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Evaluation of Anonymous Re-Identification Technology to Measure Commercial Vehicle Wait Time at the San Luis II Port of Entry

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ADOT

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16. Abstract
This research assessed the suitability of Anonymous Re-identification (ARID) technology to measure northbound commercial vehicle wait time at the San Luis II Commercial Port of Entry (POE) in San Luis, Arizona. The study aimed to (1) determine the preferred ARID technology (Wi-Fi or Bluetooth) for the study location; (2) determine whether the sample size of the collected data was sufficient to confidently measure border wait times of commercial vehicles; and (3) compare the costs to install a permanent ARID system with the costs for an alternative system, Radio Frequency Identification (RFID).

On-site field investigation determined that Wi-Fi was preferable to Bluetooth for use in ARID. Wi-Fi detected 58 percent of commercial trucks as they crossed the border from Mexico into Arizona. However, the volume of trucks at the San Luis II POE was relatively low, averaging about 10 northbound trucks per hour in December 2017. The study found that the sample size of trucks was too low to confidently measure wait times. Furthermore, trucks experienced considerable travel time variability, which does not allow confident prediction of wait times using technological methods. Based on the study findings, permanent ARID technology is not recommended at the San Luis II POE. The research found that the estimated cost to install a permanent ARID system at the San Luis II POE was approximately half that of a permanent RFID system. Although ARID technology was not recommended at the San Luis II POE, it may be an effective alternative to RFID in other applications with greater traffic volumes.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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List of Abbreviations and Acronyms

ADOT	Arizona Department of Transportation
ARID	anonymous re-identification
BTS	US Bureau of Transportation Statistics
CBP	US Customs and Border Protection
FAST	Free and Secure Trade
MAC	media access control
PDF	probability density function
POE	port of entry
RFID	radio frequency identification

EXECUTIVE SUMMARY

PURPOSE

The Arizona Department of Transportation (ADOT) initiated this study to determine whether advanced technological methods could be used to accurately measure the wait time of trucks crossing into the United States from Mexico at the San Luis II Commercial Port of Entry (POE).

San Luis II, which serves only commercial vehicles, is located near San Luis, Arizona, at a site about 5 miles east of the San Luis noncommercial POE.

At another POE, ADOT has used Radio Frequency Identification (RFID) to measure the travel time of border-crossing vehicles. A drawback of RFID technology is that it requires a transponder tag to be affixed to vehicles so they can be detected.

An alternative technology known as Anonymous Re-Identification (ARID) eliminates that issue. ARID technology uses the unique digital signature of mobile electronic devices, such as smartphones, to detect individual vehicles. ADOT and other jurisdictions have successfully used ARID technology in many applications, in both temporary and permanent configurations.

ARID equipment can detect either Bluetooth or Wi-Fi signals from mobile devices, but only one of these technologies can be used in a particular application.

This study's purpose was to determine if the sample size of detectable mobile electronic devices at San Luis II was large enough to make ARID a suitable technique for confidently measuring truck travel time. In addition, the study sought to determine whether Bluetooth or Wi-Fi would be preferable, and to evaluate the cost differences between RFID and ARID equipment.

FINDINGS

The study found that commercial vehicles are highly likely to have enabled mobile electronic devices. During data collection over three days in December 2017, an average of 103 US-bound trucks per day—or about 10 per hour—used the San Luis II POE. Of those 103 trucks, 58 percent were detected via truck Wi-Fi signals on both the Mexico and US sides of the border. Wi-Fi was determined to yield a much greater sample size than Bluetooth, with Wi-Fi matches about four times higher than Bluetooth reads.

The median travel time of border-crossing trucks was about 18 minutes, but truck travel time varied considerably. About 12 percent of trucks required over one hour to travel through the POE, while about 30 percent passed through in under 10 minutes.

Furthermore, the trucks' travel time varied widely even during short time periods. Traditional queueing theory would suggest that a truck's travel time is likely to be strongly correlated with the travel time of the preceding and following trucks. However, this relationship was not evident at San Luis II. From one hour to the next, median travel time often fluctuated severely.

The study found that the cost to install a permanent ARID system is about half the cost of a permanent RFID system.

RECOMMENDATIONS

At the San Luis II POE, it is not recommended that permanent travel time measurement be implemented. Although many commercial vehicles have enabled mobile electronic devices, the total truck volume at San Luis II is too low and the travel time variability is too high to permit confident predictions of wait time.

While ARID is not suitable for use at San Luis II, at other sites it is likely to be an effective alternative to RFID because of its lower cost and its ability to collect data without the need for vehicle-based transponder tags.

CHAPTER 1. INTRODUCTION

BACKGROUND

The San Luis II Commercial Port of Entry (POE) serves exclusively commercial vehicles crossing the international border between the United States and Mexico in the vicinity of San Luis, AZ. Figure 1 shows the location of the San Luis II Commercial POE, which is about 5 miles east of the San Luis I noncommercial POE. The San Luis II POE is staffed by personnel from both US Customs and Border Protection (CBP) and the Arizona Department of Transportation (ADOT).

ADOT's Multimodal Planning Division sought to determine the ability of Anonymous Re-Identification (ARID) technology to accurately measure wait times of US-bound commercial vehicles at the San Luis II POE. ARID is a term commonly used for this technology in Arizona. It includes both Bluetooth and Wi-Fi applications. ADOT sought this information to determine if ARID could be a reliable source for communicating wait times to commercial carriers in real time and for accurately scheduling staff during peak crossing periods.

ARID detects anonymous media access control (MAC) addresses from discoverable mobile electronic devices such as smartphones, in-vehicle equipment, and global positioning systems (GPS). When a single device is detected at multiple points, it is possible to determine the elapsed time between detections. As the number of detected devices increases, so too does the confidence in the system's travel time determination.

ADOT uses a different technology, known as Radio Frequency Identification (RFID), at a POE in Nogales, AZ. This study will enable ADOT to better understand the feasibility, costs, benefits, and drawbacks of ARID, particularly when compared with RFID.

OBJECTIVES

The objectives of this study were as follows:

1. Determine the sample size of ARID-recognizable devices and assess whether the sample size is sufficient to confidently measure border wait times of commercial vehicles.
2. Determine which technology, Bluetooth or Wi-Fi, best measures commercial vehicle wait times.
3. Evaluate whether ARID technology can cost-effectively replace RFID technology in determining commercial vehicle wait times.

To accomplish these objectives, the study involved the following tasks:

- Coordinate with appropriate agencies on both sides of the international border at the San Luis II POE throughout the data collection process.
- Concurrently collect ARID and traffic volume data.
- Perform statistical analysis to identify whether ARID technology is capable of collecting reliable wait time information.
- Evaluate the feasibility of ARID by comparing its effectiveness and costs to those of RFID.

PREVIOUS STUDIES OF ARID TECHNOLOGY

ADOT has commissioned a few studies of ARID technology in Arizona. Previous studies have shown that when Bluetooth and Wi-Fi detection technologies are compared, Wi-Fi often produces more reads than Bluetooth. However, local conditions can favor one technology over the other.

Vehicle speed is a major factor in evaluating the feasibility of ARID for travel time data collection, and it heavily influences whether Bluetooth or Wi-Fi technology is preferred. One reason is that personal electronic devices do not emit Wi-Fi signals continuously, even when enabled; instead, the signals pulse intermittently. Wi-Fi technology is more likely to detect a vehicle moving at a lower speed, because the vehicle remains within the ARID detection range longer than a vehicle moving at a higher speed. Bluetooth technology does not suffer from this limitation, because when enabled, Bluetooth devices emit a signal continuously. However, enabled Wi-Fi devices are more prevalent in the traffic stream than enabled Bluetooth devices.

