction 1 (EB, NB)

$TT_2$: Travel time for direction 2 (WB, SB)

The weighted degradation index for the traffic signal system was calculated for traffic growth values ranging from 5 to 25 percent to represent system degradation due to frequency of retiming and traffic growth. The results are presented in Figure 26.

Figure 26 shows the weighted degradation index due to changes in traffic patterns for different traffic conditions in the test models (AO: AM off-peak; PM: PM peak hour; EH: evening hour; MD: midday hour). It can be observed that the magnitude of the increase in the weighted degradation index varies between sites. It is necessary to include additional variables to characterize each test case. The variable found to be most significant and useful to explain between-sites variations was the average volume per hour per lane as a measure of congestion. The maximum weighted degradation index was 16 percent.

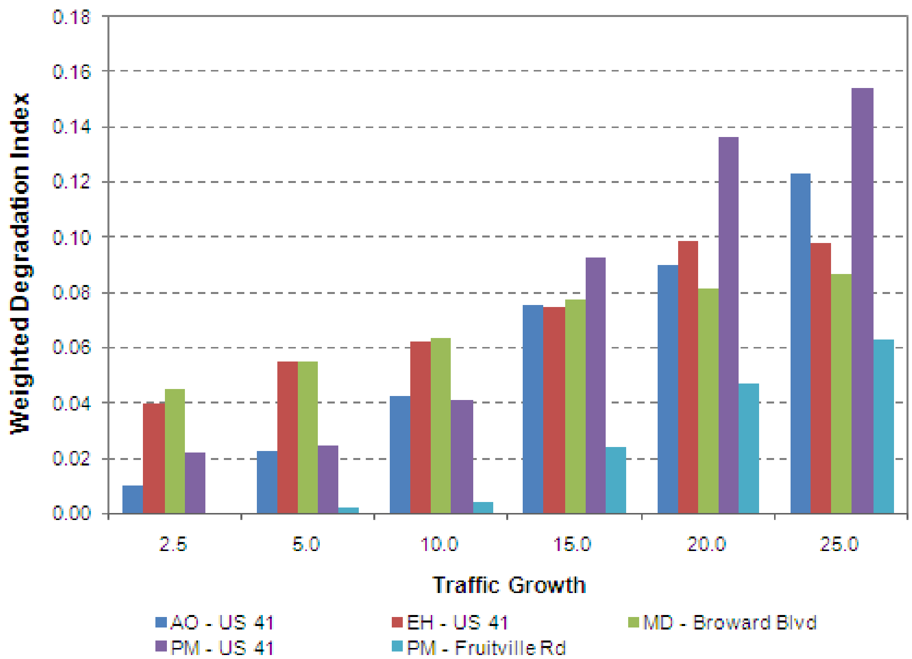



**Figure 26 Weighted Degradation Index for Degradation Due to Changes in Traffic Patterns**

# 8. DEVELOPMENT OF SIGNAL SYSTEM PERFORMANCE

The degradation of a traffic signal system is a relative measure of the system's capability to improve with respect to the prevailing conditions and system attributes. During the experimentation phase, several prevailing condition scenarios were tested (e.g., AM peak, PM peak, off-peak). It was noted that the degradation of a system is related to the level of traffic demand and the status of the detection and communication components. These aspects are discussed in detail in this section.

## 8.1 System Performance Model for Detection and Communication Degradation

Detection and communication play an important role in traffic signal system performance. These two aspects together can lead to up to 40 percent degradation of the travel time in a corridor. The Degradation Index (DI) is proposed as one of the major measures of system performance. When applied to the control section travel time, this index can be interpreted as the percent of the observed travel time attributable to degradation of communication and detection components or, equivalently, the expected reduction in travel time on a corridor if thorough maintenance or repair is performed on such components.

To develop a model for the estimation of system performance as a function of the status of the communication and detection components, it was necessary to define how these variables will be measured. Also, a variable representing the prevailing conditions was necessary to help explain the variation in the impact of the different degradation levels of detection and communication components. One important requirement for the performance model was that it needed to use only a few variables, and they needed to be easy to measure from a practical perspective.

The performance model is focused on the operational performance of a signalized intersection for the main coordinated directions. Specifically, the degradation index is measured with respect to travel time along a control section.

### 8.1.1 Detection System Status

Detection problems can occur at different components of a traffic control system (e.g., at the cabinet) and depend on the detection technology (e.g., video detection). One important aspect of the detection equipment is its fail-safe mode, which is set on constant call to avoid phase skipping. The effect of detection in traffic performance is associated with the phasing configuration at the intersection.

Based on previous experiments, it was found that left turns on the main street have a significant effect on the degradation index; therefore, it was decided to select a variable referencing these movements. Similarly, another set of variables representing the side street was also required. The selected detection status variables are defined as follows:

- *Percent of main street left-turn detection failed (LD):* Number of left-turn phases on the main direction with at least one detector failure divided by the total number of operational phases in the system. If a phase is on maximum or minimum recall (e.g., coordinate direction) as part of the timing plan it is not considered as degradation.
- *Percent of side-street detection failed (SD):*_ Number of side-street phases with at least one detector failed divided by the total number of operational phases in the system.

For the phasing example provided in Figure 27, one of the detectors of phase 5 failed; therefore, the entire phase is counted as failed. The detectors of the remaining phases are operational; therefore, they are not included in the total. There are a total of 6 operational phases, the percent of left-turn detection failed (LD = 1/6) and the percent of side street detection failed (SD = 0).

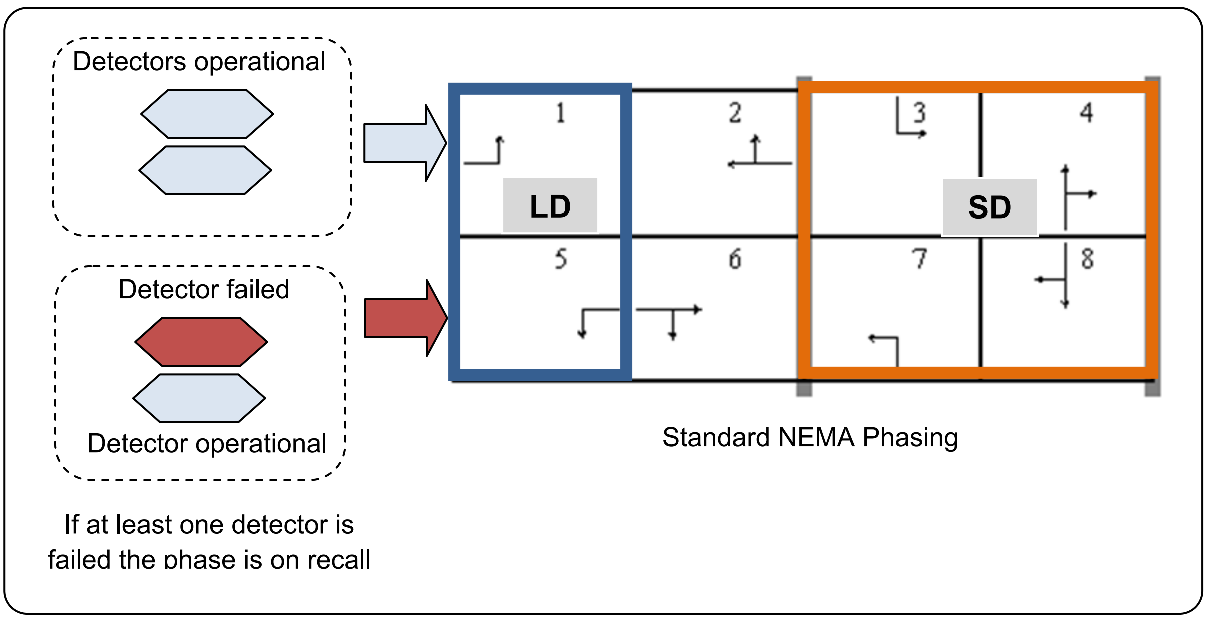



**Figure 27 Detection Status Variables Example**

### 8.1.2 Communication System Status

The status of the communication system is a time-dependent variable due to the drifting of the controller timeclock. This is mainly related to the severity of the drifting, which at the same time is a function of the downtime of the communication failure. This means that every day the signal is not fixed, the communication system degradation index can increase.

Communication status will affect the coordination plan by equivalently altering the offset of the signal that loses the communication by one second per day, on average. The number of days to repair a communication failure is regarded as the severity of the communication failure and is the variable used to describe the status of the communication system. When only one signal loses communication and is not repaired within a few days, the benefits of coordination can be significantly lost. When several signals get off-line at the same time, there are many possible cases. One of them is if the controller clock drift is in the same direction and magnitude for most intersections, then the system degradation may not be greatly affected. When only the critical intersection loses communication, the control section may suffer significant degradation.

### 8.1.3 Prevailing Conditions

The most significant prevailing condition for a traffic signal system is the demand. Additional factors such as the number of lanes and the distance between intersections are also part of the prevailing conditions. Location-specific definitions for the factors describing the prevailing conditions were avoided to achieve general insight of the impact of degradation of detection and communication on traffic signal system operations. After a factor screening process, it was found that the average number of vehicles per hour per lane (two-way) was a meaningful yet general variable to explain the prevailing conditions in the control sections. This variable was referred as VPHPL in the performance model.

### 8.1.4 Performance Model for Detection

The previously described variables were the most significant and practical to measure in the field out of the available information from the traffic microsimulation packages. A regression model was applied to the information extracted from the intensive simulation model runs. The results of the model are shown in Table 15.

**Table 15 Performance Model for Detection**

| Variables | Coefficient | Std. Err. | p-value |
|---|---|---|---|
| Intercept | 0.473 | 0.056 | <0.001 |
| Percent of main street left turn detection failed (LD) | 0.085 | 0.010 | <0.001 |
| Percent of side street detection failed (SD) | 0.129 | 0.009 | <0.001 |
| Logarithm of the volume per hour per lane (VPHPL) | -0.073 | 0.009 | <0.001 |

Equation:

$$DI = 0.473 + 0.085LD + 0.129SD - 0.073\ln{(VPHL)}$$

Where,

$DI$: Degradation index

$L$D: Percent of main street left-turn detection failed

$S$D: Percent of side street detection failed

$VPHPL$: Average number of vehicles per hour per lane (2-way)

The coefficient of determination or $R^2$ for the model was 0.78. It is important to note that the DI was reasonably approximated by a linear model for the interval of experimental values for detection and communication failures, and volume per hour per lane.

The degradation model for detection shows the main effects of the selected variables. It can be observed that all of the detection of the side street is almost equivalent to the detection only on the main street left-turns. Degradation in both the main street left-turn and side-street detectors contributes to an increase in the degradation of the operational characteristics of the control section. On the other hand, degradation decreases as the traffic volume increases, as indicated by the negative sign of the coefficient of the VPHPL. The coefficient of the VPHPL reflects the fact that the benefits of the detection system become less as the roads become more congested. These situations are illustrated in Figures 28 and 29. For the experimental values of detection failures on the side street and at constant prevailing conditions (VPHPL), the degradation index can reach values of up to 30 percent in non-congested situations. The impact of the detection failures is reduced as the volumes in the main direction increase.

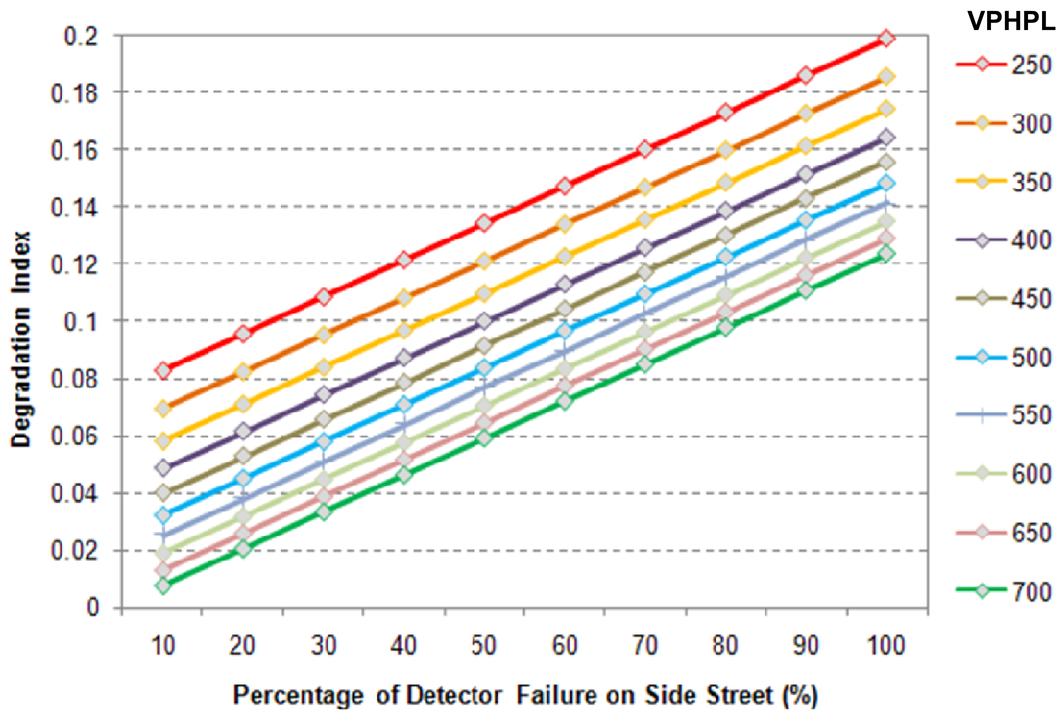



**Figure 28 Degradation Index vs. Percentage of Detector Failure on Side Street by Different Traffic Volumes (VPHPL)**

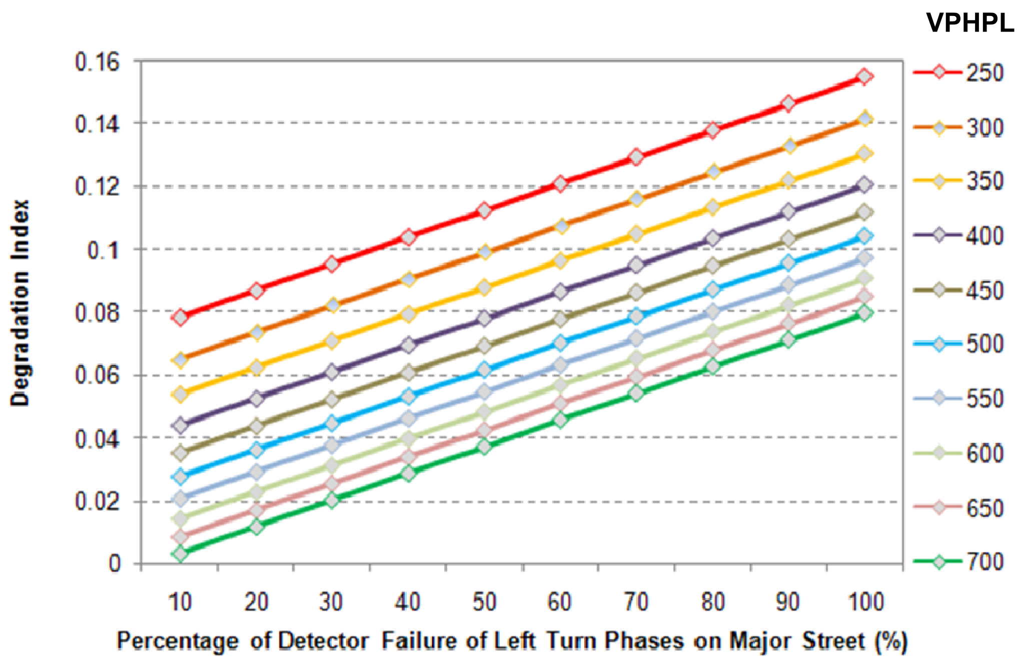



**Figure 29 Degradation Index vs. Percentage of Detector Failure of Left-Turn Phases on Major Street by Different Traffic Volumes (VPHPL)**

### 8.1.5 Performance Model for Communication Degradation

The communication failure data based on intensive traffic simulation runs were analyzed using linear regression. The severity of the degradation was measured from 0 to 60 seconds of timeclock drifting in a controller and the prevailing condition by the natural logarithm of the volume per hour per lane. The results are presented in Table 16.

**Table 16 Performance Model for Communication**

| Variables | Coefficient | Std. Err. | p-value |
|---|---|---|---|
| Intercept | -1.301 | 0.347 | <0.001 |
| Percentage of clock drifting severity (S) of the cycle length | 0.146 | 0.015 | <0.001 |
| Logarithm of the volume per hour per lane (VPHPL) | 0.216 | 0.058 | <0.001 |

Equation:

$$DI = -1.301 + 0.146S + 0.216\ln{(VPHPL)}$$

Where,

*DI*: Degradation index

*S*: Percent of clock drifting severity of the cycle length

*VPHPL*: Average number of vehicles per hour per lane (2-way)

The coefficient of determination or $R^2$ for the model was 0.60. In spite of the relatively moderate-to-low coefficient of determination value, the model explains a significant portion of the behavior of the degradation caused by communication failures. The positive sign of the coefficient of the VPHPL reflects the fact that clock drifting will affect the vehicle platoon at every intersection in the main direction; therefore, as the traffic volume increases, the degradation of communication failures increases due to accumulated effects. The severity of the degradation is related to the mean time to repair the communication failure. The longer it takes to fix the communication problem, the more the degradation increases. Figure 30 presents the degradation due to clock drifting. It can be observed that degradation due to communication failures increase as the traffic in the coordinated direction increases. Moderate-to-low traffic volumes are not significantly affected primarily because coordination can still be achieved to a certain degree for such prevailing conditions.

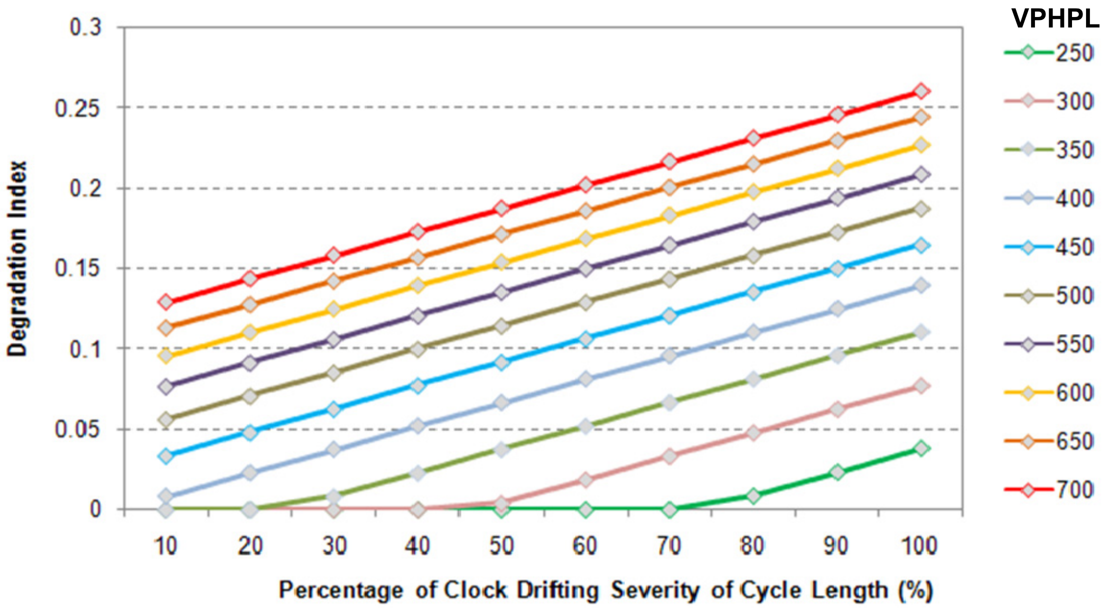



**Figure 30 Degradation Index vs. Communication Failure (Clock Drifting) by Traffic Volume (VPHPL) on Major Street**

### 8.1.6 Performance Model for Communication and Detection Degradation

Communication and detection failures were combined together by running the simulations. The degradation index was analyzed by applying the linear regression model. The severity of the degradation was measured from 0 to 60 seconds of timeclock drifting in a controller for the communication failure. Percentage of left-turn phases and side-street detectors failures are used to measure the detector failure. The result of the model is presented in Table 17.

**Table 17 Performance Model for Detection and Communication**

| Variables | Coefficient | Std. Err. | p-value |
|---|---|---|---|
| Intercept | 0.557 | 0.150 | <0.001 |
| Percent of main street left turn detection failed (LD) | 0.042 | 0.009 | <0.001 |
| Percent of side street detection failed (SD) | 0.128 | 0.032 | <0.001 |
| Percentage of clock drifting severity (S) of Cycle Length | 0.257 | 0.033 | <0.001 |
| Logarithm of the volume per hour per lane (VPHPL) | -0.089 | 0.024 | <0.001 |

Equation:

$$DI = 0.557 + 0.042LD + 0.128SD + 0.257S - 0.089\ln(VPHPL)$$

Where,

*DI*: Degradation index

*LD*: Percent of main street left-turn detection failed

*SD*: Percent of side street detection failed

*S*: Percent of clock drifting severity of the cycle length

*VPHPL*: Average number of vehicles per hour per lane (2-way)

The coefficient of determination or $R^2$ for the model was 0.78. The model explains a significant portion of the behavior of the degradation caused by detection and communication failures. Degradation in both the main street left-turn and side street detectors contributes to an increase in the degradation of the operational characteristics of the control section. The severity of the degradation is related to the mean time to repair the communication failure. The longer it takes to fix the communication problem, the more the degradation increases. The coefficient of the VPHPL is negative which reflects the fact that the effect of combined detection and communication failures on degradation index decreases when the average volume on a main street per hour per lane increases.

As shown in Figures 31 to 35, the detection failure is measured by the percentage of detector failures of left turn phases on the major street and percentage of detector failure on the side street when time drifting is at 10%, 20%, 30%, 40%, and 50% of the cycle length, respectively. With the increasing of the percentage of clock drifting to the cycle length, the degradation increases.

