City and County of San Francisco
Municipal Transportation Agency

AdvanceSF

CONNECTED CORRIDOR PROOF OF CONCEPT PROJECT

FINAL REPORT
OCTOBER 2025

SFMTA

Executive Summary

The City of San Francisco was awarded a $10,990,760 grant by the Federal Highway Administration (FHWA) under the Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) Program in 2018. Among the City's four proposed projects under the ATCMTD grant, The Connected Corridor Proof of Concept (PoC) Project deployed a multimodal intelligent traffic signal timing system aimed to increase safety and reduce signal delays for all roadway users.

The Connected Corridor project was divided into multiple phases. Phase 1 involved establishing the groundwork for technological deployment and assessing system integration feasibility of several new components within San Francisco's existing traffic signal infrastructure. As the project progressed into Phase 2, data collection and analysis became central to evaluating the effectiveness of the deployed solutions. Phase 2 aimed to provide actionable insights into traffic patterns, congestion management, and impacts to the environment.

The project location for Phase 1 and Phase 2 shared many of the same intersections, with the primary focus on the 3rd Street Corridor in San Francisco's Mission Bay neighborhood, an area on the eastern part of the city. The project team faced various challenges, such as limitations with object detection, balancing the needs of competing stakeholders for traffic signal timing allocation and changing traffic patterns and behaviors stemming from the COVID pandemic.

Despite the challenges, the project team achieved meaningful outcomes during the limited period the dynamic traffic signal timing system was in operation. Transit experienced notable improvements, with red-light delays reduced by 73% and travel times reduced by 15%. These benefits were realized without placing a significant burden on other vehicles or pedestrians.

The PoC yielded highly promising results, and the project team seeks to build on this success by pursuing additional future funding to expand the initiative to see if these results can be replicated and sustained across the entire corridor over a longer duration.

Background

The City of San Francisco applied for the United States Department of Transportation (USDOT) Smart City Challenge in 2016 for an award to improve surface transportation performance through creative and innovative ideas to address existing challenges. Although San Francisco did not win the 2016 Smart City Challenge, the City took the lessons learned from this process and repackaged some of the proposed projects for another grant through USDOT's Federal Highway Administration (FHWA).

In 2018 FHWA awarded the city $10,990,760 through their Advanced Transportation and Congestion Management Technologies Deployment (ATCMTD) Program. The City's proposal contained a suite of 4 projects:

1) Treasure Island Autonomous Shuttles
2) Treasure Island Congestion Toll System
3) Shared Rides Project
4) Connected Corridor PoC Project

This report focuses on the Connected Corridor PoC Project, which was delivered in two phases. The first phase took place from August 2019 to January 2020 with the second phase occurring from December 2020 to August 2021. Initial plans for the PoC called for implementation across 2 distinct contexts – the Tenderloin neighborhood and on the 3rd Street Corridor. Due to Covid pandemic that started in 2020, the project team adjusted the site locations to reflect changes in resources (people, access to locations and equipment, procurement processes) to focus solely on the 3rd Street corridor. This project was classified as a PoC due to technological complexities of integration within the agency's traffic signal ecosystem. San Francisco has over 1200 traffic signals and although each intersection shares one main commonality with the same traffic signal controller model, there is a mix of various signal software and firmware, signal cabinet types, detection hardware, and networking capabilities. With so much variability within our agency's signal infrastructure at each intersection, integrating new hardware and software requires extensive testing, typically for a duration of 12 months, to ensure compatibility within the infrastructure ecosystem and to determine maintenance needs for ongoing operations. Once a piece of hardware and software passes agency tests, we can potentially expand the usage of the product beyond a PoC phase to long term operability if it meets the use cases for the specific intersection design.

Proof of Concept Phase 1

Phase 1 began when Cisco approached SFMTA in 2019 through our Technology Integration Section (TIS) within the Finance and Infrastructure Technology (FIT) Division to test equipment provided through the in-kind donations listed in Table 1:

Equipment and Resources	Purpose
Network Switch	Upgrade existing network switches to connect field devices (cameras, object detection sensors, traffic signal controllers, vehicle message signs) to the SFMTA network for communication and data transfer
Dedicated Short-Range Communication (DSRC) sensors	Collect speed and volume data from equipped newer model passenger vehicles
Light Detection and Ranging (LiDAR) sensors	Detect objects by size, speed, direction
Labor	Design, configuration, integration, evaluation

Table 1. PoC Phase 1 In-Kind Donations

The goal of Phase 1 was to visualize and analyze traffic flow and curb usage. The project locations were various intersections in the South of Market (SOMA) and Mission Bay neighborhoods, selected due to the combination of the presence of existing traffic signal infrastructure (fiberoptic communications, networking equipment) and the surrounding land use. The SOMA and Mission Bay neighborhoods are home to many trip generated attractions such as sports venues, a major hospital, medical research facilities and connections to regional transit.

The three main new technologies deployed were:

- Light Detection and Ranging (LiDAR) – laser sensors used to determine location, speed, heading and size of objects. The equipment tested was the Quanergy M8-PoE+ Sensor.
- Dedicated Short Range Communications (DSRC) – wireless information exchange via radios between objects, such as between vehicles and infrastructure to determine location, speed, heading. The equipment tested was the Cohda Wireless MK5 RSU.
- Network Switches – additional network switches were installed in the cabinets to connect more devices, such as LiDAR and DSRC to the SFMTA network for communication purposes. Depending on whether the devices required more bandwidth or reduced latency, a Cisco IE4000 branded network switch was selected over SFMTA's current standard of a Cisco IE3000.

Table 2 summarizes the locations and deployed equipment.

No.	Intersection	Deployed Equipment
1	4th/King	DSRC + 2nd IE3000 network switch
2	3rd/Channel	DSRC + 2nd IE3000 network switch
3	3rd/Warriors	DSRC + IE4000 network switch
4	3rd/18th	DSRC + 2nd IE3000 network switch
5	7th/16th/Mississippi	DSRC + 2nd IE3000 network switch
6	3rd/Campus	LiDAR (4 sensors, 1 on each intersection corner) + IE4000 network switch
7	3rd/16th	LiDAR (4 sensors, 1 on each intersection corner) + IE4000 network switch
8	16th/Terry Francois	LiDAR (4 sensors, 1 on each intersection corner) + IE4000 network switch
9	Terry Francois/Warriors	LiDAR (4 sensors, 1 on each intersection corner) + IE4000 network switch

Table 2. Deployed Equipment by Intersection

The project team developed three use cases along with potential example scenarios that would utilize the gathered data based on discussions with the traffic engineering team as shown in Table 3.