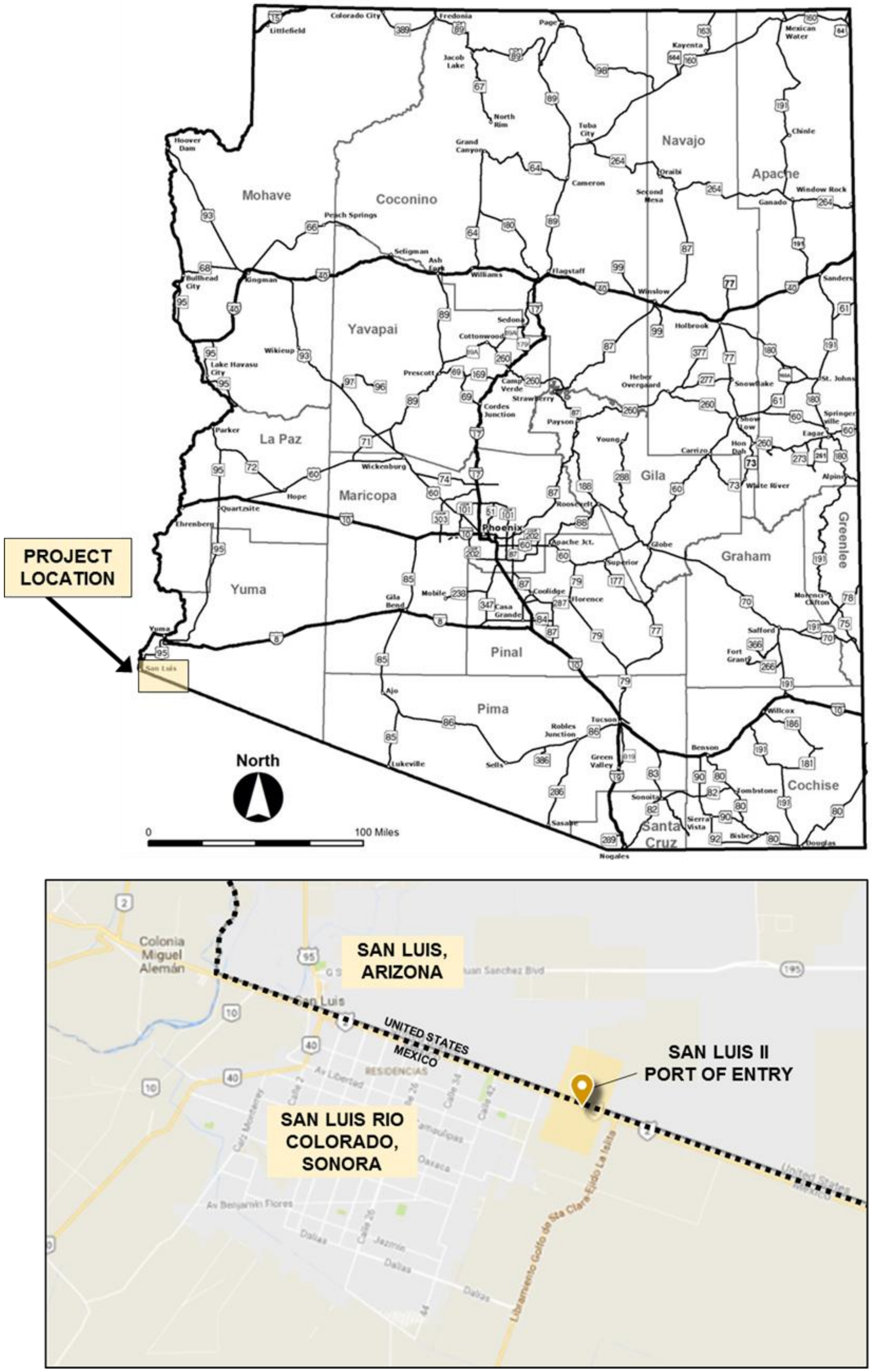
In most previous studies that compared Bluetooth and Wi-Fi detection technology, Wi-Fi was preferred. One example is a 2015 study of a segment of Interstate 17 in Phoenix (Paul et al. 2015).

However, the unique characteristics of a corridor or of the traffic stream may suggest that Bluetooth is preferable. This was the case in a 2017 ADOT study of a segment of westbound U.S. Route 60 approaching Interstate 10 in Tempe, AZ (AECOM 2017).

Two factors unique to the San Luis II POE make a comparison of the two technologies instructive:

- The prevalence of mobile devices among drivers on an urban freeway corridor is likely to be different than the prevalence among international cross-border commercial vehicle drivers. The prevalence of devices has a direct relationship with the ARID read rate.
- Some mobile devices may incur different operating costs in Mexico than in the United States, which may lead some commercial vehicle drivers to turn off their mobile devices as they cross the international border. If a device is turned off or on as a vehicle crosses the border, it prevents a travel time match from being recorded. Drivers' mobile device operating strategy at the POE is possibly very different than on an urban freeway corridor, where it is unlikely that mobile devices are powered off for this reason.

In addition, usage of in-vehicle electronic devices is changing quickly over time as new vehicles enter the fleet with advanced communications features and as personal mobile devices become increasingly ubiquitous.



(Local map courtesy Google Maps)

Figure 1. San Luis II POE Vicinity Map

CHAPTER 2. DATA COLLECTION METHODOLOGY

The San Luis II POE study collected two types of data: ARID data, to determine truck travel times, and traffic volume data, to determine the proportion of trucks recorded by the ARID detectors. Field data were collected on three weekdays during December 2017, a time of year when the POE was open from 9:00 a.m. to 7:00 p.m. on weekdays. ARID travel time data and traffic volume data were collected to assess the suitability of ARID technology at the San Luis II POE.

TRAVEL TIME DATA COLLECTION

ARID data collection devices were deployed to collect travel times of US-bound trucks. Wi-Fi and Bluetooth signals have unique MAC addresses, which were recorded at different locations along a route and then matched through software algorithms to determine the elapsed time between detections at the deployment locations. The ARID sensors, including a data processing device, Bluetooth/Wi-Fi antenna, and cellular modem, were powered by a 12-volt battery and secured within a roadside hard case. These units were locked and secured to fixed objects in the study area. Figure 2 shows the ARID equipment and its deployment.

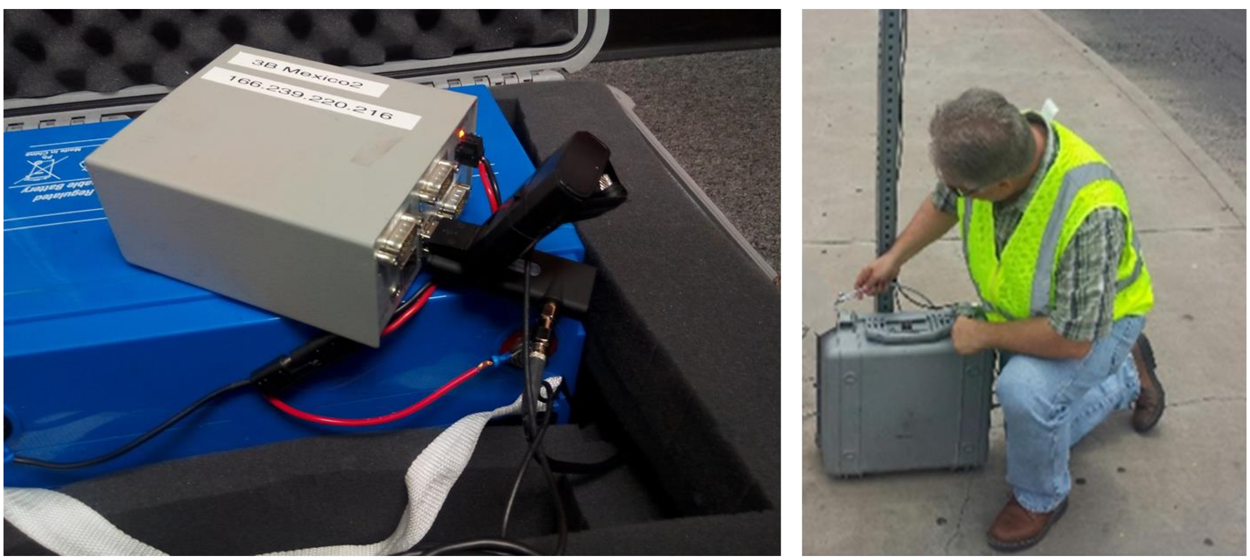


Figure 2. ARID Equipment Components and In-Field Deployment

A pilot study was conducted to determine which ARID technology, Wi-Fi or Bluetooth, was more suitable for the San Luis II location. Two sets of devices were deployed, one with Wi-Fi and the other with Bluetooth, in similar locations and during the same time period on Monday, December 11, 2017, to capture the same traffic flow. The technology with the greater sampling of traffic flow was to be selected as the sole method used for the remaining days of the data collection.