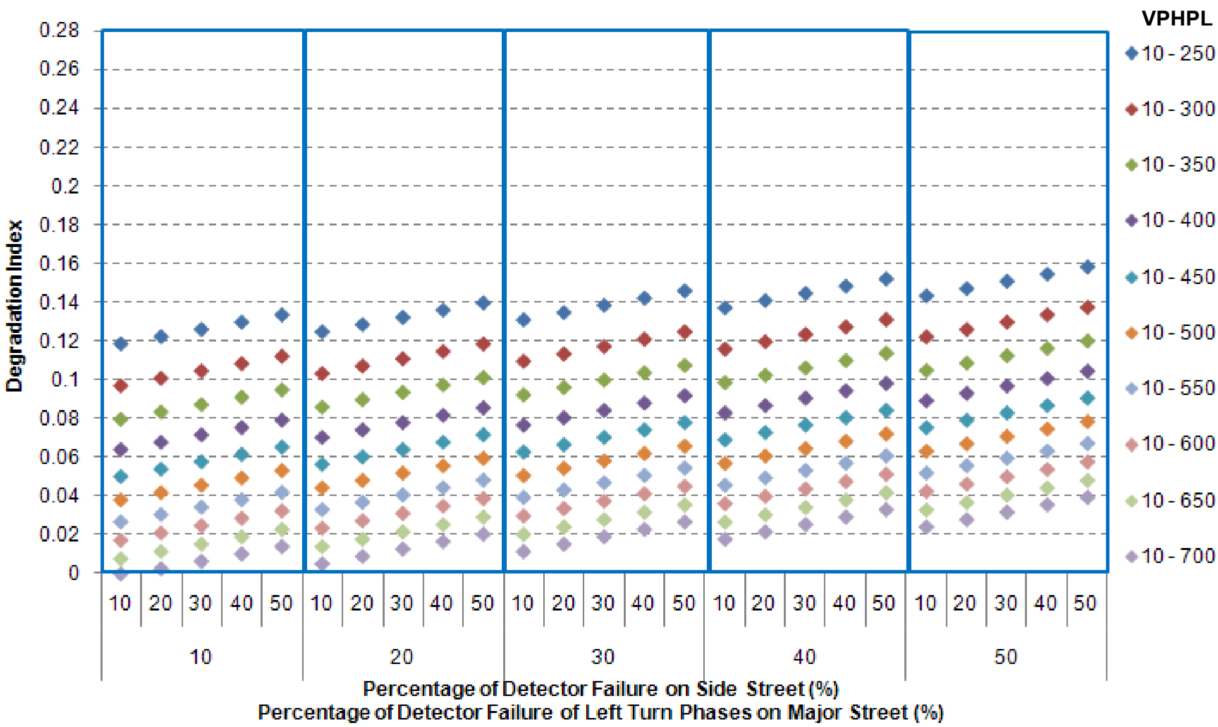



**Figure 31 Degradation Index vs. Detection Failure by Different Volume on Major Street for 10% Clock Drifting**

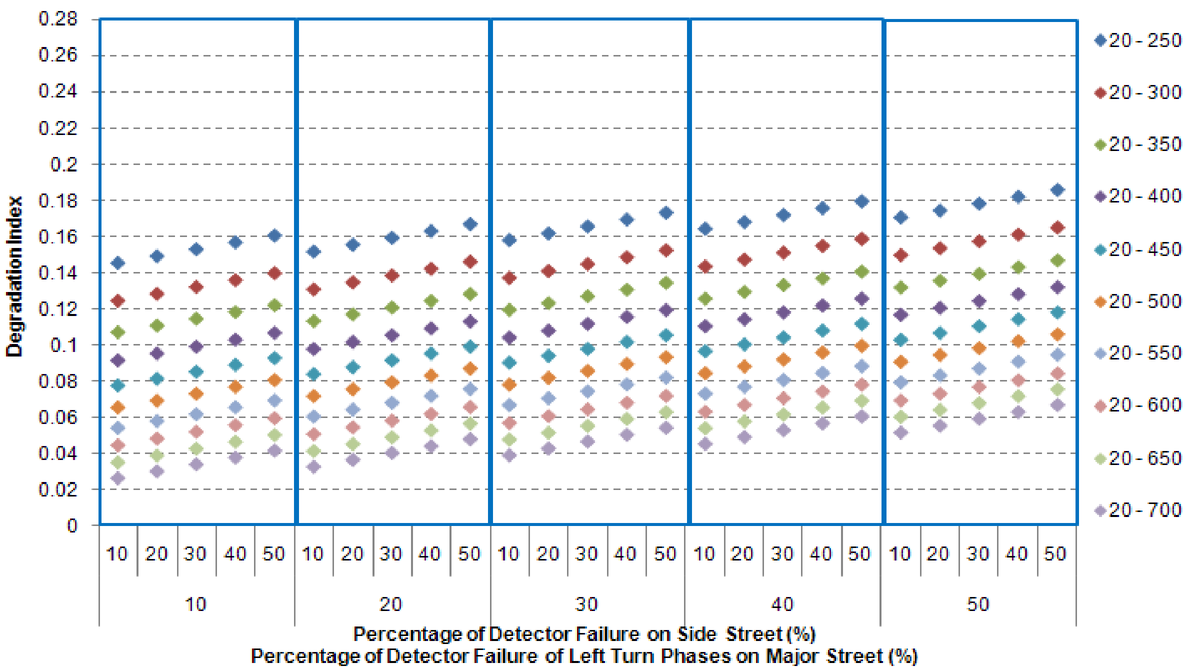



**Figure 32 Degradation Index vs. Detection Failure by Different Volume on Major Street for 20% Clock Drifting**

VPHPL

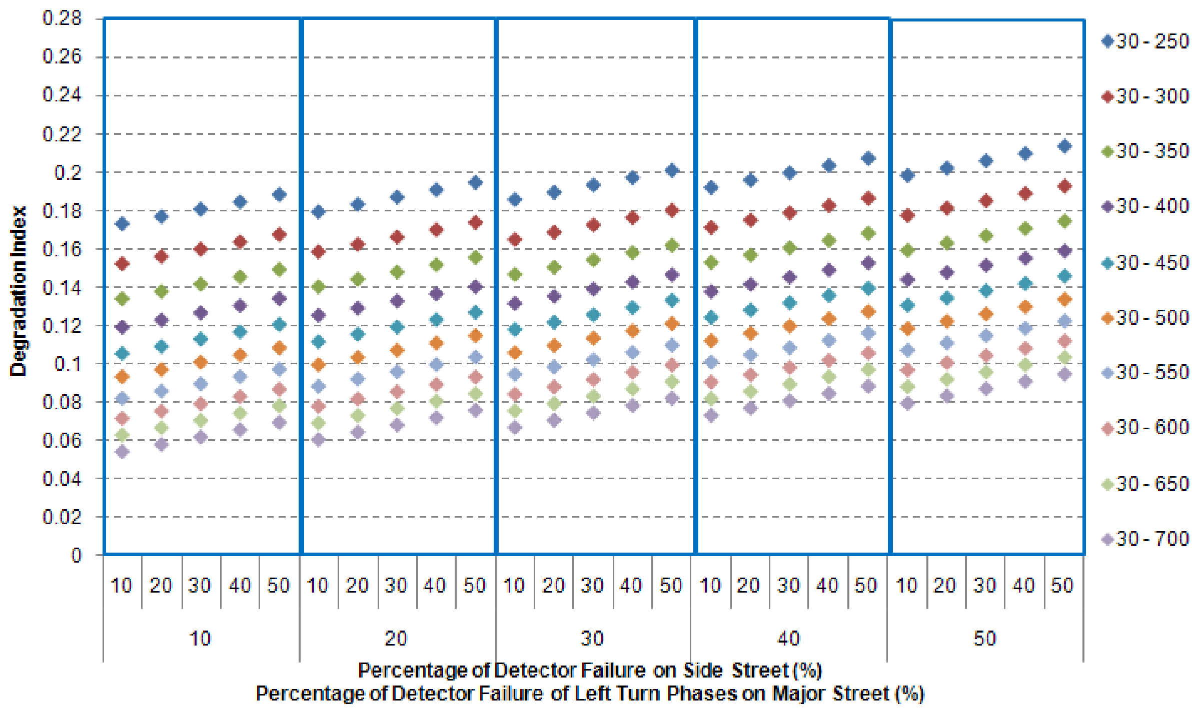



**Figure 33 Degradation Index vs. Detection Failure by Different Volume on Major Street for 30% Clock Drifting**

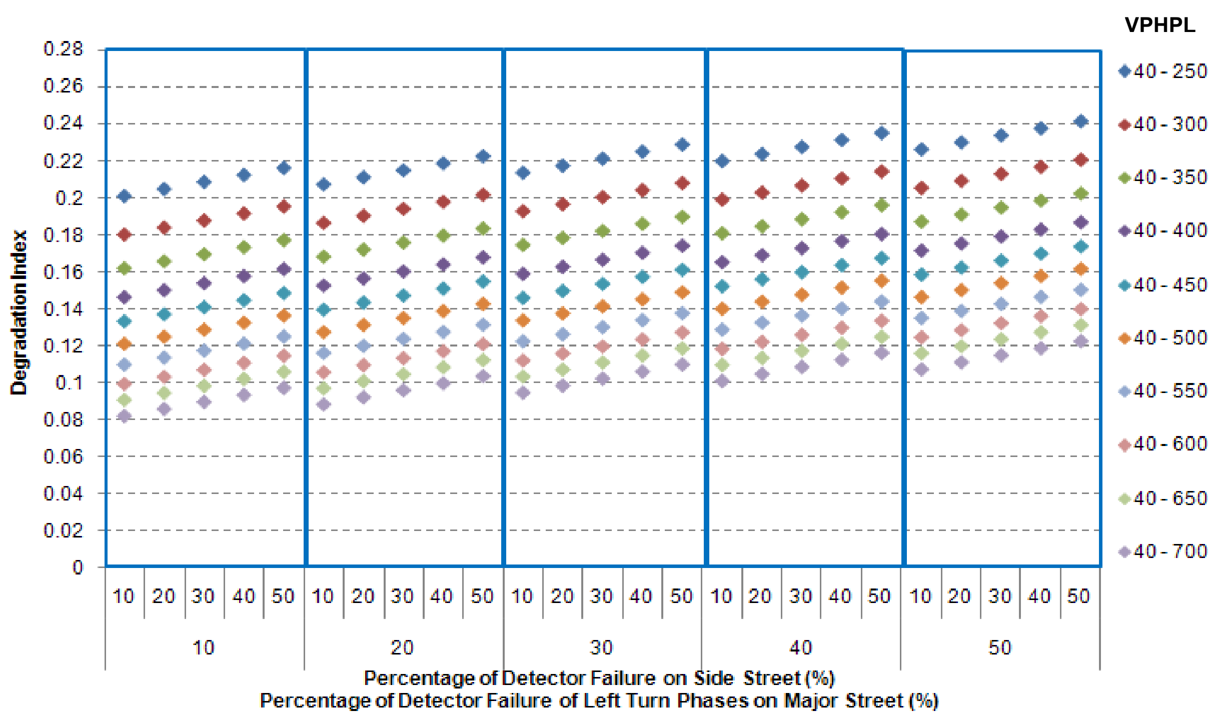



**Figure 34 Degradation Index vs. Detection Failure by Different Volume on Major Street for 40% Clock Drifting**

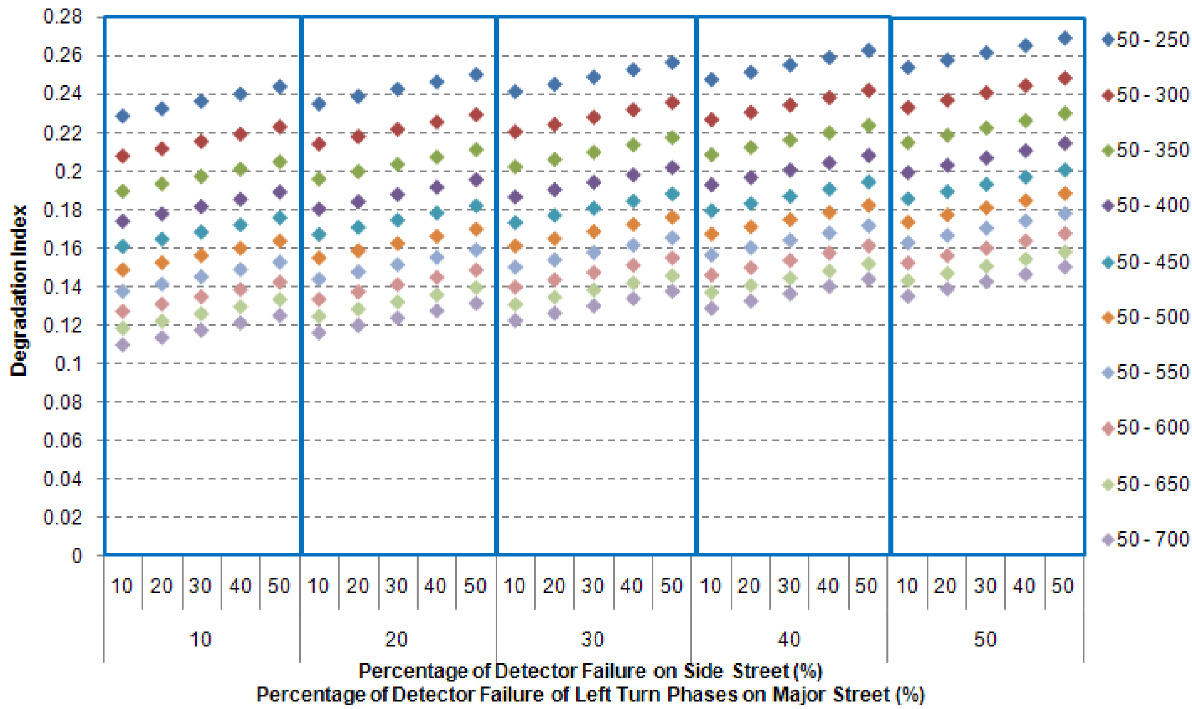



**Figure 35 Degradation Index vs. Detection Failure by Different Volume on Major Street for 50% Clock Drifting**

## 8.2 System Performance Model for Signal Timing Degradation

Signal timing is closely related to the degradation of communication and detection components. Failure of these two components will translate into an erroneous signal timing display. On the other hand, degradation can occur from signal timing itself as traffic volumes increase through time. Several scenarios of volume increase were tested to construct a performance model as a function of the prevailing conditions and the volume increase. The increase in travel time due to a growth of traffic volumes was predicted by a linear model, and the resulting predicted value was used estimate the degradation index. Table 18 lists the result of the performance model for signal timing degradation.

**Table 18 Model for Predicting the Change in Travel Time Based on Traffic Growth**

| Variables | Coefficient | Std. Err. | p-value |
|---|---|---|---|
| Intercept | -74.50 | 11.37 | <0.001 |
| Traffic Growth Rate (G) | 2.34 | 0.28 | <0.001 |
| Volume per Hour per Lane (VPHPL) | 0.14 | 0.02 | <0.001 |

Equation:

$$DI = -74.50 + 2.34G + 0.14VPHPL$$

Where,

*DI*: Degradation index

*G*: Traffic signal growth rate

*VPHPL*: Average number of vehicles per hour per lane (2-way)

The coefficient of determination or $R^2$ for the model was 0.81, and the model represents the seconds of increase in travel time due to signal timing degradation. It can be observed that the travel time increases with respect to the volume per hour per lane and the traffic growth rate for the control section. This behavior is illustrated in Figure 36. The estimated increase in travel time was used to derive a prediction of the degradation index as a function of the volume per hour per lane and the traffic growth. The predicted DI is presented in Figure 37.

The degradation index can also be interpreted as a measure of the potential system improvement. Figure 37 shows the predicted degradation index with respect to volumes per hour per lane and growth rates. At congested volumes (VPHPL>700), the degradation due to growth tends to slow down for 15% to 25% growth rate. On the other hand, when volume is low, the opportunity to improve the system is also low because the existing timing may handle the traffic increase reasonably. One can also observe that for the low volume scenarios, higher growth rates will have higher degradations. There is a range of critical volumes where there can be significant improvements by retiming or keeping the timing plans up to date with the volumes. From Figure 37, it can be observed that between 400 and 500 VHPPL, the degradation index reaches its maximum; therefore, corridors with this characteristic should be monitored regularly to seek opportunities for improvement.

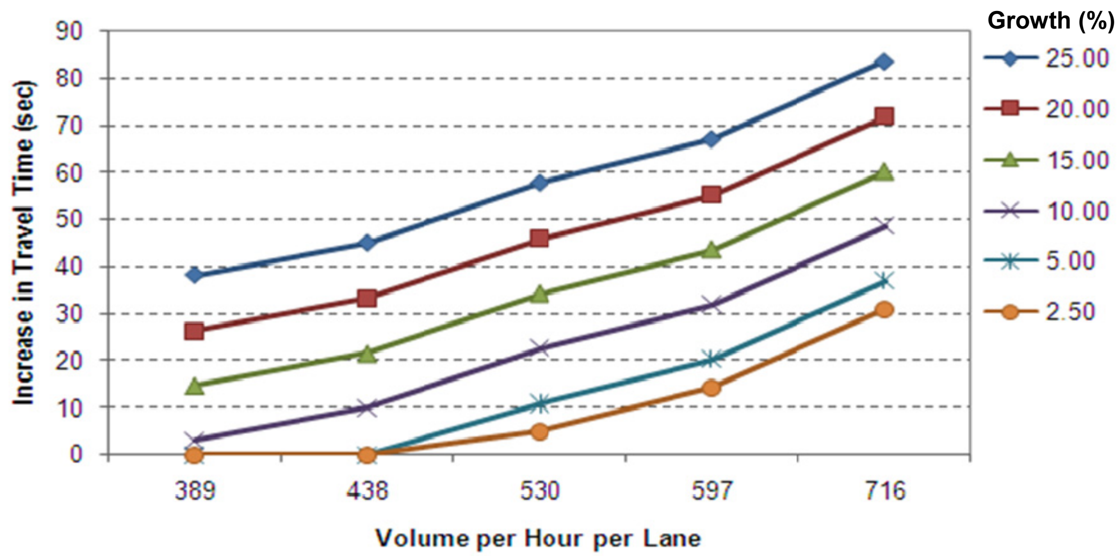



**Figure 36 Increase in Travel Time with Respect to Traffic Volumes per Hour per Lane on Major Street**

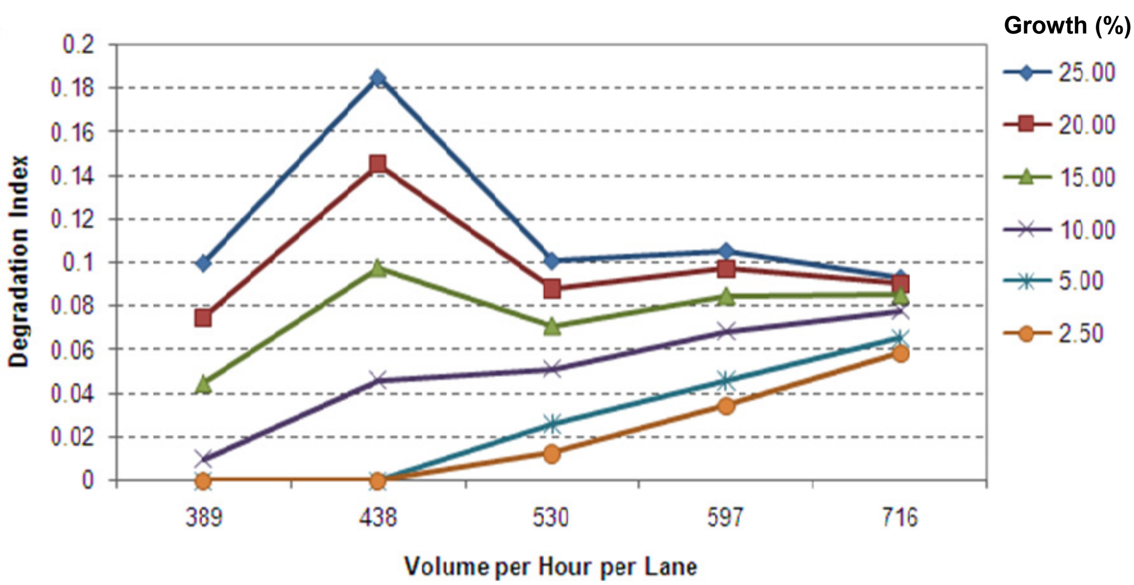



**Figure 37 Predicted DI with Respect to Traffic Volume per Hour per Lane on Major Street**

# 9. DEVELOPMENT OF RESOURCE ALLOCATION MODEL

## 9.1 Resource Allocation Performance Model

Functional detection and communication can significantly contribute to achieve operational performance goals (e.g., improvement of travel time) and functional performance goals (e.g., the number of intersections on-line). On the other hand, the degradation of detection and communication components may impose a barrier to achieve and maintain operational performance goals. To achieve and maintain an acceptable or target operational level (e.g. 90% or 95% of detectors functional), traffic signal system management has to prioritize the resource allocation such that the overall system goals are met.

Based on the agency survey and detailed interviews, it was discovered that the maintenance function for traffic signal systems is performed differently at each location. Usually, agencies assign personnel with several functions to achieve cost efficiencies. These situations lead to a wide variety of organizational configurations for the maintenance of traffic signal systems. Variations in accounting systems between agencies also may lead to underestimating or overestimating maintenance costs, depending on the charges applied to the maintenance department. Since the generic control section is a common element for all of the traffic systems, a performance-oriented resource allocation model was developed. The performance-oriented resource allocation consists of establishing the relationship between system degradation (e.g., degradation in travel time) and main detection and communication resources that may be available. This relationship allows the traffic signal system management to set the amount of resources applicable to detection and communication maintenance that are needed to achieve the desired operational goals.

### 9.1.1 Overview of the Effect of Resource Allocation in System Performance

The detection and communication components for a traffic signal system should be maintained at a minimum level to achieve the desired operational performance. The components of the system suffer breakdowns due to a variety of reasons such as equipment malfunctions and failures, environmental conditions, and installation procedures, among others. When a system is at the planning stage, all the performance estimations generally are based on a fully-operational system. In reality, the system may not perform as desired, and it likely experiences component failures, which are referred to as the degradation of the system components. These components failures are characterized by their frequency and the time it takes to repair them. This time between the start of component failure and completion of repair is usually referred as to the downtime of the component failure or degradation of the component. Generally, the frequency of failure is an intrinsic characteristic of a component. Changes to equipment with better technologies will have an effect in the frequency of failures, whereas improving the maintenance operations will reduce the downtime of the components. This relationship is explained in Figure 38.

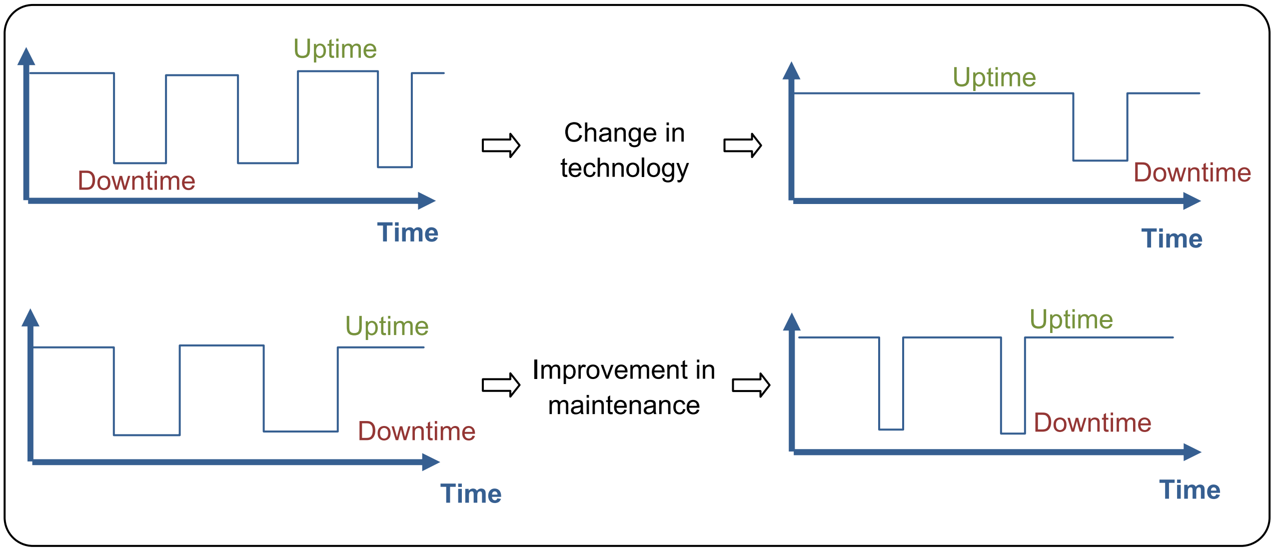



**Figure 38 Effect of Improvement Actions in System Status**

One of the critical tasks of the maintenance of a traffic signal system is to identify the failure as soon as it takes place. In one of the survey questions, traffic agencies were asked to rank the most common alternatives to determine detector malfunctions or failures. The ranked list is as follows:

1. Customer complaints about timing
2. Reported by traffic operations personnel
3. Scheduled inspections
4. Traffic signals systems alarms
5. Signal system reports
6. Other

Since the primary source of system feedback is customer complaints, in many cases the actual downtime of a component could be longer and unknown to the system operators. Based on this premise, the downtime of component in a traffic signal system can be decomposed into passive downtime, discretional downtime, waiting downtime, and repair downtime time. Passive downtime is the time interval between occurrence and detection of the failure. This component of downtime can be reduced by an effective communication infrastructure and increased preventive maintenance. Discretional downtime is applicable only to outsourced maintenance jobs and comprises the time lapse between reporting of the failure and the instant when the work order for an external contractor is issued. Discretional downtime is the result of a service agreement between the external contractor and the transportation agency and may vary from one agency to the other (e.g., issue a work order for six or more loops). Once the failure has been identified and scheduled for repair, the waiting downtime is directly related to the availability of maintenance technicians or contractors. Ideally, all the downtimes can be reduced to the effective repair downtime, as illustrated in Figure 39.

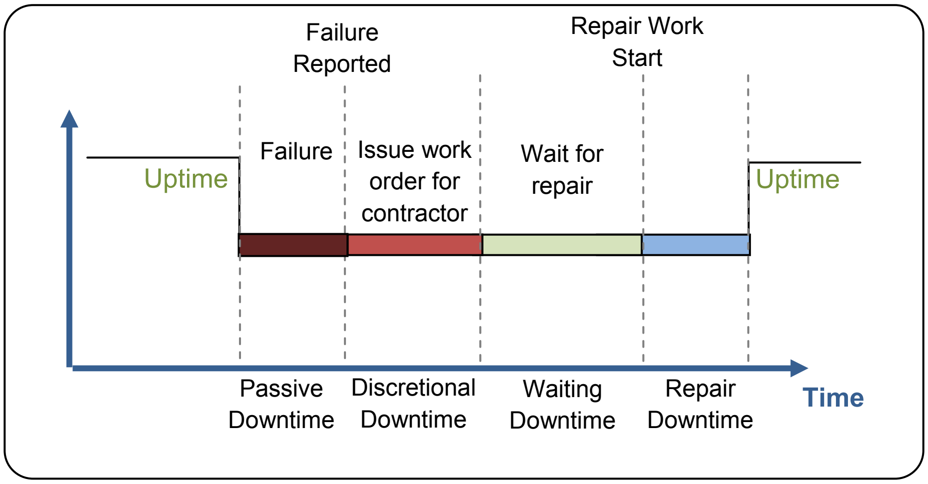



**Figure 39 Decomposition of Downtime of a Traffic Signal Component**

### 9.1.2 Evaluation of Improvement Actions

Improvement actions are oriented to minimize the impact of detection and communication equipment failures in traffic signal system operations. The degradation of communication and detection components can be translated into the increase of travel time by applying the degradation index (DI) concept discussed in the previous section. The degradation index is an instant measure of the proportion of observed travel time attributable to failures in detection and communication components.

The degradation index can be used in conjunction with the failure rate of system components and their associated downtimes to obtain a more comprehensive measure of total increased system travel time. To illustrate the concept, the most representative hour for the prevailing conditions on a corridor section during a day was taken as the unit of analysis. For example, the hour that best represents a traffic flow of the control section during a day is 300 vehicles per hour per lane (VPHPL). The observed travel time for the corridor is denoted by T, and the quantity of (DI x T) represents the increased travel time due to degradation. On any given day, there could be one or more component failures; thus, there is a degradation index $DI_{PC,\,t}$ for each day of system downtime (t), as shown in Figure 40. The selected performance measure is this quantity totaled for each day of detection or communication failures during a year for unit values of T. It is important to note that as the downtimes for equipment become longer, the chances of concurrent failures increase. A discrete-event simulation approach was taken to compute the desired parameter.

$$\begin{matrix} Travel\ Time\ Lost\ per\ Year\ per\ Vehicle\ During \\ an\ hour\ at\ the\ Prevailing\ Conditions \end{matrix} = \sum_{\substack{t: Days\ of\ Downtime \\ during\ a\ Year}} DI_{PC,t} * T$$

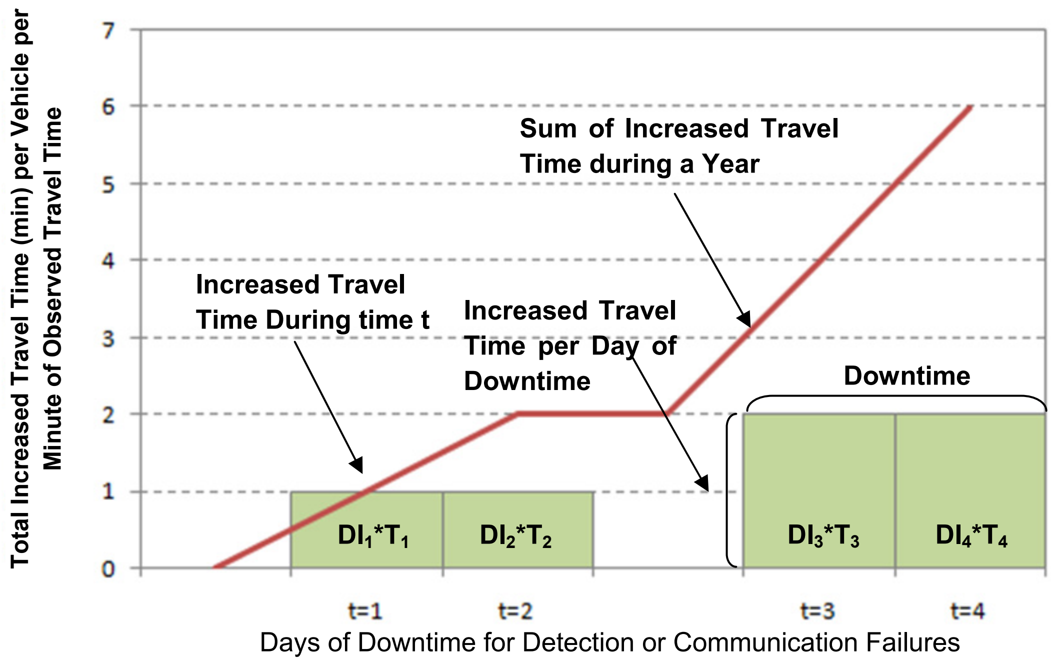



**Figure 40 Performance Measures for Evaluation of Improvement Actions**

## 9.2 Strategies to Improve Detection

The following section proposes and evaluates several major improvement strategies that can be adopted to decrease the impact of detection degradation in traffic signal system operations.

### 9.2.1 Upgrade Detection Technology

Inductive loop is the detection technology most used by agencies, followed by video detection. Minor detection malfunctions can be fixed by resetting the detector inside the cabinet or performing minor repairs. According to the agency survey, this can be done in less than three days for both inductive loops and video detection. On the other hand, major failures require a significant amount of time, especially for loop detectors. Most agencies in the survey indicated it takes more than 15 days to repair broken loop detectors. The results from the agency survey are presented in Figures 41 to 43.

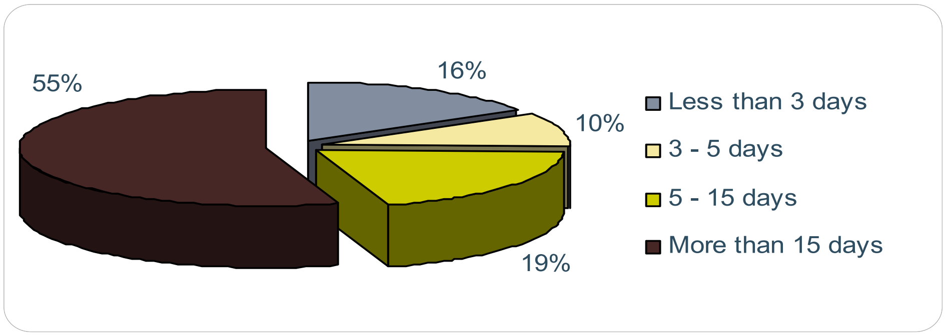



**Figure 41 Repair Time for Broken Detectors for Inductive Loop Detectors**

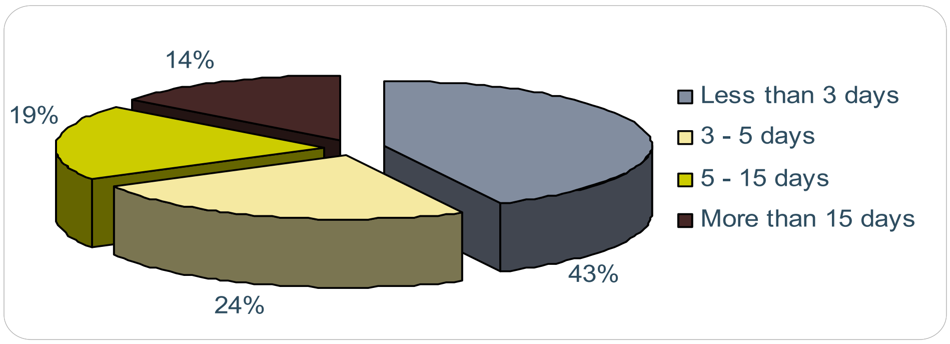



**Figure 42 Repair Time for Broken Detectors for Video Detectors**

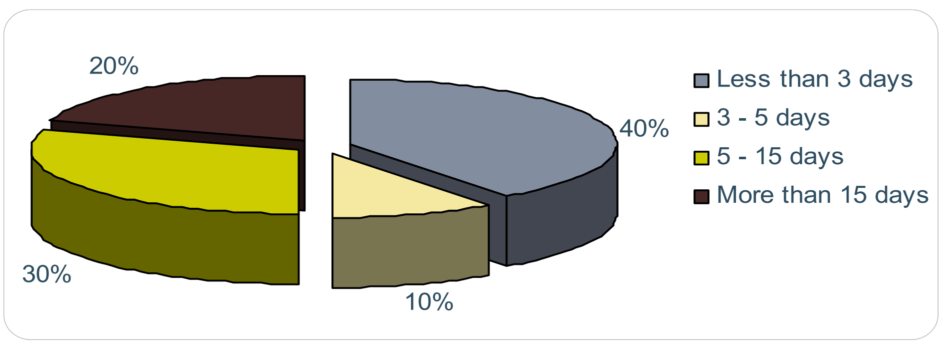



**Figure 43 Repair Time for Broken Detectors for Microwave Detectors**

The above data represent the current situation in Florida, according to the agency survey. This situation reflects ongoing practices that include contracting out the detector repair work. The expected life of the detection equipment is 10 years for both loop and video detection [10]. Using this information, a discrete-event simulation model was built to evaluate the average degradation index per year for the control section. The simulation consisted of a total of 180 scenarios. For each scenario, detector failures were simulated according to their life expectancy and downtime, measuring the traffic signal system degradation index per day. A summary of the results is presented in Table 19.

