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Measuring Border Wait Time at Land Ports of Entry: Technology Assessment and Data Dissemination

Project Report

Released May 2021

The Borders, Trade, and Immigration Institute

A Department of Homeland Security Center of Excellence
Led by the University of Houston

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Measuring Border Wait Time at Land Ports of Entry: Technology Assessment and Data Dissemination

Final Report

Prepared by

Texas A&M Transportation Institute

Prepared for

BTI Institute

Borders • Trade • Immigration

A Department of Homeland Security Center of Excellence

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1. Project Background

1.1 Introduction

Over 5 million vehicles drive across the U.S.–Mexico border every year. Border wait times at land ports of entry are an important measurement of port performance, trade, and regional competitiveness. U.S. Customs and Border Protection (CBP) requires border wait time information to manage border-crossing operations and inform the users on the operation characteristics of every border crossing.

Systematic, consistent, and accurate border wait time information is a priority for CBP since without a system to measure this information using technology, officers would need to perform the estimation and enter data into the system manually. CBP along with federal and state agencies such as the Federal Highway Administration and the Texas, New Mexico, and Arizona departments of transportation funded the development and implementation of a commercial vehicle (CV) border wait and crossing time measuring system that uses radio frequency identification (RFID) technology.

Developed by the Texas A&M Transportation Institute (TTI), the system typically includes four RFID reader stations in the truck path from Mexico into the United States. A truck entering the United States passes under two or more RFID reader stations at the border crossing, and the RFID reader station detects the truck's tag identification number and makes a time stamp of the record. Some examples of truck tags include toll tags, CBP's annual fee tag, and a recent Decal and Transponder Online Procurement System (DTOPS) provided by CBP. The tag IDs and time stamps are transmitted to the central server via communication links for further processing and archiving. The RFID truck border crossing and wait time measurement system estimates times for regular trucks and Free and Secure Trade (FAST) times at the crossings with a FAST lane. The typical setup includes four reading stations:

- In Mexico at the end of the queue heading into the Mexican Customs facility (R1)
- At the exit of the Mexican Customs facility before the truck crossed the border (R2)
- At the CBP primary inspection facility (R3)
- At the vehicle state inspection facility (R4)

Figure 1 depicts the location of the readers in a typical configuration. The travel time between R2 and R3 is the CBP wait time, the time between R1 and R3 is the wait time, and the travel time between R1 and R4 is the crossing time.

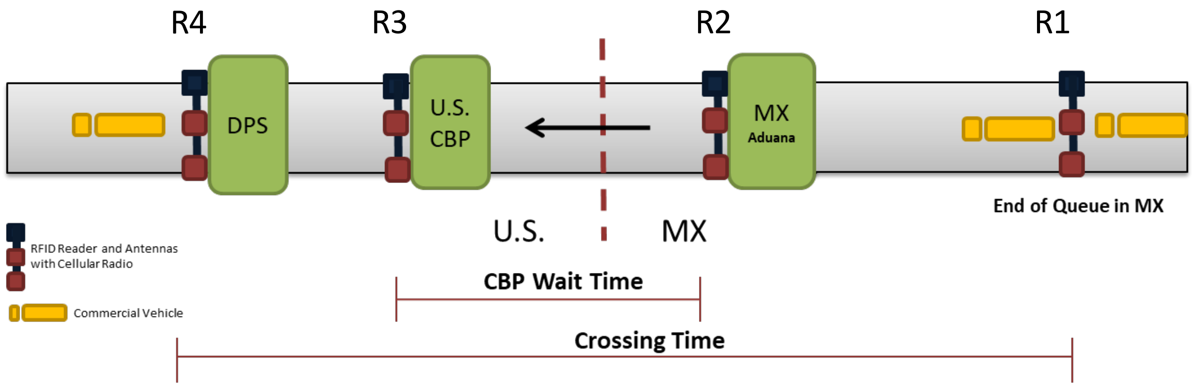

Figure 1. The Typical Configuration of a CV Border-Crossing Measuring System.

TTI also measures privately owned vehicle (POV) wait times with a similar system that was implemented at three border crossings in El Paso, Texas. The system is based on Bluetooth®/Wi-Fi technology and cannot differentiate between regular, Ready, or Secure Electronic Network for Travelers Rapid Inspection (SENTRI) vehicles crossing the border from Mexico into the United States.

The main goals of this research project were to improve the current RFID and Bluetooth/Wi-Fi border crossing and wait time measuring system, and to analyze emerging technologies to strengthen the system capabilities to provide accurate border crossing times for CVs and POVs.

A TTI research team conducted the project and worked closely with CBP's field operations office in Washington, D.C.; Santa Teresa, New Mexico; Nogales, Arizona; and Otay Mesa (San Diego), California.

1.2 Project Objectives

The project had five specific objectives:

1. Analyze the current system's operation and maintenance practices
2. Finalize the installation of RFID equipment at the Otay Mesa border crossings
3. Identify needed improvements to the POV border wait time measurement
4. Research emerging technologies for dynamic vehicle wait time reporting
5. Overhaul the current border wait time measurement system software to a cloud-based environment

Each objective included specific goals:

- **Objective 1:** The goals were to operate and maintain the existing CV border crossing time measurement system at Santa Teresa and Nogales, pay communication fees that are used to transmit information collected in the field to the server, perform regular software or firmware upgrades to the system, and solve any issues caused by hardware failures or software glitches.

- **Objective 2:** The RFID-based border wait time measurement system at the Otay Mesa border crossing was incomplete at the project's inception. The main goal was to work with Mexican Customs (Aduana); the local authorities in Tijuana, Mexico; and the California Highway Patrol (CHP) to secure permits and authorizations to install RFID equipment at their premises. This goal also included configuring and testing the system before installation, field testing, and verifying the information collected after installation, and modifying the software to update the Border Crossing Information System (BCIS) and the feed data for CBP and other stakeholders.

- **Objective 3:** The Bluetooth technology that is currently used to measure POV border wait time does not allow differentiating travel times among the three type of travelers (SENTRI, Ready, and regular). The goal was to investigate Bluetooth and other technologies such as automatic license plate readers (ALPRs) or cameras to disaggregate travel times by lane type at POV border crossings.

- **Objective 4:** The goal was to study the viability of integrating vehicle global positioning system (GPS) tracking and Blockchain technologies to report CV wait times from Mexico into the United States dynamically.

- **Objective 5:** The BCIS software was developed more than 10 years ago. The goal under this objective was to upgrade the system to be responsive in handling additional ports of entry and user queries and updated to recent web standards.

1.3 Organization of the Report

The TTI research team presented individual reports for Objectives 2 through 5. These reports are attached as separate documents. The following section describes the project achievements and results for each of the five objectives.

2. Project Results

2.1 Objective 1: Analyze the Current System's Operation and Maintenance Practices

The TTI research team worked with CBP field offices to identify ways that the border wait and crossing time information could be transmitted in a more efficient way that tailors the information to CBP's needs. Because of the travel restrictions implemented due to COVID-19, the research team developed a network of local maintenance providers in Mexico, New Mexico, Arizona, and California to perform routine maintenance remotely. When travel was allowed, TTI researchers traveled to Nogales to perform routine maintenance and exchange a malfunctioning RFID reader at the port of entry. The solar sites at Nogales were upgraded with new rechargeable batteries. The research team worked with Aduana administration to secure the authorizations and permits to reconnect the system on the Mexican side of the border in Santa Teresa and perform regular maintenance and troubleshooting on the U.S. side of the border.

In addition, the research team conducted software and firmware upgrades to the system and reported the hardware failures. Every month, the research team analyzed the data and prepared a summary report for each crossing. The reports included the following metrics:

- The crossing time distribution for the month
- The crossing time by day of the week during the month
- The crossing time by hour during the month
- A comparison of crossing times of the month compared to the previous month
- A graph displaying the 95th percentile (crossing time of 95 percent of trucks) of truck crossings

The monthly reports were uploaded to the BCIS website[1]. Figure 2 presents a sample report.

[1] BCIS Monthly Border Crossing Profile Reports, https://bcis.tti.tamu.edu/Commercial/en-US/projectReports.aspx

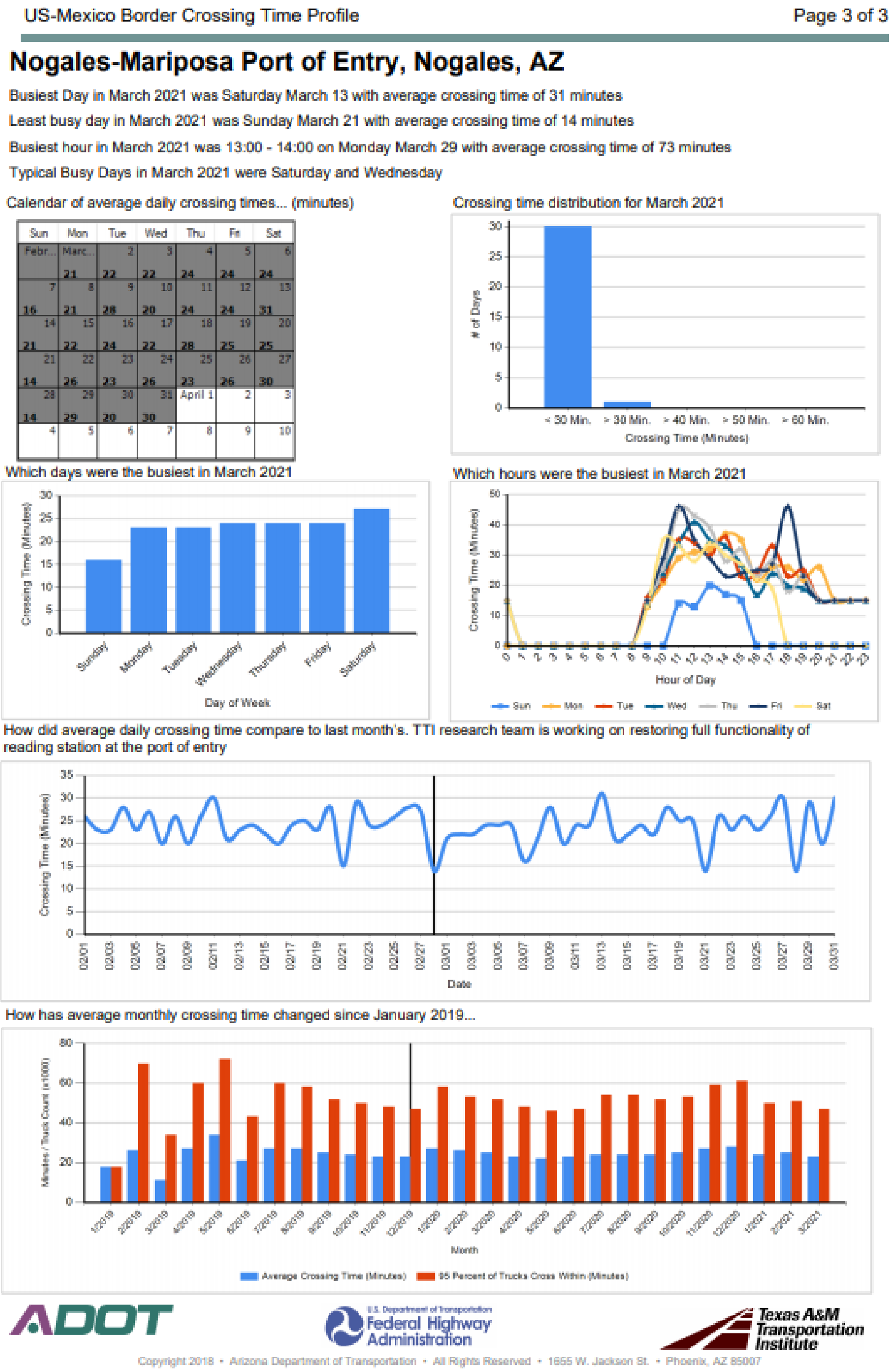

Figure 2. A BCIS Monthly Report for the Nogales–Mariposa Port of Entry.

The research team developed a monthly status report for each of the border crossings. The monthly status reports provided vital information regarding the status of each of the border crossings. Each of the four main subsystems were measured, and any anomalies were reported. The border wait time field subsystems were:

- Field devices
- Data collection
- Information dissemination
- CBP interface

Outages in any of the subsystems were logged with detailed information on corrective actions. Figure 3 presents a sample of the *System Reliability Report*.

Measuring Border Wait time at Land Ports of Entry:
Technology Assessment and Data Dissemination

Texas A&M Transportation Institute

System Reliability Report

Santa Teresa Port of Entry, Santa Teresa, NM

	Field Devices Subsystem	Data Collection Subsystem	Information Dissemination Subsystem	CBP Interface
February 2021				

No Outages
Partial Outage
Complete Outage

Outage details

February 2021

Outage 1

Outage ID: BCIS012020001z

Start	*Resolved*
01/21/2020 7:30 am CST	02/05/2021 1:32 pm CST

Details

BCIS reading station located at the Santa Teresa tollbooth in Mexico is going under renovations and the power has been cutoff.

Corrective actions

Local contractor performed a site visit on 02/04/2021 and reconnected the reading station to the main grid on 02/05/2021. TTI will continue to monitor the state of the system and make changes accordingly.

Subsystems affected.

Field Devices Subsystems

Figure 3. A *System Reliability Report* for Santa Teresa.

As of April 30, 2021, the systems at Santa Teresa, Nogales, and Otay Mesa are functional and collecting data.

2.2. Objective 2: Finalize the Installation of RFID Equipment at the Otay Mesa Border Crossings

The research team worked with Aduana, the local municipal authorities in Tijuana, CHP, and CBP to secure permits and authorizations to install and/or maintain RFID equipment at their premises. The research team configured and tested each of the reading stations at the TTI headquarters building and shipped the reading stations to San Diego to coordinate the installation remotely and on-site once the travel restrictions were lifted. The equipment installations and testing were conducted at the San Diego CHP vehicle safety inspection facility exit and at the end of the queue/Aduana export lot, respectively.

Once the first set of readers was installed in Tijuana at the end of the queue or R1, the TTI research team identified an issue that was not contemplated in the original work plan. The tag penetration test revealed a relatively low number of tag reads compared to the actual truck volume using this border crossing (30 percent). After more detailed testing, the TTI team identified that most of the CVs at the Otay Mesa border crossing had a relatively new tag that CBP distributed identified as the Decal and Transponder Online Procurement System(DTOPS) and the DTOPS tag was not read-compatible with the RFID readers that were installed. TTI contacted TransCore, the RFID reader manufacturer, and negotiated a reader upgrade to read multiple tag protocols. The research team coordinated with CBP, CHP, and Aduana to replace the RFID readers at R1, R3 (CBP Primary), and R4 through local contractors.

After long negotiations with Aduana, the research team managed to secure the necessary upgraded equipment and authorizations from local stakeholders in Mexico to perform the installation at the Aduana export lot and the side entrance from Calle Sor Juana Inés de la Cruz (shown in Figure 4). This installation was finalized in April 2021. A new tag penetration test analysis revealed great improvement in the sample rate and better travel time estimations for the entire segment along the port of entry.

Figure 4. Unified Cargo Processing Access into Aduana Export Lot at Otay Mesa Port of Entry.

The border crossing has been updated and added to the BCIS. The feed data are being sent to CBP and other stakeholders. The research team tested the new RFID readers and proved that the readers can read the DTOPS tags as well as the legacy tags. The research team prepared several unique documents: the *Otay Mesa Commercial Border Wait Time Installation Report* and the *Otay Mesa Commercial Border Wait Time Penetration Test Report*.

2.3. Objective 3: Identify Needed Improvements to the POV Border Wait Time Measurement

Bluetooth® technology is currently used to measure POV border wait time at land border crossings. This technology does not allow differentiating travel times among the three types of POV travelers that cross the border from Mexico into the United States:

- Secure Electronic Network for Travelers Rapid Inspection (SENTRI)
- Ready
- Regular

The main objective of this task was to investigate technologies that could be used to disaggregate travel times by lane type at POV border crossings. The research team analyzed emerging technologies to disaggregate travel times by lane type at the POV border crossings. A systematic review method was used to gather the available literature, analyze the technologies used, and compare the literature and technologies to identify the advantages and disadvantages of each technology. The research team examined more than 100 references on vehicle detection; identified many different variables, technologies, and crucial data; and created a table to organize the literature reviewed. Three searches were performed through the Transport Research International Documentation, the Institute of Electrical and Electronic Engineers, and Google Scholar regarding vehicle detection technologies, vehicle travel time estimation, and automated tolling from the last five years.

The literature review objectives were to:

- Identify the technologies and processes that could be used to measure vehicle detection, travel time estimation, and tolling systems
- Analyze each technology's applicability for the border-crossing environment
- Compare the technologies with one another to identify the advantages and disadvantages when applying the technologies in the POV border-crossing environment

The technology assessment results identified that by combining ALPRs, GPS and Bluetooth technologies, a system could be developed to detect vehicles at multiple points during the border crossing trip and re-identify at each lane of travel to estimate travel times by lane type (SENTRI, Ready and regular).

With these findings, the research team designed a prototype based on the current Bluetooth-based POV wait time measuring system, adding added GPS and ALPR data as shown in Figure 5.

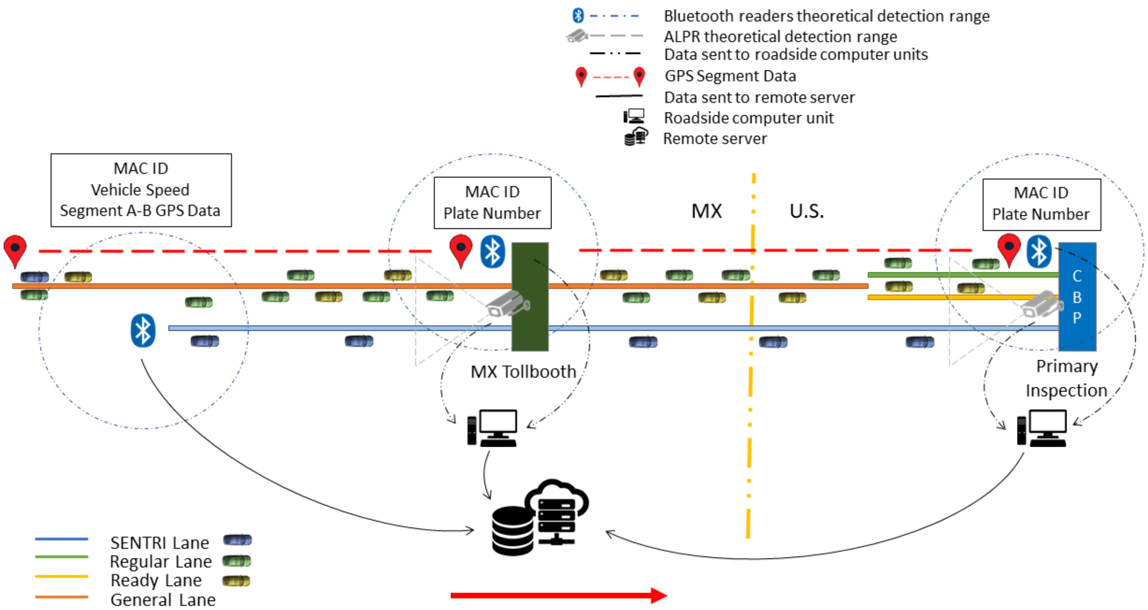

Figure 5. POV Lane Detection Prototype Design and Dataflow.

ALPRs were tested at The Texas A&M University System's RELLIS Campus to determine if the technology was feasible for lane detection and vehicle identification. The team performed several tests in a controlled environment and concluded that ALPRs are capable of re-identifying vehicles in a border-like scenario using the proper calibration, a custom setup, and a data-matching algorithm to process and store enough data to calculate travel times by the user type or lane used.

The research team prepared the report, *Identify Improvements to POV Border Wait Time Measurement*, that discusses the test results, recommendations, and proposed next steps to perform a test at a land port of entry.

2.4 Objective 4: Research Emerging Technologies for Dynamic Vehicle Wait Time Reporting

The research team studied the viability of integrating vehicle GPS tracking to report CV wait times from Mexico into the United States dynamically. The research team reviewed previous experiences using GPS to measure travel times at the border and roadways in the United States and Mexico. The research team also gathered and analyzed crowdsourced data from different data sources to identify data quality to measure travel times. GPS data suppliers that were considered include HERE, Google, and INRIX among others. The selected suppliers were HERE and Google since the data provided by the two companies were more abundant in the border environment compared to the others. The data from each of the providers were carefully analyzed to identify the data volume and reliability and determine whether the data were in real time. In conjunction with the Objective 3 findings, the research team designed a new Hybrid Border Wait Time Measuring System (HBWTMS).

The HBWTMS was designed to use different technologies to improve the system's reliability while decreasing the cost of installation, maintenance, and operation. The concept of the hybrid system includes analyzing vehicle travel time from the moment the vehicle enters the queue to cross the border to the moment the vehicle arrives at a CBP Primary inspection booth. The hybrid system uses primary information obtained from the infrastructure installed along the border and the secondary information from GPS information obtained from a third party such as Google and HERE. The hybrid system leverages information obtained from third-party GPS sources such as Google and HERE to measure the first segment of a vehicle's trip. The second segment of travel is measured by the current RFID infrastructure. Using RFID technology allows for differentiating between vehicles traveling in the FAST and regular lanes. The third segment (R3–R4) is measured primarily by RFID. GPS technologies are used at this segment to complement the RFID measurements and fill in any data gaps that may occur from RFID failures or mismeasurements. (Figure 6).

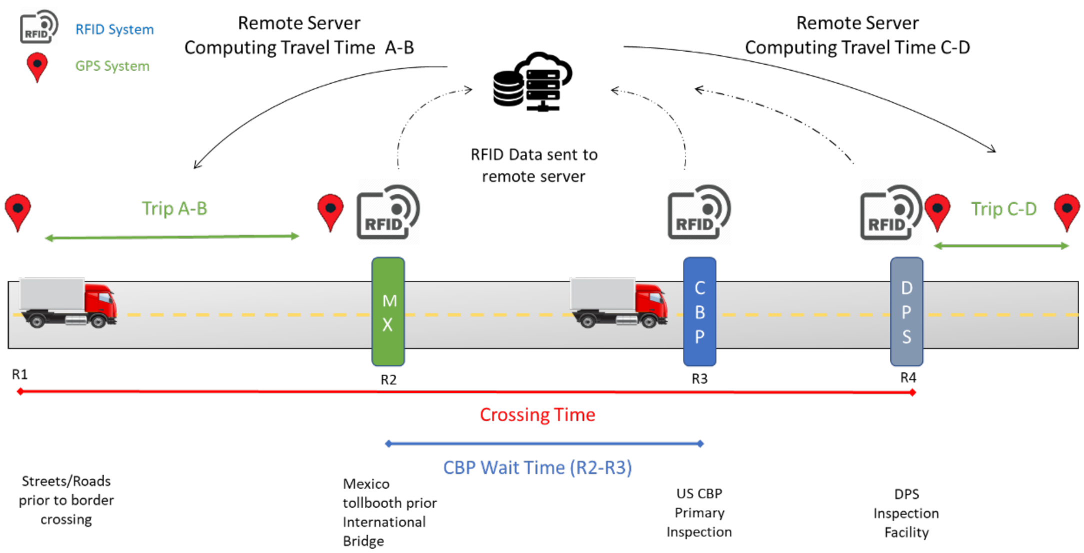

Figure 6. The CV HBWTMS.

The HBWTMS possesses the potential to enhance POV border wait time measurement by providing wait time estimates by vehicle type (SENTRI, Ready, or regular). Other benefits of the proposed POV hybrid system are:

- The system will increase reliability and uptime by obtaining data from a structureless source. Using GPS information to estimate wait times greatly reduces the need for fixed stations outside of the Mexican and U.S. toll booths where scarce power sources are available and the reading stations are prone to vandalism, accidents, and malfunctions.
- Future installations can be designed with only two sets of reading stations, resulting in planning, installation, maintenance, and operation cost savings.
- CBP already has ALPRs at the primary inspection booths. If that information is made available to the HBWTMS, only one additional set of ALPR reading stations is needed to estimate the wait times by the lane of travel.
- Using structureless sources and physical reading stations means reduced or no maintenance/operation costs.

- Combining technologies provides enough data for the system algorithm to fuse the datasets to estimate a more accurate wait time for the POV border crossings while also considering the lane of travel.

The HBWTMS has the potential of being used to measure both, CV and POV border crossing and wait times, offering the same benefits that are described above. The only difference is that the POV wait time estimations use Bluetooth technology as the primary source of information, while CV border wait time estimation uses RFID technology.

The research team prepared and submitted a research paper describing the proposed HBWTMS at the 2020 Transportation Research Board Annual Meeting. The findings of this task were presented at the 2021 Port of the Future Conference. The paper is attached to this report and titled *Integrating Multiple Technologies to Estimate Border Wait Time for Privately Owned Vehicles*.

2.5 Objective 5: Overhaul the Current Border Wait Time Measurement System Software to a Cloud-Based Environment

The research team successfully overhauled and redesigned the BCIS software to a cloud-based environment in the Microsoft® Azure platform. The upgrade focused on six main factors:

1. **Uptime**—The new system provides high uptime, which would ensure uninterrupted data for the stakeholders with minimal data gaps.
2. **Security and Privacy**—The system should be as secure as possible; at the same time, the system should maintain the privacy of the data users whose data were collected.
3. **Portability**—The system should be sufficiently portable to enable other entities to host the system with minimal effort.
4. **Storage Space**—The system should require minimal storage space requirements so that the hosting cost could be kept under control in the long term.
5. **Maintenance**—The system should have minimum maintenance requirements. Fewer maintenance requirements would minimize the maintenance window, which would result in high uptime and reduced maintenance cost.
6. **Graphical User Interface**—The system user interface was upgraded to recent web standards.

The new BCIS system was successfully implemented in a cloud-based environment on the Microsoft Azure platform. The data generated by the system were compared against the existing on-premises system and found to be consistent with the existing system.

In addition, the upgrade focused on increasing the response time in handling additional ports of entry and user queries. The system architecture was revamped to handle additional workload in the future. Once again, the data generated by the system were compared against the existing on-premises system and found to be consistent with the existing system.

Due to the necessity of user datagram protocol communication between roadside equipment and the virtual machine, the researchers were unable to develop a completely serverless solution. Further research is needed to explore the use of other communication protocols, which could enable a complete serverless solution.

Figure 7 provides a dataflow diagram for the entire system; a complete description of each component of the diagram can be found in the *Border Crossing Information System Overhaul Report*.

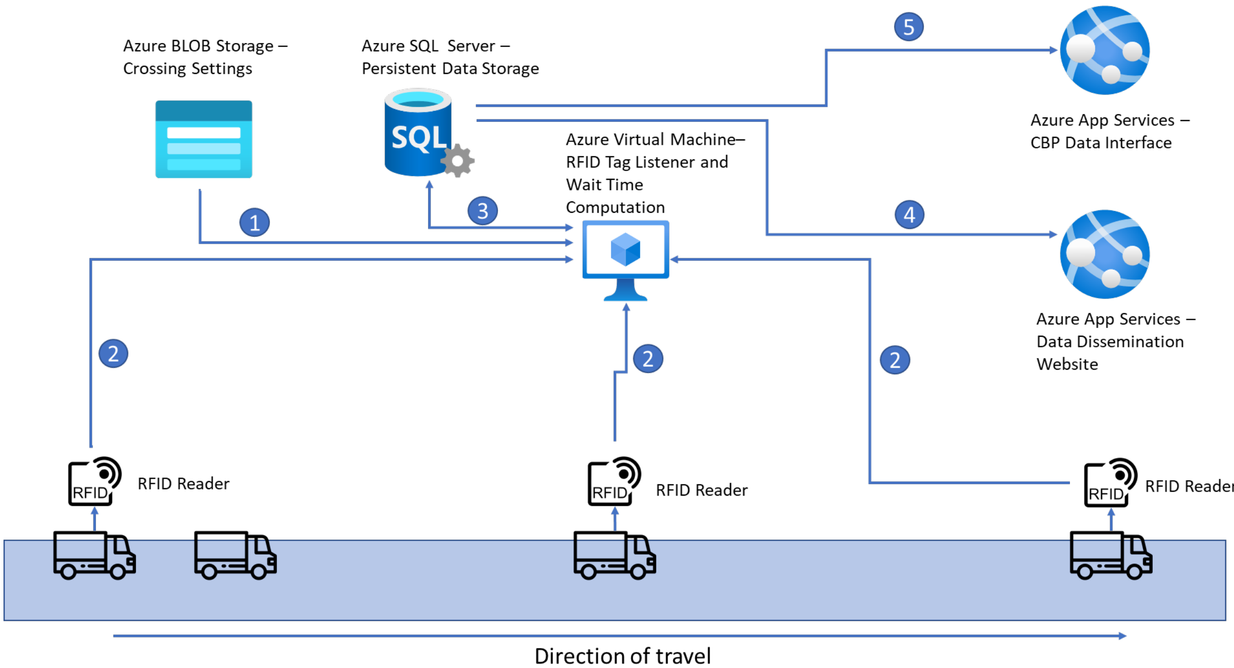

Figure 7. The BCIS System Overhaul Dataflow.

Measuring Border Wait Time At Land Ports Of Entry: Technology Assessment And Data Dissemination

Otay Mesa Commercial Border Wait Time Penetration Test Report

Prepared by

Texas A&M Transportation Institute

Prepared for

BTI Institute

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List of Abbreviations

BTI	Borders, Trade, and Immigration Institute
BWTMS	Border Wait Time Measuring System
CBP	U.S. Customs and Border Protection
CHP	California Highway Patrol
CV	Commercial Vehicle
DTOPS	Decal and Transponder Online Procurement System
FAST	Free and Secure Trade
IP	Internet Protocol
POE	Port of Entry
RFID	Radio Frequency Identification
RSS	RDF Site Summary or Really Simple Syndication
SAT	Servicio de Administración Tributaria (Mexican Customs)
TTI	Texas A&M Transportation Institute
UCP	Unified Cargo Processing
UDP	User Datagram Protocol
XML	Extensible Markup Language

Chapter 1:
Background and Overview

BACKGROUND

Funding for this project was provided by the Department of Homeland Security's Science and Technology Directorate and managed in collaboration with the Borders, Trade, and Immigration Institute (BTI). The project resulted in the expansion of radio frequency identification (RFID) equipment to measure border wait and crossing times of commercial vehicles (CV) traveling from Mexico into California at the Otay Mesa Port of Entry (POE). The system is based on RFID technology and typically includes four RFID reader stations in the truck path from Tijuana, Mexico into the United States.

The initial installation of RFID readers and antennas was proposed at four locations to be consistent with other similar implementations along the U.S.-Mexico border. However, during this phase of the project, only three stations have been deployed on this POE (R1, R3 and R4).

The proposed locations include:

- R1. At the furthest location where queue could be measured; at the Otay Mesa POE the location is at the intersection of Calle 12 Norte and Callejón de Exportación in México
- R2. Before crossing the border, located at the Mexican Customs (SAT) Export Inspection booths and the side entrance from Calle Sor Juana Inés de la Cruz.
- R3. At the U.S. Customs and Border Protection (CBP) Primary inspection booths
- R4. At the California Highway Patrol (CHP) vehicle safety inspection station.

This distribution of readers allows measurement of crossing and wait times. Figure 1 depicts the location of the readers. Travel time between R2 and R3 is the CBP Wait Time, while the time between R1 and R3 is Wait Time, and the travel time between R1 and R4 is the crossing time. It is expected to perform the installation of the system at SAT/Aduana export booths (R2) during the first quarter of 2021, permits are being processed by authorities in Mexico.

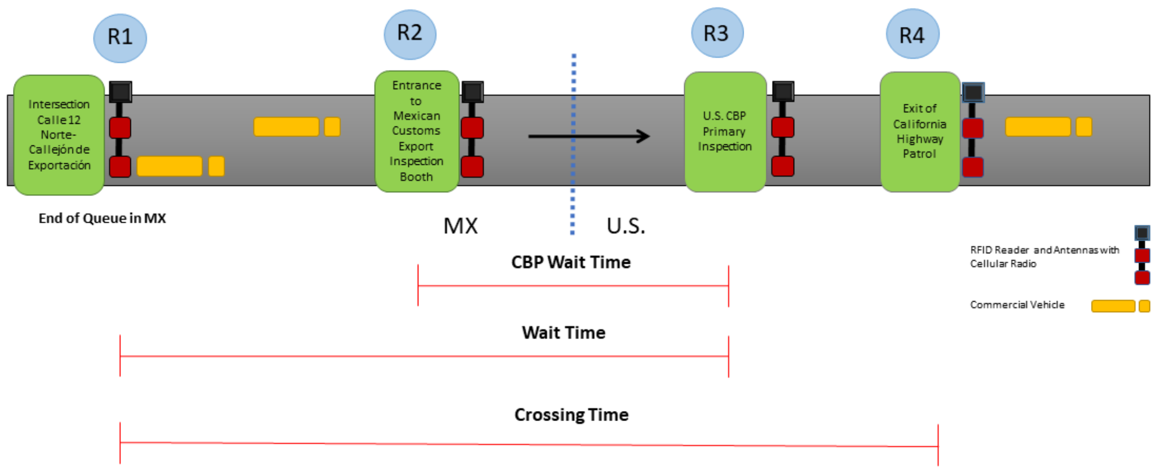


Figure 1. General RFID Reader Location Diagram

Wait and crossing time are defined as:

- Wait time is the time it takes for a vehicle to reach the CBP primary inspection booth after arriving at the end of the queue. This queue length is variable and depends on traffic volumes and processing times at each of the inspection facilities throughout the border crossing process.
- CBP Wait Time is similar as wait time, but the total time is measured from the entrance to Mexican customs export booth to the CBP primary inspection booth.
- Crossing time has the same beginning point in the flow as wait time, but its terminus is the departure point from the last inspection compound that a vehicle transits in the border crossing process. As a metric, wait time is of greater significance than crossing time to CBP operations, whereas crossing time is of relatively greater interest to carriers and shippers.

Chapter 2:
Data Collection and Analysis

This chapter highlights some of the key findings of the data collection and analysis portion of the project.

It is composed of a brief explanation on how the algorithm works, the analyses performed by the Texas A&M Transportation Institute (TTI) Research Team to identify patterns and trends on the wait times and trucks crossing through this POE

DATA COLLECTION AND WIRELESS TRANSMISSION

Each RFID station has an antenna located over each lane at the location. The antenna positioning is such that vehicles that have readable tags and pass under both reader stations should receive a tag match. The location of each reader was chosen to limit the number of antennas required for site coverage. The antenna connects with a traditional tolling-quality RFID tag reader that can reliably read the protocol of a variety of tags carried by trucks crossing the border. The tag reader continually scans for a passing tag. It is important for the tag to be correctly positioned and under the windshield's glass for best readability results. As a tag passes the reader's antenna, a unique code is recovered from the tag via an exchange of radio frequency energy. The code is converted into a digital message and forwarded to the RFID station's onsite data-logging component.

The tag read messages are routed out of the field site and toward a central server in near real-time. The communication setup at each station includes data transmission between the RFID station and the central server via cellular data.