The pilot study used four ARID sensors: two Wi-Fi sensors and two Bluetooth sensors. One sensor of each technology was positioned near the northbound entrance gate of the Mexico POE facility, and the other sensor of each technology was positioned near the northbound exit gate of the United States POE facility. These sensors were positioned to capture the travel time of northbound vehicles from the time they entered the Mexico facility to the time they exited the US facility. The Wi-Fi and Bluetooth devices were positioned far enough away from each other to avoid interfering with each other's signals. The position of the devices during the pilot study is shown in Figure 3.

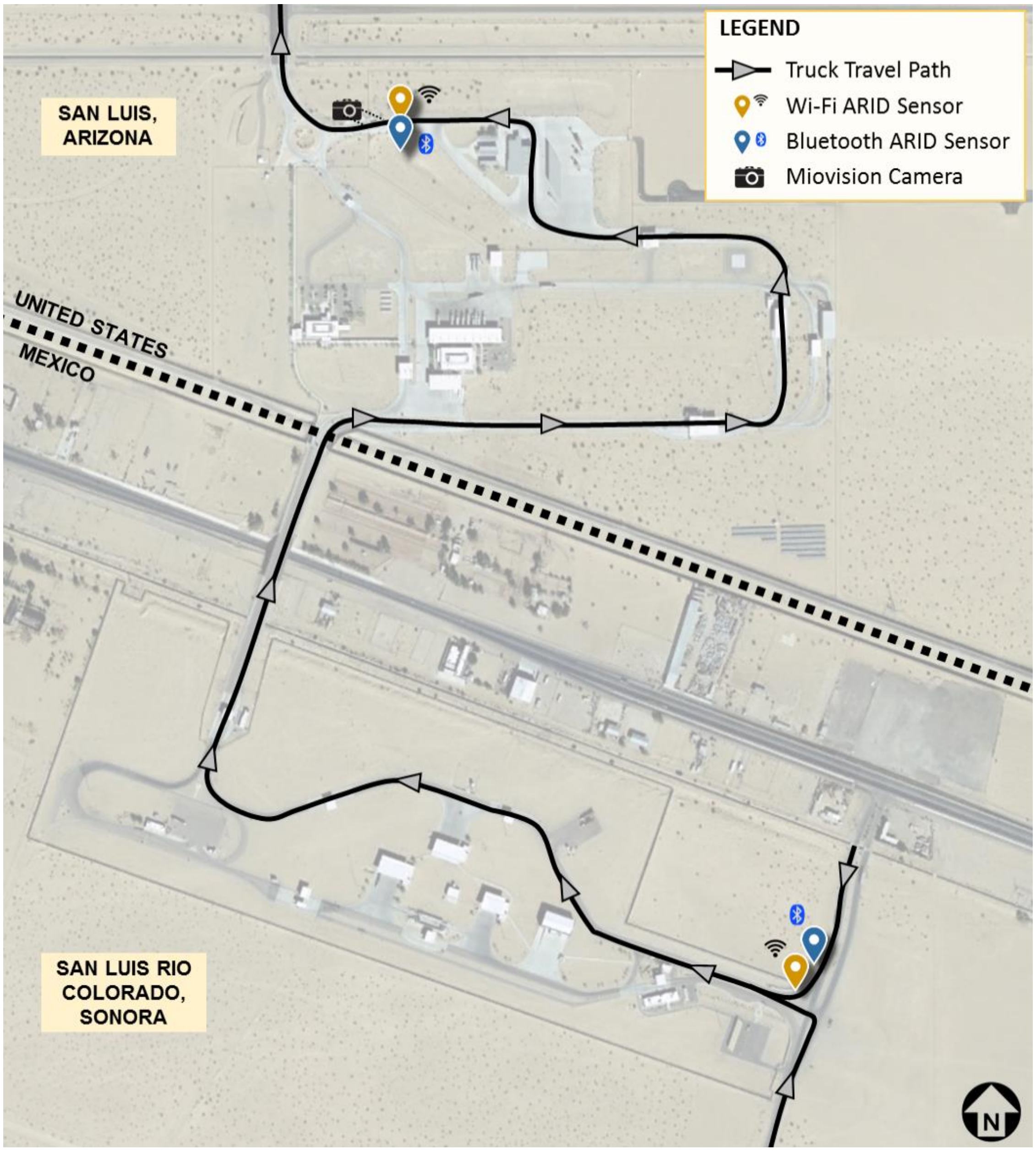


Figure 3. Wi-Fi and Bluetooth Sensor Positioning for Pilot Study
(Background Image Source: Google Earth)

After the pilot study, the two sensors of the less-favorable technology were removed from the field for the remainder of the data collection period.

Once deployed in the field, the equipment continued to collect data independently. Staff regularly monitored the security of the equipment and confirmed that the units continued to receive power. These devices have the capability to send real-time data for remote data monitoring and data analysis, but their location near the international border limited the range of the available wireless communication coverage. In this study, the data were downloaded at the end of each day, once the ARID sensors had been transported to an area where US wireless communication was available. The ARID data were then uploaded and available for postprocessing. During the three days of data collection, over 20 hours of travel time data were collected.

TRAFFIC VOLUME DATA COLLECTION

The volume of northbound commercial vehicle traffic was measured using video-based traffic count equipment from Miovision Technologies. The Miovision equipment was deployed on the US side of the border, near the northbound exit from the POE. The equipment was positioned in such a way that it was able to capture all vehicles exiting the POE. Video data were collected and processed for the same three days for which the ARID data were collected, Monday, December 11, to Wednesday, December 13, 2017. Data were segregated into two categories:

- **Trucks—**truck and semi-trailer combinations, box trucks, and semi-tractors without a trailer
- **Nontrucks—**passenger cars, pickup trucks, and vans

The Miovision count successfully captured all trucks crossing the border, as well as all nontruck vehicles exiting the facility (e.g., vehicles belonging to POE staff).

The traffic count data were used to determine the read rates and match rates of the ARID sensors in comparison to the number of vehicles recorded by the Miovision equipment as passing through the port of entry.

A *read* indicates that an ARID detector has registered the signature of a single mobile electronic device. It should be noted that ARID detectors often register the same mobile device more than once as it traverses the detector. A software algorithm identifies and eliminates duplicate reads of the same mobile device that occur in a short time period.

The number of unique reads an ARID detector records is almost always less than the number of vehicles passing by the detector. In theory, the number of reads can be greater than the traffic volume if some vehicles have more than one mobile electronic device enabled, but in practice, the number of reads is usually a fraction of the traffic volume.

A *match* indicates that two different ARID detectors have registered the signature of the same mobile electronic device. The match rate is calculated as the ratio of valid matches to the total number of trucks in a given time period. Nontruck traffic was omitted from the match rate calculation.

The number of matches is almost always less than the number of reads, but the specific fraction is highly dependent on the ARID detectors' placement and nearby traffic circulation patterns. At the San Luis II POE, all commercial trucks entering the United States passed both sets of ARID detectors along their route, so the match rate was expected to be higher than in a typical study.

Data collection challenges in the field resulted in fewer data than originally anticipated. Despite those challenges, over 20 hours of data were collected. The amount and quality of collected data were considered adequate to perform the analysis and draw meaningful conclusions, as discussed later in the report.