Use Case	**Scenario**
(1) Visualize Traffic Flow	(a) Traffic Flow on 3rd St., between 16th St. and Mission Bay Blvd North
	(b) People embarking/disembarking at the UCSF/Chase Center Platform (between South and 16th St), crossing the street and walking to/from the Chase Center entrance
(2) Traffic Flow Obstructions	(a) Obstruction to the traffic flow on 3rd St., between 16th St. and Mission Bay Blvd North
	(b) Obstruction to the traffic flow on Terry A. Francois Blvd.
(3) Curb Management	(a) Curb occupancy at Terry A. Francois Blvd. where transportation network companies (e.g. Uber, Lyft) drop off and pick up spots are located
	(b) Curb usage at Mission Bay Blvd. North and South, east of 3rd St., and on 16th St., east of 3rd St.

Table 3. PoC Phase 1 Use Cases and Test Scenarios

The desired outcome of the use cases was to gather data to allow traffic engineers and planners to make better decisions, such as adjustments to traffic signal timing to adapt to the collected data. Data prior to this PoC was either collected manually (individual observations) or not collected at all due to resource constraints.

Installation of equipment listed in Table 2 was performed by SFMTA signal shop electricians. The LiDAR vendor performed calibration (adjustments of the tilt, pan, and rotation of the sensors) of their equipment and mapped out the detection zones via their software. The SFMTA IT team worked with the signal shop and the third-party vendors to integrate the equipment into the SFMTA network.

After several weeks of testing the Project Team provided the following key findings:

- SFMTA was able to capture, transport and process large amounts of data in real time
- The collected data would provide an improved ability to make signal timing adjustments. However, there are already several off-the-shelf products that can provide the same data metrics with less integration requirements and resource needs.
- LiDAR provides good object detection with 93% accuracy, but stability (issues with sensor uptime) could be improved.
- DSRC captured less than 1% of vehicles making it an insufficient choice of sensor to analyze and manage traffic flow and to broadcast real time information, such as traffic signal status, to users. The project team sought to disseminate real time information to a larger audience that can benefit from and act on the information and decided that this could be best achieved through improvements in transit reliability which would then allow for better transit arrival predictions

that users would see on bus shelters and through mobile websites and 3rd party smartphone apps.

- Collecting curb management data was not successful due to limitations in the LiDAR sensors. The sensors tested do not see further than ~200 feet and the selected blocks were more than 800 feet long. Given these results, our selected LiDAR sensors should not be the sensor of choice for curb management purposes but there may be a possibility that other LiDAR sensors could have the necessary range to detect objects at greater distances.

While the project team could not collect data for the third use case of Curb Management, they were able to successfully collect and process data for the first two use cases.

The first use case to Visualize Traffic Flow can be observed through Figures A-D, which showcases data from January 2020.

- Figure A provides an hourly count of the number of vehicles observed through the LiDAR equipped intersections (5) during a 4-day period

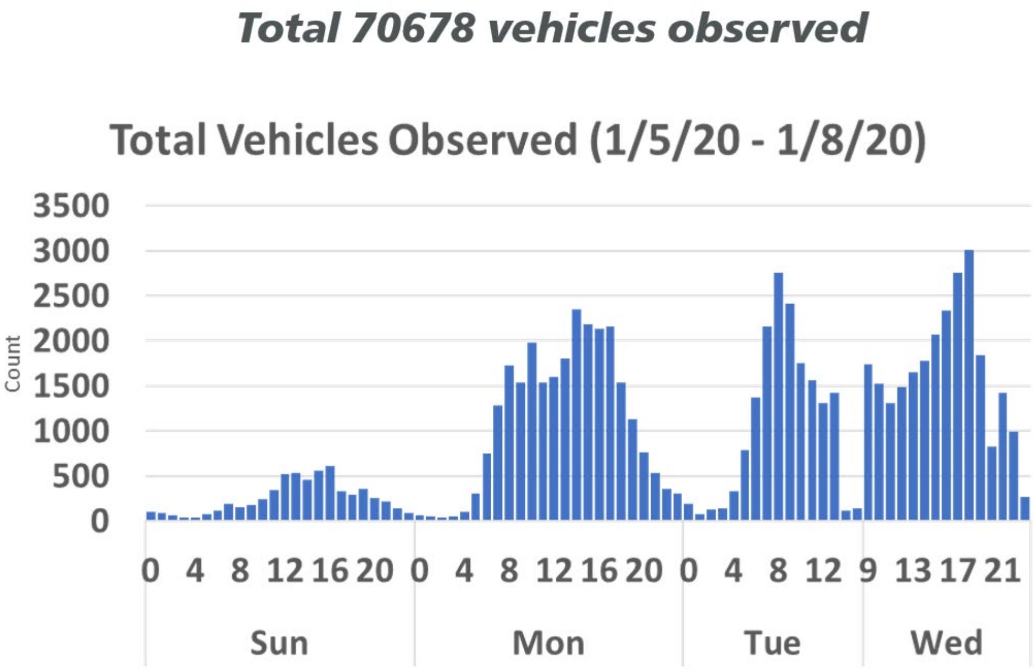


Figure A. Hourly Vehicle Count (1/4/20-1/8/20)

- Figure B breaks down the 4-day period of observed vehicles by direction of travel (WB = westbound, EB = eastbound, NB = northbound, SB = southbound)

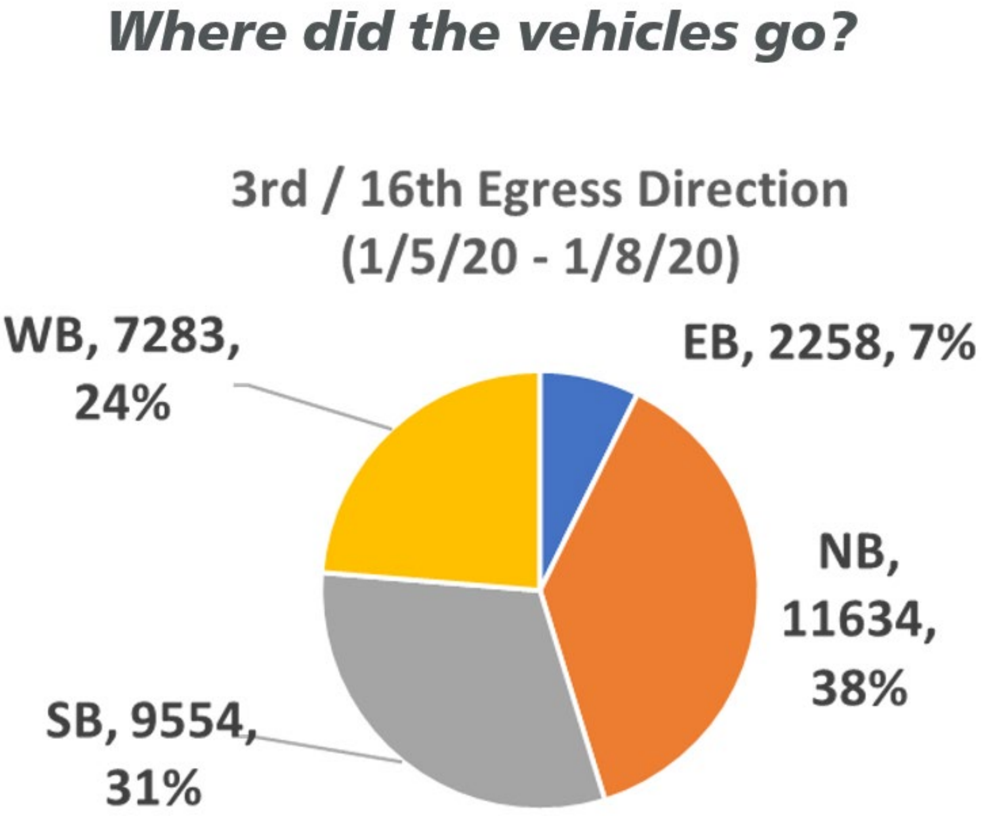


Figure B. Vehicle Egress Direction (1/5/20-1/8/20)