Radio frequency identification readers send data to the fixed Internet Protocol (IP) address on a fixed User Datagram Protocol (UDP) port number using a cellular modem. The UDP listener on the central server monitors the UDP port for any incoming data packets. When the UDP listener detects any data packets on the incoming port, it reads the data packets, associates a timestamp with the data read, and invokes a stored procedure on the database. This stored procedure then inserts the data read into the raw data table. A trigger is fired whenever any new data are inserted into the raw data table. This trigger verifies whether the data are coming from a valid combination of reader ID and IP address. If a valid combination is detected, then the tag number (in human readable format) is extracted from encoded (non-human readable format), and the tag number and associated timestamp are inserted in the processed data table. If the combination is not valid, then the raw data and timestamp are inserted into the error data table. Figure 2 illustrates the entire data transmission and archiving process.

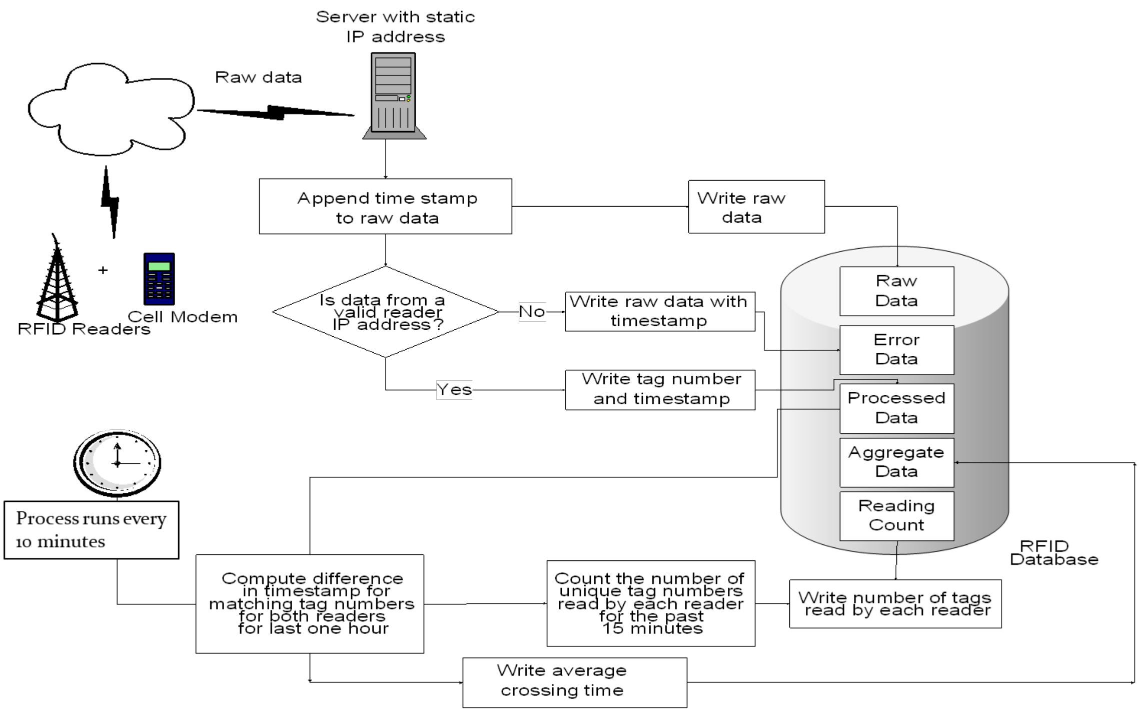


Figure 2. Data Communication and Archiving Process

AUTOMATED MEASUREMENT OF CURRENT TRUCK CROSSING TIMES

To calculate crossing times, an aggregation process that runs on the database server every 10 minutes was developed. The server, after receiving the raw tag identification data, calculates the average crossing times of trucks every 10 minutes using a 2-hour time window. The average travel times between the readers are determined using the following procedure:

- The average travel times are calculated every 10 minutes (e.g., 9:00 a.m., 9:10 a.m., and 9:20 a.m.).

- The procedure uses 250 minutes as the time window, meaning this value is used as a maximum travel time that could occur at any given segment and total crossing time. For example, to calculate the average travel time between R1 and R3 at 9:00 a.m., all the tags that were read between 7:00 a.m. and 9:00 a.m. are matched, and travel times of matched tags are averaged (simple mean).

The average truck crossing time determined by the abovementioned procedure is also used to update Extensible Markup Language (XML) data files, which are shared via the RDF Site Summary (RSS) process. Using RSS, external users can obtain the most recent truck crossing time via the Internet. The central database server maintained at TTI's office in College Station includes several database tables where raw and processed data are archived.

DAILY CAPTURE RATES

Currently, three reader stations are used to measure crossing time at Otay Mesa (Figure 3): R1 at the intersection of Calle 12 Norte and Callejón de Exportación in México, R3 at the entry of U.S. CBP primary inspection booths, and R4 at the exit of California Highway Patrol vehicle inspection station on the U.S. side.

Figure 3. RFID Locations at Otay Mesa POE

Table 1 shows the calculation of monthly capture rates for the Otay Mesa POE. The capture rate is the proportion of matched tags read by the system to the total volume of trucks, as reported by CBP.

Table 1. Daily Capture Rate Calculation At Otay Mesa

Date	Total Northbound Truck Volume (CBP)	R4 Transponder Sample Size	Capture Rate Based on R4 Sample Size
1	**2**	**3**	**(4) = (3) × 100/(2)**
Monday, October 26	3,776	1,302	34.48%
Tuesday, October 27	3,870	1,431	36.97%
Wednesday, October 28	3,848	1,331	34.58%
Thursday, October 29	3,211	1,064	33.13%
Friday, October 30	3,342	1,143	34.20%
Saturday, October 31	1627	647	39.76%
Sunday, November 1	878	235	26.76%
Monday, November 2	3,541	1,123	31.71%
Tuesday, November 3	3,802	1,305	34.32%
Wednesday, November 4	3,827	910	23.77%
Thursday, November 5	3,856	915	23.72%
Friday, November 6	3,580	890	24.86%
Saturday, November 7	1,443	387	26.81%
Sunday, November 8	840	139	16.54%

DATA ANALYSIS AND TRENDS

One key objective in analyzing the daily transponder count is to understand trends. Figure 4 shows transponder read information for the period of October 26 to November 1, 2020 for the Otay Mesa POE, these values include all transponders detected by reading station. Higher truck volumes are read at the beginning of the week. Saturdays and Sundays the POE operates reduced hours.

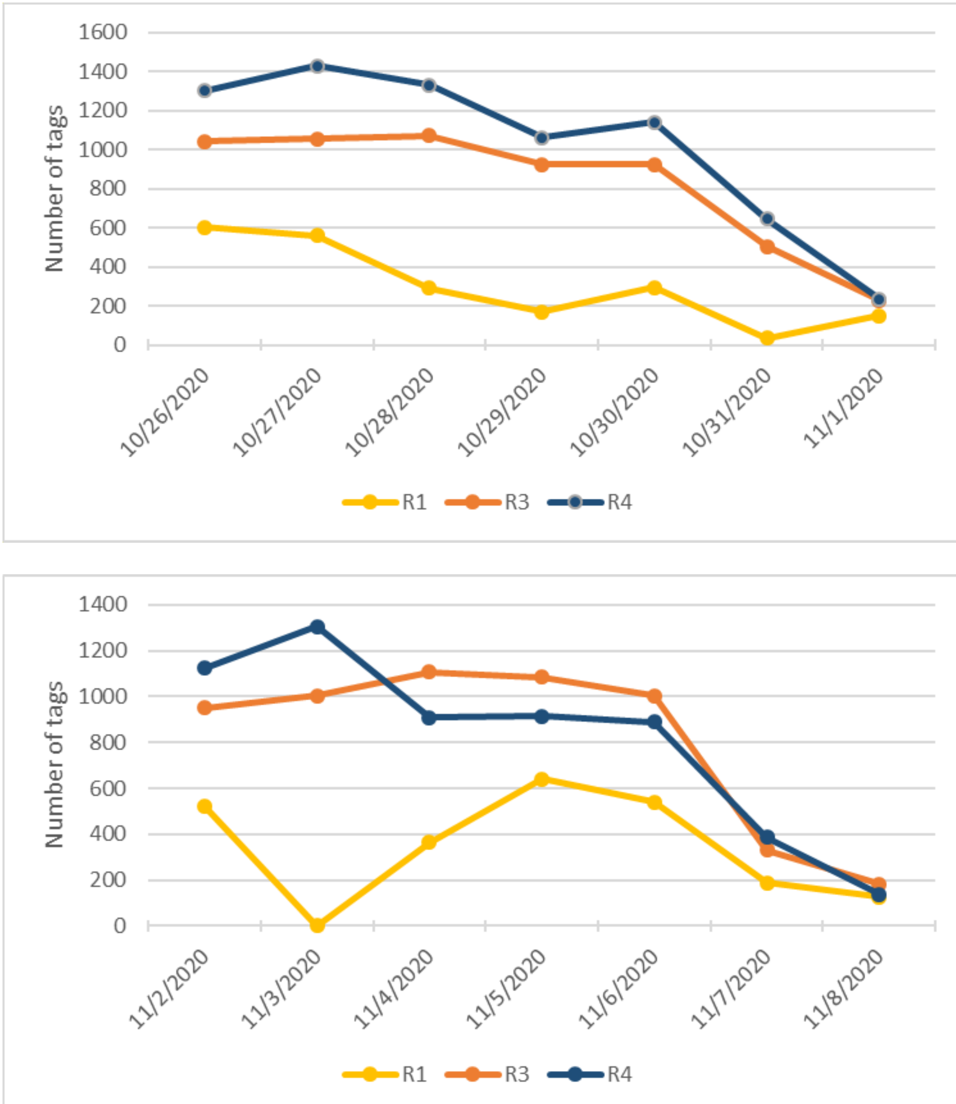


Figure 4. Transponder Count Summary for Otay Mesa POE

Tag reads at the initial station at Calle 12 (R1) are lower than the other two stations due to the UCP route. The Research team contacted SAT to verify the route and volume at the UCP, and an average of 800 trucks per day are using this route, which has no RFID reading station implemented yet. The following charts (Figure 5) show transponder count reads adding 800 tags per day at R1. By adding these 800 tags reads to R1, all three stations have a very similar number of tags.

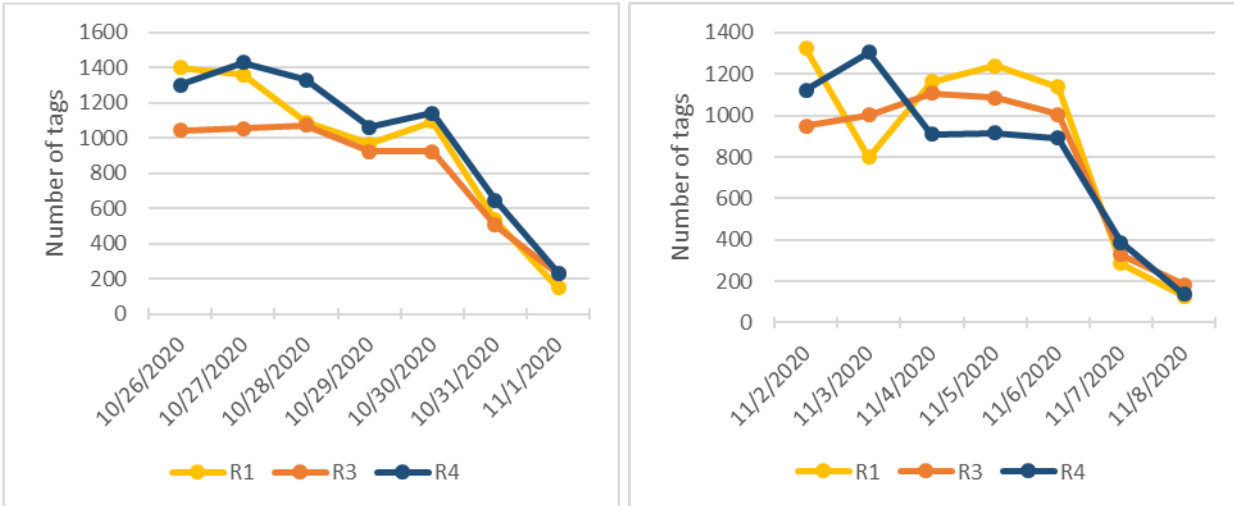


Figure 5. Transponder counts including UCP averages from SAT

Figure 6 shows the tag count per hour during the period of October 26 to November 01 (Monday to Sunday), the trend can be easily seen on the schedule of the crossing and the peak hours (6 am to 8 pm). In addition, it is important to note that R1 has a significant lower tag count compared to the other reading stations, due to the UCP program which is mentioned at the beginning of this section.

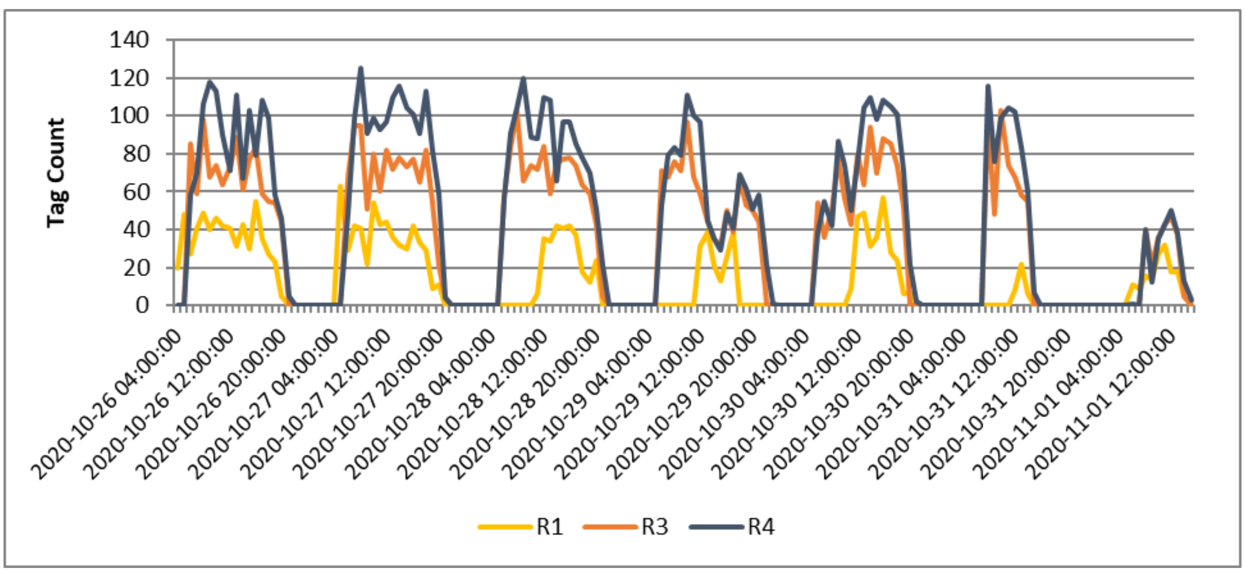


Figure 6. Otay Mesa POE tag count from October 26 to November 01

Matched tag reads for the system, also known as the sample size, are the total number of tag IDs that were detected at R3 after having been previously detected at R1 within a certain buffer period, and tag IDs that were detected at R4 after having been previously detected at R3 and R1 within a certain buffer period. This variable is important because the sample size is used for travel time calculations and estimations.

Figure 7 shows the sample size between two segments, the similarity of the graphics indicates that the sample size is good along the two segments of the trip. Sample size is lower between R1-R3 than in R3-R4 due to trucks not going through R1 and using the UCP lane.

This buffer period is set so that travel times for trucks that can make more than one trip a day are not counted as one single long trip and trucks that spend more than the average do not affect the average travel time sample. The current buffer time is set at 250 minutes and it can be adjusted in the algorithm.

The average match rate is between 55% and 60%. The match rate could be improved with changes to the reader protocol, so all tags are read and installing a reader at the UCP lane to capture 100% of trucks using this border crossing.

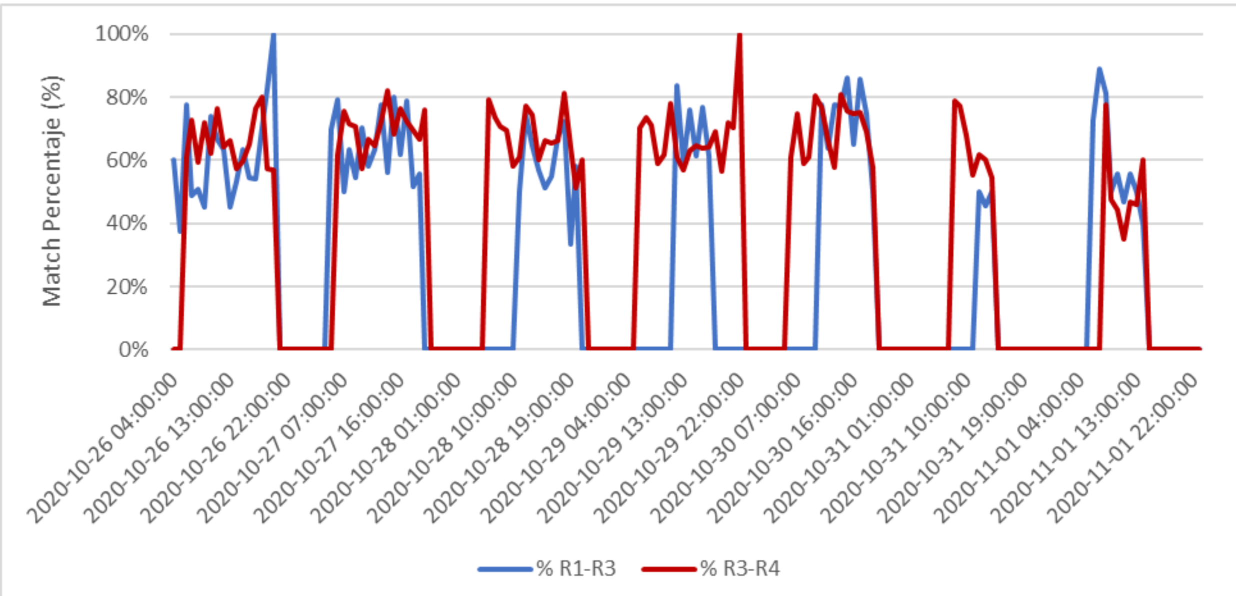
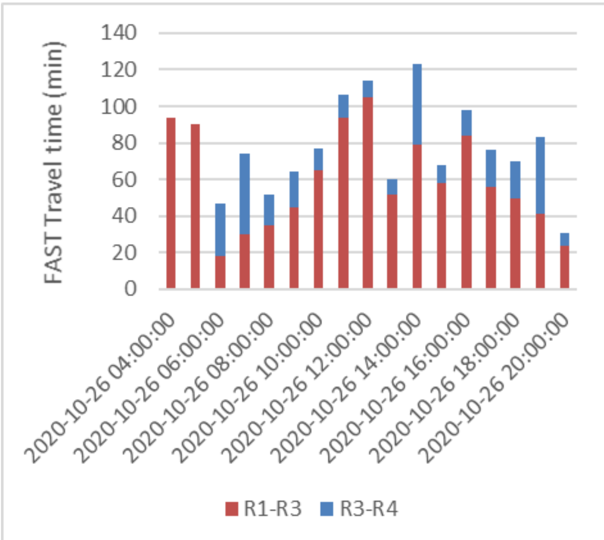


Figure 7. Tag count match percentage between reading stations

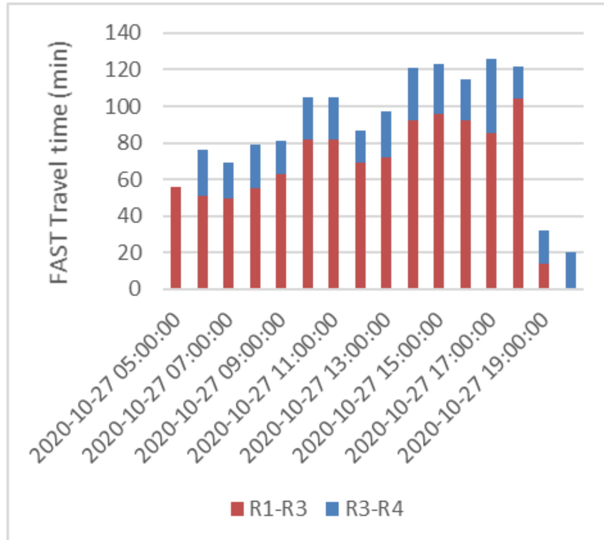
HOURLY AND DAILY VARIATION OF AVERAGE WAIT AND CROSSING TIMES

Figure 8 through Figure 10 present a snapshot of hourly average travel times (wait time composed of R1-R3 and travel time between R3-R4. Adding these two segments of the trip will provide the crossing time. Charts include travel times at Otay Mesa POE for Monday through Sunday for Free and Secure Trade (FAST), empty and regular lanes. The data was collected during the weeks of October 26 to November 08, 2020 and has been processed by the TTI Research Team to provide daily average travel times by hour of the day.

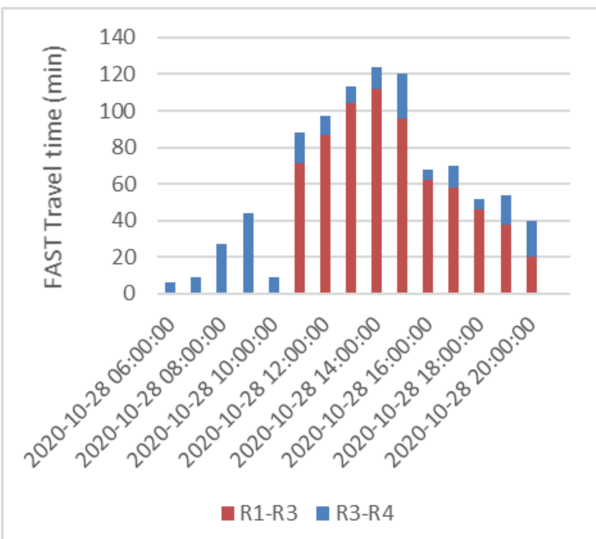
The following charts show that most of the trucks line up early in the morning which causes a high average wait time during the first hours of operation. In addition, the first three days of the week have more traffic compared to the others. The FAST lane only operates from Monday to Friday compared to the other lanes which are also open on weekends. These figures also illustrate a noticeable increase in average wait times starting at 13:00 hours.



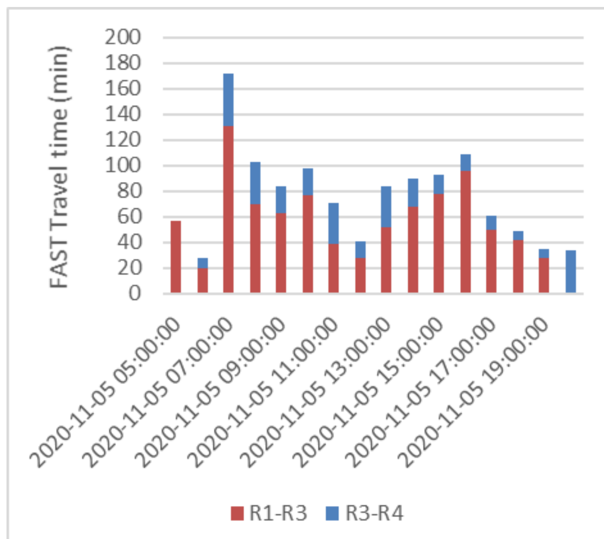
(a) Monday FAST Times



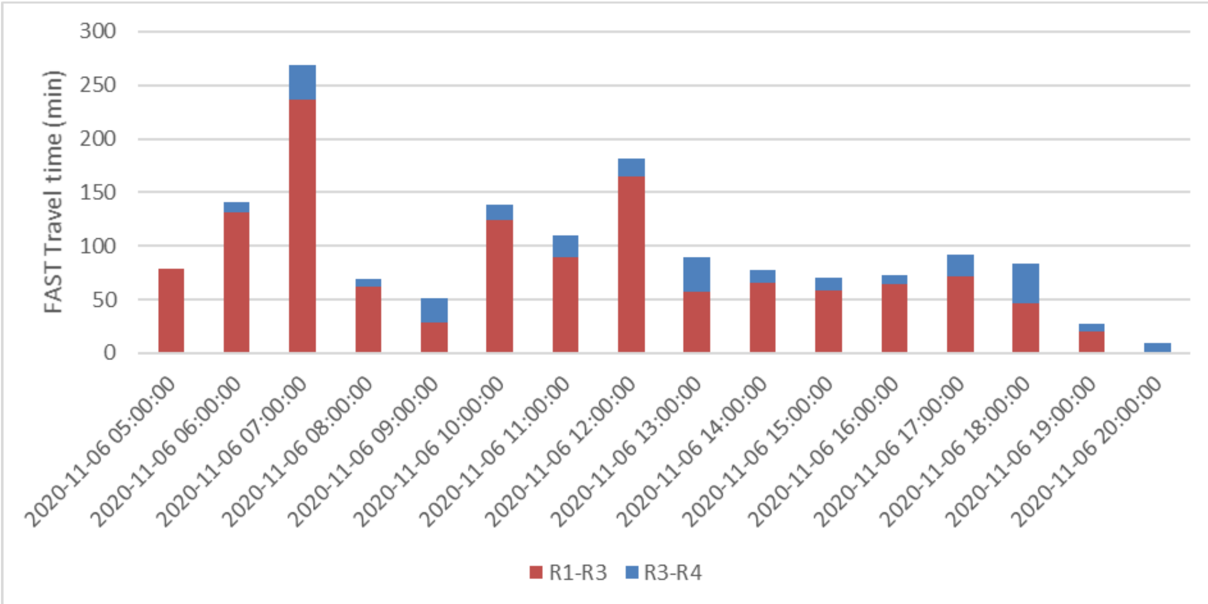
(b) Tuesday FAST Times



(c) Wednesday FAST Times



(d) Thursday FAST Times

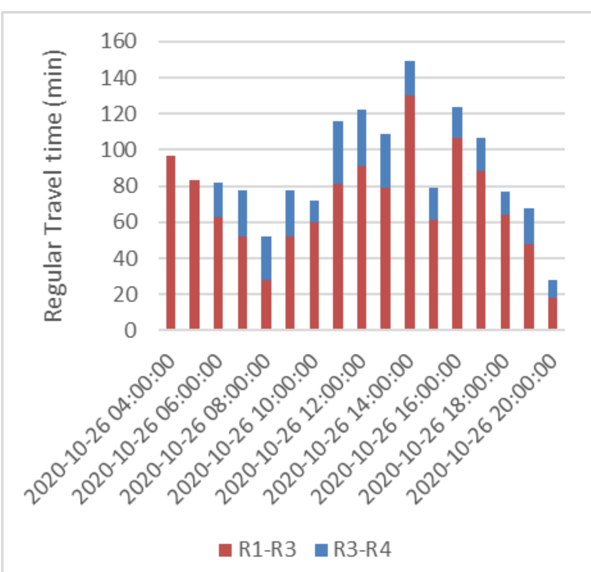


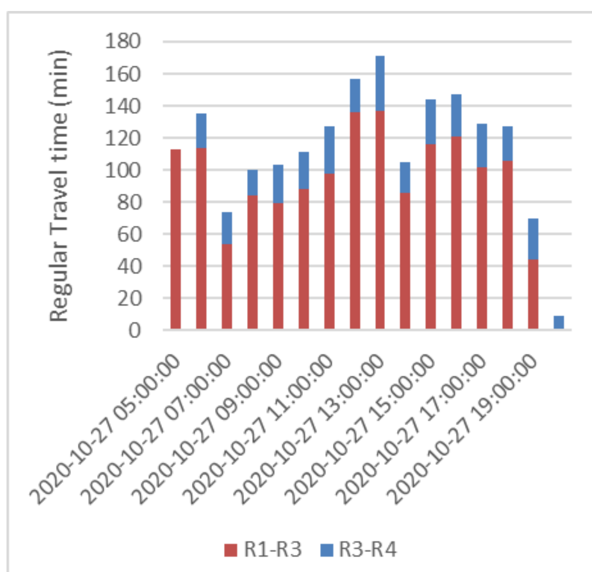
(e) Friday FAST Times

Figure 8. Daily variation of truck average wait times October 26 to November 8, 2020 FAST Lane

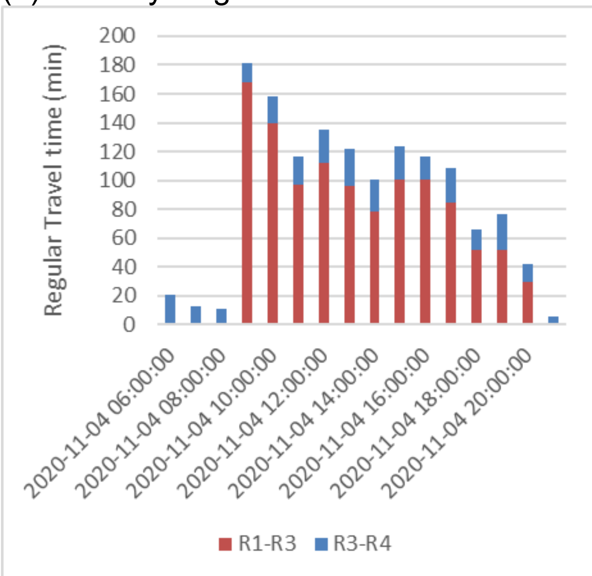
The following charts portray **regular lane travel times** (Figure 9), and they show a significant increase in average travel times compared to FAST lane. However, the same pattern of high travel times during early hours of operation can be observed, followed by a decrease of travel time around 10 a.m. during most of the days.

The regular lane is opened during weekends and it can be observed a high wait time during early hours, a similar pattern to weekdays. Despite this, around 7 a.m. traffic volume lowers considerably causing travel times to reduce drastically.

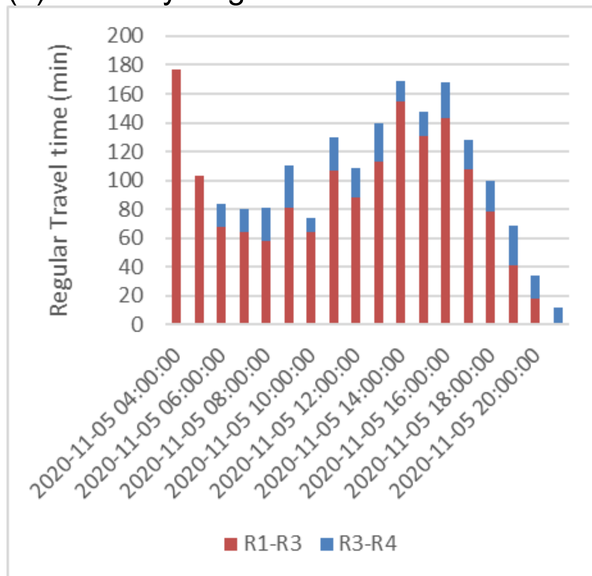




(a) Monday Regular Times

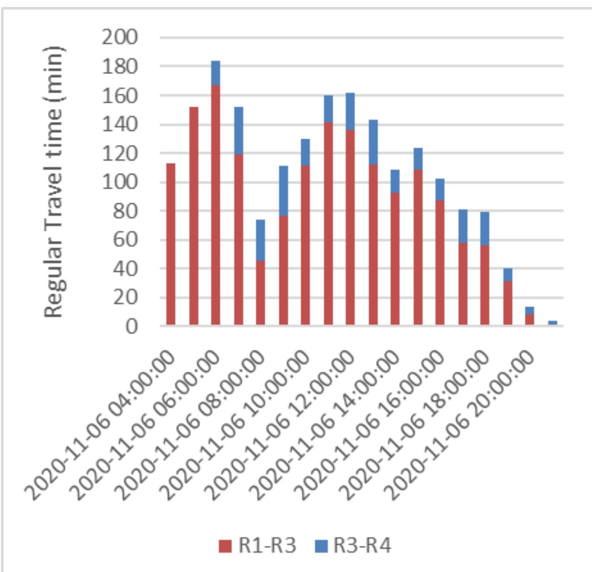


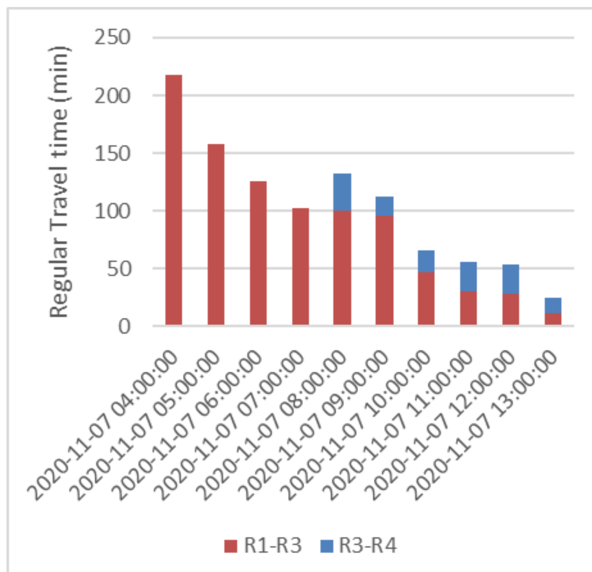
(b) Tuesday Regular Times



(c) Wednesday Regular Times

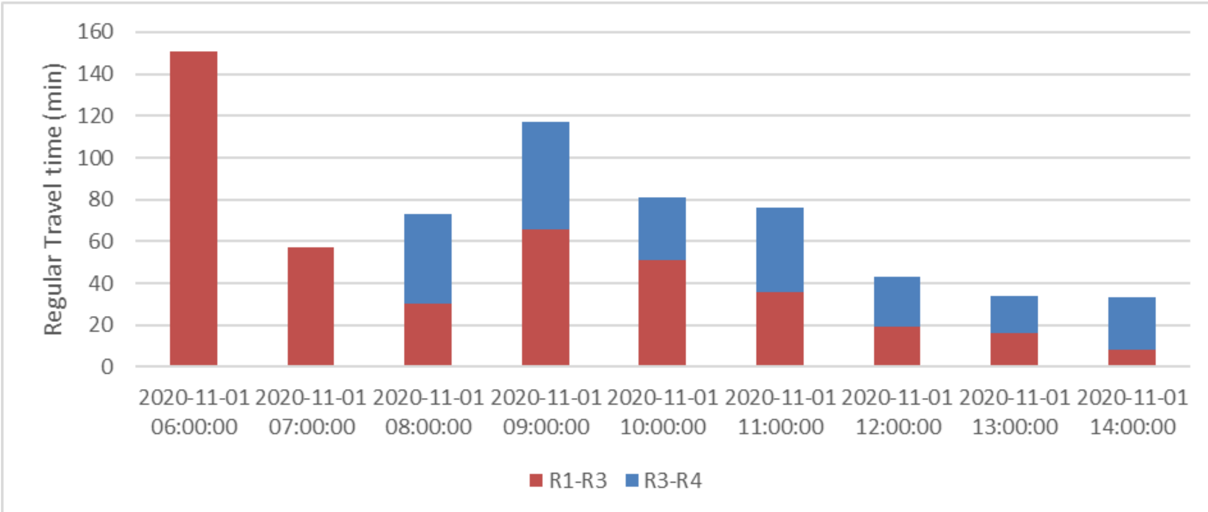
(d) Thursday Regular Times





(e) Friday Regular Times

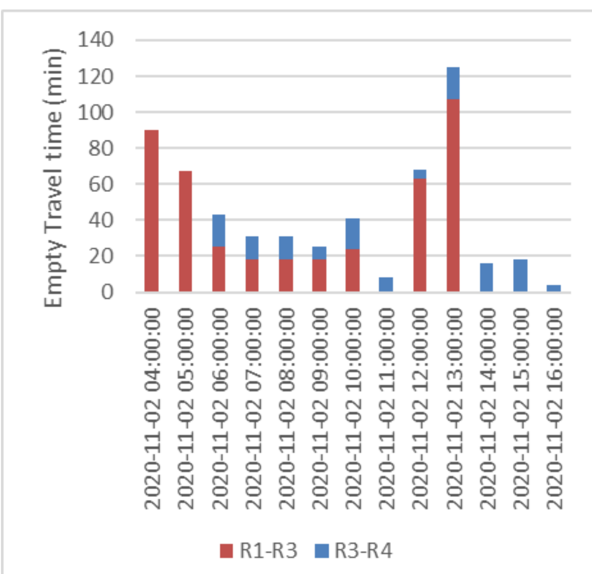
(f) Saturday Regular Times



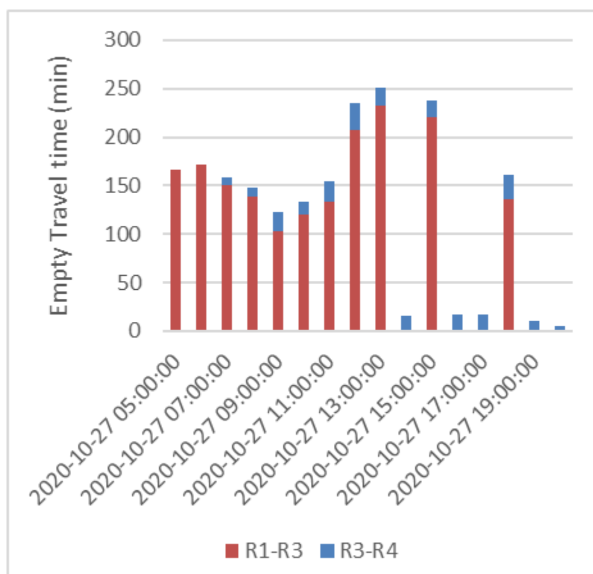
(g) Sunday Regular Times

Figure 9. Daily variation of truck average wait times October 26 to November 8, 2020 Regular Lane

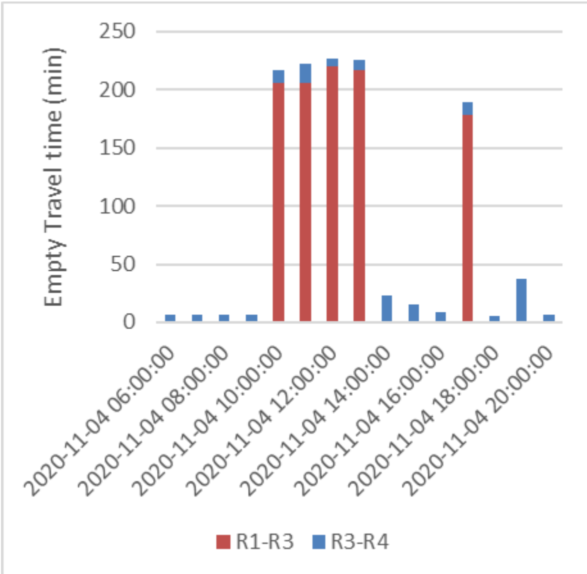
Finally, Empty trucks wait times show high travel times early in the week and they follow the same pattern of high wait time during early hours of operation. However, as mentioned previously, the UCP lane implemented by SAT is affecting regular and empty lanes. Empty truck travel patterns are very inconsistent. Some days of the week, like Wednesday and Thursday travel times for R1 to R3 does not show during the morning hours of the day. Most likely, CBP use the Empty lane for laden or FAST trucks (Figure 10).