CHAPTER 3. ANALYSIS AND RESULTS

The ARID truck volume data and travel time data were analyzed to determine the match rates of the Wi-Fi and Bluetooth sensors, verify sample size at the POE, and evaluate the suitability of ARID technology for determining commercial vehicle wait times.

TRAFFIC VOLUME DATA

The truck traffic volume data, collected from Monday, December 11, to Wednesday, December 13, 2017, are shown in Table 1.

Table 1. Northbound (US-Bound) Truck Volumes, December 2017

	Dec. 11	Dec. 12	Dec. 13
Total number of trucks per day	110	107	93
Average number of trucks per operating hour	11	11	9
Maximum number of trucks per hour, morning	15	18	13
Maximum number of trucks per hour, afternoon	18	15	15
Hour with the maximum number of trucks, morning*	9:30 to 10:30	10:00 to 11:00	10:30 to 11:30
Hour with the maximum number of trucks, afternoon*	1:45 to 2:45	3:15 to 4:15	4:45 to 5:45

* Times indicate when vehicles exit the POE.

The volume of northbound truck traffic at the POE is relatively low, particularly when compared with the volumes at POEs that serve passenger-vehicle traffic. The San Luis II POE was compared with other POEs using border crossing/entry data from the US Bureau of Transportation Statistics (BTS) for December 2017. During that month, BTS data showed that the San Luis II POE served an average of 77 trucks per day, and the field data showed an average of 103 trucks per day during the three-day study period. By contrast, the Nogales POE served over 10,000 passenger vehicles per day in December 2017, a volume more than 130 times greater than at San Luis II. A larger volume of crossing vehicles results in a greater level of statistical confidence in the resulting measured travel times. It should be noted that the truck volume at San Luis II varies by season. In 2017, the peak truck volume occurred in March, when an average of 144 trucks per day were served. July had the fewest trucks, with an average of 40 per day. Based on BTS data, the average daily truck volume in December was about half of the peak-month average. During the data collection period, the three-day average daily truck volume was approximately 72 percent of the BTS peak-month average.

The data collected showed that a diurnal peaking trend does not exist at San Luis II. None of the three days evaluated show a peak truck volume at the same time of day. The afternoon volume is notable for its lack of consistency from day to day. For example, the hour between 1:45 and 2:45 p.m. showed a peak of 18 trucks on December 11, but that same hour saw only three trucks on December 13. The low volume of trucks and the lack of consistent peaking patterns complicate the prediction of wait times. Unfortunately, no statistical or measurement techniques are available to overcome those two complications.

ARID EQUIPMENT DEPLOYMENT

ARID data were collected using detectors on both sides of the international border. The first day of data collection was planned to serve as the pilot study, which would identify the more suitable ARID technology (Bluetooth or Wi-Fi) for the remainder of the data collection period. For this purpose, two sets of ARID detectors were deployed, one set in Mexico and one in the United States (four devices total). In each country, one set was configured to collect data using Bluetooth technology, and the other set, using Wi-Fi technology. The devices were deployed in such a way as to avoid interference between the two technologies.

The data collected on day 1 from the Bluetooth and Wi-Fi devices were intended to be evaluated in real time to decide which technology to use for subsequent days of the data collection. During those final days, a total of two ARID devices were planned to be deployed, one on each side of the border, using the technology identified in the pilot study as preferable.

On day 1, the ARID Bluetooth detector on the Mexico side of the border failed, while the remaining three ARID detectors collected data as anticipated. This failure precluded the ability to generate Bluetooth match data, but Bluetooth read data were available for the ARID Bluetooth detector located in the United States, and complete read and match data were available for the two Wi-Fi detectors.

To provide as much Bluetooth read data as possible, Bluetooth data continued to be captured on the second day of data collection, twice as long as originally planned. The additional Bluetooth read data helped provide further support for the selection of Wi-Fi as the preferred technology.

A review of the results determined that despite the failure of one detector, the available data were sufficient to complete the first two study objectives:

- **Objective 1—**Determine the sample size of ARID-recognizable devices and assess whether the sample size is sufficient to confidently measure border wait times of commercial vehicles.
- **Objective 2—**Determine which technology, Bluetooth or Wi-Fi, best measures commercial vehicle wait times.

PILOT STUDY RESULTS: WI-FI VERSUS BLUETOOTH

The results demonstrate that Wi-Fi is preferable to Bluetooth for this border crossing application. The number of US Bluetooth reads was used as a surrogate for Bluetooth matches—because of the equipment issue—and was compared with both the number of Wi-Fi matches and the actual truck volume. Table 2 presents the relevant data.

Table 2. ARID Bluetooth versus Wi-Fi Data, December 2017

	Dec. 11	Dec. 12	Total both days
Total US Bluetooth reads	17	13	30
Total valid Wi-Fi matches	72	54	126
Total truck volume	110	107	217
Bluetooth reads as a percent of total truck volume	15%	12%	14%
Valid Wi-Fi matches as a percent of total truck volume	65%	50%	58%

As noted earlier, the number of reads is almost always higher than the number of matches. Despite the advantage conveyed by measuring Bluetooth reads instead of matches, total Bluetooth reads for the two days are still considerably lower than Wi-Fi matches, by a factor of over four. If Bluetooth match data were available instead of Bluetooth read data, the difference between the two technologies would almost certainly be even more pronounced.

The overall Wi-Fi match rate of 58 percent is higher than that seen in previous studies. In a study of other POEs in Arizona (Lee Engineering 2015), Wi-Fi match rates of approximately 30 percent were observed. At San Luis II, it is possible that the slower speeds, the placement of the ARID detectors, and the consistent routing of all vehicles along the same path were more conducive to registering mobile electronic devices than was possible at other POEs. It is also possible that the prevalence of enabled mobile devices has increased in the years since the other POEs were studied.

Given the consistent performance of both Bluetooth and Wi-Fi during data collection, and given the gap between the two sets of results, it is clear that Wi-Fi is preferable at the San Luis II POE.

ARID RESULTS: DAILY

Figure 4 shows a histogram of the ARID Wi-Fi travel time data. The travel times shown reflect the total time required to travel between the two Wi-Fi ARID detectors. The total travel time can be expressed as the sum of free-flow time, service time, and wait time:

- **Free-Flow Time** is the time required to travel between the ARID detectors, excluding the time needed to stop or slow for service or queued vehicles.
- **Service Time** is the time required for vehicles to be actively inspected or evaluated. The POE contains multiple service points, such as CBP and ADOT facilities; the POE service time represents the sum of the service times at the individual service points.
- **Wait Time** is the cumulative time vehicles spend waiting in a queue to reach the different service points within the POE.