- Figure C shows the average speed of the observed vehicle in increments of 5 miles per hour (mph) e.g. 0-5 mph, 5-10 mph) as it passes through an intersection on one specific day (1/21/2020)

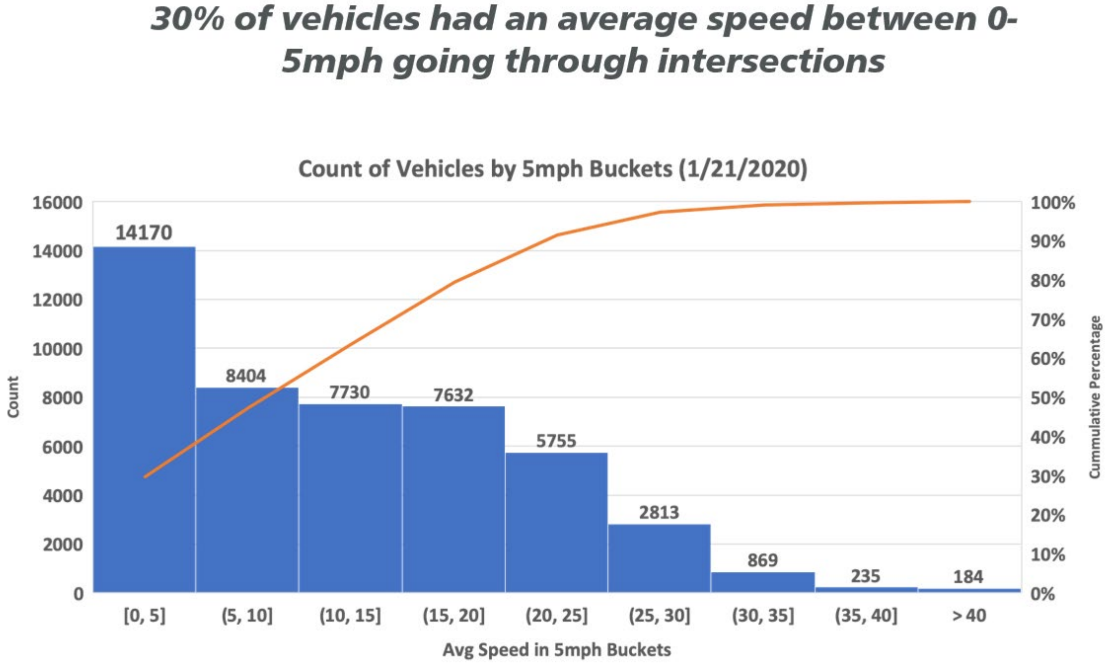

30% of vehicles had an average speed between 0-5mph going through intersections

Figure C. Average Vehicle Speed by 5 mile per hour buckets (1/21/20)

- Figure D classifies vehicles by type (passenger car, truck, other) during a 4-day period in January 2020

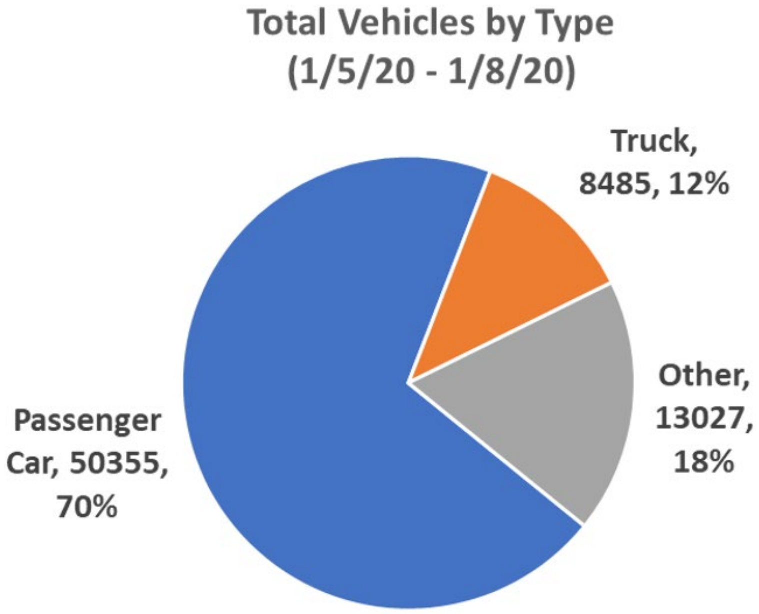


Figure D. Vehicle Classifications Type (1/5/20-1/8/20)

- We were not able to accomplish the visualization of the scenario to capture passengers going to and from the train platform at 3rd/16th due to limitations with the LiDAR sensors (reflected laser beams from platform glass panels rendered data to be inaccurate). Also, we found issues where counting pedestrians were more difficult when they were grouped together as the object detection would at times recognize a group of people as a single person.

The second use case to view Traffic Flow Obstructions can be observed in Figures E and F.

- Figure E provides an hourly count of the number of vehicles stopped within the intersection, which by law vehicles are not allowed to due to obstructions to flow (vehicles and pedestrians) in the perpendicular direction, on a specific day (1/21/2020)