**Table 19 Degradation Index for Detection Technologies Based on Agency Survey Information**

| | Average Downtime of Major Detection Failures (Days) | Average Degradation Index | | |
|---|---|---|---|---|
| | | 300 VPHPL | 400 VPHPL | 500 VPHPL |
| Loop | 19.04 | 5.27% | 2.71% | 0.72% |
| Video | 7.705 | 5.54% | 2.98% | 1.00% |
| Microwave | 10.00 | 5.55% | 2.99% | 1.00% |

The total increased travel time per vehicle per year during the periods of detection downtime is presented in Figure 44. At a prevailing condition of low volume such as 300 VPHPL, the system will benefit the most from actuated signal control and, therefore, failures in detection equipment will have a relatively high impact in the control section performance. When volume is high, all the available green time is mostly used, and the systems become less sensitive to regular detection failures. The systems with high volumes require more degradation to be impacted significantly.

Figure 44 shows a significant difference between inductive loop and non-intrusive detection technologies such as video detection and microwave detection. This difference is mainly due to the cumulative effect of the longer downtimes experienced for loop repairs. These downtimes are currently being experienced by many agencies in Florida, according to the agency survey conducted at the early stages of this project. The percentage of reduction in the impact on travel time due to degradation of detection equipment is presented in Table 20. Note that this comparison is for the current situation based on survey data.

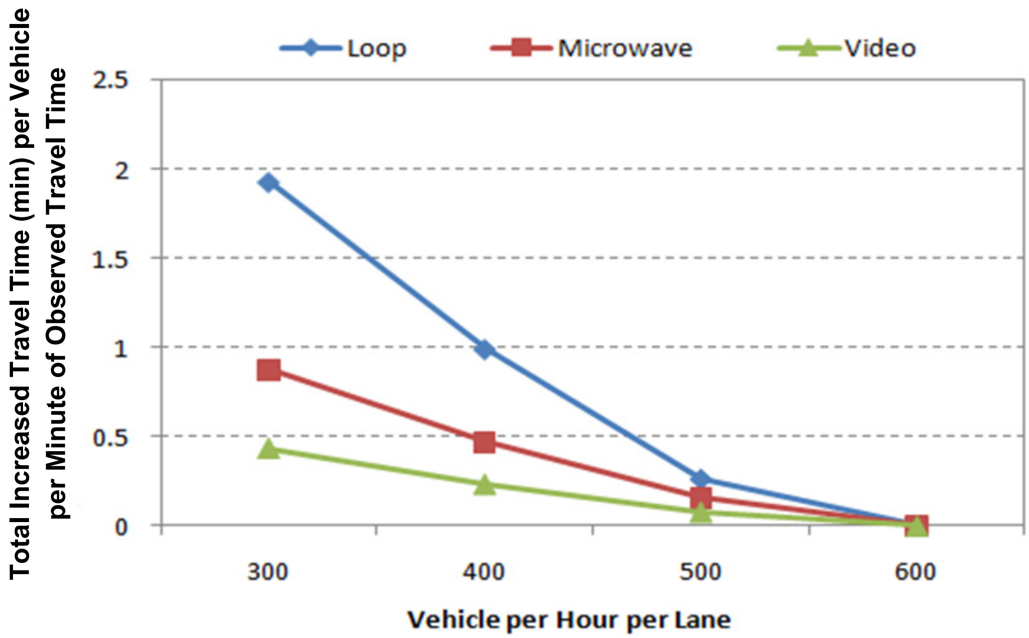



**Figure 44 Total Increased Travel Time per Minute per Vehicle of Observed Travel Time during Detection Breakdowns**

**Table 20 Percentage of Reduction on Increased Travel Time Due to Detection Failures Using Non-Intrusive Detection**

| From | To | 300 VPHPL | 400 VPHPL | 500 VPHPL | 600 VPHPL |
|---|---|---|---|---|---|
| Loop | Microwave | 55% | 52% | 41% | - |
| Loop | Video | 78% | 77% | 71% | - |
| Microwave | Video | 51% | 51% | 50% | - |

Under equivalent conditions of expected life and downtime, video detection and microwave detection behave in a similar fashion. Inductive loops will exhibit more failures than cameras since the number of loops is two or more times greater than that of cameras for a typical control section. This relatively large number of units increases the chance for loop detectors to fail and cause degradation, as observed in Figure 45.

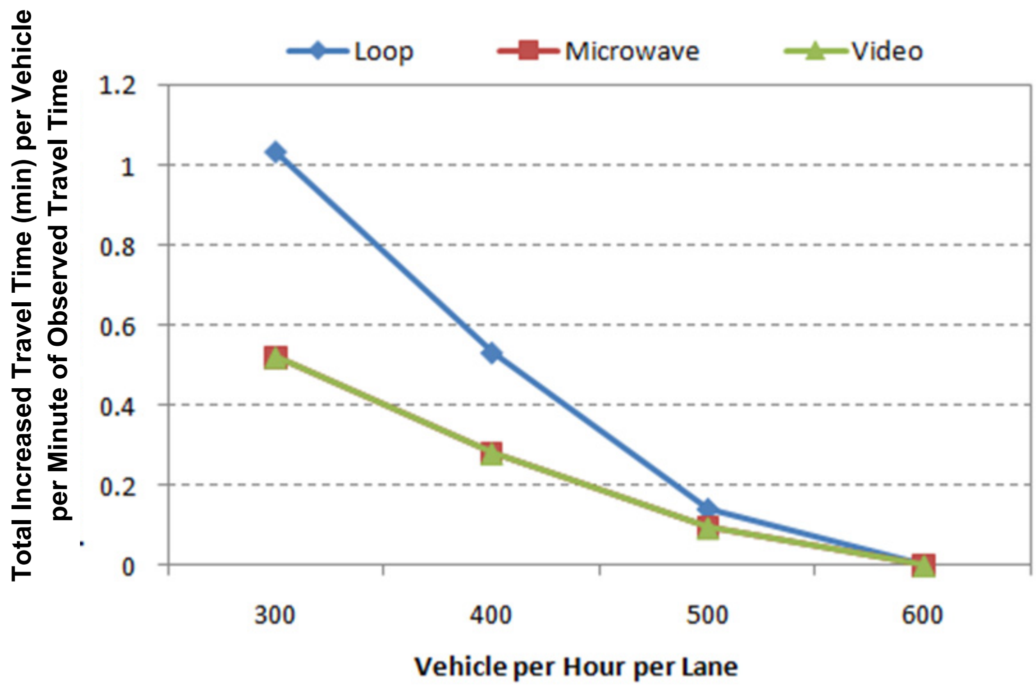



**Figure 45 Comparison Between the Different Types of Detection Technologies Under Equivalent Conditions**

### 9.2.2 Reduction in Detector Downtime by Improving the Responsiveness of the Contractors

From the agency survey, it was determined that 57 percent of the respondents contract out 75 percent or more of the detection repair work, which is mostly inductive loops. When repair work is contracted out, there is an additional downtime due to paperwork and negotiations with the contractors. Figure 46 shows the effect of reducing the downtime for the loop repair work from the current situation (19.2 days on average) to 15, 10, and 5 days downtime on average.

In Figure 46 it can be observed that when loops are fixed in a timely manner, their effectiveness can be close to that of other detection technologies. Reducing the amount of time to complete a detection repair job could be a cost-effective policy, especially for agencies relying heavily on loop detection. As an example, a policy consisting of completing a job order within 3 to 7 days (5 days on average) was simulated. The simulation results of the application of the policy for the different types of detection technologies and for different prevailing conditions are presented in Figure 47.

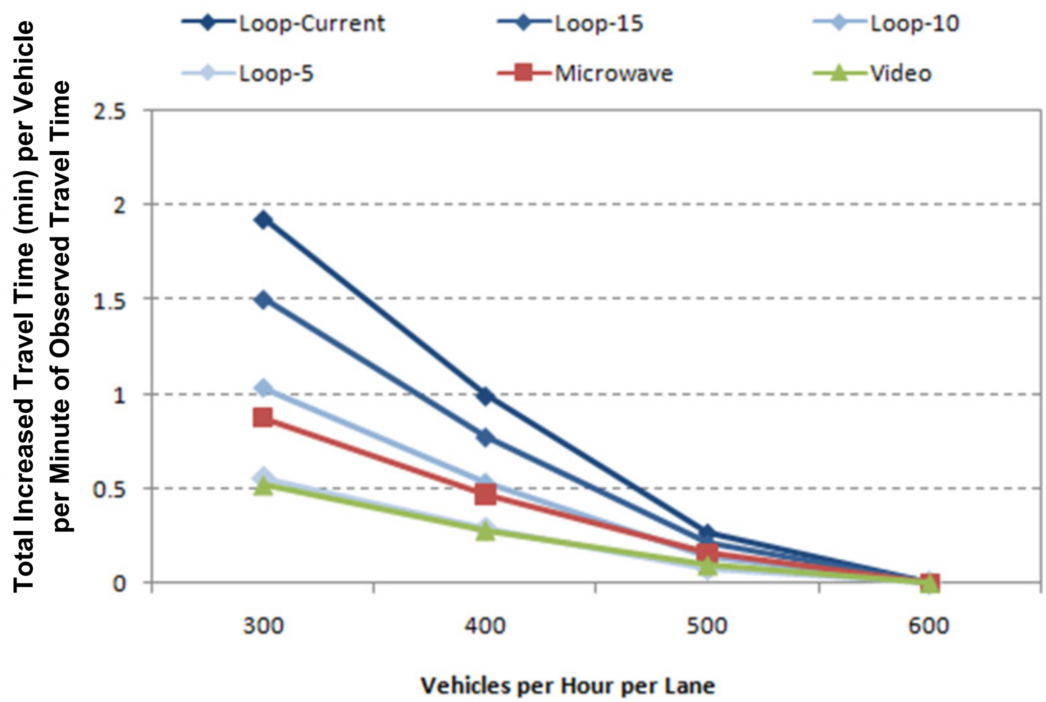



**Figure 46 Reduction on the Total Increased Time per Minute per Vehicle of Observed Travel Time for Improving the Responsiveness on Loop Repair Work**

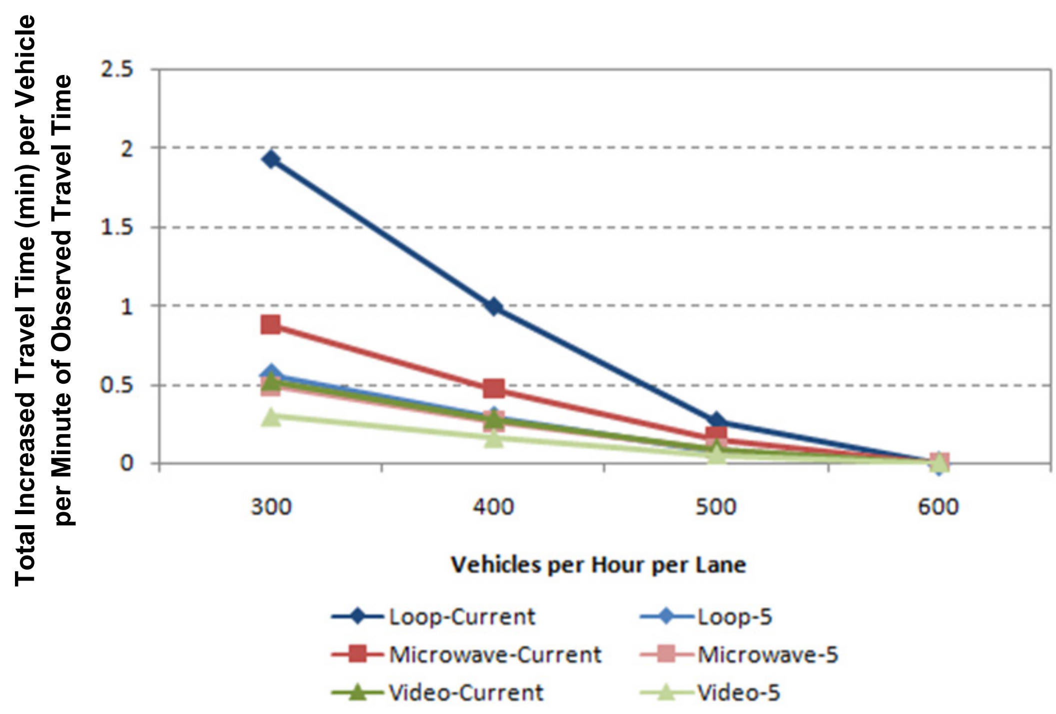



**Figure 47 Expected Improvements if Repair Works are Completed Within Three to Seven Days**

Table 21 presents the percentage of improvement if the repair time of detection work can be shortened either in-house or through a contract.

**Table 21 Percentage of Reduction on Increased Travel Time Due to Detection Failures by Improving Responsiveness**

| From | To | 300 VPHPL | 400 VPHPL | 500 VPHPL | 600 VPHPL |
|---|---|---|---|---|---|
| Loop-Current | Loop-15 | 22% | 22% | 22% | - |
| Loop-Current | Loop-10 | 46% | 46% | 46% | - |
| Loop-Current | Loop-5 | 71% | 71% | 71% | - |
| Video-Current | Video-5 | 43% | 43% | 43% | - |
| Microwave-Current | Microwave-5 | 44% | 44% | 44% | - |

### 9.2.3 Increase the Detector Uptime by Providing Adequate Training and Procedures for Installation of Detectors

The nominal value for the life of video detectors and loop detectors is 10 years. This value assumes that proper installation and regular maintenance are performed to the detection equipment. When these conditions are not met, the expected life of the equipment starts to decrease. Improper installation practices can decrease the life of the detection equipment dramatically. These situations can be avoided by providing thorough installation training in the case of in-house detection maintenance or closely inspecting jobs assigned to external contractors. This will help to achieve the maximum operational life of the detection equipment. The effect of technician training in the performance of traffic signal system is difficult to measure. An indirect assessment of the effect of training and inspection of a suitable range for the equipment life varying from 2 to 10 years was divided into three equally-spaced intervals (low, medium, and high). In the same fashion, three levels of training have been determined (low, medium, and high). As it is logical to think that better training and inspection help to achieve the maximum life of the equipment, it may be useful to relate each level of training to the corresponding level of equipment life. The results of the simulation test are presented in Figure 48 and Table 22. It can be observed that loops have more potential to be affected by training and inspection than microwave and video detection technologies.

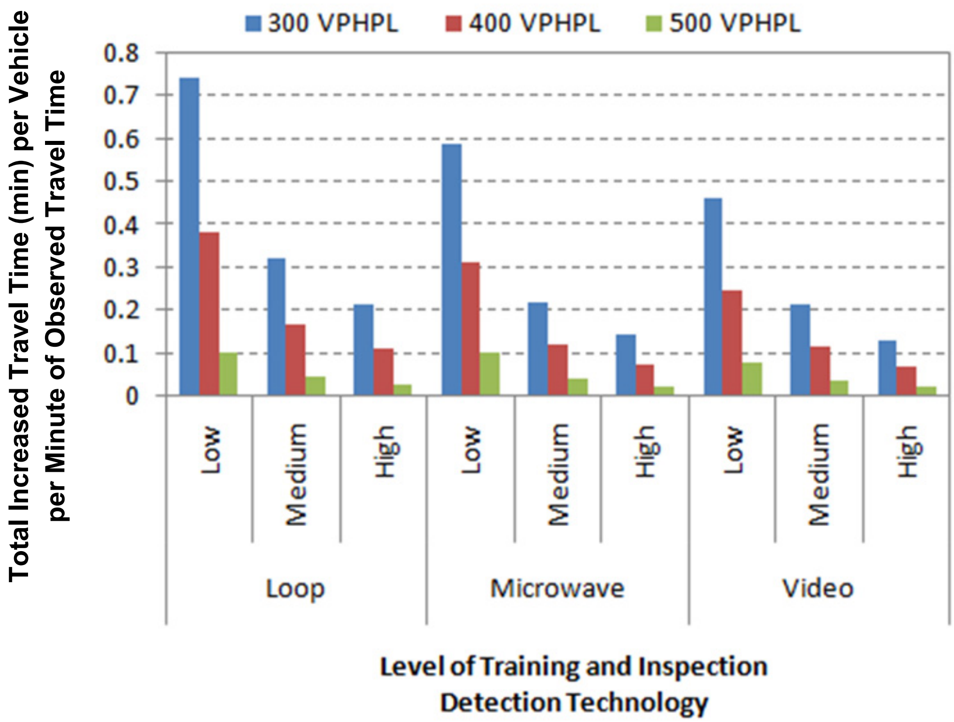



**Figure 48 Effect of Training and Inspection in the Total Increased Travel Time by Detection Technology**

**Table 22 Percentage of Reduction on Increased Travel Time Due to Improvement in Training and Installation Inspection**

| Detection Technology | From | To | 300 VPHPL | 400 VPHPL | 500 VPHPL |
|---|---|---|---|---|---|
| Loop | Low | Medium | 56.4% | 56.4% | 56.3% |
| Loop | Low | High | 71.1% | 71.1% | 71.2% |
| Loop | Medium | High | 33.8% | 33.8% | 34.2% |
| Video | Low | Medium | 53.1% | 53.1% | 52.9% |
| Video | Low | High | 72.1% | 71.9% | 71.3% |
| Video | Medium | High | 40.4% | 40.1% | 39.0% |
| Microwave | Low | Medium | 62.2% | 62.0% | 61.1% |
| Microwave | Low | High | 75.6% | 75.6% | 75.7% |
| Microwave | Medium | High | 35.4% | 35.8% | 37.5% |

## 9.3 Actions to Improve Communication

Communication is a key feature in advanced traffic management centers. It allows for both monitoring and controlling of traffic signal timing parameters. Coordinated signals can usually communicate with the traffic management center by different communication technologies, ranging from dial-up to wireless communication. The communication technology depends on the architecture of the traffic signal system. Central control typically has the highest communication requirement among the different control architectures. Time-based architectures present some elementary form of communication that may not be able to generate status reports. Communication can help to reduce the downtime of detection problems by enabling system operators to run status checks periodically. Communication failures are usually translated into loss of coordination due to clock drifting. The following section includes a list of actions seeking to minimize the impact of communication failures on the performance of the traffic signal system.

### 9.3.1 Increase Responsiveness in the Repair Time

According to Gordon [1], most communication failures are resolved in less than three days by the majority of agencies. This result is consistent with the information obtained from the agency survey applied in Florida. A simulation of different response times from 3 days to 20 days and the corresponding lost time during the downtime period was collected. The results of the simulated scenarios are presented in Figure 49. It can be observed that communication failures also affect high traffic volumes. This effect was not observed in the detection failure experiments since the advantage of actuated control decreases at higher volumes. Table 23 presents the percentage of improvement if the repair time of communication links can be shortened, whether in-house or through an external contractor.

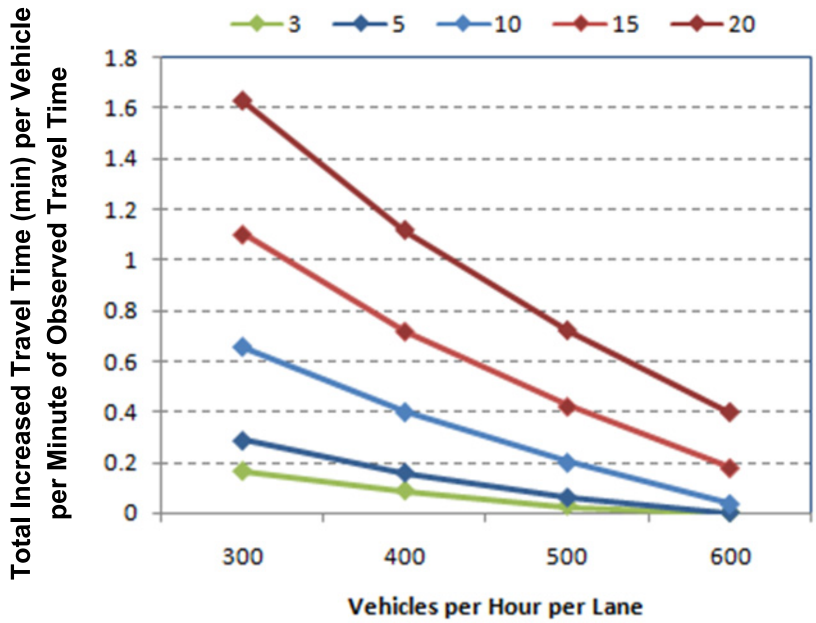



**Figure 49 Effect of Response Time to Communication Failures in the Total Increased Travel Time per Vehicle**

**Table 23 Percentage of Reduction in Increased Travel Time Due to Communication Failures by Improving Responsiveness**

| From | To | 300 VPHPL | 400 VPHPL | 600 VPHPL |
|---|---|---|---|---|
| 20 days | 15 days | 32% | 36% | 42% |
| 15 days | 10 days | 41% | 45% | 52% |
| 10 days | 5 days | 41% | 60% | 70% |
| 5 days | 3 days | 43% | 46% | 56% |

### 9.3.2 Increase Frequency of Inspection

Communications subsystem performance of twisted pair and leased line systems often can be improved by periodic maintenance of system reports and some simple diagnostic tests. As with detector maintenance strategies, regular periodic checking of communications systems performance can aid in reducing downtime.

For systems that have communications performance measures, operators should periodically scan the reports on a channel-by-channel basis. Communication channels with throughput generally above 95 percent will usually give satisfactory performance. Communications channels that are operating between 90 and 95 percent should be scheduled for investigation. Channels operating below 90 percent may experience frequent off-line conditions and should be targeted for immediate investigation and resolution. As a measure of system performance, the effects of different frequencies of inspection were simulated. The time between the occurrence of the failure and the actual discovery of the failure was collected. This is an estimation of the passive downtime of the system, as presented in the preceding section. The results of the simulation are presented in Figure 50. Table 24 presents the results of improving the frequency of inspection. It can be observed that for congested volumes by running communication checks every 15 days, the increase in travel time due to communication failures is greatly reduced.

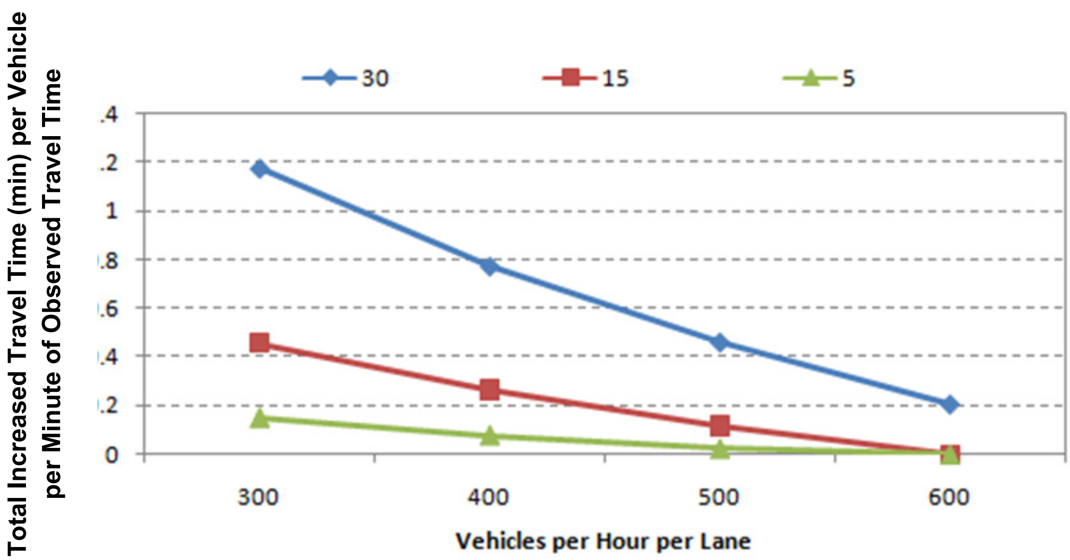



**Figure 50 Effect of Frequency of Inspection for Communication Failures in the Total Increased Travel Time**

**Table 24 Percentage of Reduction on Increased Travel Time Due to Communication Failures by Improving the Frequency of Inspection**

| From | To | 300 VPHPL | 400 VPHPL | 500 VPHPL | 600 VPHPL |
|---|---|---|---|---|---|
| 30 days | 15 days | 62% | 66% | 75% | 100% |
| 15 days | 5 days | 67% | 71% | 81% | - |

### 9.3.3 Install Time-of-Day Receivers (GPS Clock)

When communication fails, the time-of-day is not maintained with the required precision and the relative offsets of the controllers will begin to drift, causing a loss of coordination. In time-based systems, technicians must check the individual locations regularly to make sure that the time of day is being properly maintained and must reset the time-of-day clocks as necessary. This is also the case when communication is lost in a centralized system.

To alleviate this situation, vendors have supplied external electronic clocks that are installed in each intersection cabinet. Generally, the clocks receive time-of-day broadcasts from the NIST's WWV time service or from GPS satellites. The clocks generally output a pulse once per day to reset the controller's time-of-day clock to a specified time. This will keep the intersections in a control section synchronized in the event of a communication failure.

### 9.4 Recommendation for Optimal Allocation of Maintenance Resources

The optimal allocation of maintenance resources on traffic signal systems may vary from agency to agency depending on the goal of the agency, the need for the system, and the available resources including budget, manpower, equipment, and facilities. However, the basic principle to determine the best use of available resources is similar. This research project analyzed several practical short-term improvement strategies for detection and communication systems and presented the benefits of each improvement strategy in terms of reducing the increased travel time on a traffic control section due to degradations. This information of each improvement strategy is very valuable. To determine an optimal method for allocating maintenance resources for traffic signal systems, the following simple steps are recommended:

1. Determine the cost for performing each improvement strategy considered.
2. Determine the benefit (e.g., travel time reduction) of each improvement strategy considered. The benefits can be computed from the tables of percentage of reduction in increased travel time for selected improvement strategies presented in the previous section.
3. Compute the benefit per dollar invested in the improvement strategy, based on the information obtained from Steps 1 and 2.
4. Rank the improvement strategies, based on the results from Step 3.
5. Select improvement strategies, based on the needs for the traffic signal system and available maintenance resources of the agency.

The recommended short-term and mid-term improvement strategies are achievable for most traffic agencies by properly reallocating the available resources. Long-term improvement strategies may require some policy decisions and new funding.

## 9.5 Resource Allocation Model

The previous approach presented a heuristic method to select improvement strategies. The problem of selecting the best set of improvement strategies can be solved by means of mathematical programming. The resulting model seeks to maximize the benefit for traffic control section by selecting the most suitable strategies within the allocated budget for improvement. This model corresponds to the typical resource allocation problem and is known as the 0-1 knapsack problem.

$$X_i = \begin{cases} 1\ if\ improvement\ strategy\ \boldsymbol{i}\ is\ selected\ for\ implementation \\ 0\ otherwise \end{cases}$$

$$C_i = Implementation\ cost\ for\ improvement\ strategy\ \boldsymbol{i}$$

$$B_1 = \frac{Benefit\ from\ reduction\ of\ increased\ travel\ time}{(due\ to\ sysyem\ degradation)\ by\ implementing\ strategy\ \boldsymbol{i}}$$

$$MAXIMIZE \left\{ \sum_{i=1}^{\substack{number\ of \\ alternatives \\ n}} B_i X_i \right\}$$

$$Subject\ to:$$

$$\sum_{i=1}^{\substack{number\ of \\ alternatives}} C_i X_i \leq Available\ budget\ for\ Improvement$$

## 9.6 Recommendations for Operations and Maintenance Resource Allocation Strategies

Based on the literature review, agency survey, detailed interviews, and input from the contractor, the recommended list of possible resource allocation strategies is presented in Table 25.

