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December 2025

Hardening the Economical Acquisition of Intersection Data to Improve System Integrity

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16. Abstract

Modern traffic management systems increasingly depend on real-time Signal Phase and Timing (SPaT) data generated by Traffic Signal Controllers (TSCs) to support safety, mobility, and emerging connected-vehicle applications. The applications of SPaT outputs require timely and reliable access to such data from the traffic signal controllers. However, these controllers are safety-critical infrastructure and exposing them to external networks introduces significant cybersecurity and operational risks. Thus, there is a need for mechanisms that provide secure, low-latency access to SPaT data without compromising controller integrity. The information flow methods that are used traditionally for connected and automated vehicle (CAV) environments have several security weak points. There exists a need for new communication protocols through which new system implementation paradigms can be evaluated at higher levels of information security. Two previous CCAT projects addressed this need by developing and testing a hardware-enforced data diode architecture and device that enable strictly one-directional extraction of SPaT data from traffic signal cabinets. The system prevents any inbound communication to the controller while allowing real-time data dissemination over existing network paths, requiring no new communication infrastructure. The current study was motivated by the potential use of systems engineering and model-based design to reduce development complexity and cost. The Cubicon design methodology, a new graphical language that translates high-level system behavior into executable software, improving maintainability and architectural clarity, was adopted. The phase of the project implemented a lightweight communication protocol with differential SPaT updates to reduce bandwidth usage and improve scalability. Together, these contributions demonstrate a more secure, efficient, and cost-effective approach for extracting and disseminating SPaT data, supporting both current traffic operations and future connected transportation systems. The research product can have profound and far-reaching impacts. For the hundreds of thousands of signalized intersections that currently exist in the United States, the economical and secure acquisition of SPaT information facilitates critical traffic management functions including red-light violation warnings, signal priority, and trajectory planning.

17. Key Words Data diode, Traffic signal controller, Signal phase & timing (SPaT), Smart Cities.	**18. Distribution Statement** No restrictions.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

DSRC	Dedicated Short-range Communications
MAP	Intersection Map
NATS	Neural Autonomic Transport System
NCTIP	National Transportation Communications for ITS Protocol
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
TSC	Traffic Signal Controller
TSCBM	Traffic Signal Controller Broadcast Messages
UART	Universal Asynchronous Receiver-Transmitter
UDP	User Datagram Protocol

CHAPTER 1 INTRODUCTION

1.1 Problem Statement and Study Objectives

State and local agencies in the United States have collectively invested $122 billion in the planning, design and construction of signalized intersections, with annual operating and maintenance expenditures totaling over $1.2 billion and annual additional capital program spending of $0.763 billion (National Operations Center of Excellence and ITE, 2019). To ensure that these massive investments provide maximum service efficiency, road agencies pursue effective traffic management systems. These systems increasingly depend on real-time Signal Phase and Timing (SPaT) data generated by Traffic Signal Controllers (TSCs) to support safety, mobility, and emerging connected-vehicle applications (Bullock and Urbanik, 1999; National Academies of Sciences, Engineering, and Medicine, 2015). SPaT information enables functions such as red-light violation warnings, traffic signal priority, and vehicle and pedestrian trajectory planning (Abernethy et al., 2012; Das et al., 2022; Wagner et al., 2023; Bhat & Chen, 2023; Kazemzadehazad et al., 2026); these applications require reliable and timely access to controller outputs. However, traffic signal controllers are safety-critical, and exposing them to external networks causes significant cybersecurity and operational risks (USDOT, 2020; Feng et al., 2022).

Thus, there is a need for mechanisms that provide secure, low-latency access to SPaT data without compromising controller integrity. The information flow methods that are used traditionally for connected and automated vehicle systems can have security weak points (Petit & Shladover, 2015; USDOT, 2020). There exists a need for new communication protocols through which new system implementation paradigms can be evaluated at higher levels of information security.

This work represents the latest in a series of CCAT sponsored research on cyber-infrastructure and traffic signal related operations of autonomous vehicles. Gowda et al. (2023) developed a device that facilitates the secure acquisition, processing, and dissemination of SPaT data from traffic signal controller cabinets for specified end-users of this data. Subsequently, Gowda et al. (2024) documented the implementation efforts including bench tests and field deployment tests of the device at Lansing, Michigan, and Owosso, Michigan, respectively.

These two previous projects addressed this need through a hardware-enforced data diode architecture that enables strictly one-directional extraction of SPaT data from traffic signal cabinets. The system prevents any inbound communication to the controller while allowing real-time data dissemination over existing network paths, requiring no new communication infrastructure.

A key motivation of this phase of the three-part series is the use of systems engineering and model-based design to reduce development complexity and cost. The Cubicon design methodology was used to translate high-level system behavior into executable software, improving maintainability and architectural clarity. In addition, a lightweight communication protocol with differential SPaT updates was implemented to reduce bandwidth usage and improve scalability. Together, these contributions demonstrate a secure, efficient, and cost-effective approach for extracting and disseminating SPaT data, supporting both current traffic operations and future connected transportation systems.

1.2 Organization of this Report

The remainder of this report is organized as follows: Chapter 2 presents background information on traffic control systems, SPaT and MAP data structures, the Cubicon systems engineering methodology, and prior work related to secure data diode architectures. Chapter 3 describes the system architecture and implementation details of the proposed data diode platform, including signal flow, software block design, client–server communication, differential SPaT encoding, and traffic signal controller configuration. Chapter 4 presents the experimental evaluation and performance analysis of the system. Metrics such as end-to-end latency, reliability, bit error rate, processing overhead, and differential update efficiency are analyzed using data collected from both local and wide-area deployments. Chapter 5 outlines the deployment market plan for the data diode device, Chapter 6 discusses the overall benefits of the SPaT data that is made available by the developed device, and Chapter 7 concludes the report by summarizing key findings, discussing their implications for secure and scalable SPaT dissemination, and outlining potential directions for future work. Chapter 8 provides a synopsis of the standard USDOT performance indicators as they relate to this project, and Chapter 9 presents the study outcomes and outputs.

CHAPTER 2 STUDY BACKGROUND

2.1 Traffic Control System

Modern traffic signal systems operate as distributed cyber-physical control networks composed of signal controllers, field devices, communications backhaul, and operational timing logic. At the core of each signalized junction is a Traffic Signal Controller (TSC), typically conforming to National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) standards and housed within a cabinet that also contains load switches, conflict monitors, detection interfaces, and power distribution hardware (AASHTO, ITE, & NEMA, 2020). The controller executes pre-programmed timing plans, typically optimized by practitioners to satisfy safety, throughput, and coordination constraints across multi-modal traffic. Inputs originate from embedded inductive loops, microwave detectors, radar sensors, video analytics, and pedestrian pushbuttons, which transmit actuations to the controller at millisecond-scale latency. These actuations feed into a finite-state sequencing engine that determines phase calls, timing extensions, preemptions, and barrier transitions. (FHWA, 2015). Figure 2.1 presents a representative traffic signal cabinet and controller configuration.

The cabinet network environment supports internal high-speed Ethernet, SDLC serial communication, and cabinet I/O wiring. However, because the controller directly governs real-world right-of-way allocation, external communication links expand the cybersecurity attack surface and may expose field devices to unauthorized access if not properly segmented (National Academies of Sciences, Engineering, and Medicine, 2019). As new connected and automated vehicle (CAV) applications demand real-time access to controller outputs at sub-second granularity (USDOT, 2023), architectures such as uni-directional data diodes and data mirrors have emerged as secure mitigation strategies. They enable the extraction of high-frequency controller telemetry without providing any return-path that could modify timing parameters, actuator states, or controller firmware, preserving both operational safety and regulatory compliance.

Figure 2.1: Typical TSC system

2.2 SPaT Data

Signal Phase and Timing (SPaT) data represent a structured, machine-readable description of the temporal state of an intersection's signal control logic. SPaT messages are commonly disseminated using NTCIP 1202v2 Traffic Signal Controller Broadcast Messages (TSCBM). These messages encode phase indications (red/yellow/green), pedestrian indications, overlap states, ring-barrier group timing, phase call status, and predicted end times for active phases (AASHTO, ITE, & NEMA, 2020). The SPaT structure is inherently temporal: it captures current signal indications and provides near-term predictions based on active controller timing plans, coordinated offsets, and local actuation history. Complementary MAP messages provide static lane-level geometric definitions, permissible turning maneuvers, stop-bar locations, and lane-connection topology.

Together, MAP and SPaT constitute a fused spatiotemporal representation of an intersection, enabling precise lane-specific signal interpretation. SPaT broadcasting rates range from 10 Hz to 20 Hz, depending on controller configuration, producing high-velocity data streams with minimal interframe differences (USDOT, 2023; SAE International, 2016). For CAV and infrastructure-to-vehicle (I2V) systems, SPaT enables eco-approach algorithms, Red-Light Violation Warning systems, signal priority control, and trajectory optimization. The structured nature of SPaT further supports differential encoding, data compression, and predictive filtering techniques. Consequently, accurate and low-latency SPaT dissemination is critical, as microsecond-scale timing latency variation or packet loss can degrade trajectory prediction accuracy and advisory performance (Petit & Shladover, 2015).

2.3 Cubicon

Cubicon is a graphical, model-based development methodology designed to support systems-driven software engineering (Moyer, 2015; Klausner, 2011). Unlike traditional text-based programming environments, Cubicon emphasizes parameterization of predefined functional components within a structured graphical framework. This approach promotes top-down system refinement and traceability from conceptual models to executable implementation.

According to the creator, Sandy Klausner, Cubicon represents a multi-paradigm graphical programming language that abstracts underlying computational complexity through structured component composition. He added that Cubicon "leverages a basic human capacity to effectively deal with spatial information in the expression of general systems as a sharable mental Cube Model. Cubicon is a multiple paradigm language, enabling a domain expert to express intricate program structure and behavior in a completely syntax-driven and semantically bound declarative environment that effectively abstracts away the underlying computational engine much like an electronic spreadsheet."

Within the current CCAT project, Cubicon serves as an important tool for reducing design complexity and improving the efficiency of building and validating physical and functional system components. One of the project objectives specifically highlights the investigation of Cubicon to reduce the cost of designing physical and functional objects while maintaining an understanding of the design to ensure the integrity of existing infrastructure.

The methodology aligns well with the Systems Engineering V-model (ISO/IEC/IEEE 15288, 2015) that was used throughout the project. Through its model-centric approach, Cubicon helps encode domain understanding and supports translating high-level behavior models into machine-independent and eventually executable code. This capability is essential as the project advances toward building the Data Diode demonstration system and integrating new communication elements such as CubeProtocol.

By supporting abstraction, code reduction, and structured behavioral modeling, Cubicon enables faster, clearer design cycles. It helps ensure that the implementation of system objects remains consistent with the intended architecture and functional requirements, improving long-term maintainability. Ultimately, Cubicon contributes to a more reliable development process, allowing the project to evolve while preserving accuracy, integrity, and extensibility in system behavior.

2.4 Previous Data Diode Project

The previous phases of this research (Gowda et al., 2023; Gowda et al., 2024) focused on the developing a cost-effective data diode system to acquire and distribute Signal Phase and Timing (SPaT) and MAP data from roadway traffic controllers. The goal was to make controller timing data accessible to field devices and mobile platforms without compromising signal cabinet security or increasing infrastructure costs. The solution consisted of a one-directional, two-microcontroller architecture positioned between the Traffic Signal Controller (TSC) cabinet and downstream data consumers. The first microcontroller was connected directly to the TSC Ethernet interface and acquired SPaT data over SNMP, applying integrity protection through CRC encoding before forwarding the data through a unidirectional UART link to a second microcontroller. Due to the simplex data path, no external commands or write operations could reach the controller, thereby preventing the device from serving as a bidirectional attack vector. The second microcontroller integrated with a 4G cellular modem and pushed the processed SPaT data into a cloud-based NATS messaging system, where each TSC intersection streamed data on its own unique channel for organization and accessibility. Mobile applications and backend scripts were then used to match user GPS coordinates to the nearest intersection and retrieve the corresponding timing data in near real time. This platform demonstrated a secure, scalable approach to roadway SPaT distribution and highlighted the potential of such technologies to enhance traffic operations for human-driven vehicles and connected autonomous vehicles. Figure 2.2 presents the hardware configuration of the developed data diode device.

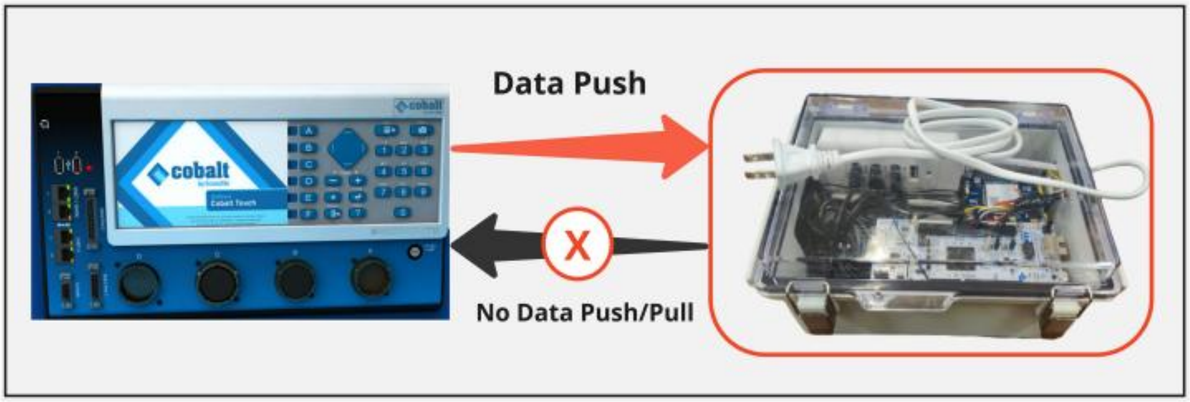


Figure 2.2: The data diode device (shown on right)

CHAPTER 3 SYSTEM ARCHITECTURE AND IMPLEMENTATION

3.1 Implementing the Cubicon Model

The hardware component development of the data diode device was successfully completed in the previous phases of the project. The objective of the current phase is to enhance the system efficiency, maintainability, and scalability by migrating the software architecture to the Cubicon environment. Cubicon provided a structured model-based framework and an existing block-level architecture that described the functional data flow between modules (Klausner, 2011; Moyer, 2015). Our primary goal was to translate this high-level design into an operational software implementation.

To accomplish this goal, the research team first analyzed the relationships and dependencies between the system blocks defined in Cubicon. This required studying the Cubicon-generated low-level specifications and translating them into executable logic. These relationships were then implemented using Go computer language (Golang) for its concurrency support, static typing, and suitability for systems-level development (Gerrand, 2010). The initial step in the coding stage involved mapping each Cubicon block to a corresponding software module and defining the inter-module communication interfaces. Conditional execution paths and structured state transitions were implemented to preserve the behavioral logic defined in the Cubicon model.