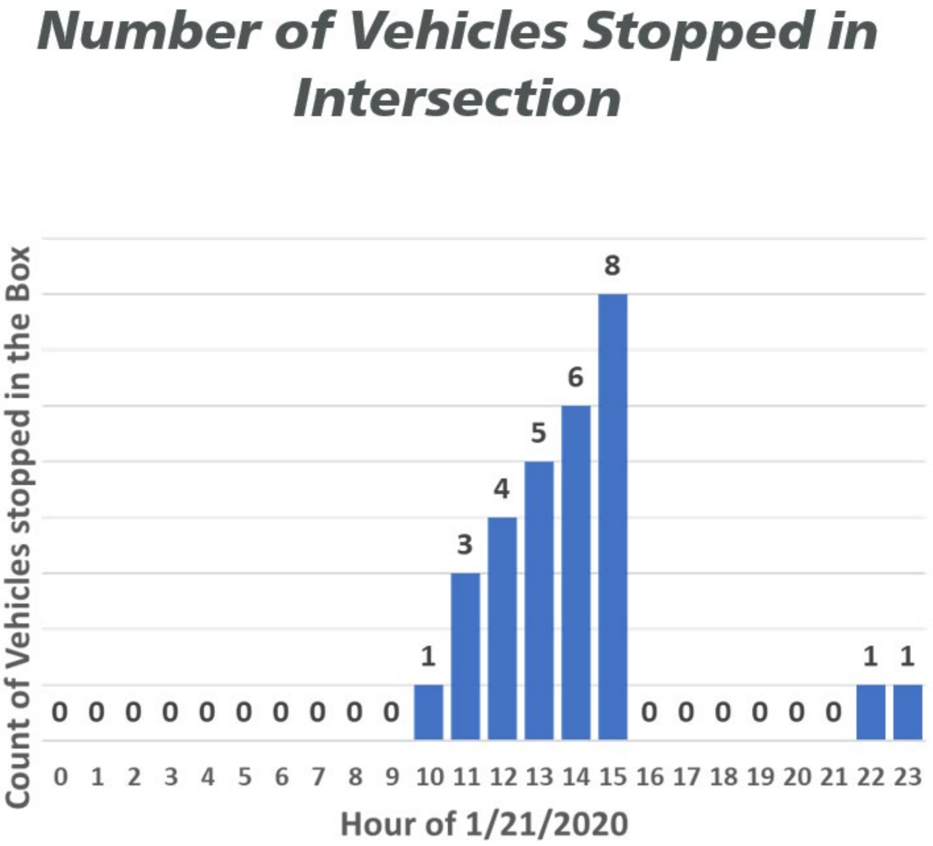
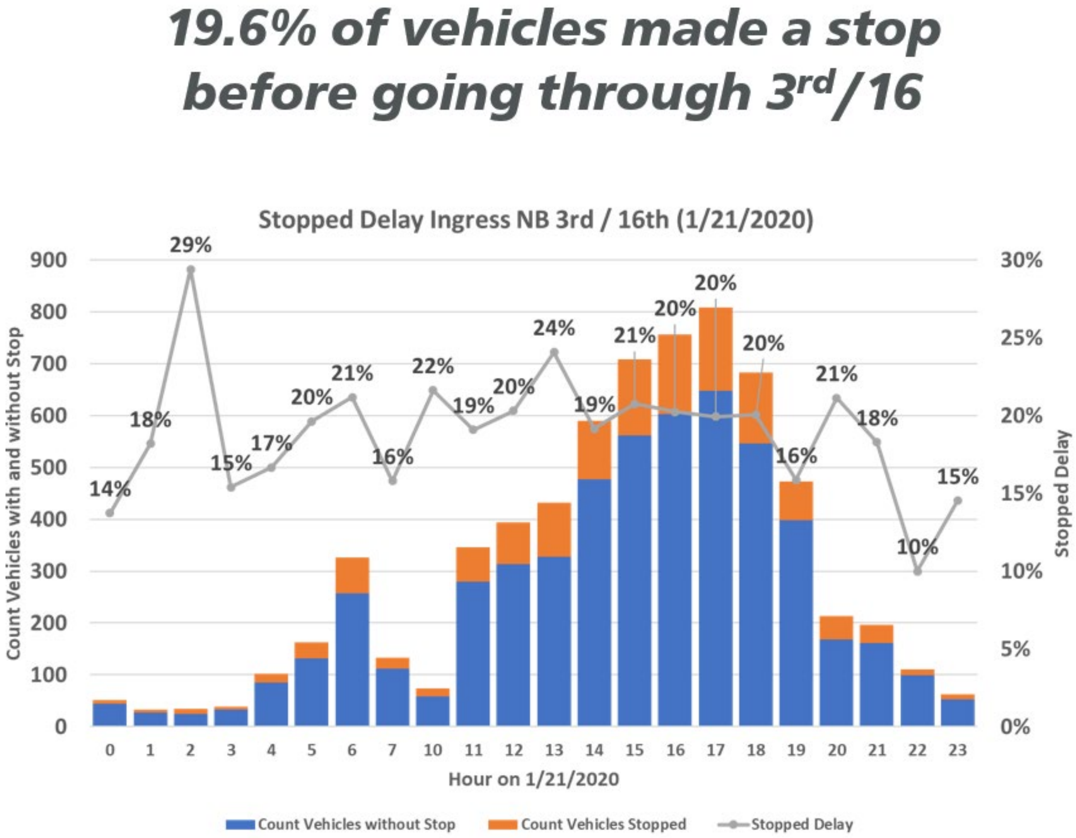


Figure E. Hourly Count of Vehicles Stopped in Intersection on 1/21/20

- Figure F shows the number of vehicles by hour that had to stop in the northbound direction before going through the intersection of 3rd and 16th Streets on a specific day (1/21/2020). This graph would provide information on whether signal timing coordination is optimized and/or whether queues form during specific times of the day because of an increase in the number of vehicles.



Graph F. Vehicle Count and Percentage of Vehicles that stopped prior to entering the intersection of 3rd Street @ 16th Street in the Northbound direction on 1/21/20

Phase 1 of the PoC proved that the project team could successfully read information generated from the sensors (object counts, speeds, orientation) with accuracy, providing tools for engineers and planners to passively adjust signal timing if warranted. While no direct adjustments were made immediately following the completion of Phase 1, potential adjustments include:

- Using vehicle count data to allocate an increased proportion of the signal timing to travel directions with more cumulative red-light delay
- Using a combination of vehicle turning movement counts and pedestrian crosswalk counts to determine if an introduction of a Leading Pedestrian Interval (LPI) would be appropriate given potential vehicle turning movement conflicts with pedestrians
- Using speed data (average, 85th percentile, max) to inform engineers to conduct speed tests via traditional methods (radar, tube) to verify if posted speed limits are appropriate

- Using “blocking the box” data, which counts the number of vehicles stopped in the intersection, to determine whether to deploy parking control officers to mitigate delays for opposing pedestrian and vehicle crossings

While receiving the above data during PoC Phase 1 is an upgrade over a situation where data did not exist, or would be difficult or labor intensive to obtain, there were still opportunities to make process improvements in a future phase of work (Phase 2) as outlined in Table 4.

