Concept Exploration and Recommendations Report

CASCADE GATEWAY ADVANCED BORDER INFORMATION SYSTEM (ABIS) DESIGN PROJECT

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1.0 Background

In 2023, the Whatcom Council of Governments (WCOG) was awarded funding through Stage 1 of the Strengthening Mobility and Revolutionizing Transportation (SMART) Grants Program. This program, funded through the Bipartisan Infrastructure Law (BIL) and administered through the U.S. Department of Transportation (USDOT), funds purpose-driven innovation to build data and technology capacity and expertise for State, local, and Tribal governments, with the goal of using new technologies and approaches to target real-world challenges and create benefits. The program is structured in two stages, in which applicants initially seek Stage 1 Planning and Prototyping Grants. Selected projects are then eligible to apply for Stage 2 Implementation Grants, for which the Notice of Funding Opportunity is expected to be issued in Summer 2024. The purpose of this Stage 1 project is to identify technology options and to develop a complete implementation plan with cost estimates for a new Cascade Gateway Advanced Border Information System (ABIS). The existing system, known as the Advanced Traveler Information System (ATIS), is 20 years old. As such, this Stage 1 project involves design only, and the ABIS will not be fully implemented until Stage 2 funding is secured. Figure 1 below provides a graphical overview of the project area. For additional information, please refer to the Current State Assessment & Existing Measurement Technology Review Report, which was developed for this project as part of a previous task.

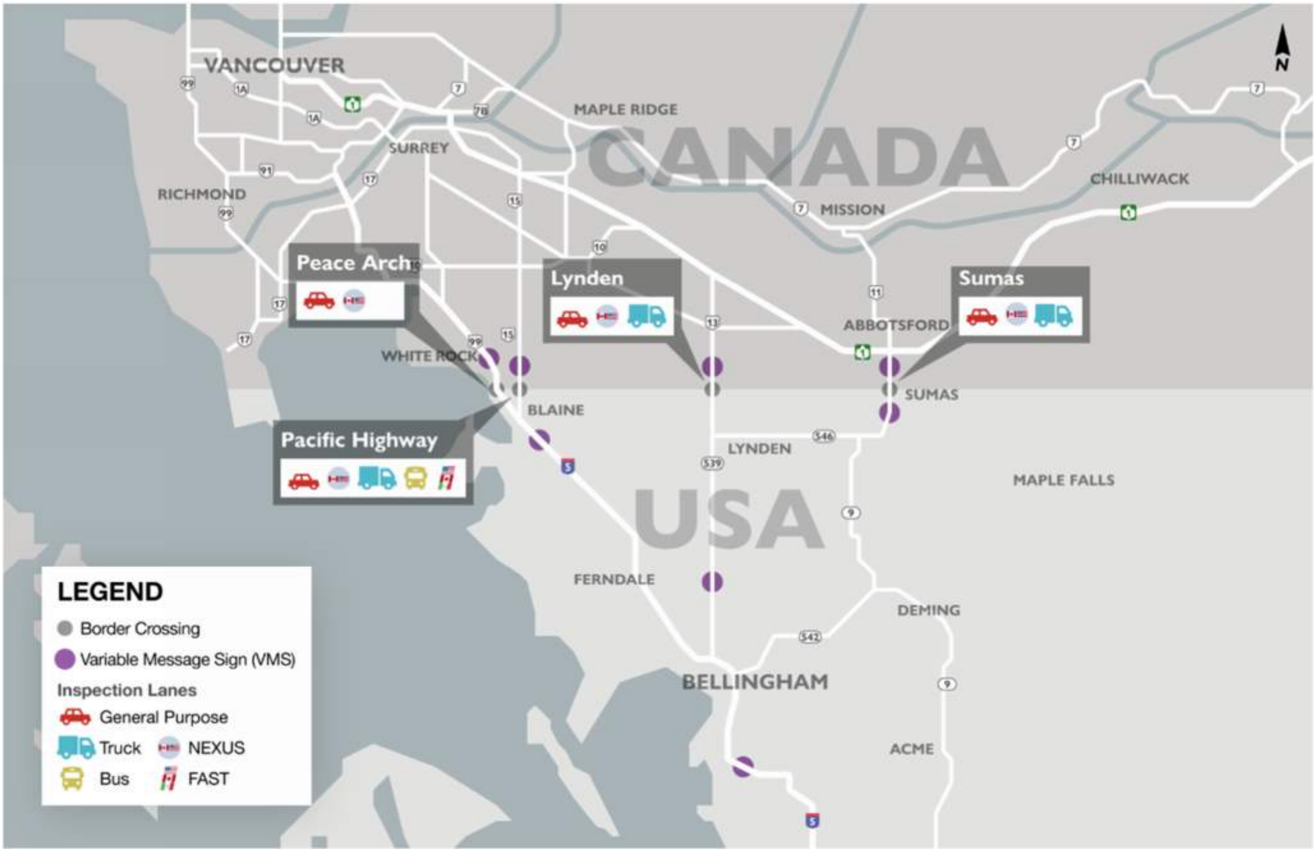


Figure 1. The Cascade Gateway ABIS Project Area Overview

1.1 Introduction

Figure 2 below shows the seven tasks and deliverables as part of the Cascade Gateway Advanced Border Information System (ABIS) Design Project. Building on the Task 2 (Current State and User Needs Assessment) and Task 3 (Existing Measurement Technology Review) report, this Task 4 Report expands on the technology options and is more focused on feasible hybrid technology concepts that meet the user needs of the stakeholders.

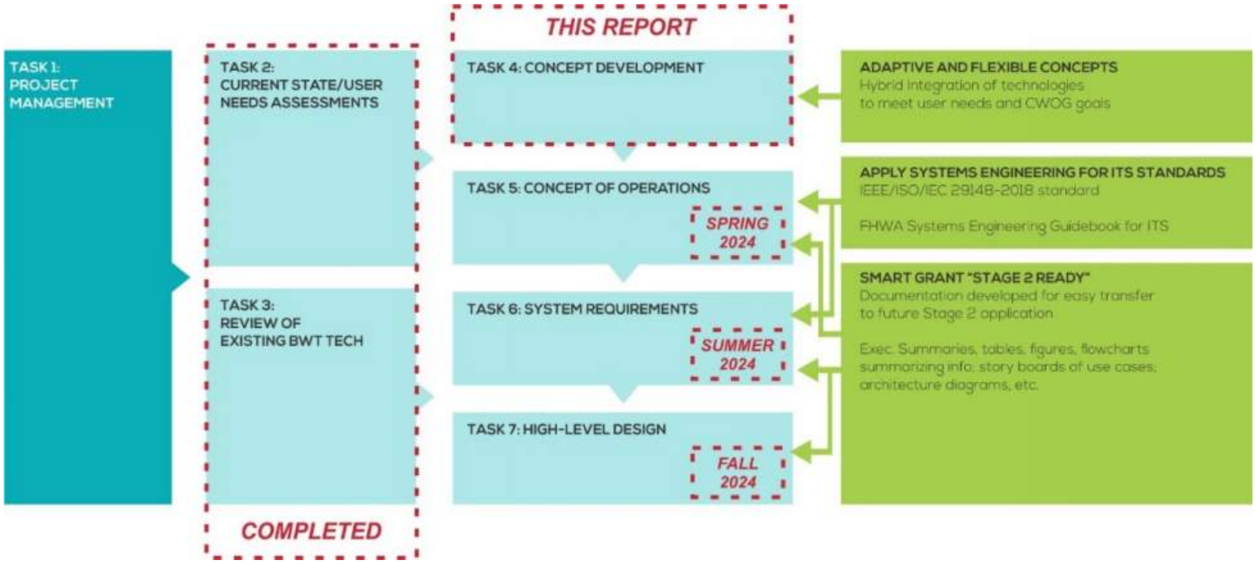


Figure 2. Overview of ABIS Design Project Tasks

This Task 4 Concept Exploration and Recommendations Report consists of six sections:

- **Section 2** delves into some of the traditional technologies, including current methodologies employed at the Cascade Gateway Ports Of Entry (POE) for estimating border wait times. While most of the technologies have been discussed or mentioned in previous deliverables, this report analyses the technologies from the perspective of their feasibility and implementation for this project. This section discusses the advantages and disadvantages of these proven technologies, which are expected to still play a prominent role in the Cascade Gateway ABIS.
- **Section 3** introduces some innovative, cost-effective technologies that transcend traditional BWT methods in accuracy and efficiency. Notably, it highlights the application of Artificial Intelligence (AI) models and the latest advancements in Global Positioning Satellite technology (i.e., GPS III). In addition, the section explores the feasibility of cutting-edge newer technologies such as minimum infrastructure or infrastructure-less methods of measuring border wait times that conform to two of the most important requirements in BWT systems, namely high accuracy and low cost.
- **Section 4** examines how these technologies could be combined into hybrid technology concepts that align with the needs of users and stakeholders. This section presents three such concepts, though additional concepts may become apparent as part of the systems engineering process and as additional discussions with stakeholders take place.

- **Section 5** provides an overview of how the hybrid technology concepts have been evaluated and scored.
- **Section 6** includes conclusions and recommendations, based on the stakeholder input and the evaluation process, as well as information gathered as part of the vendor showcases.

2.0 Traditional Border Wait Time Technologies

Over the past 15 years, the quest for precise Border Wait Time (BWT) measurements has been a focal point for researchers, policymakers, and agencies. Both the northern and southern U.S. borders have witnessed numerous studies and technological innovations aimed at enhancing our understanding of this critical aspect of cross-border movement. In this comprehensive review, we delve into landmark studies, explore various measurement technologies, and highlight key findings and conclusions.

Recent BWT Landmark Studies

There are at least four past studies on border wait time measurement, one developed most recently as part of this current project. These include the following:

1. "*Automated Wait Time and Trade Facilitation Performance Measures*" (July 2016)
    - Prepared by U.S. Customs and Border Protection (CBP) in response to a Congressional request, this study assessed the progress made in measuring BWT using cost-effective technologies.
    - *Key Findings:*
        - The Hybrid Data Solution, which combines data from multiple technologies, emerged as the most effective approach.
        - Site-specific conditions play a crucial role in technology selection.
2. "*Border Wait Time Technologies and Information Systems*" (White Paper, October 2017)
    - Conducted by the San Diego Association of Governments (SANDAG), this white paper examined 11 different BWT technologies from the past and present, and highlighted the limitations of relying solely on a single technology.
    - *Key Findings:*
        - Wi-Fi technology outperforms Bluetooth.
        - The choice of technology should align with site conditions.
        - Ongoing technological advancements offer new possibilities.
3. "*Border Wait Detection Pilot Program*" (April 2017)
    - Implemented by the California Department of Transportation (Caltrans District 11) at the SB I-5/Tijuana Port of Entry (POE), this project retrofitted call boxes with antennas and readers to capture travel time using Wi-Fi, and utilized solar-powered Wi-Fi readers.
    - *Key Findings:*
        - There were some issues with accuracy. Contact with Caltrans yielded no response regarding accuracy.
        - Some Smart Border Coalition members express skepticism.
4. "*Measuring Border Wait Time at Land Ports of Entry: Technology Assessment and Data Dissemination*" (April 2021)
    - Conducted by Texas A&M Transportation Institute, this is the most recent assessment and implementation report. Technologies used include Radio Frequency Identification (RFID) for trucks, Automated License Plate Recognition (ALPR) to identify vehicles by lane type, and Bluetooth.
    - *Key Findings:*

- A hybrid approach consisting of Wi-Fi, GPS, and ALPR technologies will likely result in the most optimal and desirable results. GPS technologies, such as Google, Waze and others, will help in infrastructure-less BWT measurement.

Table 1. Comparison of Commonly-Used BWT Technologies

Aspect	Bluetooth	Wi-Fi	RFID
Availability	Since 1991	Since 1994	Widely used since the 1970s
Frequency	2.4 GHz (varies)	2.4, 3.6, and 5 GHz	Various frequencies (e.g., 12.5) KHL 13.56 MHz)
Bandwidth	800 Kbps	11 Mbps	Low data rate (typically in kbps)
Range	1 to 100 meters (depending on class)	Up to 92 meters	Varies (from a few centimeters to several meters)
Latency	200 ms	150 ms	Minimal latency
Bitrate	Up to 328 kbps	2.1 Mbps	Up to 600 kbps
Typical Devices	Compliers, phones, input devices (mice/keyboards), fitness trackers, headsets, smart devices	Computers, game consoles, phones, smart TVs, Internet of Things (IoT) devices	Tags, cards, labels, and sensors embedded in objects
Required Hardware	Built-in Bluetooth radio or Bluetooth adapter connected to each device	Wi-Fi adapter connected to each device, and a wireless router or access points	RFID tags and readers
Use Cases	Connecting devices to each other (e.g., headsets, speakers)	Connecting devices to the internet (e.g., streaming media) browser	Asset tracking, inventory management, tolling, access control, supply chain visibility
Speed	Slow data rates and not suitable for real lime applications	Faster (capable of high band width data transfers) and suitable for real lime BWT applications	Low-speed data
Power	Lower power	Higher power	Passive (powered by the reader's electromagnetic field) or active
Accuracy	Depends on smart phone penetration. Match rate is typically 10%. Manufacturers ship with Bluetooth discover mode off	Match rate is more than 25-40%. Manufacturers ship with discover mode on	Highly accurate if mounted on gantries over the lanes with clear line of sight especially for commercial vehicles

Aspect	Bluetooth	Wi-Fi	RFID
Life Cycle Costs (5 Years)	Generally lower total cost due to simpler hardware requirements	Typically, higher total costs due to more complex infrastructure (routers, access points, etc.)	Variations based on tag type and application. Expensive for Tolling and Border Wait Time measurement compared to Wi-Fi and Bluetooth
Advantages	Mature technology, low cost, can be anonymous, easy deployment	Mature technology, low cost, easy implementation, can be anonymous, high bandwidth and data rate	Dependable and mature technology, low operating cost, precise, most trucks have transponders from other programs
Disadvantages	Complex matching and data processing, low match rate, overestimates travel times, need to combine with other technologies	Cumbersome and complex algorithms are required for matching, Requires increased battery power for long range communication	installation of readers can be expensive, high cost of roadside equipment and hardware required, not suitable for private vehicles because of transponders and low penetration rate

Vendor showcases took place for during the week of April 15, 2024, during which various technology providers were invited to present on their product offerings and answer questions specifically as they related to BWT applications like the Cascade Gateway ABIS. On May 9, 2024, these vendors were evaluated with WCOG, WSDOT, BC MOTI, and the project team; the results of this evaluation is summarized below. Only vendors who provide technologies that were mature enough and applicable to the BWT environment were carried forward in the evaluation.

Table 2. Vendor Showcase Summary

Vendor/Technology Information			**Metrics/Evaluation Criteria**					
Vendor	**Technology**	**Technology Maturity/ Applicability**	**Back of Queue**	**Number of Vehicles in Queue**	**Vehicle Re-Identification**	**Speed**	**Accuracy**	**Cost (Including O&M)**
Wavetronix	Radar	Pass. Runner up to Houston Radar	✓	✓		✓	High	Low-Med
Houston Radar	Radar	Pass. Preferred technology.	✓	✓		✓	High	Low-Med
Miovision	Video Analytics, Bluetooth/Wi-Fi	Fail. Technology is not mature enough for BWT applications.						
Currux Vision	Video Analytics, Vehicle Reidentification	Fail. Technology is not mature enough for BWT applications.						
Adaptive Recognition	Video Analytics, Bluetooth/Wi-Fi	Fail. Technology is not mature enough for BWT applications, and vendor is a hardware-only provider.						
CLR Analytics	Loop Signatures, Pavement Sensors	Fail. Technology is not mature enough for BWT applications.						
TTI	LiDAR	Pass	✓	✓		✓	High	Low-Med
Transcore	RFID (Commercial Vehicles)	Pass. However, this technology is duplicative of other technologies and does not count all trucks			✓			High
Tattlile	Machine Vision, ALPR	Fail. Technology is not mature enough for BWT applications.						

2.1 Traditional Embedded Inductive Loops Detectors (ILD)

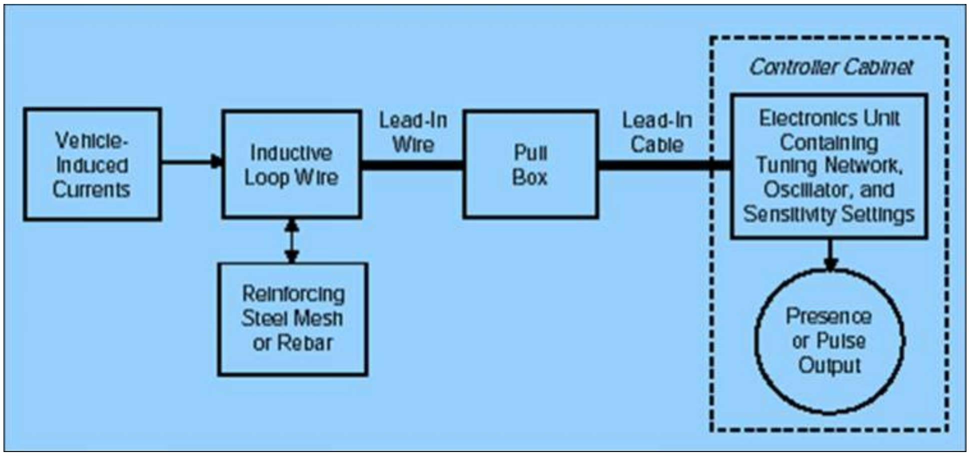


Figure 3. Overview of In-Pavement Loop Detectors (FHWA: Traffic Detector Handbook)

Although new technologies have evolved that are less disruptive in terms installation and traffic flow, in-roadway inductive-loop detectors, introduced in the early 1960s, are still the most utilized sensor in traffic management and traffic flow systems. The principal components of an inductive-loop detector system include:

- One or more turns of insulated loop wire wound in a shallow slot sawed in the pavement.
- Lead-in cable from the curbside pull box to the intersection controller cabinet.
- Electronics unit housed in a nearby controller cabinet.

Figure 3 displays a notional diagram of an inductive-loop detector system and the vehicle and steel reinforcement elements in the roadway with which it reacts. Table 3 below provides the advantages and disadvantages of roadway inductive loop detectors.