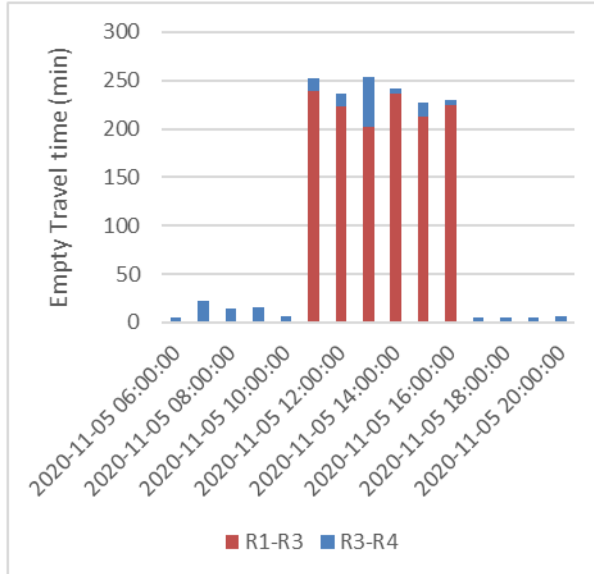
(a) Monday Empty Times



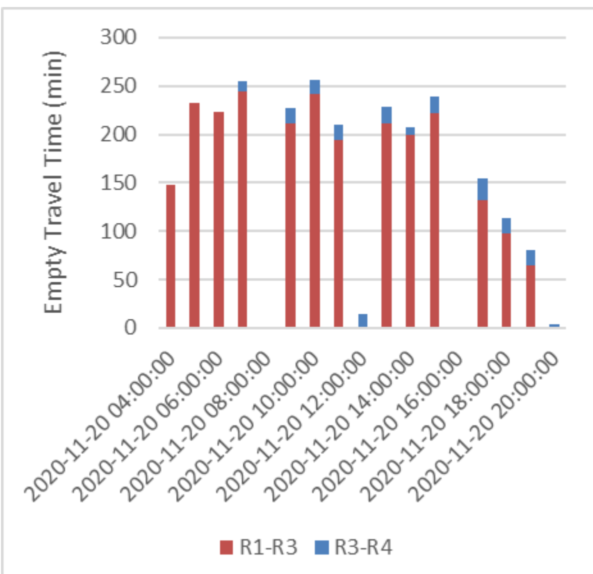
(b) Tuesday Empty Times



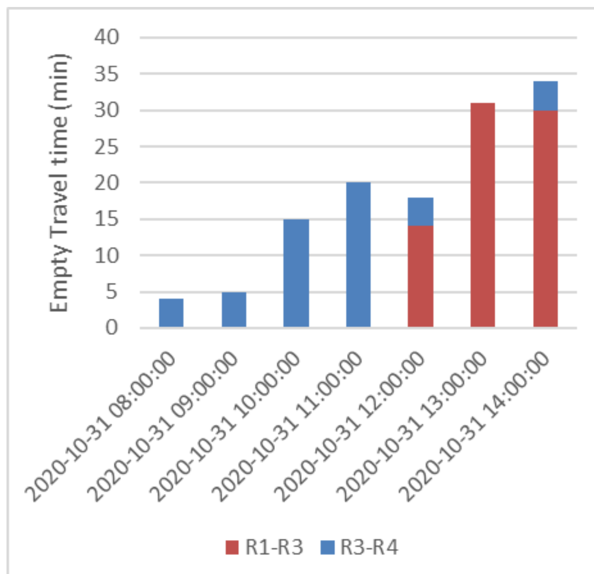
(c) Wednesday Empty Times



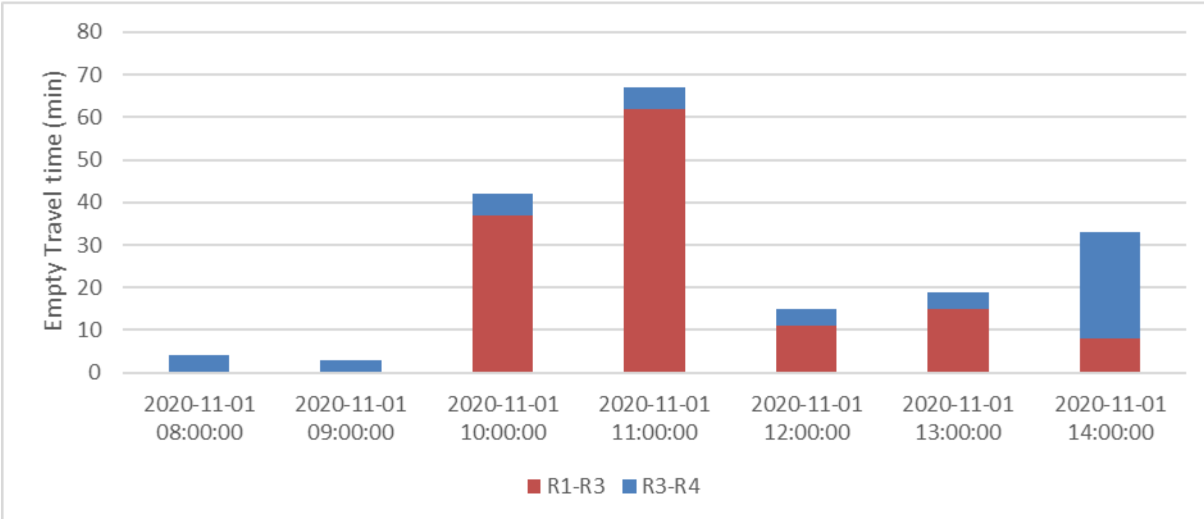
(d) Thursday Empty Times



(e) Friday Empty Times



(f) Saturday Empty Times



(g) Sunday Empty Times

Figure 10. Daily variation of average wait times of trucks during the weeks of October 26 to November 8, 2020 for empty lane

FOUND ISSUES AND APPLIED APPROACH AT OTAY MESA POE

The information reveals that the capture rate was low as shown in column 4, averaging 30 percent. Based on the data analysis and field observations from the Research Team, two issues were identified that produce the low penetration rate:

1. A large proportion of trucks at the Otay Mesa are carrying a new RFID tag issued by CBP. The Decal and Transponder Online Procurement System (DTOPS) tag has a new protocol that is not compatible with the RFID readers currently installed.

2. The Unified Cargo Processing (UCP) program has been implemented at this border crossing with a new route entering the SAT compound through an adjacent street (Calle Sor Juana Inés de la Cruz) instead of Calle 12 and skip reading station 1 (R1). Mexican customs export lot and line on the queue directly to CBP primary inspection as shown in Figure 11. This route is used from 6:00 to 12:00 hours by empty and laden trucks, and from 12:00 to 21:00 hours by laden trucks.

Figure 11. Unified Cargo Processing Route at Otay Mesa POE

As of April 2021, the TTI Research Team managed to obtain authorization from local stakeholders in Mexico to perform the installation of the Border Crossing Information System in the Aduana export lot and the side entrance from Calle Sor Juana Inés de la Cruz, as shown in Figure 3.

Figure 12. Otay Mesa R2 systems installation

As mentioned before, there were two main issues at this border crossing, causing a reduced sample number of CVs to measure border wait times in the BCIS system. The first one was the newly implemented DTOPS transponders used by U.S. CBP, while the second issue being missing truck readings from UCP entrance at the side of Aduanas Export lot and installation at Aduanas Export Booths.

These issues were addresses by coordinating a reader upgrade with Transcore for each Encompass E4 reader located at this border crossing and the readers were replaced in R3 and R4 through a local contractor, while in Otay R2 which was installed in April 2021 already included the upgrade for DTOPS reading capabilities. All the upgraded readers are capable of handling DTOPS transponders in addition to the protocols used previously which are eGo and ATA.

On the other hand, TTI was able to coordinate an installation with a local contractor for the remaining sites shown as R2 and R2A in Figure 3. The system was configured , tested remotely and on-site. All the reading stations from R2 to R4 have upgraded DTOPS readers allowing the system to gather enough truck samples. The total tag count was compared to the volume numbers provided by U.S. CBP; note that the tag count sometimes will be higher as some trucks carry more than one RFID transponder in their windshields causing a higher sample size than the total of trucks. This is approached through the algorithm by comparing tags and timestamps provided by the system and does not affect the final calculations.

The following tables show sample size obtained comparing each of the reading stations with the values provided by CBP. As we can observe, the sample size has improved greatly compared to Table 1. Reading station 1, located in Tijuana, is pending from the reader upgrade, hence why the sample size at this location is lower compared to the other three stations (Table 2, Table 3, Table 4, and Table 5.

Table 2 New Daily Capture Rate Calculation At Otay Mesa R1

Date	Total Northbound Truck Volume (CBP)	R3 Transponder Sample Size	Capture Rate Based on R4 Sample Size
1	2	3	(4) = (3) × 100/(2)
Monday	3,634	1,942	53.43%
Tuesday	3,700	1,851	50.02%
Wednesday	3,495	1,430	40.91%
Thursday	2,356	1,122	47.62%
Friday	2,065	1,818	88.03%
Saturday	901	584	64.81%
Sunday	822	129	15.69%

Table 3. New Daily Capture Rate Calculation At Otay Mesa R2

Date	Total Northbound Truck Volume (CBP)	R3 Transponder Sample Size	Capture Rate Based on R4 Sample Size
1	2	3	(4) = (3) × 100/(2)
Monday	3,634	2,461	67.72%
Tuesday	3,700	2,534	68.48%
Wednesday	3,495	2,703	77.33%
Thursday	2,356	2,684	113.92%
Friday	2,065	2,500	121.06%
Saturday	901	799	88.67%
Sunday	822	537	65.32%

Table 4. New Daily Capture Rate Calculation At Otay Mesa R3

Date	Total Northbound Truck Volume (CBP)	R3 Transponder Sample Size	Capture Rate Based on R4 Sample Size
1	2	3	(4) = (3) × 100/(2)
Monday	3,634	3,895	107.18%
Tuesday	3,700	3,788	102.37%
Wednesday	3,495	2,690	76.96%
Thursday	2,356	2,537	107.68%
Friday	2,065	2,929	141.84%
Saturday	901	1,211	134.40%

Sunday	822	732	89.05%

Table 5. New Daily Capture Rate Calculation At Otay Mesa R4

Date	Total Northbound Truck Volume (CBP)	R4 Transponder Sample Size	Capture Rate Based on R4 Sample Size
1	**2**	**3**	**(4) = (3) × 100/(2)**
Monday	3,634	4,284	117.88%
Tuesday	3,700	4,188	113.18%
Wednesday	3,495	4,760	136.19%
Thursday	2,356	4,685	198.85%
Friday	2,065	3,152	152.63%
Saturday	901	1,396	154.93%
Sunday	822	722	87.83%

As shown on the previous chart, data gathered by reading stations R2-R4 is much better, and it can also surpass CBP numbers. This is caused by trucks having multiple transponders on the window; however, this does not affect travel times estimations. On the other hand, R1 readers have not been replaced, and this can be confirmed by comparing its values to the other reading stations.

The following figures, show the average segment travel time per hour during each day of the week for FAST and regular traffic. Busiest days can be observed during the week and the longest segment travel times are usually from R1 to R2 for Regular vehicles, while the longest segment travel times for FAST vehicles can vary from R2-R3 or R2-R4.

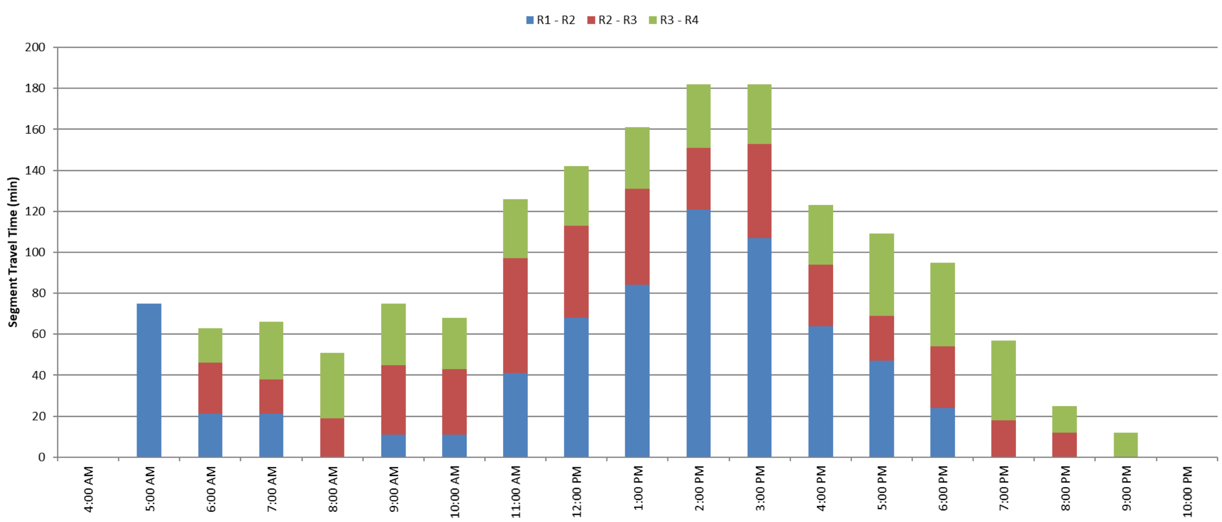


Figure 13. Otay Mesa Weekly Regular Segment Average Travel Time

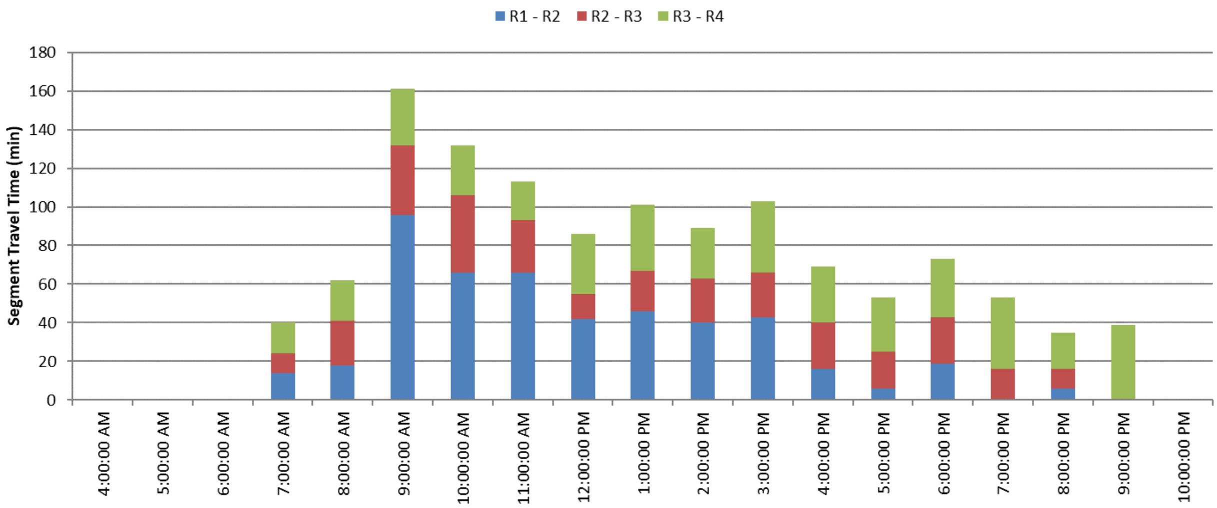


Figure 14. Otay Mesa Weekly FAST Segment Average Travel Time

Chapter 3:
Conclusions and Future Operation Plan

GENERAL CONCLUSIONS

The border crossing and wait time measurement system at Otay Mesa is operational, and data is being collected regularly. The system is stable, and there are no major maintenance requirements for the existing three sites in the near future, except for any unforeseen natural causes.

Based on the analysis of the initial data collection, the following issues have been addressed to improve system reliability:

- Install an RFID reading station at the current UCP entrance to SAT (R2A), this helped to improve border crossing and wait time estimation for empty and regular lanes by increasing the tag sample at R2.

- RFID readers were upgraded or installed in R2, R3 and R4, this allows the system to read the newly implemented transponders (DTOPS). Readers at R1 will be replaced as soon as the upgraded readers arrive from Transcore facilities.

CBP announced that the Otay Mesa POE will be under constructions starting in January 2021 and finalize the new facilities by January 2022. On the other hand, SAT also announced plans to add lanes to the primary inspection exports booths, eliminating the current UCP entrance at the Sor Juana Ines de la Cruz street, there is no timeline for these changes, however. Once these two projects are completed additional equipment would be needed to cover the new lanes and reading stations at R3 would be relocated.

TTI has been working thoroughly to address and anticipate future issues with stakeholders in order to provide a more robust system and reliable wait and crossing time estimates.

Measuring Border Wait Time At Land Ports Of Entry: Technology Assessment And Data Dissemination

Otay Mesa Commercial Border Wait Time Installation Report

Prepared by

Texas A&M Transportation Institute

Prepared for

BTI Institute
Borders • Trade • Immigration
A Department of Homeland Security Center of Excellence

April 2021

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List of Abbreviations

BCIS	Border Crossing Information System
BTI	Borders, Trade, and Immigration Institute
CA	California
CBP	U.S. Customs and Border Protection
CHP	California Highway Patrol
CV	Commercial Vehicle
DTOPS	Decal and Transponder Online Procurement System
FHWA	Federal Highway Administration
IP	Internet Protocol
POE	Port of Entry
RFID	Radio Frequency Identification
TTI	Texas A&M Transportation Institute
UCP	Unified Cargo Processing
VDC	Direct Current Voltage
VPN	Virtual Private Network

Organization of the Report

The report is organized as follows:

- Chapter 1 includes a general background and overview of the project and radio frequency identification (RFID) system.
- Chapter 2 presents a description of the characteristics of Otay Mesa Commercial Vehicles (CV) Port of Entry (POE)
- Chapter 3 describes the technology implementation process, including the technology evaluation and reader station location processes.
- Chapter 4 presents a description of the equipment procurement and installation at each location across the Otay Mesa POE.
- Chapter 5 presents the conclusions of the equipment installation at the Otay Mesa POE.
- The report includes two appendices: Appendix A presents the equipment list at each reading station and Appendix B includes the detailed report of the equipment tests and evaluation.

Chapter 1:
Background and Overview

BACKGROUND

Funding for this project was provided by the Department of Homeland Security's Science and Technology Directorate and managed in collaboration with the Borders, Trade, and Immigration Institute (BTI).

Reliable border crossing time information is important for all stakeholders that participate in the process. U.S. Customs and Border Protection (CBP) use the border crossing time information for staffing planning, and other internal activities, while the trade community consumes border crossing time data to plan trips and improve supply chains efficiency. CBP collects the border crossing and wait time information manually at some ports of entry (POEs), dedicating valuable officers' time estimating travel times and reporting the information to headquarters.

CBP, the U.S. Department of Transportation through the Federal Highway Administration (FHWA) and state department of transportation funded the development and implementation of a border crossing and wait time measurement system that used radio frequency identification (RFID) to estimate travel times for trucks crossing from Mexico into the U.S. The Border Crossing Information System (BCIS) has been implemented by the Texas A&M Transportation Institute (TTI) at nine truck border crossings across the U.S.-Mexico border. The BSIF estimates border crossing time information which is disseminated in real time and it also provides historical data at https://bcis.tti.tamu.edu/. The information is also shared with CBP in a real time basis.

The objective of this task was to implement the RFID system at the Otay Mesa Port of Entry POE in California. The project started in 2017 under a different contract and was interrupted due to change of administration in Mexico. BTI contracted with TTI to finalize the RFID equipment installation at the Otay Mesa POE. This report documents work that TTI performed during the installation and testing of the equipment. A separate report "Penetration Analysis" documents the data analysis that was performed once data was collected.

To be consistent with other similar implementations along the U.S.-Mexico border, the implementation plan includes four RFID reading stations. The proposed locations include:

- R1. At the furthest location where queue could be measured; at the Otay Mesa POE the location is at the intersection of Calle 12 Norte and Callejón de Exportación in México

- R2. Before crossing the border, located at the Mexican Customs Export Inspection booths

- R3. At the U.S. Customs and Border Protection (CBP) Primary inspection booths

- R4. At the California Highway Patrol (CHP) vehicle safety inspection station.

This distribution of readers allows measurement of crossing and wait times. Figure 1 depicts the location of the readers. Travel time between R2 and R3 is the CBP Wait Time, while the time between R1 and R3 is Wait Time, and the travel time between R1 and R4 is the crossing time. At each reading station, RFID readers will capture the transponder ID and this anonymous data will be transferred to a server which will add a timestamp and process it into a database to provide travel times as shown.

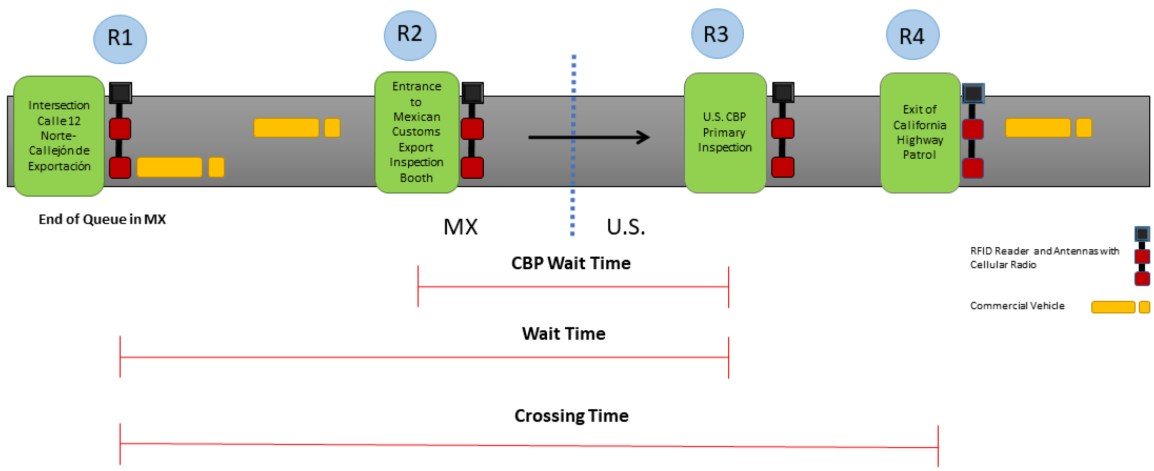


Figure 1. General RFID Reader Location Diagram

Wait and crossing time are defined as:

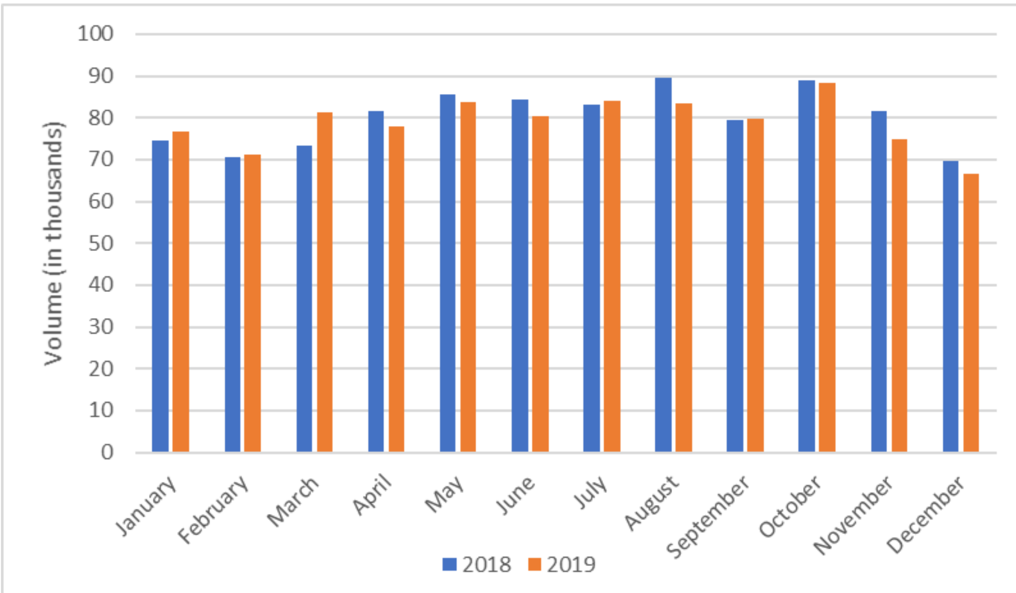
- Wait time is the time it takes for a vehicle to reach the CBP primary inspection booth after arriving at the end of the queue. This queue length is variable and depends on traffic volumes and processing times at each of the inspection facilities throughout the border crossing process.

- CBP Wait Time is similar as wait time, but instead, the total time is measured from the entrance to Mexican customs export booth to the CBP primary inspection booth.

- Crossing time has the same beginning point in the flow as wait time, but its terminus is the departure point from the last inspection compound that a vehicle transits in the border crossing process. As a metric, wait time is of greater significance than crossing time to CBP operations, whereas crossing time is of relatively greater interest to carriers and shippers.

Chapter 2:
Otay Mesa Border Crossing Sites Description

Figure 2 shows the total volume of trucks that crossed northbound from Mexico into the United States through the Otay Mesa POE for the two-year period of 2018-2019. CV crossing volume is an important indicator to identify trends and possible changes per year at a border crossing. In 2019 volumes were slightly lower than in 2018, and the peak months were August and October.



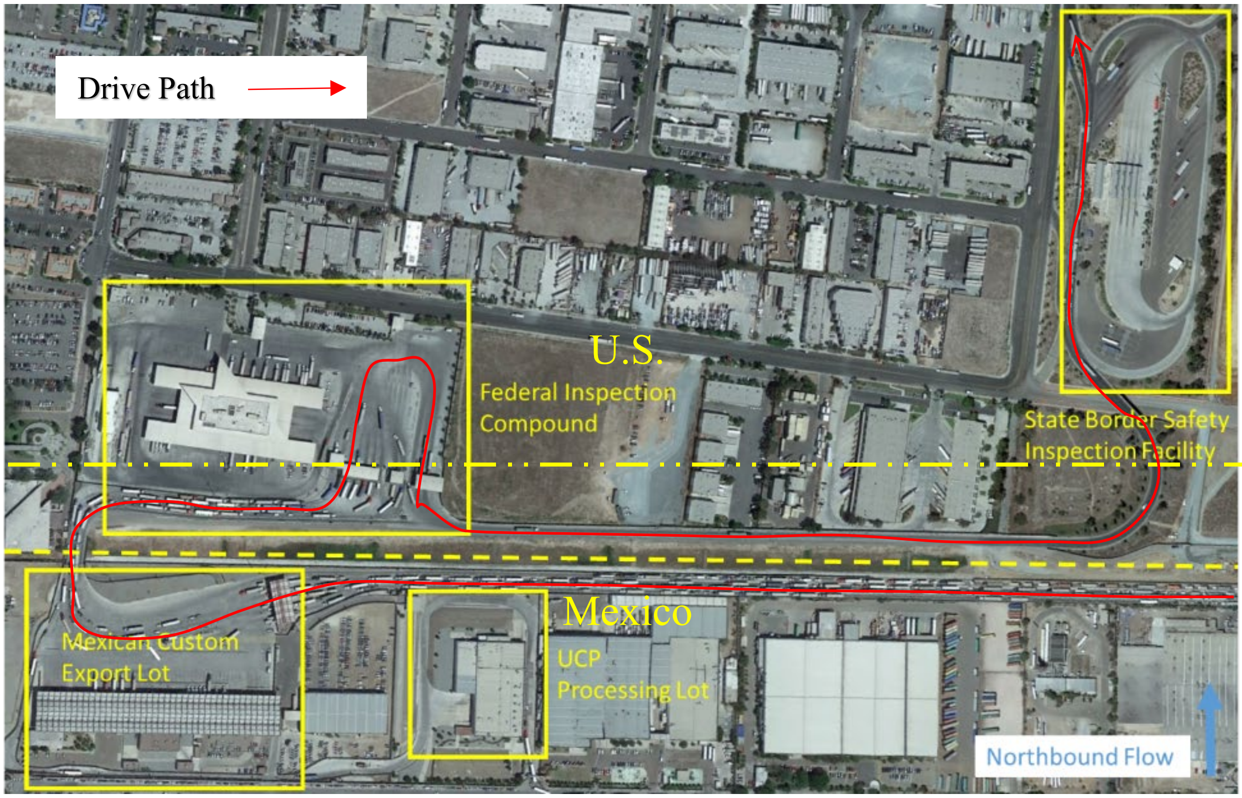
Source: U.S. Department of Transportation, Bureau of Transportation Statistics

Figure 2. Monthly Northbound Truck Crossings at Otay Mesa POE

The border crossing process for CVs entering the United States requires several steps in which the vehicles need to stop. The time it takes a truck to cross would depend on the time spent at each of these points of inspection, at toll collection, and while moving from one station to the next, which is a function of traffic volume and the number of available staffed booths.

At the Otay Mesa POE, the northbound commercial border crossing is measured at the intersection of Calle 12 Norte and Callejón de Exportación on the Mexican side of the border in Tijuana. The Callejón de Exportación road is used only by trucks leading to the US side of the border and leads to the Mexican Customs Export Inspection lot. After clearing export customs on the Mexican side, the trucks proceed to travel into the U.S. CBP Primary Inspection booths. At these primary inspection booths, a CBP agent determines whether the truck requires a secondary inspection and directs the driver to it, or otherwise instructs the driver to simply proceed to the exit. Empty trucks use a dedicated lane and go through a special lane at the CBP compound. Final clearance to exit the Federal Inspection Compound is given at booths located at the exit of the premises. After leaving the Federal inspection jurisdiction, the truck proceeds to CHP vehicle inspection station, where a visual inspection is performed, and trucks could be sent to undergo a secondary inspection if needed.

Figure 3 presents a satellite view of Otay Mesa POE, each one of the facilities and the truck path to cross into the U.S. with a red line.



Source: TTI using Google Earth

Figure 3. Satellite View of Otay Mesa POE and Facilities

Chapter 3:
Border Crossing and Wait Time Technology Implementation

READER STATION LOCATION

The analysis of traffic flows and existing infrastructure at the Otay Mesa POE led to an implementation plan with several alternatives. The selected layout includes four reading stations:

- R1. At the intersection of Calle 12 Norte and Callejón de Exportación in México
- R2. Mexican Customs (Aduana) Export inspection booths
- R2A. Aduanas Unified Cargo Processing (UCP) side entrance from Calle Sor Juana Inés de la Cruz
- R3. CBP primary inspection booths
- R4. CHP vehicle inspection station

Figure 4 shows the final locations for the RFID equipment at Otay Mesa POE

Source: TTI using Google Earth

Figure 4. RFID Locations at Otay Mesa POE

The final configuration of the reader stations is presented in Table 1. The list of equipment for this project is presented in Appendix A.

Table 1. Final Reader Station Configuration

Reading Station	Number of Readers	Number of Antennas	Solar Power
R1—Intersection of Calle 12 Norte and Callejón de Exportación	3	4	Yes
R2—Mexican Aduana Inspection Booth (pending approval for installation by Mexican Authorities)	3	6	No
R2A—Aduana UCP side entrance	1	1	No
R3—US Primary Federal Inspection Compound	6	10	No
R4—US State Inspection booth	1	2	No
TOTAL	**14**	**23**	

CONCEPT OF OPERATIONS

The RFID-based border crossing and wait time measurement system concept was developed using this technology as most CVs that cross the U.S./Mexico already have RFID tags installed in the windshield for toll payment or for other purposes such as proof of border crossing annual fee payment to CBP. Figure 5 presents examples of tags located on truck windshields.