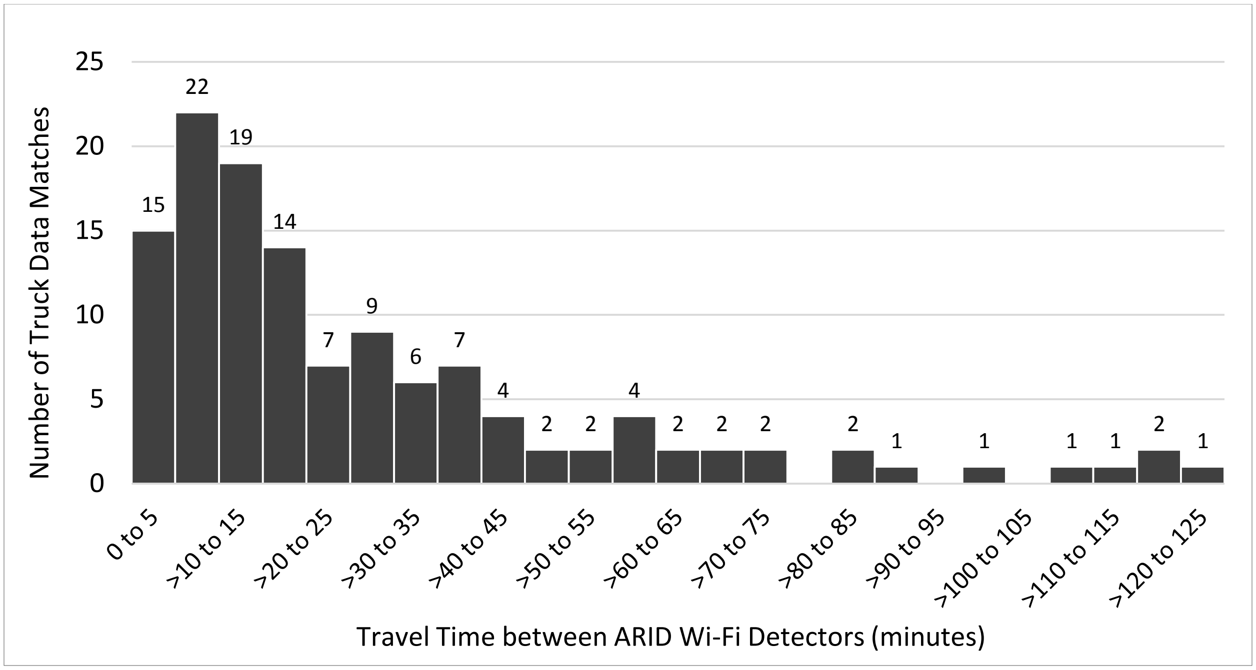


Figure 4. Frequency Distribution of Travel Times at San Luis II POE, December 11 and 12, 2017

When one truck experiences a very long travel time, the mean travel time is disproportionately affected. The mean travel time of the 126 trucks in the dataset is 27.8 minutes, but this is not necessarily the best measure of typical travel time because it is heavily impacted by a few trucks with very long travel times.

Alternatively, the trucks' median travel time, or the time exceeded by 50 percent of trucks, is 17.8 minutes. The median may be a better indicator of typical travel time because it is less impacted by very long waits. Notably, the median is a full 10 minutes, or 36 percent, shorter than the mean.

The large difference between the mean and the median is one indication that the collected travel time data are not distributed normally. The lack of a normal distribution is also evident from the histogram itself, since the distribution is skewed heavily toward the left side. The reason for the skewing is that most trucks passed through the POE with relatively little delay, but others were required to undergo secondary inspection, which can add significant travel time. A few trucks were recorded to take as long as two hours to pass through the POE.

Since the data are not normally distributed, an evaluation was undertaken to identify a statistical distribution that would serve as an accurate representation of the sample data. The following three statistical tests were used to evaluate a series of possible distributions:

- **The Kolmogorov-Smirnov Test**—This goodness-of-fit test compares sample data with a known distribution to determine how the data are distributed. The Kolmogorov-Smirnov Test is based on the maximum distance between the sample-data curve and the distribution curve. This method is advantageous because the test statistic does not depend on the underlying cumulative distribution. This test is limited to continuous distributions.

- **The Anderson-Darling Test**—This test was developed as a modification of the Kolmogorov-Smirnov Test. The Anderson-Darling Test allows for more sensitive testing but requires critical values to be calculated for each distribution evaluated. This test is limited to continuous distributions.
- **The Chi-Squared Test**—This goodness-of-fit test is also used to compare sample data with known distributions. For this method, data must be separated into bins to generate the chi-squared statistic. The Chi-Squared Test may be used in more applications, as it can be applied to discrete distributions (e.g., binomial and Poisson) in addition to continuous distributions.

All three of these tests are distribution-free; that is, they are able to identify the goodness of fit of sample data mapped to any distribution. The parameters associated with each distribution that was considered were optimized for the sample data prior to evaluation of the distributions according to the three tests. Based on those evaluations, it appears that the sample data can be accurately represented by a lognormal distribution. This distribution is common in the field of probability, but it is appropriate whenever the logarithms of the data points are normally distributed. The lognormal distribution has two parameters: σ and μ. Figure 5 presents charts showing the probability density function (PDF) for the lognormal distribution using four values of the parameter σ (Evans et al. 2000).

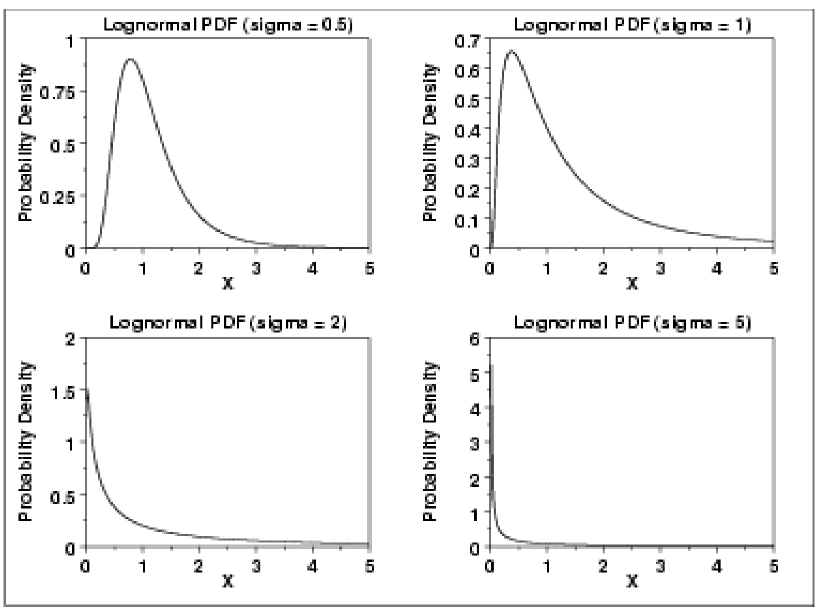


Figure 5. Probability Density Function (PDF) for Lognormal Distribution for Four Values of σ (Evans et al. 2000)

When fit to the sample data, the parameters σ and μ were determined to have the following values: $\sigma = 0.947$, and $\mu = 2.8892$. (The optimal value of σ is approximately equal to 1, so the resulting lognormal distribution looks much like the chart in the upper right corner of Figure .) Using those two parameter values, Table 3 presents the results of the three statistical tests.

Table 3. Statistical Goodness-of-Fit Test Results

	Kolmogorov-Smirnov Test	**Anderson-Darling Test**	**Chi-Squared Test** (6 degrees of freedom)
Sample size	126	126	126
Test statistic	0.06062	0.79309	3.0929
P-value	0.72005	n/a	0.79709
Critical value when $\alpha = 0.01$	0.14512	3.9074	16.812
Reject H_o?	No	No	No