Table 3. Advantages and Disadvantages of Inductive Loop Detectors

Aspect	Advantages	Disadvantages
Detection Accuracy	Highly accurate in detecting vehicles.	Limited sensing area confined to a specific lane.
Real-time Data	Provides real-time data for traffic operations.	High installation costs and disruption during installation.
Adaptability	Easily adaptable to various traffic strategies.	Maintenance challenges and potential wear and tear.
Reliability and Loop Failures	Reliable data if there are no loop failures	Loops require high maintenance due to the following eight common types of failures. Pavement cracking and moving. Breakdown of wire insulation. Poor sealants or inadequate sealant application. Inadequate splices or electrical connections. Damage caused by construction activities. Improper electronics unit tuning. Electronics unit failure. Lightning/electrical surges.
Low Maintenance Costs	When a loop fails, however infrequent though that may be, it is costly to repair/replace.	Susceptibility to wear and tear over time.
Inductive Technology	Immune to environmental conditions.	Limited sensing area and for some speed measurements, may require dual loop configuration
Installation Costs		High initial installation costs.
Disruption during Installation		Disrupts traffic; may require road closures or restrictions.
Maintenance Challenges	Routine maintenance involves cleaning and calibration.	Repairs can be challenging and time-consuming.
Challenges		Challenging to measure BWT at lanes merging and forking

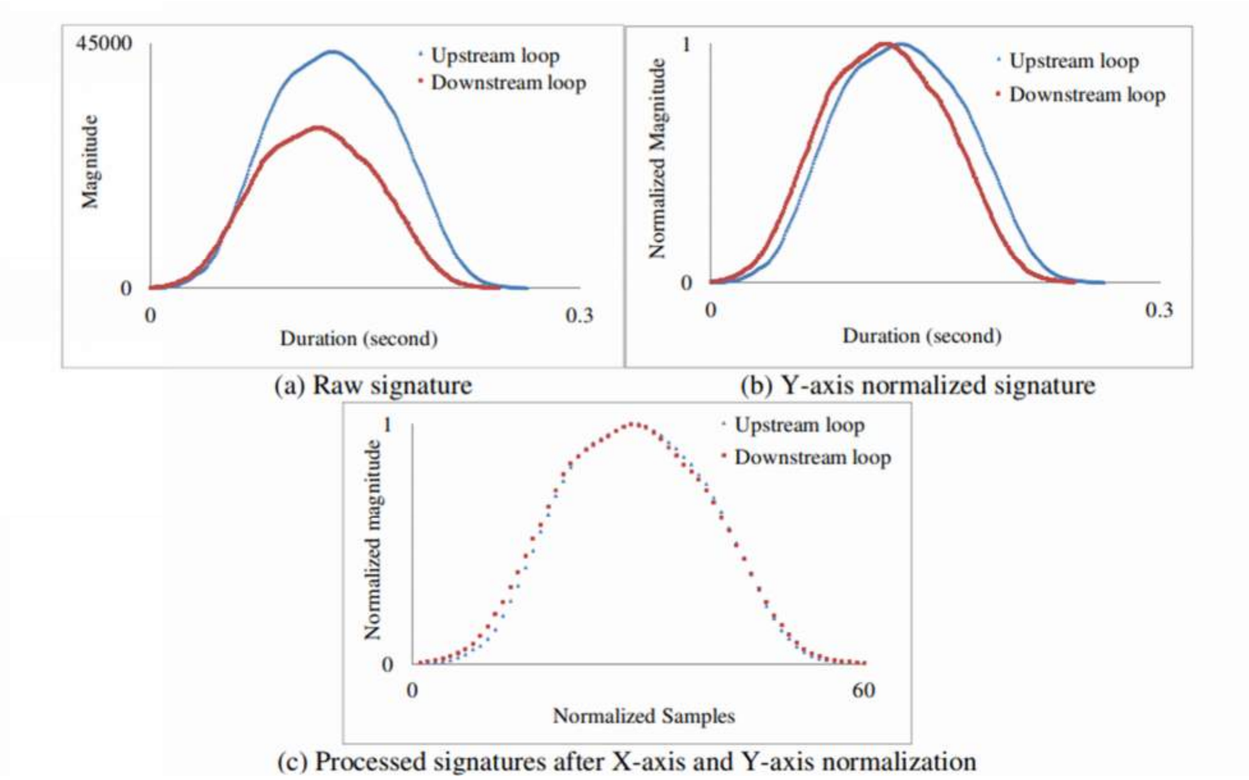
2.1.1 Re-Identification of Vehicles Using Inductive Loop Signatures

Inductive Loop Detector (ILD) systems are currently the most invested technology for obtaining traffic data in the United States and are widely deployed on many major freeway networks. Inductive loop detectors are connected to traffic controllers via conventional bivalent ILD cards and they provide traffic agencies with accurate volume and occupancy information. When installed in a double loop speed trap configuration, they can also provide point speed information.

There is currently an active Transportation Pooled Fund Study TPF-5(520) *Improving Traffic Detection Through New Innovative i-LST Technology Demonstration Pilot* in which several states across the country are piloting and deploying ILD signature technology for purposes that include vehicle reidentification, travel time, vehicle classifications, and enhancing accuracy of existing systems. Inductive loop signature technology has seen increasing adoption for the purposes of vehicle re-identification via vehicle signature reidentification algorithms. These algorithms re-identify a vehicle at a downstream detection station by matching an inductive signature from an upstream detection station. It is assumed that a vehicle will possess essentially the same normalized inductive signature when passing though different loop detection stations. The match rate is significant based on the actual deployment of the technology in many states, such as California.

Based on the evaluation by UC Irvine along NB I-405 in Irvine, CA and California PATH (UC Berkeley), the results from this pilot study showed desired performance for vehicle reidentification and travel time estimation under both free-flow and congested flow traffic conditions. The system correct matching rate was between 75% and 79% under the free-flow condition and between 52% and 70% during congestion. Vehicles that transition from free flow to congested flow will have different peaks (since the amount of time spent on a loop detector is inversely proportional to speed) so the signatures must be normalized. Figure 4 below shows the raw and normalized signature matches between upstream and downstream loops. Note that while ILD signatures are unique to each vehicle, the degree to which they vary – and therefore the ability for the system to distinguish unique vehicles – varies by vehicle type. For example, the system would not be able to distinguish one Honda Civic from another Honda Civic, unless substantial modifications have been made, but would likely be able to distinguish a Honda Civic from a Toyota Sienna. Additionally, observations from FHWA's research have shown that the ILD signatures for freight vehicles have significantly greater variance, so the applicability and benefit of this technology for re-identifying freight vehicles is particularly promising.

While the technology has been around for many years, the software algorithms that enable accurate matching of loop signatures has lagged behind. It has not been until the past decade that AI algorithms have enabled these increased match rates. However, although the special loop detector cards that are needed to collect ILD signature information are off-the-shelf products, these software algorithms are generally proprietary and only provided by a handful of vendors, such as CLR Analytics. However, note that CLR Analytics was invited to take part in the vendor showcases for this project – see Section 2.0 for details.



(a) Raw signature (b) Y-axis normalized signature

(c) Processed signatures after X-axis and Y-axis normalization

Figure 4. Inductive Loop Signatures

For the Cascade Gateway ports of entry, since the existing northbound and southbound ATIS both currently utilize ILDs, it could be a viable option to upgrade the existing Vehicle Detector Stations (VDS)/data stations to provide the existing infrastructure with the capability of re-identifying vehicles and measuring BWT. Given that existing loop detectors are also present at freeway diverge points (e.g., off-ramps), these provide the system with additional information, allowing it to filter out vehicles that have left the freeway, thereby potentially increasing the accuracy rate. However, the technology will need to be further evaluated to ensure that it operates at the desired level of accuracy in a stop-and-go traffic environment. In addition, special reidentification detector cards will need to be installed within each controller cabinet, which can be accommodated in the existing roadside controller cabinets on both sides without major modification to the existing systems or operations.

Additionally, the use case for border wait time viability has not been tested using this technology. One way to determine the suitability of this signature matching technology is to conduct a limited field deployment as proof-of-concept at a representative port of entry such as Pacific Highway, where both commercial trucks and passenger vehicles are present.

2.1.2 Reconfiguration and Recalibration of Exiting Loops for Better Accuracy

WSDOT and BC MOTI both use loop detectors in a two-loop speed trap configuration at the Cascade Gateway POEs. Under ideal operating conditions, the measurements derived from loops are accurate up to 95%, but this depends on various factors such as the channelization, driver behavior, condition of the loops, weather, interference, vehicle size, vehicle speed, ground clearance, and sensitivity settings of the loops, among other things. However, reconfiguring and recalibrating these existing loop detectors could provide better accuracy.

Configuring each detection point with tandem loops offers the advantage of acquiring additional measurements, such as travel speed, and serves to mitigate errors inherent in the distinctive dynamics of a border wait time system. Border crossing lanes typically witness two primary states: vehicles either flow freely (approaching back-of-queue) or come to a near halt as in stop-and-go traffic. To ensure accurate readings, the detection zone for each sensor must be sufficiently small and not spill over to the adjacent lane types. This precaution prevents overlaps in detections during bumper-to-bumper traffic scenarios, ensuring that multiple vehicles are not misconstrued as a single extended vehicle. In addition, in some instances there are no clear lane markings and travelers may change lanes to ones that serve different vehicle types. In such cases, the BWT calculation has to depend on other technologies, since loop detectors are not able to detect and re-identify vehicles outside of fixed locations. In the case of the BWT mobile application, data can be collected based on the user’s selected lane type, as well as the GPS location of the vehicle.

Deploying two compact detection area sensors strategically positioned at a distance exceeding the standard vehicle gap ensures that if either sensor detects a vehicle, the detection point is marked as occupied. Nonetheless, the system relies solely on the first sensor in the sequence to ascertain vehicles traversing the detection point. The subsequent sequence delineates this setup, involving two sensors linked to a singular detection point. The sequence of diagrams below shows this process of using dual detectors from no vehicle on the detector to arrival and departure of a new vehicle.

It is important to regularly calibrate sensors and validate their accuracy against ground truth data. For the Cascade Gateway ABIS, the potential technology concepts involve the use of existing BC MOTI Vehicle Detector Stations (VDS) and existing WSDOT data stations, among other technologies, and ensuring that they are calibrated so that the counts are very close to ground-truth data (e.g., what CBP RFID counters measure at the primary inspection). However, since the approach loops are located on the “other side” of the international border, it can be complicated to calibrate the loops and maintain them regularly.

No vehicles over sensors

The back of queue does not reach the detection point.

A truck is detected over the sensors

A new vehicle is detected and back of queue is calculated beyond the detection point.

The queue advances and only one sensor detects a vehicle

Since one of the sensors is activated, the detection point is still considered occupied.

The queue advances and multiple vehicles are detected by the sensors

The detection point is still considered occupied.

The queue advances and the truck leaves the first sensor

The detection point is still considered occupied since the second sensor detects a vehicle.

The queue advances and a new vehicle enters the first sensor

A new vehicle is detected. The back of queue continues to be calculated beyond the detection point.

Figure 5. Progression of Vehicles Traveling Over Loop Detectors

2.1.3 Back-of-Queue Calculation

The back-of-queue calculation involves a complex and sophisticated process utilizing existing VDS/data stations and software synchronization to accurately determine the back of the queue for each lane and the number of vehicles present. This calculation is crucial for estimating the expected wait time for each lane type, including NEXUS, Ready and General Lanes. Other factors include processing times and the number of lanes/gates open. Based on discussions with project stakeholders, the queues often extend beyond the existing last detector. In such cases, additional VDS/data station locations will need to be considered. The system determines the back of the queue based on the farthest sensor from the primary inspection that detects standstill traffic. Standstill traffic is detected when a vehicle occupies the loop for a pre-determined occupancy time threshold. Wen this happens, it triggers a traffic level change, prompting the system to analyze the traffic flow between sensors.

Figure 6 below illustrates how the back of the queue is determined by a combination of detector occupancy and software that talks to upstream and downstream detectors.

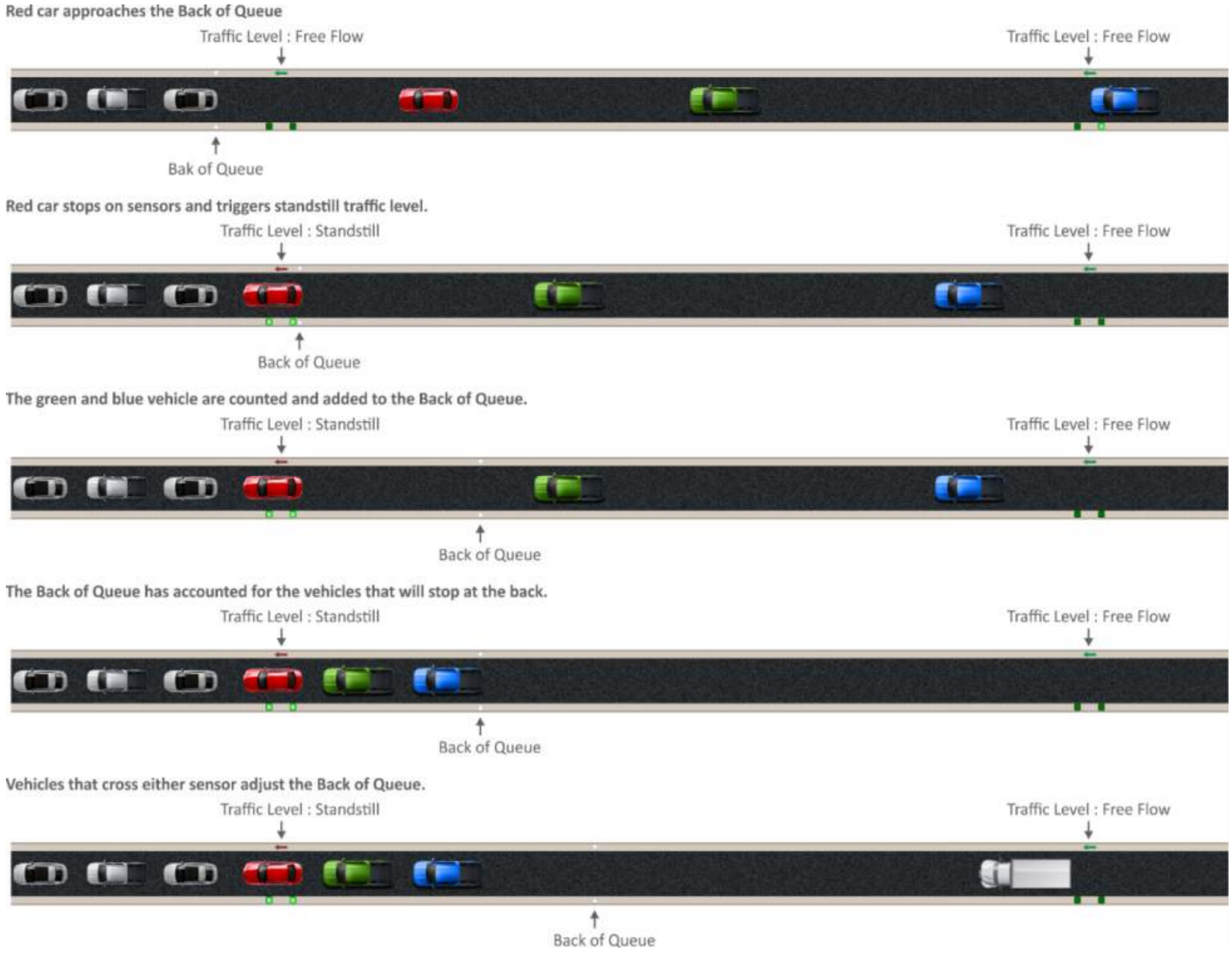


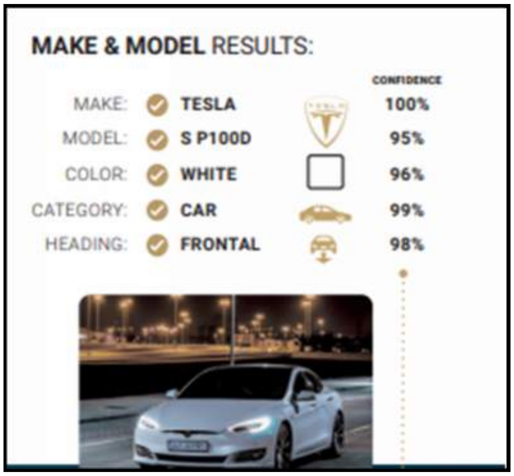
Figure 6. Back-of-Queue Calculation

When the red car triggers a standstill traffic level, the system tallies the vehicles passing the subsequent sensor after the red car's passage and determines the number of vehicles that have passed over an immediate upstream detector and adds those vehicles to the back of the red car or the queue. Subsequently, the back of the queue marker adapts dynamically as vehicles cross over the sensors, ensuring that precise adjustments for changes in lane progression or vehicle presence is made. This enables the system to determine the back of the queue, even between two VDS/data stations. Similar adjustments are made for the downstream VDS/data stations.

2.2 Vehicle Identification Cameras

Recent developments in AI, machine vision, and video signature technologies have resulted in the ability to identify vehicles by make, model, color, and state/country of registration, with an accuracy of up to 95%. Systems such as the one by Adaptive Recognition/Vidar, come with a built-in database of 250 makes, 1,000 models, and an array of color palettes and can be specific to each country or continent. Since these systems do not re-identify vehicles using personally identifiable information, privacy concerns are mitigated. Figure 7 below provides an example of vehicle reidentification using make, model, and color.

A subset of vehicle identification cameras also includes ALPR cameras; however, the purchase of these cameras is not currently allowed as part of Stage 1 of the SMART Grants program, and this restriction is assumed to apply to Stage 2 as well. As such, although ALPR cameras would be the most accurate method to re-identify vehicles and validate border wait times, and while privacy concerns could potentially be mitigated by processing data anonymously in the field (edge computing), further discussion of these cameras has not been included in this report. After the vendor showcase, it was apparent that re-identifying vehicles based on the make and model alone was not reliable from Adaptive Recognition.



MAKE & MODEL RESULTS:

		CONFIDENCE
MAKE:	✓ TESLA	100%
MODEL:	✓ S P100D	95%
COLOR:	✓ WHITE	96%
CATEGORY:	✓ CAR	99%
HEADING:	✓ FRONTAL	98%

Figure 7. Example of Vehicle Reidentification by Make, Model, and Color

3.0 Emerging Border Wait Time Technologies

The following sections provide an overview of some key emerging technologies that should be considered for potential application to the Cascade Gateway ABIS.

3.1 Location Tracking and GPS

The future of BWT systems can benefit from highly accurate Positioning, Navigation and Timing (PNT) services, particularly the newer generation of interoperable Global Navigation Satellite Systems (GNSS). Once fully deployed, BWT using PNT services will be the most cost effective and accurate BWT technology option.

Before understanding how Global Positioning System (GPS) works in cars and for measuring BWT, it is important to understand how GPS works. GPS generally refers to the constellation of 32 satellites deployed by the United States in medium earth orbit (at about 20,200 km altitude, with two orbits in 24 hours at 55-degree angle at an orbital speed of 14,000 km/hr). GPS receivers in phones or other devices listen for the radio signals from these satellites. The signals travel at the speed of light and calculate their distance from the satellites by using a process called trilateration. This involves signals from at least three satellites, from which the receivers can determine the location with an accuracy of approximately +/- 6 meters (approximately 20 feet) 95% of the time.

The location accuracy in a smartphone depends on the GNSS receiver (chipset), its positioning engine (software), its antenna quality, and the hardware integration. In addition to pure GNSS positioning, current smartphones use inertial sensors (such as gyroscopes, accelerometers, and barometers) and network-based positioning (which rely on cellphone networks and Wi-Fi). These different technologies help partially compensate for location and precision errors due to lack of GNSS satellite signals.