Figure 5. RID Tags in Truck Windshield.

The System is based in the concept that RFID tag readers are installed at four locations in the truck path. The RFID reader captures the unique identifier for each vehicle, similar to a serial number and forwards the resulting data record to a central location for further processing via a data communication link. The server applies a timestamp to each of the obtained tags to ensure all readers utilize the same clock. The RFID antenna located above the truck reads the tag in the windshield as illustrated in Figure 6.

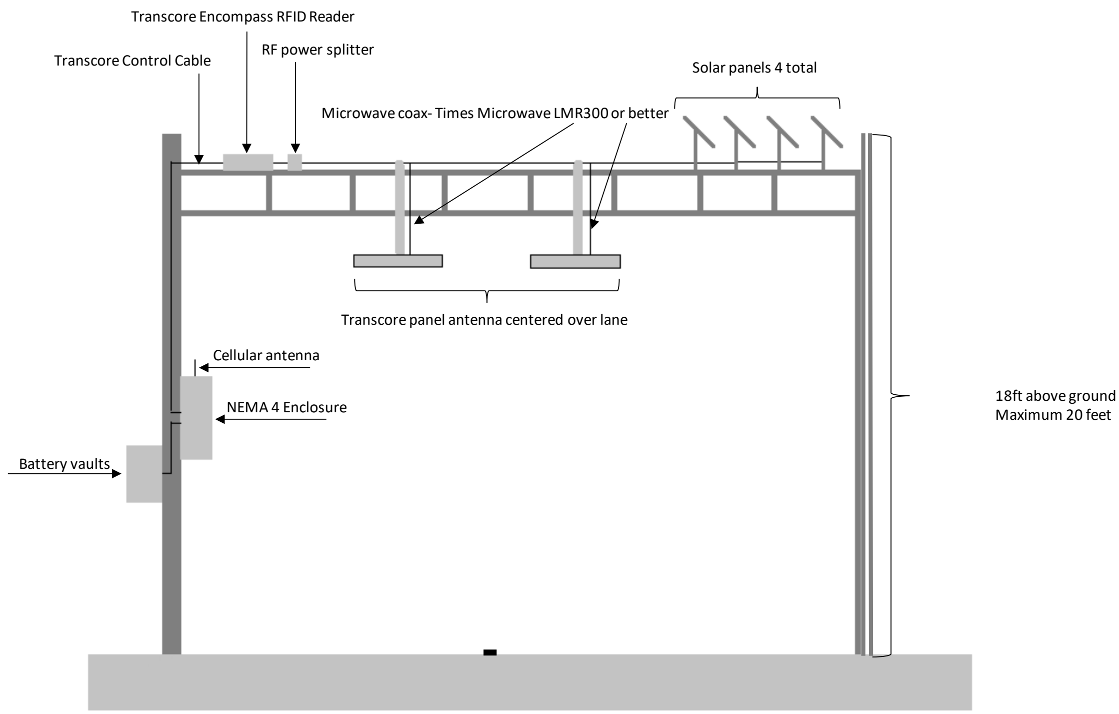


Figure 6. Two Lane Tag Reading System Installation (Not to Scale)

The concept of operation was modified to meet the Otay Mesa border crossing time measurement requirements, since there is an extra entrance to Aduanas for UCP cargo. The border crossing measurement system is organized into three subsystems representative of each component's function:

- Field subsystem: comprised of the RFID tag detection or reading stations and the communication equipment; a minimum of two detection stations are required, one in Mexico and one in the United States; the detection station reads RFID tags and passes the data to the central subsystem via the communication equipment.

- Central subsystem: receives tag reads from the field detection stations and performs all processing to derive and archive the aggregate travel times between the stations.

- User subsystem: interacts with the central subsystem to provide an Internet web portal for data users (stakeholders, the public, etc.) to access current border crossing times and to access archived crossing time data.

Figure 7 shows the system's organization:

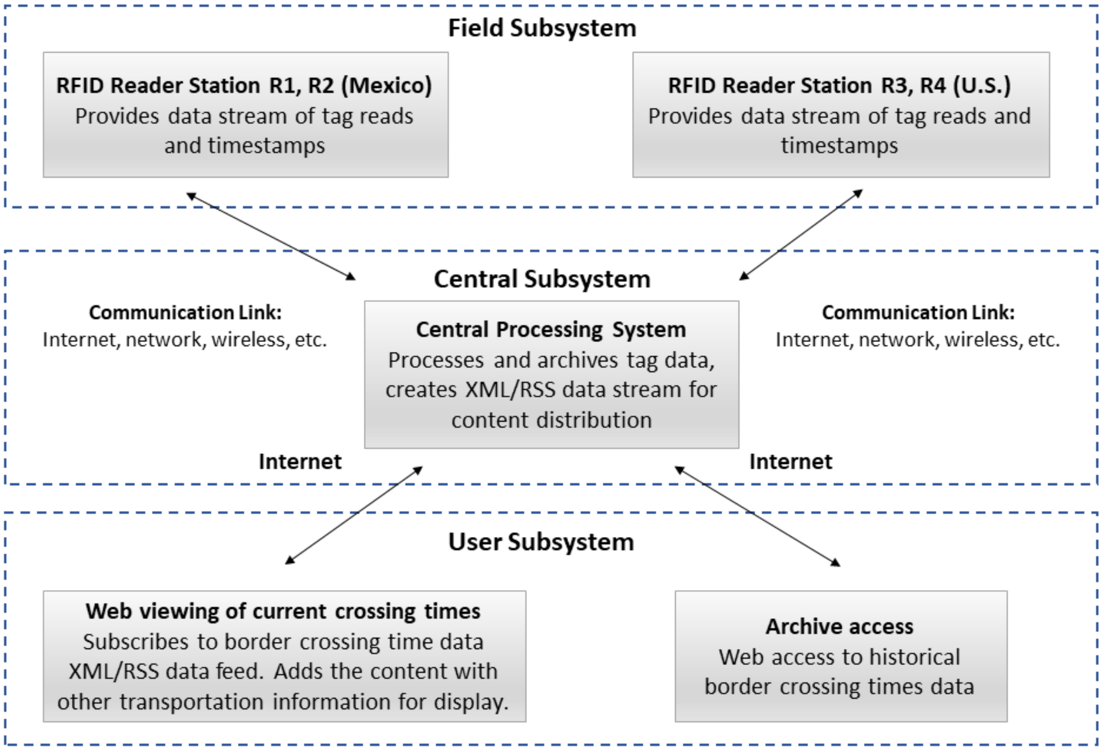


Figure 7. Subsystem Organization Diagram

The central facility receives data from all tag-reading stations associated with the project. The central facility is a secured database server located at TTI's office located in College Station, TX. The database server stores all inbound raw reader station data and subsequent processed data in an archive for future access and use by regional transportation agencies and other authorized stakeholders. In essence, the database server acts as a data center for the system. The database server has enough storage space to archive several years of data from the system, and the server is expandable if additional storage space is required in the future.

The raw data are processed to match tag reads of individual trucks at the entrance point on the Mexican side and the exit point on the U.S. side. The difference in time stamps yields a single truck's progression as a function of time through the POE. The tag matching and travel time computation of individual tags happens in real time; however, the aggregation of individual travel times to compute wait time and crossing time for reporting purposes happens every 10 minutes.

The user subsystem manages access of border crossing time data for the users. The most recent average crossing time data are available to the public via an RSS subscription. TTI has developed a border crossing information system through funding from Federal Highway Administration (FHWA) and CBP. The system includes a map-based website to view the most recent average crossing time data and segment travel times and will also include interfaces to query archived border crossing data.

Chapter 4: Equipment Procurement and Installation

EQUIPMENT PROCUREMENT AND INSTALLATION

With the technology implementation plan, the equipment list could be finalized and proceed to procurement. The RFID readers had the longest lead time, between two and three months. Once all the RFID equipment was ordered, the other communication equipment was purchased, and equipment cabinets were assembled and tested at the TTI Headquarters before deploying in Otay Mesa POE.

In order to perform the installation across the POE, the TTI research team identified local contractors on both the Mexican and U.S. sides of the border to provide necessary equipment and tools. R1 and R4 installations were delayed due to COVID-19 travel restrictions. R3 equipment at CBP Primary was completed previously through a different contract, and R2-R2A installations were performed during April 2021 once all the equipment and permits were obtained.

Reading station 1 (R1)

The installation of equipment at R1 started with the solar equipment (solar panels and voltage controllers) and was finalized in August 2020 when the TTI Research Team obtained authorization from the Mexican federal government to deliver the RFID equipment to Tijuana (Figure 8).

Figure 8. R1 completed installation at Otay Mesa POE

The reading station is solar powered, and data collection started in September 2020. Figure 9 presents an inside photo of the RFID cabinet.

Figure 9. RFID Equipment cabinet at R1

Reading Station 2 (R2)

Reading station 2 is located in Aduanas Export booths. It covers a total of six lanes, 1 for FAST vehicles, 4 for Regular, and 1 for Empty trucks. This installation was performed by the local contractors and TTI Researchers during April 2021.

During the first day, all the conduits required to mount the equipment under the roof were installed, the system cabinet was previously assembled at the contractor's office, and during the second day all the equipment and cabling was mounted on the structure (Figure 10).

Figure 10. Conduit structure at Otay R2

The system cabinet was mounted on the side of the booth for easier access (Figure 11). Then, the system was tested on site and remotely to guarantee correct functionality.

Figure 11. System cabinet location at Otay R2

Reading Station 2A (R2A)

As shown on the Port of Entry diagram, there is a temporary entrance to Aduanas Export Booths, located on Calle Sor Juana Inés de la Cruz, where UCP vehicles line up to enter the facilities. The installation of this system was performed in April 2021, after receiving authorization from local stakeholders. The system was mounted on a tripod pointing towards commercial vehicles entering the facility (Figure 12). It is located on top of the entrance booth which also provided AC power to the system.

Figure 12. Otay Mesa R2A System installation

Reading Station 3 (R3)

Installation on the U.S. side for R3 was finalized in June 2018. The installation was performed during POE closing hours at the facility. During the last day of installation, ground tests were performed to validate reads and a general walkthrough with CBP officials was conducted to explain the setup, demo, and connectivity.

Figure 10 shows a layout of the setup used to cover a total of 10 lanes using 6 readers and 10 antennas with one cabinet per plaza.

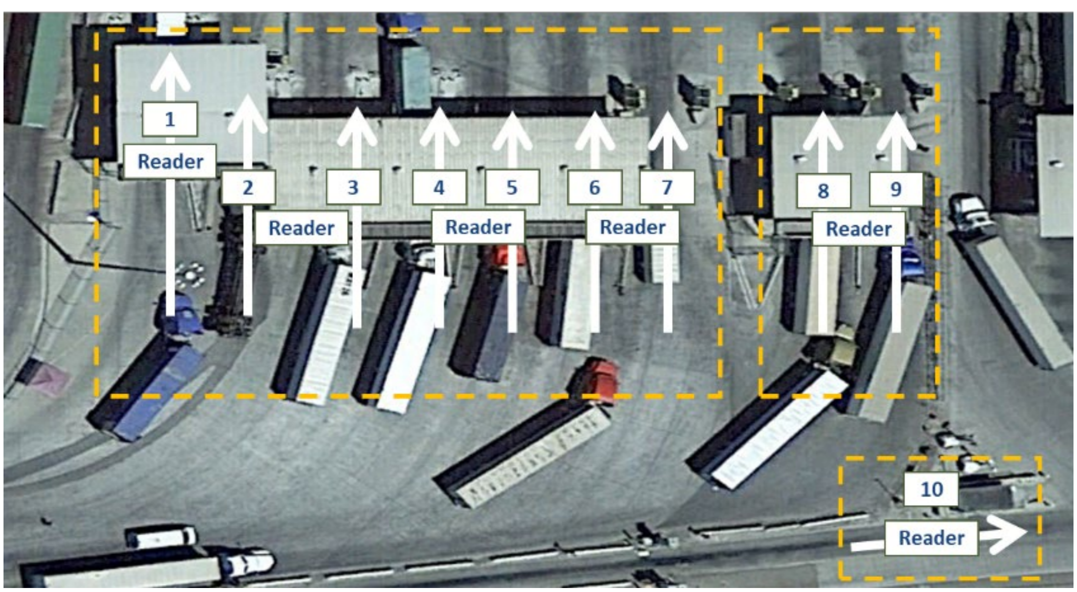


Figure 13. RFID system layout at CBP Primary in Otay Mesa

Reading Station 4 (R4)

R4 is located at the exit of the CHP vehicle safety inspection facility (Figure 11). The equipment was installed on August 2020 through a local contractor, while the RFID setup was finalized in September 2020 after a TTI researcher traveled to California to configure and test the reader.

Figure 14. Reading Station 4 at California Highway Patrol

Chapter 5:
Lessons Learned, Operation and Conclusions

This section of the report presents conclusions of this task of the project and lessons learned that could be applied for future expansion and operation of the border wait time measurement system.

LESSONS LEARNED.

The key to the success of the implementation was to have constant contact with both customs agencies, CBP and Aduana. Particularly with Aduana, as it is the Mexican government changes port directors in a regular basis. The TTI Research team was able to succeed in obtaining authorizations through a constant follow up with Aduana authorities in Mexico City as well as with local officials in Tijuana. INDAABIN, which is the Mexican equivalent to the General Services Administration, is another key agency in Mexico that needs to be involved in the process. INDAABIN owns some of the federal properties at the land port of entry and equipment installation authorizations are also required from this agency.

Once the system is installed, it is important to keep track on a regular basis of the system functionality. Cellular communication networks at the border usually fluctuate between carriers. At some locations, the Mexican cellular carrier has a stronger signal and the system roams into that carrier. The TTI Research Team has developed tools that alert of communications with the field systems are lost or interrupted.

The solar-powered sites also require a constant verification of the energy provided to the batteries. At some instance after the installation at R1 in Otay Mesa, the equipment lost power. After the TTI Research Team sent the local contractor to check the site, it was identified that dust had accumulated in the solar panels and there was not sufficient power generated to charge the batteries. The local contractor cleaned the panels, and the system was working properly again. A routine maintenance of the solar panels has been established.

SYSTEM SCALABILITY, OPERATION AND EXPANSION

The border crossing time measurement system has been implemented at other nine border crossings and has been operational for over ten years. Under a different task of this project, the TTI Research team is analyzing improvements to the system that include analyzing other technologies different to RFID. Global Positioning Systems (GPS) is a technology that could provide an infrastructure-less border wait time measurement system. The TTI Research Team will continue investigating potential implementation of a hybrid system with RFID and GPS technologies. This will reduce operation and maintenance costs, particularly for reading sites that require solar power, consequently more maintenance.

The system has proven to be scalable, for example at the Otay Mesa border crossing the system is capturing travel times for empty, regular, and FAST trucks. This is the first border crossing where this segregation of times has been implemented as there is a special truck lane for empty trucks. The system has been developed in a way that it can be scaled to serve specific needs of each border crossing. Additional reading stations could be installed in the truck route to measure travel time at other segments of the trip.

The border crossing and wait time measurement system at Otay Mesa is operational, and the system started collecting data since October 2020. System operation, as with the other nine systems along the border require data management to prepare monthly summary reports and checking all systems in the field are operational. Operation costs also include payment of communications fees for the wireless communication of routers. In another task under this project, the TTI Research Team is finalizing the system software overhaul, moving the data from a physical server to a cloud-based platform in Azure. There are costs associated with data storage and management are also part of the overall operation costs of the system. As mentioned earlier, maintenance costs also include field visits to verify the proper operation of the field devices.

CBP recently informed the TTI Research Team that current primary inspection facilities will be relocated, and additional primary inspection booths will be included in the layout. This expansion will require relocating RFID border wait time measurement equipment and adding other stations to cover all primary inspection booths. The relocation is expected to start in January 2022.

Aduana has also planned to upgrade their facilities to accommodate three more lanes to their current booths export inspection booths. This will require additional RFID equipment to the used for R2 in order to cover the future booths.

During the penetration test subtask, it was identified the CBP is issuing new RFID Tags and the current RFID readers firmware were not capable of reading the DTOPS transponders. TTI has handled this by negotiating with Transcore to upgrade the RFID readers to be capable of reading the current protocols and DTPOS transponder protocols. Additionally, TTI coordinated with local contractors to replace readers with the upgraded ones. Currently all the sites have DTOPS capable readers, except for R1 which will be replaced once they arrive from Transcore facilities.

CONCLUSIONS

As with the other border wait time measurement systems along the border, the system requires and operation and maintenance contract to secure reliable and systematic border wait time information. The operation and maintenance costs have been covered by CBP and state departments of transportation. When this contract ends, a new contract mechanism with these agencies should be implemented to secure operation continuity of the system.

Appendix A: List of Equipment

Table A-1. Equipment installed at Reading Station 1

Otay Mesa POE Crossing Travel Time Measurement - Detection Stations Summary			
Detection Station R1 - 4 lanes			
mounted at signage structure			
Item	**Make**	**Model**	**Qty**
Yagi antenna	Transcore	AA3100	4
RF power splitter (multi-lane site)	INSTOCK	PD2021	1
RF Surge Protection	Laird Connectivity Inc.	LABH2400NN	3
RFID Reader	Transcore	Encompass E4	3
RS-422 Protocol Converter	Advantech	BB-485LDRC9	3
Coax cable with connectors	Times Microwave systems	LMR-600	1
Solar panels 24VDC 250W	Suntech	STP250-20/Wd	4
Solar controller	Mornigstar	PS-30M	1
Spectre 4G router	Advantech	SmartFlex SR305	1
External cellular antenna	Laird Connectivity Inc.	TRAB806/17103	1
Remote reboot	Dataprobe	iBoot G2	1
Misc. Back panel construction parts	N/A	N/A	1

Table A-2. Equipment installed at Reading Station 2 and 2A

Otay Mesa POE Crossing Travel Time Measurement - Detection Stations Summary			
Detection Station R2 - 6 lanes/R2A 1 lane			
mounted at Aduana export booths and side entrance			
Item	**Make**	**Model**	**Qty**
Yagi antenna	Transcore	AA3100	7
RF power splitter (multi-lane site)	INSTOCK	PD2021	3
RF Surge Protection	Laird Connectivity Inc.	LABH2400NN	3
RFID Reader	Transcore	Encompass E4	4
RS-422 Protocol Converter	Advantech	BB-485LDRC9	4
Coax cable with connectors	Times Microwave systems	LMR-600	4
Spectre 4G router	Advantech	SmartFlex SR305	2
External cellular antenna	Laird Connectivity Inc.	TRAB806/17103	2
Power Supply 24VDC-240W	Meanwell	SDR-240-24	2
Remote reboot	Dataprobe	iBoot G2	2

Misc. Back panel construction parts	N/A	N/A	2

Table A-3. Equipment installed at Reading Station 3

Otay Mesa POE Crossing Travel Time Measurement - Detection Stations Summary			
Detection Station R3 – 10 lanes			
mounted at CBP Primary booths			
Item	**Make**	**Model**	**Qty**
Yagi antenna	Transcore	AA3100	10
RF power splitter (multi-lane site)	INSTOCK	PD2021	4
RF Surge Protection	Laird Connectivity Inc.	LABH2400NN	6
RFID Reader	Transcore	Encompass E4	6
RS-422 Protocol Converter	Advantech	BB-485LDRC9	6
Coax cable with connectors	Times Microwave systems	LMR-600	6
Spectre 4G router	Advantech	SmartFlex SR305	3
External cellular antenna	Laird Connectivity Inc.	TRAB806/17103	3
Power Supply 24VDC-240W	Meanwell	SDR-240-24	3
Remote reboot	Dataprobe	iBoot G2	3
Misc. Back panel construction parts	N/A	N/A	3

Table A-4. Equipment installed at Reading Station 4

Otay Mesa POE Crossing Travel Time Measurement - Detection Stations Summary			
Detection Station R4 - 2 lanes			
mounted at exit of CHP			
Item	**Make**	**Model**	**Qty**
Yagi antenna	Transcore	AA3100	2
RF power splitter (multi-lane site)	INSTOCK	PD2021	1
RF Surge Protection	Laird Connectivity Inc.	LABH2400NN	1
RFID Reader	Transcore	Encompass E4	1
RS-422 Protocol Converter	Advantech	BB-485LDRC9	1
Coax cable with connectors	Times Microwave systems	LMR-600	1
Spectre 4G router	Advantech	SmartFlex SR305	1
External cellular antenna	Laird Connectivity Inc.	TRAB806/17103	1
Power Supply 24VDC-240W	Meanwell	SDR-240-24	1
Remote reboot	Dataprobe	iBoot G2	1
Misc. Back panel construction parts	N/A	N/A	1

Appendix B: RFID Test and Evaluation Results

The following tests indicate results from the RFID readings, these were designed by the researchers considering important measurements (voltage of the system, signal, etc.), to actions or features performed on the RFID readers which help reading transponders from trucks and remote troubleshooting.

The system works at 24VDC, this measurement is important as the system should operate at equal or higher voltage to guarantee correct functioning. On the other hand, signal strength and quality are relative, quality usually operates between -10 to -20 dB while strength operates between -80 to -110 dB. Researchers configure the router to prioritize capturing 4G LTE signal close to the station but on a border crossing this might be affected due to network providers and roaming services.

Finally, the remaining tests are functions performed manually or automatically on the reader and router that are required to operate, maintain, or troubleshoot the system remotely. Passing these tests and obtaining the best signal results guarantees a correct installation and configuration.

Table 1 shows a sample of raw transponder data captured by the reading stations R1, R2 and R3 which is stored in the central subsystem encrypted through a Virtual Private Network (VPN), the other columns show the reader identifier and timestamps attached to each tag in order for the algorithm to match them and calculate a travel time between each reading station. More information about this process can be found in the Otay Mesa Penetration Test Report.

Table B-1. Transponder sample readings at Otay Mesa POE

TagId	ReaderId	ReceivedTimestampLocal	Hour
#E022465402D4CEC8	Otay_R1C	2020-10-26 06:08:14	2020-10-26 06:00
#E022465402BCF640	Otay_R3B	2020-10-26 06:08:23	2020-10-26 06:00
#E022465402FC1AFE	Otay_R1A	2020-10-26 06:08:32	2020-10-26 06:00
#E0224654032D9F29	Otay_R3D	2020-10-26 06:09:47	2020-10-26 06:00
#ASC0033042	Otay_R3B	2020-10-26 06:10:00	2020-10-26 06:00
#E022465403EF8B06	Otay_R3A	2020-10-26 06:10:22	2020-10-26 06:00
#E00400009861F507	Otay_R4	2020-10-26 06:10:44	2020-10-26 06:00
#E022465402160755	Otay_R3A	2020-10-26 06:11:06	2020-10-26 06:00
#E0224654037841A7	Otay_R4	2020-10-26 06:11:38	2020-10-26 06:00
#E022465402BCFED1	Otay_R3A	2020-10-26 06:11:48	2020-10-26 06:00
#E022465400ABEB9C	Otay_R1C	2020-10-26 06:11:52	2020-10-26 06:00
#E022465403CF287A	Otay_R3C	2020-10-26 06:12:00	2020-10-26 06:00
#E022465403811E79	Otay_R3B	2020-10-26 06:12:03	2020-10-26 06:00
#E02246540252BCFF	Otay_R1B	2020-10-26 06:36:23	2020-10-26 06:00

TESTING AT THE ENTRANCE OF THE MEXICAN IMPORT LOT

The RFID tag-reading system installed at the end of the queue on Callejón de Exportación was tested to ensure proper operation and configuration. Table B-2 documents the results.

Table B-2. Test Otay Mesa R1

Test	Measurement
24-VDC reading	28.8 VDC
Router Signal Quality	−19 dB
Router Signal Strength	−107 dBm
Tag read	PASS
Tag read reliability	See results below
Static IP	PASS
Router accessibility via Internet	PASS
Auto power cycle	PASS
Remote request power cycle	PASS
Remote configuration of reader	PASS (#00)
Wireless data transfer	PASS
Data retrieval application	PASS

TESTING AT ADUANAS EXPORT BOOTHS

The RFID tag-reading system installed at Aduanas Export Booths was tested to ensure proper operation and configuration. Table B-3 documents the tests results.

Table B-3 Test Otay Mesa R2

Test	Measurement
24-VDC reading	23.8 VDC
Router Signal Quality	−11 dB
Router Signal Strength	−99 dBm
Tag read	PASS
Tag read reliability	See results below
Static IP	PASS
Router accessibility via Internet	PASS
Auto power cycle	PASS

Remote request power cycle	PASS
Remote configuration of reader	PASS (#00)
Wireless data transfer	PASS
Data retrieval application	PASS

TESTING AT ADUANAS EXPORT LOT SIDE ENTRANCE

The RFID tag-reading system installed at Aduanas Export Lot side entrance was tested to ensure proper operation and configuration. Table B-4 documents the tests results.

Table B-4 Test Otay Mesa R2A

Test	Measurement
24-VDC reading	24.1 VDC
Router Signal Quality	−10 dB
Router Signal Strength	−84 dBm
Tag read	PASS
Tag read reliability	See results below
Static IP	PASS
Router accessibility via Internet	PASS
Auto power cycle	PASS
Remote request power cycle	PASS
Remote configuration of reader	PASS (#00)
Wireless data transfer	PASS
Data retrieval application	PASS

TESTING AT CBP

The RFID tag-reading system installed at the Otay Mesa primary inspection booth was tested to ensure proper operation and configuration. Table B-5 documents the tests results.

Table B-5. Test Otay Mesa R3

Test	Measurement
24 VDC reading	23.8 VDC
Router 1 Signal Quality	−12 dB
Router 1 Signal Strength	−83 dBm
24 VDC reading	24 VDC
Router 2 Signal Quality	−13 dB
Router 2 Signal Strength	−77 dBm
24 VDC reading	23.9 VDC
Router 3 Signal Quality	−12 dB
Router 3 Signal Strength	−85 dBm
Tag read	PASS
Tag read reliability	See results below
Static IP	PASS
Router accessibility via Internet	PASS
Auto power cycle	PASS
Remote request power cycle	PASS
Remote configuration of reader	PASS (#00)
Wireless data transfer	PASS
Data retrieval application	PASS

TESTING AT CALIFORNIA HIGHWAY PATROL

The RFID tag-reading system installed at the CHP exit was tested to ensure proper operation and configuration. Table B-6 documents the tests results.

Table B-6. Test Otay Mesa R4

Test	Measurement
24-VDC reading	23.9 VDC
Router 1 Signal Quality	−14 dBm
Router 1 Signal Strength	−96 dBm
Tag read	PASS
Tag read reliability	See results below
Static IP	PASS
Router accessibility via Internet	PASS

Auto power cycle	PASS
Remote request power cycle	PASS
Remote configuration of reader	PASS (#00)
Wireless data transfer	PASS
Data retrieval application	PASS

Integrating Multiple Technologies to Estimate Border Wait Time for Privately Owned Vehicles

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ABSTRACT

In 2019, more than 73 million privately owned vehicles (POVs) traveled across land ports of entry (POEs) between Mexico and the United States. The border crossing process is complex and having accurate and systematic information about the border crossings and wait times is important for users and agencies that manage the process in both countries. POVs traveling from Mexico into the United States through POEs can use a regular lane, a Ready Lane, or a Secure Electronic Network for Travelers Rapid Inspection lane. The current Bluetooth®-based POV border wait time measuring system that has been implemented at the U.S.-Mexico border is not capable of identifying wait time by traffic lane. This research analyzed innovative technologies that allow measuring border wait time by lane of travel and developed the concept of a new hybrid POV border wait time measuring system that integrates a global positioning system, Bluetooth, and automatic license plate readers. The hybrid system captures data across the border crossing process by identifying each user lane at the U.S. federal inspection booth and merging these data sources to provide accurate wait time estimates for each type of POV vehicle type at the U.S.–Mexico border crossings.

INTRODUCTION

In 2019, more than 73 million privately owned vehicles (POVs) crossed the border between Mexico and the United States [1]. The U.S.-bound border crossing process involves inspections by U.S. Customs and Border Protection (CBP) and payment of tolls at those crossings where there is a tolled bridge. U.S.-bound POVs pay a toll in Mexico before crossing the border and then proceed to the U.S. federal compound that is managed by CBP. At non-tolled crossings, POVs cross the border from Mexico and travel directly to the U.S. federal compound. At all POV crossings, there are three types of potential lanes that POV travelers can use:

- At the U.S.-Mexico border, CBP has implemented the Secure Electronic Network for Travelers Rapid Inspection (SENTRI) program, which provides expedited processing for preapproved, low-risk travelers entering the United States. Applicants must voluntarily undergo a thorough biographical background check against criminal, law enforcement, customs, immigration, and terrorist indices; a 10-fingerprint law enforcement check; and a personal interview with a CBP officer. SENTRI users have access to specific, dedicated travel lanes that are segregated from the rest of the traffic from Mexico into the United States [2].
- Ready Lanes are reserved for travelers with radio frequency identification (RFID)-enabled documents. These are dedicated processing lanes for Ready Lane–eligible travel cards. Ready-eligible travelers can save time at the border by navigating to designated Ready Lanes, keeping their eligible travel cards in hand, and displaying cards to the in-lane RFID card readers before proceeding to a CBP officer for inspection at a primary inspection booth.
- Travelers without a Ready-enabled document or who are not part of the SENTRI program are directed to the regular inspection lanes.

Regular and Ready Lane users are comingled in the queue in Mexico and then divided once the vehicle approaches the CBP primary inspection booth. SENTRI users have a segregated lane all the way from Mexico.

The Texas A&M Transportation Institute, with support from the Federal Highway Administration, the Texas Department of Transportation, and CBP, developed and implemented a system to measure border wait time for POVs entering Texas from Mexico based on Bluetooth® technology. The Bluetooth-based POV border wait time measurement system currently in operation is not able to differentiate wait times among the three types of POV travelers who cross the border from Mexico into the United States. Figure 1depicts a typical POV border crossing at the Texas-Mexico border that includes an international bridge with a toll collection booth in Mexico.

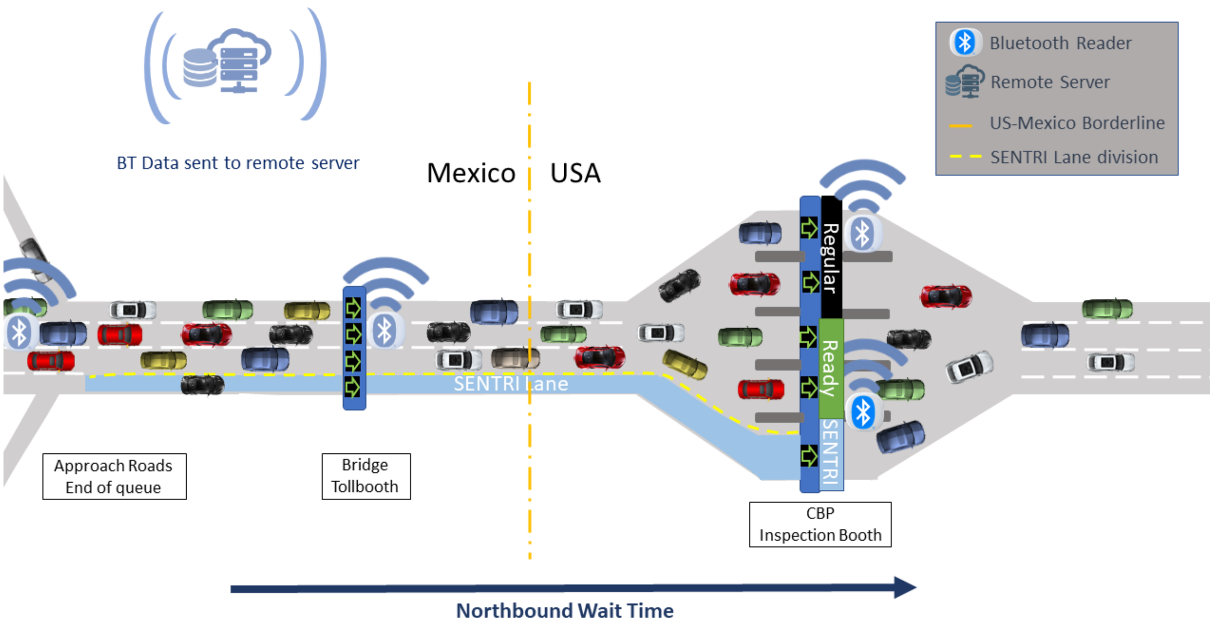

Figure 1 Illustrated sketch of Bluetooth-based wait time measurement system for POVs

The system that is currently in operation requires roadside equipment to identify Bluetooth signals emanating from mobile devices on board POVs or devices in a vehicle itself at several fixed locations. The majority of mobile phones already have embedded Bluetooth technology. Figure 1 shows the overall concept of the Bluetooth-based border wait time measurement system for POVs at land ports of entry (POEs). Several Bluetooth reading stations are strategically placed in Mexico at the actual border crossing and at the CBP inspection facility. Queues form in Mexico at the various approach roadways that lead to the POE. Bluetooth readers are placed as far south of the border as possible to detect the end of the queue.

The Bluetooth protocol is a widely used, open-standard, wireless technology for exchanging data over short distances. The technology is frequently embedded in mobile telephones, global positioning systems (GPSs), computers, and in-vehicle applications such as navigation systems. Each Bluetooth device uses a unique electronic identifier known as a media access control (MAC) address. Conceptually, as a Bluetooth-equipped device travels along a roadway, it can be anonymously detected at multiple points where the MAC address, time of detection, and location are logged. By determining the difference in detection time of a particular MAC address, the wait time and average travel speed between locations can be derived.

This paper describes research conducted to develop a system capable of measuring U.S.-bound POV wait times by traffic lane. The research first conducted a literature review that identified various technologies that could be used to meet the research objective. These technologies were evaluated, and those technologies that have potential to be used at the border were identified. A hybrid system was developed that combines multiple technologies by incorporating the location of field devices and the system configuration, including data streams.

TECHNOLOGY ASSESSMENT

In order to identify potential technologies that could be used to more accurately measure wait time at land POEs, a literature review was conducted based on the following criteria: (a) technologies and processes that can be used for vehicle detection, (b) wait time estimation, and (c) tolling systems. The literature review identified past, current, and emerging technologies that can be used to measure wait time and estimate wait times by identifying a vehicle at different stages during the border crossing. The analyses resulted in identifying a few technologies that were reviewed to identify their advantages and disadvantages to measure wait times of POVs at land POEs. These technologies include GPS, connected vehicle technology, automatic license plate readers (ALPRs), and RFID.

Global Positioning System

GPS technology uses over 30 navigation satellites circling Earth to locate or provide a geolocation to a GPS receiver anywhere on Earth. These satellites continuously transmit a radio signal with time and data of location coordinates. The user's GPS receives all data with direct sight to the receiver and determines position based on the time it takes the signal to reach the receiver (Figure 2).