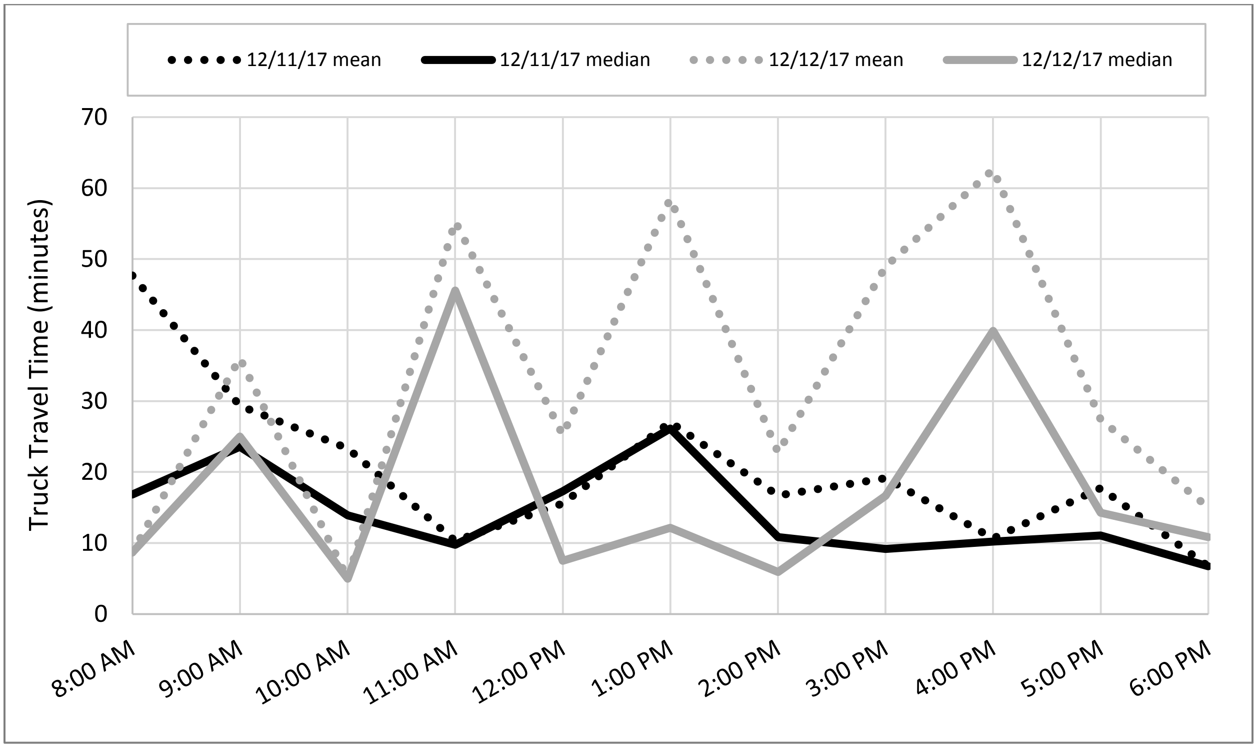
In this case, the null hypothesis (H_o) is that the sample data can be accurately represented by the lognormal distribution. The alternative hypothesis (H_1) is that there is not enough evidence to conclude that the sample data can be accurately represented by the lognormal distribution. All three tests show that the null hypothesis cannot be rejected with $\alpha = 0.01$, providing a strong indication that the lognormal distribution is an accurate representation of the sample data. The results indicate that the sample size is sufficiently large to obtain a high level of statistical confidence.

ARID RESULTS: HOURLY

While the complete data set can be represented by a lognormal distribution, the picture is considerably different when looking at data over shorter time periods. For shorter periods, queueing theory suggests that a different relationship is to be expected, because the travel time of a particular truck often depends on the travel time of the preceding and following trucks.

A goal in obtaining ARID data would be to use real-time information about truck travel time to communicate actual wait times to the public. However, the truck volume at San Luis II is so low, and the variability in travel time is so high, that real-time travel time information would be unlikely to be both meaningful to commercial vehicle drivers and statistically sound.

For example, Figure shows mean and median travel times by hour. One hour is likely too long a collection period for this purpose, because wait time can change considerably during a one-hour period. The wait time experienced by trucks at the beginning of the period may not be representative of the wait time at the end of the period. However, the hourly data are illustrative because they demonstrate how much variability was observed. On December 11, mean travel times varied from a low of about 10 minutes at 11:00 a.m. to about 25 minutes by 1:00 p.m. Variability was even more pronounced on December 12, when mean travel times fluctuated from a low of less than 10 minutes at 10:00 a.m. to over 50 minutes at 11:00 a.m., then back to about 25 minutes by noon, and to nearly 60 minutes by 1:00 p.m. The median travel time varied less than the mean, but it too fluctuated considerably.



Note: The times shown indicate when vehicles enter the POE on the Mexico side of the border.

Figure 6. Mean and Median Truck Travel Times at San Luis II POE, December 11 and 12, 2017

As noted previously, the total travel time experienced by border-crossing trucks comprises three components: free-flow time, service time, and wait time. Travel time volatility is caused in part by different service requirements for different trucks. Only certain trucks are required to undergo certain secondary inspections, which means that the service time component of the total travel time can vary considerably from truck to truck within the same hour. If service time were not a factor and the only variability were due to a truck's wait time, then the variability would likely be reduced, because queues tend to form and dissipate slowly. Consequently, the mean travel time is disproportionately affected when one truck undergoes a lengthy secondary inspection, particularly when the overall truck volume during that hour is low.

Table 4 presents detailed hourly truck match data, along with the results of the Kolmogorov-Smirnov Test used to assess the normality of the sample data.

While it would be possible to use a data collection period shorter than one hour, that would result in even fewer trucks being recorded than in a one-hour period. As it is, for a one-hour data collection period, even with the comparatively large sample size, the number of trucks per hour with travel time data ranges from a low of one per hour to a high of 16 per hour, with the average being 5.7. Half of the 22 hourly periods in the data set yielded four or fewer truck matches per hour. The threshold of four matches per hour is significant, because in common statistical practice, it is not feasible to evaluate the goodness of fit of a distribution with a sample size smaller than five.

Table 4. Hourly Truck Match Data

Hour beginning	Number of truck matches	Mean travel time (min.)	Median travel time (min.)	Standard deviation of travel time (min.)	Kolmogorov-Smirnov Test *p*-value
Mon. 8 a.m.	4	47.7	16.8	44.1	**
Mon. 9 a.m.	15	29.3	23.5	32.1	< 0.01
Mon. 10	9	23.3	13.9	25.7	0.014
Mon. 11	11	10.3	9.8	6.5	> 0.15
Mon. noon	4	15.6	17.3	6.3	**
Mon. 1 p.m.	8	27.0	26.1	19.6	> 0.15
Mon. 2 p.m.	4	16.7	10.8	15.0	**
Mon. 3 p.m.	8	19.1	9.2	24.4	0.034
Mon. 4 p.m.	3	10.7	10.2	5.9	**
Mon. 5 p.m.	5	17.7	11.1	17.2	> 0.15
Mon. 6 p.m.	1	6.7	6.7	*	**
Tues. 8 a.m.	1	8.7	8.7	*	**
Tues. 9 a.m.	16	36.0	25.0	29.9	> 0.15
Tues. 10	1	5.0	5.0	*	**
Tues. 11	4	55.3	45.6	30.5	**
Tues. noon	7	25.2	7.5	7.6	> 0.15
Tues. 1 p.m.	3	58.5	12.1	4.7	**
Tues. 2 p.m.	6	22.7	5.9	2.5	0.122
Tues. 3 p.m.	5	49.0	16.7	7.5	> 0.15
Tues. 4 p.m.	3	62.6	39.9	11.6	**
Tues. 5 p.m.	6	27.4	14.3	15.0	0.026
Tues. 6 p.m.	2	15.0	10.8	1.2	**
* Standard deviation cannot be calculated with fewer than two samples.					
** Goodness-of-fit testing is not feasible with fewer than five samples.					
[yellow]	Not normally distributed (insufficient match data)				
[green]	Possibly normally distributed				

The last column of Table 4 reports whether data from each particular hour can be said to be normally distributed. As noted earlier, half of the hours evaluated have too few trucks to permit any conclusions about statistical distribution. A *p*-value is presented for the remaining hours.

When a *p*-value falls below a selected significance threshold, it can be said conclusively that the data are not normally distributed, based on the mean, standard deviation, and number of samples. For a selected threshold value $\alpha = 0.05$, data from four hours (highlighted in yellow in Table 4) are determined not to be normally distributed. For the other seven hours with sufficient match data (highlighted in green), it is not possible to reject the null hypothesis that the data can be accurately represented by the normal distribution. This could be because the data are normally distributed, or because there are not enough samples to conclude otherwise.

For the seven hours when the null hypothesis cannot be rejected, and when it is thus possible that the data are normally distributed, a statistical confidence interval was determined based on the sampling error and the sample size. The hourly confidence intervals are shown in Table 5.

Table 5. Hourly Confidence Intervals

Hour beginning	Mean travel time (min.)	Statistical confidence interval of the mean based on hourly match data	95% confidence interval limits (min.)
Mon. 11 a.m.	10.3	95% ± 37.4%	6.4 to 14.2
Mon. 1 p.m.	27.0	95% ± 50.2%	13.4 to 40.6
Mon. 5 p.m.	17.7	95% ± 85.2%	2.6 to 32.8
Tues. 9 a.m.	36.0	95% ± 40.6%	21.4 to 50.6
Tues. noon	25.2	95% ± 22.2%	19.6 to 30.8
Tues. 2 p.m.	22.7	95% ± 8.9%	20.7 to 24.7
Tues. 3 p.m.	49.0	95% ± 13.4%	42.4 to 55.6

Note: This table shows only hours for which the data are possibly normally distributed, as outlined in Table 4.