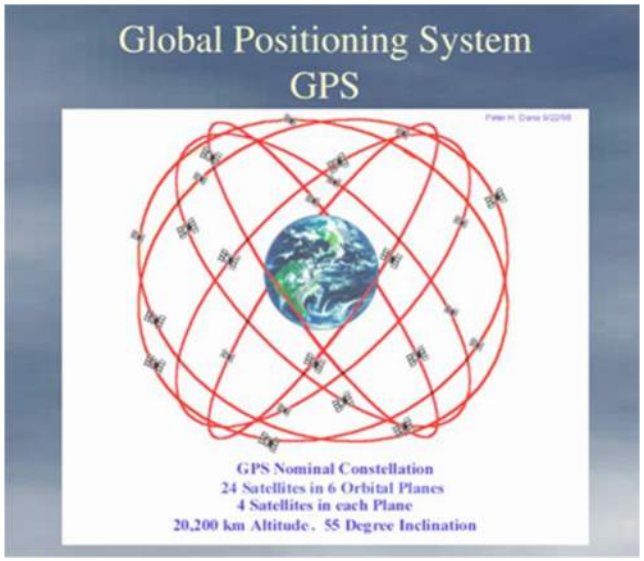
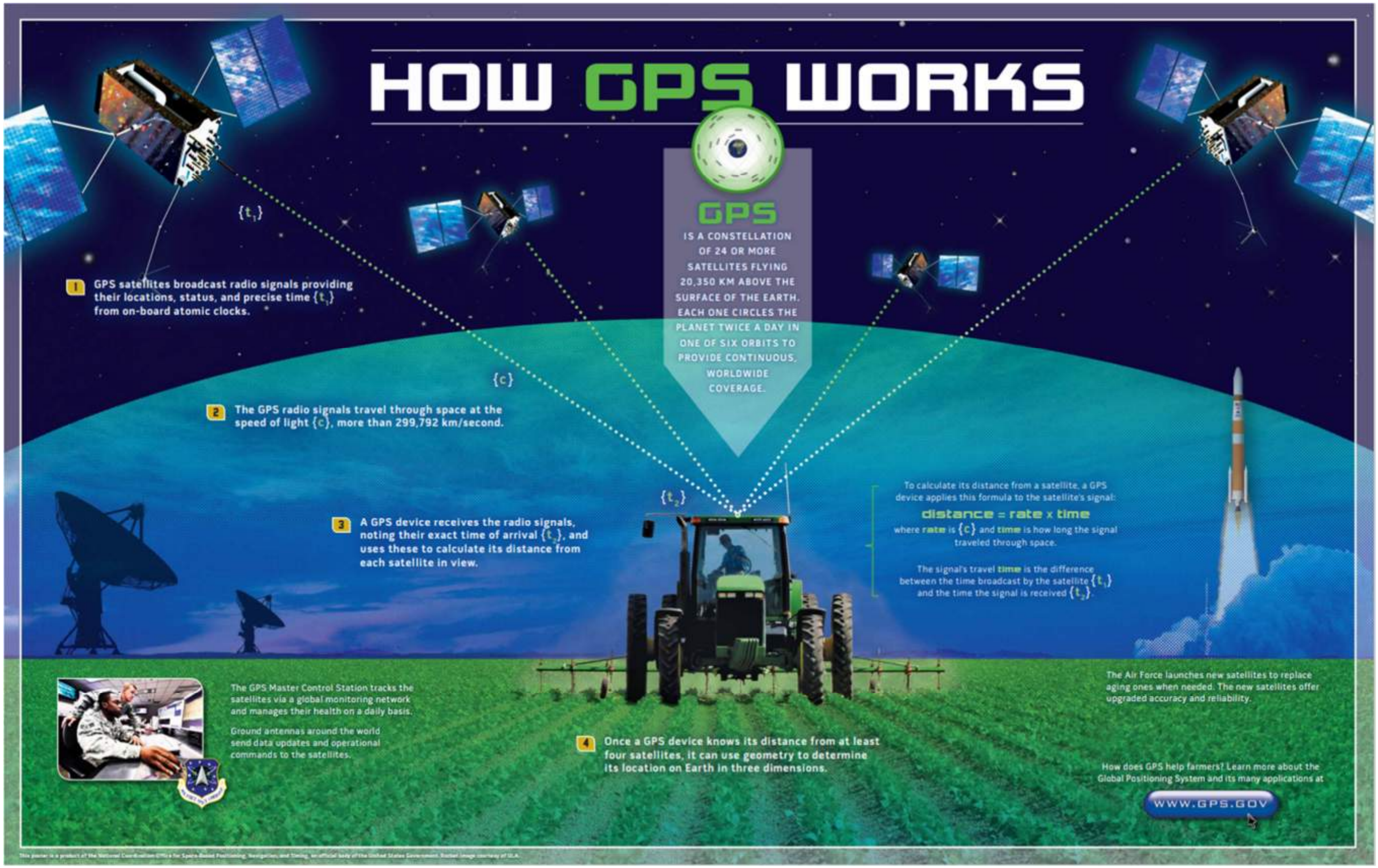


Figure. GPS Constellation Overview (Source: The Institute of Navigation)

The future accuracy of GNSS and the advancements in smartphone civilian dual-band receivers (L1 band frequency: 1,575.42 MHz, L2 band frequency 1,227.60 MHz and L5 frequency: 1,176.45 MHz) are pivotal developments that promise to revolutionize a wide array of industries through enhanced location tracking capabilities. These improvements help to achieve centimeter-level accuracy even on consumer devices including smartphones. Many newer generation chipsets from Qualcomm, Broadcom, Intel, and U-Blox that supply chipsets to the majority of smartphones in the world have developed dual frequency communication chips that can receive signals from GPS, Galileo, or other GNSS constellations, which will enable horizontal accuracy to less than an inch 95% of the time.



HOW GPS WORKS

GPS IS A CONSTELLATION OF 24 OR MORE SATELLITES FLYING 20,350 KM ABOVE THE SURFACE OF THE EARTH. EACH ONE CIRCLES THE PLANET TWICE A DAY IN ONE OF SIX ORBITS TO PROVIDE CONTINUOUS, WORLDWIDE COVERAGE.

1. GPS satellites broadcast radio signals providing their locations, status, and precise time $\{t_1\}$ from on-board atomic clocks.
2. The GPS radio signals travel through space at the speed of light $\{c\}$, more than 299,792 km/second.
3. A GPS device receives the radio signals, noting their exact time of arrival $\{t_2\}$, and uses these to calculate its distance from each satellite in view.
4. Once a GPS device knows its distance from at least four satellites, it can use geometry to determine its location on Earth in three dimensions.

To calculate its distance from a satellite, a GPS device applies this formula to the satellite's signal:

distance = rate x time

where rate is $\{c\}$ and time is how long the signal traveled through space.

The signal's travel time is the difference between the time broadcast by the satellite $\{t_1\}$ and the time the signal is received $\{t_2\}$.

The GPS Master Control Station tracks the satellites via a global monitoring network and manages their health on a daily basis.

Ground antennas around the world send data updates and operational commands to the satellites.

The Air Force launches new satellites to replace aging ones when needed. The new satellites offer upgraded accuracy and reliability.

How does GPS help farmers? Learn more about the Global Positioning System and its many applications at

WWW.GPS.GOV

This poster is a product of the National Coordination Office for Space-Based Positioning, Navigation, and Timing, an official body of the United States Government. Rocket image courtesy of ULA.

Figure 8. Overview of How GPS Works (Source: www.GPS.gov)

In addition to civilian dual-band smartphones, GPS systems are constantly being upgraded to improve accuracy. The proposed US Global Positioning System III, with ten additional precise satellites being deployed by the US by the end of 2025, will share a common L1C civilian standard with Europe's Galileo system, which has a 24 satellite constellation. The advent of multi-constellation and dual-band navigation satellite technology represents a vast improvement over earlier satellite navigation system. Newer GNSS such as GPS III and Galileo receivers have correction services (errors due to the earth's ionosphere and clock errors) built into the double and triple-band constellation signals, and soon will become commonplace in smartphones. The performance accuracy of the new GPS III system (full deployment expected by the end of 2026) will be close to 1 meter (about 3 feet). In practical terms, this enhanced accuracy has far-reaching implications. For example, the new accuracy will enable improvements in the granularity at which vehicles can be located, from the current standard at the roadway level, down to which specific lane a vehicle is using on the roadway.

For border wait time applications, this improved accuracy can enable border agencies to measure BWT by lane type (NEXUS, Ready and General) without having to deploy any additional infrastructure. The system could potentially just use BWT mobile apps or crowdsourced data such as INRIX, Google, and HERE. With the expected accuracy of GPS III, an infrastructure-less system could be both highly accurate and highly cost effective, since there will be no need to deploy physical infrastructure such as Bluetooth/Wi-Fi, RFID, vehicle identification cameras, or other such devices.

Table 4 below provides an overview of the major satellite system providers in the world. All these systems provide PNT services on a global or regional basis. They operate independently of any telephonic or internet reception, though these technologies can enhance the usefulness of the positioning information generated.

Table 4. Overview of the Major Satellite System Providers (Source: Institute Of Navigation [ION])

GNSS System	**GPS**	**BeiDou (BDS)**	**Galileo**	**GLONASS**	**NavIC**	**QZSS**
Coverage	Worldwide	Global (China)	Global (European Union)	Global (Russia)	Regional (India)	Regional (Japan)
Number of Satellites	At least 24 operational satellites	35 operational satellites	24+ operational satellites	24+ operational satellites	7 operational satellites	4 operational satellites (expanding to 7)
Altitude	~20,200 km (12,550 miles)	Varies (Medium Earth Orbit)	Varies (Medium Earth Orbit)	~19,100 km (11,870 miles)	Varies (Geosynchronous and Geostationary orbits)	Varies (Medium Earth Orbit)
Orbit Period	~12 hours	~12 hours	~14 hours	~11 hours	Geo-stationary satellites remain fixed over India	~8 hours

GNSS System	GPS	BeiDou (BDS)	Galileo	GLONASS	NavIC	QZSS
Frequency	L1 (1575.42 MHz) and L2 (1227.60 MHz)	B1 (1561.098 MHz) and B2 (1207.14 MHz)	E1 (1575.42 MHz) and E5 (1176.45 MHz)	L1 (1602 MHz) and L2 (1246 MHz)	L5 (1176.45 MHz) and S-band (2492.028 MHz)	L1 (1575.42 MHz) and L5 (1176.45 MHz)
Status	Fully operational	Operational	Initial services declared	Fully operational	Operational	Services declared
Accuracy	Within 18 feet	Within 18 feet	Within 18 feet	Within 18 feet	Within 18 feet	Within 15-18 feet

The following table provides some advantages and disadvantages related to the use of GPS in vehicle tracking to derive BWT.

Table 5. Advantages and Disadvantages of Using GPS for BWT Applications

Advantages of using GPS to Measure BWT	Disadvantages of using GPS to Measure BWT
Continuous Tracking – Unlike other methods that capture information at specific points (Wi-Fi, Bluetooth etc.,) GPS allows for dynamic tracking as vehicles approach primary inspection. In addition, the use of a mobile application can allow drivers to select their lane type, enabling lane-by-lane vehicle tracking.	**Privacy Concerns** – Users must agree to share their location information.
No Installation Requirements – Since most people carry GPS-enabled devices such as smartphones, there is no need for additional installations or device upgrades. With higher accuracy such as GPS III, BWT systems can go infrastructure-less.	**Data Accuracy** – GPS signals may experience interference in certain environments, such as tunnels or urban canyons, potentially affecting the accuracy of wait time estimations. However, for Cascade Gateway POEs, this is not an issue.
Real-Time Visibility – Agencies gain real-time visibility into the location of each vehicle, enabling proactive border management and responsiveness to changing traffic patterns and demand for border crossings.	**BWT by Lane Type** – At present, this is somewhat of a challenge and GPS needs augmented technologies such as sensors or cameras in each lane type or to increase accuracy.
Dynamic Customized BWT – The BWT can be customized to an individual's location, position in the queue, and current wait times.	**High Cost for Higher Accuracy** – Enhanced Differential GPS and Real Time Kinematic (RTK) GPS that provides accuracy levels of less than one inch are prohibitively expensive

Advantages of using GPS to Measure BWT	Disadvantages of using GPS to Measure BWT
Cost Effective – Since there are no roadway infrastructure deployments needed, they are highly cost effective with little or no operation and maintenance requirements. However, there is a cost for the back office or use of cloud storage, which is common for both infrastructure-based and infrastructure-less options.	**Dependency on Map Providers.**

3.1.1 The Future of GPS in the Context of Border Wait Time

Improved location tracking, particularly with advancements in interoperable Global Navigation Satellite Systems (GNSS), GPS III, and dual-band GNSS receivers in smartphones, will significantly enhance the estimation and management of border wait times (both experienced and anticipated) without needing for the deployment of traditional technologies. The integration of high-precision location tracking technologies offers numerous benefits to CBP, CBSA, and other border enforcement and transportation agencies. It also improves border crossers and traveler experience by providing customized and dynamic border wait times to a particular vehicle depending on its location in the queue. This is also true for commercial trucks and the logistics industry. Other advantages of improved location accuracy within the context of border wait time measurement and traveler information include but are not limited to the following:

1. **Accurate Wait Time Predictions**
   a. *Real-Time Data Collection:* Enhanced location tracking allows for the real-time collection of anonymized vehicle positions along the approach to CBP/CBSA primary inspection. This data can be used to calculate the current wait times more accurately and predict future wait times based on the volume of traffic and its speed (proxy to processing times) by NEXUS, Ready, and Standard Lane types.
   b. *Dynamic Updates:* With centimeter-level accuracy, updates on wait times can be made available to travelers and logistics companies with unprecedented precision, allowing for better planning and decision-making.
2. **Optimized Traffic Flow**
   a. *Queue Management:* Improved location tracking can help border authorities in managing queues more effectively. By understanding the exact length and the number of vehicles in the queues, border agencies such as CBP and CBSA can adjust processing rates, open more lanes, or direct traffic to less congested crossings.
   b. *Predictive Analytics:* Analyzing historical and real-time location data enables the development of predictive models for border wait times. These models can forecast peak times and suggest optimal travel times to the public.
3. **Improved Traveler Experience**
   a. *Dynamic Route Suggestions:* Travelers can receive dynamic route suggestions based on current border wait times and traffic conditions, helping them choose the fastest crossing points. This is particularly true for high traffic corridors such as travel between Bellingham

    and Vancouver, where timely and advance information will help the traveler chose the best POE to cross, thus spreading the wait times between crossings.
    b. *Mobile Applications:* Smartphone applications can integrate this precise location data to provide users with real-time updates on border wait times, enabling them to make informed decisions about when and where to cross.

4. **Logistics and Supply Chain Efficiency**
    a. *Scheduling and Routing for Commercial Vehicles*: Logistics companies can benefit from accurate border wait times for better scheduling of shipments and optimizing routes, reducing idle time for commercial vehicles and enhancing supply chain reliability.
    b. *Cost Reduction*: Improved efficiency in border crossings can lead to significant cost savings for the logistics industry by reducing fuel consumption and minimizing delays.

3.2 Real-Time and Predictive Open-Source BWT Algorithms

An algorithm is a set of steps to solve a problem or to achieve a task. We use algorithms in our daily lives without realizing it. For example, we follow a step-step daily routine in preparing to go to work in the morning (brushing teeth, showering, breakfast, coffee, and head out at same time every weekday). For more complex routines, we use computers, especially for big and complex data sets such as border traffic data. When these complex routines are pre-programmed (as an Application Program Interface), they will become part of Artificial Intelligence (AI) and Machine Learning (ML) models. Algorithms are the backbone of computations and provide structured instructions to solve complex problems. In the process, these algorithms learn about the data complexity and unpredictable nature of the border traffic and make reasonable and reliable predictions. As the model matures over time, the predictions become more and more accurate.

There are two major types of algorithms. Parametric and non-parametric. Parametric algorithms make strong assumptions about the underlying data distribution. Non-parametric algorithms do not assume prior knowledge of the data distribution. In the context of BWT, border traffic flow is stochastic (random) and non-linear. For this reason, non-parametric algorithms are well suited for BWT applications, with human involvement in the final decision and control. The following table provides a comparison between the two types of algorithms.

Table 6. Comparison Between Parametric and Non-Parametric Algorithms (Source: www.geeksforgeeks.org)

Comparison Aspect	Parametric Algorithms	Non-Parametric Algorithms
Assumptions About Raw Data	Make strong assumptions about the data distribution.	Do not assume prior knowledge of the data distribution.
Data Requirements	Require fewer data points for training.	Often require larger datasets due to their flexibility.
Learning Process	Simplify the function to a known form (e.g., linear regression).	Do not impose specific functional forms, allowing more versatility. Not affected by outliers in data.

Comparison Aspect	Parametric Algorithms	Non-Parametric Algorithms
Model Complexity	Fixed-size parameters (independent of training examples).	Flexible model complexity, adapting to the data.
Examples	Linear regression, logistic regression.	Decision trees, K-Nearest Neighbors (KNN), Support Vector Machines (SVM), deep neural networks.
Advantages	Faster training time, especially with limited data.	slightly longer training time due to complex relationships, adapt well to diverse data.
Limitations	May fail to capture intricate patterns in the data.	Slower training, occasional overfitting with small datasets.
Use Cases	Well-suited when assumptions align with the problem (e.g., linear relationships).	Well-suited when assumptions are unclear and dealing with diverse non-linear data such as complex border crossing data.

3.2.1 The Role of Open-Source AI in BWT

Open-source AI models offer a suite of powerful non-parametric algorithms for managing and predicting BWT. Recent advancements in open-source AI models offer promising solutions for more accurate BWT forecasting and scenario modeling. These models can empower border agents to proactively optimize resource allocation and reduce delays. Their implementation holds the potential to streamline border operations, reduce delays, and improve the overall experience for individuals and border civilian and enforcement agencies. Many of these models have the following capabilities:

- **Real-Time Analysis:** AI models can process live data feeds from sensors and other sources to provide up-to-the-minute wait time information.
- **Predictive Forecasting:** Based on the analysis of historical traffic patterns, time of the day, day of the week, month, and yearly traffic variations, by lane types and number of lanes open during any given time period will serve as the seed and learning data for AI models. Based on these and other external input factors, AI models can predict future wait times and traffic loads.
- **Adaptive Decision Support:** AI models support border agencies to make proactive, informed decisions based on reliable data-driven insights and patterns.
- **Cost Effectiveness:** Reduced cost over the long term because these models are open-source and free.

The following are some of the most commonly used non-parametric AI models. Selection of a particular model depends on the nature of data for that hour or day:

- **K-Nearest Neighbor (KNN):** The model works by analyzing nearest similar or the K nearest data points (k neighbor) in training data and the new target data. It then classifies or predicts the value of the new data point by using appropriate statistics.
    - **Strengths:** Ability to learn from seed or previous data, simple, intuitive, easy to implement, adaptable to irregular wait time patterns and not sensitive to outliers caused by events and incidents.
    - **Potential Use:** Predicting short-term fluctuations in wait times by finding similar historical traffic patterns.
- **Random Forest (RF):** Random Forest algorithm is a powerful tree learning technique in AI and Machine Learning. It works by creating several Decision Trees (Forest) during the training phase.
    - **Strengths:** Handles non-linear relationships well, robust to noise and outliers, good at capturing complex interactions between features.
    - **Potential Use:** Predicting wait-times based on a variety of factors (time of day, season, holidays, special events, etc.)
- **Principal Component Analysis (PCA)**: Principal Component Analysis (PCA) is a powerful mathematical technique used for dimensionality reduction in data analysis. In the context of BWT, the model helps to uncover the most significant patterns and structures in the Border Wait Time data.
    - **Strengths:** Dimensionality reduction, identifying key influencing factors in traffic data that might not be immediately obvious.
    - **Potential Use:** Simplifying the dataset for other models, visualizing traffic flow trends.

A robust BWT forecasting algorithm will likely leverage either one or a combination of these open-source AI techniques to minimize variance between observed real-time BWT and predicted BWT for next 15-, 30- and 60-minutes intervals. In addition, many of the model's predictions can be compared to benchmarks such as CBP vehicle counts through RFID counters at Primary Inspection (item number 6 in the figure below, which shows the typical instrumentation used at primary inspection booths for inbound vehicles into the United States) and processing times at the primary inspection booths, and other estimates using ground loops to measure the number and rate of vehicles in the queue. This approach will help make the wait time predictions as accurate as possible.