## Table 25 Resource Allocation Strategies

| Strategy Type | Improvement | Actions | Reduce Passive Downtime | Reduce Discretional Downtime | Reduce Waiting Downtime | Reduce Repair Downtime | Increase Uptime | Reduce Timing Degradation | Increase Monitoring Capabilities |
|---|---|---|---|---|---|---|---|---|---|
| Long-Term | Detection | Upgrade to video detection | | | | x | x | | x |
| | | Upgrade to microwave detection | | | | x | x | | |
| | | Upgrade pedestrian detection buttons | | | | | | | |
| | Communication | Upgrade communication to wireless | x | | | | x | | |
| | | Upgrade communication technology to fiber optic | x | | | | x | | x |
| Middle-Term | Detection | Keep a safety stock of spare cameras and video processors | | | | x | | | |
| | | Impose high-responsiveness restrictions on contractors to promptly fix detection problems at critical locations | | x | | | | | |
| | | Increase available hours for in-house detection maintenance | | | x | | | | |
| | | Increase hours of preventive maintenance for detection equipment | x | | | | x | | |
| | | Use of readily-deployable alternate detection technologies in cases of detector failures | | | | x | | | |
| | Communication | Impose high-responsiveness restrictions on contractors to promptly fix communication problems at critical locations | | x | | | | | |
| | | Increase available hours for in-house communication maintenance | | | x | | | | |
| | | Increase hours of preventive maintenance for communication equipment | x | | | | | | |
| | | Use of readily-deployable wireless technologies in cases of communication failures | | | | x | | | |
| | | Install time-of-day receivers (GPS clock) | | | | | x | | |
| | Signal Timing | Check/input time-of-day and coordination plans in controller once per month (time-based systems) | | | | | | x | |
| | | Synchronize frequency of retiming with traffic growth | | | | | | x | |

**Table 25 Resource Allocation Strategies (continued)**

| Strategy Type | Improvement | Actions | Reduce Passive Downtime | Reduce Discretional Downtime | Reduce Waiting Downtime | Reduce Repair Downtime | Increase Uptime | Reduce Timing Degradation | Increase Monitoring Capabilities |
|---|---|---|---|---|---|---|---|---|---|
| Short-Term | Detection | Provide adequate training to maintenance staff | | | | | x | | |
| | | Run system reports for detection failures checking at critical intersections every other day (including pedestrian detection) | x | | | | | | |
| | | Closely inspect new installations of detectors, especially inductive loop | | | | | x | | |
| | Communication | Provide adequate training to maintenance staff | | | | | x | | |
| | | Run system reports for communication channels once per week | x | | | | | | |
| | Signal Timing | Check/input time-of-day and coordination plans in controller once per month (time-based systems) | | | | | | x | |
| | | Broadcast time-of-day plans to local controllers at least once per day | | | | | | x | |
| | | Fine-tune signal timing as needed | | | | | | x | |

## 9.7 Short-Term and Mid-Term Strategies to Improve Detection and Communications Infrastructure Performance

The following subsections provide a series of detailed short-term and mid-term recommendations to improve the expected life of loop detectors since, currently, loops constitute over 90 percent of the detectors in Florida. In addition, short term strategies to improve communication performance are also provided.

### 9.7.1 Improvement of Detection Subsystem Performance

Failure of detection equipment leads to, at a minimum, driver dissatisfaction, as actuated approaches that do not have demand are served unnecessarily or for excessive periods of time each cycle, and potential safety hazards if real demand is not served due to detection failures. In cases where a vehicle is not detected, motorists will choose to run the red light after one or more cycles, resulting in increased risk of injury or death to themselves and others. Detection subsystem failures are among the most prevalent in a traffic control system. In studies by the New York State Department of Transportation, it was observed that approximately 25 percent of 15,000 loops were malfunctioning at any given time. Further, the average expected operating period before requiring maintenance was two years.

Short-term strategies to improve detection system performance include:

- Better inspection and quality control of detector component installation
- Periodic monitoring of detector performance during routine and on-demand cabinet visits
- Use of readily deployable alternate detection technologies in cases of detector failures
- Use of central system features to monitor detector performance
- Structuring of on-call services to address realistic detection failure scenarios

Following is a detailed discussion of strategies to improve detector system performance.

#### 9.7.1.1 Better inspection and quality control of detector component installation

Main detection system failures can be traced to fairly common installation issues. With loop detector, correct installation of the loop and lead-in in a stable pavement base are crucial to long-term performance. However, the installation of this critical component often suffers from poor quality and lax oversight. Common failures during the installation process include:

- Installation of the loop in a failing pavement surface
- Improper saw cutting of the loop channel
- Improper cleaning of the channel and placement of cushioning material prior to insertion of the loop conductor
- Improper application of sealant
- Improper termination of the loop wires to the home run cables

All of these items are easily remedied by proper training, strict adherence to the manufacturer’s installation recommendations, and proper oversight by trained and experienced inspectors. Loops may be installed by agency personnel or by contract services. In both cases, it is imperative for agency personnel to verify that the pavement is in suitable condition to support loop installation prior to attempting to install the loops. If agency personnel are installing the equipment, this can be done by use of a pre-installation checklist by the agency. The pavement surface should be in sound condition with no deterioration, cracks, or other physical instabilities. It is critical that the pavement around the loop not be subject to any shifting and that the loop wire be held securely in place. Shifting of the pavement or the loop wire will quickly lead to destruction of the loop wire insulation or complete severing of the loop conductor, causing failure. When third-party contract forces perform the installation, it is crucial that agency inspectors check that the pavement is in sound condition prior to releasing the installation task to the contractor. If this is not done, the likely result is that the contractor will install the loop in a failing surface and collect payment for a loop that functions at the time of installation, but that will fail relatively quickly.

Adequate staff training and supervision or contractor inspection is absolutely necessary if reliable installations are to be accomplished. Inspectors should be present at all phases of contractor-based installation to ensure that care is taken in the installation of the loops and that shortcuts are not taken that will compromise detector performance and life. A detailed checklist should be prepared and used with each detector installation. Inspectors should be aggressive in their inspection and should promptly pursue any anomalies or deviations.

#### 9.7.1.2 Periodic monitoring of detector performance during routine and on-demand cabinet visits

Given that studies have shown that average loop life expectancy is approximately two years, periodic evaluation of loop performance should be performed at least once annually during a routine inspection. At a minimum, this inspection should include inspection of:

- Each loop and surrounding pavement conditions
- Insulation resistance (megger) test of each loop circuit
- DC resistance of each loop circuit
- Visual confirmation that presence of a vehicle over each loop results in the detector electronics placing a steady, consistent call

Anomalies should be investigated, especially any observed changes in the insulation resistance or the DC resistance of the loop circuit form previous checks.

In addition, whenever unscheduled maintenance is performed at the controller cabinet, the technicians should perform a visual inspection of the pavement around each loop. Any observed deterioration should be noted, and a full check of the affected loop should be scheduled.

#### 9.7.1.3 Use of readily-deployable alternate detection technologies in cases of detector failures

Agencies that rely heavily on loop detection are well aware of the relatively long period of time it takes to effect repairs. Accordingly, it is recommended that a strategy be developed to deploy temporary detection technologies when loops are damaged. Video detection is non-obtrusive and often can be deployed using existing poles, mast arms, and signal wiring raceways.  An agency should consider establishing a stock of temporary video detection devices that can be deployed in place of damaged loop detectors until loop repairs can be effected.

#### 9.7.1.4 Use of central system features to monitor detector performance

Many modern central supervisory and control systems have some mode of detector monitoring capabilities. These facilities should be used where possible to detect patterns of irregularity in detector operation. Depending on the system, the following capabilities may be present:

- Stuck on, stuck off, chatter failure monitoring
- Volume and occupancy monitoring
- Display of detector calls in real time

When automated failure checking is available, daily review of the failures should be instituted and follow-up performed. If this feature is not available, periodic review of volume and occupancy reports should be performed. Detectors displaying out-of-range volume and occupancy values should be explored. As a third resort, many modern systems offer real-time graphical display of detector calls. Detectors could be monitored for stuck-on or stuck-off conditions without the need to visit individual intersections. The important aspect to successfully using any of these regiments is to set up a schedule for regularly and periodically reviewing the available data and assigning resources to follow-up on any potential problems.

#### 9.7.1.5 Structuring of on-call services to address realistic detection failure scenarios

As discussed previously, the primary source of problems with detection subsystems resides in the loop wire and lead-in components. However, replacement of these devices can be difficult and can result in disruption of traffic, since lane closures are required to perform the service. In addition, failures do not occur with a predictable frequency or within a given geography; therefore, maintenance strategies should address these realities. Maintenance, whether done by agency or contractor forces, should recognize these conditions. In particular, detector replacement contracts should be structured on an "on-call" basis. When contract forces are used, the contract documents must establish that detector loop replacement may be required in small lots at varying intervals.

## 9.8 Improvement of Communications Systems Performance

Communications subsystem performance of twisted pair and leased line systems can often be improved by periodic maintenance of system reports and simple diagnostic tests. As with detector maintenance strategies, regular periodic checking of communications systems performance can aid in reducing downtime.

For systems that have communications performance measures, operators should periodically scan the reports on a channel-by-channel basis. Communications channel throughput that is generally above 95 percent usually will give satisfactory performance. Second-by-second control systems, such as UTCS, may be a little more demanding; distributed systems will be less sensitive. Communication channels that are operating between 90 and 95 percent should be scheduled for investigation. Channels operating below 90 percent may experience frequent off-line conditions and should be targeted for immediate investigation and resolution.

As with the maintenance of the detection subsystem, regular periodic checks of the communications are essential to maintain system uptime. In addition, if communication problems are not addressed as they occur, multiple failures can occur on one channel, which can make isolating the source of the problem much more difficult. For that reason, it is recommended that communication channels be checked when the performance has fallen slightly, rather than when it deteriorates to the point of complete failure.

# 10. CONCLUSIONS AND RESEARCH RECOMMENDATIONS

Detection and communication component failures significantly affect the operation of a traffic signal system. These components are mainly affected by two major factors: the technology of the component and the maintenance policies of the traffic agency. This project provides an operational view of the effects that the failure of the different detection and communication components have on the performance of a traffic signal system. Also, a set of maintenance policies and resource allocation alternatives were evaluated from an operational standpoint through a series of traffic microsimulation models of a generic traffic control section. The conclusions of the study as well as direction for further research are presented in the following sections.

## 10.1 Conclusions

1. Interconnected traffic signal systems can be configured as centralized, distributed, or hybrid (combination of centralized and distributed) systems. Different architectures have their advantages and disadvantages. Detection and communication failures will affect a traffic signal system under any system architecture. In general, the systems under distributed architectures are less sensitive to communication failures than are centralized architectures. Adaptive traffic control systems, which are mostly under centralized architectures, are especially sensitive to detection failures.

2. The results of a traffic agency survey in Florida indicated that most traffic agencies rank themselves slightly better on communication and detection system maintenance than on keeping their signal timing up to date.

3. The result of the traffic agency survey showed that the top three suggestions to improve traffic signal system performance were (1) well-trained engineers, (2) well-trained technicians, and (3) increased budget. Adding communication and detection improvements in one category places it second on the list, which is just below well-trained engineers. The importance of signal timing was also highlighted in the traffic agency survey.

4. Based on a literature review and agency surveys, commonly-used operational performance measures for a control section reflecting motorist experiences include travel time, travel time reliability, average delay, average speed, and progression bandwidth.

5. A practical traffic signal performance should measure the performance of the traffic signal system itself and include the impact on system degradation. The degradation

of detection and communication as well as outdated signal timing plans can adversely affect the performance of a traffic signal system. A signal system degradation index and performance index developed in this study provide a simple way to measure the performance of a traffic signal system itself.

6. For a typical control section with 8 – 10 coordinated signals, if all detectors fail, the average travel time on the corridor can increase up to 40 percent when compared to the system ideal condition, with detection and communication fully functional and timing plans up to date. If only a couple of side-street detectors fail, the travel time will generally increase up to 6 percent. However, the failure of the opposing left-turn detector on the main street at its critical intersection can cause more than a 6 percent increase in travel time.

7. This study found that failure of opposing left-turn detectors on the main street generally has more impact on the travel time than those of side streets through detectors and requires a higher priority of response. The reason is that it can consume significant amount of accumulated unused green time from a side-street left turn phase (if any) and a side-street through phase. The failure of side-street through detectors has more impact on travel time than those of side-street left turns.

8. For a typical control section with 8 – 10 coordinated signals, if all communications fail, the average travel time on the corridor will increase up to 22 percent when compared to the system under its ideal condition, with detection and communication fully functional. Except for some centralized architectures, the signals on the control section will run the coordination timing plans stored in the controllers after loss of communication between signals and their masters or TMC. The communication losses can sometimes cause timeclocks in some controllers to drift. Based on the sensitivity analysis, the communication failures after 2 – 3 days may increase travel time on the corridor up to 5 percent. The worst case may occur when the timeclock at the most critical intersection drifts to half of the cycle length.

9. For a typical control section with 8 – 10 coordinated signals with combined detection and communication failures, the average travel time on the corridor will increase up to 40 percent from that under its ideal condition.

10. There are many potential causes for degradation or outdated traffic signal timing plans. This study found that a significant growth (15% or more) of traffic volume along the control section is the major contributing factor. Slow degradations on coordination timing plans were found when the growth occurs under light traffic volumes (e.g., 300 – 400 through-vehicles per hour per lane on a main street) or

heavy volumes (e.g., 700 – 800 through-vehicles per hour per lane on a main street). A large degradation was found when the growth occurs under median traffic volume (500 – 600 through-vehicles per hour per lane on a main street). This study also found that a typical benefit of traffic signal retiming can reduce the average travel time on the corridor up to 16 percent for a 15–25 percent growth of traffic volume since the last signal retiming. The benefits can increase more than 16 percent if the coordination signal timing was not properly retimed in the past. It is most beneficial to retime traffic signal systems when significant growth occurs on a control section with medium traffic volume because there is a significant room for improvement through signal retiming. When traffic volume is light, the benefit of signal retiming is less than that of medium volume. When traffic volume is heavy, there is limited room for significant improvement through signal retiming.

11. Based on a large number of traffic microsimulation models, it was found that the degradation due to detection failures gradually decreases as volume increases. This is because less available green time of a phase is wasted due to detector failures when volume of the associated phase increases.

12. Detection failures had more effect at low-to-moderate traffic volumes. This was mainly due to the fact that, at higher volumes, the benefits of actuated control are diminished. On the other hand, communication failures had the most effect at higher traffic volumes. A plausible explanation for this behavior is that communication failures affect coordination, which results in increased travel times in a corridor, especially if the volume in the major direction is high.

13. Three types of strategies to improve detection and communication degradation infrastructure performance are included in this report: short-term, mid-term, and long-term. The benefits of major improvement strategies in terms of reduction of travel time are presented in detail. These strategies include upgrading detection technologies, improving the responsiveness to detection and communication repair work, providing adequate training, increasing the frequency of inspection, and installing a GPS clock to maintain synchronization of the timeclock in the controller.

14. Any transportation agency can use the process presented in this study to compute the percent improvement per dollar invested in the improvement strategy. After ranking the considered strategies, the agency can select the strategies with the highest ranking matching its needs.

## 10.2 Research Recommendations

1. This research focuses on the assessment of the impact of detection, communication, and signal timing on a generic traffic signal system and provides recommended strategies to better allocate available resources to improve the performance of the traffic control section. It builds a solid foundation for addressing the impact of signal system degradations at a city- or county-wide level and provides resource allocation strategies. Each city and county maintains a significant number of traffic signals under different system architectures. To provide substantial benefits to traffic agencies, it is recommended that further research can be conducted to expand the results of the current research to cover city- and county-wide signal systems. This recommendation is directed towards agencies.

2. From agency surveys and interviews, it was discovered that many agencies in Florida were interested in this research, which is highly related to their daily operations. It is recommended that future research conduct case studies in several cities and counties. Future research can also include before-and-after analysis throughout these case studies to document the benefits.

3. This research developed several analytical models to estimate traffic signal system degradation and performance as well as resource allocations. It will be beneficial for future research to develop a user-friendly software application so traffic agencies can easily use the application as a tool to effectively improve or enhance their traffic signal systems within their jurisdictions.

# 11. REFERENCES


1. Gordon, R.L., et al. (2003). *Systems Engineering Processes for Developing Traffic Signal Systems – A Synthesis of Highway Practice*, Transportation Research Board, NCHRP Synthesis 307.

2. Federal Highway Administration (April, 1997). *Advanced Transportation Management Technologies – Participant Reference Guide*, Publication No FHWA-SA-97-058, Chapter 3.

3. National Transportation Operations Coalition (2007). *2007 National Traffic Signal Report Card*, Online: www.**ite.org/reportcard**/technical_**report** final.pdf.

4. Federal Highway Administration (2004). *Elements of a Comprehensive Signal Asset Management System.* Publication No. FHWA-HOP-05-006. Prepared by Cambridge Systematics, Washington, D.C.

5. Institute of Transportation Engineers (2000). Components of traffic control systems, *Traffic Control Systems Operations: Installation, Management and Maintenance* (pp. 3). Washington D.C.

6. Montgomery, Douglas (2004). *Design and Analysis of Experiments. 6th ed.* John Wiley & Sons.

7. Broward County (2008). *Operating Budget 2008* Online: www.broward.org/budget/yr2008/operating/adopted/13publicworkstransportation.pdf.

8. Miami Dade County (2007). *Public Works Business Plan Report*. Online: http://www.miamidade.gov/mppa/library/PDFs/businessplans/FY07/Q2/neighbor_dpw.pdf.

9. Balke, K., Charara, H., and Parker, R. (2004). *Measuring the Performance of Traffic Signal Systems Using Existing Detector Technology*, Texas Transportation Institute, the Texas A&M University System, College Station, Texas.

10. Federal Highway Administration (2006). *Traffic Detector Handbook 3th ed*. Publication No FHWA-HRT-06-108.

## APPENDIX A

# Florida Traffic Agency Survey Report

# LIST OF FIGURES

Figure A-1 Signals maintained by surveyed agencies ........................................ 117

Figure A-3 Signals coordinated by surveyed agencies ........................................ 118

Figure A-4 Distribution of the number of signals coordinated by surveyed agencies ........................................ 118

Figure A-5 Percentage of coordinated signals sorted in increasing order ........................................ 119

Figure A-6 Distribution of frequency of retiming ........................................ 119

Figure A-7 Percentage of average annual traffic growth rates ........................................ 120

Figure A-8 Percentage of coordinated signals of the surveyed agencies by system architecture ........................................ 120

Figure A-9 Number of control section per 100 coordinated signals ........................................ 121

Figure A-10 Distribution of the control sections per 100 coordinated signals ........................................ 121

Figure A-11 Number of signals per control section ........................................ 122

Figure A-12 Distribution of the number of signals per control section ........................................ 122

Figure A-13 Number of agencies with adaptive signal control ........................................ 123

Figure A-14 Types of adaptive signal control ........................................ 123

Figure A-15 Use of adaptive signal control in the next three years ........................................ 124

Figure A-16 Percentage of signals per controller type ........................................ 124

Figure A-17 Percentage of signals per type of detection system ........................................ 125

Figure A-18 Frequency distribution of the number of agencies by functions performed by the detectors of the traffic signal system ........................................ 127

Figure A-19 Repair time for detector malfunction for inductive loop detectors ........................................ 129

Figure A-20 Repair time for detector malfunction for video detectors .......................... 129

Figure A-21 Overall repair time for detector malfunction ............................................ 130

Figure A-22 Repair time for broken detectors for inductive loop detectors .................. 130

Figure A-23 Repair time for broken detectors for video detectors................................ 130

Figure A-24 Repair time for broken detectors for microwave detectors........................ 131

Figure A-25 Overall repair time for broken detectors .................................................. 131

Figure A-26 Frequency distribution of the number of agencies by repair cost of detection devices ........................................................................... 132

Figure A-27 Percentage of repair work contracted out to private companies ................ 134

Figure A-28 Distribution of the repair work contracted out to private companies ........ 134

Figure A-29 Relationship between detector failures and system functionality.............. 136

Figure A-30 Percentage of signals per type of communication between signalized intersections ........................................................................... 137

Figure A-31 Percentage of signals per type of communication system between signalized intersections and traffic management centers........................... 138

Figure A-32 Miles of arterials and local streets with interconnected signals................. 139

Figure A-33 Distributions of the miles of arterials and local streets with interconnected signals................................................................... 139

Figure A-34 Miles of arterials and local streets with aboveground/underground interconnected signals................................................................... 140

Figure A-35 Repair time for communication failures .................................................. 142

Figure A-36 Frequency distribution of the number of agencies by repair cost per communication device ................................................................... 143

Figure A-37 Percentage of communication repair work contracted out to private companies ........................................................................... 144

Figure A-38 Distribution of the communication repair work contracted out to private companies ........................................................................... 144

Figure A-39 Relationship between communication failures and system functionality ........ 145

Figure A-40 Estimated annual maintenance budget for traffic control systems, ITS infrastructure, loops and video detection ........ 147

Figure A-41 Distribution of the estimated annual maintenance budget for traffic control systems, ITS infrastructure, loops and video detection ........ 147

Figure A-42 Distribution of the frequency of maintenance activities ........ 149

Table A- 13 Ranked list of performance measures for traffic signal systems ........ 150

Figure A-43 Distribution of the ratings of the status of the components of the traffic signal system ........ 151

Figure A-44 Number of signals under ATMS ........ 153

Figure A-45 Distribution of the number of signals under ATMS ........ 153

Figure A-46 Percentage of failed detectors at any time under ATMS ........ 154

Figure A-47 Distribution of failed detectors at any time under ATMS ........ 154

Figure A-48 Percentage of intersections not operating efficiently due to detector failures under ATMS ........ 155

Figure A-49 Distribution of intersections not operating efficiently due to detector failures under ATMS ........ 155

Figure A-50 Percentage of signalized intersection with communication failures under ATMS ........ 156

Figure A-51 Distribution of signalized intersection with communication failures under ATMS ........ 156

Figure A-52 Number of signals operating in traffic responsive mode ........ 157

**LIST OF TABLES**


Table A- 1 Other controller types in use ... 125

Table A- 2 Other detection systems in use ... 126

Table A- 3 Other functions performed by detectors ... 128

Table A- 4 Ranking of methods for finding detector failures ... 128

Table A- 5 Ranked list of detector maintenance issues ... 135

Table A- 6 Other detector maintenance issues ... 135

Table A- 7 Other observations of the relationship between detector failures and system functionality ... 136

Table A- 8 Other types of communication between signalized intersections ... 137

Table A- 9 Other types of communication between signalized intersections and traffic management center ... 138

Table A- 10 Ranked list of communication failure issues ... 141

Table A- 11 Other repair costs of communication devices ... 143

Table A- 12 List of signals system software used by responding agencies ... 146

Table A- 14 Rating of the current status of the traffic signal system components ... 151

Table A- 15 Suggested actions to improve traffic signal system performance ... 152

Table A- 16 Number of agencies with ATMS ... 152

Table A- 17 Benefits and challenges of ATMS ... 158

Table A- 18 Ranked list performance measures for agencies with ATMS ... 159

**Overview**

A comprehensive survey was developed and conducted to obtain information on traffic signal system infrastructure and architectures, maintenance policies related to detection and communication infrastructure, performance measures, and resource availability. The survey also gathered information on the relationship observed between degradation of detection and communication infrastructure and loss of system functionality. The data and information obtained from this survey will be used to further investigate the impact of degradation of signal system infrastructure on the performance of the system.

Many agencies responsible for maintaining the signal system in the State of Florida were surveyed. During the month of January 2008, the survey was conducted online with 54 Florida traffic agencies. The survey had a high response rate (63%) of 34 agencies, which maintain approximately 12,000 signals. This report contains the results of the responses from these 34 agencies.

The results of the multiple selection questions are presented in percentage form if a majority of the agencies have responded to those questions. If half or less of the agencies have responded to a particular question, then the results are presented in numerical count form. The survey also included questions in which agencies were asked to rank the top 5 items. In these cases the responses are presented in a list sorted by relevance in descending order. For open ended questions a summary of the responses is presented when the majority of the respondents answered the question. When only a few responses are available the complete responses are presented.