Situation	Limitations	Phase 2 Change
PoC phase 1 data was released on a weekly basis via a spreadsheet provided by the Contractor.	• Data is outdated • Data is dependent on Contractor providing the spreadsheet • Data storage limitations using a spreadsheet	• Collect and display data in real time via online dashboards
Potential signal timing adjustments are based on passive data	• Data is outdated and may not be relevant due to special circumstances (e.g. special event, collisions, weather can impact traffic volumes)	• Signal timing adjustments to be made in real time based on observed conditions
DSRC dataset was small	• Less than 1% of vehicles on the road had the communication capability	• Drop DSRC component and collect all data through Phase 1’s LiDAR setup
No network connection to traffic signal controller	• Inability to pull state of traffic signal information (timestamped information on green light duration by traffic phase)	• Connect to traffic signal controller to pull second-by-second signal phasing data

Table 4. PoC Phase 1 Limitations and Improvements Sought in PoC Phase 2

Proof of Concept Phase 2

The initial planning work for Phase 2 of the PoC began upon the completion of Phase 1 in Spring 2020. Through the successful outcomes of Phase 1, the Project team was confident that they could achieve the desired outcomes as indicated in the ATCMTD grant proposal:

- Increase safety for all modes
- Improve public transit speeds/reduce travel time
- Reduce signal delays for all travelers
- Reduce idling and GHG Emissions

The key project activities in Phase 2 would be to (1) network 10 intersections and centralize traffic phase decision making and (2) understand in real time the position, speed, and size of every object. This was achieved without storing any personal data to comply with the City’s Surveillance Ordinance. Collected data is processed and analyzed in real time via edge computing with no storage of video or LiDAR streams.

The project location narrowed its focus to the 3rd Street Corridor in the Mission Bay neighborhood, carrying over some locations from PoC Phase 1, and shifting the mixture of devices from LiDAR and DSRC to exclusively LiDAR as shown in Table 5 and Figure G.

#	Intersection	Change from PoC Stage 1
1	3rd/Channel	DSRC component swapped with LiDAR solution
2	3rd/Mission Rock	New PoC Stage 2 intersection
3	3rd/Mission Bay	New PoC Stage 2 intersection
4	3rd/Warriors	DSRC component swapped with LiDAR solution
5	3rd/Campus	No Change
6	3rd/16th	No Change
7	3rd/Mariposa	New PoC Stage 2 intersection
8	3rd/18th	DSRC component swapped with LiDAR solution
9	3rd/19th	New PoC Stage 2 intersection
10	3rd/20th	New PoC Stage 2 intersection
Intersections Removed from PoC Phase 2		
A	4th/King	PoC Phase 1 DSRC location
B	7th/16th/Mississippi	PoC Phase 1 DSRC location
C	16th/Terry Francois	PoC Phase 1 DSRC location
D	Warriors/Terry Francois	PoC Phase 1 DSRC location

Table 5. PoC Phase 2 Locations

Figure G. PoC Phase 2 Locations

The 1-mile segment on 3rd Street, from Channel Street to 20th Street, was selected for the following reasons:

- **Highly visible location with multiple, large trip generators** – area is home to a major hospital, research and medical facilities, 2 sports venues.
- **Multi-modal traffic flow** – large presence of public transportation (light rail and bus), pedestrians, bicycles, passenger vehicles and trucks.
- **Construction** – changing roadway conditions with lane closures and re-routes from construction activity (housing and commercial).
- **Closed Corridor** – access points to the corridor were limited (e.g. few driveways) in that objects would be detected entering the geofenced area via Channel St to the North, 20th Street to the South and via the East-West crossings of 3rd Street.
- **Connected to SFMTA's Communication Network** – The entire 3rd Street corridor is connected to SFMTA's fiber network, providing 2-way communications with traffic signals, traffic cameras to support information processing via a cloud-based data center.

3rd Street has many positive attributes that would contribute to a successful Phase 2 implementation, but it is not without challenges. This corridor contains long coordinated traffic signal cycle lengths, closely spaced traffic signals, wide pedestrian crossings, and variable transit dwell times. 3rd Street serves as the primary north-south roadway through the Mission Bay corridor, with high-capacity bus and light rail transit lines carrying 32,000 passengers on a typical pre-COVID pandemic weekday. Staff have addressed the easy, low hanging fruit in terms of small fixes, but it was time to innovate and tackle the difficult challenges through a different approach and thinking.

The project team met with various groups within the agency (Livable Streets, Traffic Engineering, Transit, Curb Management, Taxis & Accessible Services, Vision Zero and Autonomous Vehicles) to understand specific data collection needs, use cases and to seek implementation opportunities as part of Phase 2. Through this outreach process one constant emerged from meeting each of the groups – the desire to improve safety through more data to allow for better decision making. Groups sought data to (1) understand potential issues or opportunities for improvement, (2) check adherence levels to existing regulations and (3) evaluate newly implemented projects to determine effectiveness of recent changes. Table 6 summarizes the links between desired outcomes, uses cases and success criteria.

Desired Outcome	Use Case	Value to Realize	Success Criteria
1. Increase safety for all modes	More insight to enable better decision making	• Traffic Patterns • Expected and realized impacts of projects • Adherence to regulation	Ability to analyze metrics
2. Reduce public transit travel time	Increase percentage of LRV arrivals on green light on 3rd St., between Channel and 20th St.	Better experience for transit riders and operators	Increase average LRV speed and reduce travel time variability in corridor
3. Reduce traffic signal delays	Reduce stoppage and red-light duration based on mode prioritization and rules	Reduce delay for all modes	Reduce red light arrival percentage and red-light duration of stops
4. Reduce idling and Greenhouse Gas (GHG) emissions	Derived from other outcomes	Derived from other values	Reduce idling and need for acceleration

Table 6. PoC Phase 2 Desired Outcomes, Uses Cases and Success Criteria

The desired outcome of optimizing traffic signal timing would also lead to reduced impacts on the environment. The existing conditions that lead to less-than-ideal signal timing conditions for public transit include:

- Static Traffic Signal Controller LRV (Light Rail Vehicle) Arrival Information – the signal controller receives fixed value travel time position updates when (1) a train departs the previous platform and (2) the train arrives at the near and far sides of the previous intersection. The travel time inputs are derived from staff observations for travel time and include static platform dwell for boarding and alighting that do not consider real time information, such as large numbers of people on board the train or on the platform. The travel times that are input into the traffic signal controller can differ from actual values, which can change depending on operator, weather conditions, and cross traffic volumes. The static dwell times can change by time of day, such as heavier boarding and alighting volumes during morning and evening peaks and during special events.
- Lack of timely Light Rail Vehicle (LRV) position and speed data – LRVs publish position information every 60 seconds but this information is not communicated to the traffic signal controller. LRVs also pass by fixed locations in the track, called VETAG controllers, which is the equipment used to provide traffic signal controllers with the fixed travel time information as indicated above.
- Lack of transit platform data (e.g. number of people waiting to board train) – More people on the platform would likely lead to longer LRV dwell times but since there is no ability to collect this information we must rely on observed fixed travel time inputs that represent the "average" or "typical" situation.