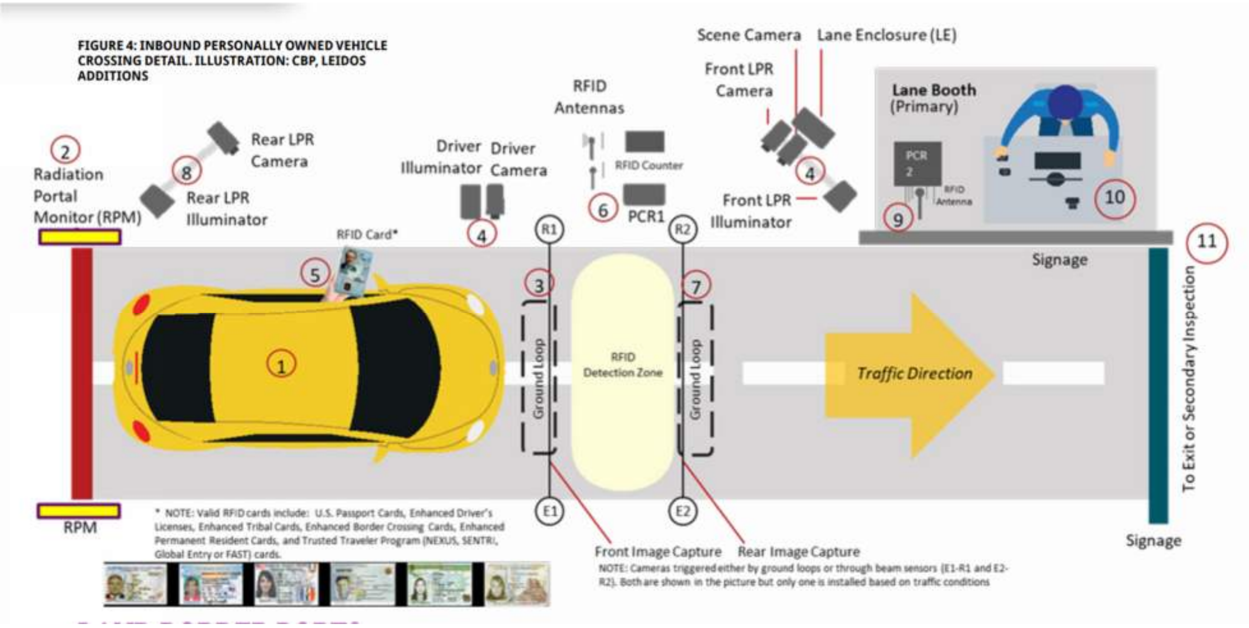


Figure 9. U.S. Primary Inspection Booth Overview

3.3 Border Wait Time Dashboards

Border wait time dashboards are visual representations of data that provide a concise overview of port of entry operations. They consolidate various wait time metrics, Key Performance Indicators (KPIs), and real-time data into a single interface. Dashboards allow agencies to make informed decisions based on relevant insights. For the Cascade Gateway Ports of Entry, it is anticipated that dashboards can be utilized by U.S. CBP, CBSA, WSDOT, BC MOTI, and the public, through the Cascade Gateway Border Data Warehouse. Well-designed dashboards empower border agencies and travelers with actionable insights, leading to smoother operations and improved traveler experiences crossing the border. Benefits of implementing dashboards include:

1. *Real-Time Monitoring:* Dashboards offer real-time visibility into border operations. Staff can track wait times by lane type, number of vehicles in each lane, back of the queue, and lane processing times and utilization instantly.
2. *Resource Allocation:* By analyzing data on the number of vehicles waiting to cross the border (demand), staffing levels (supply), and processing times, agencies can allocate resources effectively. For instance, during peak hours, additional staff can be deployed to manage traffic efficiently.
3. *Performance Metrics:* Dashboards display KPIs related to border wait times, processing rates, and inspection outcomes. Agencies can set performance targets and measure their progress.
4. *Predictive Insights:* Historical data and trends help predict future demand. Agencies can anticipate busy periods and allocate resources accordingly.
5. *Customization:* Dashboards can be tailored to specific user roles. For example, officers, supervisors, and management may need different views and metrics.

6. *Transparency: Publicly* accessible dashboards enhance transparency by sharing wait times and border conditions with travelers. This improves trust and communication.

Some design considerations for developing effective dashboards include:

1. *Clear Objectives:* Define the purpose of the dashboard. Is it for real-time monitoring, resource allocation, or performance tracking?
2. *Data Sources:* Integrate data from various sources, including sensors (e.g., license plate recognition, RFID), databases, and external systems (e.g., weather forecasts).
3. *Visual Elements:*
    - Widgets: Use charts (line graphs, bar charts, pie charts), tables, and maps to display data.
    - Color Coding: Highlight critical information (e.g., red for long wait times).
    - Filters: Allow users to drill down by date, location, or lane type.
4. *User Experience (UX):*
    - *Responsive Design:* Ensure dashboards work well on different devices (desktop, tablets, mobile).
    - *Intuitive Navigation:* Users should find information easily.
    - *Minimal Clutter:* Avoid overwhelming users with too much data.
5. *Security and Privacy:*
    - *Access Control:* Restrict access based on user roles (officers, supervisors, administrators).
6. *Data Anonymization:* Protect travelers' privacy by aggregating data.
7. *Integration and Deployment:*
    - *Data Collection:* Gather data from sensors, cameras, and databases.
    - *Data Processing:* Transform raw data into usable formats (e.g., wait times, vehicle counts).
    - *Dashboard Development:*
        - *Tools:* Use dashboard-building tools (e.g., Tableau, Power BI, custom web applications).
        - *APIs:* Integrate with existing systems (e.g., border management, traffic control).
    - *Deployment:*
        - *Cloud or On-Premises:* Choose a hosting environment.
        - *User Training:* Train staff on dashboard usage.
        - *Feedback Loop:* Continuously improve based on user feedback.

The following are examples of some of the agency dashboards that can be modified to meet the agency requirements and different management levels. These dashboards are preliminary in nature and give a glimpse of what is possible.

Figure 10. Example Dashboard for U.S. CBP

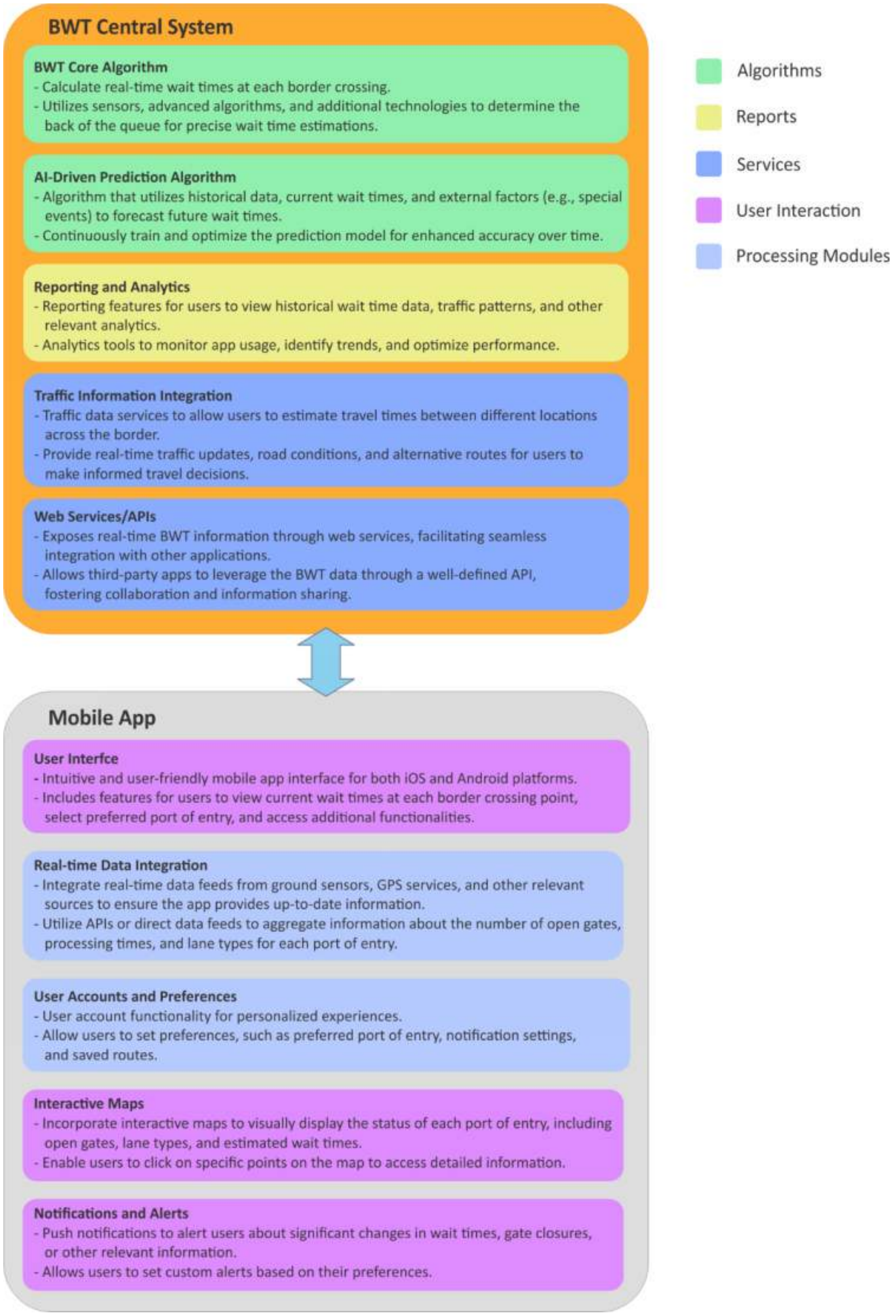
Figure 11. Example Dashboard for WSDOT

Figure 12. Example Dashboard for CBSA

3.4 Custom Cascade Gateway BWT Application

A BWT app that is developed specifically for the Cascade Gateway Ports of Entry can utilize the voluntary sharing of GPS information from users to further refine location accuracy within the border area, enabling tailored and precise wait time predictions. Additional granularity can be obtained by allowed users to choose their preferred lane type, facilitating the central system in assigning accurate GPS information for refined wait time estimations. The app could also provide traveler information in the form of updates on port status, encompassing details such as open gates, processing times, and schedules. With the integration of traffic information, the app can also provide travel time estimates, while an AI-driven prediction algorithm anticipates wait times based on historical data, current BWT information, and special events. The development of a custom application would involve several key components to ensure a comprehensive and user-friendly experience, as outlined in Figure 13 below.

Many public agencies have developed BWT apps, including CBP's BWT Version 2. However, this app is only as good as the accuracy and reliability of the wait time information. Caltrans District 11 (San Diego) and the San Diego Association of Governments (SANDAG) are in the process of rolling out a pilot BWT app, which is expected to be released in the summer of 2024. This app will cover the San Ysidro, Otay Mesa, and Otay Mesa East ports of entry. Since there are no loop detector stations at these ports of entry, the system uses Wi-Fi technology for vehicle reidentification, and computing border wait times. The Wi-Fi estimations are validated using the traveler's location data, which is collected using an ArcGIS location sharing survey module called *survey123*. The survey asks frequent travelers to manually pin their starting location on the map once they have entered the back-of-queue and start the timer embedded in the survey to measure how long it takes to reach primary inspection. The results are summarized in the back office and used for validation of border wait times estimated. The survey results can also be used as a benchmark for comparing it with prediction algorithms.



BWT Central System

BWT Core Algorithm
- Calculate real-time wait times at each border crossing.
- Utilizes sensors, advanced algorithms, and additional technologies to determine the back of the queue for precise wait time estimations.

AI-Driven Prediction Algorithm
- Algorithm that utilizes historical data, current wait times, and external factors (e.g., special events) to forecast future wait times.
- Continuously train and optimize the prediction model for enhanced accuracy over time.

Reporting and Analytics
- Reporting features for users to view historical wait time data, traffic patterns, and other relevant analytics.
- Analytics tools to monitor app usage, identify trends, and optimize performance.

Traffic Information Integration
- Traffic data services to allow users to estimate travel times between different locations across the border.
- Provide real-time traffic updates, road conditions, and alternative routes for users to make informed travel decisions.

Web Services/APIs
- Exposes real-time BWT information through web services, facilitating seamless integration with other applications.
- Allows third-party apps to leverage the BWT data through a well-defined API, fostering collaboration and information sharing.

Mobile App

User Interfce
- Intuitive and user-friendly mobile app interface for both iOS and Android platforms.
- Includes features for users to view current wait times at each border crossing point, select preferred port of entry, and access additional functionalities.

Real-time Data Integration
- Integrate real-time data feeds from ground sensors, GPS services, and other relevant sources to ensure the app provides up-to-date information.
- Utilize APIs or direct data feeds to aggregate information about the number of open gates, processing times, and lane types for each port of entry.

User Accounts and Preferences
- User account functionality for personalized experiences.
- Allow users to set preferences, such as preferred port of entry, notification settings, and saved routes.

Interactive Maps
- Incorporate interactive maps to visually display the status of each port of entry, including open gates, lane types, and estimated wait times.
- Enable users to click on specific points on the map to access detailed information.

Notifications and Alerts
- Push notifications to alert users about significant changes in wait times, gate closures, or other relevant information.
- Allows users to set custom alerts based on their preferences.

Figure 13. Key Components of a Custom Cascade Gateway BWT App

Table 7 below provides some of the potential features and functionality that a custom Cascade Gateway BWT app can provide to government agencies as well as the traveling public.

Table 7. Cascade Gateway BWT App Features for Agency and Public Users

Agency Focus Features	Traveling Public Focus Features
Infrastructure-less or minimum infrastructure BWT system, providing a cost effective and accurate BWT solution	Reliable, accurate, and customized dynamic border wait times based on the traveler's commute pattern and lane type use
Provides information on number of vehicles and back-of-queue in each lane type: NEXUS, Ready and General and Trucks	Real-time dynamic wait times by lane type and turn-by-turn instructions
Interactive agency specific dashboards for trend and scenario analysis and processing times by individual lane type for performance monitoring	Predictive wait times based on historical and real-time data algorithms
Predictive demand for crossing by lane type, by 15-, 30- and 60-min time slices and for resource allocation	Live Google Maps integration for the traveler's location in the queue
Live Google Maps integration for traffic visualization and lane management	Natural language interface for time to arrive and time to destination questions
Hidden data pattern recognition and effective port of entry management using open AI algorithms	Route and port preference optimization and re-routing, based in changing real-time wait times and alerts
Time of day, day of the week, and week of the month statistics for historical and real-time trend and pattern behavior	Personalized map-based wait times at the port and commute times for the preferred commute route, including alerts if wait time changes
Natural language interface for queries and what if scenario analysis	Natural language interface for checking commute times
Automation of CBP reporting requirements for 90 min and 180 min delay report filing	Personalized estimated wait times, which can be dynamic. When a vehicle is halfway in the queue en route, the application can provide the updated or remaining wait time to cross the border, which can be different from when they joined the back-of-queue. In addition, the wait time is personalized to the location of the traveler before he/she gets to the back-of-queue, as well as their position while in the queue.
Compliance with Federal Risk and Authorization Management Program (FedRAMP)* and State RAMP	Location is tracked only within a geofenced area. Anonymous and secure.

* Government program that provides a standardized approach to security assessment, authorization, and continuous monitoring specifically for cloud products and services used by federal agencies to store, process, and transmit federal information

3.5 Conceptual Design and Data Flows for the Cascade Gateway Border Wait Time Mobile App

The Cascade Gateway BWT mobile application (the App) will be a user-friendly mobile application designed to provide timely, real-time, reliable, and personalized decision-quality BWT to motorists who cross the US-Canadian border between British Columbia and Washington State and the stakeholder agencies that operate and manage the ports of entry. The App also has the capability for predictive border wait times that will be useful for crossing motorists and agencies like CBP and CBSA to more optimally manage the POEs to keep the wait times to a minimum. The stakeholder agencies will benefit from more accurate real-time information to better plan and manage the infrastructure leading to the POEs.

3.5.1 System Architecture

The general architecture of the App revolves around a central system that comprises Application Protocol Interface (API) services, a SQL database, and connections to external services.

Overview of the Architecture:

1. **API Services**: The central system hosts a set of API services responsible for handling various functionalities of the BWT solution. These services include Real-Time Border Wait Time Service, Real-Time POE Information Service, Account Service, GPS Processing Service, Trip Service, Map Service, Notification Service, and AI Assistant Service. Each service exposes endpoints that the App can interact with to access specific features and data.
2. **SQL Database**: The central system relies on a central SQL database to store both general information and dynamic data related to BWT and POE status. The database schema encompasses tables for user accounts, trip history, POE details, wait time records, and other relevant entities. This centralized data repository facilitates efficient data management, retrieval, and analysis across the BWT solution.
3. **External Services Integration**: The central system integrates with various external services to augment its functionalities and provide additional value to users. These external services include Traffic Information services for real-time traffic updates, Map Services for displaying maps and plotting trips, and Generative AI APIs (such as OpenAI API) for enhancing the AI Assistant functionality with natural language processing capabilities. By leveraging external services, the BWT solution can enrich its features and provide users with comprehensive and accurate information relevant to border crossing.
4. **Communication Channels**: The App communicates with the central system via secure HTTP (HTTPS) protocols, enabling encrypted and authenticated data exchange between the client (app) and server components. API endpoints handle incoming requests from the app, retrieve or update data from the SQL database, and interact with external services as necessary to fulfill user queries and requests. Asynchronous communication mechanisms may be employed for real-time updates and notifications. The software system will be compliant with Federal Risk Authorization and Management Program (FedRAMP) standards (a requirement for cloud services and federally funded projects and NIST 800-53 federal cybersecurity and data protection standards against critical attacks and data breaches, and also complied by states and local agencies).

5. **Scalability and Reliability**: The architecture is designed to be scalable and resilient, capable of handling a large volume of concurrent users and fluctuating traffic demands. Load balancing and horizontal scaling techniques will be implemented to distribute incoming requests across multiple server instances, ensuring optimal performance and availability. Redundancy measures and fault-tolerant designs will be employed to minimize downtime and maintain service continuity.

3.5.2 BWT Service API

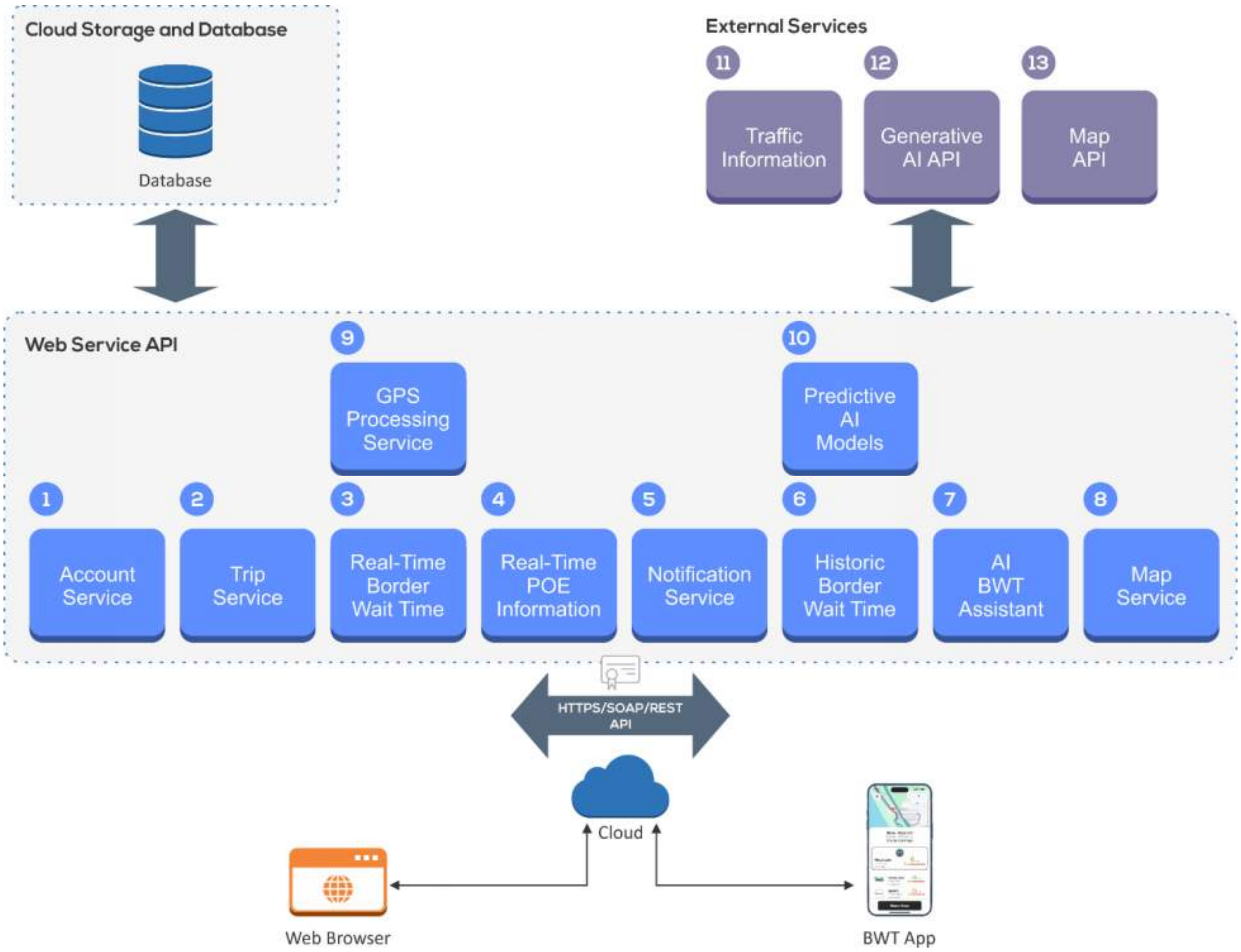


Figure 14. BWT App Interfaces

The following are the Web Service API services hosted by the BWT Central System:

1. **Account Service:** The Account Service manages user accounts within the app, handling tasks such as user registration, authentication, and profile management. It stores user information securely and provides interfaces for users to access their account details, view their history, adjust privacy settings, and manage preferences. This service ensures a personalized and secure experience for app users, allowing them to access relevant features and information tailored to their needs.