For the purpose of providing travel time information to the public, it is ideal to have a confidence interval as narrow as possible. Wide confidence intervals indicate that there is not sufficient information for the public to make informed decisions about current travel times.

Most of the confidence intervals shown in Table 5 are excessively wide; in fact, only one of the seven hours results in a confidence range of less than 10 percent at the 95 percent confidence level. For the remaining hours, attaining a 95 percent confidence level requires a range of travel time so wide that it does not enable meaningful information to be communicated to the public.

Furthermore, as noted earlier, these seven hours are a minority of the 22 hours observed at the POE. The remaining hours do not have enough data to allow a determination to be made about the distribution, or the data are determined to not be normally distributed.

Only two of the hours listed in Table 5 are consecutive, but the predicted travel times for those two hours are markedly different. The mean travel time on Tuesday at 3:00 p.m. is more than 26 minutes greater than the mean travel time one hour earlier. While the confidence intervals for these two hours are the narrowest of any in the study, they do not even come close to overlapping. If these data were used as a basis for communicating real-time travel time to the public, they would show a large increase in travel time at 3:00 p.m. that might not reflect actual site conditions.

RESULTS SUMMARY

The data collected were sufficient to complete the study's first two objectives, as follows:

- **Objective 1—**Determine the sample size of ARID-recognizable devices and assess whether the sample size is sufficient to confidently measure border wait times of commercial vehicles.

  The collected data showed an average Wi-Fi match rate of 58 percent of crossing truck traffic, considerably higher than that observed in previous studies. Even so, the low truck volume at San Luis II and the high variability of truck travel times have conclusively determined that truck travel time cannot be reported with both statistical confidence and a travel time range narrow enough to be helpful to the public. According to Bureau of Transportation Statistics data, truck volume drops in the summer by about 50 percent from its level in December, when data were collected for this study. It is even less likely that statistical confidence could be achieved in a lower-volume month. The truck traffic volumes at the San Luis II POE resulted in too few ARID Wi-Fi matches to confidently measure and report travel times to the public.

- **Objective 2—**Determine which technology, Bluetooth or Wi-Fi, best measures commercial vehicle wait times.

  Bluetooth and Wi-Fi technologies both have the ability to provide travel time data, but each system captures data differently. In some applications, it may be advantageous to use one technology rather than the other, based on conditions specific to the site. The two technologies are often evaluated at new project sites to determine the preferred technology. At permanent installations, only one technology is used to collect and report travel time data.

  The study conclusively demonstrated that Wi-Fi technology offers a much greater sample size of commercial vehicles. Wi-Fi matches were more than four times the number of Bluetooth reads, a ratio that held steady on both data collection days.

CHAPTER 4. COST ESTIMATES

The third objective of this study was to compare the estimated cost to implement a permanent ARID travel time measurement system at the San Luis II POE with the cost to implement an alternative technology known as Radio Frequency Identification (RFID). With adequate traffic volumes, a permanent travel time measurement system would enable ADOT and border authorities to continuously measure and report travel times for commercial vehicles crossing through the San Luis II POE facility.

RFID technology is currently in place at the Port of Entry in Nogales, AZ, and is being considered for implementation at other POEs. RFID technology involves two components: tags and readers. Tags contain electronically stored data that are transmitted to an RFID reader via radio waves. In freight applications, RFID tags are affixed to freight trucks and are read at Ports of Entry, locations along freight corridors, and other points in the supply-chain process. Businesses use RFID for tracking and fulfillment purposes; ADOT and other agencies use it to obtain vehicle identification data, load and weight information, and data on travel times between multiple RFID readers. Data transfer between an RFID tag and a reader occurs from a distance, where physical contact and a direct line of sight are not required.

Arizona does not require all freight vehicles to have RFID tags at its Ports of Entry, but many trucks have them. The tags may be required by goods suppliers or by tolling stations or POEs in other states. They also may be used at border crossings with voluntary RFID lanes for expedited processing. At the Nogales POE, Free and Secure Trade (FAST) lanes have been implemented to enable expedited processing for known, low-risk shipments entering the United States. Freight vehicles that are approved for the FAST program must use RFID tags.

RFID and ARID technologies can both provide travel times for freight trucks going through border-crossing facilities. The estimated costs of installing each system are described in the subsequent sections. The costs provided are preliminary and are intended for planning purposes only. Further refinement of anticipated costs would be necessary prior to implementation. At the same time, it should be noted that this study found that truck volume at the San Luis II POE is so low that reliable travel time forecasting is likely not possible. Caution should be exercised before implementing any technology at San Luis II for that purpose.

ESTIMATED COSTS OF PERMANENT ARID SYSTEM INSTALLATION

A permanent ARID system would require two general categories of equipment:

- Equipment at each detection site
- A central software system

The necessary components are as follows:

Detection Site Equipment—The equipment consists of a process controller, Wi-Fi adapter, antennas, mounting materials, and associated cables. ARID sensors read MAC addresses from Bluetooth- and Wi-Fi-enabled discoverable mobile electronic devices. The sensors would be installed in at least two locations along the truck path through the San Luis II POE. Each ARID sensor also requires communication capability, preferably via wired Ethernet access, to send the data it collects to the central system. If Ethernet access is not available, ARID sensors can send data wirelessly via cellular modems, which would require an additional antenna and ongoing operating costs. ARID sensors should be installed within a secure enclosure and must have access to a continuous and reliable power source. All components are installed within the enclosure except for the antennas, which are mounted to the exterior of the enclosure. Sample ARID process controllers are shown in Figure. The authors and ADOT do not endorse specific products, vendors, or manufacturers. Images of sample equipment are included for informational purposes only, to illustrate hardware and system components.

A

B

A – Image Courtesy of Iteris, Inc.:
https://www.iteris.com/products/travel-time/vantage-velocity

B – Image Courtesy of Sensys Networks:
http://www.sensysnetworks.com/products/flexcontrol

Figure 7. Sample ARID Process Controllers

Central System—The central system contains all the hardware and software to collect, analyze, and transfer data to ADOT. The analysis determines travel times between sensor locations along the truck path. The system contains a user interface that allows conditions to be monitored and reported in real time, and provides system tools for comparing current travel times with historical travel times in a given week, day, or month. The reporting tools of the central system may be customized based on the desires of ADOT and the CBP. An example of a software interface system is shown in Figure . Local servers, rather than cloud-based systems, are recommended for storing data.

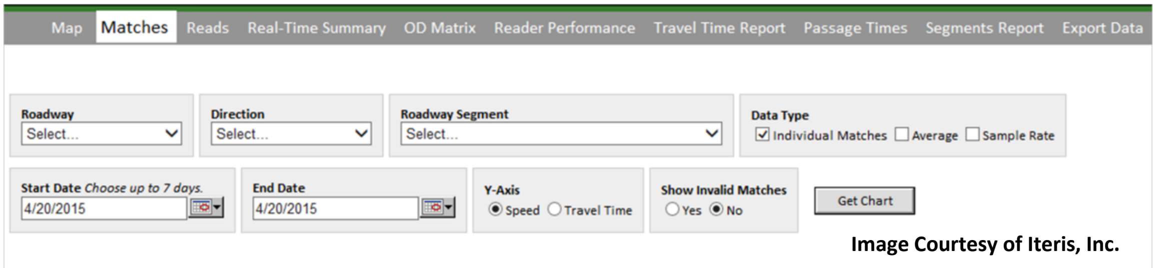


Image Courtesy of Iteris, Inc.

Figure 8. Sample ARID Software User Interface

At least two ARID sensors are needed to collect travel time information along the path of trucks passing through a POE. One ARID sensor can be positioned near the entrance to the POE, and a second sensor, near the ADOT or CBP inspection station.