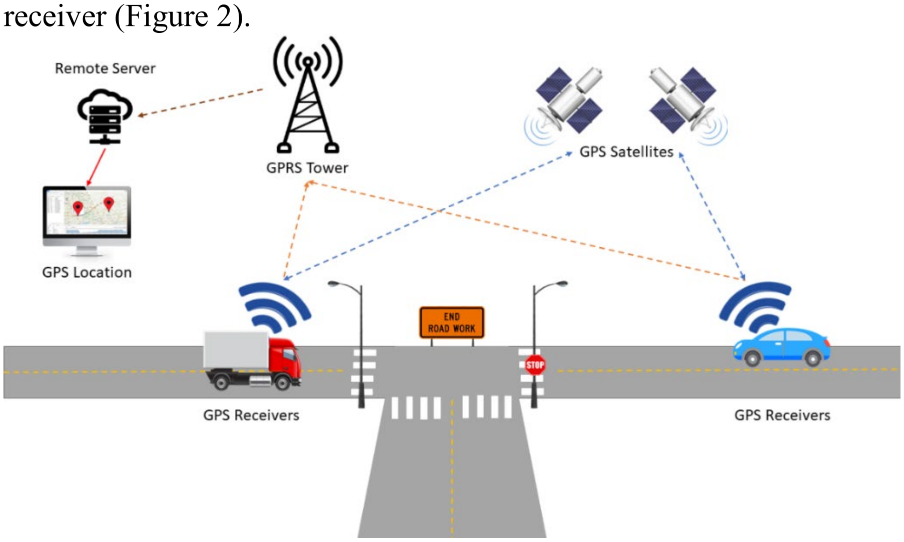

Figure 2 GPS satellite ranging

The implementation of GPS technology in vehicles and mobile devices has increased over the years, which makes it a strong candidate for wait time estimation. The increased use of vehicle satellite navigation and tracking systems in mobile devices and personal vehicles benefits manufacturers, companies, and agencies by creating large datasets of useful information that help to develop optimized methods for wait time estimation and more reliable transportation systems. GPS technology systems have been implemented to predict and estimate travel time for highways, bus routes, and border crossings [3] [4].

Connected Vehicle Technology

Connected vehicles are equipped with dedicated short-range communications (DSRC) that operate using the Federal Communications Commission–granted 5.9 GHz band. These devices provide a set of important data to nearby vehicles or roadside units (RSUs). The data are utilized for traffic and travel time estimation [5]. In addition, they help to manage initiatives aimed at improving safety and mobility by intelligent transportation systems [6]. Connected vehicle technology is able to capture, transmit, and receive traffic information and car data, such as location and speed, through communication protocols known as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) (Figure 3) [7]. These protocols use cellular networks, Wi-Fi, satellite, or DSRC as the means to transfer data between the devices and vehicles. Connected vehicle technologies and data collection approaches provide improvements to transport efficiency, route assessment, productivity, and travel time estimation [8].

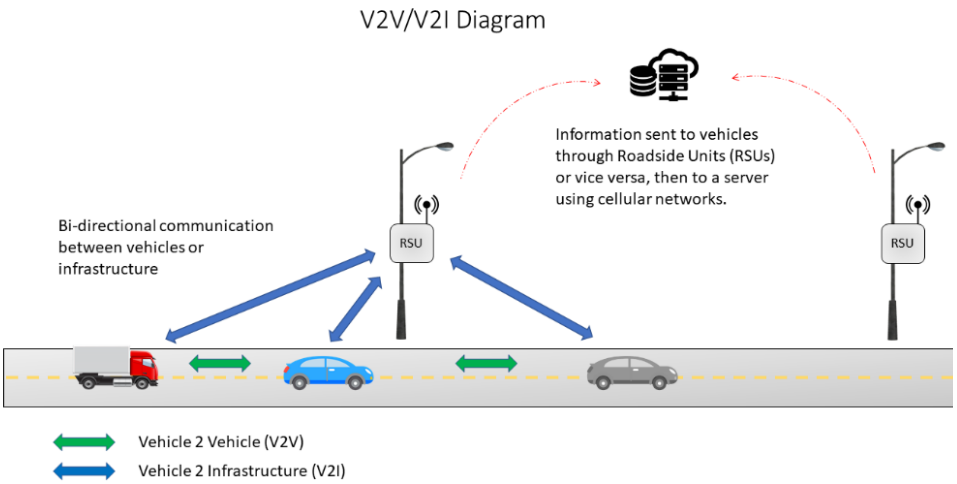

Figure 3 V2I/V2V technologies diagram

However, the increase of autonomous vehicles and technologies requires an infrastructure capable of handling all the data exchanges between RSUs and other vehicles. Newer levels of automation require major support from infrastructure in order to ensure that information provided to drivers and autonomous systems can be interpreted properly and respond adequately to different circumstances. In addition, the increased use of connected vehicle technologies results in high samples of data and costs in storage systems [9].

Automatic License Plate Readers

The ALPR system works by electronically recording the front and rear license plates of vehicles. This technology uses optical character recognition, which is a process to convert text into machine-encoded text. The process consists of an algorithm that processes the text and identifies each character according to the algorithm data. Such algorithms are used on images to read and identify the plate numbers of passing vehicles [10]. This technology mostly relies on a video camera (e.g., surveillance and infrared) to identify the plate number. ALPRs have been used at POEs to identify stolen cars but have the potential to be used to identify vehicles for vehicle tracking and wait time estimation [11]. Figure 4 shows an interface of the vehicle and license plate recognition integrated with an ALPR.

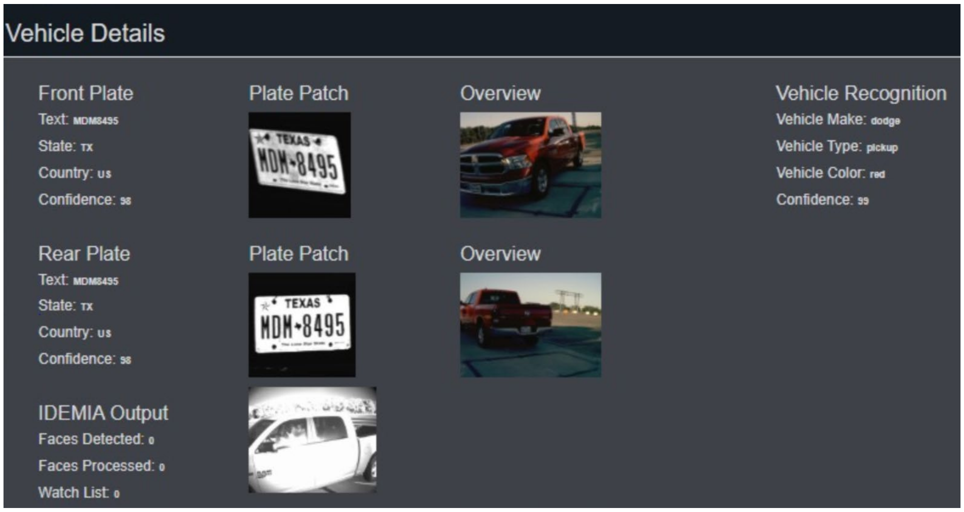

Figure 4 ALPR vehicle recognition interface

Radio Frequency Identification

RFID technology requires a reader and a transponder or tag. The reader broadcasts an interrogation signal from its antenna. When a transponder comes within the antenna's coverage range, the transponder returns the signal to the roadside reader with the RFID tag identification number. The information is time stamped and then retransmitted for further processing and storage.

By using a reader at the entrance to the border crossing and one at the exit, time-stamped data can be gathered on individual vehicles and used to calculate border crossing times. The RFID readers are not affected by adverse weather conditions; however, the transponders must be within 18 feet of the reader for data to be collected. RFID technology requires distributing tags to border users to measure wait/crossing times.

Technology Comparison

These technologies were evaluated in terms of cost (maintenance, equipment, and installation), accuracy, availability, and reliability. Each technology has strengths and limitations that make them suitable for different applications. Table 1 shows a brief description of the advantages and disadvantages of the potential candidates and other characteristics.

Table 1 Summary of Advantages and Disadvantages of Potential Technologies

Technology	Advantages	Disadvantages
Bluetooth/ Wi-Fi	• Widely used by vehicles and occupants • Does not interfere with user privacy • Low maintenance • Short-range antennas improve accuracy • Wi-Fi sensors considerably outperform Bluetooth when capturing MAC addresses, especially in low-traffic areas	• Does not identify vehicle lanes during traffic flow • Can collect non-vehicle data that bias the sample • Small detection range • Requires relatively large sample size (proportion of active devices per vehicle)
GPS	• Built into modern vehicles and portable devices • Ideal for predicting traffic congestion and estimating travel time on most roads • Combining this technology and a sensor provides reasonable estimates of the traffic stream	• Real-time data need to be sent continuously • Hardware upgrades are needed if accuracy is important • If app-based, requires users to permit continuous data to be sent • Vehicle identification accuracy is low at dense-traffic areas
ALPR	• If integrated with an algorithm, can detect license plate numbers in complex traffic situations • Only technology able to differentiate and reidentify vehicles on roads by itself • Can detect license plates at high and low speeds	• Depending on the manufacturer, can be affected by sunlight, night, or different weather conditions • May be affected when license plates are placed differently or deformed
RFID	• Reidentification capabilities based on the ID of the tag for each vehicle • Can detect the lane used by the vehicle while passing across the booths • Does not require a high processing algorithm or devices	• Requires direct sight from the antenna to the tag to work properly • RFID tags are not always present on POVs • Multiple RFID tags present in a vehicle can generate wrong data or small samples • Performance might be affected if multiple systems are using the same frequencies

The three technologies that have potential to effectively measure wait time at the border crossings are ALPR, Bluetooth/Wi-Fi, and GPS. Data obtained individually by Bluetooth technology are not enough to meet a considerable sample for wait time estimation and are unable to differentiate wait times among the three types of POV travelers who cross the border from Mexico into the United States. ALPRs have a constant high capture rate capable of identifying vehicles and the lane in which each vehicle is traveling.

GPS has proven reliable for data collection in real-time applications having a high penetration rate and for increased accuracy if combined with floating sensor networks. This reliability is achieved by collecting data through mobile networks and road sensors at specific locations where the GPS signal needs greater accuracy for granular detection. All these data are processed through a data fusion algorithm to achieve an improved result. GPS data can be processed into useful information if the correct data processing algorithm was executed considering traffic variables and route segments.

These three technologies perform well by themselves in specific situations. However, in a border crossing environment, the research team found that the best results for POV detection can be obtained using a combination of technologies to provide enough data to calculate wait time, similar to other research studies that have shown significant increases in overall accuracy of various systems by using combined technologies [12] [13]. The process—known as data fusion—involves putting together multiple data from different sensors or technologies to generate a consistent or accurate result rather than relying on a single technology system configuration. Research on this technique has increased and shows that it provides better accuracy of sensor readings or technology data for wait time.

PROPOSED HYBRID POV BORDER WAIT TIME MEASURING SYSTEM

The proposed hybrid border wait time measuring system (HBWTMS) utilizes different technologies that complement each other and jointly provide a more efficient, accurate, and cost-effective solution. The concept of the hybrid system includes measuring vehicle wait time from the end of the queue in Mexico to the time vehicles exit the CBP primary inspection in the United States. The hybrid system utilizes primary information obtained from Bluetooth/Wi-Fi and ALPR infrastructure installed along the trip path and secondary information from GPSs obtained from third-party providers. To estimate travel and wait times by traffic lane, two main variables need to be measured:

- **Vehicle wait time**: To accurately measure wait time, vehicles must be detected at different points during the border crossing trip to provide a total wait time.
- **Lane detection**: To estimate crossing or wait time for each type of POV lane (SENTRI, Ready, or regular) at the CBP primary inspection booth, the designated lane must be determined.

Three points of measurement are needed in order to accurately measure wait time at land border crossings by lane type (Figure 5):

- **Phase 1: Vehicle approach**. At the end of the queue in Mexico, vehicles line up on a road that combines all types of users into multiple lanes, depending on the roadway configuration. An analysis of multiple border crossing configurations shows that, at this point of the trip, it is not possible to differentiate vehicle types since there are multiple approach roads and vehicles are bunched close together, making it difficult to use a license plate reader. Consequently, using GPS data obtained from a third-party source is the best technology at this location since their estimated times can be fused with data from the following phases to calculate an overall wait time.
- **Phase 2: Vehicle reidentification**. Once vehicles reach the tollbooth, they will select lanes according to the user type (Ready or regular). SENTRI vehicles are already segregated at

this point of the trip. The distance from this point to the final lane decision point varies from POE to POE. It is recommended that an ALPR and a Bluetooth/Wi-Fi reader be installed at this point to identify the vehicle at the tollbooth in Mexico [14]. This point is the most effective location given that vehicles must stop at the tollbooth, thereby resulting in enough clearance between vehicles to allow the ALPRs to capture the license plate number and add a time stamp. Moreover, the Bluetooth/Wi-Fi system can capture MAC addresses to correlate the data during the following phase.

- **Phase 3: Vehicle detection and data matching**. When vehicles reach the CBP primary inspection booth, MAC identifications are captured again to match addresses with the previous Bluetooth/Wi-Fi reading station, and ALPRs are used to identify the lane that each vehicle is using for the crossing. Cumulative information gathered from these four technologies (GPS, Bluetooth, Wi-Fi, and ALPR) is continuously sent to the server to be processed and fused for a stronger and more accurate estimation of wait time. It has been proven that additional data elements from multiple reading stations and technologies increase the accuracy of the system when combined [15] [16].

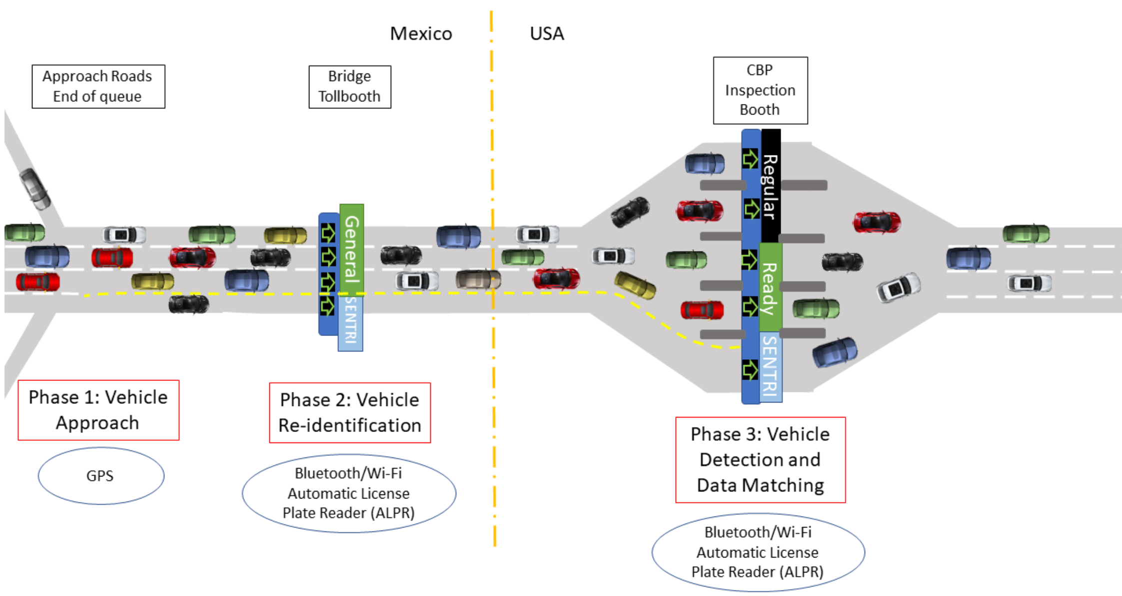

Figure 5 POV technology phases

The reidentification phase can only be done if a unique feature from every vehicle is provided because vehicles share many similar characteristics due to mass production. The system relies heavily on the ALPR capabilities of identifying vehicles by the license plate number and reidentifying them when passing by another point that again registers the license plate number. The information is matched, and the wait time is calculated. This technique does not require identifying the entire vehicle population to estimate wait time; only a sample is needed to have an accurate estimation.

This reidentification phase is important, particularly for Ready and regular POVs crossing the border because the traffic for these two programs does not separate until the last part of the trip. Regular and Ready vehicles separate when they reach the CBP primary inspection booth; SENTRI travelers have a dedicated lane that is segregated from other traffic from Mexico until they reach the CBP primary inspection booth.

The U.S.-bound POV trip can be broken in two main segments (see Figure 6): (a) the approach segment that occurs in Mexico on the various roadways that lead to the border and reaches the tollbooth in Mexico or before the border line (A-B), and (b) the second part of the trip as the vehicle travels from the tollbooth in Mexico or before crossing the border to the CBP primary inspection booths (B-C).

Figure 6 shows the structure of a typical POV hybrid border wait time measuring system. GPS data sources are used to calculate Segment A-B travel time. This segment of the border crossing trip comprises roads that lead to the border crossing (usually a tollbooth is located before international bridges at the Texas-Mexico border). Travel time at Segment B-C is measured through a combination of two technologies. ALPRs will differentiate and identify the actual travel lines of each vehicle, while Bluetooth/Wi-Fi technology will capture MAC vehicle addresses and a time stamp.

A second ALPR-Bluetooth/Wi-Fi reading station is installed at the CBP primary inspection booth. License plate numbers and lane information are captured by the ALPR, and MAC addresses and time stamps are collected by the Bluetooth/Wi-Fi station.

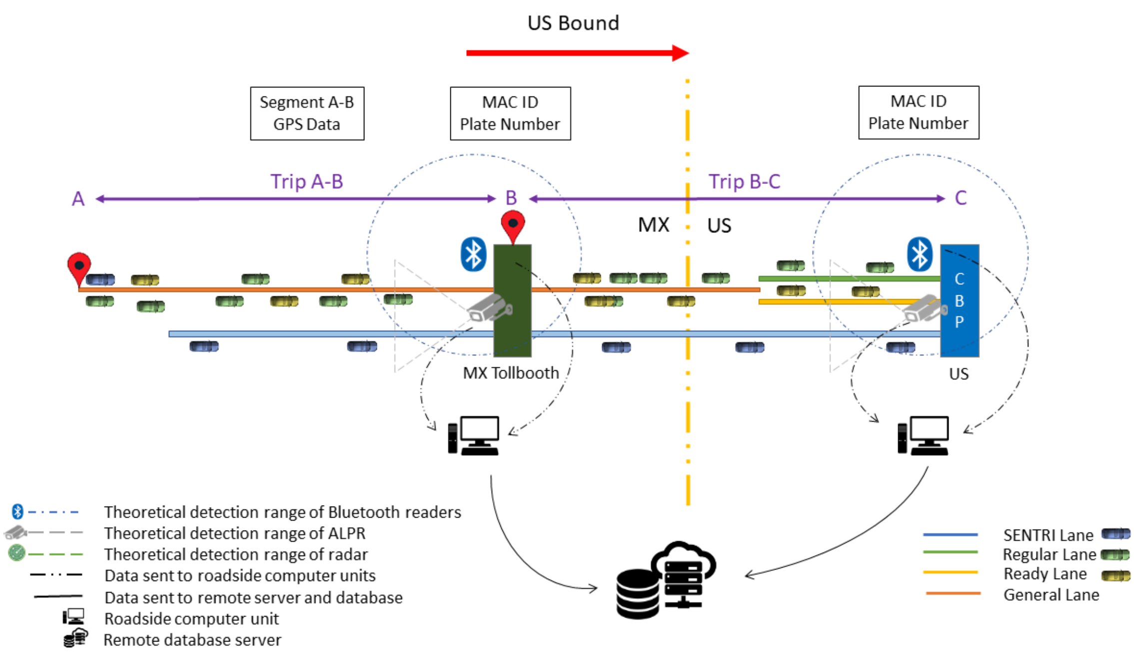

Figure 6 Hybrid border wait time system dataflow

The backend of the system is composed of a centralized database in which the data captured from all the different sources are stored. Before the server stores data, it will process received packages to organize them by source and date and to eliminate wait time outliers and misread data. The matching algorithm of the system will be able to match data across sources based on the time stamp of each record. For example, if the database contains records with the same time stamp for Segments A, B, and C in that order, and for Segment A it has a travel time coming from ALPR, for Segment B it has a travel time coming from Bluetooth, and for Segment C it has a travel time coming from GPS, then the system will add these three records and consider that as the wait time of the whole segment. Therefore, the proposed database structure for the system will have a warehouse architecture in which data can be matched and merged based on time stamps. In addition, the algorithm will be capable of estimating wait time by lane type, matching license plates, and MAC IDs.

CONCLUSION

The HBWTMS possesses the potential to enhance POV border wait time measurement by providing wait time estimates by vehicle type (SENTRI, Ready, or regular). Other benefits of the proposed POV hybrid system are:

- The system will increase reliability and uptime by having data obtained from a structureless source. Using GPS information to estimate wait times greatly reduces the need for fixed stations outside of the Mexican and U.S. toll booths, where scarce power sources are available, and the reading stations are prone to vandalism, accidents, and malfunctions.
- Future installations can be designed with only two sets of reading stations, resulting in planning, installation, maintenance, and operation cost savings.
- CBP already has ALPRs at the primary inspection booths. If that information is made available to the HBWTMS, only one additional set of ALPRs reading station is needed to estimate wait times by lane of travel.
- Using structureless sources and physical reading stations means reduced or no maintenance/operation costs.
- Combining technologies provides enough data for the system algorithm that fuses the datasets to estimate a more accurate wait time for POV border crossings while also considering lane of travel.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design—Carlos Silva, Jose Rivera Montes de Oca, Daniel Escoto, Juan Carlos Villa; literature review analyses—Daniel Escoto, Juan Carlos Villa; hybrid system proposal—Carlos Silva, Jose Rivera Montes de Oca, Daniel Escoto; draft manuscript preparation—Carlos Silva, Jose Rivera Montes de Oca, Daniel Escoto, Juan Carlos Villa. All authors reviewed the results and approved the final version of the manuscript.

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Measuring Border Wait Time At Land Ports Of Entry: Technology Assessment And Data Dissemination

Identify Improvements to POV Border Wait Time Measurement

Prepared by

Texas A&M Transportation Institute

Prepared for

BTI Institute
Borders • Trade • Immigration
A Department of Homeland Security Center of Excellence

September 2020

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1. Introduction

Bluetooth® technology is currently used to measure privately owned vehicle (POV) border wait time at land border crossings. This technology does not allow differentiating travel times among the three types of POV travelers that cross the border from Mexico into the United States:

- Secure Electronic Network for Travelers Rapid Inspection (SENTRI),
- Ready, and
- regular.

Objective

The main objective of this task of the project was to investigate technologies that could be used to disaggregate travel times by lane type at POV border crossings. During this part of the project, the research team performed a technology assessment and selected several technologies to build a prototype system that was tested at the Texas A&M University System RELLIS Campus to determine the performance of the selected technologies under a controlled environment. This Bluetooth analysis report documents three milestones of the project:

- M.4. POV research prototype
- M.5. POV research test
- M.6. Bluetooth analysis report

This report also includes recommendations and next steps to perform a test at a border crossing in future phases of the project.

Report Organization

The report is organized following the research methodology. Chapter 2 presents the POV border crossing process, describing the different types of travelers that are under analysis (SENTRI, Ready, and regular). Chapter 3 describes the Bluetooth-based border measuring system that is currently being used. These two chapters serve as the background information that is the foundation for the definition of the research objective presented in Chapter 4.

Chapter 5 presents the methodology and results from a literature review that was conducted to identify potential technologies that could be used to solve the research problem, and Chapter 6 presents the results of the technology assessment. The results of the technology assessment identified three technologies that in combination will provide sufficient information to measure POV wait times by travel type. A research prototype was developed, and Chapter 7 shows the proposed design.

Chapter 8 presents the design and results of the technology test that was conducted at The Texas A&M University System RELLIS Campus. Chapter 9 presents conclusions and recommendations for future research.

2. Privately Owned Vehicle Border Crossing Process

More than 76 million POVs crossed the border between Mexico and the United States in 2018 [1]. The U.S.-bound border crossing process involves inspections by U.S. Customs and Border Protection (CBP) and, at some crossings where there is a tolled bridge, paying tolls (Figure 1). At international tolled bridges, POVs pay a toll in Mexico before crossing the border and then proceed to the U.S. Federal Compound. At non-tolled crossings, POVs cross the border and travel directly to the U.S. Federal Compound.

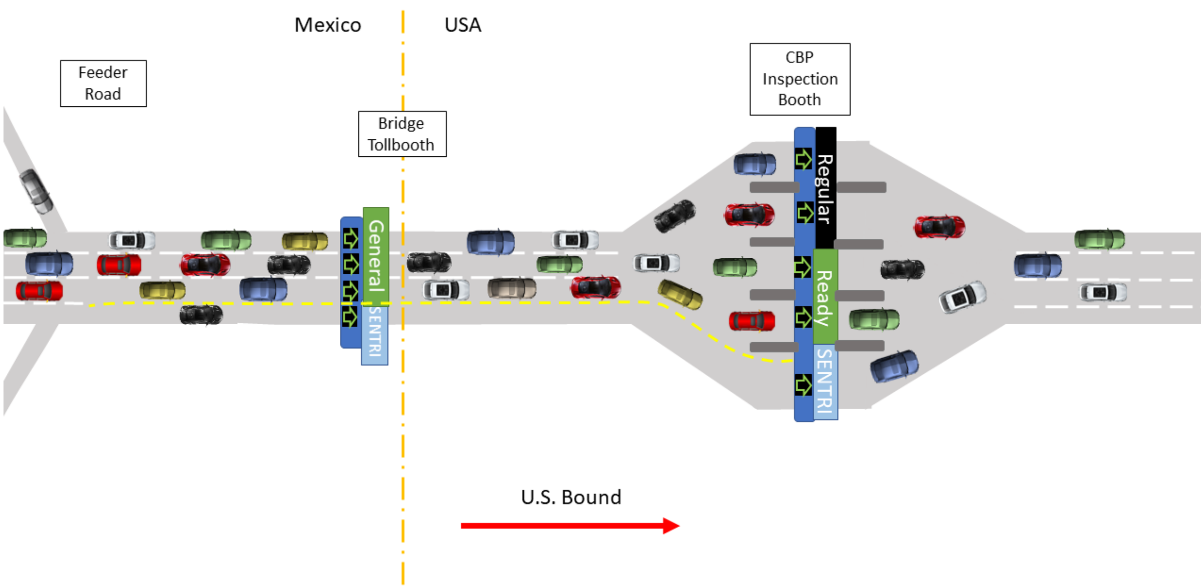


Figure 1. Diagram of a Typical POV Border Crossing

At the U.S. Federal Compound, POVs must go through primary and sometimes secondary inspections. At the primary inspection booth, CBP officers ask the individuals who want to enter the country to show proper documentation (i.e., proof of citizenship) and state the purpose of their visit to the United States. If necessary, CBP officers direct the vehicle to secondary inspection.

At the primary inspection booth, automatic license plate recognition (ALPR) scanners identify the vehicle, and computers perform queries of it against law enforcement databases that are continuously updated. A combination of electric gates, tire shredders, traffic control lights, fixed iron bollards, and pop-up pneumatic bollards ensure physical control of vehicles intending to cross.

At the secondary inspection station, a much more thorough investigation of the identity of those wanting to enter the United States and the purpose of their visit is performed. During this step, individuals may also have to pay duties on their declared items. Upon completion of this step, access to the United States is either granted or denied.

CBP's Trusted Traveler Program for POVs entering through the U.S. southern border is SENTRI, which provides expedited processing for pre-approved, low-risk travelers entering the United States [2]. Applicants must voluntarily undergo a thorough biographical background check against criminal, law enforcement, customs, immigration, and terrorist indices; a 10-fingerprint law enforcement check; and a personal interview with a CBP officer.

Once an applicant is approved, a radio frequency identification (RFID) card is issued to the traveler. A sticker decal is also issued to be affixed to the applicant's vehicle. SENTRI users have access to specific, dedicated travel lanes that are segregated from the rest of the traffic from Mexico into the United States.

When an approved international traveler approaches the border in the SENTRI lane, the system automatically identifies the vehicle and the identity of its occupant(s) by reading the file number on the RFID card. The file number triggers the participant's data to be brought up on the CBP officer's screen. The CBP officer verifies the data, and the traveler is released or referred for additional inspection.

Travelers with an RFID-enabled document are allowed to use Ready Lanes, which are dedicated processing lanes for Ready-Lane-eligible travel cards, including the following:

- U.S. passport cards,
- enhanced driver's licenses,
- enhanced tribal cards,
- enhanced border crossing cards,
- enhanced permanent resident cards,
- and Trusted Traveler Program (NEXUS, SENTRI, Global Entry, or Free and Secure Trade) cards

Ready-eligible travelers can save time at the border by navigating to designated Ready Lanes, keeping their eligible travel cards in hand, and displaying cards to the in-lane RFID card readers before proceeding to a CBP officer for inspection at a primary inspection booth [3].

Travelers that do not have a Ready-enabled document or are not part of the SENTRI program are directed to the regular inspection lanes. Figure 1 depicts a typical POV border crossing at the Texas-Mexico border that includes an international bridge with a toll collection booth in Mexico.

Wait time is defined as the time elapsed between a preestablished location on the Mexican side, as far back as possible from the border where the queue usually ends, and the United States CBP primary inspection booth. The border wait time depends on several factors, including the number of CBP primary inspections in operation, traveler demand at certain times of day, and the type of traveler—SENTRI, Ready, or regular.

3. Bluetooth-Based Border Wait Time Measurement System

Border wait time and crossing time are currently measured using Bluetooth technology or a combination of Bluetooth and Wi-Fi technologies. Considering most POVs nowadays have Bluetooth technologies integrated in the vehicle or occupants' phones, a vehicle could be detected by installing Bluetooth and Wi-Fi sensors that use antennas and readers to check regularly for signals at different points during the border crossing trip. These signals can be emitted from POVs or mobile devices carried by vehicle occupants.

When a mobile phone has Bluetooth or Wi-Fi enabled, it shares its media access control (MAC) address to try to connect with any nearby device. The Bluetooth/Wi-Fi reading station detects the device and captures its MAC address, and then the information goes to a server through the broadband cellular network and gets a time stamp. The same process is repeated at each reading station. The MAC identification information from consecutive reading stations is matched, and a computer algorithm calculates the travel time between each station. The algorithm refreshes the travel time estimation every 10 minutes, and the information is disseminated to the public via the Border Crossing Information System at https://bcis.tti.tamu.edu/ (Figure 2 and Figure 3).

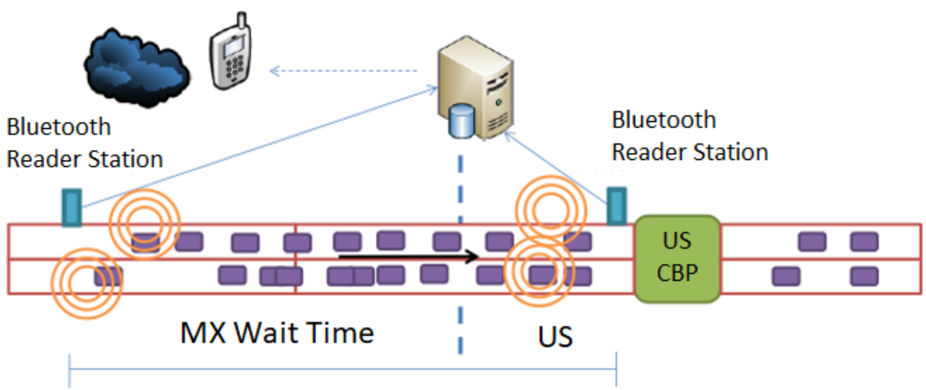


Figure 2. Illustrated Sketch of Bluetooth-Based Wait Time Measurement System for U.S.-Bound POVs

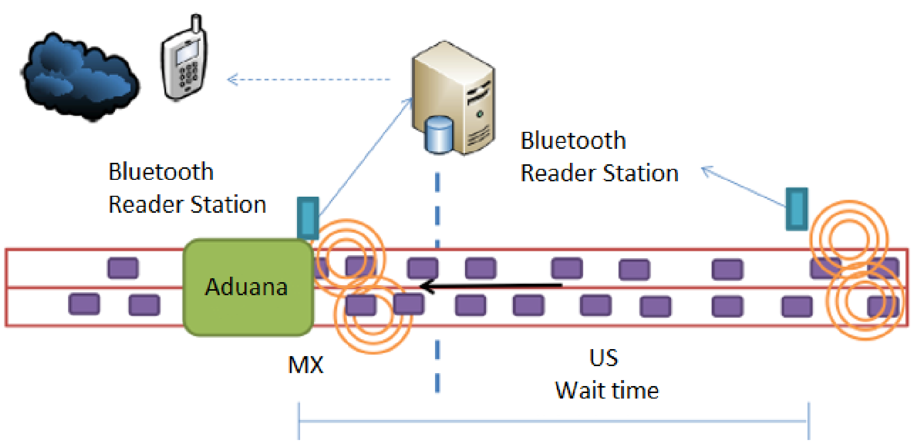


Figure 3. Illustrated Sketch of Bluetooth-Based Wait Time Measurement System for Mexico-Bound POVs

The system to measure wait time is organized into three subsystems representative of each component's function. The three subsystems are:

- Field Subsystem
- Central Subsystem
- User Subsystem

The Field Subsystem is comprised of field stations to identify POVs at different strategic locations. Field stations read vehicle identifications and pass the data to the Central Subsystem via the communication equipment. The Central Subsystem receives vehicle identifications from field stations and performs all processing to derive and archive the aggregate travel times between the stations. The User Subsystem interacts with the Central Subsystem to provide an internet web portal for data users (stakeholders, the public, etc.) to access current border wait and crossing times and archived data.

Unfortunately, the technology that is currently used cannot differentiate between the POVs using the SENTRI, Ready, or regular lanes. Also, the current configuration does not support the ability to identify if the system is not reading because there are no vehicles crossing the border or if there are no Bluetooth/Wi-Fi reads because traffic is so congested that vehicles cannot move. These issues could be solved through a combination of different technologies.

4. Research Objective

The research objective of this project was to improve the current border wait time measurement system by:

- identifying travel time for each of the different types of lanes (SENTRI, Ready, or regular) used by POVs crossing the border from Mexico into the United States
- identifying if vehicles are crossing the border and system status.

In order to estimate travel and wait times by traffic lane, two main variables need to be measured:

- **Vehicle travel time**: To accurately measure travel time, vehicles must be detected at different points during the border crossing trip to provide a total travel time.
- **Lane detection**: To estimate a travel or wait time for each type of POV (SENTRI, Ready, or regular), the specific lane type that the vehicle uses at the CBP primary inspection booth has to be identified. This is important, particularly for Ready and regular POVs crossing the border, because the travel type is determined during the last part of the trip, close to CBP primary inspection; SENTRI travelers use a separate lane that is segregated from other traffic all the way to the Mexican side of the border.

5. Literature Review

Objectives and Method

A literature review on vehicle detection, travel time estimation, and automated tolling was performed and provided an overview of technologies and methods used to solve similar issues related to this project's objective. The purpose of this research was to identify current, new, and emerging technologies that could be used to measure travel time and estimate wait times by identifying vehicles' locations.

The objectives of the literature review were to:

- identify technologies and processes that could be used to measure vehicle detection, travel time estimation, and tolling systems.
- analyze technology applicability for the border crossing environment.
- compare each technology to identify advantages and disadvantages when applying them in the POV border crossing environment.

A comprehensive assessment of current technologies applied to vehicle detection was conducted with the purpose of measuring travel time at border crossings for POVs. A systematic review method was used to gather available literature, analyze the technologies used, and compare them to identify their advantages and disadvantages.