2. **Trip Service:** The Trip Service provides the necessary information and functionality for the app to manage and display trip-related data to users. It tracks users' trips from the planning stage through to

the actual crossing, offering features such as trip history, saved trips, and notifications for planned drives. This service facilitates seamless trip management within the app, allowing users to stay informed and organized throughout their border crossing experience.

3. **Real-Time Border Wait Time Service:** This service retrieves and provides real-time BWT data for each POE and lane type. It continuously updates the wait times based on current conditions, such as the number of vehicles in the lane and the number of lanes open for each lane type. The service is crucial for the app to display accurate and up-to-date wait time information to users, allowing them to make informed decisions about their POE border crossing.
4. **Real-Time POE Information Service:** This service offers comprehensive information about each POE. It includes general information such as location, operating hours, and available services, as well as real-time data such as the number of lanes open, lane assignments for different vehicle types (passenger or commercial), and any schedule changes or closures. This service enables the app to provide users with detailed insights into the status and conditions at each POE, helping them choose the most efficient crossing point for their lane type use.
5. **Notification Service:** The Notification Service manages the delivery of alerts, updates, and notifications to app users. It sends push notifications to users' devices based on events such as changes in wait times, updates on trip status, or reminders for planned drives. This is similar to airlines letting passengers know about changes about their flight. This service ensures timely communication with users, keeping them informed about important developments and helping them make informed decisions.
6. **Historic Border Wait Time Service**: The Historic Border Wait Time Service is responsible for managing and providing access to historical BWT data for analysis purposes. This service maintains a repository of past wait time records collected from border crossings, allowing users to retrieve and analyze trends, patterns, and historical wait time data. Additionally, the service utilizes this historical data to generate estimates for current and future wait times based on predictive modeling and statistical analysis. By leveraging historical data insights, the Historic Border Wait Time Service enhances the App's functionality by offering users valuable information to plan their border crossings more effectively and anticipate potential wait times.
7. **AI Assistant Service:** The AI Assistant Service provides the interface for the app's AI-powered chat functionality, allowing users to interact with a virtual assistant to obtain information and assistance. It integrates natural language processing capabilities, which can be in multiple languages such as English, Spanish, and French, to understand user queries and provide relevant responses regarding POE details, wait times, lane types, and other border crossing-related information. This service enhances user engagement and accessibility by offering a conversational voice interface for accessing information and support within the app.
8. **Map Service:** The Map Service enables the app to display interactive maps and overlay relevant real-time information such as trip routes, traffic conditions, and POE details. It integrates with mapping APIs to provide a visual representation of border crossings, allowing users to explore routes, view traffic congestion, and locate nearby POEs. This service enhances the user experience by offering a visual interface for navigating and understanding border crossing logistics.

9. **GPS Processing Service:** This service processes GPS location data from app users to track their trips and provide real-time updates on wait times based on their location in the queue. It utilizes various technologies to determine the back-of-queue for each lane type, incorporating GPS data alongside other factors to accurately estimate wait times. By continuously analyzing GPS information, this service enables the app to deliver timely and precise updates to users as they approach the border crossing.
10. **Predictive AI Model Service**: The Predictive AI Model Service utilizes AI techniques to develop prediction models based on historical BWT data. This service employs advanced machine learning algorithms to analyze past wait time records and identify patterns, correlations, and trends in the data. By training predictive models on historical BWT data, the service generates forecasts and estimations for future wait times at border crossings. Additionally, the Predictive AI Model Service incorporates real-time data obtained from actual wait times to fine-tune and validate the accuracy of the prediction models continuously. The refined models are then utilized by the Historic Border Wait Time Service to provide users with more reliable and accurate estimates of current and future wait times, enhancing the overall effectiveness and usability of the App.
11. **External Traffic Information API:** The External Traffic Information API is an external service integrated into the system, utilized by the Real-Time Border Wait Time Service and the Map Service. This API provides real-time traffic updates and travel time estimations from any location to the back-of-queue at the border crossing. By accessing traffic data sourced from various sources such as traffic sensors, GPS data, and historical traffic patterns, the API offers insights into current traffic conditions, congestion levels, and estimated travel times along routes leading to the border crossing. The Real-Time Border Wait Time Service utilizes this information to factor in traffic conditions when calculating wait times, ensuring more accurate and reliable estimates for users. Additionally, the Map Service leverages the API to plot traffic levels and display real-time traffic conditions on maps, enabling users to make informed decisions about their route and timing for border crossings. Integrating the External Traffic Information API enhances the App's functionality by providing users with comprehensive and up-to-date traffic information to facilitate smoother and more efficient border crossings.
12. **External Generative AI API**: The External Generative AI API is an external service integrated into the App, utilized specifically by the AI Assistant Service. This API leverages advanced Natural Language Processing (NLP) and generative AI techniques to create specialized assistants capable of understanding and responding to user queries in natural language. By utilizing document retrieval methods, the API retrieves relevant information from various sources, such as documentation, manuals, and online resources, to enhance the knowledge base of the AI assistant. This allows the assistant to provide accurate and informative responses to user inquiries regarding border crossing procedures, lane types, wait times, required documents, and other related topics. Additionally, the AI assistant employs conversational capabilities to engage users in interactive chat sessions, offering personalized assistance and guidance throughout their time of border crossing. Integrating the External Generative AI API enriches the App's functionality by providing users with a sophisticated AI-powered chat interface, enhancing user engagement and accessibility while offering comprehensive support and information.
13. **External Map API:** The External Map API is an external service integrated into the App, utilized primarily by the Map Service. This API enables the app to display interactive maps and plot routes, traffic conditions, and points of interest relevant to border crossings. Leveraging the functionality of the

External Map API, the Map Service provides users with visual representations of border crossing points, surrounding road networks, and real-time traffic conditions. Additionally, the API allows users to interact with the map interface, zoom in/out, and pan across different areas to explore routes and plan their journeys effectively. By integrating the External Map API, the App enhances user experience by offering a user-friendly and intuitive mapping interface, enabling users to visualize border crossing routes and navigate traffic conditions with ease.

3.5.3 BWT App Data Flow

The following figure illustrates the flow of information and data between the App, the user, the central server, and external services. Using color-coded arrows, this section visually depicts how user-generated data, automatic data from the app, responses from services, and internal server data flow within the BWT ecosystem. **Cyan lines** denote App user-generated data sent from the app to services, **green lines** represent automatic data transmission from the app to services (such as GPS data), **orange lines** indicate responses or messages sent from services to the app, **blue lines** denote data exchange between services, **purple lines** denote data exchange between internal services and external services, and **red lines** depict data exchange within the server between services and the central database. **Blue boxes** represent services running on the central server, while **purple boxes** denote external services integrated into the BWT system.

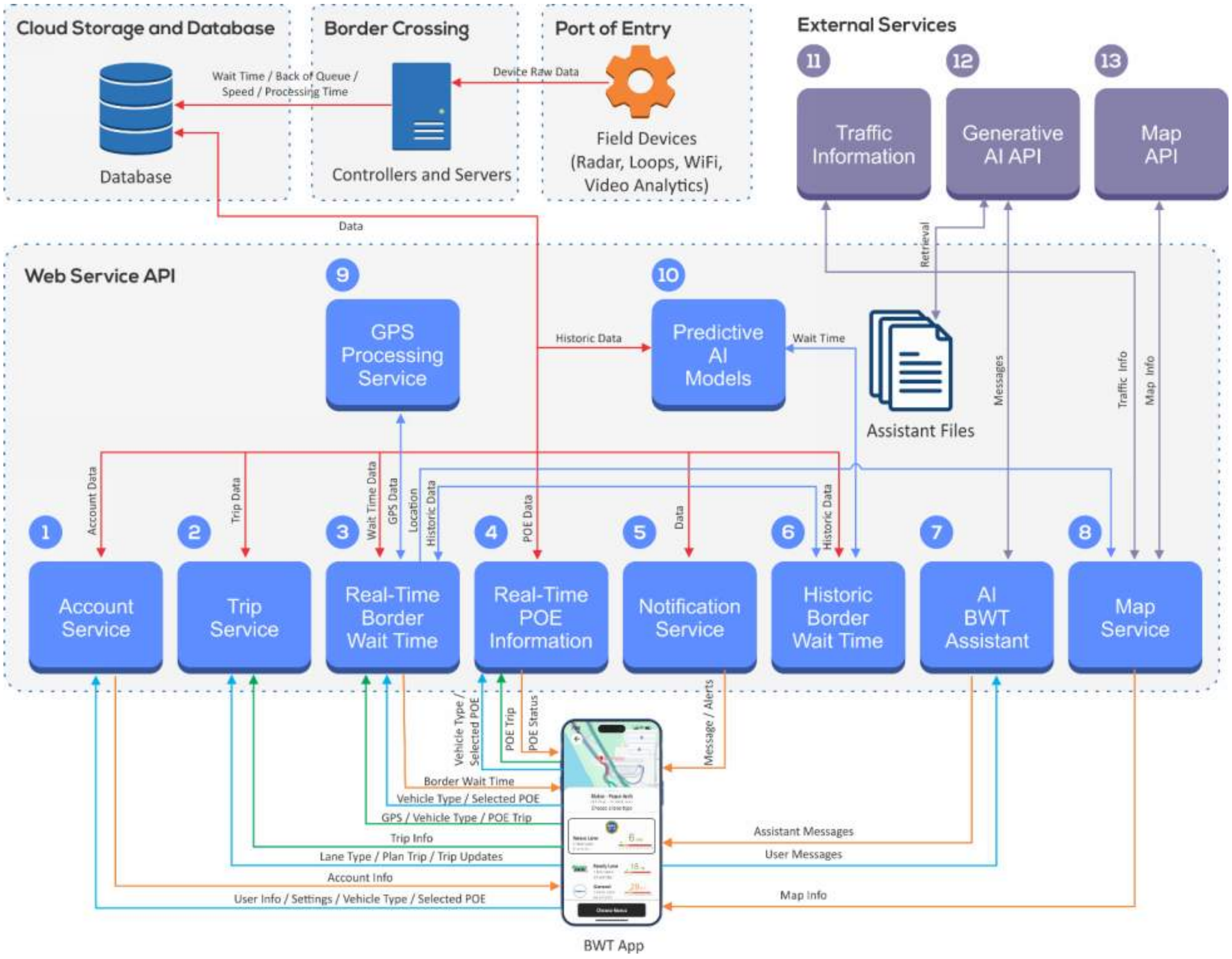


Figure 15. BWT App Data Flows

3.5.4 BWT App Communication

The communication between the App and the services hosted on a server utilizes HTTPS communication to ensure the confidentiality, integrity, and authenticity of data exchanged between the client (app) and the server.

1. **Authentication and Authorization**: Before any communication takes place, the App authenticates itself with the server using secure authentication mechanisms such as OAuth or token-based authentication. Once authenticated, the server verifies the App's authorization to access specific services based on predefined permissions and roles.
2. **HTTPS Protocol**: All communication between the App and the server is conducted over HTTPS, which encrypts data in transit using Transport Layer Security (TLS) or its predecessor, Secure Sockets Layer (SSL). This ensures that sensitive information, such as user credentials and personal data, remains confidential and protected from unauthorized access or interception by malicious actors.
3. **API Endpoints**: The server exposes a set of API endpoints that the App can interact with to access various services, such as retrieving real-time BWT data, accessing POE information, managing user

accounts, tracking trips, and sending notifications. Each API endpoint is protected by authentication and authorization mechanisms to control access based on user privileges.

4. **Data Exchange Formats**: Data exchanged between the app and the server is typically in standardized formats such as JSON (JavaScript Object Notation) or XML (eXtensible Markup Language). These formats ensure interoperability and ease of parsing on both the client and server sides, facilitating seamless communication and data processing.
5. **Asynchronous Communication**: In some cases, asynchronous communication mechanisms such as WebSockets or long-polling may be employed to enable real-time updates and notifications from the server to the app. This allows the app to receive immediate feedback or updates without the need for continuous polling, enhancing the responsiveness and efficiency of the communication.
6. **Error Handling and Logging**: The app and server implement robust error handling mechanisms to detect and handle communication errors, such as network timeouts, server failures, or invalid requests. Detailed logging is employed on both sides to record communication events, debug issues, and monitor system performance for continuous improvement and troubleshooting.

3.5.5 Stakeholder BWT Architecture

Government agencies can utilize the services provided by the BWT system not only for the benefit of the App's users, but also for their own operational and analytical purposes. These agencies can be equipped with tools to access and analyze the information available within the system. They can interact with the services through queries sent via web services or by utilizing a Dashboard Service hosted on the central system. The agencies can leverage several shared services, including Real-Time BWT, Real-Time POE Info, Historic BWT, and Map Service, to access up-to-date border wait time data, Port of Entry information, historical trends, and mapping functionalities. Additionally, agencies can utilize the Reporting Service to generate customized reports and analyze key metrics related to border crossing activities. The Dashboard Service provides a centralized platform for visualizing and interpreting data, allowing agencies to monitor border traffic, identify trends, and make informed decisions to optimize border operations and enhance security measures.

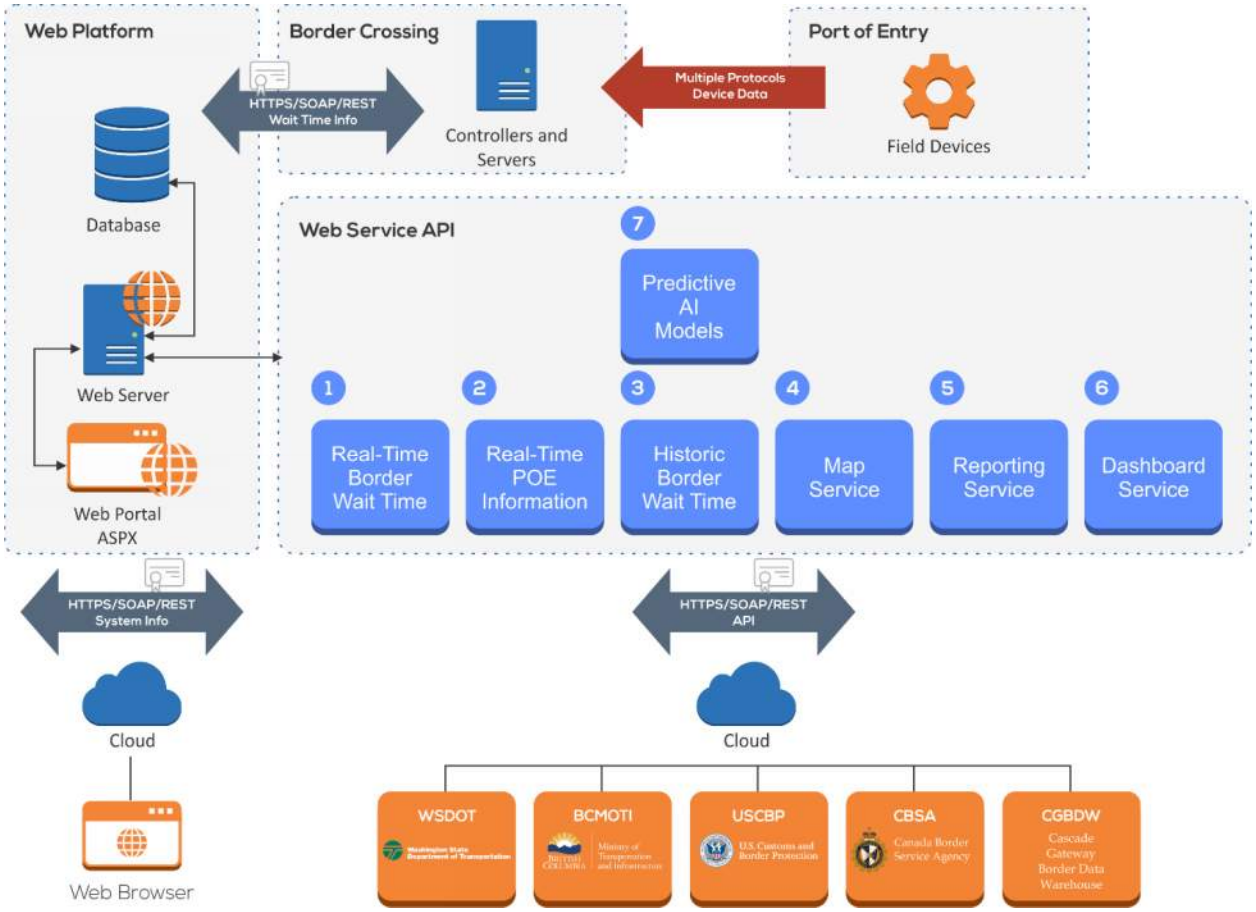


Figure 16. BWT App Stakeholder Architecture

A custom Cascade Gateway BWT app is a cost-effective way to collect and disseminate real-time and predictive border wait time information. The information can be customized to individual border crossers and the agencies. The app can be mobile and web-based, providing real-time wait time data, Google Maps integration, and AI-powered predictive wait times. The key to the success of the application is accuracy, which comes with extensive testing and benchmarking the results to a known accurate value before going live. The following are some of the systems engineering approaches and concepts that will need to be considered in the development of the custom Cascade Gateway BWT application.

1. **Planning**
   - *Requirements Gathering*: Understand the needs of travelers, government agencies, and stakeholders. Define functional and non-functional requirements.
   - *Design and Architecture*: Create a robust architecture that integrates with existing border systems. Consider scalability, security, privacy, and usability.
2. **Development**
   - *Frontend*: Develop user-friendly interfaces for iOS and Android platforms and for agency and private websites.

    - *Backend*: Implement APIs to fetch real-time data from existing and planned sources, process requests, and calculate wait times.
    - *Database*: Store historical and real-time data.

3. **Integration and Testing**
    - *Data Sources*: Integrate with existing border wait time systems, existing loops, RFID readers, and other planned data sources.
    - *Accuracy Testing*: Rigorously test wait time calculations against ground truth data until 90% accuracy is achieved before going live.
    - *Usability Testing*: Ensure the app is intuitive and user-friendly.

4. **Deployment and Maintenance**
    - Deploy to app stores (Apple App Store, Google Play, etc.,).
    - Regularly update data sources and address any issues.