A third ARID sensor can provide substantially greater data and more refined travel time information at a relatively small marginal cost. The majority of the costs associated with the installation of an ARID system are for the central software and for operations, rather than for the detection equipment components. The cost of a third ARID sensor is a relatively small expense compared with the cost of implementing the system. For these reasons, the estimated costs of a permanent ARID system were developed assuming the use of three ARID sensors. While the use of an additional sensor will provide increased travel time detail, the extra device will require adequate spacing to avoid interference and duplicative reads of one vehicle location at a certain time by two different devices. Based on the size and layout of the San Luis II POE (both Arizona and Mexico facilities), the use of three sensors is reasonable.

Approximate costs in 2018 were provided by two representative ARID vendors and were consolidated into the cost estimates shown in Table 1. The cost associated with the central software is assumed to include a one-time license fee that does not require payment of ongoing costs to the vendor.

Table 6. Estimated Costs of Permanent ARID System Installation

Item	Units	Unit cost	Quantity	Total cost
Process controller	Each	$1,700	3	$5,100
Wi-Fi adapter and antenna	Each	$500	3	$1,500
Misc. cables/mounting equipment	Lump sum	$2,000	1	$2,000
Central software and interface (includes data transfer, storage, reporting, and one-time licensing fee)	Lump sum	$35,000	1	$35,000
Local Server (HP DL360 Gen 10 with Windows server license)	Each	$3,500	1	$3,500
Total				**$47,100**

ESTIMATED COSTS OF PERMANENT RFID SYSTEM INSTALLATION

An RFID system would consist of three general categories of equipment:

- Transponder tags
- Detection site equipment
- A software tool used to collect, store, and report data

The components are as follows:

- **RFID Transponder Tag—**The RFID transponder tag is a thin sticker that is adhered to the window of a freight vehicle. The tag transmits stored information as the vehicle approaches the RFID reader's antenna. The reader can identify transponder tags up to 30 feet away. A sample RFID transponder tag is shown in Figure . The RFID tags used in border crossing applications are passive tags, which means they have no internal power source. Instead, they are powered by the electromagnetic energy transmitted by the RFID reader, which is used to read the stored data within the tag and transmit the information back to the reader.

Image Courtesy of TransCore: https://www.transcore.com/wp-content/uploads/2017/01/eGo%C2%AE-Plus-Mini-Sticker-Tag.pdf

Figure 9. Sample RFID Transponder Tag

- **Detection Site Equipment—**This consists of RFID readers and detection stations with antennas and associated equipment. The RFID readers use radio waves to identify freight vehicles with RFID tags. The RFID readers are intended to be installed in a permanent location with a continuous power supply and communication to a central server. The configuration of RFID readers would be similar to the sensor configuration in an ARID system—one reader near the northbound entrance of the border crossing facility, and a second reader near the ADOT or CBP inspection stations. As noted previously, a third device could be used to provide more detailed travel time information.

- **Software Tool—**Just as ARID technology needs a central system, RFID technology requires a software tool to collect, store, and report RFID data. Costs for the tool depend on its functionality, but generally include elements such as programming, initialization, and website development. The cost estimate also includes six months of operations.

Table 7 shows the estimated costs for an RFID system that uses three RFID readers. Approximate RFID costs were provided by ADOT, based on a previous RFID implementation project at the Nogales Port of Entry that occurred between 2009 and 2011. Those project costs were refined to account for the scale of an RFID deployment at San Luis II and were adjusted for inflation to reflect costs in 2018. An inflation factor was developed using the US Bureau of Labor Statistics Consumer Price Index from January 2010 to January 2018. The inflation factor that resulted was 1.14.

Operation of the RFID system would also involve ongoing external costs, such as staff time to supply and maintain transponder tags.

Table 7. Estimated Costs of Permanent RFID System Installation

Item	Units	Unit cost	Quantity	Total cost
1,000 RFID transponder tags	Each	$15.75	1,000	$15,750
RFID reader/antenna	Each	$13,300	3	$39,900
Additional equipment	Lump sum	$5,700	1	$5,700
Programming, communications, website development, and six months of operations	Lump sum	$34,300	1	$34,300
Total				**$95,650**

COST COMPARISON SUMMARY

The cost estimates for each technology were developed assuming the use of three field sensor/reader locations to determine travel times. The cost estimates, although preliminary, are considered to be conservative, as two sensors/readers of each technology would provide a system capable of collecting and reporting travel times. For each technology, costs are outlined for software, programming, and operations as well as for hardware. Similar internal costs are anticipated for the maintenance and operation of each system. Comparison of the cost estimates shows that the RFID system is anticipated to cost more than the ARID system, by a factor of about 2.0 ($95,650/$47,100).

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This report has documented an evaluation of travel time technology at the San Luis II Commercial Port of Entry connecting San Luis, AZ, and San Luis Río Colorado, Sonora, Mexico. Analysis of the field data supports the following conclusions and recommendations with respect to the study's three objectives.

CONCLUSIONS

Objective 1. Determine the sample size of ARID-recognizable devices and assess whether the sample size is sufficient to confidently measure border wait times of commercial vehicles.

- In the field observation, an average of 58 percent of border-crossing trucks were detected by ARID Wi-Fi sensors. This match rate was higher than in other ARID studies, possibly because of the slower speeds and more confined truck routing at the San Luis II POE.
- While the match rate was high, the total truck volume was modest. During the field observation, an average of 103 northbound border-crossing trucks were recorded per day. At the time of data collection in December 2017, the POE was open 10 hours per day, which corresponds to an average of 10.3 trucks per POE operating hour.
- Applying the 58 percent match rate to the average volume of 10.3 trucks per hour results in an average of six truck matches per hour. As many as 16 matches were observed during some hours of data collection, but four or fewer matches were observed in half of the POE's operating hours.
- Truck volume at the POE is tracked by the Bureau of Transportation Statistics. Historical data show that truck volume in the summer is about half the volume in December. As such, it is expected that average hourly truck matches drop to about three per hour during summer months.
- Too few trucks were observed during most data collection hours to draw statistically significant conclusions about truck travel time.
- Truck travel time shows significant variability, often because some trucks are required to undergo more time-consuming inspections. The high variability complicates prediction of individual truck travel time.
- In summary, the sample size of ARID-recognizable trucks is insufficient to confidently measure border wait times of commercial vehicles.

Objective 2. Determine which technology, Bluetooth or Wi-Fi, best measures commercial vehicle wait times.

- At the San Luis II POE, Wi-Fi technology was much more effective than Bluetooth in detecting border-crossing trucks. The number of Wi-Fi matches exceeded the number of Bluetooth reads by a factor of more than four during the field evaluation.

Objective 3. Evaluate whether ARID technology can cost-effectively replace RFID technology in determining commercial vehicle wait times.

- The cost estimate shows that ARID technology is a cost-effective alternative to RFID technology at ports of entry (or other locations) where traffic volume is high enough to support statistically significant travel time predictions. The cost to implement ARID technology at the San Luis II POE would be approximately half the cost to implement RFID technology.
- A major advantage of ARID technology over RFID is that vehicles need not be equipped with transponder tags to be detected by ARID devices, which eliminates one step in the deployment process and makes ARID more suitable for deployment in areas with vehicles that are unlikely to be equipped with RFID transponder tags.

RECOMMENDATIONS

- At the San Luis II POE, it is not recommended that a permanent technology-based travel time measurement and prediction method be implemented. This recommendation is based on the study's findings of low border crossing truck volume and high truck travel time variability. These issues are expected to affect all types of travel time measurement technology; hence, the recommendation applies to ARID, RFID, and other technologies.
- It is recommended that ADOT reconsider the feasibility of travel time measurement in the future if the truck volume at San Luis II increases significantly.
- At other sites, it is recommended that ADOT consider ARID technology as a cost-effective alternative to RFID technology because of its lower cost and ability to collect data without requiring vehicle-based transponder tags.

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