**Survey Results**

1. Approximately how many traffic signals are maintained by your agency?

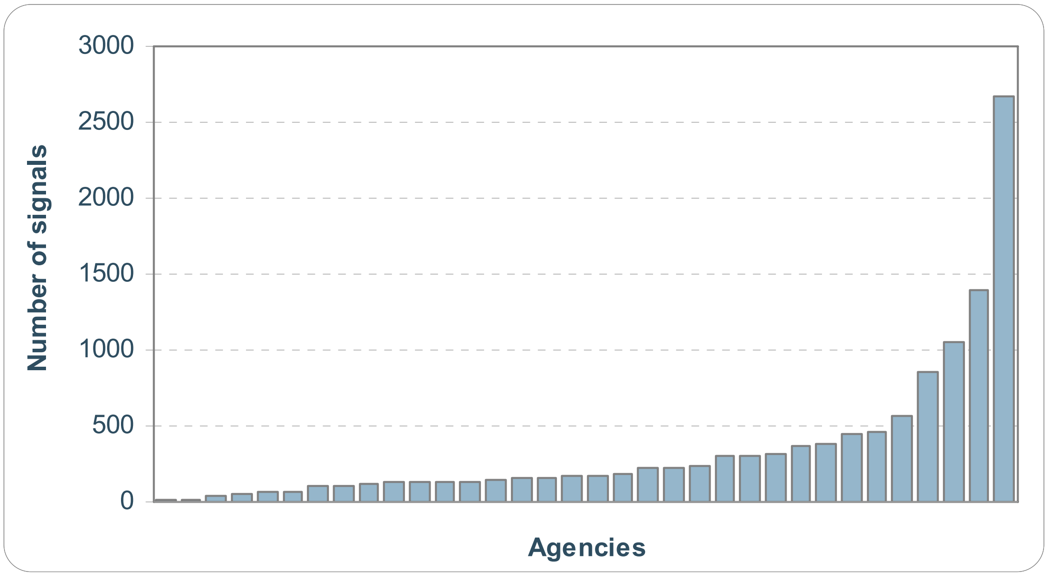



**Figure A-1Signals maintained by surveyed agencies**

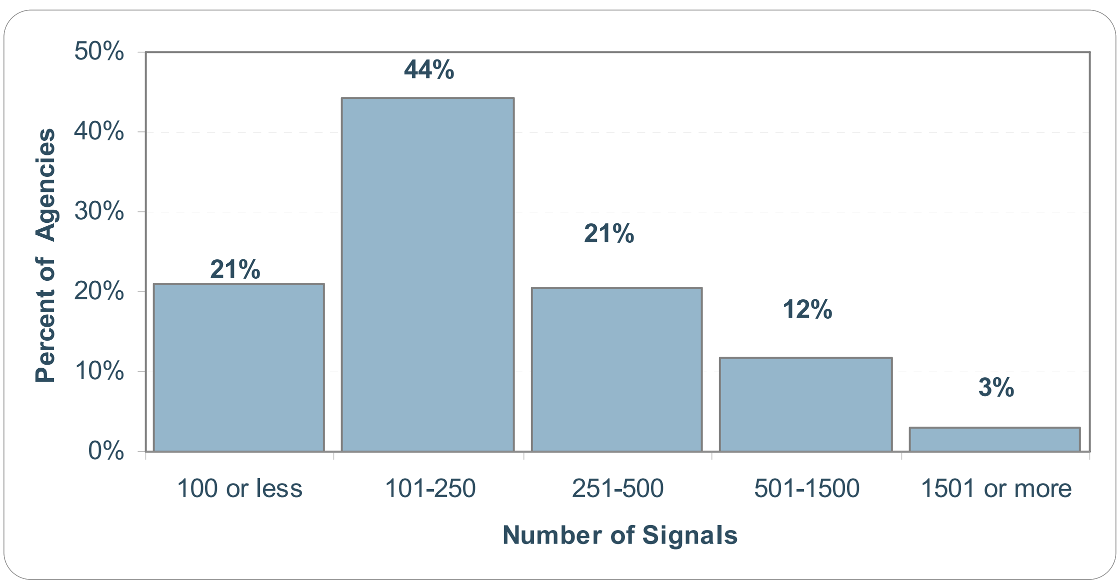



**Figure A-2 Distribution of the number of signals maintained by surveyed agencies**

2. Approximately how many traffic signals mentioned in Question 1 are normally coordinated during most of the daytime?

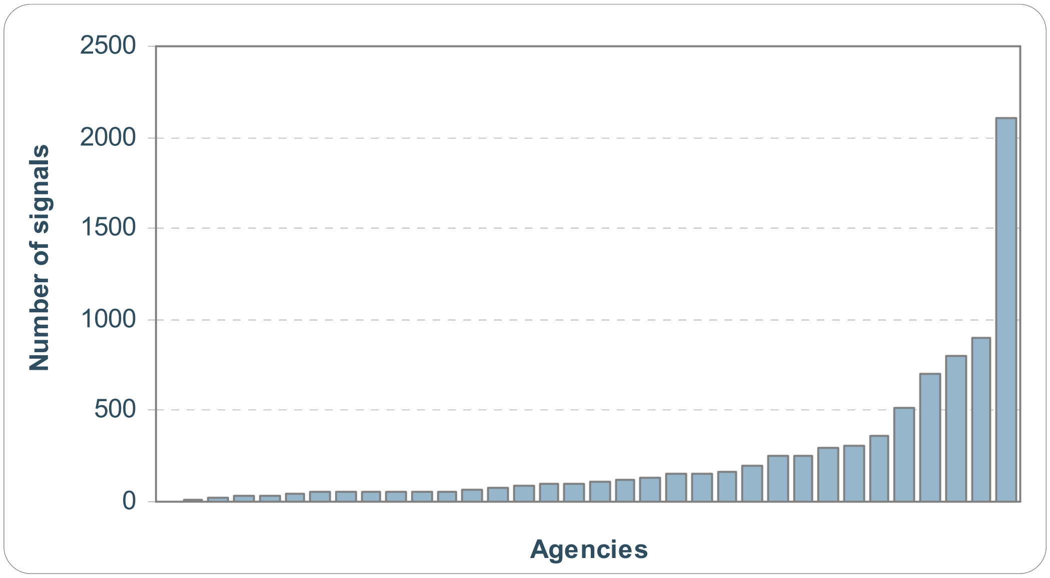



**Figure A-3 Signals coordinated by surveyed agencies**

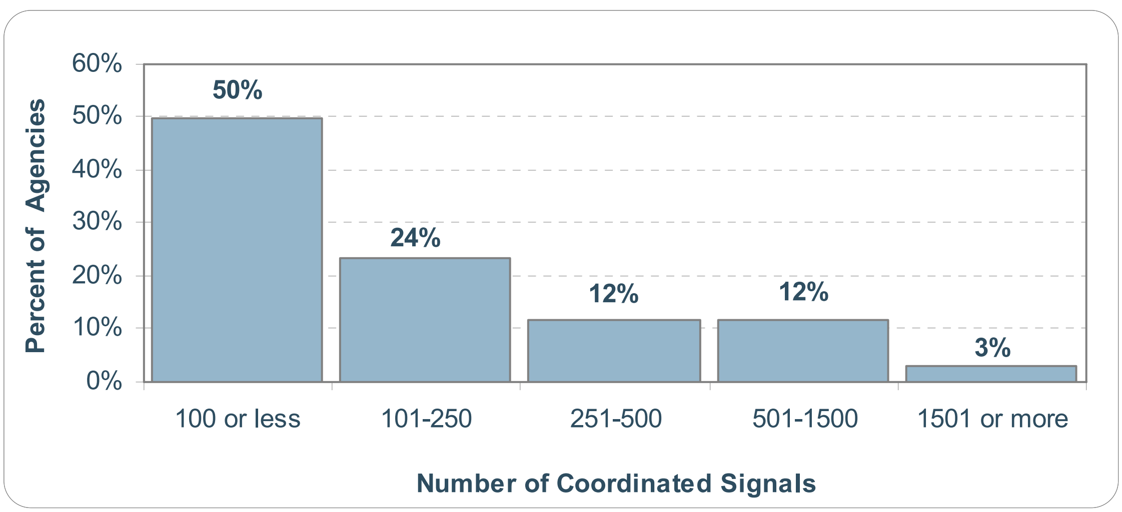



**Figure A-4 Distribution of the number of signals coordinated by surveyed agencies**

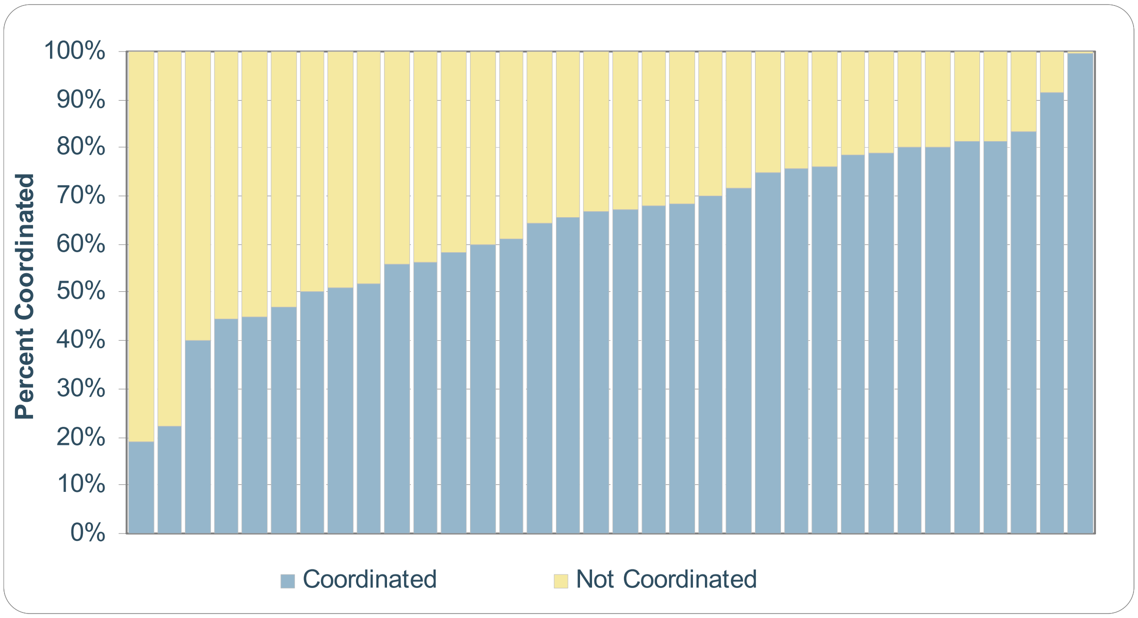



**Figure A-5 Percentage of coordinated signals sorted in increasing order**

3. Typically how often do you retime your traffic signals? (e.g. 2 years)

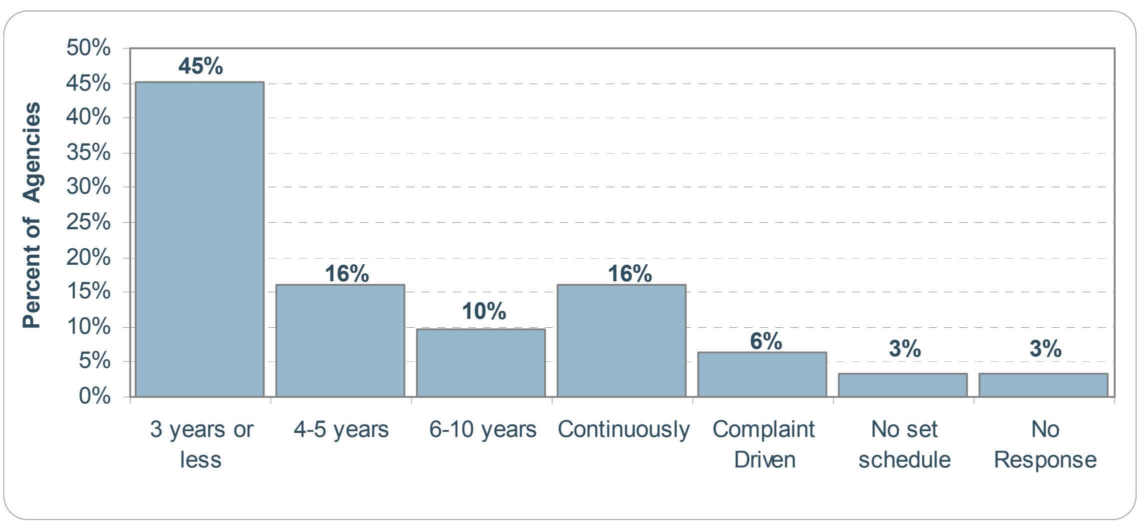



**Figure A-6 Distribution of frequency of retiming**

4. What is the average annual traffic growth rate in your jurisdiction?

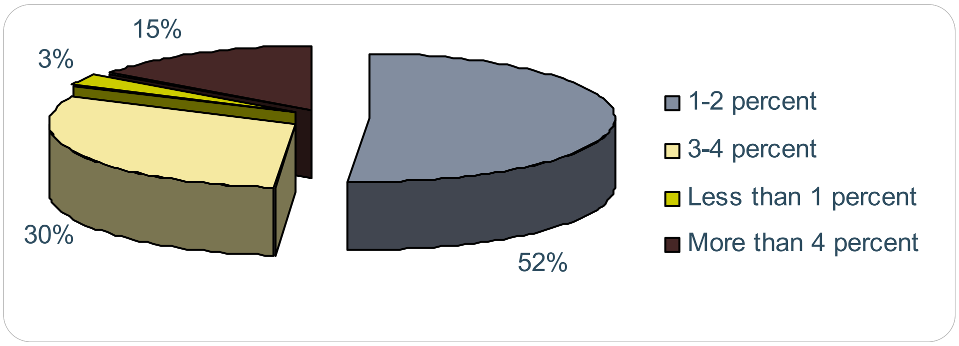



**Figure A-7 Percentage of average annual traffic growth rates**

5. In your jurisdiction, what percentage of coordinated traffic signals is interconnected using the following signal system architecture? (e.g. 20, 45)

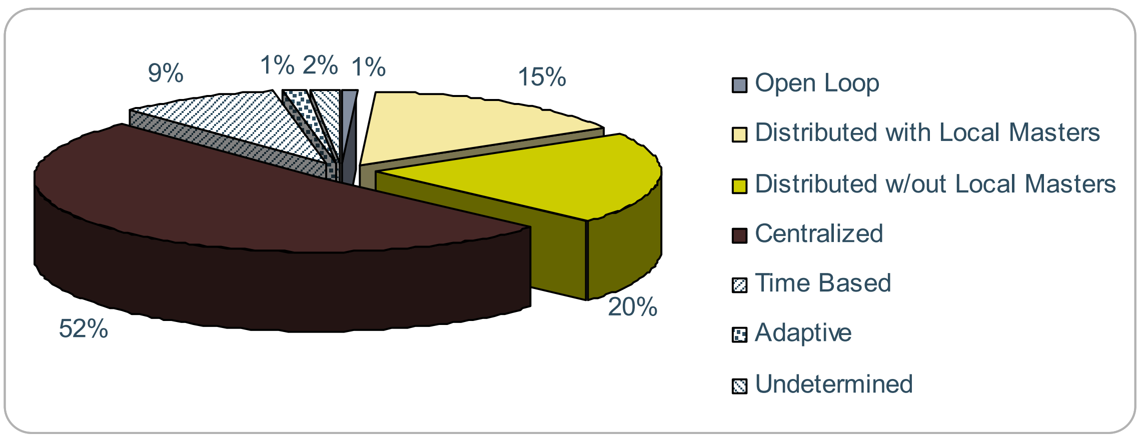



**Figure A-8 Percentage of coordinated signals of the surveyed agencies by system architecture**

6. Approximately how many control sections per 100 coordinated signals are in your jurisdiction?

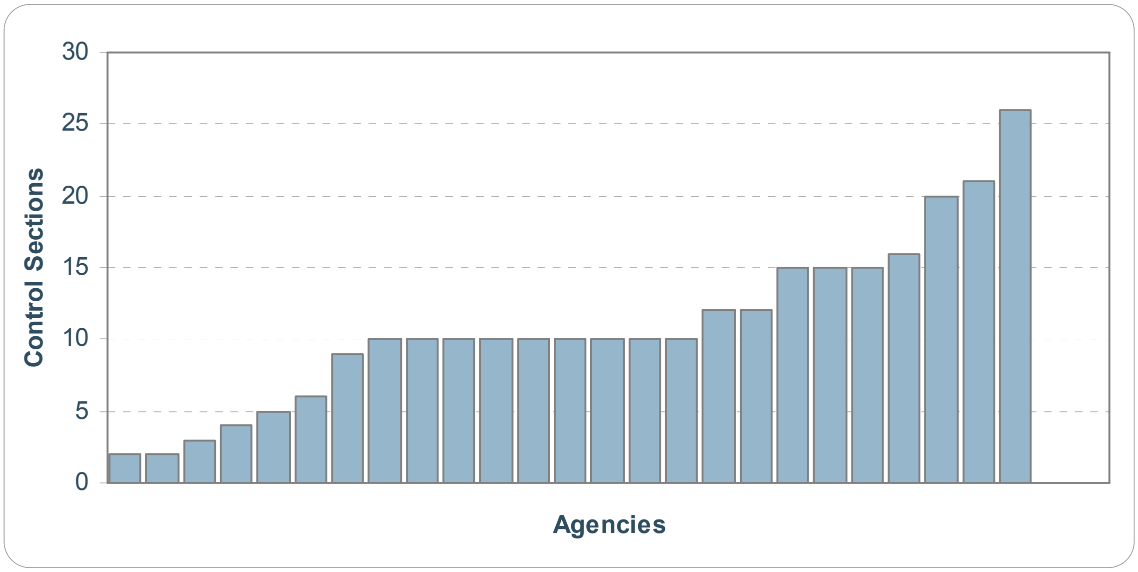



**Figure A-9 Number of control section per 100 coordinated signals**

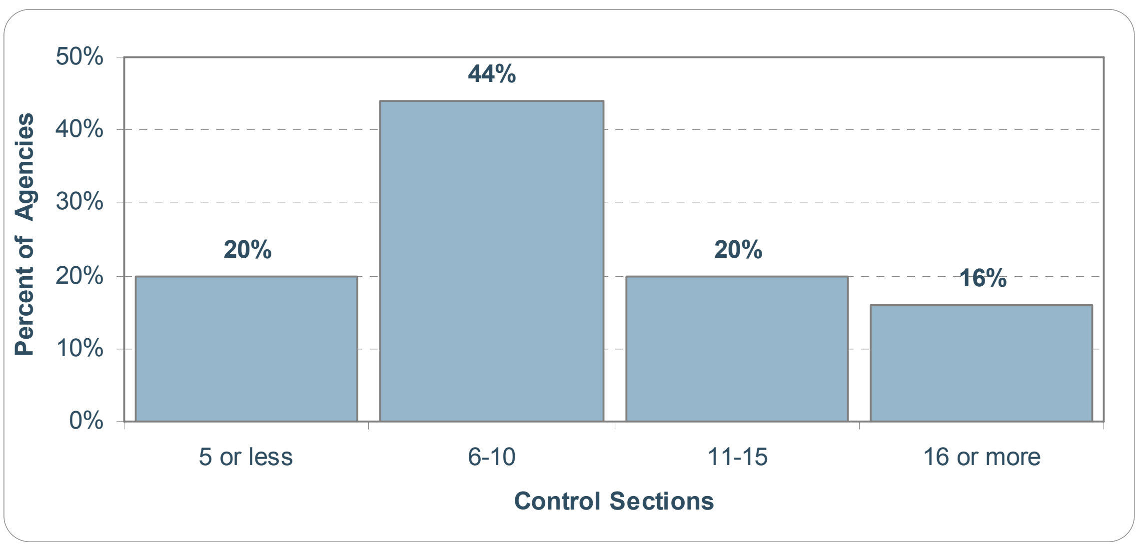



**Figure A-10 Distribution of the control sections per 100 coordinated signals**

7. How many signalized intersections are in a typical control section?

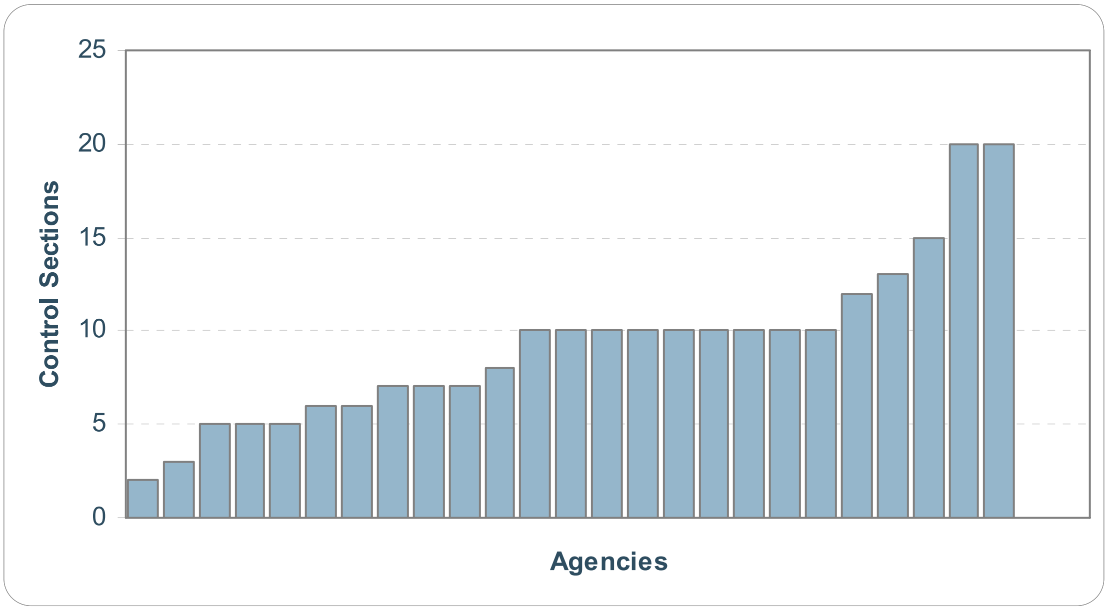



**Figure A-11  Number of signals per control section**

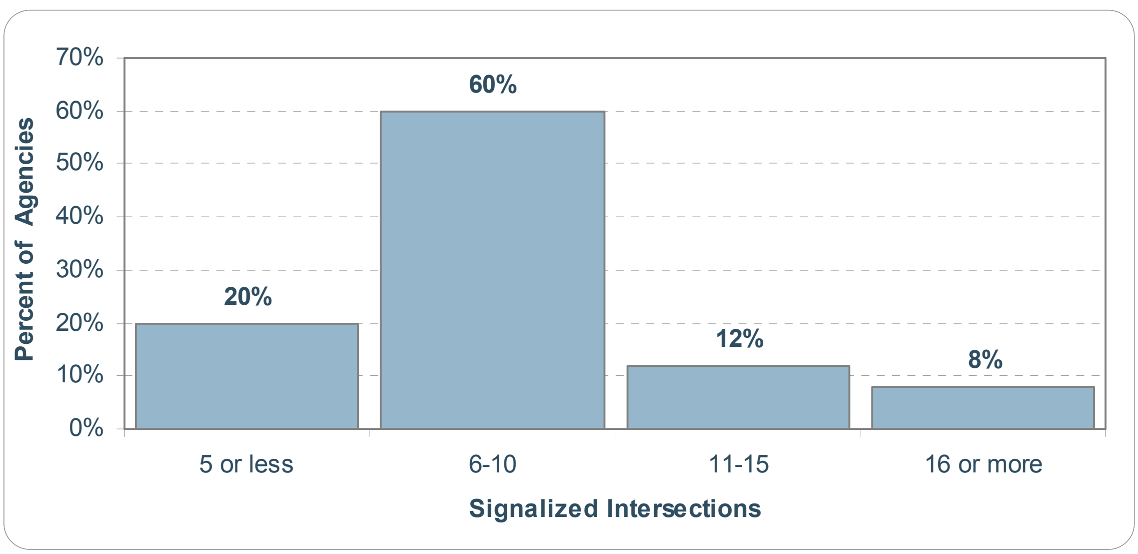



**Figure A-12  Distribution of the number of signals per control section**

8. Does your agency use adaptive traffic signal control?

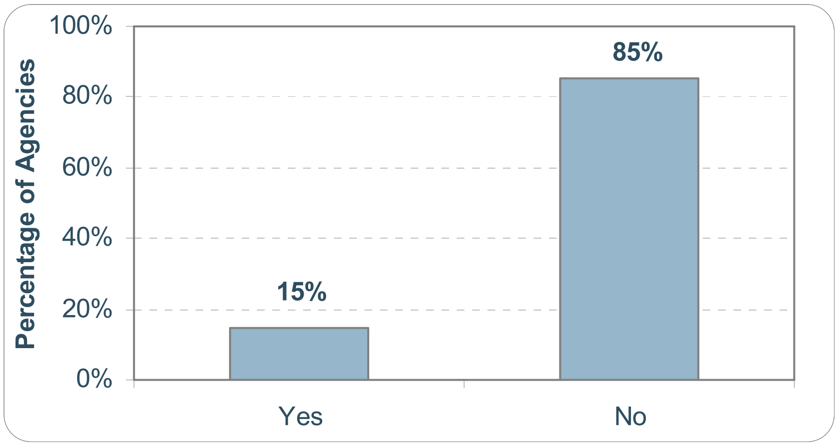



**Figure A-13 Number of agencies with adaptive signal control**

9. If yes, what type, SCOOT, SCATS, RT-TRACS, ACS-Lite, or others?

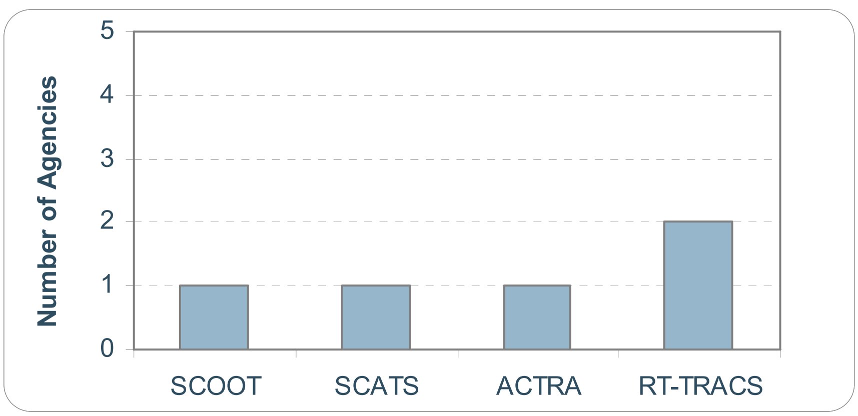



**Figure A-14 Types of adaptive signal control**

10. If no, will your agency consider using adaptive traffic signal control in the next three years?

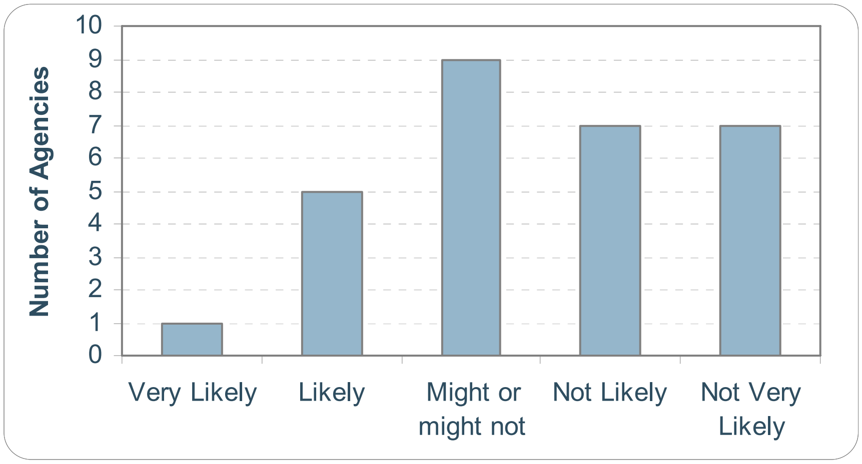



**Figure A-15 Use of adaptive signal control in the next three years**

11. Please list the percentage of signals for each type of traffic controller in your jurisdiction. (e.g. 20, 45)

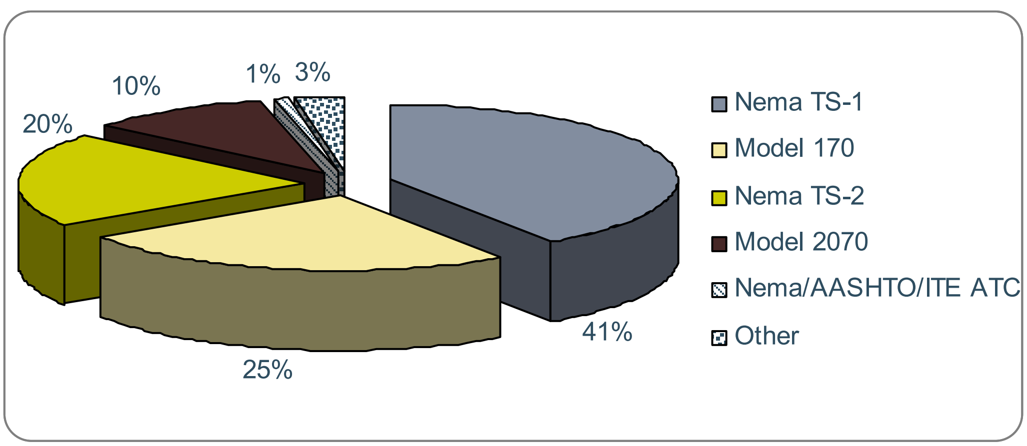



**Figure A-16 Percentage of signals per controller type**

12. If other, please specify

**Table A- 1 Other controller types in use**

| Other |
|---|
| Will change out all 43 intersections this year 08 for Nema TS-1 |
| 7% 970 (NEMA TS2 controller running in 332A cabinet) |
| Peek 1880EL have FDOT LAP project to upgrade to Peek NTCIP compliant Advanced Traffic Signal Controllers |

13. Please list the percentage of signals for each type of detection system(s) (loop, video, magnetic, microwave, infrared, etc.) used to detect vehicles at signalized intersections in your jurisdiction. (e.g. 20, 45)

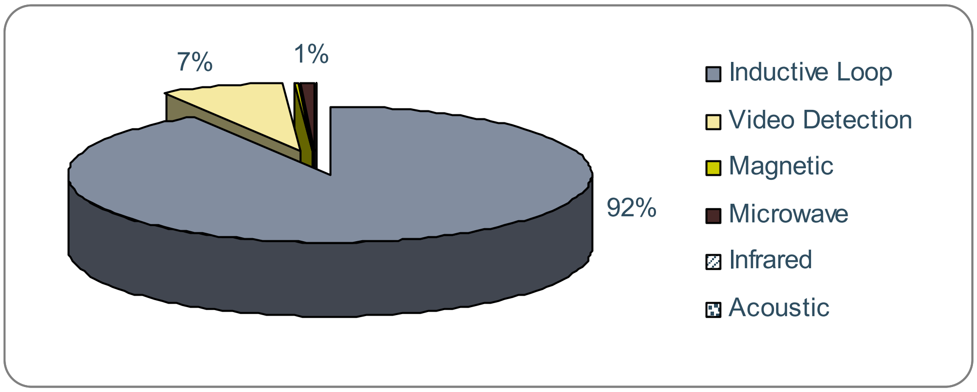



**Figure A-17 Percentage of signals per type of detection system**

14. If other, please specify:

**Table A- 2 Other detection systems in use**

| Other |
|---|
| none (pre-timed) |
| At some intersections use combination of loops video and infrared depending upon physical roadway pavement |
| Approximately 10% with no detection (fixed time operation) |

15. Approximately what percentage of detectors in your jurisdiction perform the following functions? (e.g. 20 , 45)

a. Stop bar detection (presence of vehicle) to actuate a signal timing change

b. Traffic counting

c. Advanced detection for adaptive traffic control or traffic responsive systems

d. Other

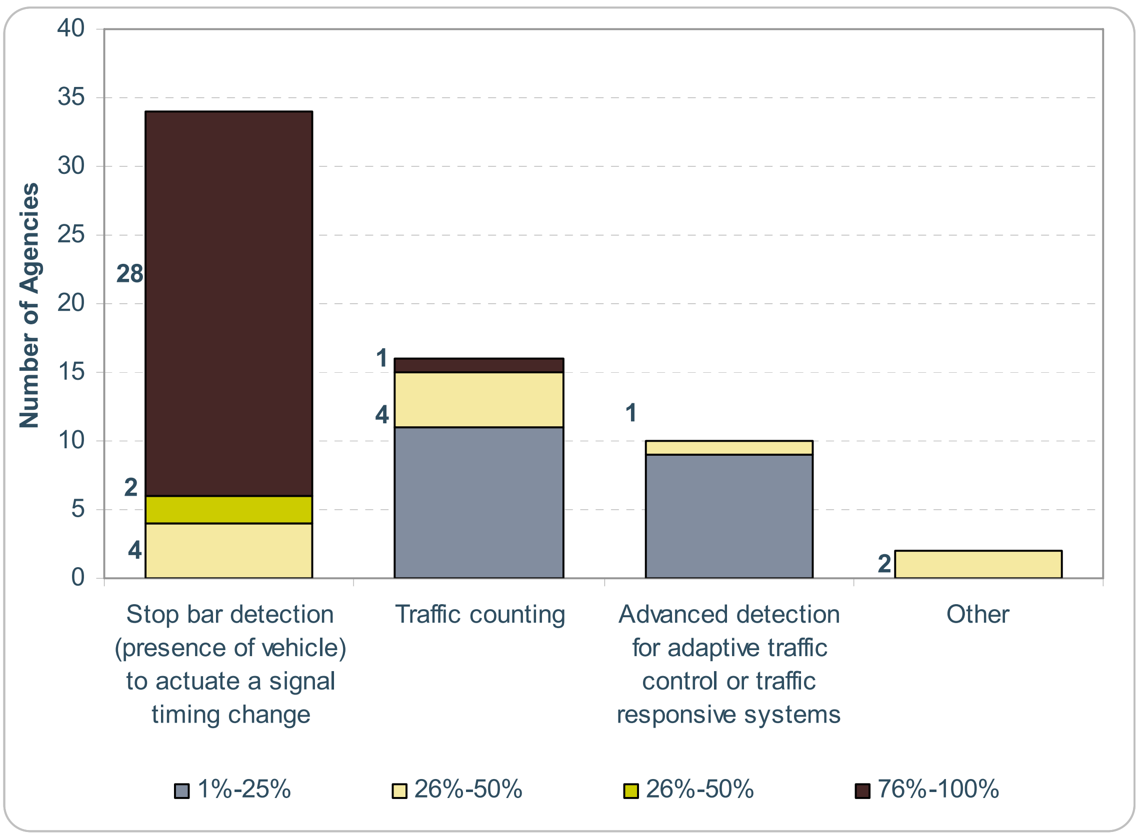



**Figure A-18 Frequency distribution of the number of agencies by functions performed by the detectors of the traffic signal system**

16. If other, please specify

**Table A- 3 Other functions performed by detectors**

| Other |
|---|
| Video feed / alarms at TMC for operator response |

17. How are the malfunctioning or broken detectors detected by the agency? (Rank 1-6, where 1 means most common and 6 means least common)

**Table A- 4 Ranking of methods for finding detector failures**

| Method | 1 | 2 | 3 | 4 | 5 | 6 | Counts | Rank |
|---|---|---|---|---|---|---|---|---|
| Customer complaints about timing | 18 | 4 | 5 | 4 | 0 | 0 | 31 | 2.0 |
| Reported by traffic operations personnel | 4 | 10 | 7 | 5 | 4 | 0 | 30 | 3.2 |
| Scheduled inspections | 4 | 5 | 11 | 4 | 2 | 1 | 27 | 4.2 |
| Traffic Signals Systems Alarms | 2 | 5 | 2 | 2 | 8 | 4 | 23 | 4.9 |
| Signal system reports | 2 | 2 | 4 | 4 | 4 | 7 | 23 | 5.5 |
| Other | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 5.5 |

18. How long does it typically take to repair a malfunctioning or broken detector after a problem is located in the detection system (the time should include the total time from identification of problem to when the signal system back to normal operation)?