However, in order for the app to provide reliable and accurate data, adequate public adoption will be needed; A statistical sample size will be determined for the number of app users needed to arrive at a 90% confidence interval with +/- 5% error. As such, it will be important to raise awareness for the app, for which professional outreach efforts are highly recommended. Some high-level approaches and best practices for marketing the BWT app are included below:

1. **Online Presence and Search Engine Optimization (SEO)**
    - *Website:* Develop a user-friendly website for the app. Include information about its features, benefits, and how it simplifies border crossing.
    - *SEO:* Optimize the website and content to appear in relevant search results. Use keywords related to border crossing, wait times, and travel.
    - *Social Media:* Leverage platforms like Twitter/X, Facebook, and LinkedIn to share updates, success stories, and engage with potential users.

2. **Mobile App Stores**
    - *App Store Optimization (ASO):* Optimize your app's listing on the Apple App Store and Google Play. Use relevant keywords, appealing visuals, and compelling descriptions.
    - *Ratings and Reviews:* Encourage users to rate and review your app. Positive reviews enhance credibility and attract more downloads.

3. **Collaborate with Government Agencies**
    - Partner and coordinate with CBP, CBSA, state, and local governments on both sides of the border to promote the app. They can endorse it as an official resource.
    - Collaborate with local transportation agencies, tourism boards, and travel-related organizations.

4. **Content Marketing**
    - Create informative blog posts, videos, and infographics about border crossing tips, wait times, and the benefits of using the app.
    - Share this content on agency websites, social media, and relevant forums.

5. **In-Person Promotion**
    - Set up booths or kiosks at border crossings, airports, and travel expos. Provide live demonstrations of the app.
    - Distribute flyers, brochures, and business cards to travelers.
6. **Partnerships and Affiliates**
    - Collaborate with travel agencies, rental car companies, hotels, and other businesses related to cross-border travel.
    - Offer incentives for referrals or partnerships.
7. **Local Media and Public Relations**
    - Reach out to local newspapers, TV stations, and radio shows. Share the app's story and its benefits.
    - Host a launch event or press conference.
8. **Paid Advertising**
    - Use targeted online ads (e.g., Google Ads, Facebook Ads) to reach potential users.
    - Consider geotargeting ads specifically to people near border crossings.
9. **User Engagement and Retention**
    - Regularly update your app with new features and improvements.
    - Send push notifications to users about real-time wait times, special events, or promotions.
    - Monitor the app's performance, gather user feedback, and adapt marketing strategies accordingly.
10. **Word of Mouth**
    - Encourage satisfied users to recommend the app to friends, family, and fellow travelers.
    - Consider referral programs or discounts for successful referrals.
11. **Financial Incentives:**
    - Some agencies (San Diego Association of Governments) in the past have provided financial incentives such as a chance to win $50 when a questionnaire is completed.

It should also be noted here that the app requires routine software maintenance and updates, especially based on new mobile operating system requirements, user feedback, or if additional functionality is desired.

3.6 Crowdsourced Data

Crowdsourcing involves obtaining services, ideas, or content from a large group of people over the internet using an open-call format. According to FHWA, crowdsourcing is a low-cost, powerful tool to overcome gaps in field instrumentation, data latency, and limitations inherent in traditional real-time traffic collection and dissemination.

According to their Every Day Counts Initiative 5 (EDC-5), "crowdsourcing turns transportation system users into real-time sensors on system performance, providing low-cost, high-quality data on traffic operations, roadway conditions, travel patterns, and more. When combined with traditional data, crowdsourcing helps agencies implement proactive strategies that improve incident detection, operational efficiency of traffic control systems, signal retiming, road weather management, traveler information, and other operational programs. Agencies can make roadways safer and more reliable, improve operational efficiency, and support cost-effective monitoring through crowdsourcing for operations."

Some of the private sector companies that collect and disseminate crowdsourced traffic data include but are not limited to the following:

1. Google
2. Waze
3. Apple
4. Bing
5. INRIX
6. TomTom
7. HERE

The states of Delaware, Utah (Citizen Reporter App for road conditions), Kentucky, and few other public sector agencies have their own mobile apps to collect information that is not provided by smartphones as sensors, especially during winter weather conditions.

For BWT measurement purposes, crowdsourcing can be challenging since the location accuracy by lane type (NEXUS, Ready and Standard lane) cannot be obtained through these third-party data sources. It is possible to have the user define the lane type in which they are traveling, but this requires user consent.

Table 8. Advantages and Disadvantages of Crowdsourced Data

Advantages	Disadvantages
Cost-effective compared to sensors and manual counts	Data quality can vary leading to inaccuracies in travel time
Provides real-time traffic delay data	Data can be misused
Can identify incidents more quickly when speeds drop around the incidents. Response can be quicker	Effectiveness of data depends on user participation and contributions, especially at low traffic volumes
Traffic data can be monitored from anywhere, any time.	

3.7 6.2 Combining Technologies and Data Sources (Hybrid Solution)

Since each port of entry has unique geometrical layouts, unique operating requirements, and security equipment (cameras, RFID readers, X-ray machines etc.) configurations, a single technology solution may not be feasible. Combining multiple methods for border wait time calculation, such as leveraging existing in-pavement sensors with advanced algorithms, vehicle identification cameras, CBP/CBSA vehicle throughput benchmarking, and GPS information services can enhance accuracy, reliability, and overall effectiveness.

Though each port of entry can vary significantly, data-driven border wait time measurement methodologies can be standardized at the enterprise level to enable scalability at the nearly 70 ports of entry along the northern and southern borders.

Some of the advantages of using a hybrid of methods and technologies for BWT include:

- Minimal or no additional hardware design and deployment to derive BWT that reflects the ground truth.
- Data-driven solutions are less disruptive to day-to-day port operations and highly cost effective, compared to the deployment of Wi-Fi/Bluetooth and RFID technologies.
- Requires less operation and system maintenance.
- Requires less administrative time from stakeholder agencies and frees up resources to concentrate on more important things.
- Hybrid measurement methods can be standardized across all busy ports at the enterprise level.
- Can be more easily automated.

Some of the challenges of using hybrid BWT methods and technologies include:

- Stakeholder acceptance needed.
- Ownership of data and its control issues need to be resolved.
- Transparency of algorithms and data processing
- Continuous monitoring and accuracy verification of BWT is needed.
- Acquisition of permits and approvals is needed.
- Data reliability at all levels of traffic conditions

The list below includes some of the methods and technologies that could be implemented for BWT systems. Together, these form hybrid technology options that can provide increased accuracy and reliability, and the specific hybrid technology packages that are proposed for consideration for the Cascade Gateway ABIS are included in Section 4.0.

1. **Primary Wait Time Calculation with In-Lane Vehicle Detection**
    - Utilize in-pavement sensors with advanced algorithms to perform the primary wait time calculation based on real-time measurements of vehicle presence, travel speed, and queue dynamics.
    - Leverage the capabilities of ground sensors to handle lane merging, forking, and chaotic conditions, providing accurate and dynamic information about traffic flow.
2. **Validation through Vehicle Identification Technology and Vehicle Throughput**
    - Implement vehicle identification technology such as Wi-Fi, as a validation mechanism to cross-verify the accuracy of the wait time calculations obtained from ground sensors/loops.

- Being able to independently identify vehicles can offer an additional layer of confirmation regarding the number of vehicles passing through specific checkpoints.
- The wait time measurements can be compared to CBP/CBSA's vehicle throughput counts (if such data is shared by CBP/CBSA) at the primary inspection.

3. **Enhanced Identification with GPS Services**
    - Integrate GPS information services to enhance the identification and tracking of individual vehicles.
    - Use GPS data to verify the accuracy of the location and movement patterns of vehicles detected by ground sensors, providing a complementary source of information.
4. **Back-of-Queue Confirmation with Ground Sensors and GPS**
    - Combine the back-of-queue determination capabilities of advanced ground sensor algorithms with GPS information to validate the accuracy of queue locations.
    - Ground sensors can dynamically determine the back of the queue between sensor points, and GPS information can confirm the location and movement of vehicles, ensuring precise back-of-queue identification.
5. **Dynamic Real-Time Updates from GPS**
    - Leverage GPS information services to continuously update and refine the wait time calculations in real-time.
    - GPS data provides ongoing insights into the changing positions and speeds of vehicles, allowing the system to adapt to dynamic traffic conditions and optimize wait time predictions.
6. **Comprehensive Reporting and Decision Support**
    - Integrate data from all three methods to generate comprehensive reports and decision-support tools for border management authorities.
    - Vehicle identification cameras, ground sensors, and GPS services collectively contribute to a holistic understanding of border crossing conditions, enabling authorities to make informed decisions about traffic management and resource allocation.
7. **Privacy Considerations and Consent**
    - Ensure that the combination of these methods aligns with privacy regulations by obtaining user consent for the use of GPS information and any other personally identifiable information.
    - Implement robust data security measures to protect sensitive information obtained from various sources.

Efficient management of traffic flow at border crossings or other critical points relies on accurate and real-time wait time calculations. Various technologies play a pivotal role in providing these calculations, each with its own set of advantages and challenges. Among these technologies, ground sensors stand out as a reliable source of ground truth, offering precise information about the presence of vehicles in a queue. In conjunction, vehicle identification technologies can contribute to and improve wait time calculations by tracking individual vehicles along designated routes.

By combining these methods, a comprehensive and resilient system that leverages the strengths of each technology can be created. This integrated approach enhances the accuracy of wait time calculations, provides validation through multiple sources, and enables dynamic adjustments to optimize border operations in real-time.

4.0 Hybrid BWT Technology Concepts

It is recommended that the Cascade Gateway Advanced Border Information System measure border wait times using a combination of hybrid technologies. This section outlines the methodologies and technologies aimed at improving traveler information and BWT measurements by accurately determining queue lengths and the number of vehicles, leveraging both existing infrastructures, as well as implementing new and innovative technologies. These strategies are designed to provide more accurate and real-time data that reflects the real-world ground-truth conditions, which is essential for accurate BWT measurements, the optimal allocation of resources, and the seamless facilitation of border traffic. Specifically, three concepts are proposed to achieve this goal, which are further detailed in the following sections.

Each concept presents a balance between technological innovation and practical challenges, including cost and implementation complexity and reliance on existing VDS/data stations for determining the back-of-queue and number of vehicles by lane type. The choice among these concepts will depend on specific border crossing needs at each land port of entry, available resources, and strategic priorities for the project stakeholders. Since all ports of entry are different, a tailored approach to measuring BWT may result in improved accuracy and reduced costs.

Although not described in these concepts, real-time information about BWT and lane status changes will also be communicated to travelers via digital signage at and approaching the border, similar to how it is done today. The data will also be archived within the Cascade Gateway Border Data Warehouse.

Details on the implementation approach for the selected technology concept(s) will be included as part of the *High-Level Design & Implementation Plan*, to be completed as part of Task 7.

4.1 Concept I – Loop Detectors, Vehicle Re-Identification, and AI

Concept I utilizes the existing VDS/data stations, vehicle re-identification technologies (which may take the form of Bluetooth/Wi-Fi readers, RFID readers, and/or video analytics to perform Make, Model, and Color Recognition [MMCR]; for the purposes of the figures below, video analytics is shown, but the technology can be interchangeable), and leverages AI. The technologies used in this concept are shown in Figure 17, with proposed deployment locations shown in Figure 18. Figure 19 shows the concept's proposed system architecture and data flow diagram.

Existing loop detectors are utilized as part of BC MOTI's VDS and WSDOT's data stations. If necessary, new in-lane vehicle detection may also be needed to cover the extended queue on weekends and holidays. Vehicle re-identification technologies may include Bluetooth/Wi-Fi readers, RFID readers, and video analytics. Bluetooth/Wi-Fi readers are the most technologically mature and reliable technology that allows the system to re-identify vehicles by the MAC addresses of smart devices. RFID can also be used to measure wait times for commercial vehicles. Lastly, video analytics, specifically the use of machine vision and AI to match and re-identify vehicles solely based on the make, model, and color, could be an alternative to ALPR, which is not currently allowed as part of the SMART Grants program. However, while video analytics and MMCR is not currently mature enough for BWT applications, the technology has developed significantly over recent years and may reach maturity within the next few years; although not recommended for deployment at this time based on the findings of the vendor showcases, the project team will stay apprised of the technology's developments. Finally, the application of Artificial Intelligence (AI) and cloud-based data analytics enables the processing of real-time and predictive data.

The Cascade Gateway BWT algorithm will be developed and extensively tested based on real-time and historical loop detector data. The live-streamed data can either reside in the cloud (recommended), or in a back-office server. Any significant deviations from a historical pattern will be treated as outliers by the algorithm and filtered out. The algorithm will learn from both the historical and live-streamed data (filtering and moving average method) to determine what data is routine, and what is an outlier. For the prediction of wait times in the next +15 minute, +30 minute and +60 minute time slices, the algorithm will use historical, real-time, and back-of-the-queue arrival patterns and vehicle counts. The algorithm will also be benchmarked against the total number of vehicles processed by CBP/CBSA during that period, these models will be tested and compared with actual travel time surveys until they reach the desired accuracy and maturity.