By completing this stage, a functional foundation that mirrors the Cubicon system design in software was established enabling further development, testing, and performance optimization in subsequent phases. The resulting architecture was compiled into executable binaries capable of running independently on designated system nodes.

```go
package main

import "fmt"

func main() {
	// declaration
	var RG int8 = 1
	var VA int8 = 1
	var GAQ int8 = 42
	var CT int8 = 0
	var PB bool = false
	var SE bool = true
	// main code
P1:
	if RG != 0 {
		goto P2
	}
	goto P1
P2:
	RG = 0
P3:
	if VA != 0 {
		goto P4
	}
	goto P1

P4:
	// Simulate: *IF = *GAQ
	fmt.Println("P4: Loading GAQ into IF equivalent:", GAQ)
```

Figure 3.1 Signal flow

3.2 Coding the Blocks

The next stage in the workflow was to implement the individual functional blocks defined within the Cubicon architecture. Based on the system requirements, the implementation was structured as two primary program sets. The first set corresponds to the Base node, which operates as the server component responsible for data extraction from the traffic signal controller, processing, and controlled output transmission. The second set corresponds to the Peer node, which acts as the requester, initiating communication and retrieving data from the Base node in a secure, unidirectional manner consistent with data diode architecture. All components were developed in Golang, leveraging its goroutine-based concurrency model and strong type safety to ensure reliable inter-module behavior.

3.3 Client–Server Relationship Between Base and Peer

To enable real-time SPaT data transfer across the data diode architecture, a UDP client–server model was implemented between the Base node (server) and the Peer node (client). The Server is hosted on a publicly routable IP address, enabling Peers located outside the internal network to reach the Base without tunneling or VPN requirements. The server port was protected using firewall filtering and access control lists to prevent unauthorized access attempts. Every 100 ms, the Peer node sends a small request message to the public server at the specified address, to request the latest SPaT data update.

On the server side, the Base listens on a predefined UDP socket and awaits incoming traffic. When a request arrives, the Base automatically learns the IP address and port of the requesting Peer from the received packet header. This mechanism enables dynamic client addressing without requiring static configuration. Upon receiving a request, the Base retrieves the most recent SPaT data frame cached from the traffic signal controller and prepares the data for transmission. For a new client, the server responds by sending the complete SPaT packet in raw binary form, creating an initial synchronized state on the Peer side. Subsequent client queries follow a continuous request–response loop operating at a 100 ms frame interval.

After receiving each response, the Peer reconstructs the incoming data and logs the timestamp and payload size for later analysis. This cyclic exchange enables reliable, low-latency data transfer without requiring a persistent TCP session, making it well suited for one-directional data diode communication (Postel, 1981). Although the current implementation operates with a single Peer–Base pair, the design can be readily extended to support multiple Peer clients. Each Peer would independently request and reconstruct SPaT data in the same manner without modifying the underlying server architecture.

3.4 Differential Encoding of Client–Server Data

During initial experimentation, several raw SPaT packets generated by the Traffic Signal Controller were examined. These packets arrive every 100 ms and contain information such as lane identifiers, signal group states, permitted movements, and phase timings. A key observation was that the binary SPaT payload changed only minimally from one frame to the next. For example, across consecutive packets, fewer than 2–3% of the bytes changed, often consisting only of phase countdown counters decreasing by one unit.

This temporal redundancy suggested an opportunity to reduce bandwidth usage and increase update throughput. Therefore, **differential encoding** was implemented, meaning that only byte-level changes are transmitted after the initial packet exchange.

The differential encoding process operates in two stages:

1. Incoming SPaT frames are cached in a server-side buffer
2. **Stage 1 Initial State Transfer:**
   The first packet transmitted to a Peer consists of a complete SPaT frame structure (approximately 150–200 bytes depending on the controller configuration). This initializes a synchronized copy on the Peer side.
3. **Stage 2 Delta Transmission Phase:**
   For each subsequent 100 ms update interval:
    - The Base compares the newly received SPaT frame with the previously transmitted frame version.
    - Only modified byte indices are extracted.
    - These changes are paired and encoded (index, new_value) byte tuples.
    - The resulting differential byte (delta) stream is transmitted to the Peer.

At the receiver, the Peer applies the incoming update list directly to its stored SPaT copy. Any (index, value) pair overwrites the corresponding byte, reconstructing the full next SPaT frame without transmitting the entire payload. This technique yields two major benefits:

- **Bandwidth Reduction:** Instead of sending ~180 bytes every 100 ms, the server frequently sends fewer than 20 bytes. This is especially advantageous for satellite, multi-hop, and congested cellular paths.
- **Latency Improvement:** Smaller update packets reduce transmission time and lower the probability of congestion-induced delay variation.

The trade-off involves computational preprocessing at the server side to compute byte differences. However, the cost of computing deltas is significantly lower than the cost of transmitting full frames repeatedly, especially in multi-client deployments.

An example SPaT hexadecimal frame segment illustrating byte-level differences between consecutive frames is shown in Figure 3.2. Consecutive frames differ only in a few byte positions (highlighted), illustrating the minimal temporal change that enables differential compression:

```
2A001C000451313433353138CD1001003200B7000000000000000002005A00DF005AFFFF000000000300BEFFFF00000000000000000400BE03EB00BEFFFF0000000005003200B7000000000000000006005
AFFFF005AFFFF000000000700BEFFFF00000000000000000800BEFFFF00BEFFFF0000000009000000000000000000000000000A000000000000000000000000000B000000000000000000000000000C00000000000
00000000000000D000000000000000000000000000E000000000000000000000000000F000000000000000000000000001000000000000000000000000000FFEE00000011FFFF00000000FFFF00000000000000000000
081200D72D0000
2A001C000451313433353138CD10010032003E000000000000000002005A0066005AFFFF000000000300BEFFFF00000000000000000400BE037200BEFFFF00000000050032003E000000000000000006005A
FFFF005AFFFF000000000700BEFFFF00000000000000000800BEFFFF00BEFFFF0000000009000000000000000000000000000A000000000000000000000000000B000000000000000000000000000C000000000000
0000000000000D000000000000000000000000000E000000000000000000000000000F000000000000000000000000001000000000000000000000000000FFEE00000011FFFF00000000FFFF000000000000000000000
88B00D7390000
2A001C000451313433353138CD10010032003D000000000000000002005A0065005AFFFF000000000300BEFFFF00000000000000000400BE037100BEFFFF00000000050032003D000000000000000006005
AFFFF005AFFFF000000000700BEFFFF00000000000000000800BEFFFF00BEFFFF0000000009000000000000000000000000000A000000000000000000000000000B000000000000000000000000000C00000000000
00000000000000D000000000000000000000000000E000000000000000000000000000F000000000000000000000000001000000000000000000000000000FFEE00000011FFFF00000000FFFF00000000000000000000
088C00D7390000
```

Figure 3.2 SPaT Data showing deltas

After differential updates are transmitted and logged, the Peer reconstructs the original full SPaT stream by reversing the operations. The final output is stored in timestamp-tagged CSV format for verification and performance validation. This differential SPaT streaming architecture provides the required reliability for real-time traffic control communication while reducing load on the data diode pipeline and improving update consistency across hostile or unstable network paths. The complete data diode hardware test setup is shown in Figure 3.3.

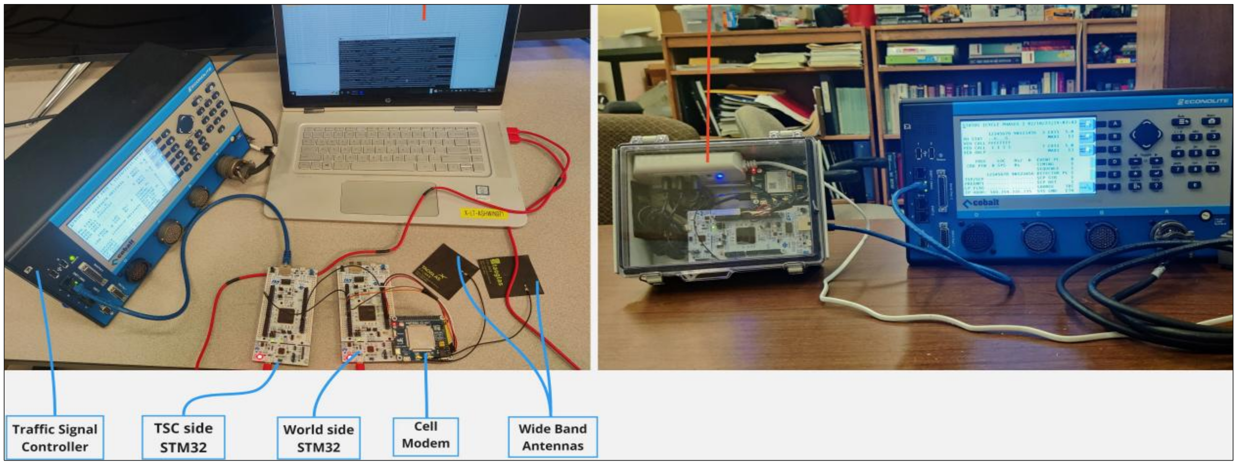


Figure 3.3 Data diode practical representation

3.5 Configuring the TSC

3.5.1 Programming the Traffic Signal Controller to Transmit SPaT Data from ENET1

The TSC configuration started with the transmission of SPaT messages via the ENET1 port, and involved the steps shown below:

1. Press ”Main”->”MAIN MENU” -> ”CONFIGURATION” option -> CONFIGURATION sub menu -> ”2” -> ”COMMUNICATIONS” option -> ”ETHERNET” option
2. Using an Ethernet cable, connect TSC ENET-1 port to a PC that possesses an Ethernet port and type the following command:

```
$ snmpset -v 1 -c public 169.254.235.235:501
1.3.6.1.4.1.1206.3.5.2.9.44.1.1 i 2
```

This will generate a response that indicates execution success of the SNMP SET command:

```
SNMPv2-SMI::enterprises.1206.3.5.2.9.44.1.0 = INTEGER: 2
```

After this, the Econolite TSC is primed to commence the transmission of data through its ENET1 port, consistent with established procedure (Case et. al., 1990). The configuration menu navigation is shown in Figure 3.4.

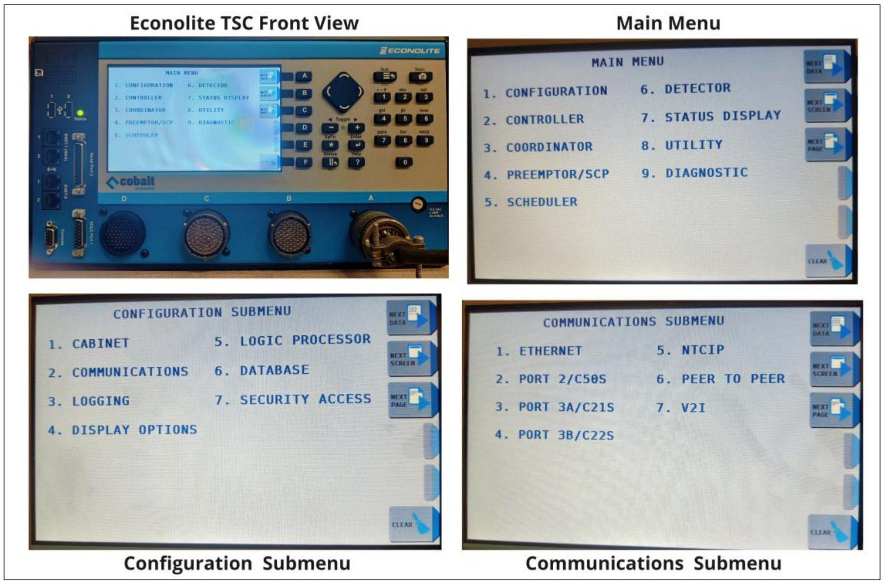
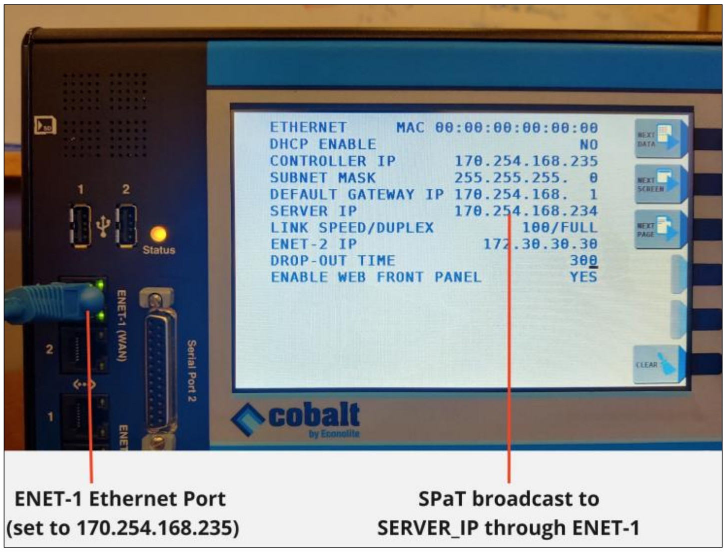


Figure 3.4 Econolite display settings



```
ETHERNET      MAC 00:00:00:00:00:00
DHCP ENABLE                      NO
CONTROLLER IP       170.254.168.235
SUBNET MASK         255.255.255.  0
DEFAULT GATEWAY IP 170.254.168.  1
SERVER IP           170.254.168.234
LINK SPEED/DUPLEX          100/FULL
ENET-2 IP              172.30.30.30
DROP-OUT TIME                   300
ENABLE WEB FRONT PANEL          YES
```

ENET-1 Ethernet Port (set to 170.254.168.235)

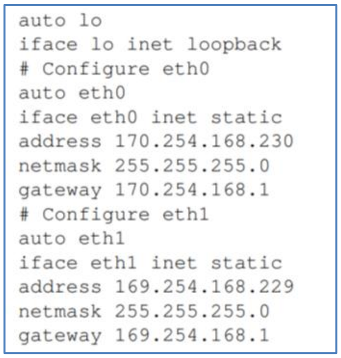
SPaT broadcast to SERVER_IP through ENET-1

Figure 3.5 Broadcasting on ENET-1 -- Sample network settings

3.5.2 Configuring SPaT Message Transmission on TSC ENET2 Port:

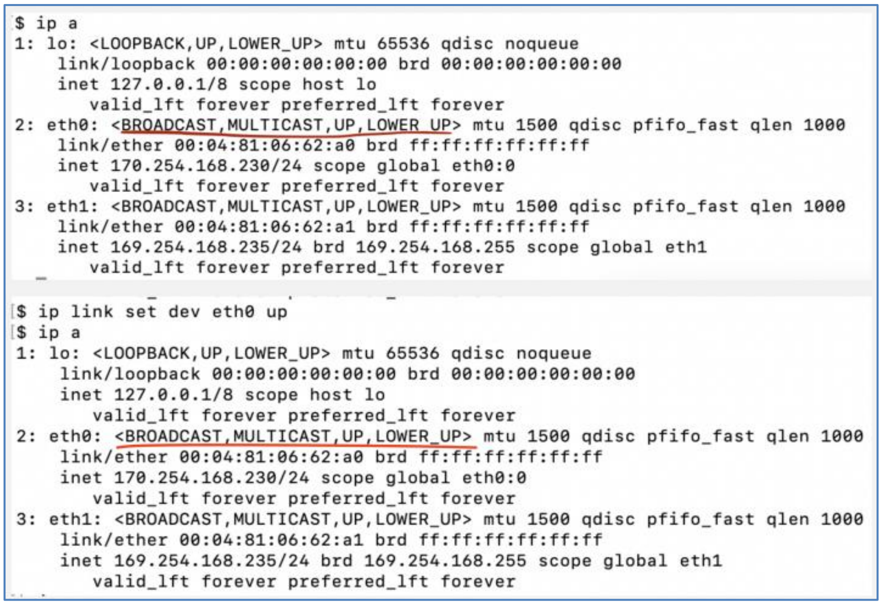
For TSC reconfiguration for transmitting the SPaT data through the ENET2 network rather than the ENET1, the following steps are carried out. Figure 3.5 presents an example screen of the network configuration for SPaT broadcasting.