The Texas A&M Transportation Institute (TTI) research team examined more than 100 references on vehicle detection; identified many different variables, technologies, and crucial data; and then created a table to organize the literature reviewed. Three searches were performed, through the Transportation Research International Database, Institute of Electrical and Electronic Engineers (IEEE), and Google Scholar, regarding vehicle detection technologies, vehicle travel time estimation, and automated tolling from the last 5 years.

Main Technologies

The results indicated that multiple technologies could be used for this project. To produce better estimates, the system required more data coming from sensors or readers. In addition, while there are more cost-effective technologies, they cannot be used for vehicle re-identification because either they can be affected by weather conditions, or their data reliability can be impacted if the field of view or illumination is not adequate [4] [5].

The following technologies should be tested in different circumstances, especially high traffic volume since that is a typical characteristic at border crossings:

- light detection and ranging (LiDAR) sensor.
- Bluetooth
- Wi-Fi
- global positioning system (GPS)

- video camera
- radar sensor
- inductive loop detector
- ALPR

Many research articles suggest that these technologies should be used together and in conjunction with different algorithms in order to obtain optimal results or improve the overall results. These technologies have been widely used in many applications for traffic automation, such as toll collection systems, vehicle detection and classification, traffic estimation, and route detection.

Some of these technologies are being used for toll roads or border crossings. Bluetooth and Wi-Fi have been used for POV detection due to the low-cost of implementation and ease of maintenance. Some technologies are used for traffic and route estimation, and their use in daily commuting is increasing, while others have been implemented in transportation-related settings such as traffic lights, intersections, highways, and logistics.

For the purpose of this research, these technologies were reviewed and analyzed to identify their advantages and disadvantages in POV detection (a complete analysis of technologies can be found in the Appendix). The following is a general description of the main technologies mentioned in the research articles.

LiDAR Sensor

Light Detection and Ranging (LiDAR) technology is a laser-based system that illuminates the target zone and uses return times for reflected light to create three-dimensional (3D) models. LiDAR data is used to calculate or measure variables such as distance, speed, direction, and traffic volume. The sensor may vary depending on the manufacturer, but its main component is a laser light that can be integrated with other systems to identify the mentioned variables and their environment. In addition, these devices are small compared to other sensors, which means that they can be placed either on a gantry or at the side of the road depending on the traffic and the desired data.

Bluetooth

This wireless technology is used for mobile devices to communicate over short distances via short-wavelength, ultra-high-frequency radio waves and personal area networks. Bluetooth is considered a wireless RS-232 protocol replacement. Bluetooth devices use a master/slave role, a master Bluetooth device can communicate with a maximum of seven devices, and these devices can also switch roles during connection.

Due to the rise of this wireless radio wave technology in everyday use, Bluetooth devices are becoming increasingly cost effective. The technology is equipped in headsets, vehicle radios, mobile phones, laptops, and more, which indicates that a great percentage of users crossing over the border will be detected and a good sample of data can be captured.

Wi-Fi

This technology works in a similar way to Bluetooth since both are wireless technologies based on radio waves. The main difference is that Wi-Fi was implemented as a replacement for local area networks, while Bluetooth is intended for portable equipment. Wi-Fi has grown in many industry, home, and portable applications and can readily be found in daily use devices (i.e., mobile phones and laptops).

During the process of connection/pairing, both Bluetooth and Wi-Fi use a media access control (MAC) address to communicate with the device and specify both the destination and the source of each data packet sent when communicating. This process does not need any user intervention beyond just having Wi-Fi/Bluetooth enabled in the devices and does not affect user privacy.

GPS

The Global Positioning System (GPS) technology uses satellite radio navigation to locate or provide a geolocation to a GPS receiver anywhere on Earth when four or more satellites have a direct sight to the receiver. These satellites continuously transmit a radio signal with time and data about position. The user’s GPS receives all these data from different satellites and determine position; the more satellite data collected, the more accurate the position.

This technology developed a while back, however, it was until 2000s that this technology fully developed and started appearing in luxury cars, and some mobile phones by 2010. According to Statistic Brain Research Institute, 82% of people use their phones for GPS app usage.

Video Camera

This technology is widely known due to its use in many industries. When it comes to vehicle detection, video cameras are used simultaneously with another hardware or software technology since they can only record video at the location where they are placed.

The most common use of this technology is to equip a camera with an infrared (IR) sensor, which helps with night vision or when there is insufficient light to record clearly. Once the data are captured, an algorithm processes the video and identifies the desired variables. This can be done in real time for continuous surveillance.

Radar Sensor

Radio detection ranging (RADAR) technology works via the same principle as a LiDAR sensor, but it uses radio waves instead of laser light to determine the range, angle, or velocity of the target. A radar sensor comes with a transmitter that emits radio or microwaves and an antenna that receives the radio signal and measures time of travel or any other variable according to the manufacturer.

Radars are used widely for different applications and, depending on the variable to measure, use different effects and algorithms to process radar signals and measure distance or speed.

Inductive Loop Detector

This in-road technology helps detect vehicles that pass through using alternating current to induce an electric current in a nearby wire. This insulated loop is installed in the pavement, and a vehicle passing over the detector increases the loop's inductance, which indicates that a metal mass passed through.

Detecting only the metal of the vehicle or certain weight mass helps reduce false positives from pedestrians carrying any metal material, bicycles, or motorbikes. All of the previous detection features depend on the manufacturer, designated purpose, and calibration since these data could be important for some research.

Automatic License Plate Recognition

Also known as automatic number plate recognition (ANPR), automatic license plate recognition (ALPR) technology uses optical character recognition, which is a process to convert text into machine-encoded text. This process consists of an algorithm to process the text and identifies each character according to the algorithm data. Such algorithms are used on images to read and identify the plate numbers of passing vehicles. This technology mostly relies on a video camera (i.e., surveillance and IR) to be able to identify the plate number.

Considerable research exists on this technology using conventional cameras, specific-purpose cameras, or surveillance cameras. This technology is used for toll collection, road-rule enforcement, or even vehicle registration checking through a database.

6. Technology Assessment

The research team compared and identified each hardware technology to identify those that could answer the research questions and perform as planned during dense traffic conditions at land border crossings. The advantages and disadvantages of the previous technologies were analyzed (Table 1) according to the project objectives, with the main objective being POV lane detection at border crossings. Bluetooth and Wi-Fi were considered collectively in the technology comparison since they use a similar principle for detecting users.

Table 1. POV Technology Comparison

Technolog y	Advantages	Disadvantages
LiDAR	• High detection capabilities (including pedestrians, buildings, bikes, etc.) • Sensor portability • High detection range • Captures micro-level data from traffic • Classifies vehicles according to their size • Low maintenance	• Complex traffic situations decrease shape detection results. • Ideal for vehicle detection at intersections, but it does not read license plates or identifies specific vehicles. • Does not differentiate vehicles with the same features (color, size, and axles)
Bluetooth/ Wi-Fi	• Widely used by vehicles and occupants • Does not affect user privacy • Low cost maintenance • Short-range antennas improve accuracy • Wi-Fi sensors considerably outperform Bluetooth when capturing MAC addresses, especially in low-traffic areas	• Does not differentiate vehicle lanes • Can collect non-vehicle data that bias the sample. • Small detection range • Requires relatively large sample size (proportion of active devices per vehicle)
GPS	• Built-in modern vehicles and portable devices (2010 onwards). • Ideal for predicting traffic congestion and estimating travel time on most roads. • Combining this technology and a sensor provides reasonable estimates of the traffic stream.	• Real-time data need to be sent continuously. • Hardware upgrades are needed if accuracy is important. • If app-based, requires users to approve continuous data to be sent. • Vehicle identification accuracy is low at dense-traffic areas
Video camera	• Able to identify vehicles when integrated with an algorithm. • Most traffic cameras come with a built-in system that detects vehicle features or license plate numbers	• Only records video if using independently. • Does not easily differentiate vehicles with the same features. • Can be affected by sunlight, night, or different weather conditions.
Radar sensor	• High reliability for vehicle detection • Widely used for multiple applications in transport • Performance increases when using an appropriate algorithm.	• High/slow speeds affect radar detection. • High speeds decrease result detection accuracy. • Rain can affect vehicle detection. • Multiple lanes require more sensors to avoid losing accuracy
Inductive loop detector	• Capable of detecting vehicles, their speed, and their classification. • No significant change in performance during different weather conditions.	• Installation in pavement • High maintenance cost • Maintenance requires road closures. • Requires an inductive loop per lane.
ALPR	• If integrated with an algorithm, it can detect license plate numbers in complex traffic situations. • Only technology able to differentiate and re-identify vehicles at crossing roads.	• Depending on the manufacturer, it can be affected by sunlight, night, or different weather conditions. • May be affected when license plates are placed differently or deformed.

Most technologies perform well by themselves in specific situations. However, in a border crossing environment, the research team found that the best results for POV detection can be obtained using a combination of technologies to provide enough data to the system and calculate travel time. Several research studies [6] [7] [8] showed that using a sensor in combination with portable device data (i.e., GPS, Bluetooth, or Wi-Fi) can significantly increase overall accuracy of the system to estimate travel times. Implementing such a technique could enhance the current system configuration, which uses Bluetooth and Wi-Fi technologies to calculate wait time.

The process known as data fusion involves putting together multiple data from different sensors or technologies to generate a consistent or accurate result compared to a single technology system configuration. Research on this technique has grown and shows that it provides better accuracy of sensor readings or technology data for travel time.

7. POV Research Prototype

Measurement Points

To have a better estimation of the total travel time by lane, the current system configuration needs to be complemented. This can be achieved by using additional technologies to capture data at different points of the trip from Mexico into the United States. The TTI research team identified three points where measurements are needed in order to reach the objective of accurately measuring travel time at land border crossings by lane type (Figure 4):

- **Vehicle detection phase:** At the end of the queue in Mexico, vehicles line up on a road that combines all types of users into multiple lanes depending on the roadway configuration. This is where current technologies (Bluetooth/Wi-Fi) should be complemented by other technologies that measure the speed and provide enough data for vehicles traveling across that segment of the road.

  The analyses of multiple border crossing configurations show that at this point of the trip, it is not possible to differentiate vehicle types since there are multiple feeding roads and vehicles are bunched close together, making it difficult to use a license plate reader. However, having the travel time data and speed from multiple GPS devices and detecting vehicles using the current reading stations is enough to obtain an accurate travel time at this phase. That being said, GPS data combined with the current Bluetooth/Wi-Fi system is the best technology to collect this information, as GPS data will provide multiple trip values from different devices complementing Bluetooth readers which capture the MAC address to identify a vehicle at this initial phase of the trip. These identifiers will be used during the following reading phases to provide a total travel time and wait times.

- **Vehicle re-identification phase:** Once vehicles reach the tollbooth; they will start selecting lanes according to the user type (Ready or regular). The distance from this point to the final lane decision point varies from border crossing to border crossing. As mentioned previously, SENTRI users would already be using a segregated lane. It is recommended that an ALPR be installed at this point to identify the vehicle [9] at the tollbooth in Mexico. This is the most effective location because as vehicles approach a tollbooth, they encounter a stop sign, so cars will leave some space between each other, thus allowing the ALPRs to capture the plate number and add a time stamp to it. Once the vehicle crosses the border and reaches the CBP inspection booth, the same process will be performed; both identifiers will be matched, calculating the total time for this segment of the trip. Number plate data are also complemented with Bluetooth/Wi-Fi readers between each booth during the bridge crossing.

- **Vehicle detection and data matching phase:** When vehicles reach the CBP primary inspection booth, MAC identifications are captured to match addresses from each Bluetooth reading station, and ALPRs are used to identify the lane that each vehicle is using for the crossing. Cumulative information gathered from these four technologies (Bluetooth, Wi-Fi, GPS, and ALPR) is continuously sent to the server to be processed and combined for a stronger and more reasonable estimation of travel time. It has been proven that additional data elements from multiple reading stations and technologies are fused to increase the accuracy of the system [10] [11].

The TTI research team designed this prototype based on the technology assessment and objectives of the project. The research team developed a test plan to analyze system's functionality and the performance of the technologies in a controlled environment while simulating real-life border crossing situations. Figure 4 depicts the proposed data collection stations during each phase of the trip.

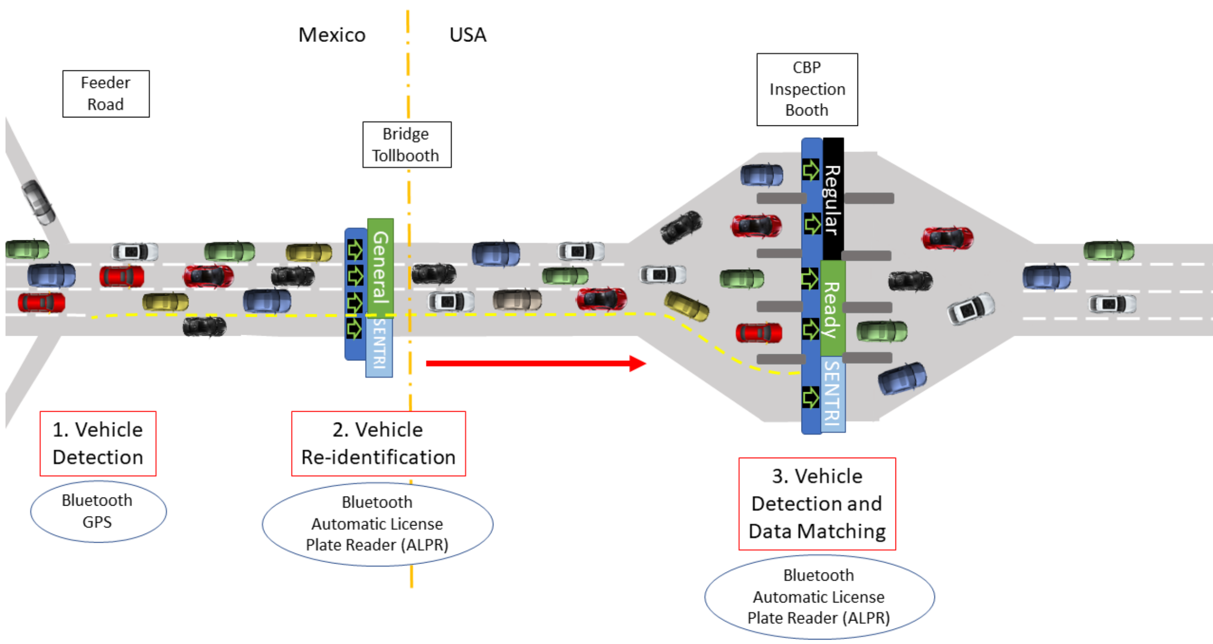


Figure 4. POV Technology Phases

From the three main technologies shown in the figure (Bluetooth, GPS, and ALPR), the ALPR technology is the most important to achieve the objective of lane detection. The re-identification phase can only be done with a unique feature from every vehicle because they share many characteristics due to mass production. The test aims to prove ALPR capabilities of detecting a vehicle by the plate number and re-identify it when passing by another point using the plate number.

POV System Dataflow

Figure 5 presents the system dataflow and shows the process during the border crossing by focusing on the data generated by each technology, the range, and how the technologies work together to capture information along the border to estimate times and provide wait times.

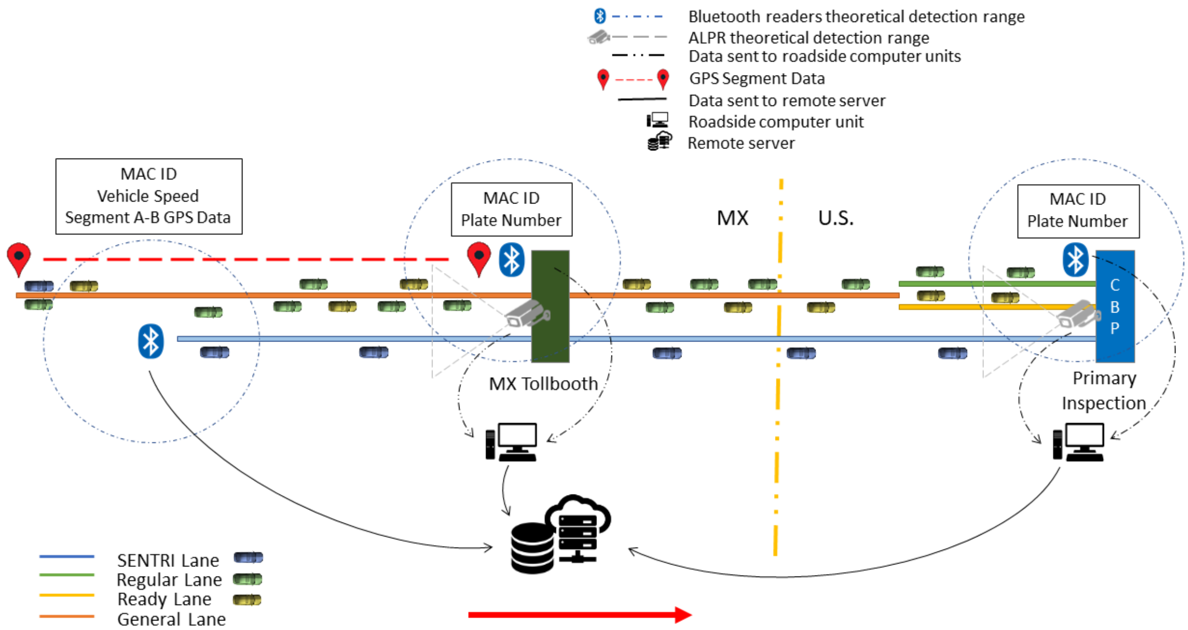


Figure 5. POV Dataflow Diagram

During the first part of the trip, while vehicles are in Mexico, the GPS data facilitates determination of the current traffic situation, average speeds and estimate travel times during that segment. The Bluetooth reader retrieves MAC addresses. These data elements are processed, sent to the main server and database via wireless communication. At this phase, no lane identification is needed, and none of the technologies will identify vehicles per lane.

At the second reading station at the Mexican tollbooth or a gantry (at border crossings with no tollbooths) before crossing the U.S./Mexico border, an ALPR will be used to identify vehicles per lane. The ALPR will capture license plate numbers, and the software in the ALPR will add the reading confidence, lane identification, and time stamp to the record. A Bluetooth reader will capture the MAC address, which will be used to identify the vehicle at the second reading station. The data from the Bluetooth reader does not identify user lanes. The information is processed through a local computer installed in the cabinet and sent to the main server and database via wireless communication.

The third reading station is at the CBP primary inspection booth, with a similar configuration to the second station. The main difference is that at the CBP primary inspection booth, each vehicle is identified at the lane used to enter the United States (SENTRI, Ready, or regular), and there is a clear view of the front license plate from the booth. Data are processed in the same way as at the previous station.

The local computer located in each reading station cabinet will help the TTI research team to troubleshoot remotely. The ALPR and computer will function as a client-server combination using File Transfer Protocol (FTP) to exchange data. The computer will also process data from readers and sensors to send data as clean as possible to the main server, making the whole process more efficient.

8. POV ALPR Field Tests

The TTI research team analyzed various potential POV border crossing scenarios that are present at border crossings and different locations across the border (ALPR at the Mexican tollbooth, no tollbooth and use of gantries, and CBP primary inspection upper and lower position), and designed specific tests to determine if the ALPR is an optimal technology to measure travel times by vehicle re-identification.

The first set of tests involved human subjects driving a state-owned vehicle around a course set up at the RELLIS test track as a loop, as Figure 6 shows. An existing gantry on the north side of the track was used to install the ALPR. This was used to capture the front and rear license plates of the vehicles as they drove under the gantry at speeds below 10 mph. Tailgating is common in the border crossings between Mexico and the United States. Therefore, the subjects were instructed to drive close together to simulate tailgating. The information captured from the ALPR was transferred to a computer and consisted of the license plate number, lane identification, time stamp, and read confidence.

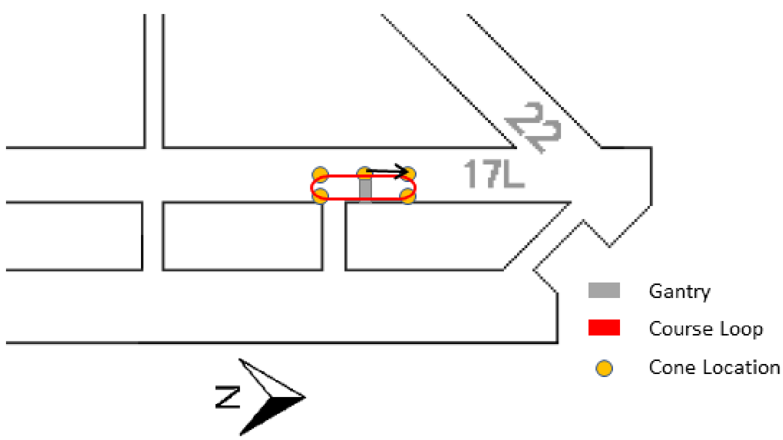


Figure 6. TTI Test Track Diagram

Eight subjects were involved in the study and drove multiple laps along the course indicated in Figure 6. Between each lap, research staff analyzed captured data and guided the drivers through the course.

The equipment included:

- one ALPR
- one power generator for the equipment and ALPR
- eight different vehicles, which were used to drive under the gantry at the RELLIS test track
- orange cones to mark the path for the vehicles

The experimental procedure was as follows:

- Research staff held an informational meeting with test subjects to explain the procedure of the test at the TTI Headquarters building
- All test subjects drove a state-owned vehicle at all times
- Each test run was composed of two laps starting at the gantry. Three different types of vehicles were used (trucks, sedans, and SUVs).
- Each vehicle was required to drive through the test at 10 mph or less

Prior to the testing, the TTI research team set up the area at the TTI RELLIS test track and configured an ALPR angle of 65 degrees below the gantry and a height of 20 feet from the ALPR to the ground (Figure 7). All the needed configuration and safety procedures were followed so the ALPR location was able to capture the two lanes in a single field of view.

Figure 7. ALPR Installation under the Gantry at the RELLIS Test Track

The camera view was configured, and the detection limits were identified to define the ideal area of detection for the eight-vehicle test. As shown in Figure 8, the red-car detection rate was better when entering the area in all four corners of the view. License plates can be detected outside the indicated area, but the detection and reading confidence increases if the subject is located inside the area. This is important when setting up the ALPR for two lanes in order to properly identify any car passing through each lane.

Figure 8. Camera View Detection Limits

The ALPR only sends a record when a license plate is in the detection zone. During the configuration, when license plates were read in the detection zone, the confidence rate was between 85 and 96 percent. The confidence rate ranges between 0 and 100 percent and is estimated by the ALPR optical character recognition based on images from the color and infrared cameras.

Once the lane setup was finalized, the TTI research team tested tailgating between two vehicles. The results of were successful as the ALPR was able to detect both tailgating vehicles during each test, as shown in Figure 9.

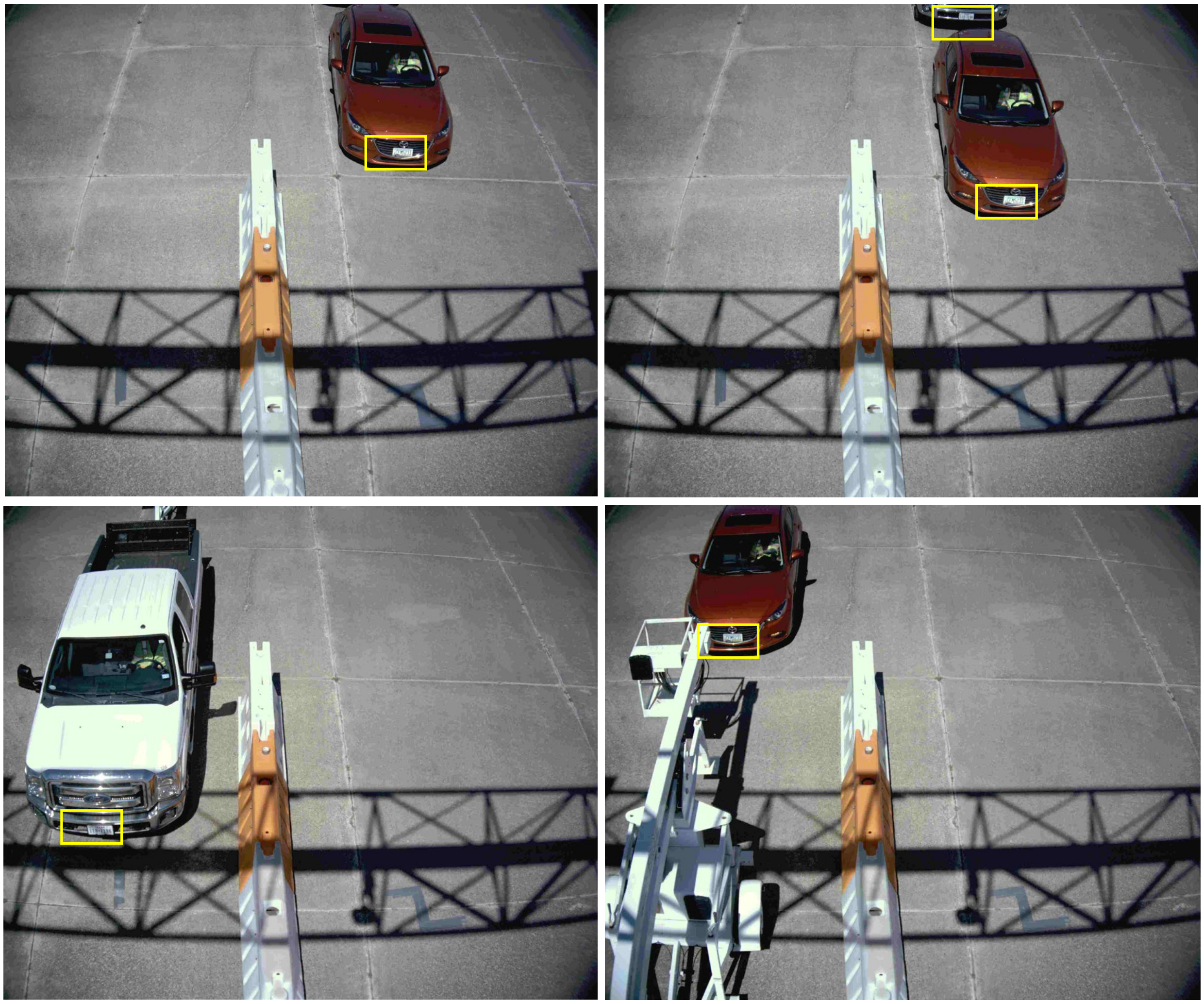


Figure 9. Tailgating Detection between Two Cars

These configuration tests confirmed that the ALPR setup (angle, height, and location) under a gantry is a good location if placed on a border crossing, where vehicles move close to each other tailgating. A set of 8 tests was designed by the TTI Research Team, to consider any possible scenario in the border crossing, including license plate location (where vehicles from Mexico or the U.S. might not have front license plates depending on their state regulations), speed or tailgating between vehicles. The tests were performed under the following conditions:

1. Slow-speed ALPR facing front plates
2. Free-flow ALPR facing front plates
3. Stop and go ALPR facing rear plate
4. Stop-and-go ALPR facing front plates
5. Stop-and-go ALPR facing front plates
6. Slow-speed ALPR facing rear plates
7. Free-flow ALPR facing rear plates
8. Stop-and-go ALPR facing rear plates

Figure 10 and Figure 11 show some photographs taken during the tests. The test vehicles ranged from pickups to sedans. This allowed for different tailgating cases where smaller cars drive behind a big pickup or vice versa. Also, a TTI researcher guided the drivers to make the test as similar as possible to a real-life situation.

Figure 10. Rear Plates Reading Testing

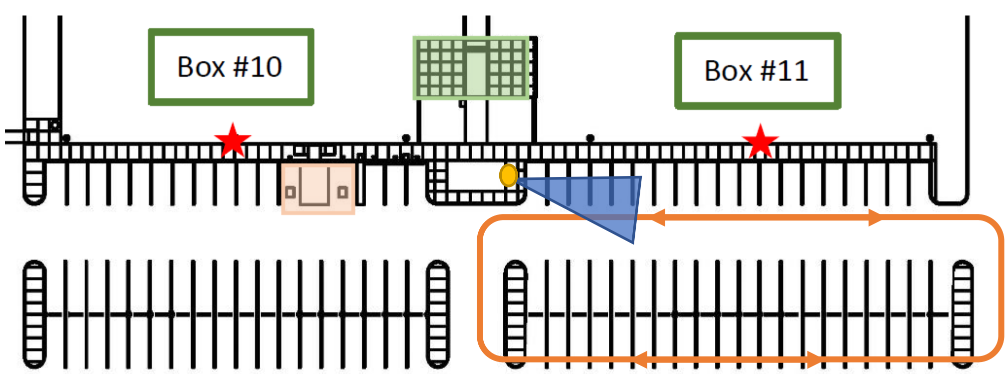
Figure 11. Front Plates Reading Testing

The second set of tests was conducted with the ALPR at ground level on the TTI parking lot. This ALPR location would be similar to what CBP has implemented on the border where vehicles stop prior to entering the primary inspection booth (Figure 12). During both tests, different license plates were used to test the ALPR capabilities of detecting multiple types of plates. Additionally, depending on the manufacturer, the TTI Research Team identified that the reading accuracy improves after each capture and processing made by the ALPR, improving results over time.

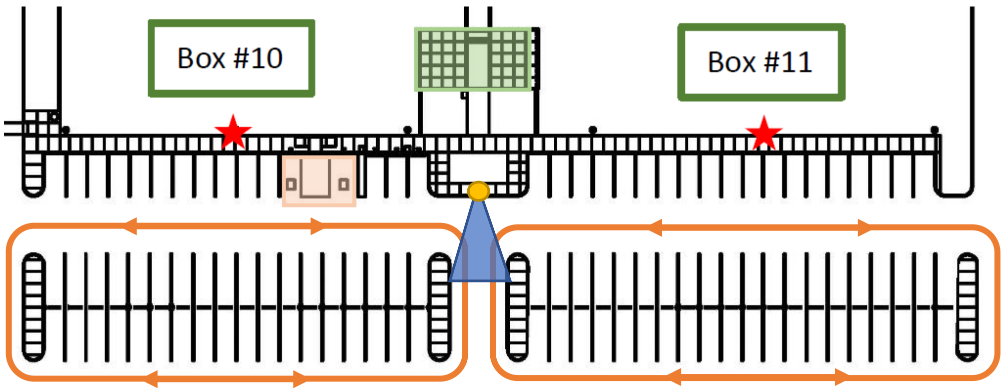
Figure 12. ALPR roadside setup facing front plates

Two course setups were used to analyze the detection rate and accuracy of the ALPR (Figure 13). The first image shows the ALPR (yellow circle) on the roadside, and the detection range (blue triangle), while the loop (orange line) shows the path followed by the vehicles involved in the tests.

The second diagram shows the ALPR location in the middle of two paths to capture evenly two lanes of travel and test the reading capabilities of both front and rear plates.



Setup A



Setup B

Figure 13. TTI Parking lot roadside tests setup (A & B)

The same eight tests that were conducted previously with the ALPR on the gantry at the TTI test track were performed using the setting shown in the previous figure using three different vehicles. A computer was connected to the ALPR via ethernet to receive the data through an FTP server. The data transferred to the computer included a color image, an infrared (IR) image and the license plate read patch as shown in the following figures:

a) Color Image

b) Infrared image

c) License plate read patch

Figure 14. Image files sent to the server by the ALPR

9. Results and Recommendations

The technology assessment results suggest that by using a combination of Bluetooth/Wi-Fi, ALPR, and GPS technologies, sufficient information can be obtained to estimate travel times at land ports of entry by POV travel type. The TTI research team developed a prototype that includes Bluetooth, ALPR, and GPS technologies as the system set up to achieve the objectives of estimating wait time for POVs.

To guarantee proper lane and vehicle identification the ALPR was tested twice. The first test detected the ALPR capabilities to detech license plates when located under a gantry at an elevated position. In addition, the detection area was identified and the vehicles were tested under different conditions (tailgating, free-flow, stop and go) reading front and rear plates.The second tests were similar but the ALPR was placed on the roadside and the data captured during this test was analyzed to identify the ALPR capture rate and vehicle re-identification. Table 2 shows the results of the tests performed at the TTI parking lot, using two different setups:

Table 2. ALPR Tests Result Analysis

Test	Setup	Average Read Confidence	Read Accuracy
1. Slow-speed ALPR facing front plates	A	74.80%	70%
2. Free-flow ALPR facing front plates	A	67.98%	77%
3. Stop and go ALPR facing rear plate	A	78.75%	75%
4. Stop-and-go ALPR facing front plates	A	88.50%	70%
5. Stop-and-go ALPR facing front plates	B	75.38%	81%
6. Slow-speed ALPR facing rear plates	B	75.35	65%
7. Free-flow ALPR facing rear plates	B	84.75%	100%
8. Stop-and-go ALPR facing rear plates	B	90.25%	100%

The Average Read Confidence is an average value from the Read Confidence variable, which is a value provided by the ALPR once the system has finished processing the IR, color image, and the OCR algorithm generates a license plate number. These values are added, including missed readings (considered as 0%) and wrong readings (the ALPR provides a Read Confidence value even when the license plate provided does not match the real one), and averaged to obtain the Average Read Confidence shown per test. Figure 15 shows the results for each test, averaging 80%.

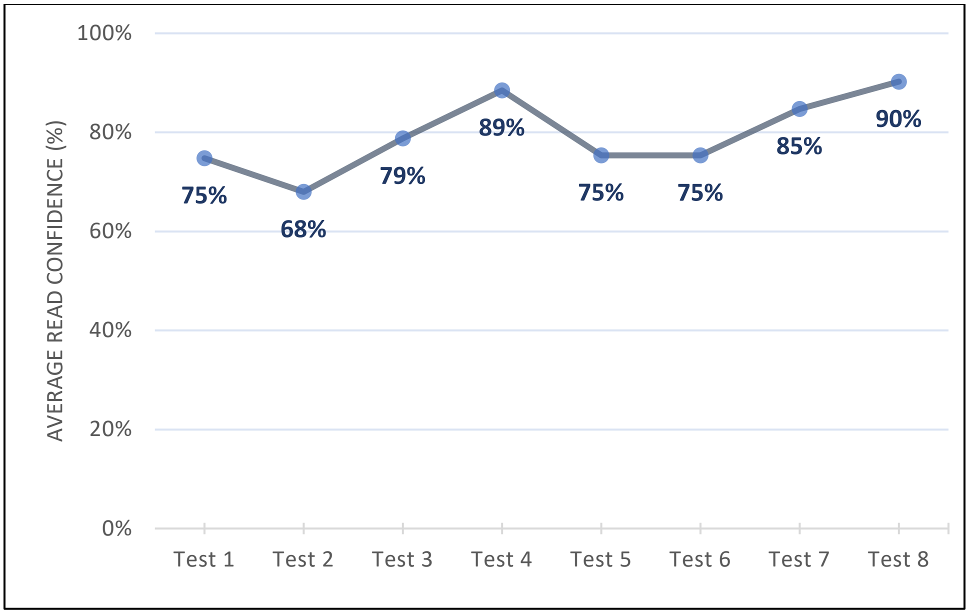


Figure 15. ALPR Average Read Confidence

Read Accuracy is the percentage of accuracy considering only accurate readings of the license plate divided by the total number of runs for each test. As mentioned above, there is a significant improvement once the correct configuration and calibration is performed (Figure 16).