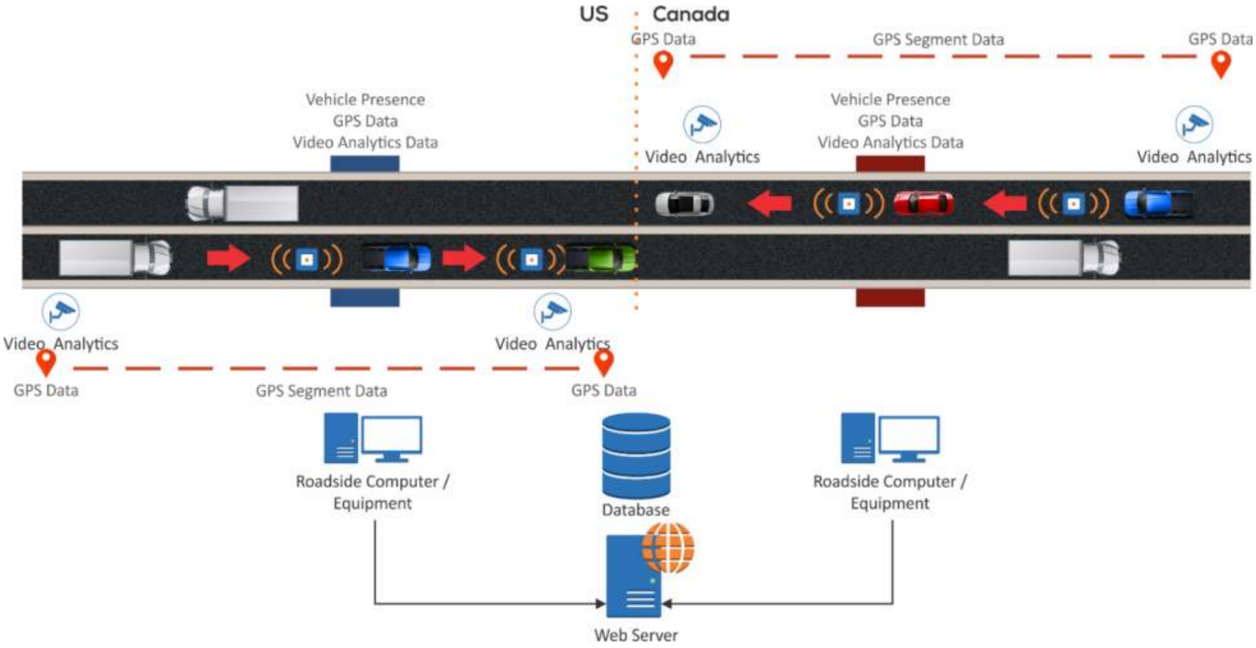


Figure 17. Concept I - Proposed Technologies Overview

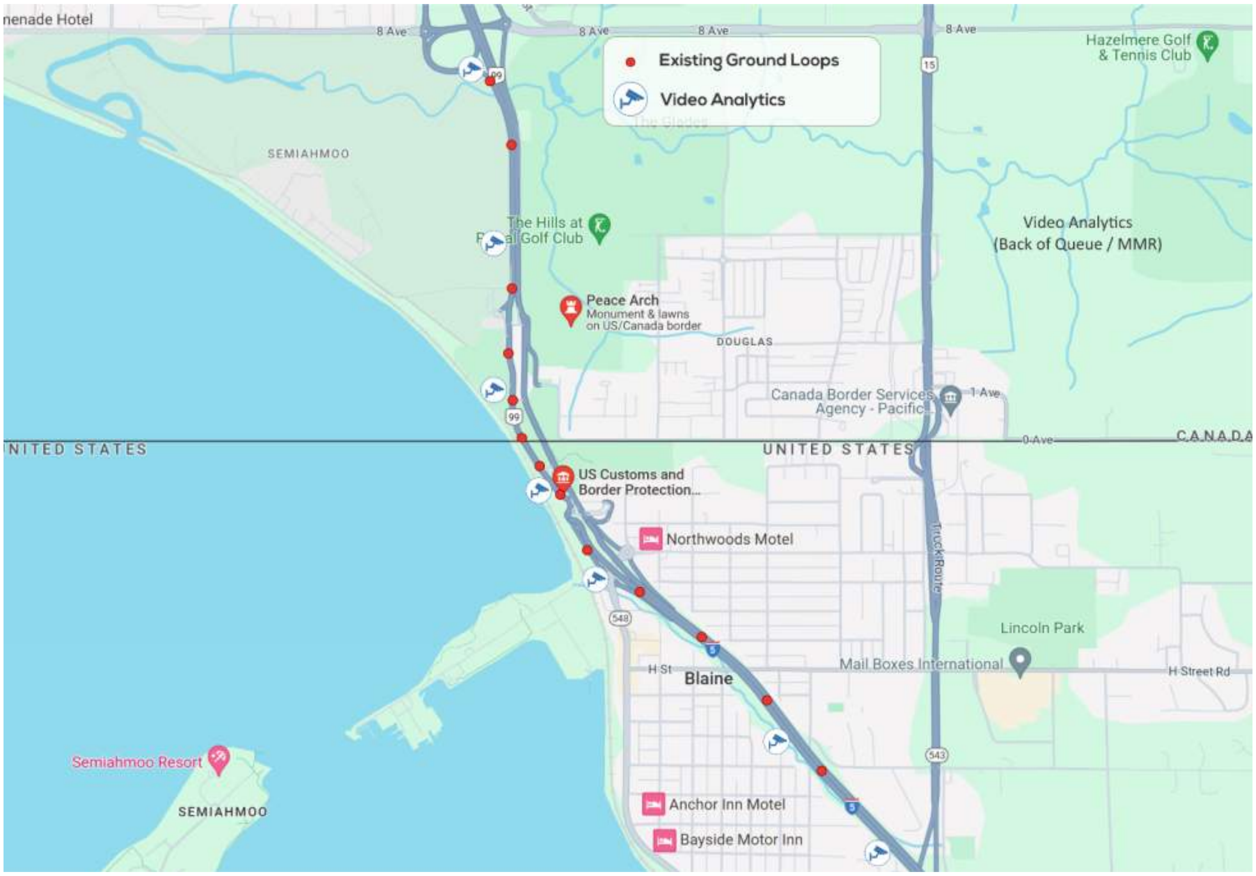


Figure 18. Concept I - Proposed Roadside BWT Measurement Technologies

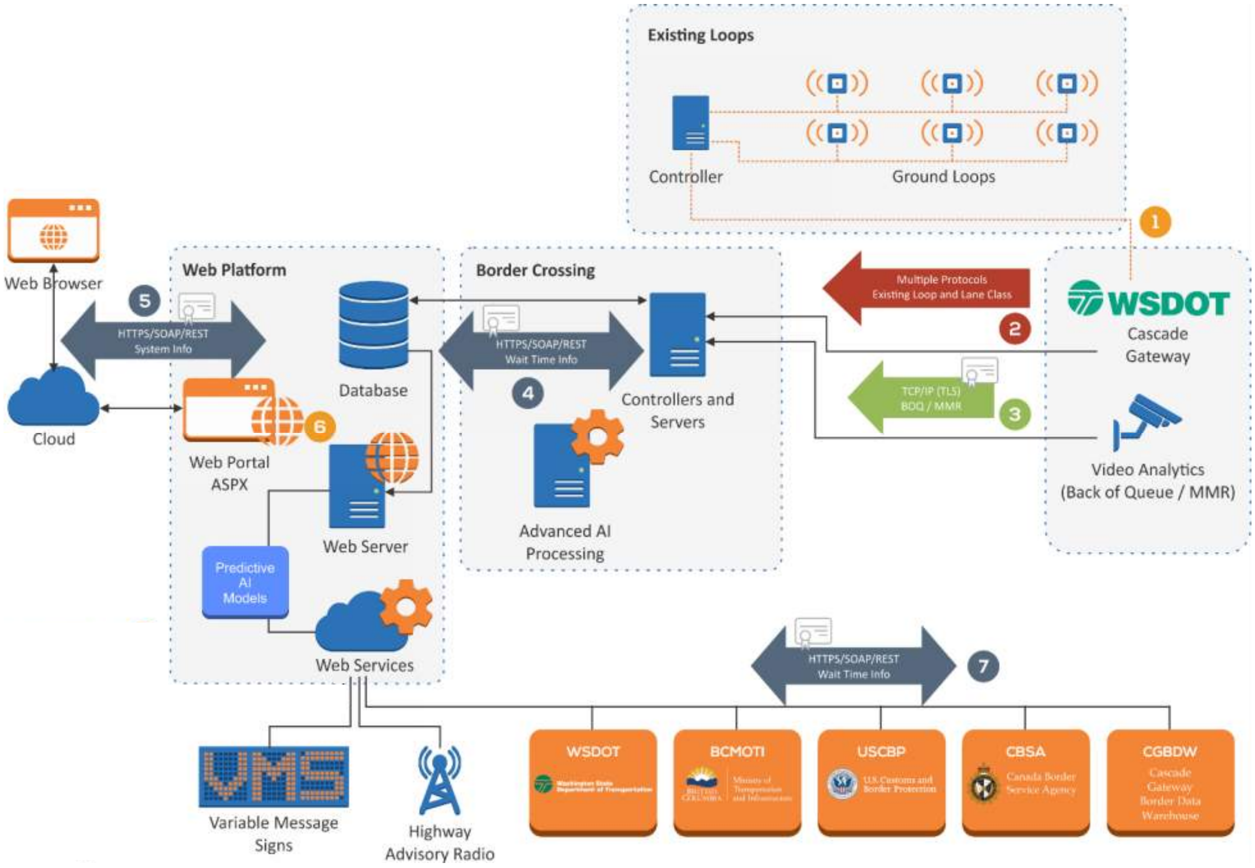


Figure 19. Concept I - Proposed System Architecture and Data Flow

In summary, Concept I combines the existing VDS/data station infrastructure and enhances the accuracy of the existing loop detectors by recalibrating and implementing new algorithms, deploys new in-lane vehicle detection to capture back-of-queues during peak periods (if necessary), implements vehicle re-identification technologies (e.g., Bluetooth/Wi-Fi readers, RFID readers, and video analytics) for re-identifying privately-owned and commercial vehicles, and utilizes AI and advanced data analytics to optimize BWT measurement and management. Table 9 below provides a summary of the technologies proposed in Concept I, while Table 10 provides a summary of the concept's advantages and disadvantages.

Table 9. Concept I - Summary of Proposed Technologies

Technology	Purpose	Comments
Loop Detectors	Determine the number of vehicles (counts) and back of the queue.	New loops to capture the back-of-queue beyond the last existing loop (only if necessary and agreed by project stakeholders). Recalibrate existing loop detectors and deploy new algorithms. Maintenance of loop detectors near the border has

Technology	Purpose	Comments
		been a pain point for the agencies.
Bluetooth/Wi-Fi Readers	Vehicle identification and re-identification and wait times for all vehicles.	Bluetooth/Wi-Fi readers cannot reliably differentiate between NEXUS, Ready, and standard lane groups.
RFID Readers	Vehicle identification and reidentification and wait times for trucks.	FAST and Non-FAST
Video Analytics	Vehicle identification and re-identification and wait times for all vehicles.	Technology is not mature enough for deployment at this time, but in the future could differentiate between NEXUS, Ready, and standard lane groups.
AI	Analysis of existing data, dashboards, reports, predictive BWT capability, and data archival.	What If scenario analysis and predicting traffic surges based on analytics
Mapping Interface	Map based interface; real-time data depicted on map.	

Table 10. Concept I - Advantages and Disadvantages

Advantages	Disadvantages
Enhanced accuracy of wait time measurements using recalibrated VDS/data station loops, additional detection, Bluetooth/Wi-Fi, RFID, and AI algorithms.	Reliance on loop detectors, which are prone to damage, frequent failure, and are expensive to relocate during construction.
Leverages the use of existing VDS/data station infrastructure.	Need for additional VDS/data stations to cover extended back-of-queues during high demand.
Predictive analytics for better resource allocation and improved efficiency.	Video analytics technology is not technologically mature at this time.
Improved traveler experience through real-time data and predictive analytics.	
Scalable and flexible system that is adaptable to various traffic patterns and border POEs.	

4.2 Concept II – Mobile Application (GPS II), Bluetooth/Wi-Fi, Radar, and AI

Concept II utilizes Bluetooth/Wi-Fi for re-identifying vehicles using the MAC addresses of smart devices, radar detection for determining the number of vehicles and the back-of-queue, develops the BWT App, and leverages AI. The technologies used in this concept are shown in Figure 20, with proposed deployment locations shown in Figure 21. Figure 22 shows the concept's proposed system architecture and data flow diagram.

The Cascade Gateway BWT application can help provide increased accuracy with lower implementation costs due to the minimal infrastructure required. With user consent, the BWT app, once installed, tracks vehicles continuously (within the geofenced area) from the time a vehicle joins the back of the queue to the time it exits primary inspection. However, GPS II technology does not allow for tracking of vehicles within individual lanes, so the BWT app will need to ask users to identify which lane they are traveling in, in order to measure BWT by lane type. This approach minimizes the need for roadway infrastructure and makes it very cost effective. It can be used for determining BWT for both passenger and commercial vehicles.

The location tracking process is anonymous and secure and complies with Federal Risk and Authorization Management Program (FedRAMP) standards, a government program that provides a standardized approach to security assessment, privacy, authorization, and continuous monitoring of IT products and services used by federal agencies to store, process, and transmit information. The program is based on the Risk Management Framework (RMF) that implements the Federal Information Security Modernization Act (FISMA) requirements and NIST SP 800-53. While the VDS/data station loop detectors will continue to provide data on the number of vehicles in the queue and the distance to the back of the queue, GPS II offers an additional layer of accuracy by tracking vehicle movements with satellite-based positioning. By integrating GPS readings into the system, Concept II enhances the precision of vehicle identification and wait time calculations. This approach retains the reliability of loop detectors while harnessing the benefits of GPS technology for improved real-time tracking and data accuracy.

Radar detection could be used in addition to/conjunction with existing loop detectors, where feasible. For example, at locations upstream of the POEs where stop-and-go traffic is not typically present, existing loop detectors could potentially remain and be recalibrated, while radar detection is installed near the POEs where vehicles are traveling more slowly and maintenance activities could benefit from non-intrusive forms of detection. Alternatively, radar detection can be used completely in lieu of existing loop detectors.

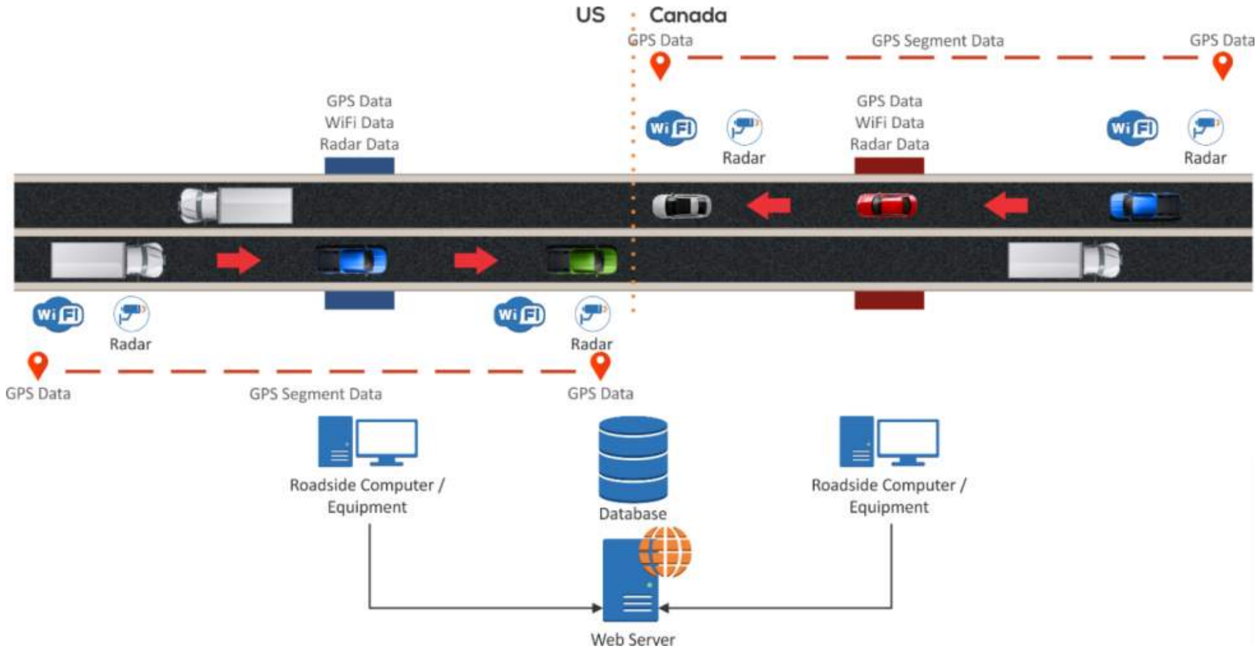


Figure 20. Concept II - Proposed Technologies Overview

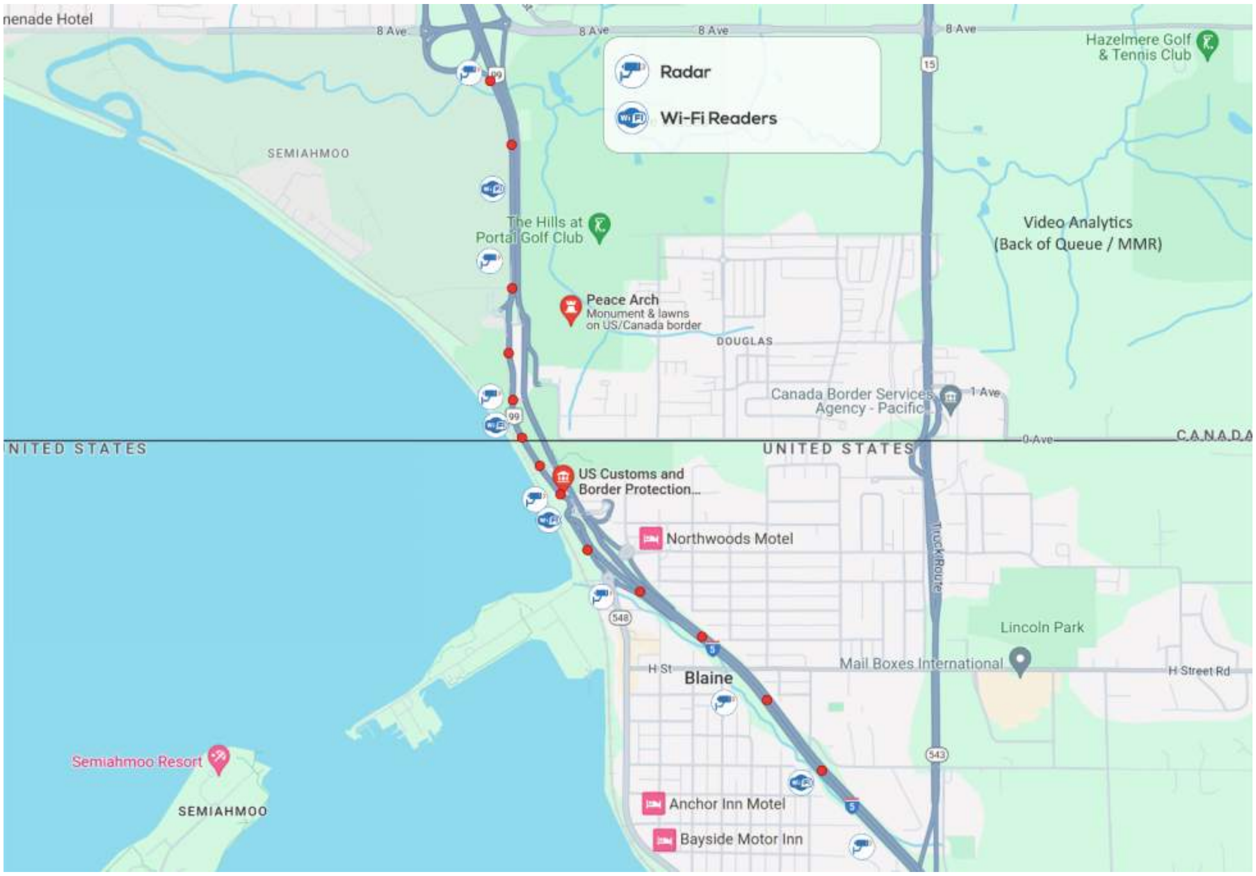


Figure 21. Concept II – Proposed Roadside BWT Measurement Technologies

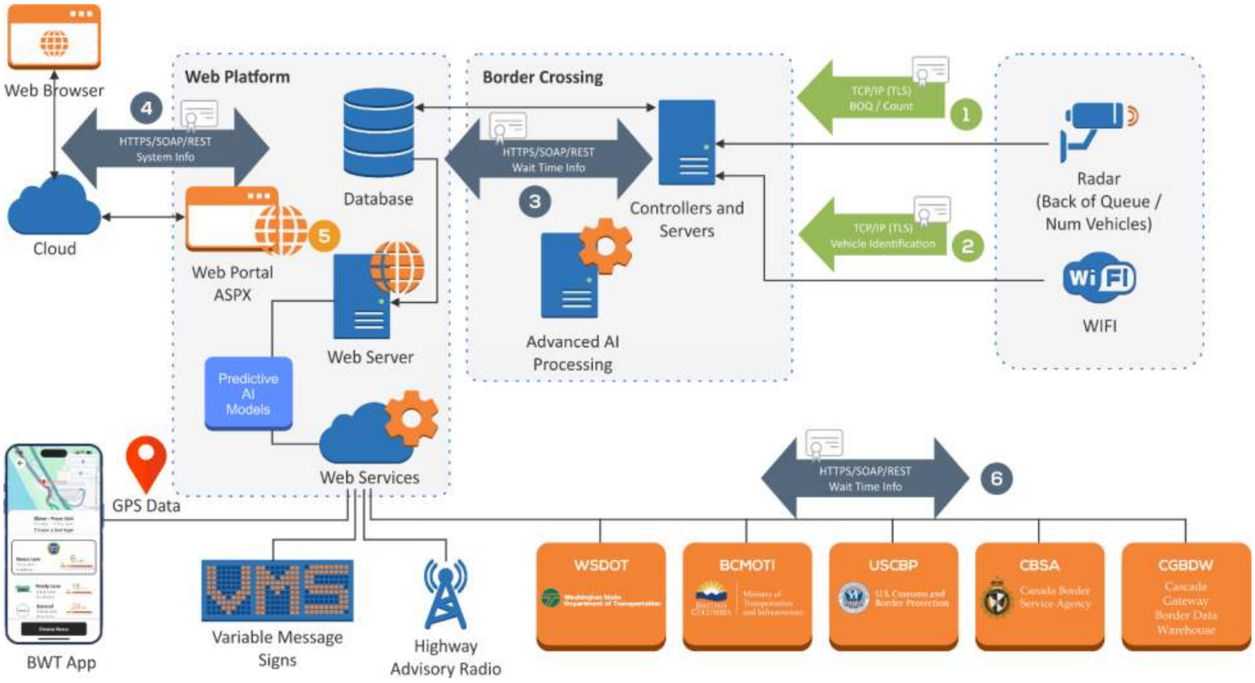


Figure 22. Concept II – Proposed System Architecture and Data Flow

In summary, Concept II combines the existing VDS/data station infrastructure and enhances the accuracy of the existing loop detectors by recalibrating and implementing new algorithms or by replacing existing loop detectors with radar detection, deploys new radar detection to capture back-of-queues during peak periods, develops a new dedicated Cascade Gateway BWT app based on GPS II technology, deploys Bluetooth/Wi-Fi readers to re-identify vehicles and supplement the data gathered from the BWT app, and utilizes AI and advanced data analytics to optimize BWT measurement and management. Table 11 below provides a summary of the technologies proposed in Concept II, while Table 12 provides a summary of the concept's advantages and disadvantages.

Table 11. Concept II - Summary of Technologies

Technology	Purpose	Comments
Radar Detection	Determine the number of vehicles (counts) and back of the queue.	Radar can be more accurate than loop detectors in stop-and-go traffic, and can provide additional traffic data (e.g., vehicle classifications). As a non-intrusive form of detection, maintenance of radar detection is expected to be easier when compared to loop detectors.
Loop Detectors	See Concept 1. Note that loop detectors would only be needed if the agencies desire for the existing loop detectors to remain.	

Technology	Purpose	Comments
Bluetooth/Wi-Fi Readers	See Concept I.	
Cascade Gateway BWT App	Measure BWT by lane type, after user consent for location tracking and lane type usage feedback and acceptance. Geofencing enables tracking of vehicles only while the vehicle is approaching/crossing the POE.	Smartphone tracking within a geofenced area with GPS II receivers.
AI	See Concept I.	
Mapping Interface	See Concept I.	

Table 12. Concept II - Advantages and Disadvantages

Advantages	Disadvantages
Similar to Concept I: -Enhanced accuracy of wait time measurements using radar detection, additional detection, and AI algorithms. -Leverages the use of existing VDS/data station infrastructure. -Predictive analytics for better resource allocation and improved efficiency. -Improved traveler experience through real-time data and predictive analytics. -Scalable and flexible system that is adaptable to various traffic patterns and border POEs.	Similar to Concept I: -Reliance on physical detection like radar or loop detectors. - Need for additional VDS/data stations to cover extended back-of-queues during high demand.
Reduced reliance on loop detectors compared to Concept I.	Users need to download the app, which may be a barrier to entry. Approximately 10-15% penetration rate is needed for accurate measurements.
The use of the Cascade Gateway BWT app serves as the backup and a validation method to ensure increased accuracy and lower overall costs.	Users need to provide consent for tracking within geofenced port of entry approaches.
The Cascade Gateway BWT app can provide additional traveler information, such as dynamic routing to alternative POEs based on real-time demand, communicating lane status and changes, etc.	Manual user input is needed to select which lane they are traveling in.

Advantages	Disadvantages
Hybrid solution that utilizes more than one data source for measuring wait times, making it easier for cross verification and validation	App will require maintenance and marketing.

4.3 Concept III – Mobile Application (GPS III) and AI

Concept III leverages GPS III technology for the Cascade Gateway BWT application as the primary source of vehicle positioning and back-of-queue detection. With the imminent arrival of GPS III by the end of 2026, which will provide significant improvements to precision, the system will be able to accurately pinpoint vehicle positions, including the specific lane in which they are traveling, without the need for physical roadway infrastructure. Similar to Concept II, the BWT app, with user consent, tracks vehicles continuously within a geofenced area to determine BWTs for both passenger and commercial vehicles. However, since GPS III technology has significantly improved accuracy, users will no longer need to self-declare the lane type in which they are traveling. Note that once GPS III has been deployed, it may be possible that the Cascade Gateway BWT application's functionality will become built into existing navigation apps such as Google Maps or Waze.