1. Link to the controller through the port ENET-1 and SSH:
    - ssh econolite@<ipAddress> [ipAddress is the CONTROLLER IP (that is, ENET-1 IP)], using an appropriate password
2. Run commands to edit the network interfaces file. An example Linux interfaces file configuration is shown in Figure 3.6.
3. Cary out edit of the file. Then, add the relevant interface for eth0. Figure 3.6 illustrates the interface file settings, with eth0 (that is, ENET2), set to `170.254.168.230` as illustrated in the figures below.



```
auto lo
iface lo inet loopback
# Configure eth0
auto eth0
iface eth0 inet static
address 170.254.168.230
netmask 255.255.255.0
gateway 170.254.168.1
# Configure eth1
auto eth1
iface eth1 inet static
address 169.254.168.229
netmask 255.255.255.0
gateway 169.254.168.1
```

Figure 3.6 Example of the interface file settings



```
$ ip a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
2: eth0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast qlen 1000
    link/ether 00:04:81:06:62:a0 brd ff:ff:ff:ff:ff:ff
    inet 170.254.168.230/24 scope global eth0:0
       valid_lft forever preferred_lft forever
3: eth1: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast qlen 1000
    link/ether 00:04:81:06:62:a1 brd ff:ff:ff:ff:ff:ff
    inet 169.254.168.235/24 brd 169.254.168.255 scope global eth1
       valid_lft forever preferred_lft forever

$ ip link set dev eth0 up
$ ip a
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
    inet 127.0.0.1/8 scope host lo
       valid_lft forever preferred_lft forever
2: eth0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast qlen 1000
    link/ether 00:04:81:06:62:a0 brd ff:ff:ff:ff:ff:ff
    inet 170.254.168.230/24 scope global eth0:0
       valid_lft forever preferred_lft forever
3: eth1: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast qlen 1000
    link/ether 00:04:81:06:62:a1 brd ff:ff:ff:ff:ff:ff
    inet 169.254.168.235/24 brd 169.254.168.255 scope global eth1
       valid_lft forever preferred_lft forever
```

Figure 3.7 Checking of eth0

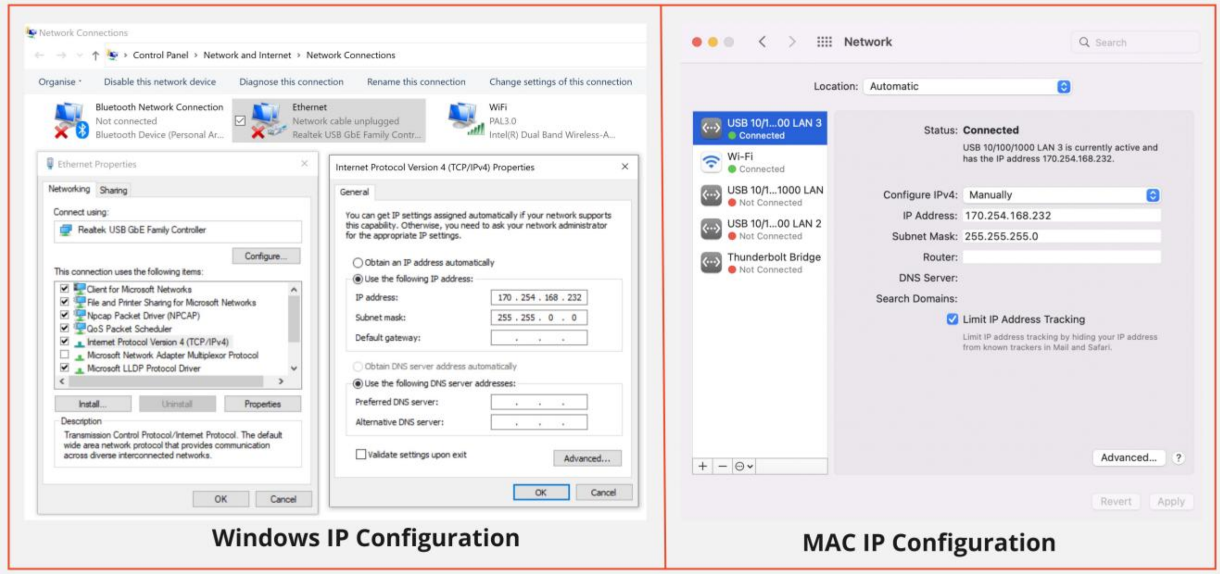
5. Using $ip a, ascertain whether eth0 is down. If affirmative, restore it up using the command $ip link set dev eth0 up.

6. using *$ip route*, check to ascertain whether the eth0 route is set. If no, establish the route using the command $ip:
route add <subnet> dev eth0 cmd, as shown in the figure.

7. In the communication panel, set the server IP to Base IP. The verification of eth0 interface status is shown in Figure 3.7.

8. Push the same SNMP command from a previous step with the IP address replaced by ENET-2 IP (`170.254.168.230` in the sample settings). This ensures flow of the data from ENET2 to the address of the destination IP.

This ensures that all the data flows to `169.254.168.234` through ENET-1, mirrored to `170.254.168.234 on ENET-2.`
Access the computer network settings and assign a static IPv4 address within the same subnet as the TSC ENET port. For example, `169.254.168.234` for `ENET-1` or `170.254.168.234` for `ENET-2`). It should be ensured that the subnet mask matches the controller network settings. Example host Ethernet configuration settings for both Windows and macOS systems are shown in Figure 3.8.



Connect using: Realtek USB GbE Family Controller

This connection uses the following items:
☑ Client for Microsoft Networks
☑ File and Printer Sharing for Microsoft Networks
☑ Npcap Packet Driver (NPCAP)
☑ QoS Packet Scheduler
☑ Internet Protocol Version 4 (TCP/IPv4)
☐ Microsoft Network Adapter Multiplexor Protocol
☑ Microsoft LLDP Protocol Driver

Description
Transmission Control Protocol/Internet Protocol. The default wide area network protocol that provides communication across diverse interconnected networks.

You can get IP settings assigned automatically if your network supports this capability. Otherwise, you need to ask your network administrator for the appropriate IP settings.

○ Obtain an IP address automatically
● Use the following IP address:
IP address: 170 . 254 . 168 . 232
Subnet mask: 255 . 255 . 0 . 0
Default gateway: . . .
○ Obtain DNS server address automatically
● Use the following DNS server addresses:
Preferred DNS server: . . .
Alternative DNS server: . . .
☐ Validate settings upon exit

Windows IP Configuration

Location: Automatic

USB 10/1...00 LAN 3 – Connected
Wi-Fi – Connected
USB 10/1...1000 LAN – Not Connected
USB 10/1...00 LAN 2 – Not Connected
Thunderbolt Bridge – Not Connected

Status: **Connected**
USB 10/100/1000 LAN 3 is currently active and has the IP address 170.254.168.232.

Configure IPv4: Manually
IP Address: 170.254.168.232
Subnet Mask: 255.255.255.0
Router:
DNS Server:
Search Domains:
☑ Limit IP Address Tracking
Limit IP address tracking by hiding your IP address from known trackers in Mail and Safari.

MAC IP Configuration

Figure 3.8 Ethernet IP settings

3.6 Test Setup

3.6.1 Deployment Configurations

Two deployment configurations were tested to validate system performance:

<u>(A) Local Same-Machine Test</u>
In the initial stage, both the Base (server) and Peer (client) modules were executed on the same laptop.

- The laptop was connected to the Econolite TSC via Ethernet.
- Network IP/subnet settings matched the TSC configuration (as described previously).
- SPaT data were read every 100 ms from the TSC.
- The Base cached each incoming SPaT frame and responded to Peer requests using either:
    - **Full SPaT transfer mode**, or
    - **Differential transfer mode**, where only byte-level changes were transmitted.

This configuration validated system logic before testing across real networks.

<u>(B) Distributed Purdue–Michigan Test</u>
A second deployment simulated real operational conditions across geographical boundaries:

- **Base Location:** Purdue University, West Lafayette, Indiana
- **Peer Location:** Michigan
- Base laptop connected to the TSC via Ethernet and configured with public IPv4 routing (lab IP).
- The Peer connected over the Internet to the Base's exposed UDP port.
- When public routing was temporarily unavailable, both endpoints were placed on the same virtual network using the Tailscale VPN. Virtual private networking was implemented using peer-to-peer encrypted tunneling (Tailscale Inc., 2023).

3.6.2 Client–Server Operation

Both deployments used the same Go-based UDP request–response logic:

- The **Base module**:
    - Listened for SPaT packets from the TSC (UDP port 6053),
    - Cached the most recent packet,
    - Generated either full or byte-level delta responses,
    - Logged changes and timestamps.
- The **Peer module**:
    - Issued a UDP request every 100 ms,
    - Received either a full SPaT frame (first request) or differential updates,
    - Reconstructed the complete SPaT packet using index/value updates,
    - Logged data to CSV for later analysis.

3.6.3 Measurement Metrics

Two primary metrics were evaluated:

(A) Reliability Analysis

- The Base and Peer each logged their sent and received SPaT data.
- Logged datasets included timestamps, data lengths, and hex-encoded payloads.
- By aligning these logs offline, the following were verified:
    - packet loss events,
    - reconstruction correctness,
    - Packet loss and reconstruction verification were evaluated using standard UDP reliability assessment practices.

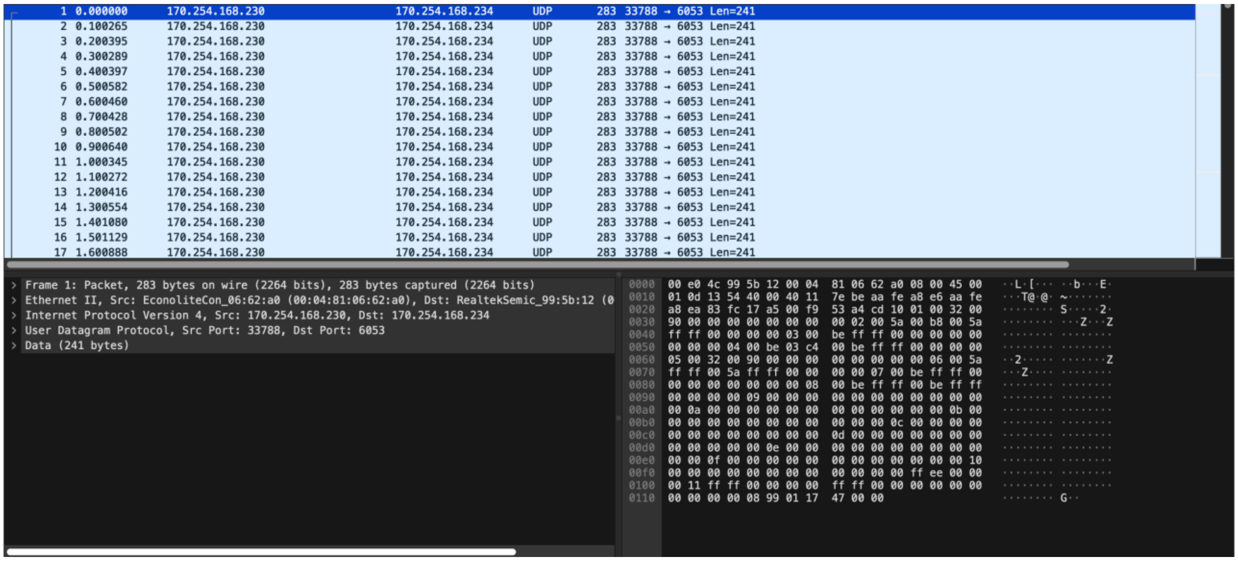
(B) Latency Analysis

- End-to-end latency was measured as the one-way delay between the transmission of a SPaT update at the Base node and its reception at the Peer node.
- Transmission and reception timestamps were recorded at microsecond resolution and logged to CSV files for offline analysis. Timestamping was performed using system-level high-resolution timers synchronized to the local operating system clock.
- Latency statistics were computed from pairwise differences between aligned transmit–receive timestamps, providing a direct measure of real-time SPaT delivery performance.