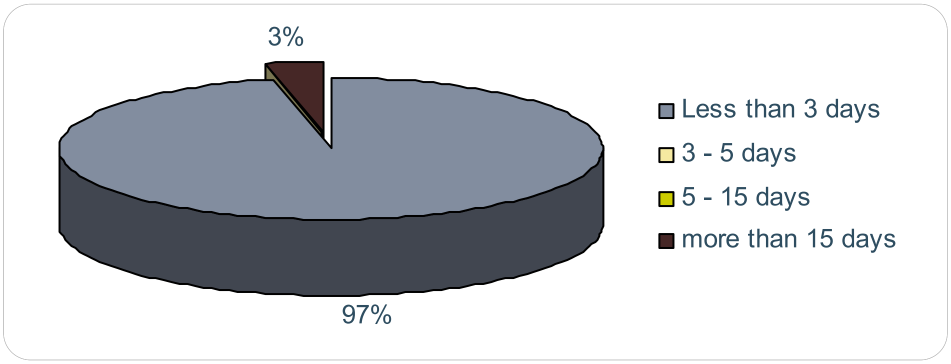



**Figure A-19 Repair time for detector malfunction for inductive loop detectors**

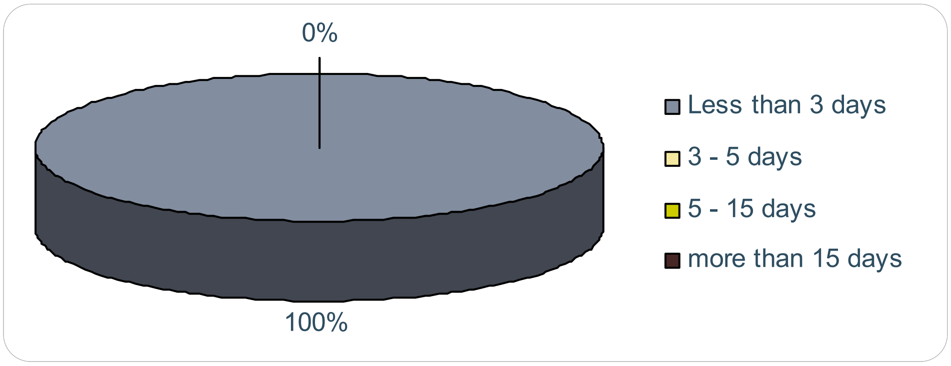



**Figure A-20 Repair time for detector malfunction for video detectors**

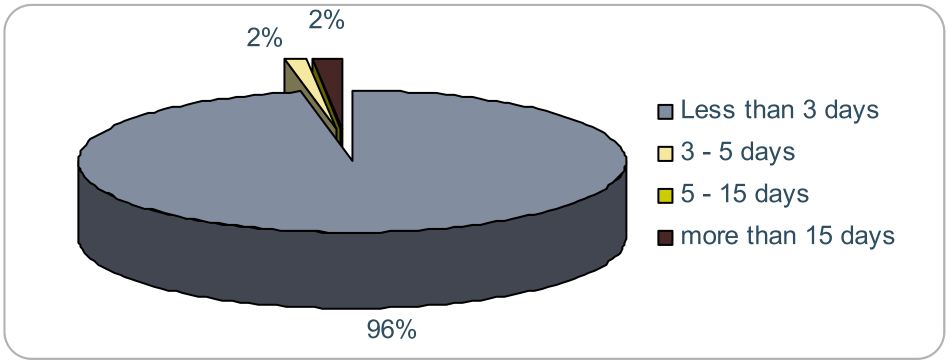



**Figure A-21  Overall repair time for detector malfunction**

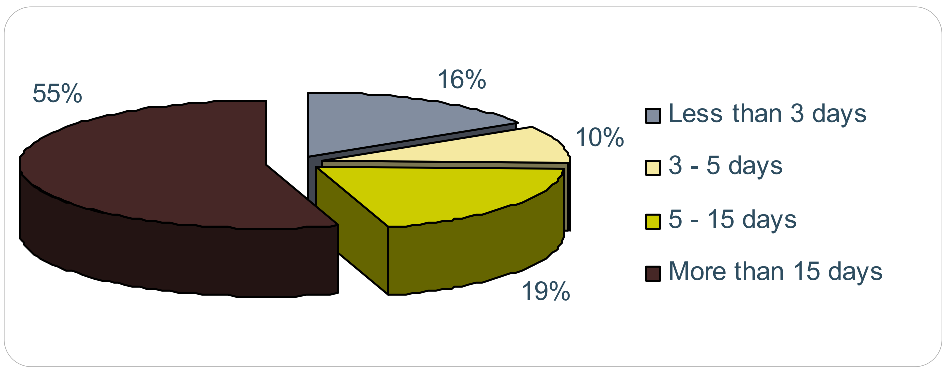



**Figure A-22  Repair time for broken detectors for inductive loop detectors**

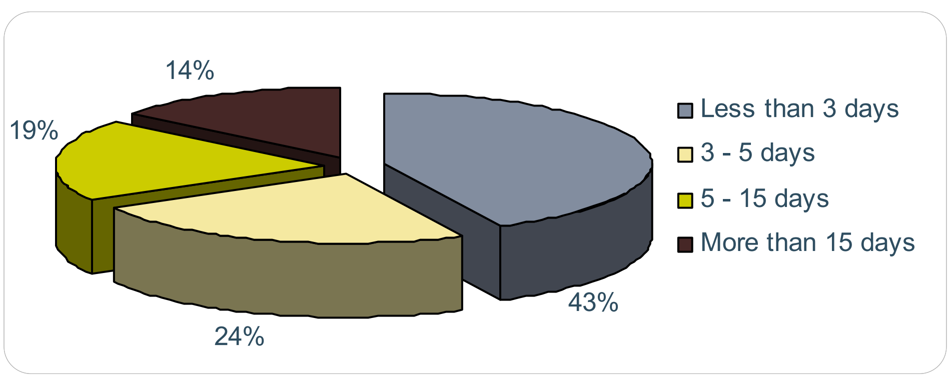



**Figure A-23  Repair time for broken detectors for video detectors**

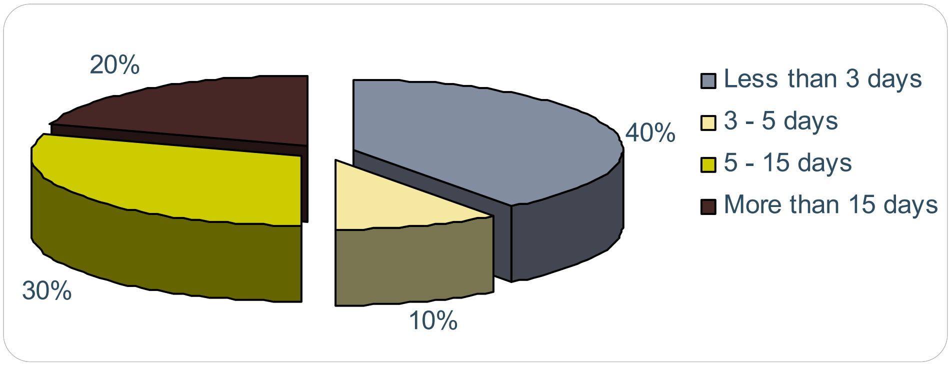



**Figure A-24 Repair time for broken detectors for microwave detectors**

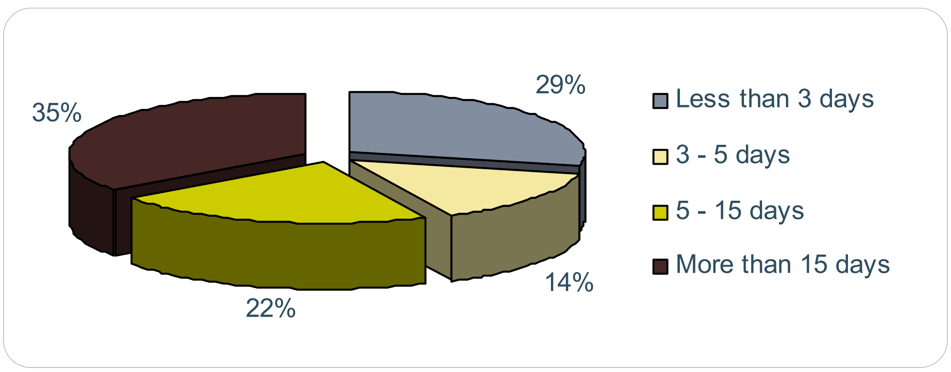



**Figure A-25 Overall repair time for broken detectors**

19. How much does it cost to replace/fix the following detection devices?

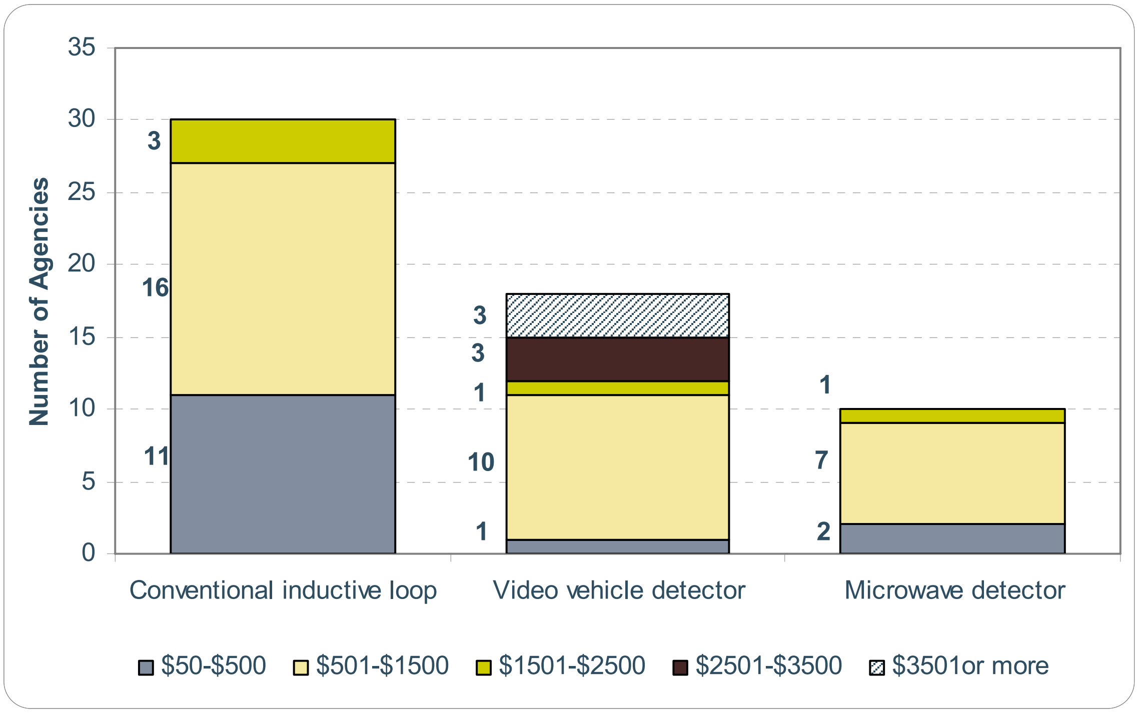



**Figure A-26 Frequency distribution of the number of agencies by repair cost of detection devices**

20. What measures does your agency employ to reduce detection "down time"?

Summarizing the responses, the top two most commonly encountered measures are:

Preventive maintenance and scheduled inspections (15 counts)

Keep stock of spare parts for non-loop detectors (7 counts)

Other responses encountered were:

Increase availability of personnel

Hire contractors for loop replacement

Use microwave detectors for backup for temporary loop replacement

21. Does your staff have adequate training to diagnose and repair current vehicle detection technologies? (Open ended question)

The great majority of the agencies responded affirmatively to this question (29 counts).

22. What percentage of the detector repair work does your agency contract out to a private company?

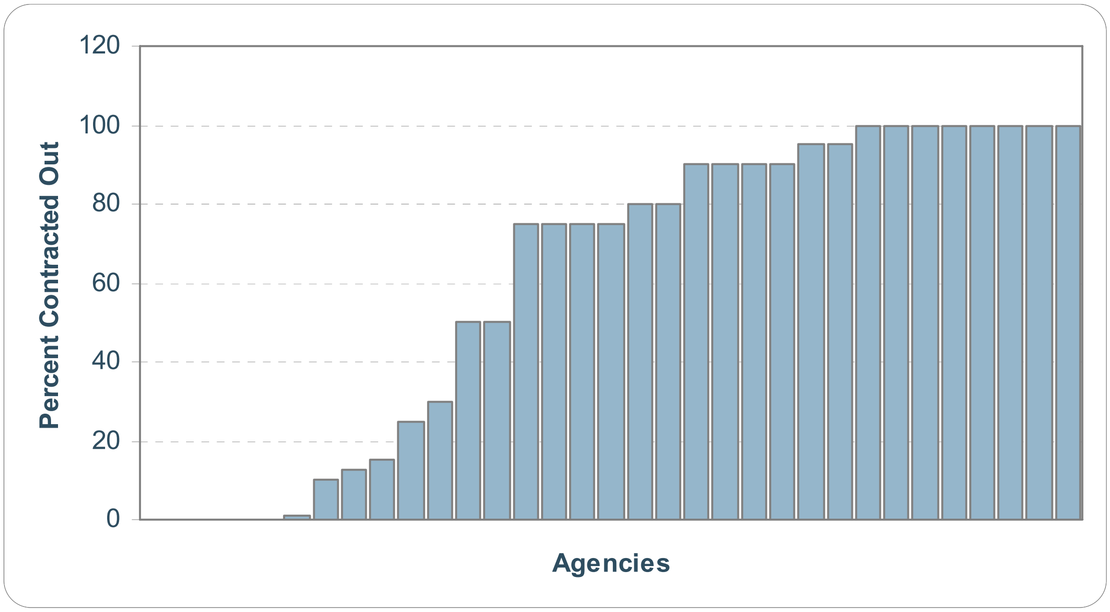



**Figure A-27 Percentage of repair work contracted out to private companies**

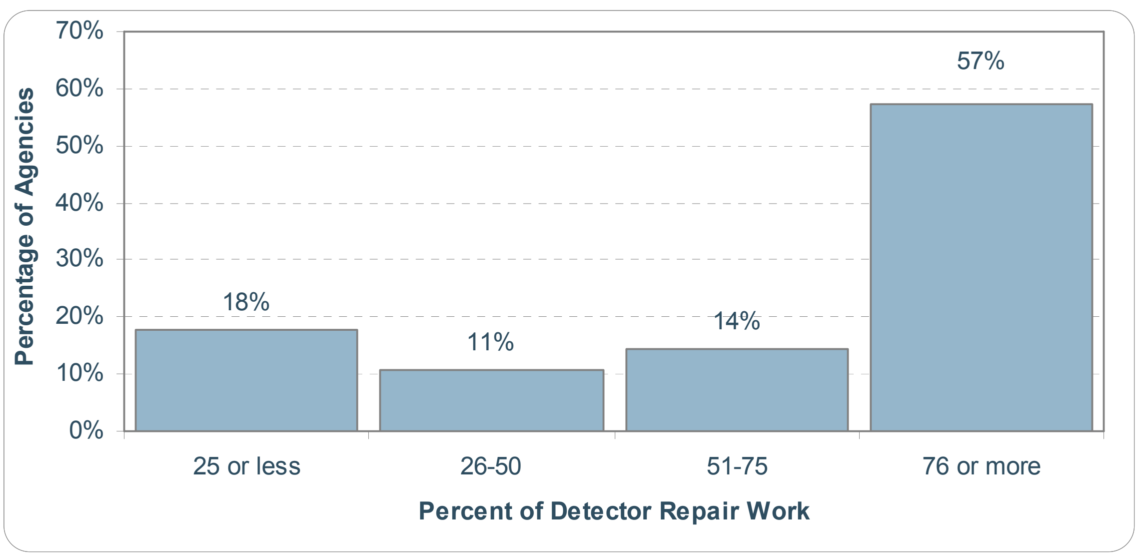



**Figure A-28 Distribution of the repair work contracted out to private companies**

23. Rank the detector maintenance issues (1 being most commonly encountered and 6 being least encountered)

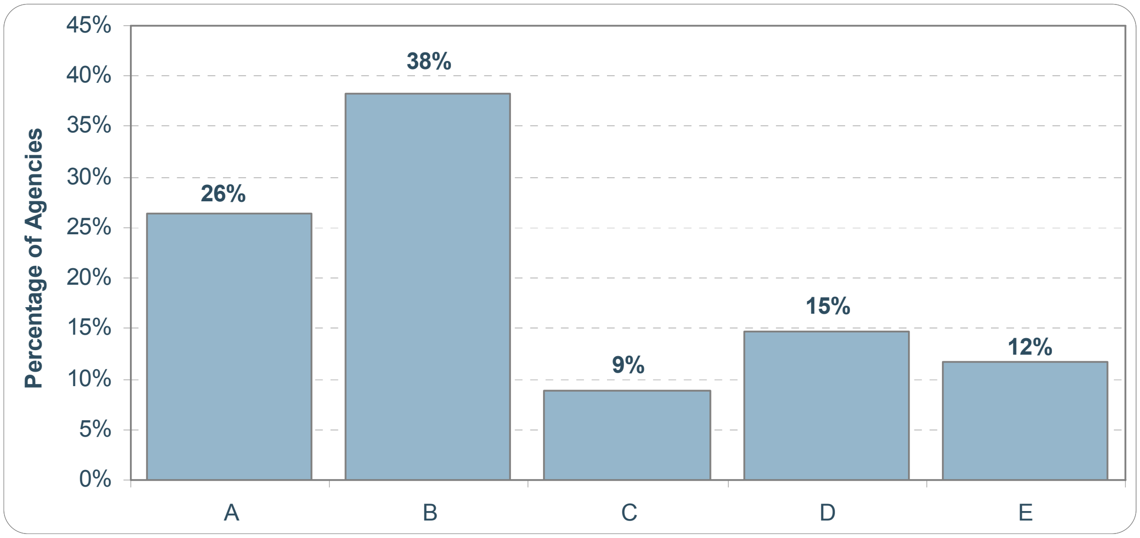
**Table A- 5 Ranked list of detector maintenance issues**

| Detector Maintenance Issues | 1 | 2 | 3 | 4 | 5 | 6 | Counts | Rank |
|---|---|---|---|---|---|---|---|---|
| Lack of funding to maintain or/and repair | 8 | 6 | 4 | 3 | 5 | 0 | 26 | 2.7 |
| Detector maintenance is outsourced and sometimes or most of time broken detectors cannot be repaired in a timely manner | 4 | 9 | 4 | 2 | 2 | 2 | 23 | 2.8 |
| Too busy to effectively maintain or repair detectors | 3 | 3 | 6 | 9 | 1 | 2 | 24 | 3.3 |
| Lack of skilled workforce to meet the demand | 4 | 0 | 2 | 2 | 9 | 9 | 26 | 4.5 |
| Not the priority of my agency | 0 | 1 | 3 | 4 | 6 | 11 | 25 | 4.9 |

**Table A- 6 Other detector maintenance issues**

| Other Detector Maintenance Issues |
|---|
| With at least 2 dozen intersections affected by or under construction it is difficult to get contractors or subcontractors to understand and respond to the need for working detection at the sites where they are doing work. |
| Current contractor not keeping up with demand and available funds for loop replacements. |
| Inductive loop replacement is #1 ---lane closure law enforcement weather lack of reliable contractors, etc all prolong the repair process. |
| We give top priority to repairing detector systems and in fact we are noted for that in the area. |
| 36% of the signal system intersections we maintain are local city controlled and they are under more financial constraints than the county. |

24. Did your agency observe a relationship between percent of non-operational detectors in the system and percent of system functionality (e.g. coordination) lost?




A. Small percentage of detector failure results in minor loss in system functionality

B. Percentage of detector failure results in proportionate loss in system functionality

C. Small percentage of detector failure results in major loss in system functionality

D. No relationship was observed

E. Other observation

**Figure A-29 Relationship between detector failures and system functionality**

**Table A- 7 Other observations of the relationship between detector failures and system functionality**

| Other observations |
|---|
| Depending on the location of the failure it could be any of the above. |
| It depends; detector failures on coordinated or isolated intersections cause hassle or delay, whereas detector failures even a small number wreak havoc upon the nodes of our SCOOT system. |
| Currently not using system loops; we are currently 98% operational on all stop bar loops. |

25. Please list the percentage of signals for each type of communication system used between signalized intersections in your jurisdiction. (e.g. 20, 45)

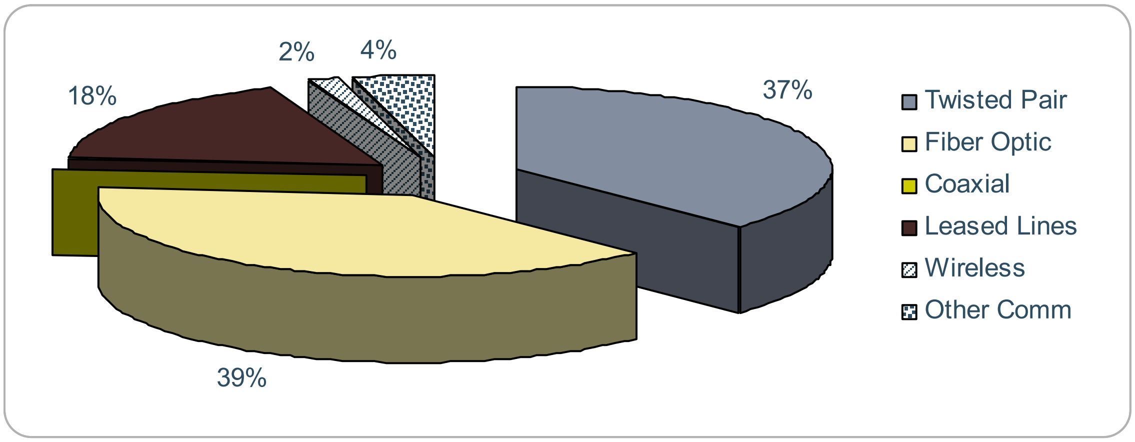



**Figure A-30 Percentage of signals per type of communication between signalized intersections**

26. If other, please specify

**Table A- 8 Other types of communication between signalized intersections**

| Other types of communication |
|---|
| Time based |
| We have fiber back bone to hubs and copper from hub to signals. |
| We use telephone to get into the twisted pair copper closed loop. |
| Transitioning to fiber optic with each project and new installation at this time. |

27. Please list the percentage of signals for each type of communication system used between signalized intersections and traffic management center in your jurisdiction. (e.g. 20, 45)

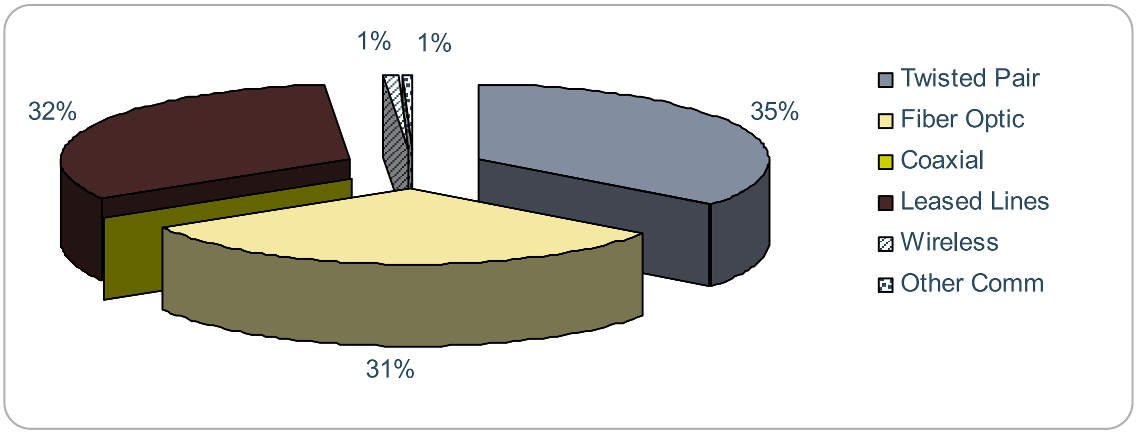



**Figure A-31 Percentage of signals per type of communication system between signalized intersections and traffic management centers**

28. If other, please specify

**Table A- 9 Other types of communication between signalized intersections and traffic management center**

| Other types of communication |
|---|
| Time based |
| No communication = 10% |

29. Approximately how many miles of arterials and local streets where signals are interconnected in the traffic signal systems are in your jurisdiction?