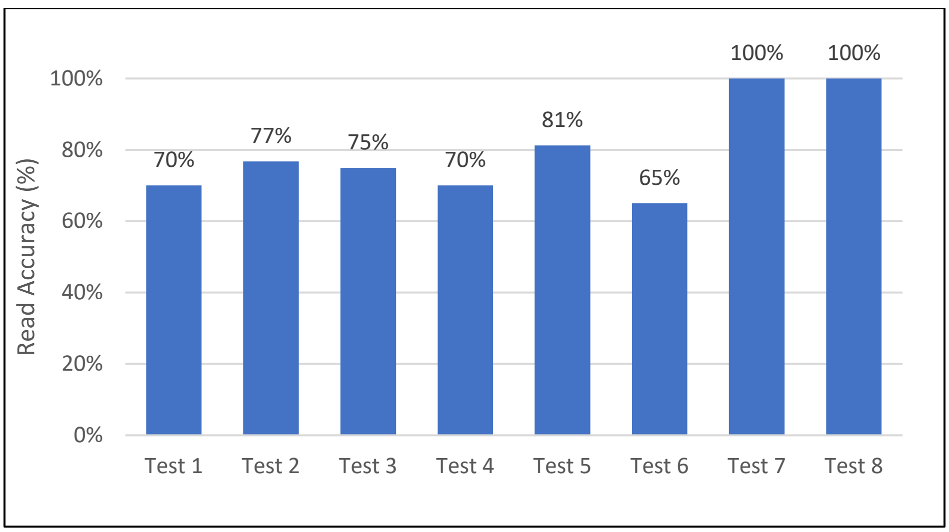
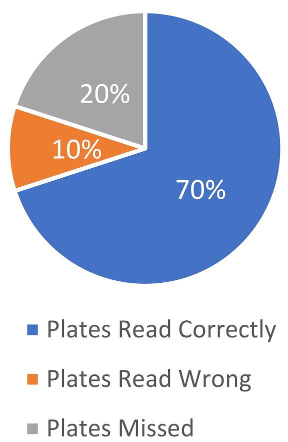


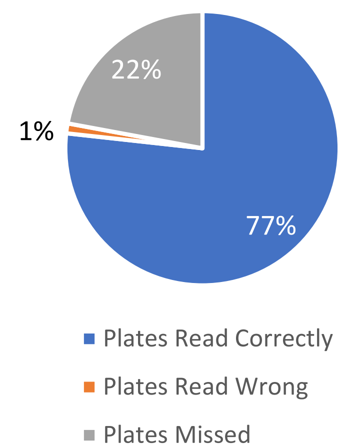
Figure 16. ALPR Read Accuracy

It is important to note that the camera configuration and calibration is crucial. During the tests performed, the research team identified different configuration values that need to be adjusted based on the location of the ALPR (upper or roadside) and area range. The cameras values (IR and Color) were adjusted after the first, fourth and six, showing a considerable improvement of the readings after those adjustments and the latter tests which can be seen in the two previous figures.

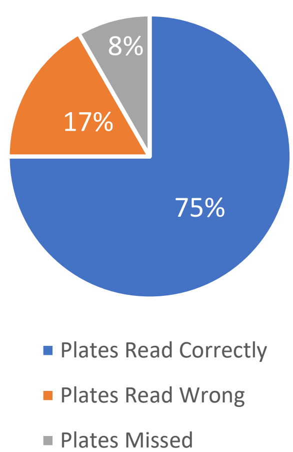
Data from each run was analyzed considering three variables: Plates Read Correctly, Plates Read Wrong and the Plates Missed. In most of the tests, the plates were read successfully by a 70% or more, however, this could be improved by an internal algorithm because most of the plates read wrong were usually symbols that the OCR finds similar, i.e. 1 and I, 8 and B, 0 and O, etc. These can be observed in the following charts:



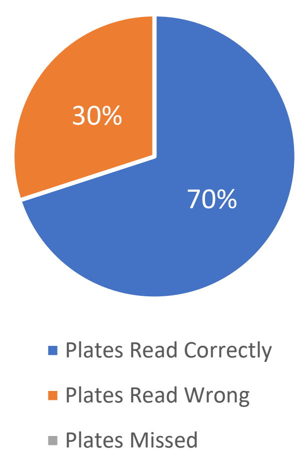
Test 1. Slow-speed ALPR facing front plates



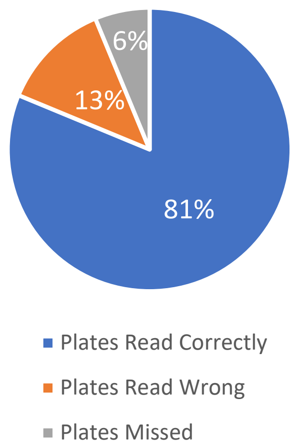
Test 2. Free-flow ALPR facing front plates



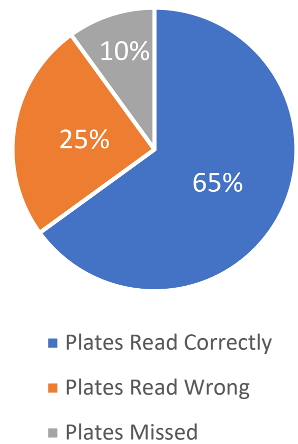
Test 3. Stop and go ALPR facing rear plate



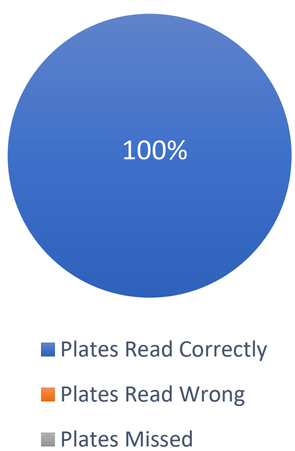
Test 4. Stop-and-go ALPR facing front plates



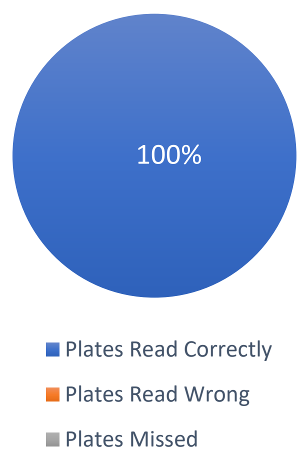
Test 5. Stop-and-go ALPR facing front plates



Test 6. Slow-speed ALPR facing rear plates



Test 7. Free-flow ALPR facing rear plates



Test 8. Stop-and-go ALPR facing rear plates

Figure 17. License plate identification read accuracy charts

The ALPR does not capture all the vehicles present in the field of view at the same time but sequentially, depending on the order the vehicles enter the field of view. However, this does not affect the detection rate because the capture is fast, and the traffic speed at these two phases is below 10 mph, giving the ALPR enough time to capture almost every vehicle passing by.

The results confirmed the capabilities of the ALPR to detect multiple vehicles in different circumstances passing by the field of view, some of the main circumstances presented on a border crossing are vehicles traveling really slow, tailgating each other until they reach the tollbooth or CBP Primary Inspection or having damaged, deformed or relocated license plates (note that a 100% of capture rate is only possible in a controlled environment and the sample needed to measure travel times can be as low as 70%).

The TTI Research Team concluded that the ALPR line of sight, when located under a gantry or roof, is the least affected, but it must be set up appropiately to have an accurate reading. On the other hand, the ALPR location on the middle of two lanes (Setup B) or even one ALPR per lane is the ideal setup to capture license plates with an accuracy over 70% and a read confidence of more than 80%, this is ideal for Mexican tollbooths before entering the border crossing or CBP Primary Inspection booths. Nonetheless, a proper calibration of the ALPR using any setup provides enough data to calculate travel times and re-identify a vehicle by matching the license plate number.

Given the succesful tests under a controlled environment, the TTI Research Team proposes to perform test of the system developed under this research at a land border crossing, where the technoogy could be tested under real border crossing conditions that include mutiple traffic characteristics, light, and weather circumstances.

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Appendix

The following table presents the results of the literature review.

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
1	Vehicle Detection Technologies.	Transportation Research Board.	Vehicle Detection and Tracking in Complex Traffic Circumstances with Roadside LiDAR.	Traffic data with high resolution for traffic safety due to increase of number of cars and accidents.	High-resolution micro-traffic data (HRMTD) method for vehicle detection and tracking in complex traffic circumstances.	Speed. Location. Direction. 3D distance.	LiDAR sensor360 camera (for comparison).	Vehicle detection and tracking algorithms.	Low power consumption. 3D detection (pedestrians, cars, buildings). LiDAR model is cost-effective considering its detection capabilities. Detection range of 100 m.	Complex traffic situations shape detection is not optimal. It is more ideal to identify traffic flow and volume than vehicles at border crossings. Mostly used at crossroads.	https://journals.sagepub.com/doi/10.1177/0361198119844457
2	Vehicle Detection Technologies.	Transporta-tion Research Board.	Automatic Detection of Major Freeway Congestion Events Using Wireless Traffic Sensor Data: Machine Learning Approach.	Spotting traffic congestion such as slowdowns and bottlenecks on freeways.	Machine-learning-based technology using neural networks.	Speed data. Travel time data.	Wireless re-identification. Bluetooth. Wi-Fi.	Neural networks. Machine learning.	Identification of vehicles through wireless technologies applied in POV. High potential of machine learning as reliable tools for traffic monitoring. High data detection for slowdowns in highways.	Research aims to detect traffic slowdowns using machine learning approach, which is not applicable to the project since it has been previously analyzed by TTI researchers.	https://journals.sagepub.com/doi/10.1177/0361198119843859
3	Vehicle Detection Technologies.	IEEE Transactions on Intelligent Transporta-tion Systems.	Hybrid Cascade Structure for License Plate Detection in Large Visual Surveillance Scenes.	License plate identifica-tion in complex scenes.	Cascade hybrid structure to detect license plates.	Vehicle license plates.	Camera.	Cascaded color space transformation of pixel detector. Cascaded contrast-color Haar-like detector. Cascaded convolutional network structure.	Rapid and effective license plate extraction showing great results in complex situation.	Technology focuses on license plate extraction in complex situations (small, relocated, complex surveillance scenes). The research will implement ALPR at toll booths. Requires high data-processing system.	https://ieeexplore.ieee.org/document/8447437
4	Vehicle Detection Technologies.	IEEE Transactions on Intelligent Transporta-tion Systems.	Dynamic Vehicle Detection with Sparse Point Clouds Based on PE-CPD.	Detecting dynamic vehicles with sparse	Method based on likelihood-field-based model combined with	Distance. Grid angular resolution.	LiDAR sensor.	Scaling series algorithm. Kitti dataset.	Improved identification of vehicle detection through algorithms.	Vehicle detection range is smaller than the average.	https://ieeexplore.ieee.org/document/8467531

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
				point cloud (more than 50 m from sensor).	coherent point drift.				Detection range improved from 40 to 80 m.	Extra algorithm processing is not ideal since multiple technologies will be sending data for processing.	
5	Vehicle Detection Technologies.	Department of Civil, Environ-mental, and Construction Engineering.	Detection and Tracking of Pedestrians and Vehicles Using Roadside LiDAR Sensors.	Improving use of LiDAR sensors in the field.	Critical techniques valuable for researchers toward field implementation.	Vehicle classification. Route tracking. Direction. Velocity.	LiDAR sensors.	Solution algorithms.	Real-time information of direction and classification of vehicles. Speed of the vehicles in a specific area/intersection.	Techniques for improving LiDAR sensors at intersections. Extra data captured not needed for the project.	https://www.sciencedirect.com/science/article/pii/S0968090X19300282
6	Vehicle Detection Technologies.	Multidisci-plinary Digital Publishing Institute.	Vehicle Detection in Urban Traffic Surveillance Images Based on Convolutional Neural Networks with Feature Concatenation.	Automatic analysis and vehicle detection in urban traffic surveillance.	Vehicle detection framework that improves the performance of single shot multibox detector.	Vehicle size. Video surveillance. Vehicle category.	Video surveillance system.	Neural network algorithm. High-processing graphics processing unit (GPU).	Capable of detecting vehicle category almost in real time. Vehicle size can be identified using the algorithm. Based on regular video camera systems.	Mostly based on neural network algorithms. Aimed to identify category of vehicle. Requires continuous high-performance processing GPU.	http://dx.doi.org/10.3390/s19030594
7	Vehicle Detection Technologies.	Multidisci-plinary Digital Publishing Institute.	A Novel Vehicle Detection Method Based on the Fusion of Radio Received Signal Strength and Geomagnetism.	Geomag-netic signal blind zone between front and rear axle of high-chassis vehicles leading to detection of problems.	Two-sensor data fusion vehicle detection method through combining received signal strength from radio stations with geomagnetism.	Magnetic data. Geomagnetic signal.	Long Range wide area network gateway. Battery. Geomagnetic sensor. FM radio module. LoRa module. Microcontroller.	Signal-processing algorithm.	Capable of detecting vehicles accurately.	Needs to be installed on the road. Not capable of re-identifying vehicles at different points of the crossing.	https://www.mdpi.com/1424-8220/19/1/58
8	Vehicle Detection Technologies.	Transporta-tion Research Board.	Expanding the Capabilities of Radar-Based Vehicle Detection Systems: Noise Characterization and Removal Procedures.	Capabilities of radar-based vehicle detection at signalized intersec-tions.	Dataset of continuous position and speed information for vehicles traveling on an intersection.	Speed. Position. Trajectory.	Radar sensors.	Software-based data collection system.	Detection not affected by weather. Multiple lanes covered by a single unit.	Designed for intersections and traffic lights. Used as a stop bar sensor.	https://journals.sagepub.com/doi/10.1177/0361198119852607
9	Vehicle Detection	Multidisci-plinary Digital	An Improved YOLOv2 for Vehicle Detection.	Vehicle detection in	Improved algorithm for	Video surveillance.	Video surveillance system.	Convolutional neural network.	Vehicle-type recognition.	Requires continuous video surveillance.	https://www.mdpi.com/1424-

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
	Technologies.	Publishing Institute.		intelligent transportation systems.	vehicle-type recognition.	Vehicle features. Length. Width.		YOLOv2 algorithm.	Vehicle detection based on regular video camera systems.	Requires continuous processing of the images and algorithms.	8220/18/12/4272
10	Vehicle Detection Technologies.	IEEE Transactions on Intelligent Transportation Systems.	Roadside Magnetic Sensor System for Vehicle Detection in Urban Environments.	Cost-effective vehicle detection system.	Roadside magnetic sensor system to detect adjacent lane.	Sensor signals.	Magnetic sensor system. Wireless personal area network.	State machine algorithm.	Detects vehicles adjacent to the sensor. Data sent to the system are cumulative and contribute to the results.	Detects only the lane next to the system. Requires three magnetic sensors. Can only detect when a vehicle passes by.	https://ieeexplore.ieee.org/document/8003296
11	Vehicle Detection Technologies.	Multidisciplinary Digital Publishing Institute.	Vehicle Mode and Driving Activity Detection Based on Analyzing Sensor Data of Smartphones.	Accuracy improvement in vehicle detection systems for driving assistance.	Vehicle mode-driving activity detection system.	Position. Inclination. Location. Direction. Magnetic field.	Vehicle mode detection module (accelerometer data). Driving activity detection module (accelerometer, gyroscope, magnetometer).	Machine learning classification.	Depending on the module, can detect different data from nearby devices. Capable of detecting the vehicle (car, bus, motorbike, or walking and bikes).	Prediction varies depending on the user's device. Relies on mobile device sensors (GPS, accelerometer, magnetometer).	https://www.mdpi.com/1424-8220/18/4/1036
12	Vehicle Detection Technologies.	Transportation Research Board.	An Improved Inductive Loop Detector Design for Efficient Traffic Signal Operations and Leaner Space Requirements.	Inductive loop detector (ILD) limitations toward vehicle detection.	Algorithm and system configuration for ILD to reduce maintenance and improve detection.	Vehicle Direction. Vehicle class.	Inductive loop detector. LabVIEW.	Detection algorithm.	Capable of detecting direction and classification of vehicle.	Requires an inductive installation on the ground. Needs more maintenance than other systems. Cannot differentiate/identify if the same vehicle crosses again.	https://journals.sagepub.com/doi/10.1177/0361198118798457
13	Vehicle Detection Technologies.	Transportation Research Board.	An Artificial Neural Network to Identify Pedestrians and Vehicles from Roadside 360-Degree LiDAR Data.	Connected vehicle technologies require high-resolution micro-level traffic data.	Artificial neural network system to distinguish pedestrians and vehicles from LiDAR data.	HRMTD.	LiDAR sensor.	Artificial neural network.	Roadside/onboard system. Accurate micro-level traffic data. Can identify vehicle classification.	Pedestrian data not needed. Developed for traffic surveillance. Requires continuous processing of neural network.	http://amonline.trb.org

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
14	Vehicle Detection Technologies.	Transport Research International Documentation.	An Automatic Procedure for Vehicle Tracking with a Roadside LiDAR Sensor.	Significant challenge obtaining continuous speed and location of unconnected vehicles in a mixed-traffic condition.	Method for tracking all vehicles using roadside LiDAR sensors.	Real-time number. Location. Speed.	360 degrees LiDAR sensor.	Data-processing algorithm.	Detection range up to 100 m. Lane identification after background filtering. Vehicle speed and location data.	Extraction data algorithms cannot be directly used for roadside LiDAR data. Ideal for detecting vehicle intersections, not toll roads.	https://trid.trb.org/view/1495265
15	Vehicle Detection Technologies.	Multidisciplinary Digital Publishing Institute.	Vehicle Speed and Length Estimation Using Data from Two Anisotropic Magneto-resistive (AMR) Sensors.	Estimating car length on road.	Method to estimate a car length using AMR sensors.	Magnitude of the magnetic field.	Magnetic field sensors. Microcontrollers.	Data-processing algorithm.	Can detect vehicles and their length through the signal of the magnetic sensors and the algorithm.	Results can be affected depending on small differences between vehicles. Requires being installed on the road.	https://www.mdpi.com/1424-8220/17/8/1778
16	Vehicle Detection Technologies.	Idaho Transportation Department.	Evaluation of Vehicle Detection Systems for Traffic Signal Operations.	Vehicle detection systems for traffic signal operations.	Evaluation and recommendation of different systems at traffic lights in different conditions.	Vehicle counts. Average wind speed. Average precipitation.	Image processors. Microwave radar. Passive infrared and thermal image sensors. Video-radar hybrid system.	DNA.	Radar-based systems have good performance in regular conditions. All mentioned technologies can successfully detect vehicle without road intrusion.	Video-based detection systems can have a big impact on detection if placed wrong. All mentioned technologies increase their error during harsh conditions. All these systems increase their detection error during nighttime.	https://apps.itd.idaho.gov/apps/research/Completed/RP236.pdf
17	Vehicle Detection Technologies.	Procedia Computer Science.	An Efficient Approach for Detection and Speed Estimation of Moving Vehicles.	Intelligent Traffic management and surveillance.	Efficient camera-based system to detect vehicles and their speed.	Speed. Vehicle detection. Vehicle parameters.	Video camera.	OpenCV/Java. MySQL. Video-processing algorithm.	Accurately detects vehicles and speed. Installation on existing pole/gantry in front of cars. Less processing due to vehicle database.	Only useful during the day. Relies on vehicle's database to identify vehicles; if the vehicle is not in the database, technology will not detect the vehicle.	https://www.sciencedirect.com/science/article/pii/S1877050916311103

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
18	Vehicle Detection Technologies.	Texas Department of Transportation (TxDOT), TTI.	Investigation of New Vehicle Detectors for High-Speed Signalized Intersections.	Use of newer technologies as replacement for TxDOT's legacy systems.	Performance characteristics of detectors to develop guidelines.	Speed. Classification. Distance.	Wireless magnetic sensor. Camera detection system. Radar sensor.	Data-processing algorithm.	Wavetronix shows an excellent outcome detecting vehicles, with better performance at upstream. Trafficware pods accurately detect vehicles. Video with IR cameras is better at low speeds.	Magnetometers can accurately detect a vehicle but cannot differentiate them. Aldis did not perform very well during the test, and results can drastically vary at high speeds. Iteris results can be affected by rain.	https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6828-1.pdf
19	Vehicle Detection Technologies.	Illinois Center for Transporta-tion.	Field Evaluation of Smart Sensor Vehicle Detectors at Railroad Grade Crossings—Volume 4: Performance in Adverse Weather Conditions.	Radar technology performance in adverse weather conditions.	Field evaluation of radar systems in rain, snow, fog, and wind.	False calls. Missed calls.	Microwave radar units. Surveillance system.	Computer algorithm to compare errors.	Light rain conditions do not generate a significant change in performance. Light snow condition detection is similar to good weather. Fog also does not affect system performance.	False calls increased in heavy rain. Inductive loops showed a few errors during comparison with radar systems.	https://apps.ict.illinois.edu/projects/getfile.asp?id=3382
20	Vehicle Detection Technologies.	Multidisci-plinary Digital Publishing Institute.	Analysis of Vehicle Detection with WSN-Based Ultrasonic Sensors.	High cost and low scalability of current traffic information acquisition systems.	Wireless sensor network system based on ultrasonic sensors and algorithms.	Interval time.	Ultrasonic sensors.	Vehicle detection algorithm.	Uses a methodology through an algorithm for power saving and accurate detection.	System works for multiple lanes but not very accurate if only one sensor is used.	https://www.mdpi.com/1424-8220/14/8/14050
21	Vehicle Detection Technologies.	Transporta-tion Research Board.	Dual Microwave Radar Vehicle Detection System at Four-Quadrant-Gate Railroad Grade Crossing.	Reliability of vehicle detection systems at railroad crossings.	A two-microwave radar system for vehicle detection at railroad crossings.	False calls. Missed calls. Vehicles detected.	Microwave radar units. Video camera.	Computer algorithm to identify potential errors.	Only a few false calls detected when using recommended setup. Even fewer false calls using modified setup.	Sometimes pedestrian or gate movement generated a false call. Results overall did not improve compared to the initial setup.	https://journals.sagepub.com/doi/10.3141/2458-14
22	Vehicle Detection Technologies.	Transporta-tion Research Board.	Use of Data from Point Detectors and Automatic Vehicle Identification to Compare Instantaneous and	Travel time estimation using different technologies.	Comparison between detector data and automatic vehicle identification	Instantan-eous travel time. Experienced travel time.	Microwave detectors. Bluetooth readers. Tag reader.	Data-processing algorithm.	Few differences between point detector based and AVI based on uncongested conditions.	During congested traffic conditions, AVI data (Bluetooth and electronic toll tag reader) showed a small	https://journals.sagepub.com/doi/10.3141/2470-10

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
			Experienced Travel Times.		(AVI) for travel times.	Congestion level.				difference compared to detector data.	
23	Vehicle Travel Time Estimation.	Solaris University Transporta-tion Center.	Highway Travel Time Estimation with Captured In-Vehicle Wi-Fi MAC Addresses: Mechanism, Challenges, Solutions and Application.	Passive sensing technologies to supplement traffic performance measure-ment.	Measuring traffic performance on highways based on in-vehicle Wi-Fi MAC address capturing.	MAC addresses. Epoch time.	Wi-Fi sensors.	Algorithms to estimate dynamic travel times.	Wi-Fi sensors considerably outperform the Bluetooth sensors in capturing MAC address of passing vehicles, especially in low-traffic areas. Low-cost installation and maintenance compared to inductive loops. Wi-Fi sensors can adopt short-range antennas without low sample rate issue.	Precise configuration of the antennas is important to avoid unnecessary data or fall short during the sampling.	https://rosap.ntl.bts.gov/view/dot/36835
24	Vehicle Travel Time Estimation.	Institution of Engineering and Technology.	Urban Link Travel Time Estimation Using Traffic States-Based Data Fusion.	Fusing data from different sources to estimate travel time.	Three different data source systems to quantify the accuracy of travel time estimation.	License plate number. Time stamp. Vehicle detection. Vehicle route time.	ANPR camera. Inductive loop detector. Mobile phone network. GPS.	Artificial neural network. Weighted mean approach.	Results show that with a combination of GPS and inductive loops, reasonable estimates of the traffic stream can be obtained.	Final accuracy of travel time depends on reliability of individual data fusion techniques. Fusing more data sources does not necessarily improve the quality of the final estimation. Results show that fusing highly correlated data sources can lead to a worse result.	https://ieeexplore.ieee.org/document/8436579
25	Vehicle Travel Time Estimation.	Institution of Engineering and Technology.	Real-Time Estimation of Freeway Travel Time with Recurrent Congestion Based on Sparse Detector Data.	Loop detector vulnera-bilities leading to poor travel time estimation.	Methodology for real-time freeway travel time estimation with data from sparse detectors.	Vehicle detection. Traffic patterns.	Inductive loop detector.	Mapping algorithm.	Results exceptionally accurate with smaller mean errors and Root Mean Square errors compared to the benchmark. Fewer inductive loop sensors.	Using inductive loop sensor requires maintenance road closures during activities on the sensor. Single sensor per lane.	https://ieeexplore.ieee.org/document/8267179

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
26	Vehicle Travel Time Estimation.	Multidisciplinary Digital Publishing Institute.	Heterogeneous Data Fusion Method to Estimate Travel Time Distributions in Congested Road Networks.	Provision of travel time distribution information for higher probability of on-time arrival.	Heterogeneous data fusion method to estimate travel time distributions.	Path travel time. Speed. Total travel distance. Free-flow travel. License plate number.	Autoscope video image detector. License plate reader. AVI.	Matching algorithm. Heterogeneous data fusion method.	Method can significantly reduce estimation errors for path travel time distribution in congested road networks. Fusion algorithm can generate a robust and accurate fusion of travel time distribution for different data sources.	Proposed data fusion method only considered heterogeneous data from point and interval detectors. Case of study only involved a specific path.	https://www.mdpi.com/1424-8220/17/12/2822
27	Vehicle Travel Time Estimation.	Journal of the Eastern Asia Society for Transportation Studies.	Travel Time Estimation Using Probe Data on Signalized Arterial.	Outlier and bias problems on a signalized arterial during travel time collection using probe-based systems.	Techniques to generate reliable travel times in probe-based systems.	License plate number.	Traffic detectors (loop, video image, radar). ANPR.	Ferguson statistical test. Loess smoothing technique (MATLAB). License plate matching technique.	Travel time accuracies were markedly enhanced, and differences were significant to current systems. Cost efficient compared to point-detector-based systems.	Short-term biases and outliers are two main issues to be resolved.	https://www.jstage.jst.go.jp/article/easts/12/0/12_1755/_article
28	Vehicle Travel Time Estimation.	Transportation Research Board.	Multi-sensor Fusion Based on the Data from Bus GPS, Mobile Phone, and Loop Detectors in Travel Time Estimation.	Contribution of individual sources to the quality of final estimate.	Combining three different data fusion techniques of varying complexity to quantify the accuracy of travel time estimation.	Location data. Vehicle detection.	Bus-based GPS. Inductive loop detector. Mobile phone data. ANPR.	Data fusion techniques.	In dense urban areas, bus-based GPS combined with inductive loop detectors can provide reasonable estimates of travel time.	Fusing multiple data does not necessarily enhance the performance of travel time estimation. Attention should be paid to the correlation of sources.	https://trid.trb.org/view/1438385
29	Vehicle Travel Time Estimation.	Transportation Research Board.	Analysis of Required Minimum Sample Size of Floating Cars for Estimating Urban Road Link Travel Time Considering Bimodal Distribution and Estimation Error.	Floating car data improvement in travel time and congestion estimation.	Minimum sample size of floating cars and the corresponding travel time estimation errors.	Hellinger distance. Floating car data (FCD) Sample size.	RFID.	FCD. Genetic algorithm.	Minimum sample size corresponding to different levels of travel time estimation errors can be identified.	Two critical factors affect the minimum required FCD sample size.	https://trid.trb.org/view/1438315
30	Vehicle Travel Time	Journal of Modern Transportation.	Bluetooth as a Traffic Sensor for Stream Travel Time Estimation	Emerging technologies to measure	Bluetooth as a cost-effective technology for estimation of	MAC address. Time stamp.	Bluetooth sensors. Video recording.	MAC address matching algorithm.	More than 91% of vehicles captured using Bluetooth were either light	Estimating the stream travel for an entire stream from limited	https://link.springer.com/article/10.1007%2Fs40

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
	Estimation.		Under Bogazici Bosporus Conditions in Turkey.	travel time for traffic manage-ment and operations.	travel time for heterogeneous traffic conditions.	Travel time. Speed. Flow data.	Automated sensors.		motor vehicles or two-wheelers. Bluetooth is a cost-effective technology for estimation of travel time.	Bluetooth data is a challenge.	534-016-0101-y
31	Vehicle Travel Time Estimation.	Transporta-tion Research Board.	Geo-spatial Analysis of Bluetooth Signal Reception and Its Implications on Arterial Travel Time Estimation.	Bluetooth accuracy for travel time estimation.	Analysis of detection ranges and various factors for Bluetooth-based travel time collection.	MAC address. Covering distance.	Bluetooth reader. Bluetooth-enabled vehicles.	DNA.	Average detection range of Class I Bluetooth is around 200 m (620 ft). Impact of detection range variability on travel time estimation appears insignificant.	Factors such as in-vehicle position, speed, antenna configuration, environment, and reader location can significantly influence the Bluetooth detection range.	https://trid.trb.org/view/1393964
32	Vehicle Travel Time Estimation.	Smart and Sustainable Transport.	A Robust Method for Real Time Estimation of Travel Times for Dense Urban Road Networks Using Point-to-Point Detectors.	Data collection for real-time information services.	Estimating travel times in dense urban road networks using point-to-point detection devices.	MAC address. Time stamp.	Bluetooth.	MAC address database. Real-time data analysis methodology.	Through a series of steps, outliers can be excluded from the data to provide accurate travel time estimations. This methodology can be extended to similar technologies.	Traffic characteristics of the path are necessary to select percentile values, which then help in eliminating the outliers.	https://journals.vgtu.lt/index.php/Transport/article/view/1565
33	Vehicle Travel Time Estimation.	Journal of Intelligent Transporta-tion Systems.	Reliability of Bluetooth Technology for Travel Time Estimation.	Bluetooth reliability as a vehicle detection device for travel time estimation.	Analysis of Bluetooth penetration rate in different conditions compared with a GPS.	MAC address. Travel time. Percent devices captured	Bluetooth. GPS.	Data-processing algorithm.	More accurate travel time estimate using short-range antennas. More than 80% of detections are within 100 m of the location area.	The smaller the size of the detection zone, the lower the penetration rate. A Bluetooth system depends on speed of devices, location of device, ping cycle, detection zone, and time span in the zone. There has to be a tradeoff between acceptable level of location ambiguity and penetration rate.	https://www.tandfonline.com/doi/full/10.1080/15472450.2013.856727

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
34	Vehicle Travel Time Estimation.	Missouri Department of Transporta-tion.	Freeway Travel Time Estimation Using Existing Fixed Traffic Sensors.	Travel time estimation from data gathered by field sensors.	New travel time estimation model and prototype point-to-point network travel time estimation.	Size. Color. Texture. Feature. Speed. Volume. Occupancy.	Remote traffic microwave sensors. Surveillance cameras.	Computer vision travel time collection algorithm. Vehicle matching algorithm. Vehicle re-identification. Support vector machine.	Car-following model is more accurate than other travel time models in heavily congested traffic. Vehicle re-identification provides satisfying results but very time consuming.	Travel time collection is not optimal due to low-resolution surveillance systems. Using only a few cameras and sensors with algorithms makes it very challenging to accurately estimate travel time.	https://rosap.ntl.bts.gov/view/dot/29136
35	Vehicle Travel Time Estimation.	Transporta-tion Research Procedia.	Travel Time Estimation between Loop Detectors and FCD: A Compatibility Study on the Lille Network, France	Compati-bility of inductive loop data and FCD for travel time estimation.	Data comparison between different sources to estimate travel time.	Vehicle detection. Speed. Number of vehicles.	Inductive loop data.	FCD. Extrapolation method.	FCD technology is able to distinguish between light vehicles and heavy vehicles.	Different flow regimes need differentiated algorithms and data fusion techniques to enhance reliability. Travel time results may vary between working/non-working days.	https://www.sciencedirect.com/science/article/pii/S2352146515002616?via%3Dihub
36	Vehicle Travel Time Estimation.	IEEE Conference on Intelligent Transporta-tion Systems.	Floating Car and Camera Data Fusion for Non-parametric Route Travel Time Estimation.	Data collection systems for travel time estimating.	Heterogeneous data collection system for non-parametric route travel time estimation.	License plate number. Vehicle location data.	ANPR system.	FCD. Data collection algorithm.	Fusion of the systems increases the robustness of the estimation. Fused estimates are always better than the worst of the two.	Requires vehicles that can provide mobile data. Stationary sensors have a limited network coverage.	https://ieeexplore.ieee.org/document/6957864
37	Automated Tolling.	European Commission.	State of the Art of Electronic Road Tolling.	Current electronic tolling solutions and their future potential.	Overview of current technologies, recommenda-tions, and analysis.	Units. Costs.	Electronic toll collection system. ANPR system. Global Navigation Satellite System (GNSS). Dedicated short-range communications (DSRC).	Automated vehicle classification. AVI.	Based on the benchmarking, GNSS is slightly more cost effective than a DSRC solution.	ANPR can be affected by lighting, different plate location, or positioning. Vehicle classification needs to be complemented with multiple systems in order to analyze all the features.	https://ec.europa.eu/transport/sites/transport/files/modes/road/road_charging/doc/study-electronic-road-tolling.pdf

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
38	Automated Tolling.	International Journal of Research in Engineering, Science and Management.	Smart Tolling for Highway Transportation System.	Fast toll collection systems without human interaction.	Number plate recognition (NPR) and toll collection system.	License plate number. Speed. Distance.	ALPR module. IR sensor.	Character recognition. Image-processing algorithm.	ALPR modules are really effective in detecting vehicle plates, especially at toll booths, which prevent different issues presented at regular speedways.	This configuration is a small-scale system; creating a real scene system may require different devices.	https://www.ijresm.com/Vol.2_2019/Vol2_Iss2_February19/IJRESM_V2_I2_176.pdf
39	Automated Tolling.	International Journal of Research in Engineering, Science, and Management.	Review on Different Techniques for Open Road Tolling System Using Pattern Recognition.	Open road tolling for transportation modern technologies.	Open road tolling method review using ALPR and automated vehicle control.	License plate number.	Automatic license plate reader.	Preprocessing. Neural network module for image processing and network classification.	Vehicle license plate recognition (VLPR) is high-using neural network system. VLPR system is good by itself. Neural network classification has 100% accuracy in optimal weather.	VLPR has a lower rate using a neural network system. VLPR system has some trouble with characters such as 0 and O or l and I. Neural network accuracy does not handle the shadow problem and natural weather conditions.	http://ijsrcseit.com/paper/CSEIT172339.pdf
40	Automated Tolling.	International Conference on Technologies for Sustainable Development.	Open Road Tolling in India by Pattern Recognition.	Automating toll collection systems.	Fully automated toll collection system based on NPR.	License plate number.	Image acquisition modules. License plate reader. IR cameras.	Template matching method. Histogram-based license plate localization.	Having a template for license plate helps increase the accuracy of the system.	Not every license plate follows the same pattern, especially during border crossings.	https://ieeexplore.ieee.org/document/7095911
41	Automated Tolling.	IEEE International Conference on Control System, Computing, and Engineering.	Development of a GPS-Based Highway Toll Collection System.	Traffic congestion and fuel efficiency due to toll fee payment.	GPS-based highway toll collection system.	GPS coordinates. Toll collection points.	Microcontroller and GPS module.	SQL database of travel logs.	This system is accurate enough for some toll roads; however, if the system requires accuracy, a hardware upgrade is needed.	This system may register inaccurate toll collection when road overlapping is present in a highway structure. Requires installing this system in every car.	https://ieeexplore.ieee.org/document/7893557
42	Automated Tolling.	21st International Conference on Intelligent Transportation Systems.	Deep 2.5D Vehicle Classification with Sparse SfM Depth Prior for Automated Toll Systems.	Automated toll systems on proper	3D reconstruction system for vehicle classification in toll roads.	Vehicle image data. Vehicle frames.	Static camera.	Automatic estimation of driving direction. 3D reconstruc	This system improves over the baseline without an aux branch for all input types.	This system is purely based on classification of vehicles, but it cannot re-identify a vehicle	https://ieeexplore.ieee.org/document/8569670

No.	Area	Source	Research Title	Research Problem	Research Proposal	Research Variables	Technologies		Pros	Cons	Research Link
							Hardware	Software			
				classifica-tion of vehicles.				tion algorithm based on convolutio nal neural network.	A combination of points and lines for 3D reconstruction yields the highest accuracy. This method does not need 3D information, which can be beneficial for mobile vision systems.	passing by multiple times or at different points, considering it is a border crossing.	