CHAPTER 4 RESULTS

4.1 Differential Data

Fig. 4.1 presents the Spat data captured on Wireshark.



```
 1 0.000000   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 2 0.100265   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 3 0.200395   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 4 0.300289   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 5 0.400397   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 6 0.500582   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 7 0.600460   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 8 0.700428   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
 9 0.800502   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
10 0.900640   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
11 1.000345   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
12 1.100272   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
13 1.200416   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
14 1.300554   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
15 1.401080   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
16 1.501129   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
17 1.600888   170.254.168.230    170.254.168.234   UDP   283 33788 → 6053 Len=241
```

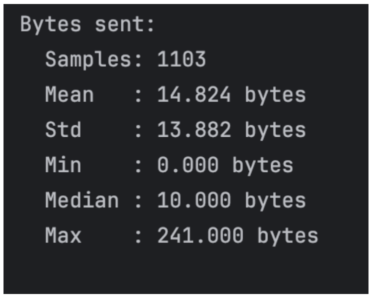
```
> Frame 1: Packet, 283 bytes on wire (2264 bits), 283 bytes captured (2264 bits)
> Ethernet II, Src: EconoliteCon_06:62:a0 (00:04:81:06:62:a0), Dst: RealtekSemic_99:5b:12 (0
> Internet Protocol Version 4, Src: 170.254.168.230, Dst: 170.254.168.234
> User Datagram Protocol, Src Port: 33788, Dst Port: 6053
> Data (241 bytes)
```

```
0000  00 e0 4c 99 5b 12 00 04  81 06 62 a0 08 00 45 00   ··L·[··· ··b···E·
0010  01 0d 13 54 40 00 40 11  7e be aa fe a8 e6 aa fe   ···T@·@· ~·······
0020  a8 ea 83 fc 17 a5 00 f9  53 a4 cd 10 01 00 32 00   ········ S·····2·
0030  90 00 00 00 00 00 00 00  00 02 00 5a 00 b8 00 5a   ········ ···Z···Z
0040  ff ff 00 00 00 00 03 00  be ff ff 00 00 00 00 00   ········ ········
0050  00 00 00 04 00 be 03 c4  00 be ff ff 00 00 00 00   ········ ········
0060  05 00 32 00 90 00 00 00  00 00 00 00 00 06 00 5a   ··2····· ·······Z
0070  ff ff 00 5a ff ff 00 00  00 00 07 00 be ff ff 00   ···Z···· ········
0080  00 00 00 00 00 00 00 08  00 be ff ff 00 be ff ff   ········ ········
0090  00 00 00 00 09 00 00 00  00 00 00 00 00 00 00 00   ········ ········
00a0  00 0a 00 00 00 00 00 00  00 00 00 00 00 00 0b 00   ········ ········
00b0  00 00 00 00 00 00 00 00  00 00 00 0c 00 00 00 00   ········ ········
00c0  00 00 00 00 00 00 00 00  0d 00 00 00 00 00 00 00   ········ ········
00d0  00 00 00 00 00 0e 00 00  00 00 00 00 00 00 00 00   ········ ········
00e0  00 00 0f 00 00 00 00 00  00 00 00 00 00 00 00 10   ········ ········
00f0  00 00 00 00 00 00 00 00  00 00 00 00 ff ee 00 00   ········ ········
0100  00 11 ff ff 00 00 00 00  ff ff 00 00 00 00 00 00   ········ ········
0110  00 00 00 00 08 99 01 17  47 00 00                  ········ G··
```

Fig. 4.1 SPaT data captured on Wireshark

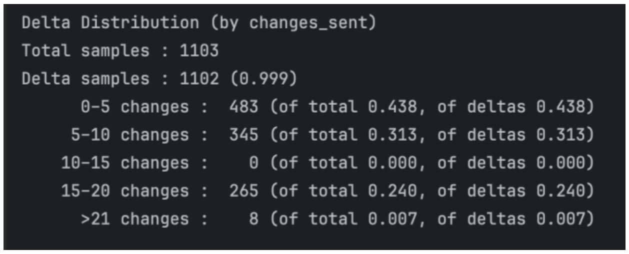
Although SPaT messages are generated at a fixed 100 ms interval, successive messages exhibit high temporal redundancy, with only small portions of the payload changing between updates. To exploit this property, the system employs a differential update mechanism in which only the modified byte positions are transmitted after an initial full-frame synchronization. A representative SPaT frame captured during experimentation is shown in Figure 4.1, illustrating the limited byte-level variation between consecutive frames.
Experimental results show that among delta updates, 43.8% contained fewer than five-byte changes, and over 75% contained fewer than ten changes, while fewer than 1% exceeded 20 changes. As a result, the average transmitted payload size was reduced to 14.8 bytes, compared to a full SPaT frame size of 241 bytes, transmission. The distribution of delta sizes is summarized in Figure 4.3, while the corresponding reduction in transmitted bytes per session is shown in Figure 4.2.

This reduction directly benefits system performance: smaller payloads reduce network load, lower serialization and processing overhead, and contribute to the observed low and stable latency. The measured distribution of processing overhead is shown in Figure 4.4. The differential update strategy therefore enables scalable, efficient SPaT dissemination without compromising reliability or timing accuracy, making it well-suited for deployment in both current human-driven vehicle systems and future connected and automated vehicle applications. Differential encoding techniques are commonly used in streaming systems to exploit temporal redundancy in sequential data structures (Salomon, 2007).



```
Bytes sent:
  Samples: 1103
  Mean   : 14.824 bytes
  Std    : 13.882 bytes
  Min    : 0.000 bytes
  Median : 10.000 bytes
  Max    : 241.000 bytes
```

Fig. 4.2 Bytes sent in a session



```
Delta Distribution (by changes_sent)
Total samples : 1103
Delta samples : 1102 (0.999)
      0-5 changes :  483 (of total 0.438, of deltas 0.438)
     5-10 changes :  345 (of total 0.313, of deltas 0.313)
    10-15 changes :    0 (of total 0.000, of deltas 0.000)
    15-20 changes :  265 (of total 0.240, of deltas 0.240)
      >21 changes :    8 (of total 0.007, of deltas 0.007)
```

Fig. 4.3 Delta distribution

4.2 Latency

It is well known that as part of designing any system that relies on data transmission and real-time predictions, communication induced latency must be evaluated. End-to-end latency was measured as the one-way delay between the transmission of a SPaT update at the Base node and its reception at the Peer node. For each update, a transmission timestamp was recorded at the Base immediately prior to packet transmission, and a reception timestamp was recorded at the Peer upon successful receipt. Latency was computed as the direct difference between these two timestamps on a per-packet basis using pairwise alignment of transmit–receive logs.

Across 1,103 matched samples, the system achieved a mean latency of 43.6 ms, with a median of 42.8 ms and a standard deviation of 4.5 ms. The minimum observed latency was 36.0 ms, while the maximum latency reached 67.4 ms, indicating a narrowly distributed delay profile with limited high-latency outliers. The resulting latency distribution is shown in Figure 4.5, and summary statistics are provided in Figure 4.6. This means latency is substantially below the 100 ms SPaT broadcast interval, ensuring that updates are received before the next nominal transmission cycle (SAE International, 2016). The few higher-latency outliers are attributable to the best-effort nature of UDP transport and transient network-level effects such as queueing and routing variability (Postel, 1980).

Importantly, the measured processing overhead at the Base node has a mean of 86.9 microseconds which is negligible compared to end-to-end latency and confirms that overall delay is dominated by network propagation and routing rather than application-level processing. The measured processing overhead statistics are summarized in Figure 4.7. These results show that the proposed UDP-based request–response architecture introduces minimal additional delay beyond the underlying network path and is well-suited for near–real-time dissemination of SPaT information over wide-area networks. Network-induced latency variation in best-effort UDP systems is typically influenced by queuing and routing variability (Tanenbaum & Wetherall, 2011).

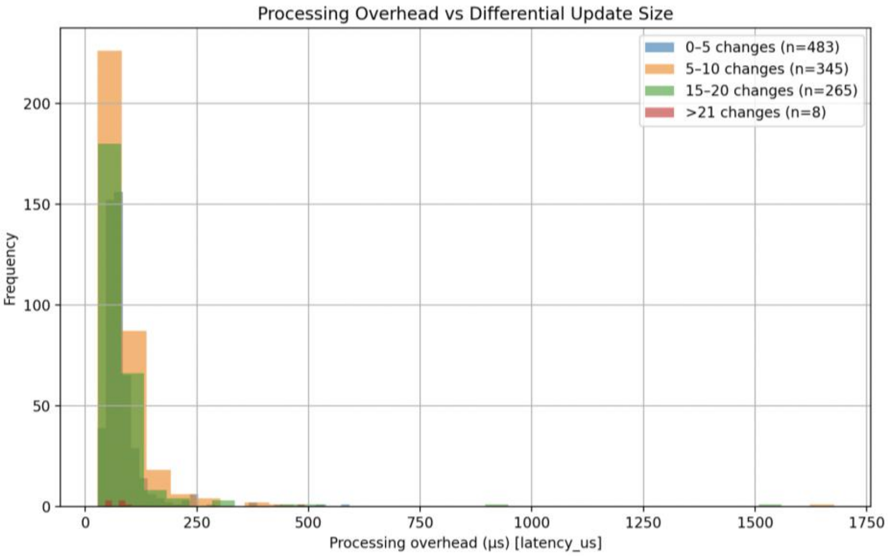


Fig. 4.4 Processing overhead statistics

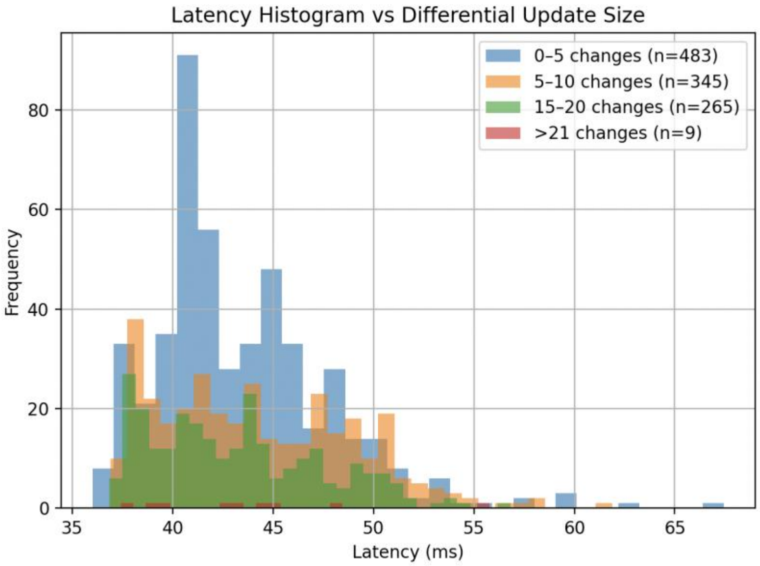
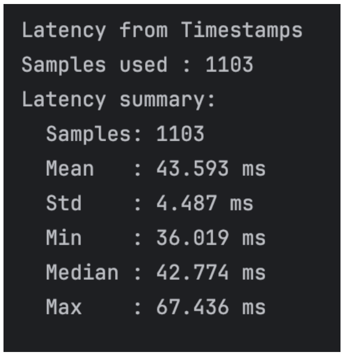
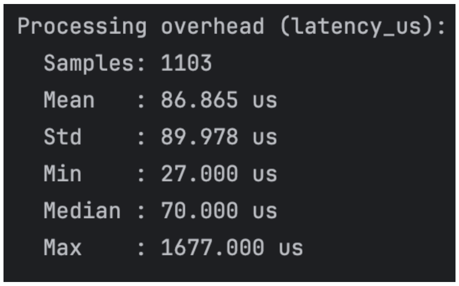


Fig. 4.5 Latency statistics



```
Latency from Timestamps
Samples used : 1103
Latency summary:
  Samples: 1103
  Mean   : 43.593 ms
  Std    : 4.487 ms
  Min    : 36.019 ms
  Median : 42.774 ms
  Max    : 67.436 ms
```

Fig. 4.6 End-to-end latency statistics



```
Processing overhead (latency_us):
  Samples: 1103
  Mean   : 86.865 us
  Std    : 89.978 us
  Min    : 27.000 us
  Median : 70.000 us
  Max    : 1677.000 us
```

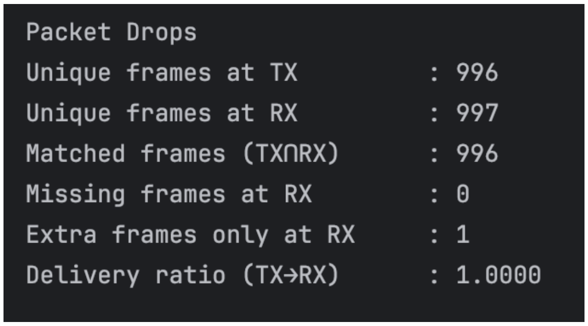
Fig. 4.7 Processing overhead statistics

4.3 Reliability

Reliability was evaluated by instrumenting both the Base and Peer nodes and performing an offline comparison of transmitted and reconstructed SPaT payloads. Packet-level delivery was assessed by comparing unique frame identifiers, while payload integrity was evaluated through byte-wise and bit-wise comparison of reconstructed SPaT messages against the transmitted reference. Packet delivery statistics are shown in Figure 4.8, and bit error rate statistics are shown in Figure 4.9.

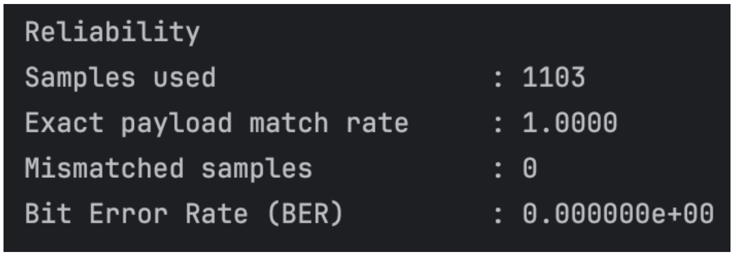
Out of 996 unique SPaT frames transmitted, all 996 were successfully received, yielding a delivery ratio of 1.000 with no missing frames. Payload-level analysis across 1,103 aligned samples showed an exact match rate of 100%, with zero mismatched packets and a measured bit error rate (BER) of 0. BER is a standard metric for evaluating digital transmission integrity (Proakis & Salehi, 2008). The difference between unique frame count and aligned samples reflects repeated logging intervals during delta reconstruction. These results confirm that the data-diode architecture ensures lossless, error-free transmission and reconstruction of SPaT data, even when operating over heterogeneous network conditions.

Collectively, the experimental results demonstrate that the differential encoding strategy substantially reduces bandwidth usage while maintaining low latency and full payload reconstruction fidelity under geographically distributed conditions. These findings validate the architectural assumptions underlying the proposed data diode communication model.



```
Packet Drops
Unique frames at TX          : 996
Unique frames at RX          : 997
Matched frames (TX∩RX)       : 996
Missing frames at RX         : 0
Extra frames only at RX      : 1
Delivery ratio (TX→RX)       : 1.0000
```

Fig. 4.8 Packet drop statistics



```
Reliability
Samples used                : 1103
Exact payload match rate    : 1.0000
Mismatched samples          : 0
Bit Error Rate (BER)        : 0.000000e+00
```

Fig. 4.9 BER statistics

CHAPTER 5 DEPLOYMENT MARKET PLAN AND SCALABILITY

5.1 Executive Summary

Overview

Increased urbanization and motorization continue to place substantial pressure on urban road networks, contributing to congestion, travel delay, and transport-related emissions (Li et al., 2021; The World Bank Group, 2024). Traffic congestion remains a chronic problem in cities, with inefficient traffic signal timing identified as a significant contributor, translating to not only economic losses (wasted fuel and time) and higher vehicle emissions but also public safety and driver frustration (Babani, 2025). In this and predecessor CCAT studies, a data diode was developed to provide road agencies with real-time knowledge of their signal timing and phase data. Reliable SPaT and high-resolution signal event data support could serve as a basis for agencies' efforts to monitor and improve traffic signal systems performance (FHWA, 2020; USDOT, 2025). This chapter discusses the deployment market potential, market considerations, and scalability of the Data Diode system. It is intended to support future entities interested in commercialization or broader implementation of the developed technology.

Product & Opportunity

The production-ready data diode device developed in this CCAT study collects high-resolution data on traffic intersection signal timing. The IoT-based device can be installed in traffic signal cabinets and continuously logs the timing of green, yellow, and red phases. The goal is to empower cities, towns, and road agencies with actionable insights to optimize signal timing, reduce congestion, and improve safety. With roughly 320,000 signalized intersections in the United States (Michigan Engineering News, 2024) and over \$23 billion in annual congestion costs tied to those intersections (FHWA, 2024; Wang et al., 2024), there is a significant need for smarter traffic signal management. The developed data diode device fills the critical data gap by providing continuous data upon which continuous traffic signal-status performance can be monitored and measured.