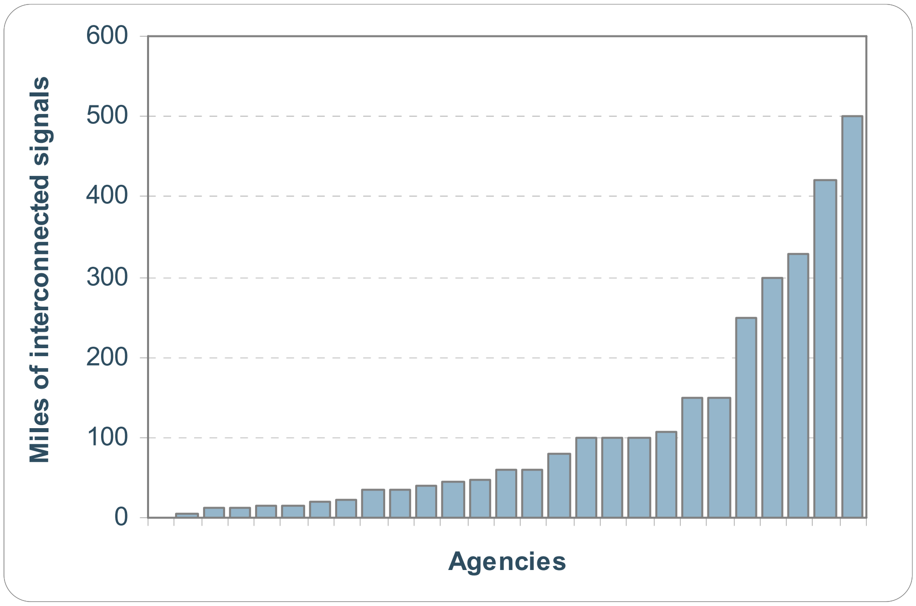



**Figure A-32 Miles of arterials and local streets with interconnected signals**

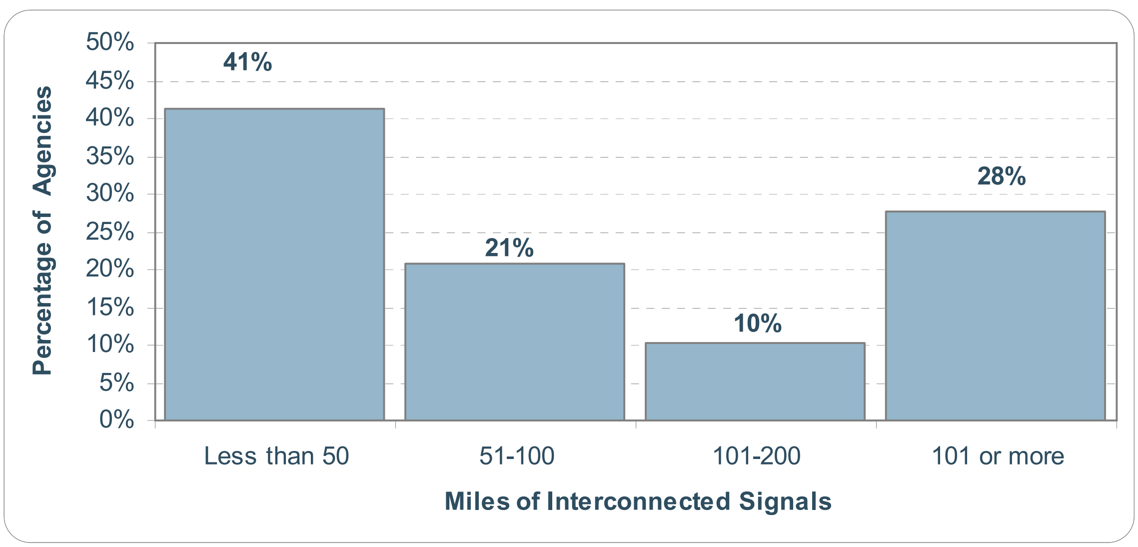



**Figure A-33 Distributions of the miles of arterials and local streets with interconnected signals**

30. Of the above number of miles, what percentage is interconnected via:

a. Aboveground

b. Underground

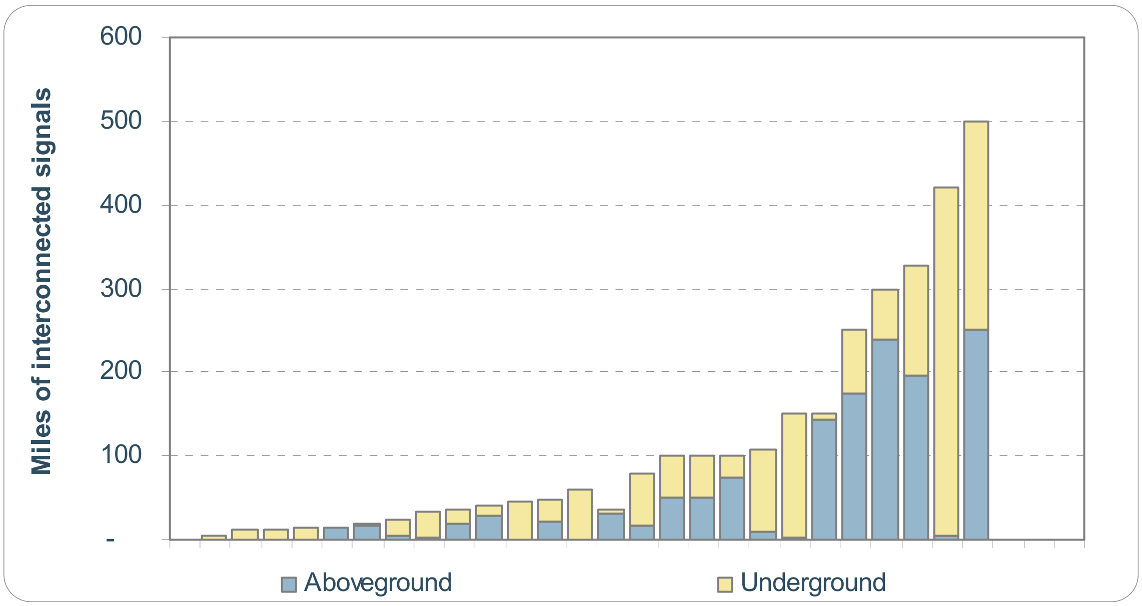



**Figure A-34 Miles of arterials and local streets with aboveground/underground interconnected signals**

31. Does your signal system utilize NTCIP communications protocol? If so, what version?

About half of the participating agencies are using the NTCIP protocol or are in the process of implementation (count of 15 out of 29 responding agencies).

32. Do you use NTCIP for peripheral devices like CMS, CCTV, Data accumulation, or other?

A total of 10 out of 26 responding agencies to this question confirmed the use of NTCIP for peripheral devices.

33. What is the most common type of communication failure issue? Rank 1- 5 (where 1 means most common and 5 means least common)

**Table A- 10 Ranked list of communication failure issues**

| Communication Failure Issues | 1 | 2 | 3 | 4 | 5 | Counts | Rank |
|---|---|---|---|---|---|---|---|
| Communication device failure | 11 | 7 | 4 | 3 | 1 | 26 | 2.1 |
| Cut or damage cable | 10 | 8 | 4 | 2 | 4 | 28 | 2.4 |
| Lightning damage | 6 | 2 | 7 | 9 | 2 | 26 | 3.0 |
| Network interference | 0 | 2 | 7 | 9 | 3 | 21 | 3.6 |

34. How long does it typically take to repair a communication failure after a communication problem is identified?

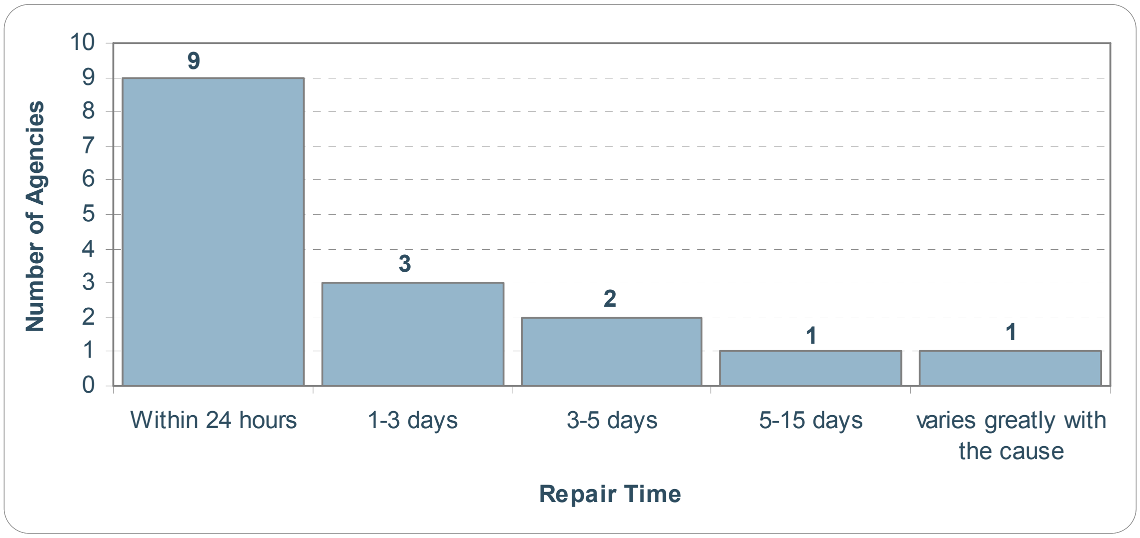



**Figure A-35 Repair time for communication failures**

35. How much does it cost to replace/fix the following communication devices?

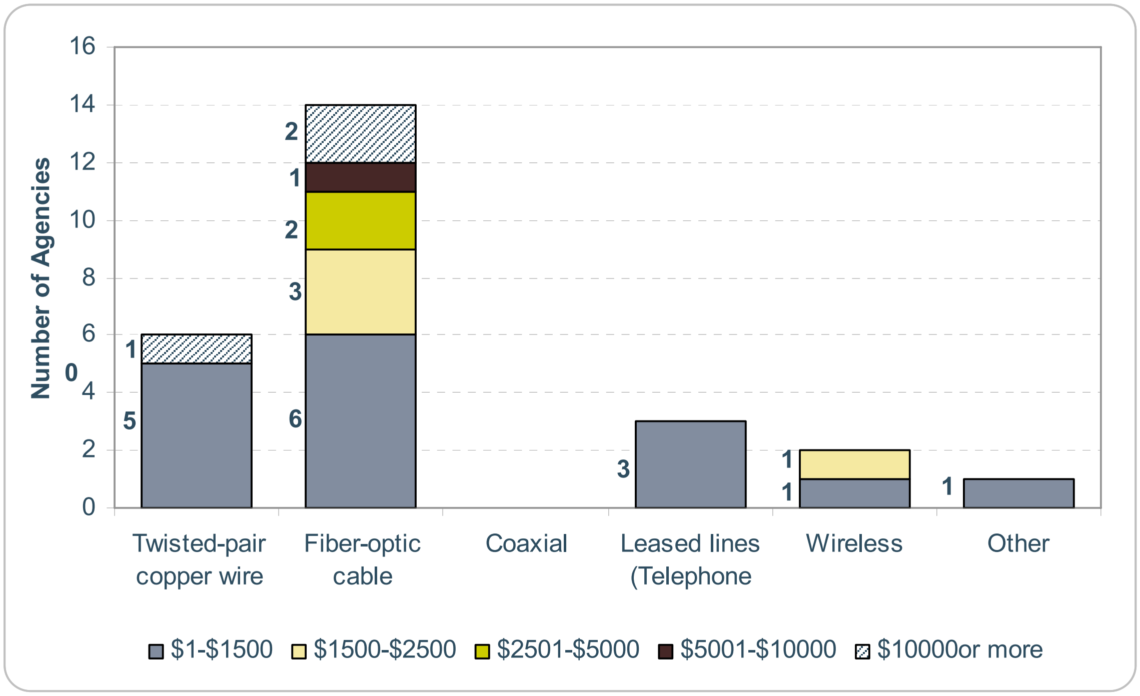



**Figure A-36 Frequency distribution of the number of agencies by repair cost per communication device**

36. If other, please specify

**Table A- 11 Other repair costs of communication devices**

| Other repair costs |
|---|
| Unsure as this is handled by another city department |
| This cost can vary depending on the problem...too vague of a question. |
| It depends; we could have a cut FO cable that requires re-splicing and the cost would depend upon the number of fibers that need to be spliced. A FO modem or FO Ethernet switch could malfunction and need to be replaced. |
| No fiber devices have gone bad yet. That is the price of a switch. |
| $3.00/foot to replace fiber and conduit underground. |
| We pay a monthly fee for each leased line. |

37. What percentage of the communication repair work does your agency contract out to a private company?

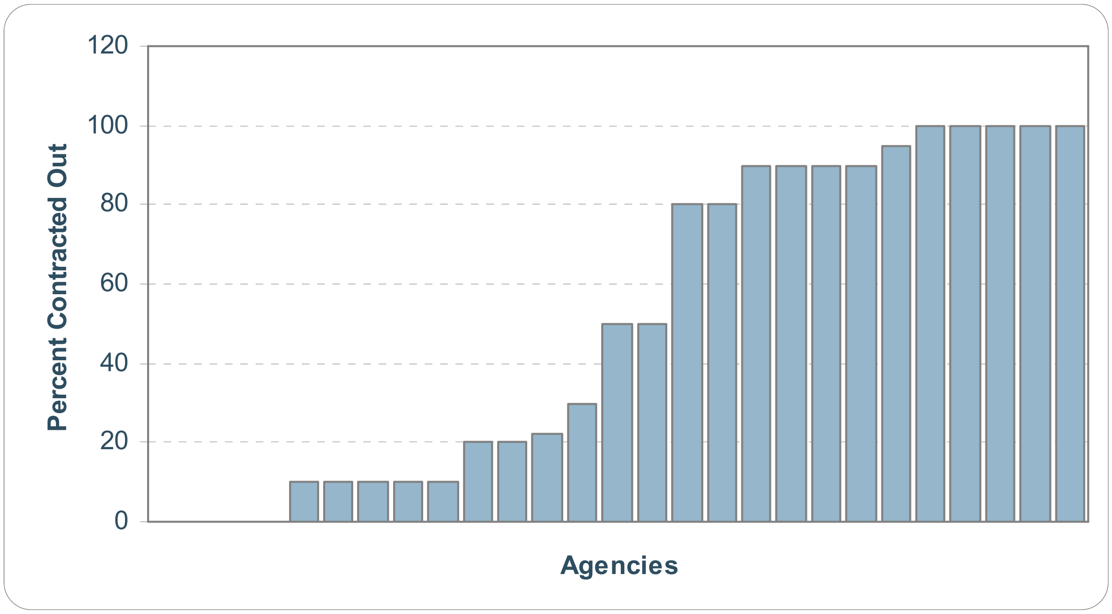



**Figure A-37 Percentage of communication repair work contracted out to private companies**

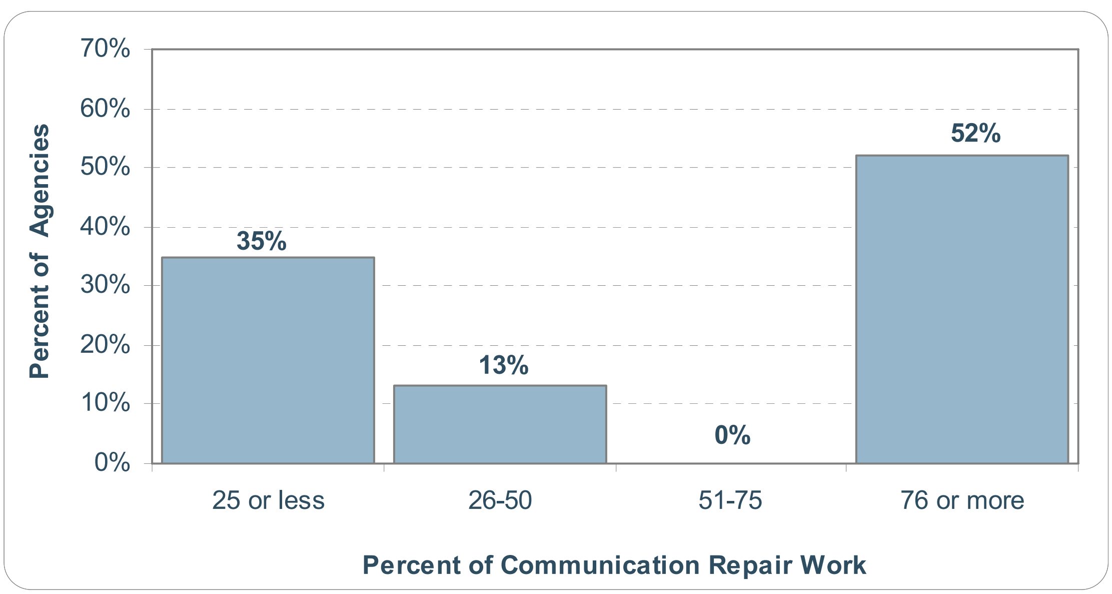
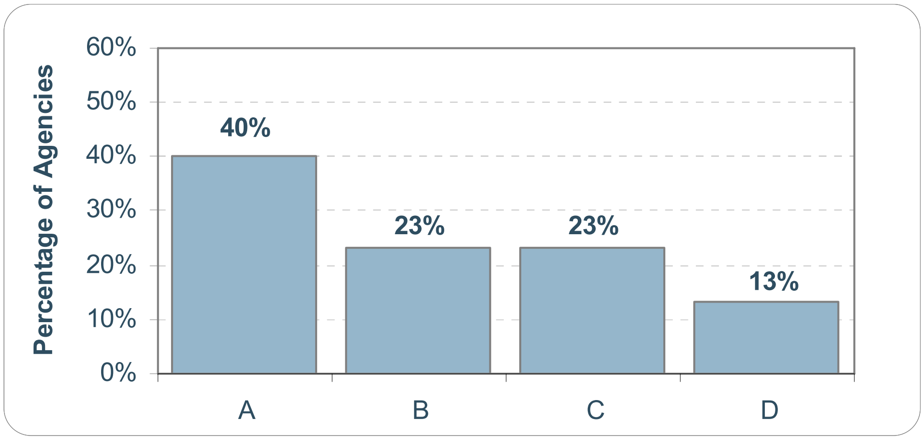



**Figure A-38 Distribution of the communication repair work contracted out to private companies**

38. Did your agency observe a relationship between percent of communication functionality lost and percent of system functionality (e.g. coordination) lost?




A. Small percentage of communication failure results in minor loss in system functionality

B. Percentage of communication failure results in proportionate loss in system functionality

C .Small percentage of communication failure results in major loss in system functionality

D. No relationship was observed

**Figure A-39 Relationship between communication failures and system functionality**

39. Which signal system software is used by your agency to operate majority of the signals?

**Table A- 12 List of signals system software used by responding agencies**

| Agency | Software | Number of Signals |
|---|---|---|
| 1 | ACTRA | 50 |
| 2 | ACTRA | 160 |
| 3 | Aries | 130 |
| 4 | Aries | 220 |
| 5 | ATMS now | 232 |
| 6 | ATMS now | 861 |
| 7 | ATMS now | 134 |
| 8 | ATMS now | 380 |
| 9 | CLMATS | 65 |
| 10 | CLMATS | 100 |
| 11 | CLMATS | 105 |
| 12 | CLMATS | 1050 |
| 13 | Kimley Horn KITS | 320 |
| 14 | LMSYSTEMS | 43 |
| 15 | MarcNx | 120 |
| 16 | MIST 2.0 | 465 |

| Agency | Software | Number of Signals |
|---|---|---|
| 17 | MTCS Protocol 90 & Aries | 568 |
| 18 | MTCS Protocol 90 | 298 |
| 19 | MTCS Protocol 90 | 370 |
| 20 | MTCS-PC | 145 |
| 21 | Smartways & ATMS now | 224 |
| 22 | Smartways & CLMATS | 170 |
| 23 | Smartways DOS Central Software | 305 |
| 24 | Smartways & StreetWise | 128 |
| 25 | Smartways, CLMATS & StreetWise | 190 |
| 26 | StreetWise | 130 |
| 27 | StreetWise | 158 |
| 28 | StreetWise | 441 |
| 29 | Transcore's Transuite | 165 |
| 30 | UTCS | 1400 |
| 31 | UTCS | 2670 |
| | | |

40. What is your estimated annual maintenance budget for your traffic control system, ITS infrastructure, loops and video detection?

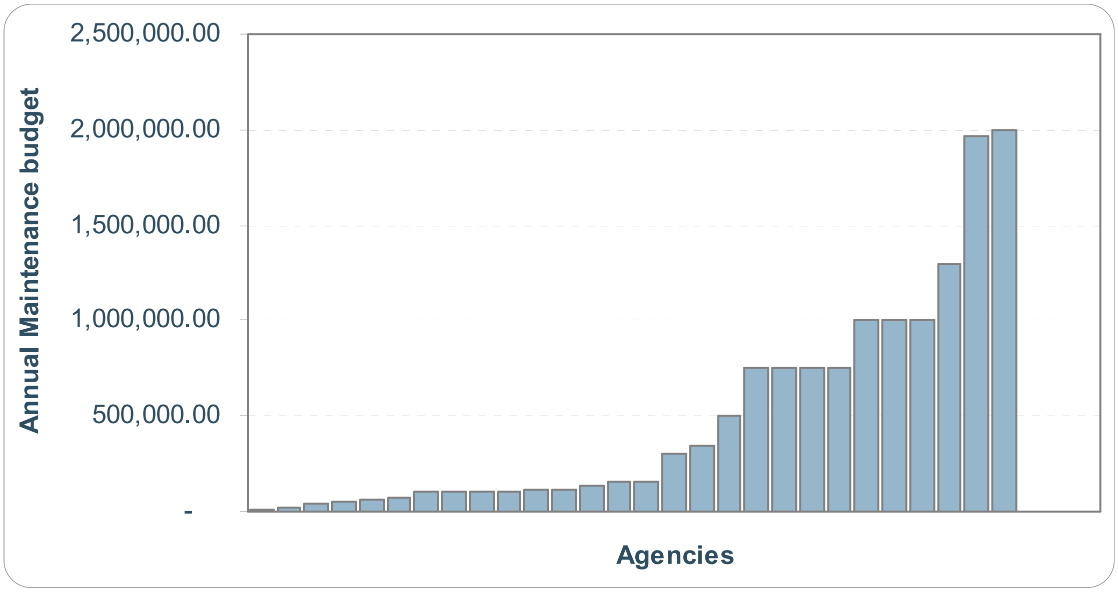



**Figure A-40 Estimated annual maintenance budget for traffic control systems, ITS infrastructure, loops and video detection**

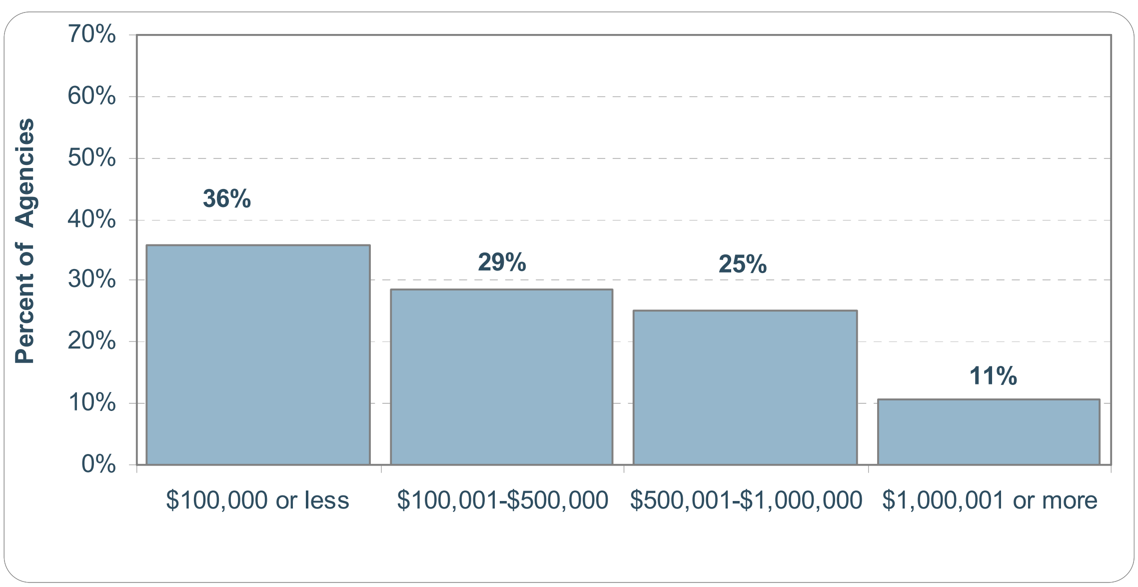



**Figure A-41 Distribution of the estimated annual maintenance budget for traffic control systems, ITS infrastructure, loops and video detection**

41. Is the current maintenance budget sufficient? If not, what percent increase in funding will address your agency needs?

Only 7 out of 31 agencies consider that the current maintenance budget is sufficient. The percent of increase ranged from 10 percent to 300 percent.

42. Does your agency plan include long term maintenance funding for signal systems, ITS projects, and CCTV installations?

The majority of the surveyed agencies (25 out of 31 responses) have plans that include long term maintenance funding.

43. How often does your agency conduct any of the following preventive maintenance procedures?

Clean and inspect traffic cabinets

Clean and inspect video detection cameras

Test communication devices

Clean and inspect CCTV

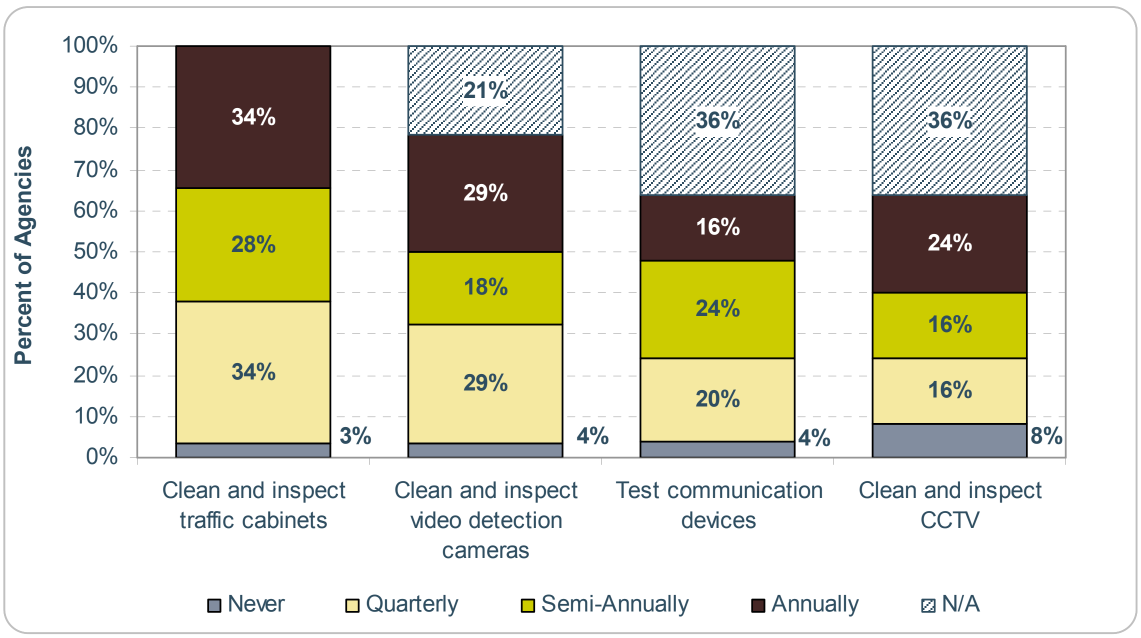



**Figure A-42 Distribution of the frequency of maintenance activities**

44. What are your agency's top five performance measures for traffic signal systems in your jurisdiction?

**Table A- 13 Ranked list of performance measures for traffic signal systems**

| Top Performance Measures | 1 | 2 | 3 | 4 | 5 | Counts | Rank |
|---|---|---|---|---|---|---|---|
| Total number of complaints received from the general public related to traffic signal systems during a certain period of time | 6 | 4 | 2 | 3 | 3 | 18 | 1.6 |
| Travel time on major corridors with traffic signal systems | 5 | 4 | 1 | 4 | 1 | 15 | 2.1 |
| Satisfaction of the general public on traffic signal progression | 2 | 2 | 7 | 3 | 5 | 19 | 2.7 |
| Vehicle delay at signalized intersections or accumulated delay on corridors | 3 | 2 | 4 | 2 | 1 | 12 | 3.1 |
| Total number of requests received from residents and sheriffs for traffic signal service | 1 | 6 | 2 | 1 | 1 | 11 | 3.4 |
| Number of stops along a traffic signal system | 2 | 3 | 2 | 3 | 2 | 12 | 3.8 |
| Percentage of functional signalized intersections (no detection and communication problems) in all traffic signal systems | 3 | 1 | 2 | 3 | 1 | 10 | 4.1 |
| Level of congestion | 3 | 2 | 1 | 1 | 4 | 11 | 4.4 |
| Percentage of functional communication at signalized intersections in all traffic signal systems | 1 | 1 | 1 | 3 | 1 | 7 | 4.6 |
| Percentage of functional detectors at signalized intersections in all traffic signal systems | 0 | 2 | 2 | 1 | 2 | 7 | 4.8 |
| Average travel speed on major corridors with traffic signal systems | 1 | 0 | 2 | 2 | 3 | 8 | 5.0 |

45. Rate the following on a scale of 1 - 5 (where 5 means excellent and 1 means poor)

**Table A- 14 Rating of the current status of the traffic signal system components**

| | 1 | 2 | 3 | 4 | 5 | Rating |
|---|---|---|---|---|---|---|
| Performance of your traffic signal system maintenance | 2 | 4 | 12 | 7 | 6 | 3.4 |
| Status of detection devices in your traffic signal system | 4 | 4 | 10 | 7 | 6 | 3.2 |
| Status of communication devices in your traffic signal system | 3 | 4 | 9 | 11 | 3 | 3.2 |
| Overall performance of your traffic signal system | 3 | 2 | 17 | 8 | 1 | 3.1 |
| Traffic signal timing up to date | 6 | 7 | 10 | 4 | 4 | 2.8 |

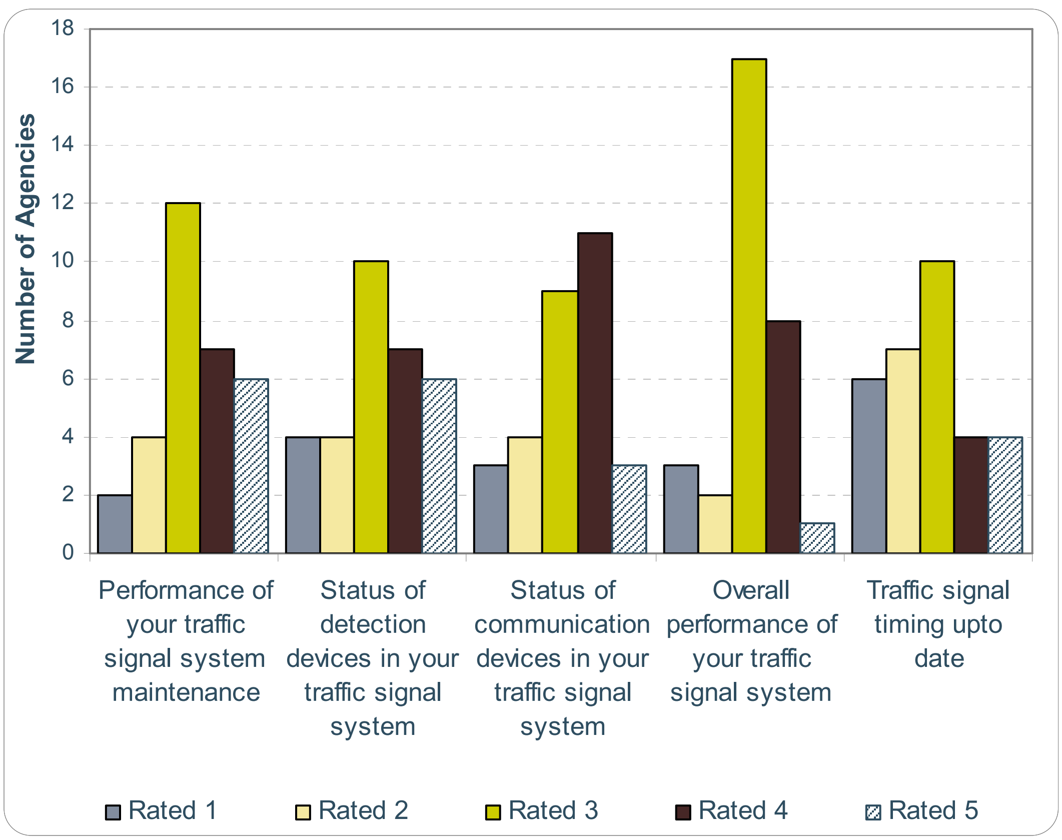



**Figure A-43 Distribution of the ratings of the status of the components of the traffic signal system**

46. Based on your experience, how can a transportation agency best improve traffic signal systems?

Although this was an open-ended question, many of the suggestions expressed by the responding agencies shared common actions (e.g. improve communication, and keep signal timing up to date). These actions can also be grouped into categories as presented in Table A- 15. A response could refer to more than one action. The number of agencies indicating a particular action was used to summarize the suggestions on how to improve traffic signal systems.