While loop/radar detectors and Bluetooth/Wi-Fi readers can remain, their role would transition to either serving as a source of backup data or being used for data validation purposes. The concept approaches an infrastructure-less solution, capitalizing on the advanced capabilities of GPS III. By harnessing GPS III's enhanced precision and ability to detect lane type and lane use information, high accuracy can be achieved. Concept III conforms to FedRAMP information security standards. The technologies used in this concept are shown in Figure 23. Since physical infrastructure will no longer be needed (aside for data validation purposes), the map of proposed deployment locations is not included for this concept. Figure 24 shows the concept's proposed system architecture and data flow diagram.

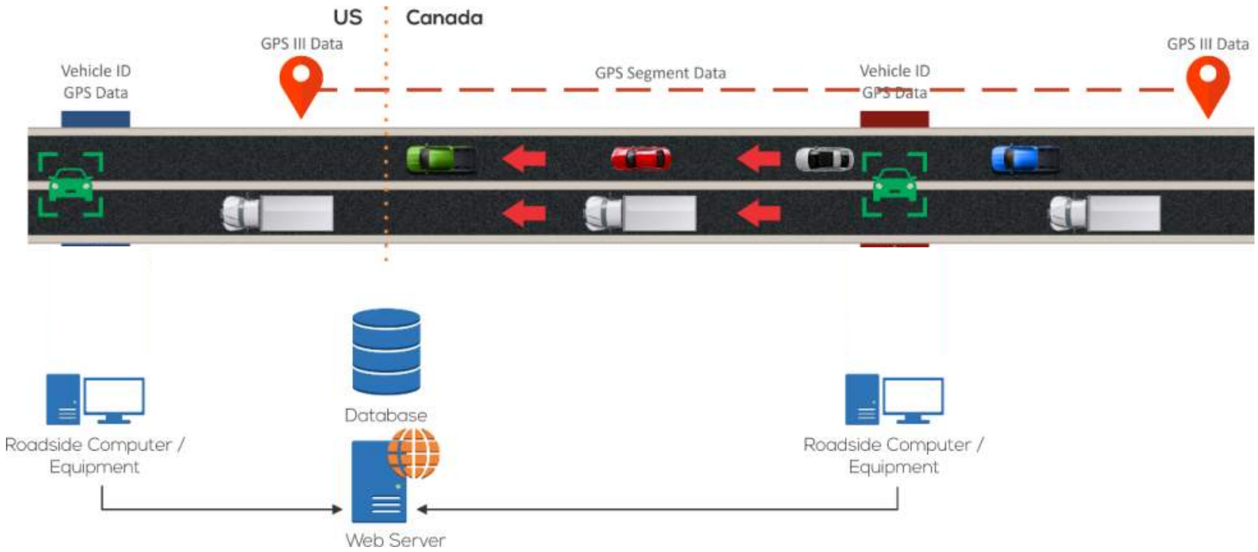


Figure 23. Concept III - Proposed Technologies Overview

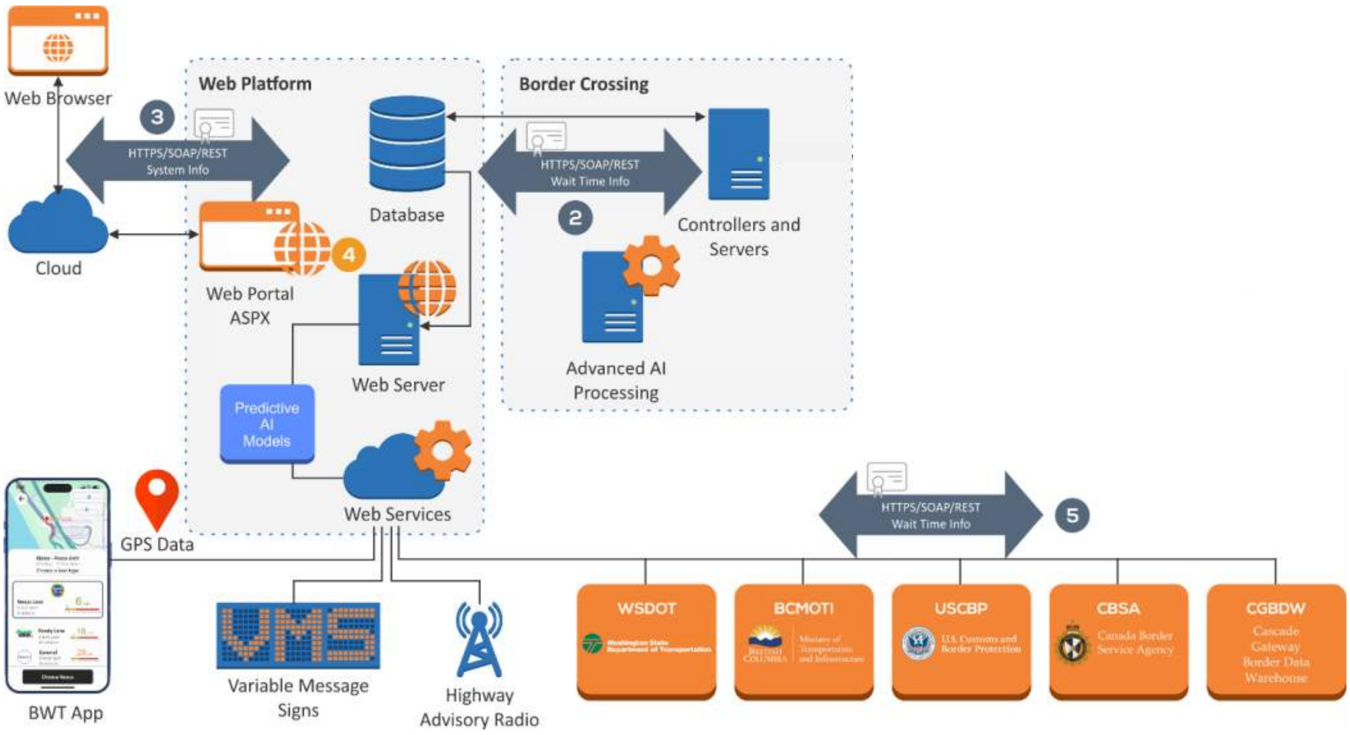


Figure 24. Concept III - Proposed System Architecture and Data Flow

In summary, Concept III develops a new dedicated Cascade Gateway BWT app based on GPS III technology and utilizes AI and advanced data analytics to optimize BWT measurement and management. Existing physical infrastructure such as existing VDS/data stations, loop detectors, radar detection, and Bluetooth/Wi-Fi readers can continue to be used, though they would primarily be used for data validation purposes. Table 13 below provides a summary of the technologies proposed in Concept III, while Table 14 provides a summary of the concept's advantages and disadvantages.

Table 13. Concept III - Summary of Technologies

Technology	Purpose	Comments
Cascade Gateway BWT App	Measure BWT by lane type, after user consent for location tracking. Geofencing enables tracking of vehicles only while the vehicle is approaching/crossing the POE.	Smartphone tracking within a geofenced area with GPS III constellation satellites (deployment expected by end of 2026) and receivers. With GPS III, users will no longer need to manually select the lane type in which they are traveling in.
Loop Detectors/Radar Detection	See Concept I and Concept II. Physical sensors would only be needed for backup data/data validation purposes.	
AI	See Concept I and Concept II.	
Mapping Interface	See Concept I and Concept II.	

Table 14. Concept III - Advantages and Disadvantages

Advantages	Disadvantages
Similar to Concept I: If backup data/data validation using physical infrastructure is desired: -Enhanced accuracy of wait time measurements using recalibrated VDS/data station loops, additional detection, and AI algorithms. -Leverages the use of existing VDS/data station infrastructure. -Predictive analytics for better resource allocation and improved efficiency. -Improved traveler experience through real-time data and predictive analytics. -Scalable and flexible system that is adaptable to various traffic patterns and border POEs.	Similar to Concept I: If backup data/data validation using physical infrastructure is desired: -Reliance on loop detectors, which are prone to damage, frequent failure, and are expensive to relocate during construction.-Need for additional VDS/data stations to cover extended back-of-queues during high demand.
Similar to Concept II: -The Cascade Gateway BWT app can provide additional traveler information, such as dynamic routing to alternative POEs based on real-time demand, communicating lane status and changes, etc.	Similar to Concept II: -Users need to download the app, which may be a barrier to entry. -Users need to provide consent for tracking within geofenced port of entry approaches.

Advantages	Disadvantages
-Hybrid solution that utilizes more than one data source for measuring wait times, making it easier for cross verification and validation.	
The use of the Cascade Gateway BWT app serves as the main source of BWT information, with VDS/data stations serving as the backup and a validation method to ensure increased accuracy and lower overall costs. This significantly reduces the need for physical infrastructure (and the reliance on loop detectors) compared to Concept I and Concept II. This option allows the BWT system to go infrastructure-less.	Complexity in implementation, requiring integration of multiple data sources and technologies, which can be complex and costly to implement.
Users no longer need to manually select which lane they are traveling in.	This technology has not yet been deployed nor tested in other locations.

5.0 Evaluation and Ranking of Hybrid BWT Technology Concepts

The objective of this section is for the project team and the stakeholders to reach consensus on what criteria are to be considered for evaluating the technology concepts and their importance (weighting). For example, accuracy should be the most important criteria that takes the highest weightage. Without accurate wait times, both the agencies and travelers will not rely on it nor use it. Evaluation criteria for evaluating the technology concepts, along with their weights, are given below.

1. **Accuracy** (Weight = 30 out of 100 points): The precision (ground-truth) of the technology in measuring real-time border wait times. High accuracy ensures the reliability of the data collected and disseminated. Score: 1 (low accuracy) to 30 10(high accuracy).
2. **Cost** (Weight = 10 points): The initial deployment cost in the technology. Lower cost is generally more desirable. Score: 1 (high cost) to 10 (low cost).
3. **User Experience** (Weight = 10 points): How easy, timely and convenient it is for the end-users (border agency staff and travelers) to use the technology. Score: 1 (poor user experience) to 10 (excellent user experience).
4. **Operation and Maintenance Costs** (Weight = 10): The costs associated with running and maintaining the technology over a 5-year period. This includes costs for things like repairs, updates, and staff training. Score: 1 (high costs) to 10 (low costs).
5. **Flexibility** (Weight = 10 points): The technology's adaptability to changes in the physical infrastructure at the port of entry. Score: 1 (low flexibility) to 10 (high flexibility).
6. **Future Proofing** (Weight = 5 points): The technology's ability to remain relevant and useful in the future, considering the rapid pace of technological advancements. Score: 1 (low future proofing) to 5 (high future proofing).
7. **Security** (Weight = 5 points): How well the technology protects data and maintains privacy (e.g., FedRAMP and National Institute of Standards and Testing NIST standards). Score: 1 (low security) to 5 (high security).
8. **Ease of Implementation** (Weight = 10 points): How easy it is to install and integrate the technology into the existing system. Score: 1 (difficult to implement) to 5 (easy to implement).
9. **Innovation** (Weight = 5 points): How innovative the technology is. Innovative technologies may offer unique features or capabilities that set them apart from other options. Score: 1 (low innovation) to 5 (high innovation).
10. **Scalability** (Weight = 5 points): The ability of the technology to handle increased workload or to be upgraded over time to the enterprise level covering entire northern or southern borders. Score: 1 (low scalability) to 5 (high scalability).

The following evaluation table has been filled out by the project team based on the results and the evaluation of the vendor showcases. This scoring was also influenced by comments provided by WCOG, WSDOT and BC MOTI in an interactive online scoring meeting. The following example provides the rationale for the scoring of Concept II.

1. **Accuracy (28):** Concept II leverages proven technologies such as Bluetooth/Wi-Fi, Radar, GPS App, and AI. These components work synergistically to cross-validate real-time measurements and predictions, resulting in high accuracy and reliability. If one technology temporarily fails, others can compensate.
2. **Initial Cost (7):** Although the initial cost appears moderately high due to the use of multiple technologies, individual components like Radar, Bluetooth/Wi-Fi, and the BWT app (which would serve all four POEs) are cost-effective.
3. **User Experience (8):** The system provides accurate and reliable information, enhancing the motorist experience. Customized data from the app contributes to a positive user experience.
4. **O&M Costs (6):** Ongoing maintenance costs are moderate. For the BWT app in particular, on-going maintenance and updates will be needed to avoid deprecation.
5. **Flexibility (10):** Concept II avoids overreliance on a single technology. Its hybrid approach provides BWT information from multiple sources, cross-validating for accuracy.
6. **Future Proofing (5):** The BWT app provide a forward-compatible solution that does not rely on physical infrastructure, while non-intrusive roadway sensors like radar detection and Bluetooth/Wi-Fi can more easily adapt to future infrastructure changes in roadway approaches.
7. **Security (5):** The BWT app, Bluetooth/Wi-Fi, and Radar adhere to ITS, NIST, and FedRAMP standards, ensuring robust security.
8. **Ease of Implementation (7):** Radar and Bluetooth/Wi-Fi installation is relatively straightforward, often without requiring roadway closures since these devices are mounted at the roadside and not in the travel way.
9. **Innovation (5):** The hybrid solution coupled with AI represents a cutting-edge approach to BWT measurement.
10. **Scalability (5):** The technologies are flexible and easily expandable to cover other POEs, including ones along the northern and southern borders.

A similar rationale was used to score Concept I and Concept III. The table below provides a summary of the scoring for all three concepts.

Table 15. Evaluation Criteria, Weighting, and Scores

Concept/ Criteria	**Accuracy**	**Initial Cost**	**User Exp-erience**	**O&M Costs**	**Flex-ibility**	**Future Proofing**	**Security**	**Ease of Implem-entation**	**Inno-vation**	**Scal-ability**	**Total Score**
Weight	*30*	*10*	*10*	*10*	*10*	*5*	*5*	*10*	*5*	*5*	***100***
Concept I – Loop Detectors, Vehicle Re-Identification, and AI	24	5	5	3	1	1	3	5	1	2	**50**
Concept II – Mobile Application (GPS II), Bluetooth/Wi-Fi, Radar, and AI	28	7	8	6	10	5	5	7	5	5	**86**
Concept III – Mobile Application (GPS III) and AI	22	5	8	7	8	5	5	7	4	5	**76**

6.0 Recommendations

Following discussions with the project stakeholders, the project team arrived at a consensus. After eliminating technologies that had not reached the desired level of maturity for BWT applications, and given the benefits of hybrid technologies, Concept II emerged as the preferred choice, as shown in the evaluation presented in Table 15.

Concept II consists of the following technologies, synergistically working together for more accurate and reliable Border Wait Times.

1. **Bluetooth/Wi-Fi readers** for re-identifying vehicles using MAC addresses.
2. **Radar detection** for detecting number of vehicles, speed and back of queue.
3. **Mobile Application** to provide a user-centric BWT solution using Global Positioning System technology.
4. **Artificial Intelligence** to provide self-learning algorithms built into the App for real-time and predictive wait time capabilities that more accurately reflect the ground-truth.
5. **Existing ITS** in the form of dynamic/variable message signs and highway advisory radio to disseminate BWT information while travelers are en route.

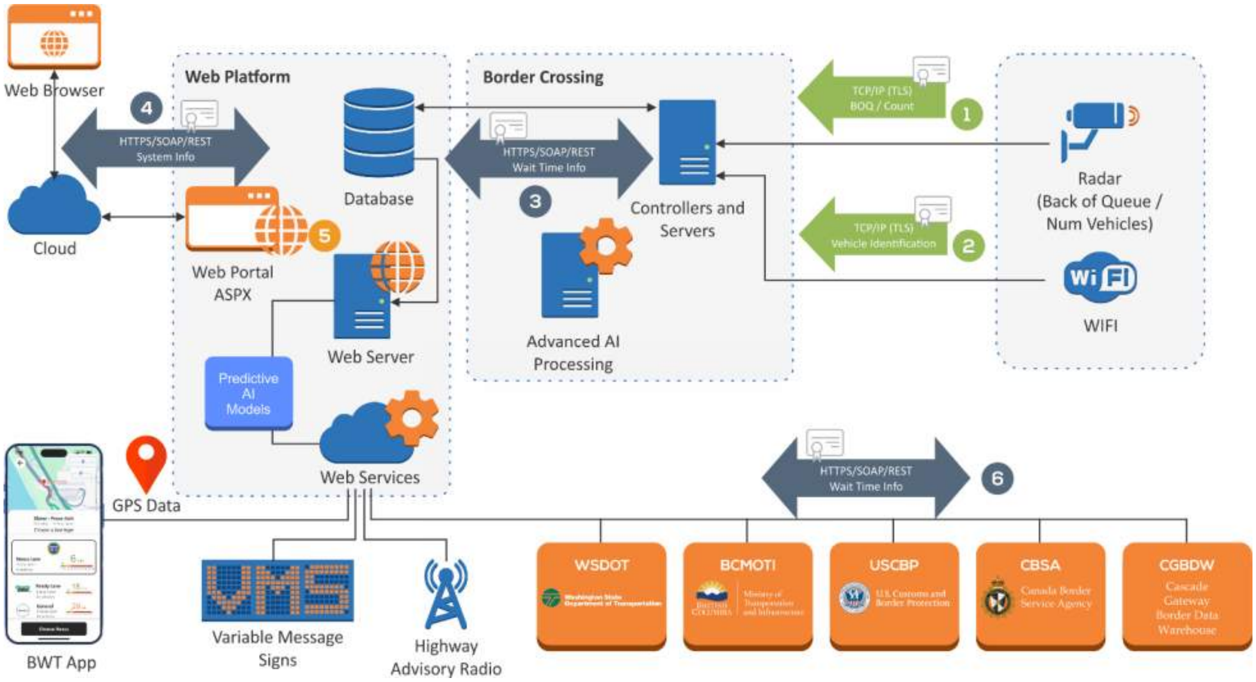


Figure 25. Concept II - Proposed System Architecture and Data Flow

Concept II presents several advantages, including:

- **Hybrid Solution:** Concept II represents a robust hybrid data-driven solution, drawing from successful pilot projects along both the northern and southern borders. By amalgamating travel data from various sources, it is possible to achieve more accurate and reliable BWT. Additionally, this approach enables cross-validation through real-time and predictive algorithms, enhancing the overall reliability of wait time estimations.

- **Technology Synergy:** The integration of Bluetooth/Wi-Fi readers for vehicle re-identification, radar technology for back-off-queue detection, and an AI-powered BWT app creates a powerful synergy within Concept II. This combination provides the ability to identify and rectify any discrepancies between actual and predicted wait times, resulting in more precise calculations. Motorists benefit from real-time and predictive capabilities, improving their travel experience at border crossings.
- **Diverse Technology Redundancy:** Concept II mitigates the reliance on a single technology. In cases where one component encounters issues or malfunctions, other technologies can continue to provide the needed data. This redundancy enhances overall system reliability.
- **Effective Information Dissemination:** Existing ITS like dynamic/variable message signs and highway advisory radio (HAR) play pivotal roles in disseminating BWT information to motorists en route. These technologies enhance situational awareness, enabling travelers to make informed decisions during their journeys.
- **Laying the Foundations for Enterprise-Wide Infrastructure-less BWT:** The BWT App, one of the cornerstones of the Concept II technologies, pioneers a novel path by measuring and estimating real-time and predictive wait times without relying on more expensive infrastructure solutions. Once successfully deployed as part of the Cascade Gateway ABIS, it can pave the way for broader adoption along the US-Canada and US-Mexico borders.