- Policy decisions and engineering judgment – the traffic signals along the corridor are fully actuated, a setting where the green light is provided when the vehicle and pedestrian detection systems detects an object. Typically, this setting would stay green for the main phase, 3rd Street, and then cycle to the side street green when a vehicle is detected or a pedestrian has pushed the pedestrian push button. There are situations where we provide green time to a side street even if there is no object on the side street, akin to fixed timing – intersections with high pedestrian volumes, or at areas near the potential vulnerable populations from schools and hospitals. These tradeoffs can impact LRV travel time as the chances of red-light delay will increase.
- Signal timing offsets are designed for peak directional flow – Typically offsets, which determine when an intersection's green light turns on relative to nearby signals, are prioritized for peak directional flow to and from the downtown core. In this case the peak directional flow would favor northbound traffic in the morning and southbound traffic in the evening. The prioritization trade-off results in opposing traffic, such as the morning southbound LRV, not receiving ideal traffic signal timing. Hours in between morning and evening peaks would typically have more balanced offsets for both directions.

With known issues identified, the project team sought to identify solutions through prioritizing 3 levels of inputs that would feed a dynamic signal timing software to determine the ideal signal timing allocation. There can be an overlap between the 3 input levels, but the priorities need to be determined so that the signal software can make the green light priority determination based on the project's team scoring. The inputs are also location dependent as the inputs in Table 7 are specific to the 3rd Street test corridor and a street with a different design may have different priorities, such as a bicycle corridor with no transit.

The 3 levels of prioritization used were:

- Road Network – Streets that intersect each other would be prioritized based on the usage type of each street. If a street with LRV presence intersects a street with a bus route, the LRV street would have the highest priority to receive the green light next.
- Modes – If two different modes of travel going in different directions arrive at the intersection at the same time, the mode with the highest priority would receive the green light next.
- Intersection– This category applies to the same direction of travel, such as all modes traveling northbound. A transit vehicle in a transit only lane would be prioritized over a passenger vehicle left turn lane traveling in the same direction.

The priority levels by input are summarized in Table 7.

	Road Network	**Modes**	**Intersection Level**
Priority Level	Highest Priority	↔	Lowest Priority
Highest Priority	LRV route	LRV	Transit Only Lane (TOL)
↕	Bus route	Bus	Pedestrian
	Freeway on and off ramp access	Pedestrian	Bike Lane
	Primary Street	Truck	Straight
Lowest Priority	Side Street	Passenger Vehicle	Left Turn
		Bicycle/Motorcycle/Scooter	

Table 7. Traffic Signal Timing Prioritization Levels

Contract

The PoC Phase 1 wrapped up activities in January 2020. Due to the short duration afforded by the grant window (initial grant expiration in February 2022) the agency went through the sole source route to maximize available time and to build upon success of the previous pilot with some of the same vendors. Arcadis was selected as the Prime Contractor and brought on sub-vendor TNL and retained Quanergy (LiDAR) from Phase 1. Environmental Review was completed in September 2020, with the project receiving both CEQA and NEPA exemptions. The contract went to the SFMTA Board on November 2, 2020, and the Notice to Proceed was issued on December 5, 2020.

Implementation

Project Management followed the Agile Methodology Framework, an iterative approach to deliver value faster by prioritizing needs and utilizing feedback to make improvements over several phases, known as sprints. The sprints focused on integrating the various signal infrastructure, existing with new, and displaying project outcomes via data dashboards.

- Sprint 1 - March 2021
    - Build dashboards to report metrics for turning vehicle counts, speeds, non-compliant turns, intersection blockage, LRV arrival on red percentage, LRV red light delay
- Sprint 2 - April 2021
    - Build dashboards to report metrics for LRV stop duration, pedestrian wait time, pedestrian crossing violations, red light violations, train platform usage
- Sprint 3 - May 2021
    - Build dashboards to report metrics for near misses, idling time by mode, GHG emissions
- Sprint 4 - June 2021
    - Build dashboards to report metrics for Heartbeats (launch page showing overall big picture of the corridor via key data points), stops breakdown by mode, LRV travel time

The project team overcame several challenges, primarily with the traffic signal controllers. SFMTA Signal Shop originally scheduled long planned traffic signal controller firmware upgrades to version 1.5L after the Connected Corridor Project (Phase 2). Phase 2 accelerated this timeline for the project corridor due to the need to receive and send commands to the controller, a feature not available without the firmware upgrade. Signal Shop staff performed extensive testing throughout the multiple months to ensure that the upgraded firmware would be stable (signals do not go into red flash mode) once deployed. Upgrading to firmware version 1.5L broke communication with existing traffic signal software on the AB3418 communication protocol however this was the necessary trade off to get Phase 2 up and running. The broken AB3418 communication link with these 10 intersections meant that we would not be able run commands to (1) automatically get information on communication errors or malfunctioning transit detector loops or (2) set predetermined timing plans for special events, such as events held at the basketball/baseball/concert venues. However, the move to firmware 1.5L opened an opportunity for the agency to investigate a next generation Central Management System (CMS) to restore (1) and (2), as the previous CMS that utilized the AB3418 protocol was reaching end of life support from its vendor and all current CMS solutions on the market rely on the newer communication protocol (NTCIP). The agency plans to upgrade to this new CMS solution in 2026.

Once the firmware updates were in place the project team was able to send commands (e.g. increase green time on a specific phase due to a detected transit vehicle, and/or skip a left turn phase) based on developed signal timing logic using the prioritization levels described above in Table 7. The logic was a points-based system to allocate which vehicle direction by vehicle type would be prioritized to get the green light next.

As shown in the Table 8, a *Priority Value* was developed for specific vehicle classifications by direction. The goal is to assign transit the highest value, 2400 in this case, to an LRV so that it would receive the highest prioritization. A vehicle on the main street (3rd Street) would have a higher priority value than a left turning vehicle from that same main street as a left turn would conflict with the center running transit lane.

Priority Value	**Classification**	**Street/Direction**
5.5	Car or small vehicle (motorcycle, bicycle, scooter)	Side Street Thru/LT/RT, Main Street LT
6	Car or small vehicle	Main Street Thru/RT
11	Pedestrian	Crossing Main Street
12	Pedestrian	Crossing Side Street
110	Bus/Truck	Side Street Thru/LT/RT, Main Street LT
120	Bus/Truck	Main Street Thru/RT
500	-	Starvation Thru
550	-	Starvation LT
2400	LRV	Main Street Thru

LT = Left Turn, RT = Right Turn, LRV = Light Rail Vehicle

Table 8. Priority Value Classifications

Using the above priority values in combination with the time that an object is waiting at the intersection (measured from the time that the object was detected via the intersection sensors) produced a *Cost*. The object with the highest *Cost* (Time Waiting*Priority Value) would then be prioritized to receive the signal timing next. The signal controller can skip or re-order phases, without violating any minimum signal clearances, to bring up the needed signal phase earlier.