Market Potential

The target market includes state and regional road transportation agencies, municipal traffic departments, and private road operators worldwide. Currently, interest in intelligent traffic systems is evidenced by government programs and smart city initiatives. According to industry market research, the global intelligent traffic signal system market was valued at approximately \$5 billion in 2024 and is projected to grow at about 10.2% annually through 2034 (Global Market Insights, 2024). The developed data diode device offers a cost-effective solution compared to alternatives that cost several tens of thousands of dollars to install at an intersection. By providing affordable and scalable hardware, a share of this growing market can be captured, helping agencies achieve significant reductions in traffic delays attributable to poor signal timing.

This market deployment plan advocates a phased go-to-market strategy focused on raising awareness, acquiring pilot customers, and securing full-scale implementation contracts. Stage 1 involves building credibility through industry conferences, case studies, and partnerships, positioning the data-diode device as an enabler of “smart intersection” initiatives. Stage 2 involves pilot deployments in a select few cities or towns, demonstrating quantifiable improvements. It is expected that successful pilots will generate reference stories and product champions. Stage 3 transforms the pilots into full contracts and scaling up deployments citywide or regionally, backed by robust implementation support. A plausible implementation trajectory would involve pilot programs lasting approximately 9-15 months, followed by conversion to revenue-based larger contracts contingent on demonstrated performance, procurement timelines, and support capacity by Year 3, and profitability by Year 5 as recurring subscription revenues increase.

Risks

The risks include competition from larger firms, lengthy government procurement cycles, and challenges of integrating the product with existing technology. These risks will be mitigated through a combination of leveraging federal grant-supported pilots targeted towards smart transportation initiatives, partnership-based deployments, phased implementation, and robust targeted marketing campaigns to transportation agencies.

5.2 Product Description

The product developed under the CCAT research projects (Gowda et al., 2023; Gowda et al., 2024) and the current project, is an engineering device for real-time traffic signal data collection (Figure 5.1). It is a compact, durable hardware unit that can be easily installed at a signalized intersection (in the signal control cabinet). The device’s core function is to continuously log the signal phase timings – essentially recording each time the traffic signal turns green, yellow, or red for each approach, along with precise timestamps.

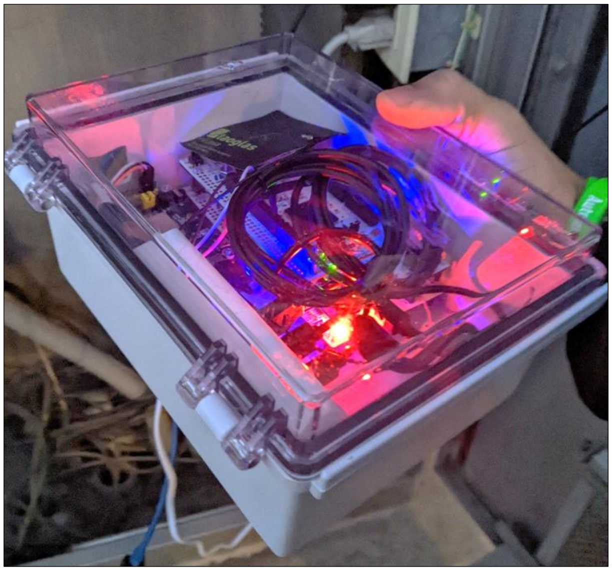


Figure 5.1 Installation-ready version of the device (Gowda et al., 2024)

The key features of the Data Diode device are as follows:

- **Non-Intrusive Installation:** As shown in the field tests at Owosso, MI, in 2023 and 2024, the device can be installed without major modifications to existing traffic hardware or intersection infrastructure. It interfaces with the signal controller output to capture signal-state information. Based on field testing, installation can typically be completed in less than one hour and does not require shutdown of the intersection. Field installation by the research team is illustrated in Figure 5.2.
- **High-Resolution Logging:** The device captures signal events at high temporal resolution, so that its output is consistent with emerging standards for Automated Traffic Signal Performance Measures (ATSPMs) workflows that rely on high-resolution controller event data to evaluate metrics like split failures, approach delay, and coordination quality (FHWA, 2016; FHWA, 2020).
- **Robust and Secure:** The data diode is designed for all-weather outdoor conditions (temperature, rain, snow) with battery backup. The system is intended to support secure data transmission and to limit exposure of controller infrastructure by maintaining one-way data extraction; detailed cybersecurity and architectural considerations are described in Gowda et al. (2023 and Gowda et al. (2024) whose research details ensure that data transmission encryption, privacy, and security standards are adhered to. Notably, the device collects operational data (signal timings), not personal data – thereby avoiding privacy-related issues associated with cameras or license plate readers. This can help promote regulatory approval and public acceptance of the device.
- **Connectivity and Data Platform:** The data diode automatically transmits the collected SpaT data to a cloud-based platform, and authorized end users such as city traffic engineers, emergency response vehicles, and other approved operations stakeholders can access the data from their cell phones or other devices to visualize the intersection signal performance (timings), download reports, or receive alerts. The system can be scaled up to integrate data from multiple intersections, providing a corridor-wide or network-wide view of signal performance.
- **Value Proposition:** By deploying this device, road agencies gain a low-cost tool (costing $200-$300) for continuous traffic signal timing monitoring and intersection performance assessment. This is a low-cost alternative to the several thousand dollars that are typically used for this purpose. The device is production-ready – having passed field testing for accuracy and reliability, and is poised for scaled implementation.

5.3 Market Analysis

5.3.1 Industry Overview and Need

In the United States, there exist more than 320,000 signalized intersections, and most of these are managed by local agencies (FHWA, 2024; FHWA, 2009; Michigan Engineering News, 2024). Yet, due to the cost and labor involved, typical practice is to retime traffic signals only once every few years (or even less frequently). Traditionally, retiming requires manual traffic counts, modeling, and field observation by traffic engineers often performed periodically rather than continuously (FHWA, 2016; FHWA, 2020). This process, costing several thousand dollars per intersection, is often triggered reactively – for example, when public complaints about a specific intersection reach a tipping point. During the period between such studies, as the road agency lacks granular data, the signal problems may go undetected and the intersection performance degrades, compounding congestion and accident risks (FHWA, 2016). The SPaT data made available by the device does not replace manual traffic counts, modeling, and field observation by traffic engineers but can be combined with these to make retiming decisions.

By continuously monitoring SPpaT data, agencies can better position themselves to implement corrective or proactive measures to improve intersection signals. Another industry trend is the rise of connected vehicle data and third-party analytics services. Broader industry trends toward connected, data-rich transportation operations, such as transferring aggregate anonymized data to and from fleet vehicles, and smartphones, and intersections, further increase the value of real-time signal data, especially where agencies seek to integrate field data with mobile, fleet, or corridor-level analytics (INRIX, 2025). This underscores the usefulness of real-time signal data.

5.3.2 Target Market Segments

The target market for the Data Diode device spans multiple segments within the broader intelligent transportation ecosystem:

- **City and County Transportation Agencies:** These include urban traffic engineering departments and public works agencies responsible for city streets and signal operations. Cities of all sizes are potential customers – from large metropolitan areas with thousands of signals (who need help managing complexity) to small/mid-sized cities with limited staff (who need a turnkey solution to improve a handful of congested corridors). Many mid-sized cities (population 50,000–500,000) have signals that are not yet “smart” and could benefit from an affordable data solution, making this segment particularly attractive.
- **State Departments of Transportation (DOTs):** State DOTs manage signals on state highways and coordinate regional traffic programs. They often have funding for corridor improvement projects and technology pilots. DOTs could deploy the developed device on state routes that traverse multiple jurisdictions or encourage cities to adopt it through state-led initiatives. State-led pilot programs (like those funded by FHWA or state research grants or matching grants) are ideal entry points.
- **Metropolitan Planning Organizations (MPOs) and Regional Agencies:** MPOs and regional traffic management centers might use the system to gather data across a metro area to inform regional timing plans or to justify infrastructure investments.
- **Private Road Operators and Smart City Integrators:** In some cases, private firms manage toll roads, large campuses, or industrial parks with their own signals. Additionally, smart city integrator companies or traffic engineering consultants could use our product as part of their solutions for clients.
- **International Markets:** Outside the U.S., rapidly urbanizing regions in Asia, the Middle East, and Latin America have a growing number of signalized intersections and severe congestion problems. These areas are investing in smart traffic solutions. In the longer term, international pilot projects may be explored where local standards, procurement frameworks, and partnership conditions are favorable to harness the benefits of in-built

geographic flexibility.. Adaptations might be needed for local standards, but the core need – access to SpaT data – is universal.

For initial market entry, focus must be placed on **North America** (U.S. and Canada), where there exists easier access to industry networks and a large installed base of signals. In North America, there exist active funding programs (federal grants, innovation challenges) that could be leveraged. As the track record is established, other international locations in Europe, Africa, South America, and Asia-Pacific must be sought for expansion, preferably, through local partnerships.

5.3.3 Market Size and Growth

To quantify the opportunity: in the U.S. alone, if even 10% of the 320k signalized intersections eventually implement continuous SpaT monitoring, that's 32,000 intersections – representing potential hardware sales in the tens of thousands of units. At an estimated price of ~$500 per device plus services, the U.S. market could be on the order of $15–20 million in device sales, plus ongoing subscription revenue. Globally, the figures are much larger. Industry market research projects continued growth in the broader intelligent transportation systems (ITS) market, with one estimate placing the global market at approximately $55.36 billion by 2030 (Markets and Markets, 2025). Another industry estimate projects the intelligent traffic signal system market to reach about $13 billion by 2034, driven by congestion, rapid urbanization, and smart-city initiatives, including technological advancements in IoT/AI for traffic management (Global Market Insights, 2024). The data diode device fits into this growing market as a relatively low-cost, high-impact component that agencies can deploy incrementally. Importantly, it complements other investments: for cities not ready to spend big on more costly alternatives, the diode offers a relatively low-cost pathway toward modernization.

5.3.4 Customer Needs and Pain Points

From the perspective of our target customers (city traffic engineers, DOT signal managers, etc.), the key needs and pain points that will be expected to be addressed during implementation include:

- **Visibility and Data:** A common operational challenge is the limited ability of agency personnel to access SPaT information remotely without traveling to the field or to a traffic operations center. Example of target customer perspective framing; *"I don't know how to access SPaT information at any of my city's traffic signals from my cell phone or other authorized device without going to the traffic operations center."* This may be a common pain point. The data diode device provides continuous visibility to the Engineer regardless of their location.
- **Efficiency and Congestion Reduction:** Agencies may also lack immediate visibility into deviations from prescribed timing plans unless staff visit the site or monitor a central system directly. Example of target customer perspective framing; *"We suspect some intersection signals may have malfunctioned and are off the prescribed timing regime, but we cannot tell unless we visit the site or go to our traffic operations center."* The data diode produces data that can be accessed from any location.
- **Resource Constraints:** Many agencies lack the staff or budget for more costly equipment for collecting intersection signal SPaT data.

- **Integration and Future-Proofing:** Potential customers (road agencies) may worry about investing in technology that might become obsolete. The developed data diode device is positioned as a **building block** for future smart city or IoT integration. It produces data that can feed into adaptive control systems or connected vehicle infrastructure. This protects the customer's investment.

In summary, the market analysis suggests that the data diode addresses a meaningful gap by providing continuous and actionable traffic signal data in a cost-effective form. Demand drivers such as congestion, operational visibility, and performance-based management align with the intended use case of the product, and by addressing the pain points of our target customers, the product implementors can position the product as a timely solution in growing markets.

5.4 Identification of the Competition Landscape

The competitive landscape for the data diode includes both **traditional approaches** and **emerging technologies**. The main categories of competitors and differentiation from the study device are outlined as follows:

- **Status Quo / Manual Services:** Currently, the most common *"competitor"* is the manual engineering study. Cities hire traffic engineering consultants or use in-house staff to conduct periodic field reviews, retiming studies, or controller checks. This approach can be costly and generally provides only a snapshot of the SPaT status of the intersection performance rather than continuous monitoring. The data diode device vastly improves on this by providing continuous data at a lower ongoing cost and enabling **ongoing optimization** rather than one-off fixes. Instead of a one-time service, the data diode provides a continuous service.
- **Traffic Data Collection Devices & IoT Sensors:** A range of relatively higher-cost traffic data collection and signal analytics systems exists in the market.
- **Integrated Traffic Management Systems:** Some major players on the ITS market offer end-to-end traffic management suites that may include SPaT data modules. These often come with hefty software packages or require upgrading signal controllers, and typically, are sold through lengthy procurement cycles. The data diode is intended to support a more incremental and modular procurement pathway: a standalone device that can be installed without a full system overhaul. This is attractive to resource-constrained road agencies. It is also possible for the data diode implementors to partner with the bigger players by feeding the data diode's data into their systems, thus turning potential competitors into collaborators in some cases (for example, providing data to an agency's existing traffic control center software).

5.5 Recommended Marketing Strategy

The marketing strategy for the device must be such that it **raises awareness** of the device, educates potential customers on its benefits, and builds a strong reputation in the traffic management community. To do this, a mix of outreach channels and tailored messaging can be used to effectively reach traffic engineers and managers at cities, towns, and road agencies. Key components of the data diode marketing plan can include designing a strategy for branding and messaging, identification of outreach channels, creation of partnerships, and adopting the concept of influencer marketing,

5.5.1 Messaging and Branding

It will be useful to brand the data diode device and platform under a moniker that is not only catchy but also easy to remember and conveys the essence of the data diode. One possible branding option is Low-Cost Unidirectional Connected Intersection Data device (**LUCID).** Marketing communications for the device could be designed to emphasize some core messages about the device. For example:

- **"Monitor Every Light, Effortlessly, From Anywhere."** The message should highlight the fact that the developed data diode allows agencies to have full knowledge of the SPaT status of every traffic signal without undue effort or without the need to be present at the traffic operations center, highlighting the convenience and the labor-saving and cost-saving benefits of the device. Example positioning statements could include, "Monitor signal status remotely and continuously."
- **"Towards Affordable Smart City Technology"** The message should position the product as a cost-effective step towards smart city infrastructure, contrasting with more costly alternatives. Example positioning statements could include, "A lower-cost pathway to data-enabled signal operations".

The messaging should be tailored to the specific audience. For traffic engineers: "the device provides ATSPM-compliant high-resolution data with operational accessibility and visibility to you from any location. To City managers: "the device emphasis may be to foster improved data collection that serves as a basis for interventions that ultimately yield beneficial societal outcomes such as congestion mitigation, improved service responsiveness, support for innovation-oriented transportation programs that improve commute times and promote innovation branding for cities."