Measuring Border Wait Time at Land Ports of Entry: Technology Assessment and Data Dissemination

Border Crossing Information System Overhaul Report

Prepared by

Texas A&M Transportation Institute

Prepared for

BTI Institute
Borders • Trade • Immigration
A Department of Homeland Security Center of Excellence

May 6, 2021

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List of Abbreviations

BCIS	Border Crossing Information System
CBP	U.S. Customs and Border Protection
RFID	Radio Frequency Identification
SQL	Structured Query Language
TTI	Texas A&M Transportation Institute
UDP	User Datagram Protocol
VM	Virtual Machine

General Overview

The Border Crossing Information System (BCIS), which was developed in 2011, was hosted on Texas A&M Transportation Institute (TTI) servers. The BCIS was initially intended for six commercial border crossings along the Texas–Mexico border. Over time, this system expanded to host nine commercial and three passenger border crossings along the U.S.–Mexico border. The additional computation as well as storage requirements and updated compute hosting requirements made it necessary to update the system with newer technology.

As part of the contract with the University of Houston, TTI upgraded the computational environment for hosting the BCIS. This document includes an overview of the upgrade process.

Section 1 describes various options considered while selecting the new hosting platform. Section 2 describes the dataflow for the entire system. Section 3 describes the user interface for the system. Finally, Section 4 provides conclusions and recommendations.

Section 1: Upgrade Options

While considering upgrade options, researchers considered various factors for the new system. The factors considered were:

- **Uptime**—The new system should provide high uptime, which would ensure uninterrupted data for the stakeholders with minimal data gaps.
- **Security and privacy**—The system should be as secure as possible; at the same time, the system should maintain the privacy of the data users whose data were collected.
- **Portability**—The system should be portable enough, which would enable other entities to host the system with minimal effort.
- **Storage space**—The system should try to minimize the storage space requirements so that the hosting cost could be kept under control in the long term.
- **Maintenance**—The system should have minimum maintenance requirements. Fewer maintenance requirements would minimize the maintenance window, which would result in high uptime and reduced maintenance cost.

After evaluating these factors for on-premises versus cloud-based hosting, the team determined that a cloud-based provider would perform better compared to the on-premises hosting options. At the time of this report's writing, there were two main cloud-based providers, Amazon Web Services and Microsoft® Azure. Researchers selected the Microsoft Azure platform for the implementation of the new BCIS due to the availability of Azure for U.S. government use,[1] which might be required in case U.S. Customs and Border Protection (CBP) decides to host the system. Researchers also evaluated various Azure Serverless solutions[2] for designing the new system. Serverless options minimize the maintenance requirements for the subscribers.

[1] Microsoft. Azure for U.S. Government. https://azure.microsoft.com/en-us/global-infrastructure/government/.
[2] Microsoft. Azure Serverless. https://azure.microsoft.com/en-us/solutions/serverless/.

Section 2: Dataflow

Figure 1 provides a dataflow diagram for the entire system. This section offers a brief description of each component.

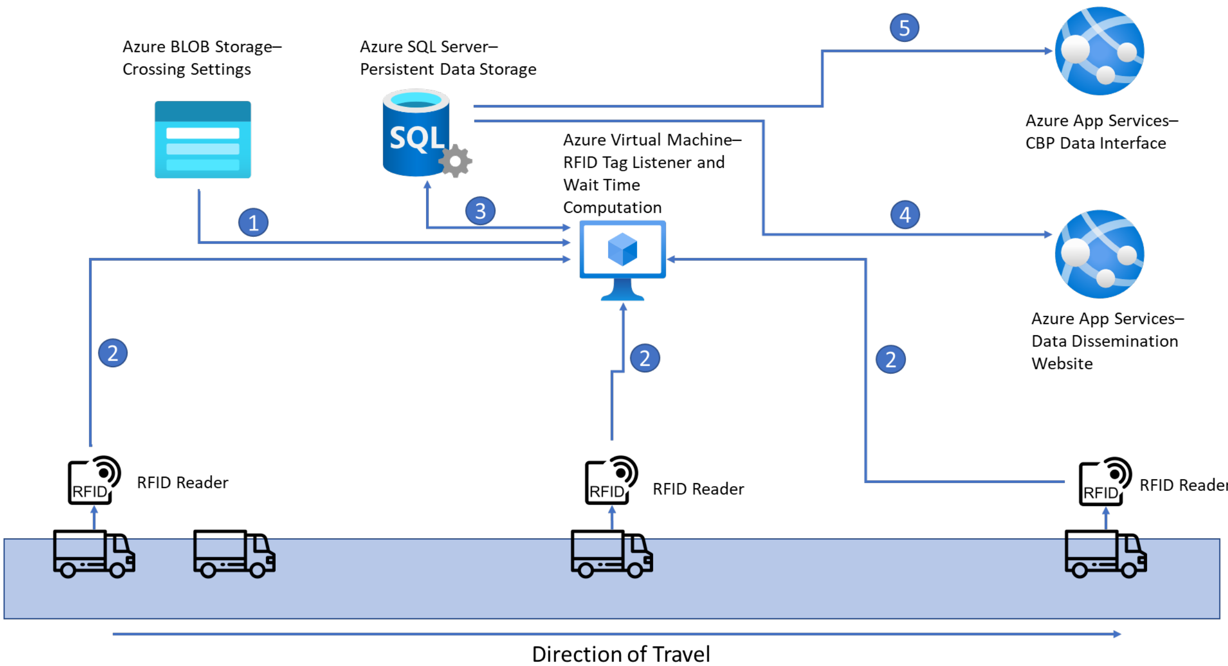


Figure 1. Dataflow Diagram.

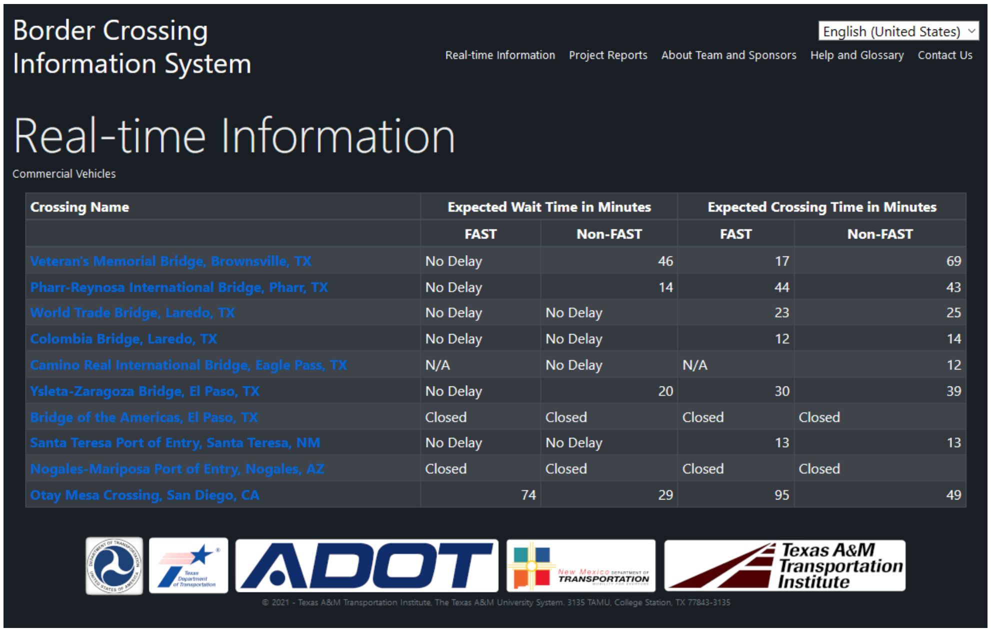
The radio frequency identification (RFID) tag reader service runs on the Azure Virtual Machine (VM). This service listens to a User Datagram Protocol (UDP) port on the VM and performs the computations to compute the wait time.

The steps in the dataflow diagram are:

1. The UDP listener service and computation service read the crossing configuration settings from the Azure Blob storage. This service listens to a UDP port, which is specified in the configuration settings.
2. The roadside RFID readers read the RFID tags on the trucks and send the Tag ID to the Azure VM. The Azure VM compares the Tag IDs to the upstream tag IDs received in the recent past. Using this information, the Azure VM computes the wait time for the tag ID.
3. The Azure VM stores the computed wait time in the Azure Structured Query Language (SQL) database.
4. The data dissemination website reads the wait time information stored in the Azure SQL database and provides this information to the users.
5. The CBP data interface service reads the wait time information stored in the Azure SQL database and provides this information to CBP.

Section 3: User Interface

Data are provided to users via a web-based interface. The home page in Figure 2 shows the wait times and crossing times at all the crossings equipped with the BCIS in a tabular format.



Crossing Name	Expected Wait Time in Minutes		Expected Crossing Time in Minutes	
	FAST	Non-FAST	FAST	Non-FAST
Veteran's Memorial Bridge, Brownsville, TX	No Delay	46	17	69
Pharr-Reynosa International Bridge, Pharr, TX	No Delay	14	44	43
World Trade Bridge, Laredo, TX	No Delay	No Delay	23	25
Colombia Bridge, Laredo, TX	No Delay	No Delay	12	14
Camino Real International Bridge, Eagle Pass, TX	N/A	No Delay	N/A	12
Ysleta-Zaragoza Bridge, El Paso, TX	No Delay	20	30	39
Bridge of the Americas, El Paso, TX	Closed	Closed	Closed	Closed
Santa Teresa Port of Entry, Santa Teresa, NM	No Delay	No Delay	13	13
Nogales-Mariposa Port of Entry, Nogales, AZ	Closed	Closed	Closed	Closed
Otay Mesa Crossing, San Diego, CA	74	29	95	49

Figure 2. BCIS Home Page.

The user interface is bilingual in English and Spanish. Users can switch the language using the language selection located at the top right of the webpage; Figure 3 shows the Spanish version of the webpage.

Crossing Name	Tiempo de Espera Estimado en Minutos		Tiempo de Cruce Estimado en Minutos	
	FAST	Non-FAST	FAST	Non-FAST
Puente Veterans en Los Tomates, Matamoros, Tamaulipas, MX	Sin Demora	46	17	69
Puente Internacional Pharr-Reynosa, Reynosa, Tamaulipas, MX	Sin Demora	14	44	43
Puente III, Nuevo Laredo, Tamaulipas, MX	Sin Demora	Sin Demora	23	25
Puente Colombia Solidaridad, Colombia, Nuevo León, MX	Sin Demora	Sin Demora	12	14
Puente Internacional Pedras Negras II, Piedras Negras, Coahuila, MX	N/A	Sin Demora	N/A	12
Puente Ysleta-Zaragoza, Ciudad Juárez, Chihuahua, MX	Sin Demora	20	30	39
Puente Internacional Córdova - Las Américas (BOTA), Ciudad Juárez, Chihuahua, MX	Cerrado	Cerrado	Cerrado	Cerrado
Puerto de Entrada Jerónimo-Santa Teresa, Santa Teresa, NM	Sin Demora	Sin Demora	13	13
Nogales-Mariposa Puerto de entrada, Nogales, AZ	Cerrado	Cerrado	Cerrado	Cerrado
Otay Mesa Crossing, San Diego, CA	74	29	95	49

Figure 3. BCIS Home Page in Spanish.

Users can see the individual segment travel times along with the crossing details by clicking on the crossing name. Figure 4 and Figure 5 show the crossing details webpage.

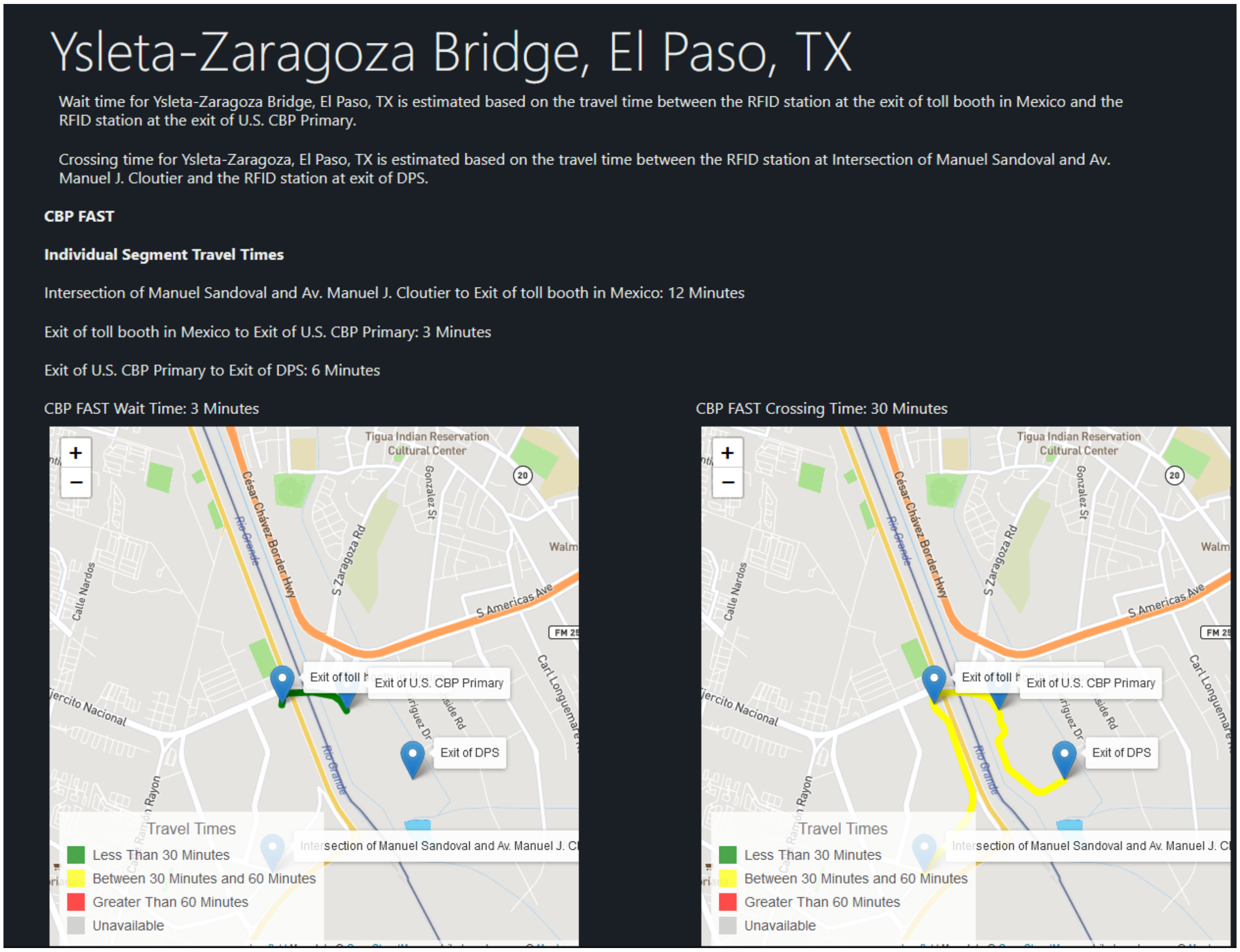


Figure 4. Crossing Details—Part 1.

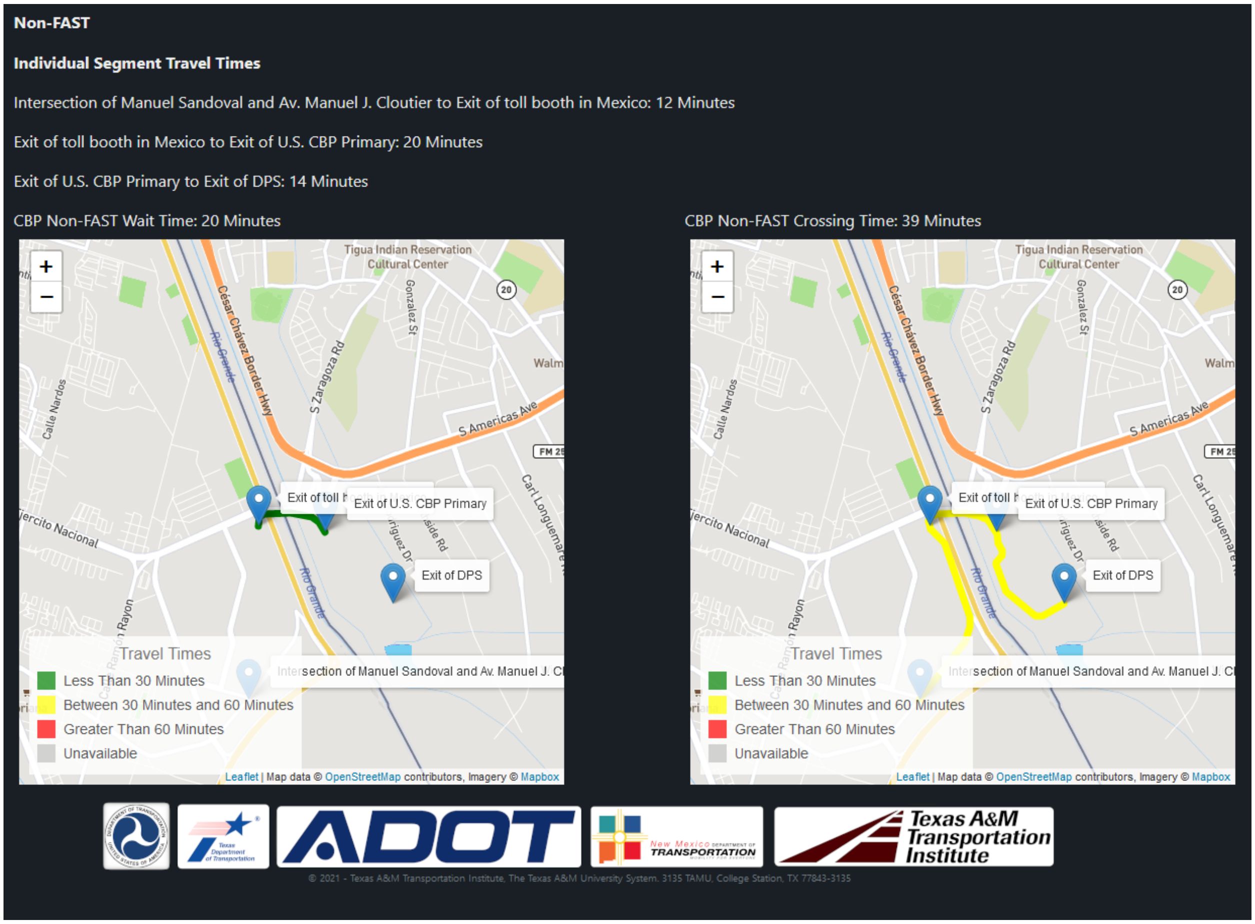


Figure 5. Crossing Details—Part 2.

Project reports and monthly crossing reports can be accessed by clicking on the Project Reports link located in the top navigation section of each webpage (see Figure 6).

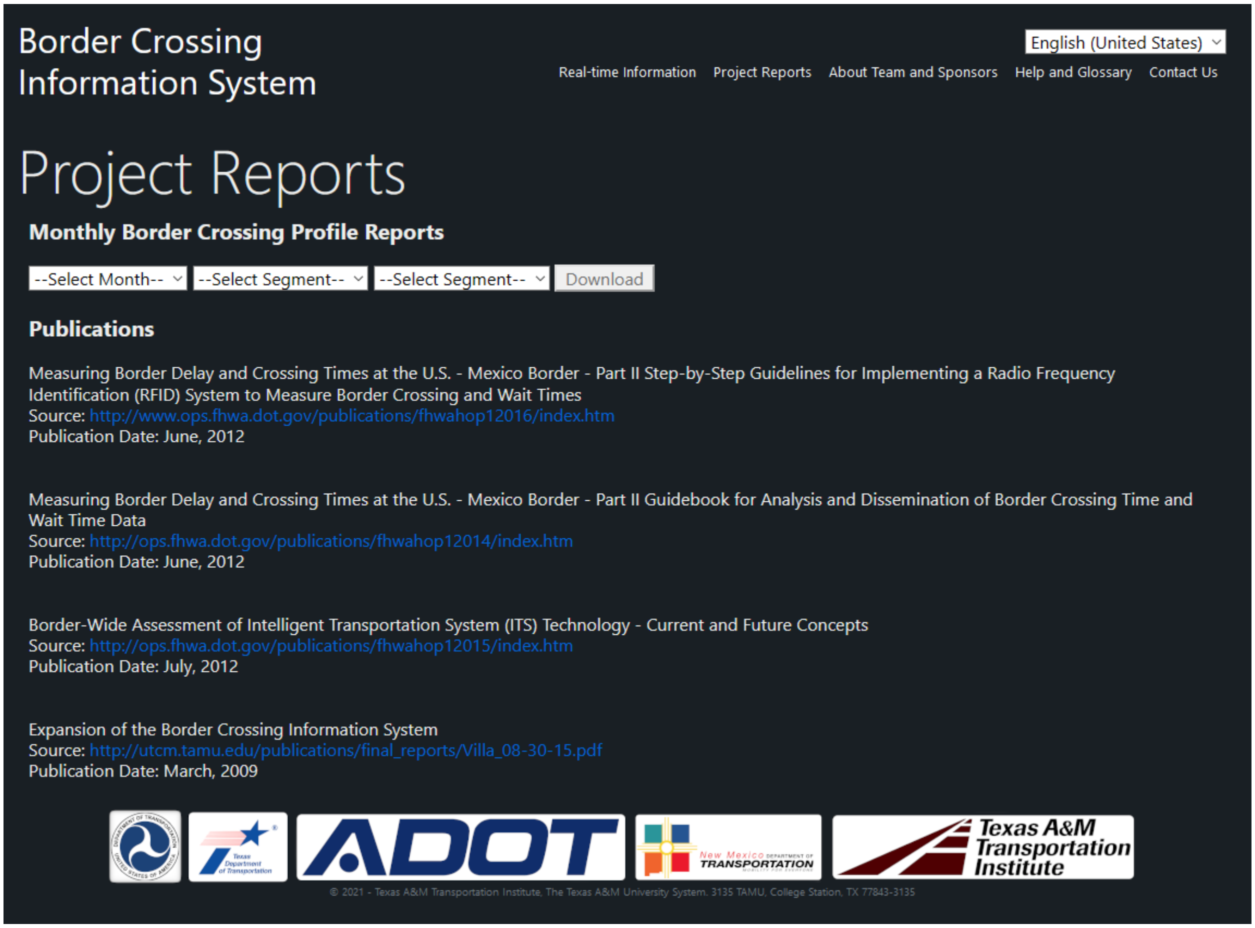
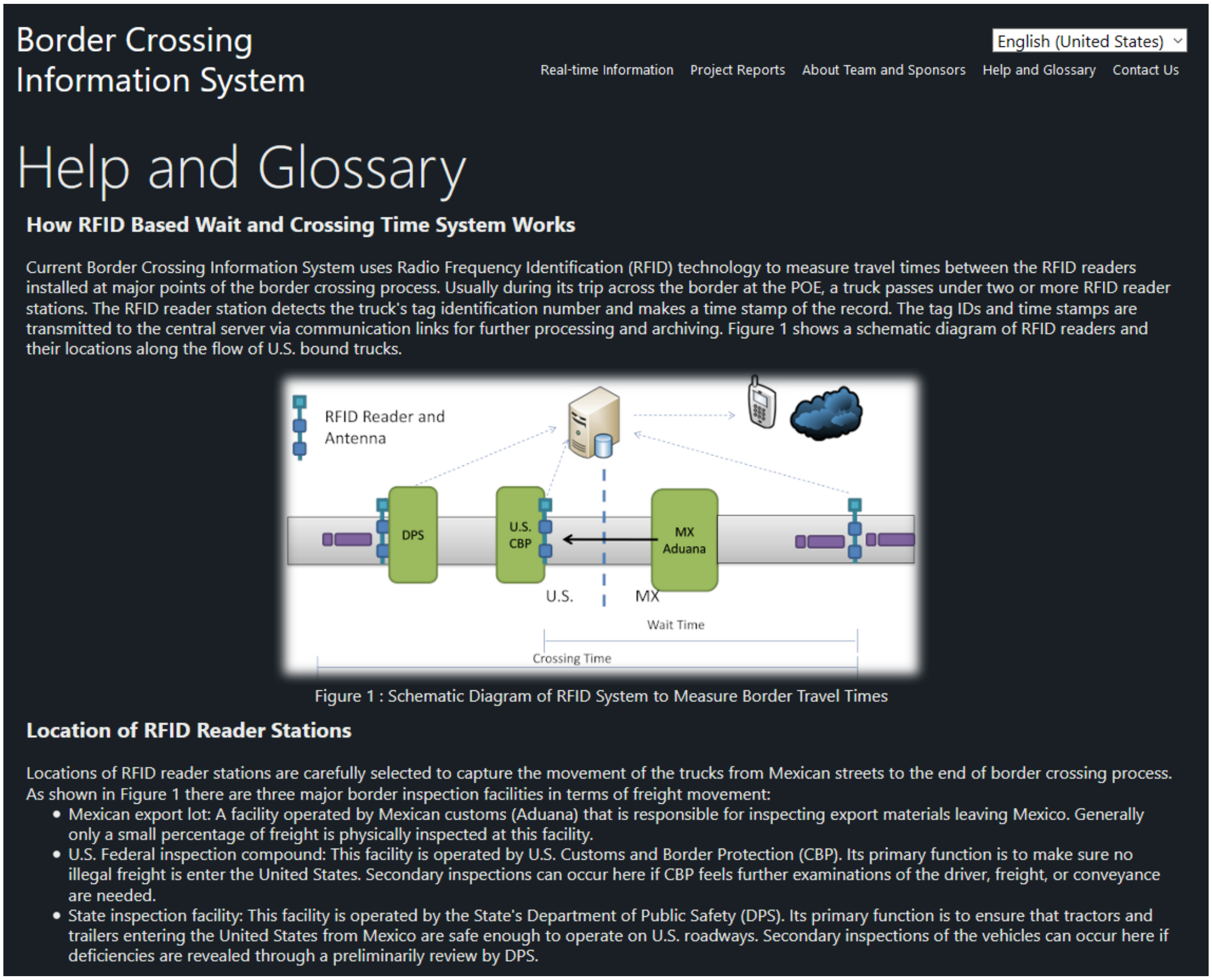


Figure 6. Project Reports Section.

Information about how the system works and a glossary of terms used can be accessed by clicking on the Help and Glossary link located in the top navigation section of each webpage (see Figure 7).



Border Crossing Information System

English (United States)

Real-time Information   Project Reports   About Team and Sponsors   Help and Glossary   Contact Us

Help and Glossary

How RFID Based Wait and Crossing Time System Works

Current Border Crossing Information System uses Radio Frequency Identification (RFID) technology to measure travel times between the RFID readers installed at major points of the border crossing process. Usually during its trip across the border at the POE, a truck passes under two or more RFID reader stations. The RFID reader station detects the truck's tag identification number and makes a time stamp of the record. The tag IDs and time stamps are transmitted to the central server via communication links for further processing and archiving. Figure 1 shows a schematic diagram of RFID readers and their locations along the flow of U.S. bound trucks.

Figure 1 : Schematic Diagram of RFID System to Measure Border Travel Times

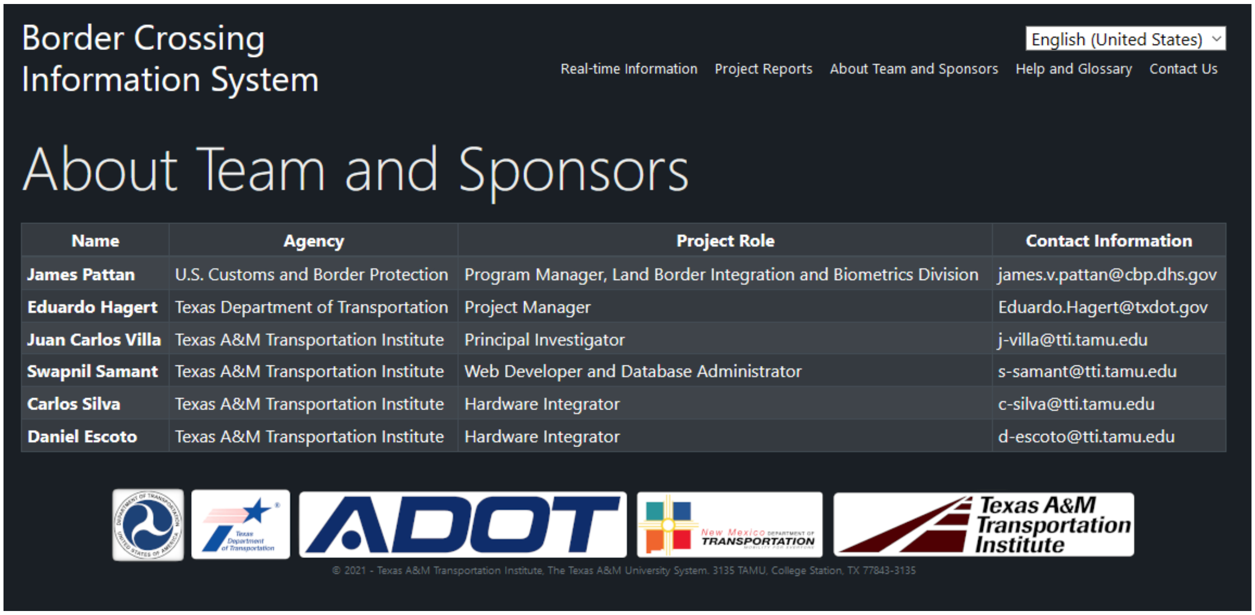
Location of RFID Reader Stations

Locations of RFID reader stations are carefully selected to capture the movement of the trucks from Mexican streets to the end of border crossing process. As shown in Figure 1 there are three major border inspection facilities in terms of freight movement:

- Mexican export lot: A facility operated by Mexican customs (Aduana) that is responsible for inspecting export materials leaving Mexico. Generally only a small percentage of freight is physically inspected at this facility.
- U.S. Federal inspection compound: This facility is operated by U.S. Customs and Border Protection (CBP). Its primary function is to make sure no illegal freight is enter the United States. Secondary inspections can occur here if CBP feels further examinations of the driver, freight, or conveyance are needed.
- State inspection facility: This facility is operated by the State's Department of Public Safety (DPS). Its primary function is to ensure that tractors and trailers entering the United States from Mexico are safe enough to operate on U.S. roadways. Secondary inspections of the vehicles can occur here if deficiencies are revealed through a preliminarily review by DPS.

Figure 7. Help and Glossary Section.

Information about the team and sponsors and the contact information can be accessed by clicking on the About Team and Sponsors and Contact Us links, respectively (see Figure 8 and Figure 9). These links are located in the top navigation section of each webpage.



Border Crossing Information System

English (United States)

Real-time Information Project Reports About Team and Sponsors Help and Glossary Contact Us

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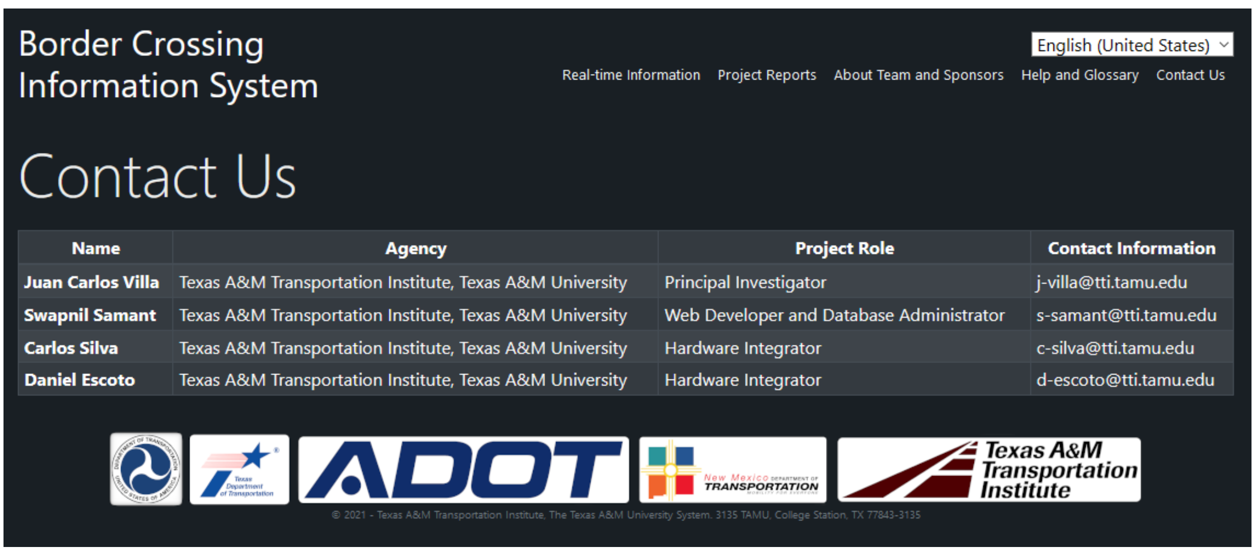
Figure 8. About Team and Sponsors Section.



Border Crossing Information System

English (United States)

Real-time Information Project Reports About Team and Sponsors Help and Glossary Contact Us

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Figure 9. Contact Us Section.

Section 4: Conclusions and Recommendations

The new BCIS was successfully implemented in a cloud-based environment on the Microsoft Azure platform. The data generated by the system were compared against the existing on-premises system and found consistent with the existing system.

Due to the necessity of UDP communication between roadside equipment and the VM, researchers were unable to develop a complete serverless solution. Further research is needed to explore the use of other communication protocols, which could enable a complete serverless solution.

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