Based on the initial field deployment a new function was introduced – starvation. Field observations saw that the LiDAR detection did not recognize or see objects with 100% accuracy and as a result a side street would not place an actuation call despite the presence of an object. LiDAR inaccuracies can arise from various factors, including direct sunlight or reflections from glass buildings that interfere with the sensor's ability to detect returned signals, as well as vibrations. The project corridor presents several challenges that may exacerbate these issues, such as the presence of numerous tall glass buildings and vibrations caused by train movements along the track. To mitigate potential detection failures, a starvation call was placed every 240 seconds, equivalent to two cycle lengths, ensuring the phase would be served even in the absence of detected objects. The 240 seconds assigned to the starvation call is customizable and can be changed with further observation/engineering judgment.

Equipment installation in the field was performed by SFMTA Signal Shop staff. Each intersection was verified that it could receive software commands with a traffic engineer and signal electrician present and with the software team reviewing remotely. The project team structured the field testing through a series of progressively longer durations of testing to ensure that any issues would be addressed immediately. Each test was staffed with multiple personnel spread across the 10 intersections to observe the system in operation as well as with remote personnel reviewing traffic camera footage in real time. In July 2021 the signal software was enabled for a series of progressively longer durations of 30 minutes, 1 hour, 2 hours and for 1 day at a time. Field personnel were not deployed continuously for the 1-day test.

An adjustment made through observations of the progressively longer durations of enabling the traffic software included implementing a maximum wait time for users on the side street (crossing the main 3rd Street corridor) to 4 minutes. There were two concerns that led to this decision - (1) prioritization calls for LRVs in both northbound and southbound directions could lead to excessive wait times for users on the side streets and (2) a risk that objects would not be detected by the sensors. For both scenarios, users may think that the traffic signal is not working correctly which could lead to potential red-light violations. Typically, a user on the side street would not need to wait for more than 2 minutes for the traffic signal to turn green, therefore the project team implemented a maximum wait time of 4 minutes. This change to implement a maximum wait time of 4 minutes would mean that the signal software would put an automatic call to activate the side street green light even if there was no object presence, mainly to alleviate concerns that the detection sensors were not working, which was a condition observed on several occasions. The tradeoff with this decision is that it would negatively impact signal timing efficiency as users on the main road may see increased odds of arriving at a red light. The project team felt it was important to establish a maximum wait time since a traveler who believes a signal is not functioning properly because their signal phase is not activated, may choose to disregard the signal, endangering themselves and/or others.

With no significant issues arising from the initial testing, the project team concluded the testing period and scheduled the longest operational period to occur for 1 week from August 2nd to 6th, 2021. However, the operational period was shortened to 3 days due to an August 4th incident where multiple northbound trains could not request traffic signal preemption calls at the intersection of 3rd and 16th Streets. We initially diagnosed the issue as a communication issue and upon further investigation there was no obvious fix, but we replaced a logic board in the controller. Based on promising initial data that showed a decrease in red light delay the project team decided to conclude the overall test on August 4th as we did not want to risk future communication issues at the specific cited intersection as well as at other locations.

Data Results and Analysis

The Connected Corridor Project Evaluation Plan identified several goals and performance measures to track the success towards these goals.

The data evaluation period was for a duration of 3 days before the traffic signal optimization software, known as Traffic Flow Engine (TFE), was turned on and a duration of 3 days after the software was turned on.

The "Before” period is made up of the 3 Mondays (6/28, 7/5 and 7/12) prior to signal software activation date of Monday 7/19/2021. The “After” period is the 3 days that the signal software was turned on – 7/19, 8/2 and 8/3, of which 2 days were on a Monday and the 3rd day landed on a Tuesday. For analysis purposes, it would have been more ideal for the 3rd day of operation to have been a Monday for consistency but observed traffic patterns and related counts were generally indifferent to the workweek day given the pandemic restrictions in place at the time. The original evaluation plan sought to analyze 1 week of data in each of the before and after scenarios, but adjustments were made in response to the August 4th, 2021, train communication incident where the period of testing concluded earlier than expected.

Table 9 summarizes the results.

Goal Area	Performance Measures - Quantitative and Qualitative (if multiple technologies apply, please note the different technologies)	Results
Improved Safety (e.g., reduced crashes)	1. Number of traffic collisions	Before: 0 Traffic Collisions After: 0 Traffic Collisions
	2. Number of pedestrian and bicycle injuries	Before: 0 Injuries After: 0 Injuries
	3. Muni collisions per 100,000 miles	Before: 0 Muni Collisions After: 0 Muni Collisions
	4. Average truck speed through corridors within pilot	Due to the setup of the object detection and data processing methods, the data for truck speed was lumped into the same category as buses and cannot be further separated into the individual truck category. The values below are averaged speeds for objects detected under the category of Trucks and Buses. Before: 14.0 mph After: 12.7 mph
Reduced Congestion/Improved mobility (e.g., travel time reliability)	1. Average transit (LRV) service speed/delay through corridors within pilot area	Before: 8.2 mph; 60.3 seconds of red-light delay After: 9.9 mph; 16.2 seconds of red-light delay
	2. Average emergency vehicle response time	The average emergency vehicle response metric was changed to a pass/fail test specific to signal controller detections of firehouse push button activations to preempt adjacent firehouse traffic signals. This new test passed but we were unable to collect data related to average emergency vehicle response time.
Improved System performance (including optimized multimodal system performance)	1. Average weekday bike counts	Due to the setup of the object detection and data processing methods, the number of bicycles were lumped into the same category as motorcycles and scooters and cannot be further separated into the individual bicycle category. The values below are averaged weekday counts for objects detected under the category of Motorcycles, Bicycles and Scooters. Before: 2016 After: 2277
Advance commitment to equity	1. Traffic related injuries in Communities of Concern	Before: 0 traffic related injuries After: 0 traffic related injuries