5.5.2 Outreach Channels

The channels for outreach may include the following:

1. **Webinars and Workshops:** The target audience for the data diode can be reached by organizing or hosting educational or industry-oriented webinars on topics including "Collecting SPaT Data to Tackle Traffic Congestion". At these webinars, the device can be featured in discussions alongside general best practices. It is possible to partner with organizations including state DOT, ITE local chapter, or ASCE local chapters to co-host webinars and workshops related to signalized intersection data collection or performance.
2. **Online Presence and Content Marketing:** A professional website can be established for the data diode, to showcase the device features, case studies, and return-on-investment calculations. A website can feature a well-maintained blog with content that includes summaries of industry research related to the device. LinkedIn and specialized forums including ITE community boards can be used to share insights and device updates.
3. **Industry Conferences and Trade Shows:** Implementors of the data diode device can have a presence at key events including ASCE ICTD conferences, ITE (Institute of Transportation Engineers) Annual Meetings, ITS World Congress, and Transportation

Research Board (TRB) conferences. These venues can help facilitate demonstrations of the data diode, distribute brochures, and network directly with city traffic professionals. The implementors of the device can seek speaking opportunities where they could present pilot case studies in conference sessions or conference workshops.

4. **Pilot Program Outreach:** Similar to the experience of the CCAT research team at Owosso, Michigan, prospective pilot cities and towns could be approached to serve as pilot testbeds or demo sites for the developed device. For marketing purposes, **Pilot Program Prospectus** (a short, compelling proposal document to send to city traffic engineers, outlining how the pilot would work, the technical support available, and cited examples of success) could be prepared for distribution.
5. **Press and Media:** The implementors can reach out to transportation and smart city publications. Publications like *ITS International, Traffic Technology Today,* and *Smart Cities Dive*, which frequently cover new traffic management technology, could be made to feature the data diode device and its benefits.

5.5.3 Partnerships and Influencer Marketing

This includes:

- **Strategic Partners:** The data diode implementors can seek endorsements or partnerships with well-regarded agencies and organizations. For example, collaborating with a respected transportation research university lab or a state or federal research program will help boost the device's credibility. The implementors could also partner with established traffic signal vendors (for example, the data diode could be marketed as compatible with Econolite or Siemens controllers).
- **Consulting Firms:** There are several traffic engineering consulting firms that advise cities on traffic technology. By building relationships with them, the data diode could be recommended in their studies. These firms could be encouraged to include the data diode as one of the hardware systems in their project proposals.
- **Early Adopter Champions:** A city or town is more likely to try a product that a peer city/town has had success with. As such, the implementors should identify and cultivate **"champion" customers** among early adopters. For example, the City of Owosso, where the CCAT research team conducted successful trials in 2023 and 2024, could be invited to share their deployment experience at conferences or with peers (possibly in exchange for discounted service or recognition).

5.6 Implementation Plan (Deployment and Support)

Implementing any new technology within city infrastructure requires careful planning to minimize disruption and ensure long-term success. In the sections below, suggestions are presented on product implementation, including how the device could be deployed, integrated with existing systems, and made to support the customers (cities and towns) throughout the product life.

5.6.1 Deployment Logistics

Site Assessment: Prior to any installation of the data diode, the implementors should conduct a site assessment (first, remotely via intersection photos or diagrams provided by the city or via Google Street View). The implementors should confirm the signal controller type and enclosure security, availability of power/connectivity within the cabinet, and the availability of space within the cabinet. The data diode is intended to be compatible with standard controller environments, subject to verification during site assessment.

Installation Process: A standard installation involves mounting the device inside the traffic signal cabinet. If inside, it connects to the controller's port (for data feed). Even though no downtime of the signal is needed, the installation can be scheduled during off-peak traffic hours to minimize any unforeseen disruption. As shown in Figure 5.2, field installation in Owosso, Michigan, demonstrated that the device can be installed within approximately one hour by a two-person team. For pilot deployments, the implementor's technicians will be on-site. For larger rollouts, the implementor's technicians can train and certify local contractors or city signal electricians to perform installations. For this, clear installation manuals and checklists will be provided.

Figure 5.2 Field installation of the data diode device by the research team at an Owosso intersection in 2023 (Gowda et al., 2024)

Testing and Commissioning: After installation, each data diode unit will undergo commissioning. This includes verifying that it is communicating with the cloud and verifying it correctly detects the signal phases (for example, comparing the device's recorded phase changes to what is observed in the field in real-time). This also involves setting the location metadata (that way, the cloud can identify the intersection in question). Field validation activities similar to those shown in Figure 5.3 can be used during commissioning to verify proper signal-state capture.

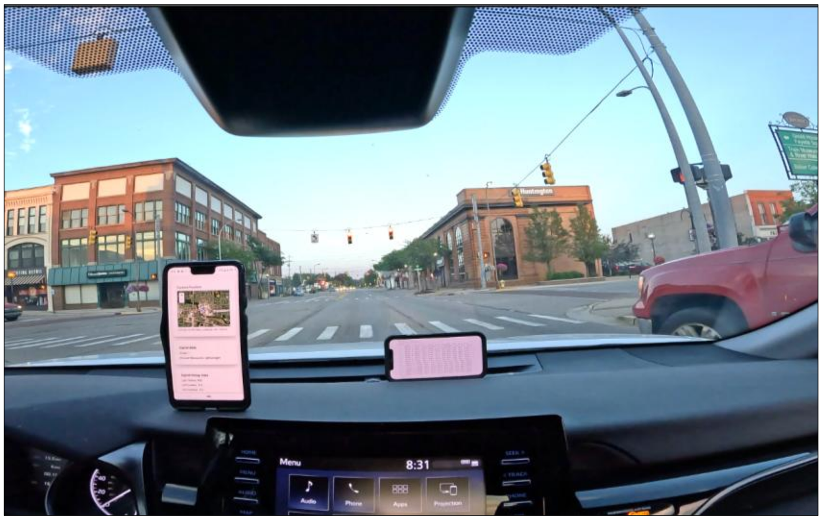


Figure 5.3 Field testing of the device by the research team at an Owosso intersection in Sept. 2023 (Gowda et al., 2024)

5.6.2 Integration with Existing Hardware and Software Systems

Many agencies have Traffic Management Centers (TMCs) or at least some central software for their signals (even if just for monitoring). As demonstrated in the first and second bench tests of the data diode at Michigan DOT's Traffic Lab in Lansing Michigan in March 2023 (Figure 5.4), the data diode can be installed without compromising the existing traffic signal systems.

Figure 5.4 First bench test of the data diode at Michigan DOT's Traffic Lab by the research team Michigan DOT engineers, Lansing, March 2023 (Gowda et al., 2024)

As demonstrated in the bench and field tests, the integration of the data diode into existing signal systems is **non-intrusive yet flexible**:

- **Stand-alone Operation:** The device and cloud platform can operate completely stand-alone. This means even if a city has no advanced central signal system, they can still use our web dashboard to see all data. This may be particularly relevant for smaller cities such as Owosso.
- **Data Export and API:** For agencies with central management software (like systems from Econolite, Siemens, or other vendors), the study device provides data export tools. The data (signal phase logs, performance metrics) can be exported in standard formats including CSV. In future, an API could be developed to enable third-party querying of the device for SPaT data.
- **Futureproofing:** Looking ahead to the future of IOT and smart cities deployments, it will be possible to integrate the data diode with connected vehicle infrastructure. The data diode could potentially broadcast SPaT data over DSRC or C-V2X systems if needed, potentially extending its role toward roadside-unit-adjacent functionality, subject to future hardware and standards integration. While not included in the initial product, the developed hardware is modular enough to add such capability, which could be a selling point for agencies planning connected vehicle pilots.

5.6.3 Ongoing Support and Maintenance

A major aspect of implementation is keeping the system running smoothly after deployment. The implementor of the data diode device can offer robust support in the following ways:

- **Customer Support Channels:** The implementor can establish a dedicated support line (phone and email) for client agencies. Given that traffic signals are critical infrastructure, **24/7 support** will be provided for urgent issues (e.g., if there is any concern that the data diode might be affecting an intersection signal – which, again, is unlikely because the device is designed as a passive one-way data extraction equipment). For routine questions, the implementor will provide support during business hours.
- **Device Maintenance:** The data diode is designed to be low maintenance (solid-state components). A device maintenance check is required at least annually. potentially extending its role toward roadside-unit-adjacent functionality, subject to future hardware and standards integration. Future technological enhancements to the device can add **remote diagnostics** capabilities for the device.
- **Software Updates:** The data diode's firmware will receive periodic updates if needed. Clients will be duly informed of major updates which will be scheduled to coincide with the client's signal maintenance schedules.
- **Training and User Community:** After the initial training, the implementors will remain available for refresher sessions. If agency staffing changes, the implementor will provide training for the new users as part of the support program (annual training sessions could be offered as part of the subscription). Additionally, as the customer base grows, the implementor will establish a user group (an online forum or annual meet-up) for customers

to share tips and use cases. This also serves as a feedback channel for the implementors and future developers to learn which features should be added.

5.6.4 Scalability and Multi-City Coordination

As the data diode is deployed increasingly at multiple cities, the implementors will scale up the operations. This will involve:

- **Development of Installation Partnerships:** As demand grows, the implementors will partner with traffic signal maintenance companies or electrical contractors in different regions who can be trained to install and support the device at various locations. This provides local labor for implementations and can speed up deployment for customers located far away.
- **Manufacturing and Supply Chain:** The implementors will ensure that production keeps up with demand. Initially, batches might be small and possibly built in-house or with a local electronics manufacturer. As orders grow, the implementors will contract manufacturing of the devices in larger quantities, keeping an inventory to meet new orders swiftly. Recognizing that city budgets often require spending within a fiscal year, the implementors will ensure that the units ordered are delivered on time.

5.6.5 Risk Mitigation in Implementation

Implementation risks including device interference or installation errors, and device performance issues, should be anticipated and managed proactively. To mitigate such risks, devices will be tested multiple times at each deployment location. Traffic industry standards will be followed. During installation, safety will be prioritized: installers will follow proper traffic safety protocols including wearing high-visibility apparel and cone installation. Installations will be carried out in the physical presence of a city's traffic operations center, as was done in Owosso in 2023 (Gowda et al., 2023; Gowda et al., 2024). In terms of support, a risk is if a device or the system fails and causes loss of trust. Transparency will be a priority. The implementor will serve as a full-solution provider not just selling a gadget, and end-to-end support will be delivered continuously, to promote customer satisfaction, long-term retention, and market penetration.

5.7 Financial Projections and Revenue Modeling

A revenue model will be developed prior to implementation. This will include forecasts of hardware sales, subscription fees, licensing/data partnerships, and service contracts. A 5- to 10-year horizon will be established to demonstrate the business's growth and profitability potential.

5.8 Risk Assessment and Mitigation

No marketing and deployment plan is complete without acknowledging the potential risks and challenges. In the sections below, key risks in developing, marketing, and deploying the data diode are identified, as well as the accompanying mitigation strategies as described below.

5.8.1 Market Adoption Risk

Agencies may be slow to adopt new technology or have bureaucratic hurdles. Public sector sales often involve long decision cycles, budget approvals, and risk aversion. To mitigate such risk, the implementor will leverage pilot programs as they provide low commitment entry and facilitate collection of evidence to help reduce the perceived risks. Influential early adopters whose success will spur others (the bandwagon effect) will be sought. The implementor will consider offering a flexible pricing structure (subscription model) for the data diode, to allow customers to categorize spending as operational expense rather than capital expenditure.

5.8.2 Competition and Technological Obsolescence

Competing solutions (especially data-only analytics or new sensor technology) might leapfrog our offering. For example, if connected vehicle data becomes extremely prevalent and inexpensive, some might question the need for physical devices such as the data diode. To avoid obsolescence, the implementors of the data diode will continue to invest in continual R&D and keep abreast of customers' needs and technological advancements, and seek shorter innovation development cycles, a capability which larger companies may generally lack.

5.8.3 Technical Performance Risk

The device or platform might not perform as expected, due to adversities such as data inaccuracy, downtime, or even interference with signal operations. If the data diode fails to accurately log timing information or maintain connectivity, it could undermine trust. To mitigate such risk, the research team that developed the product has conducted extensive testing in diverse conditions before full rollout, ensuring the accuracy of timestamping and event detection. Redundant time-synchronization mechanisms (such as GPS or NTP) are adopted so the device's clocks are accurate. The device is mostly a passive logger, so, by design, the chance of interfering with signal control is minimal. Nevertheless, the implementors will run a pilot in each new type of controller environment to double check. Product liability insurance will be carried, and the implementors will work closely with the road agencies or city authorities to meet any required certifications for field equipment.

5.8.4. Cybersecurity and Data Privacy

As an IoT and cloud solution, the study device will encounter cybersecurity risks. A breach or hack could compromise our system or, in the worst-case scenario, affect traffic operations if someone maliciously accessed the data or device. To mitigate such risk, the data diode does not control the traffic signal and there is only one direction of data flow: from the signal to the diode. This limits the risk of data exposure. Yet still, the implementors will pursue security certifications (such as ISO 27001). By being proactive on security, the implementors expect to meet the expectations of the customers' IT departments.

5.8.5. Financial and Scaling Risk

The implementors might face cash flow issues or difficulty scaling operations to meet demand. If sales of the data diode are slow, revenue may lag expenses; on the other hand, if sales are fast, fulfilling a large order could strain the implementor's team or their supply chain. To mitigate such risk, the implementors will adopt conservative financial plans, securing a line of credit or investor backing to buffer any early losses. Fixed costs will be kept low initially (for example, by keeping a small team and outsourcing manufacturing); that way, adjustments can be made if needed. For scaling up, as soon as strong demand is forecast, production capacity will be expanded (through multiple suppliers or an assembly partner) to avoid customer delays. In such cases, the implementation team will consider staggering implementations to avoid overloading of the support team. Also, in cases where demand exceeds the implementors' bandwidth, some projects will be delayed slightly to maintain quality, while communicating transparently with customers about realistic timelines. Under-promising and over-delivering will be pursued rather than over-promising or under-delivering.

5.8.6 Regulatory/Policy Risk

Changes in standards or regulations could affect the implementation of the data diode. For example, if new standards for traffic signal equipment emerge (such as mandated compatibility or cybersecurity requirements), the data diode design may need to be updated. In addition, if a federal program decides to fund only certain solutions, excluding those offered by the data diode, it could affect the market dynamics for the diode. To mitigate such risk, the implementors will need to remain engaged in the traffic signal industry committees to know what is imminent. Any future design of the data diode will be made with open standards and interoperability in mind, so it will be feasible to adapt to new rules (for example, a new communication protocol). The implementors will seek certifications for the data diode, and any DOT certifications for field hardware. By aligning the diode with federally promoted initiatives including ATSPM, the implementors will be better positioned to align with evolving regulatory expectations.

5.8.7. Natural and External Risks

Anthropogenic threats (such as supply chain disruptions including as component shortages) and "Act-of-God" events or natural disasters and could affect the diode production capacity and operational continuity, respectively. To mitigate such risks, the implementors will diversify supplier sources for critical components, keep some inventory, and possibly redesign components if certain parts become scarce. Product insurance will help with replacement if the data diode gets damaged because of high floods, earthquakes, and so on.