**Table A- 15  Suggested actions to improve traffic signal system performance**

| Action | Number of Agencies | Category |
|---|---|---|
| Well trained engineers | 13 | Staffing |
| Well trained technicians, improve signals/technician ratio | 10 | |
| Increased budgets | 10 | Budget |
| Improved signal timing and coordination | 8 | Signal Timing |
| Preventive maintenance | 7 | Maintenance of communication and detection equipment |
| Ensure detection is functional | 6 | |
| Ensure communication is functional | 5 | |

Note: Adding all categories will be more than number of agencies that responded to this question as several agencies recommended more than one action

47. Does your agency have ATMS?

**Table A- 16  Number of agencies with ATMS**

| Response | Agencies |
|---|---|
| Yes | 17 |
| No | 17 |

48. Approximately how many traffic signals are operated under the ATMS in your jurisdiction?

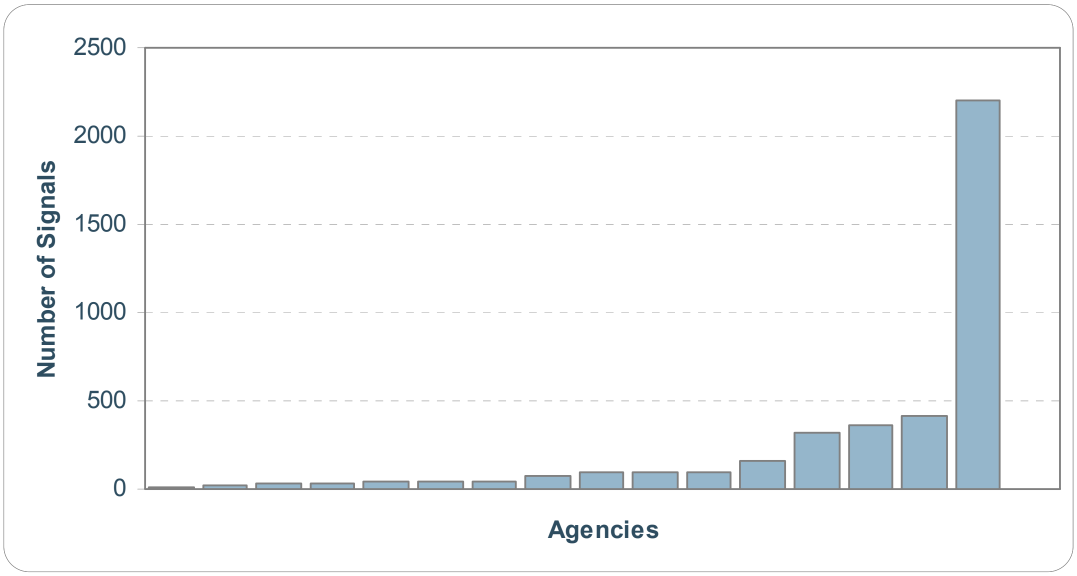



**Figure A-44 Number of signals under ATMS**

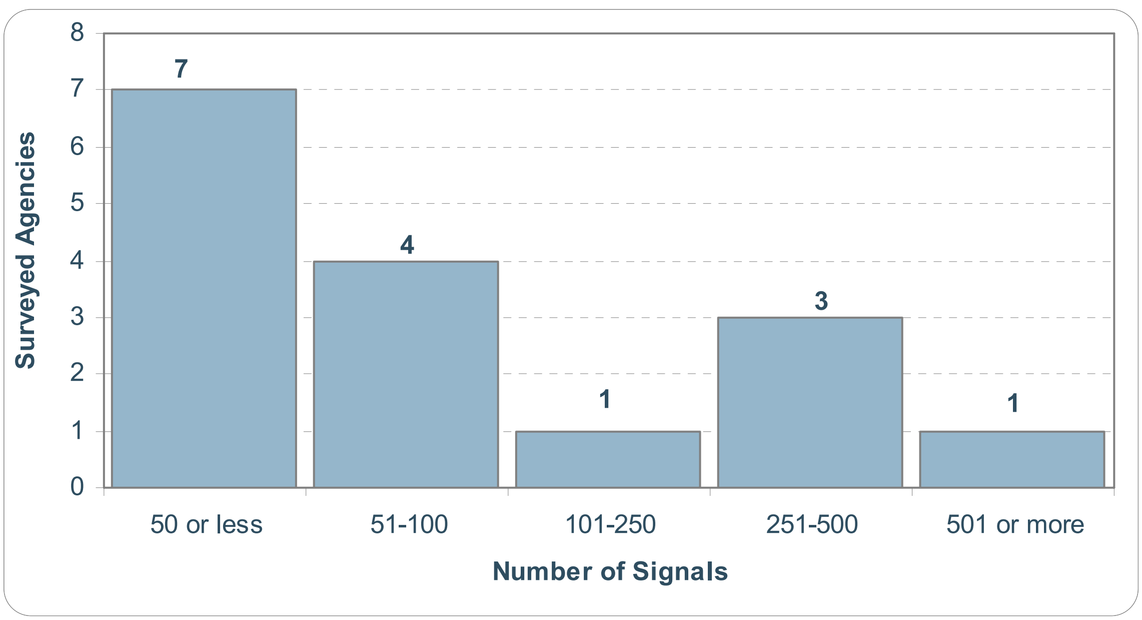



**Figure A-45 Distribution of the number of signals under ATMS**

49. At any given point in time, what percentages of detectors under the ATMS in your jurisdiction are not working due to malfunctioning or broken detectors? (e.g. 20, 45)

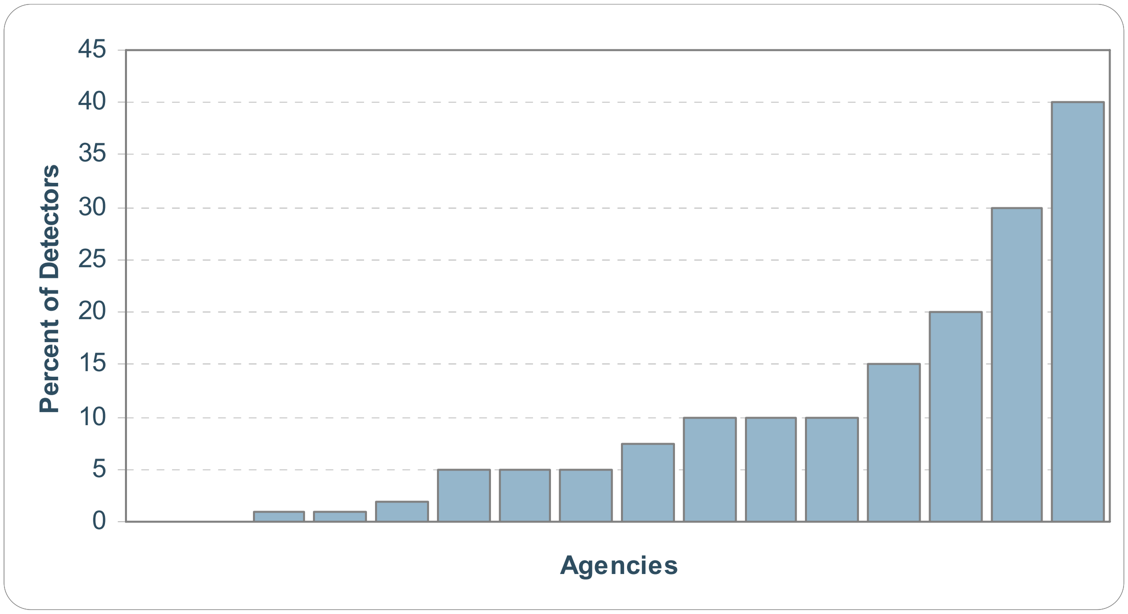



**Figure A-46 Percentage of failed detectors at any time under ATMS**

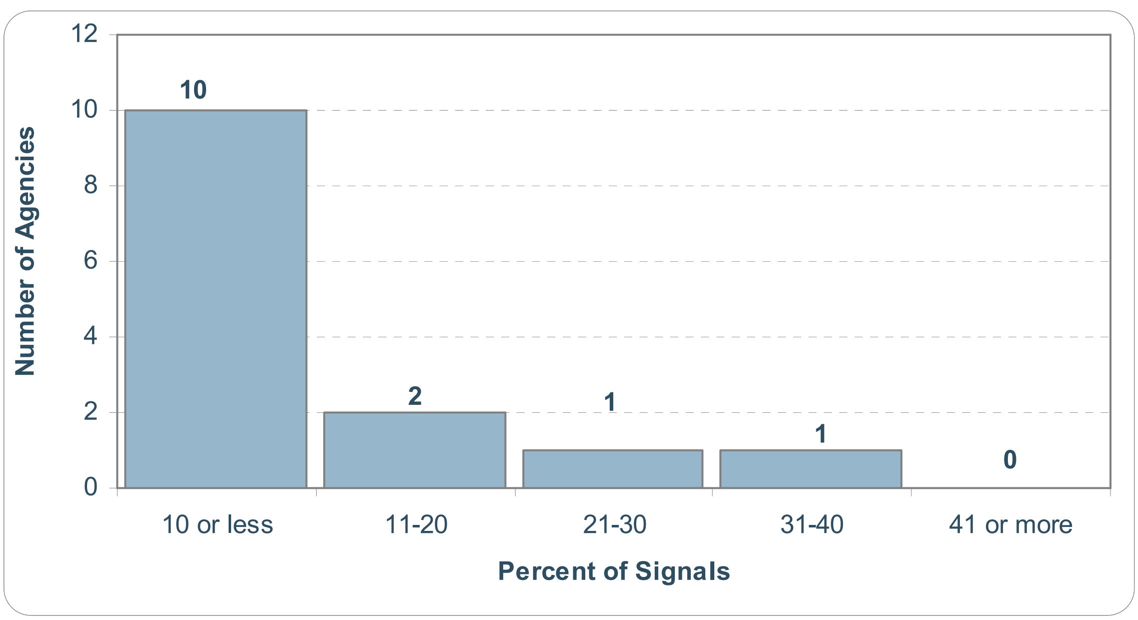



**Figure A-47 Distribution of failed detectors at any time under ATMS**

50. At any given point in time, what percentage of signalized intersections under the ATMS in your jurisdiction are not operating efficiently due to detector malfunction or broken detectors?(e.g. 20, 45)

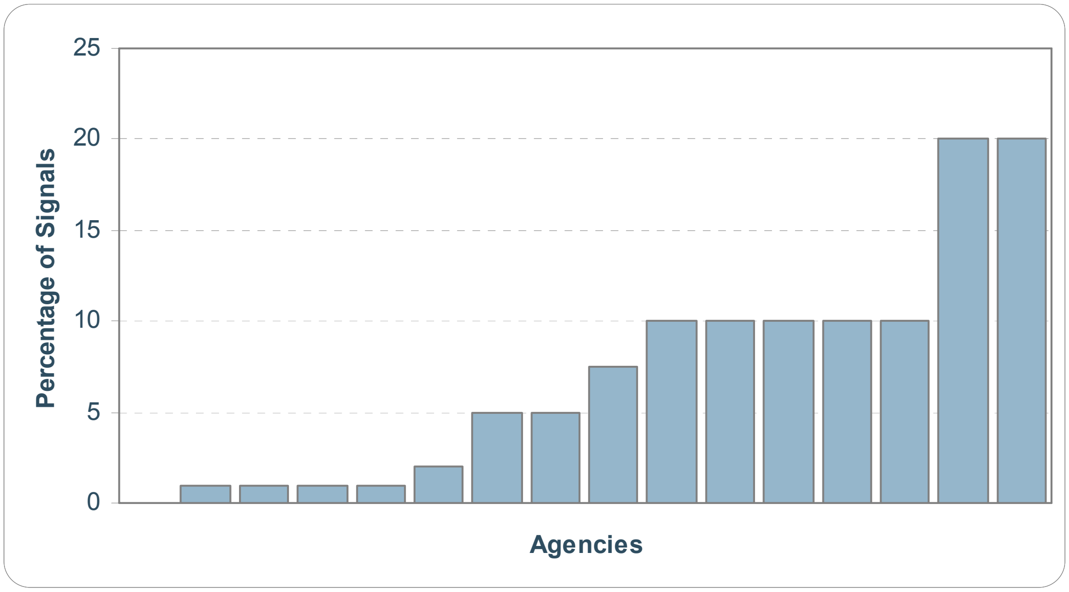



**Figure A-48 Percentage of intersections not operating efficiently due to detector failures under ATMS**

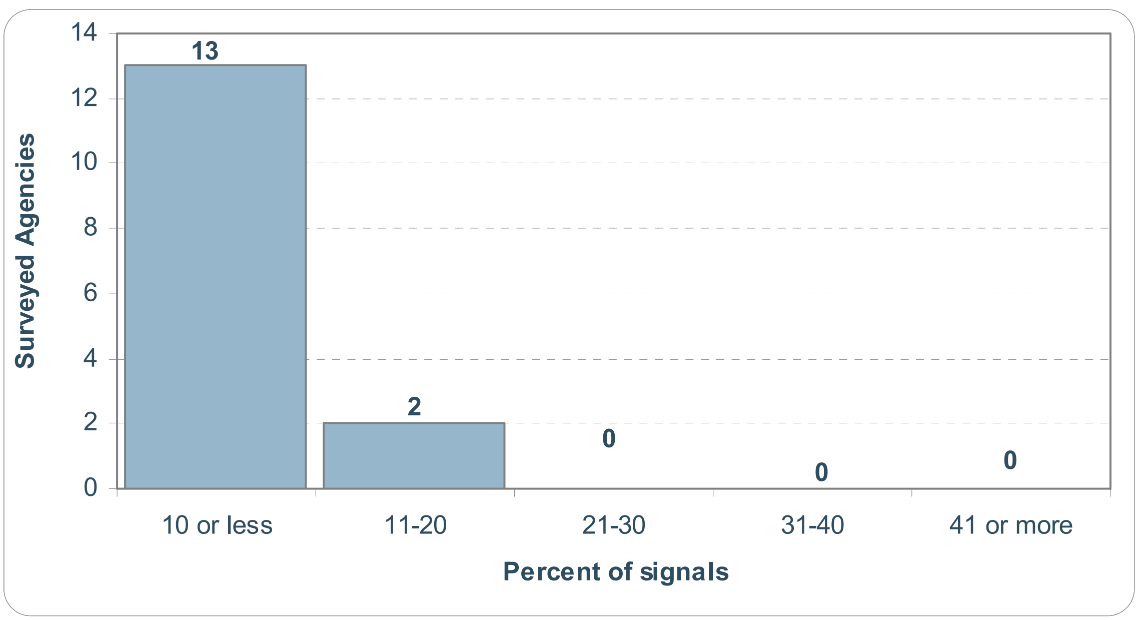



**Figure A-49 Distribution of intersections not operating efficiently due to detector failures under ATMS**

51. At any given point in time, what percentage of signalized intersections under the ATMS in your jurisdiction lost communication with your traffic management system?

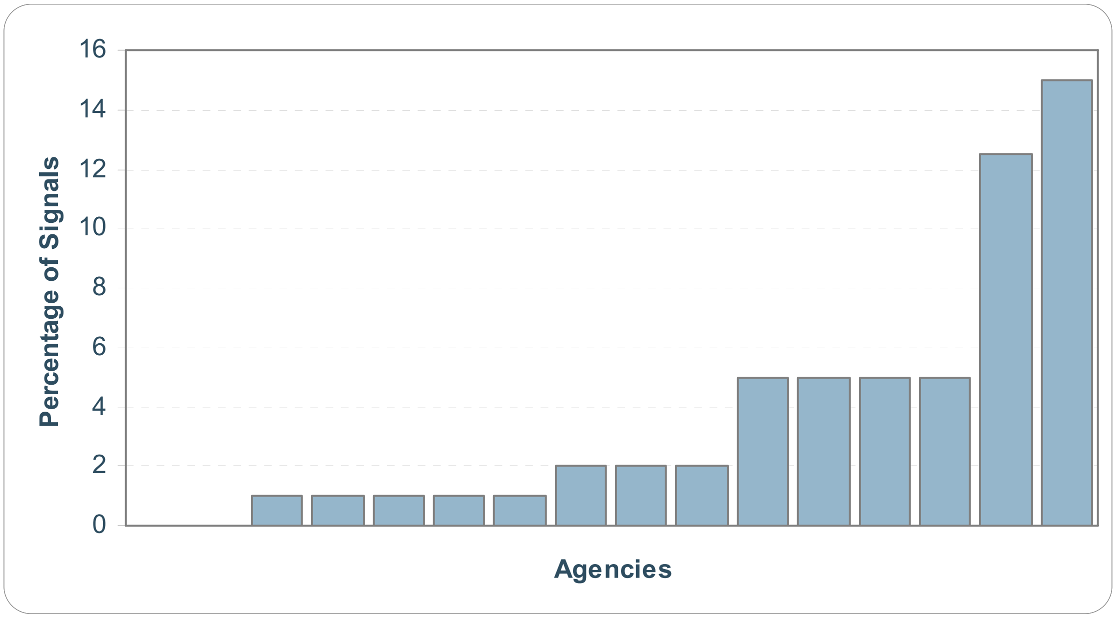



**Figure A-50 Percentage of signalized intersection with communication failures under ATMS**

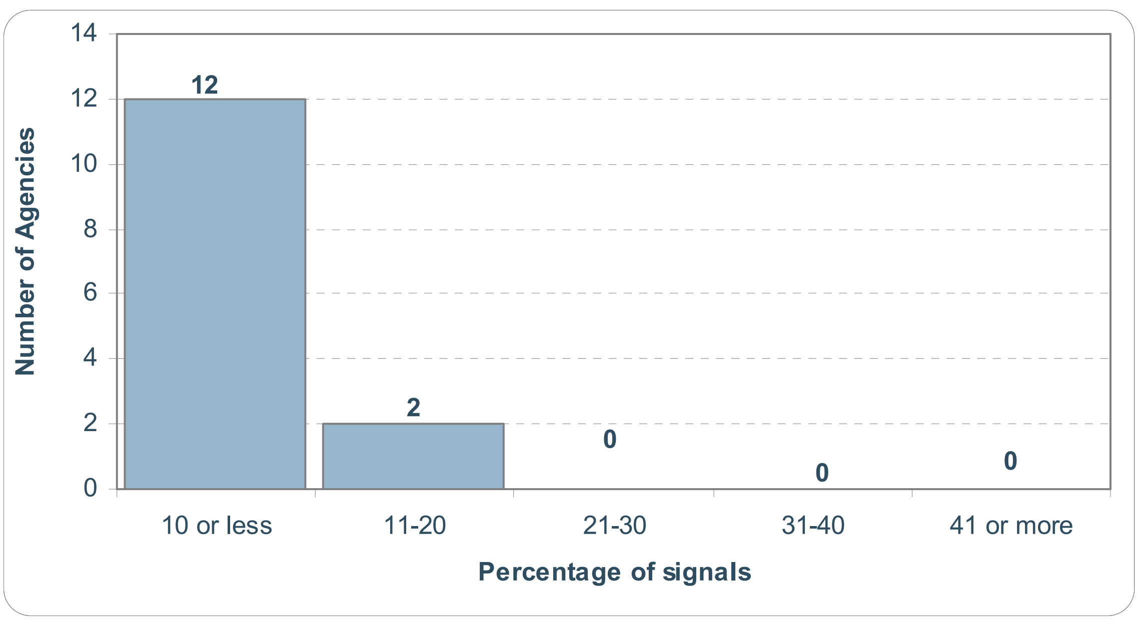



**Figure A-51 Distribution of signalized intersection with communication failures under ATMS**

52. How many traffic signals operate in traffic responsive mode?

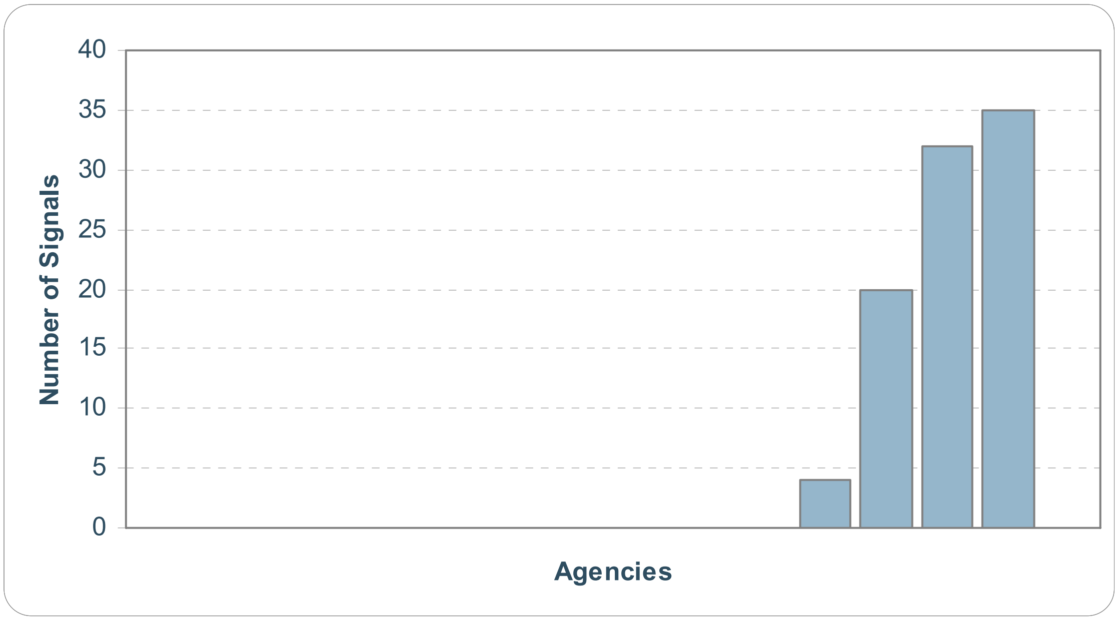



**Figure A-52 Number of signals operating in traffic responsive mode**

53. If you have adaptive traffic control system in your jurisdiction:

What are the major benefits of the adaptive traffic control system realized by your agency?

What are the major challenges of maintaining the adaptive traffic control system?

Only five agencies responded to this question, the responses are summarized in Table A-17.

**Table A- 17 Benefits and challenges of ATMS**

| Benefits | Challenges |
|---|---|
| Less delays to "mainline" traffic. | Low voltage component O & M. |
| Major noticeable reduction in delay on corridor where SCOOT is installed. | So few other users of the same system; difficult to learn & become expert user of it. |
| Less updating of timing plans and the ability to be very flexible to real time demand. | Keeping the detection system in good working order is the major challenge. |
| Increased capacity fewer complaints on signal timing. | Lack of funding and staff for proper operation and maintenance. |
| Adjusts to traffic conditions in real time, no TOD plans. Adjusts splits and offsets automatically. | Initially the fine tuning. Maintaining communications - Higher detector, hardware, software maintenance costs. |

54. What are your agency’s top five performance measures for traffic signal systems under the ATMS in your jurisdiction?

**Table A- 18 Ranked list performance measures for agencies with ATMS**

| Performance Measures | 1 | 2 | 3 | 4 | 5 | Counts | Rank |
|---|---|---|---|---|---|---|---|
| Total number of complaints received from the general public related to traffic signal systems during a certain period of time | 5 | 1 | 1 | 1 | 0 | 8 | 1.6 |
| Vehicle delay at signalized intersections or accumulated delay on corridors | 2 | 2 | 2 | 2 | 3 | 11 | 2.1 |
| Travel time on major corridors with traffic signal systems | 0 | 4 | 2 | 1 | 0 | 7 | 2.5 |
| Percentage of functional communication at signalized intersections in all traffic signal systems | 2 | 1 | 2 | 2 | 0 | 7 | 2.9 |
| Total number of requests received from residents and sheriffs for traffic signal service | 3 | 1 | 0 | 1 | 2 | 7 | 3.3 |
| Number of stops along a traffic signal system | 0 | 2 | 4 | 0 | 1 | 7 | 3.7 |
| Satisfaction of the general public on traffic signal progression | 1 | 1 | 1 | 3 | 1 | 7 | 4.0 |
| Percentage of functional detectors at signalized intersections in all traffic signal systems | 1 | 1 | 1 | 2 | 1 | 6 | 4.3 |
| Level of congestion | 1 | 1 | 0 | 2 | 3 | 7 | 4.6 |
| Average travel speed on major corridors with traffic signal systems | 1 | 1 | 2 | 0 | 0 | 4 | 4.8 |
| Percentage of functional signalized intersections (no detection and communication problems) in all traffic signal systems | 0 | 1 | 0 | 1 | 3 | 5 | 5.0 |

Other performance measures reported were:

Delays to the released platoon