CHAPTER 6 DISCUSSION

The device developed in this study can make SPaT data more readily available to authorized users across multiple locations, potentially supporting a range of operational and strategic benefits for cities and transportation agencies. SPaT data are a foundational input for connected-intersection applications because they communicate the current and predicted state of signal operations to external users and systems. In prior U.S. connected-vehicle deployments, SPaT data were commonly associated with DSRC-based communications; however, current U.S. regulatory direction for the 5.9 GHz ITS band has shifted toward C-V2X deployment. Accordingly, the broader benefit of this device is to make reliable SPaT data available for downstream V2I and ITS applications, regardless of the specific communication medium used (FCC, 2020; FCC, 2024; USDOT, 2025; U.S. Department of Transportation, n.d.). Selected documented examples of benefits associated with reliable SPaT data in connected transportation applications are summarized in Table 6.1.

6.1 Safety Enhancement

Reliable SPaT data can support the development of safety applications at signalized intersections by enabling vehicles or roadside systems to interpret signal state and timing with greater precision. Prior connected-vehicle safety analyses have suggested substantial crash-reduction potential for applications that depend on SPaT and related intersection data under appropriate deployment conditions (Sayer et al., 2018). In addition, USDOT-sponsored transit safety research demonstrated DSRC-enabled applications that warn transit operators about pedestrians in signalized crosswalks and about vehicles turning right in front of buses, indicating the broader safety potential of connected intersection communications (Zimmer et al., 2014; Valentine et al., 2014; Burt et al., 2014). These findings suggest that wider availability of reliable SPaT data can strengthen the technical foundation for future intersection safety applications.

6.2 Prioritization of Public Transportation

SPaT data and connected V2I communications can support signal priority strategies for selected vehicle classes, including transit buses and, in some implementations, emergency vehicles (ambulances, fire, and police). For transit systems, priority requests can be used to extend or advance green traffic-light phases to improve schedule adherence and service reliability when vehicles are behind schedule (Leonard, 2018). This can help preserve transit operational efficiency and improve travel-time reliability along priority corridors, especially in congested urban settings.

6.3 Reduction of Fuel Consumption

SPaT data can also support reduced fuel consumption through eco-routing and Eco-Approach and Departure (EAD) applications (USDOT, 2013; USDOT, 2014; Dong et al., 2022; Liu et al., 2025). In these applications, signal timing information is used to generate speed recommendations that reduce unnecessary stopping, idling, and aggressive acceleration near signalized intersections. USDOT materials describe EAD as an application that can provide speed guidance to help vehicles pass through intersections more efficiently, thereby reducing fuel use and emissions under suitable conditions (U.S. Department of Transportation, 2017; U.S. Department of Transportation, n.d.).

6.4 Manage Corridor Throughput and Other Uses and Benefits

Communicating speed-adjustment recommendations based on SPaT data can improve not only fuel efficiency but also traffic progression and corridor throughput. USDOT materials on connected eco-driving and safe-passage concepts indicate that signal timing information can support smoother travel through signalized corridors for a given level of traffic demand (USDOT, 2017; U.S. Department of Transportation, n.d.). Applications of such optimization are plentiful in the literature through multiple specific application contexts including Signal optimization (Roshandeh et al., 2014), dynamic traffic rerouting (Xiao et al., 2017; Du et al., 2023) and autonomous vehicle fleet routing (Bruglieri et al., 2024; Ha et al., 2025). Other uses and benefits of SPaT data were discussed by Davis (2020), Yang et al. (2022), Levin et al. (2023), and Bhat and Chen (2023). From a broader planning perspective, deployment of the data diode device and the increased availability of SPaT data may also be viewed as part of wider smart-city and digital infrastructure modernization efforts (Mezhuyev and Li, 2025; Alabi et al., 2025). Table 6.1 summarizes selected examples from the prior literature that show how reliable SPaT data have been used in connected transportation research and deployment contexts to support safety, transit priority, eco-driving, and throughput improvements.

It is worth noting that Cellular Vehicle-to-Everything (C-V2X) is gradually replacing Dedicated Short-Range Communications (DSRC) technology because it offers a farther range (20-30% further), superior reliability in obstructed environments, and more direct paths of evolution to 5G. "Cellular" in this context does refers not to the use of cellular networks but rather to the use of underlying electronics in cellular radios adapted to communicate from one radio directly to another (Gettman, 2020). C-V2X uses existing cellular infrastructure for network-based communication while maintaining direct, low-latency communication for safety-critical V2V/V2I applications.

Table 6.1 Selected Documented Evidence of the Benefits of Reliable SPaT data (USDOT, 2025)

Agency/Institution	**How SPaT was Used**	**Benefits realized**	**Reference**
University of Virginia, FHWA, Delft University, and Harbin Institute of Technology	Used simulation to test the efficacy of SPaT message delivery regarding recommended driving speeds to evaluate the impact of eco-driving on traffic flow.	Improved throughput by 11%.	(USDOT, 2025)
University of California- Riverside	Used SPaT messages collected at 6 signalized intersections to test fuel emissions for truck deceleration (braking smoothly prior to reaching a yellow light at an intersection) and acceleration (passing through the intersection)	Eco-driving yielded diesel truck fuel savings of up to 9%.	(USDOT, 2025)
Utah Department of Transportation and Utah Transit Authority	Used DSRC and schedule analysis to provide additional green light time to transit buses that were behind schedule, at 30 intersections.	Improved reliability for a specific bus route by 12%; 40% reduction in late bus arrivals.	Leonard (2018)
University of Michigan Transportation Research Institute	Used SPaT data to "forecast" crashes, injuries, and fatalities that could have happened in the no-DSRC implementation scenario.	Communication can help prevent millions of crashes.	Sayer et al. (2018)

CHAPTER 7 CONCLUDING REMARKS

The data diode device development can be considered as a meaningful advancement in cost-effective and secure collection and dissemination of intersection data. This project advanced the development of a secure, efficient, and scalable system for acquiring and disseminating Signal Phase and Timing (SPaT) data from Traffic Signal Controllers. By leveraging a hardware-based data diode architecture with strictly unidirectional data flow, the system enables real-time access to high-frequency controller outputs while preserving the integrity and safety of the signal control environment. This approach directly addresses long-standing concerns related to cybersecurity, regulatory compliance, and infrastructure risk when exposing traffic controller data to external networks (Stouffer et al., 2015; Stouffer et al., 2023).

A key contribution of this phase of the work was the migration of the system software architecture into the Cubicon model-based development environment. Cubicon provided a structured, system-level abstraction that enabled the translation of high-level functional blocks into executable software modules. By aligning the implementation with a systems engineering V-model, Cubicon helped reduce design complexity, improve traceability between requirements and implementation, and enhance long-term maintainability. This model-centric approach ensured that the deployed software remained consistent with the intended architecture while allowing efficient iteration and future extensibility, a key tenet of systems development (International Organization for Standardization, 2015).

Comprehensive experimental evaluation demonstrated high reliability and low latency under both local and wide-area deployment scenarios. Under the conditions evaluated, all transmitted SPaT frames were received and reconstructed correctly, yielding a 100% delivery ratio, zero payload mismatches, and a bit error rate of zero. End-to-end latency measurements showed a mean one-way delay of approximately 44 ms, which was well below the 100 ms SPaT update interval associated with typical 10 Hz transmissions, and, with minimal variance. Application-level processing overhead was measured to be negligible relative to network delay, confirming that the observed system performance is governed primarily by network conditions rather than computational cost.

The implementation of differential SPaT updates further enhanced system efficiency. By transmitting only byte-level changes after an initial full-frame synchronization, the system reduced average payload size by more than 90%, thereby lowering bandwidth requirements and improving scalability. This reduction directly contributes to stable latency behavior and makes the architecture well suited for deployment across multiple intersections and over constrained or variable-quality networks such as cellular links.

Regarding the market deployment plan, the developed data diode device addresses the critical data gap by providing continuous signal status data, enabling traffic signal performance to be monitored and measured. The target market includes state and regional road transportation agencies, municipal traffic departments, and private road operators worldwide. Relative to more complex signal-monitoring alternatives, the developed data diode device offers a lower-cost and more modular deployment option, particularly for agencies seeking incremental modernization (FHWA, 2024). By providing affordable and scalable hardware, a share of this growing market can be captured, helping agencies achieve significant reductions in traffic delays attributable to poor signal timing. The market deployment plan advocates a 3-phase go-to-market strategy focused on raising awareness, pilot deployments, acquiring pilot customers, and securing full-scale implementation contracts. It is anticipated that initial pilot programs will take 9-15 months, first revenue from full contracts by Year 3, and profitability by Year 5 as recurring subscription revenues increase. The risks include competition from larger firms, lengthy government procurement cycles, and challenges of integrating the product with existing technology. These risks will be mitigated by leveraging federal grants targeted towards smart transportation initiatives, strategic partnerships, phased implementation, and a robust marketing campaign.

Overall, the integration of a secure data diode architecture with a Cubicon-driven, model-based software design demonstrates a practical and robust solution for real-time traffic signal data collection and dissemination. Further, the resulting platform provides a strong foundation for future extensions, including MAP message integration, multi-client scaling, and advanced edge or cloud-based analytics. As transportation systems continue to evolve toward connected and automated operation, this work offers a viable pathway for making critical infrastructure data easily and securely available to approved parties while maintaining operational integrity and performance.

CHAPTER 8 SYNOPSIS OF PERFORMANCE INDICATORS

8.1 Part I of USDOT Performance Indicators

Over the study period for this project, two (2) transportation-related courses were offered that were taught by the PIs. Three graduate students (2 MS [1 transportation engineering and 1 electrical engineering[and 1 PhD [electrical engineering]) participated in the research project. One (1) transportation-related M.S. program utilized the CCAT grant funds from this research project to support the graduate student.

8.2 Part II of USDOT Performance Indicators

Research Performance Indicators:
One (1) conference presentation was produced from this project. The research from this project was disseminated to approximately 40 people in attendance (from industry, government, and academia) through the conference presentation. These include the Next-generation Transportation Systems Conference held in Purdue University in 2024.

Leadership Development Performance Indicators:
This research project generated 3 academic engagements and 2 industry engagements. The PIs held positions in 2 national organizations that address issues related to this research project.

Education and Workforce Development Performance Indicators:
The methods, data and/or results from this study were incorporated (or are being incorporated) in the syllabi for the Fall 2024 versions of the following courses at Purdue University:
(a) CE 299: Smart Mobility, an optional undergraduate level course at Purdue' civil engineering B.S. program, (average 12 students),

These students will soon be entering the workforce. Thereby, the research helped enlarge the pool of people trained to develop knowledge and utilize at least a part of the technologies developed in this research, and to put them to use when they enter the workforce.

The methods, data and/or results from this study will also be incorporated in future versions of the course listed above.

Collaboration Performance Indicators:
There was collaboration with other agencies, and 1 agency and 2 institutions provided matching funds.

The outputs, outcomes, and impacts are described in Chapter 9.

CHAPTER 9 STUDY OUTCOMES AND OUTPUTS

9.1 Outputs

9.1.1 Publications, conference papers, or presentations (from major conference or similar event)

(a) Conference Presentations
Kumar, M., Fehr, W., Balmos, A., Ajagu, R., Hong, D., Abbas, M., Krogmeier, J., Labi, S. (2024). Economical Acquisition of Intersection Data – Implementation, Presentation at the Next-Generation Transport Systems Conference (NGTS-4), MRGN 121, Discovery Park, Purdue University, September 22, 2024.

(b) Conference Proceedings
Kumar, M., Balmos, A., Fehr, W., Ajagu, R., Krogmeier, J., Abbas, M., Labi, S. (2024). A Secure and Cost-Effective System for Acquiring Traffic Signal Data to Facilitate CAV Operations and Other Use Cases, Accepted for publication in the Proceedings of the American Society of Civil Engineers' International Conference on Transportation and Development (ICTD), Detroit, MI, June 28 – July 1, 2026.

9.1.2 Other outputs

(a) Working Group Presentations
Ajagu, R., Labi, S. (2025). Economical Acquisition of Intersection Data to Facilitate CAV Operations and Hardening to Improve System Integrity, Presentation to the CCAT Cybersecurity Focus Group, February 10, 2025, Online.

Ajagu, R., Labi, S. (2025). Economical Acquisition of Intersection Data to Facilitate CAV Operations and Hardening to Improve System Integrity, Presentation to the CCAT Accessibility Focus Group, October 14, 2025, Online.

(b) Other
One of the research outcomes (the field case study) have been used in Purdue University's undergraduate and graduate courses directly or indirectly related to intersection operations: CE 398 (Introduction to Civil Engineering Systems) and CE 597 (Emerging Technologies in Transportation). No patents have yet been filed for the research outcomes.

9.2 Outcomes

The key outcomes of this research included a practical demonstration of a novel communication protocol and elements of a new operating system that can be applied to help foster transportation automation and connectivity. This outcome can influence road agencies' transportation system design or operational policies in at least five ways:

- Reduced cost and enhanced security of intersection data collection to support the growing implementation of connected and automated technologies at road intersections.
- Increased awareness of prevailing signal timings for those that are out-of-sight of the signal due to occlusion by large vehicle downstream, fog, and other factors.
- Awareness of signal timings by visually impaired pedestrians and other VRUs at the intersection, via connectivity between the developed device and their cell phones or wearable devices.
- Foster the integration of road intersections to wider city-scale Internet of Things (IOT) networks and smart city applications.
- Enhanced overall travel efficiency and safety of road users at urban and rural intersections.
- Consideration of the methodologies and frameworks developed in this study for long-term need assessment of intersection infrastructure and related planning functions.

9.3 List of impacts

The study product is expected to have beneficial outcomes on the transportation system, or society in general, such as reduced fatalities, decreased capital or operating costs, community impacts, or environmental benefits due to improved smoothness of traffic flow at intersections. In addition, the study has helped increase the body of knowledge and technologies related to intersection data collection and has trained at least 3 students in the specific subject area of intersection data collection. With this knowledge base, they are in a better position to develop future versions of the device that are more amenable to emerging communication technologies and protocols. A list of specific impacts from this research project is as follows:

- Helped future-proof transportation infrastructure by moving past practices that are costly to design and implement, and difficult to protect from cyber threats.
- Delivered critical intersection infrastructure information such as SPaT using available communication media, thereby demonstrating how intersection safety and mobility improvement-related policy objectives could be realized.
- Stronger justification for city managers and road departments to invest in intersection data collection. It is expected that when implemented to scale, the developed product will demonstrate the substantial cost savings associated with its collection of intersection data.
- The graduate students who worked on this project will enter the workforce in 2026 to help support the workforce that will implement new technologies such as the device developed in this study or possible future versions thereof.
- The project had an impact on education, as parts of the research outcomes were incorporated into two undergraduate courses and one graduate course at Purdue University. These students, who will soon be entering the workforce, benefited from the outcomes of this research through these academic platforms. This helps expand the pool of people trained to develop knowledge and utilize the technologies developed in this research, and to apply them when they enter the workforce.

REFERENCES

AASHTO, ITE, & NEMA. (2020). NTCIP 1202 v03 - Object definitions for actuated traffic signal controller units. NTCIP Joint Committee.

Abernethy, B., Andrews, S., Pruitt, G. (2012). Signal phase and timing (SPaT) applications, communications requirements, communications technology potential solutions, issues and recommendations, Tech. Rep. FHWA-JPO-13-002, by ARINC Incorporated, for United States DOT Joint Program Office for Intelligent Transportation Systems, https://rosap.ntl.bts.gov/view/dot/23215

Alabi, B., Du, R., Guo, R, Alinizzi, M. & Labi, S. (2025). A framework for incorporating smart city concepts into the management of municipal infrastructure. Frontiers in Engineering and Built Environment, 5(2), 109-12.

Babani, A. (2025). A cost-effective way for cities to improve traffic signal performance network-wide, INRIX Innovations and Perspectives, https://inrix.com/blog/a-cost-effective-alternative-for-cities

Bhat, P. K., & Chen, B. (2023). Real-time suitable predictive control using SPaT information from automated traffic lights. Future Transportation, 3(2), 643-662. https://doi.org/10.3390/futuretransp3020038

Bruglieri, M., Peruzzini, R., & Pisacane, O. (2024). Efficiently routing a fleet of autonomous vehicles in a real-time ride-sharing system, Computers & Operations Research 168, 106668

Bullock, D., Urbanik, T. (1999). Traffic signal systems: Addressing diverse technologies and complex user needs, Transportation in the New Millennium, TRB Committee on Traffic Signal Systems, Washington, DC.

Burt, M., Zimmer, R.E., Zink, G.J., Valentine, D.A., Knox, W.J. Jr. (2014). Transit safety retrofit package development: TRP concept of operations. https://rosap.ntl.bts.gov/view/dot/3453

Case, J., Fedor, M., Schoffstall, M., & Davin, J. (1990). A simple network management protocol (SNMP). IETF RFC 1157.

Das, D., Altekar, N. V., Head, K. L., & Saleem, F. (2022). Traffic signal priority control strategy for connected emergency vehicles with dilemma zone protection for freight vehicles. Transportation Research Record: Journal of the Transportation Research Board, 2676(1), 499-517.

Davis, A. (2020). Lessons learned from comprehensive SPaT deployment and future plans, sashto.org/Presentations/Monday,%20August%2019/A3/gdot%20sashto%20cv_alan%20davis.pdf

Dong, H., Zhuang, W., Chen, B., Lu, Y., Liu, S., Xu, L., Pi, D., & Yin, G. (2022). Predictive energy-efficient driving strategy design of connected electric vehicle among multiple signalized intersections, Transportation Research Part C: Emerging Technologies, 137, 103595.

Du, R., Chen, S., Dong, J., Chen, T., Fu, X., & Labi, S. (2023). Dynamic urban traffic rerouting with fog-cloud reinforcement learning, Computer-Aided Civil and Infrastructure Engineering, 39(6), 793-813.

FCC. (2020). Use of the 5.850–5.925 GHz band: First report and order, further notice of proposed rulemaking, and order of proposed modification (FCC 20-164).
Supports the regulatory transition from DSRC to C-V2X.
https://docs.fcc.gov/public/attachments/DOC-367827A1.pdf

FCC. (2024). Second report and order (FCC 24-123). Confirms continued transition from DSRC to C-V2X and codifies C-V2X technical parameters.
https://docs.fcc.gov/public/attachments/FCC-24-123A1.pdf

Feng, Y., Huang, S., Wong, W., Chen, Q., Mao, Z., Liu, H. (2022). On the cybersecurity of traffic signal control system with connected vehicles, IEEE Transactions on Intelligent Transportation Systems, 23(9), 16267.

FHWA (2015). Traffic signal timing manual (2nd ed.). U.S. Department of Transportation.
https://ops.fhwa.dot.gov/publications/fhwahop15016/

FHWA (2016). Automated traffic signal performance measures (ATSPMs) EDC-4 Factsheet, https://ops.fhwa.dot.gov/arterial_mgmt/pdfs/EDC-4-Factsheet_ATSPMs.pdf

Federal Highway Administration. (2020). Automated traffic signal performance measures (FHWA-HOP-20-002). U.S. Department of Transportation.
https://ops.fhwa.dot.gov/publications/fhwahop20002/fhwahop20002.pdf

Federal Highway Administration. (2024, February 5). Arterial management program. U.S. Department of Transportation.
https://ops.fhwa.dot.gov/tsmoframeworktool/resources/tss_cmf_res/index.htm

Gerrand, A. (2010). The Go programming language. Google Inc. https://go.dev

Gettman, D. (2020). DSRC and C-V2X: Similarities, differences, and the future of connected vehicles, https://www.kimley-horn.com/news-insights/perspectives/dsrc-cv2x-comparison-future-connected-vehicles/

Gowda, M.K., Fehr, W., Balmos, A., Ajagu, R., Krogmeier, J., Abbas, M., & Labi, S. (2023). Economical acquisition of intersection data to facilitate CAV operations, CCAT Report # 71 , Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN.

Gowda, M.K., Fehr, W., Balmos, A., Ajagu, R., Hong, D., Krogmeier, J., Abbas, M., & Labi, S. (2024). Economical acquisition of intersection data to facilitate CAV operations—Phase II, CCAT Report # 86 , Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN.

Ha, Y.J., Filipovska, M., Chen, S., & Labi, S. (2025). Autonomous vehicle fleet operations with constrained entropy-based dynamic autonomous vehicle routing: Insights for environmentally conscious shared mobility. Multimodal Transportation, 100236

INRIX (2025). Access systemwide traffic signal insights without investing in equipment, INRIX Signal Analytics, https://inrix.com/products/signal-analytics/

International Organization for Standardization. (2015). ISO/IEC/IEEE 15288: Systems and software engineering - System life cycle processes. ISO.

Kazemzadehazad, S., Askari, S., Miralinaghi, M., Talebpour, A., & Mohammadian, A. (2026). Enhancing transit signal priority implementation through a multi-perspective analysis. Urban Science, Accepted for Publication.

Klausner, S. (2011). Response thread to: Why did visual programming never take off and what future paradigms might change that? https://softwareengineering.stackexchange.com/questions/119463/why-did-visual-programming-never-take-off-and-what-future-paradigms-might-change

Leonard, B. (2018). Strong signal – Utah breaks new ground with connected vehicles, Roads and Bridges, www.roadsbridges.com/intelligent-transportation-systems-its/v2i/article/10650781/strong-signal

Levin, M. W., Sun, Z., Wang, S., Sun, W., He, S., Suh., B., Zhao, G., Margolis, J. Zamanpour, M. (2023). Cost/benefit analysis of fuel-efficient speed control using signal phasing and timing (SPaT) data: evaluation for future connected corridor deployment, Tech. Rep. MN 2023-06, prepared for the Minnesota Department of Transportation, Minneapolis, MN.

Li, Z., Staley, S., Moore, A. (2021). Megacity mobility: Integrated urban transportation development and management, CRC Press, Taylor & Francis, Boca Raton, FL.

Liu, H., Kurzhanskiy, A. A., Hong, W., & Lu, X. Y. (2025). Integrating vehicle trajectory planning and arterial traffic management to facilitate eco-approach and departure deployment. Journal of Intelligent Transportation Systems, 29(6), 612–625. https://doi.org/10.1080/15472450.2024.2369988.

Markets and Markets (2025). Intelligent transportation system market size, share & trends, Markets and Markets, https://www.marketsandmarkets.com/Market-Reports/intelligent-transport-systems-its-market-764.html

Mezhuyev, V., Li, Z. (2025). Second International Conference on Intelligent Transportation and Smart Cities (ICITSC 2025), Proceedings, SPIE Vol. 13682, 1368201

Moyer, B. (2015). Redefining how software is created: cubicon sees the iot as an opportunity for a restart, Journal of Electronic Engineering, https://www.eejournal.com/article/20150601-cubicon/

National Academies of Sciences, Engineering, and Medicine. 2015. Signal timing manual – 2nd. Ed., Washington, DC: The National Academies Press.

National Academies of Sciences, Engineering, and Medicine. (2019). Cybersecurity of intelligent transportation systems: Summary of a workshop. The National Academies Press. https://doi.org/10.17226/25562

National Operations Center of Excellence and ITE (2019). 2019 Traffic signal benchmarking and state of the practice report, National Operations Center of Excellence and ITE, Washington, DC.

Petit, J., & Shladover, S. E. (2015). Potential cyberattacks on automated vehicles. IEEE Transactions on Intelligent Transportation Systems, 16(2), 546–556. https://doi.org/10.1109/TITS.2014.2342271

Postel, J. (1980). User Datagram Protocol (RFC 768). IETF.

Postel, J. (1981). Transmission Control Protocol (RFC 793). IETF.

Proakis, J. G., & Salehi, M. (2008). Digital communications (5th ed.). McGraw-Hill.

Roshandeh, A.M., Levinson, H.S., Li, Z., Patel, H., Zhou, B. (2014). New methodology for intersection signal timing optimization to simultaneously minimize vehicle and pedestrian delays Journal of Transportation Engineering 140 (5), 04014009

SAE International (2016). Dedicated short-range communications (DSRC) message set dictionary (J2735_201603). SAE International. https://doi.org/10.4271/J2735_201603

Salomon, D. (2007). Data compression: The complete reference (4th ed.). Springer.

Sayer, J., Flannagan, C.A.C., and Leslie, A.J. (2018). The cost in fatalities, injuries and crashes associated with waiting to deploy vehicle-to-vehicle communication, Transportation Research Institute, Ann Arbor, MI. https://deepblue.lib.umich.edu/bitstream/handle/2027.42/147434/The%20Cost%20Ass…

Stouffer, K., Falco, J., & Scarfone, K. (2015). Guide to industrial control systems (ICS) security (NIST Special Publication 800-82, Rev. 2). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.SP.800-82r2

Stouffer, K., Lightman, S., Pillitteri, V., Abrams, M., & Hahn, A. (2023). Guide to operational technology (OT) security (NIST Special Publication 800-82 Rev. 3). National Institute of Standards and Technology. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.800-82r3.pdf

Tailscale Inc. (2023). Tailscale secure networking. https://tailscale.com

Tanenbaum, A. S., & Wetherall, D. J. (2011). Computer networks (5th ed.). Pearson.

The World Bank Group (2024). Promoting livable cities by investing in urban mobility, The World Bank Group, Washington, DC. www.worldbank.org/en/results/2024/03/13/promoting-livable-cities-by-investing-in-urban-mobility

USDOT (2013). Eco-approach and departure at signalized intersections: Field study and modeling presentation, AERIS March 2013 Workshop, March 2013. http://www.its.dot.gov/aeris/workshop_presentations.htm.

USDOT (2014). Eco-signal operations concept of operations. Available at:http://www.its.dot.gov/aeris/aeris_plan.htm.

USDOT. (2017). Research, development, and technology strategic plan.
Supports Eco-Approach and Departure framing.
https://www.transportation.gov/sites/dot.gov/files/docs/USDOT-RD%26T-Strategic-Plan-Final-011117.pdf

U.S. Department of Transportation. (n.d.). Signal Phase and Timing (SPaT). ITS Knowledge Resources. Useful for SPaT applications and benefits summary.
https://www.transportation.gov/sites/dot.gov/files/docs/USDOT-RD%26T-Strategic-Plan-Final-011117.pdf

USDOT (2020). Cybersecurity considerations for connected and automated vehicle systems. Intelligent Transportation Systems Joint Program Office. https://www.its.dot.gov

USDOT (2023). ARC-IT: Architecture reference for cooperative and intelligent transportation (SPaT information flow). Intelligent Transportation Systems Joint Program Office. https://www.arc-it.net

USDOT (2025). Signal phase and timing (SPaT), www.itskrs.its.dot.gov/sites/default/files/doc/07_SPaT%20Challenge_FINAL%20508%20VERSION_06_23_21.pdf

Valentine, D., Zimmer, R., Sheehan, R. (2014). Transit safety retrofit package (TRP): Leveraging DSRC for transit safety – Fielding results and lessons learned, Final Report, FHWA-JPO-14-142, FHWA, USDOT, Washington, DC. www.its.dot.gov/safety/pdf/trp_august2014.pdf

Wágner, T., Ormándi, T., Tettamanti, T., Varga, M. I. (2023). SPaT/MAP V2X communication between traffic light and vehicles and a realization with digital twin, Computers and Electrical Engineering 106, 108560

Wang, X., Jerome, Z., Wang, Z. et al. Traffic light optimization with low penetration rate vehicle trajectory data. Nat Commun 15, 1306 (2024). https://doi.org/10.1038/s41467-024-45427-4

Yang, H. F., Ling, Y., Kopca, C., Ricord, S., & Wang, Y. (2022). Cooperative traffic signal assistance system for non-motorized users and disabilities empowered by computer vision and edge artificial intelligence. Transportation Research Part C: Emerging Technologies, 145, 103896.

Zhao, X., Wan, C., Sun, H., Xie, D., and Gao, Z. (2017). Dynamic rerouting behavior and its impact on dynamic traffic patterns, IEEE Transactions on Intelligent Transportation Systems, 18(10), 2763-2779, doi: 10.1109/TITS.2017.2655550

Zimmer, R. E., Burt, M., Zink, G. J., Valentine, D. A., Knox, W. J. Jr. (2014). Transit safety retrofit package development: Final report, FHWA-JPO-14-118, by Battelle Memorial Institute, for the US Department of Transportation, Washington, DC.

APPENDIX

APPENDIX 1: List of resources and weblinks

A.1 NTCIP Object Definitions for Actuated Traffic Signal
Controller (ASC) Units - version 02
https://tinyurl.com/54hx86pe

Appendix 2: Sample Marketing Material – Product Brief Excerpt

(Below is an excerpt from a one-page product brochure intended for city traffic engineers and decision-makers.).

Meet LUCID, the Low-Cost Unidirectional Connected Intersection Data device!

Bringing Smart Traffic Management to Your Intersections

- **What It Is:** A compact IoT device that installs in your traffic signal cabinet to record every change of your traffic lights. Paired with a cloud-based analytics platform, it provides a continuous X-ray of your intersection performance.
- **What It Does:** Measures real-world data like how long cars wait at red lights, how often each approach maxes out its green time, and even when pedestrians aren't fully served. Translates this into easy-to-read charts and dashboards.
- **How You Benefit:** No more guessing if your signal needs retiming – you'll know! Cities using this product have cut unnecessary delay by 20–40% and reduced citizen complaints about "that long red light" on Main Street. Did you know poorly timed signals contribute to 10% of all traffic delay? By catching issues early, you can prevent major congestion problems and improve intersection safety by 10%.
- **Easy to Deploy:** Installs in under an hour with no disruption to traffic. You don't need to overhaul your entire system or buy expensive adaptive signals. It is like adding a "traffic engineer's assistant" at each intersection 24/7.
- **Proven Results:** *(Owosso, City X, City Y, etc.)* – In City X, our pilot on 3 intersections identified three signals running inefficiently and helped engineers trim average peak hour delays by 18%. City W is now expanding the system citywide after a successful 2-month trial. *(See full case studies on our website.)*
- **Cost-Effective:** Available for a low annual subscription that fits into a typical operations budget. It **pays for itself** by deferring the need for costly studies and improving travel time (saving drivers' time and fuel – a win for the economy, environment, and society!).

For more information or to schedule a live demo, contact us at xxx@data-diode.com or visit our website.