Table 9. PoC Phase 2 Performance Measures

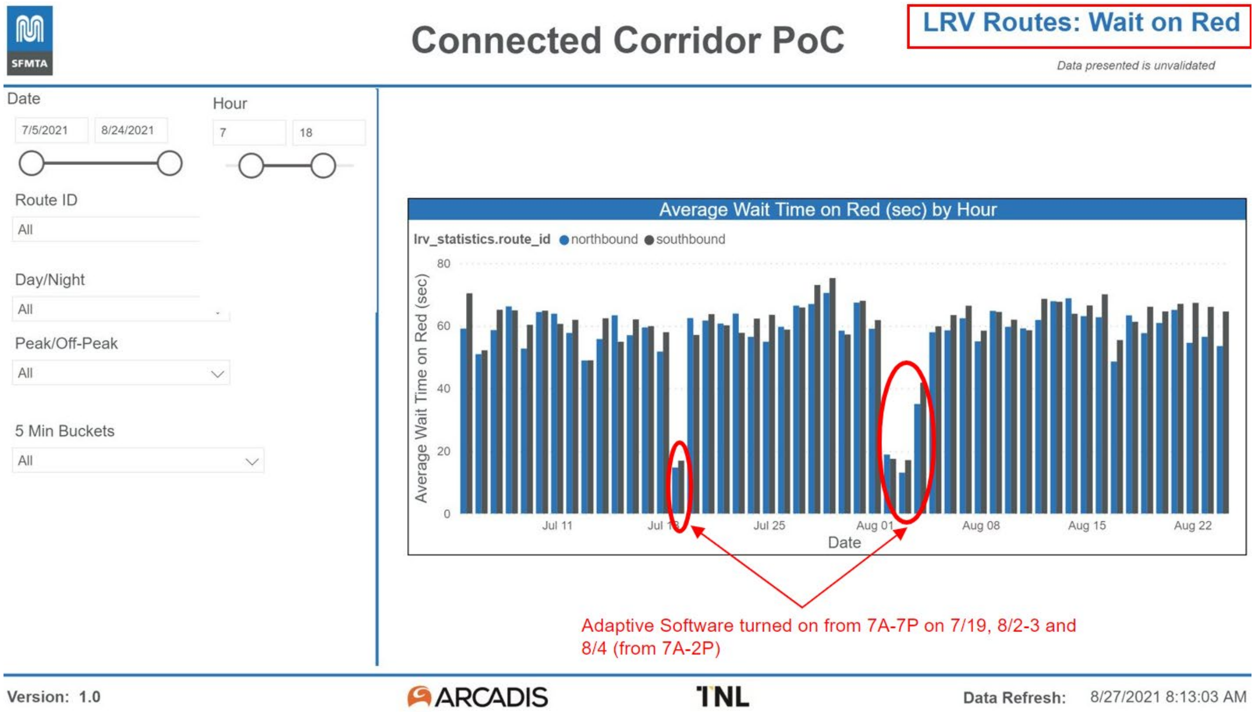
Safety metrics such as the number of collisions and injuries were zero in both the before and after scenarios, which may be a result of the limited evaluation period of 3 days. Collisions can occur due to multiple factors – driver behavior, weather conditions and roadway design. When a collision occurs, it can also be considered a random event and to truly evaluate whether a pattern in collision history exists would require an extended evaluation period.

However, the system performance metrics were based on hundreds of data points due to the large amount of transit and other vehicles that go through the corridor on a given day. The testing outcomes showed meaningful performance improvements to transit vehicles without significant negative impacts on vehicles and pedestrians.

Mode	Metric	Avg. Results
LRVs	Red Light Delay	73.2% reduced
	Travel Time	15.6% reduced
	Approach on Green	23.7% increased
	Average Speed	21.2% increased
Vehicles	Odds of Approach on Green	1.0% increased
Pedestrians	Odds of Approach on Do Not Walk	0.9% increased

Table 10. PoC Phase 2 Transit, Vehicle, Pedestrian Signal Timing Impacts

LRV travel times across the 10-intersection test corridor were reduced by an average of 66 seconds, from 424 seconds to 358 seconds. The average amount of LRV red-light delay decreased 44 seconds, from 60 seconds to 16 seconds. Figure H displays the Before and After data of the average red-light delay – July 19 and August 2-4 represent the After scenario in which the signal software was activated and have considerably lower average red-light delays.



Date
7/5/2021 8/24/2021

Hour
7 18

Route ID
All

Day/Night
All

Peak/Off-Peak
All

5 Min Buckets
All

Adaptive Software turned on from 7A-7P on 7/19, 8/2-3 and 8/4 (from 7A-2P)

Version: 1.0

Data Refresh: 8/27/2021 8:13:03 AM

Figure H. PoC Phase 2 LRV Wait Time on Red Lights by Day (July-Aug 2021)

Vehicle Impacts

There are times that improvements designed to benefit transit vehicles can come at the expense of negative impacts on pedestrians and vehicle flow. The project team analyzed the vehicle impacts through the metric of vehicle stop percentage by approach (Figure I and Table 11), which measures the likelihood of a vehicle coming to a stop as it approaches the traffic signal. In the Before scenario, the overall odds that a passenger vehicle had to stop was 24.5% which was similar to the After scenario odds of 25.7%. Breaking down the vehicle stop odds by approach direction resulted in a similar odds in the Before versus After scenarios. The transit phase are the northbound (NB) and southbound (SB) directions and are prioritized over the side streets of eastbound (EB) and westbound (WB) and would explain the reason for why a vehicle was less likely to stop in the NB and SB directions since the vehicle signals would follow the green light of the transit signals of the same approach direction.

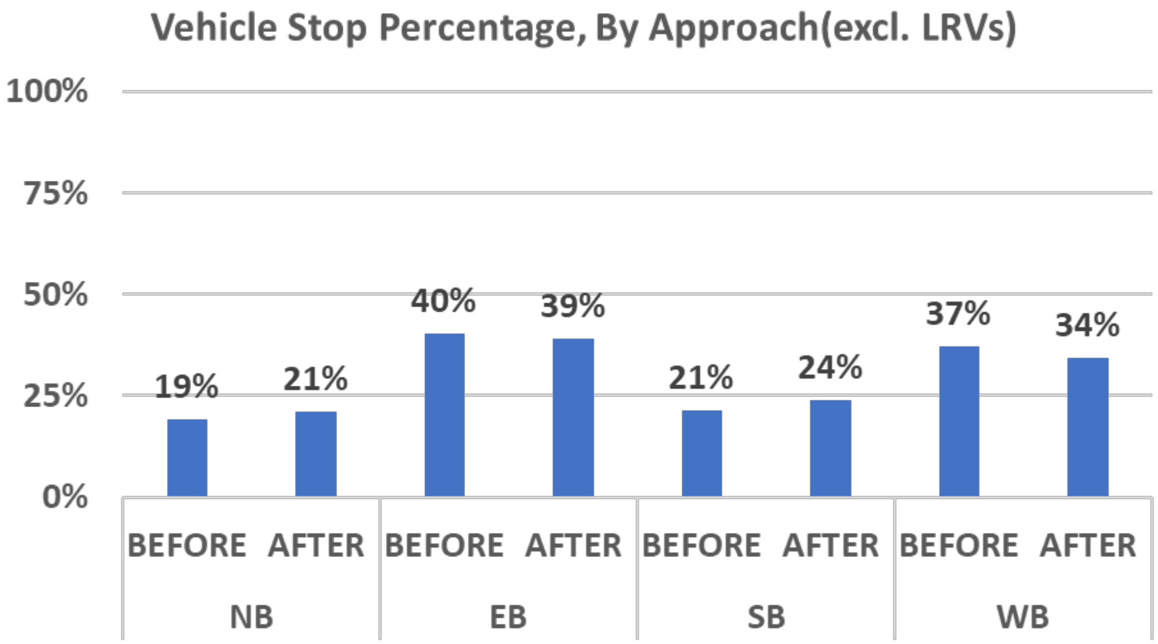


Figure I. Vehicle Stop Percentage by Approach, Comparing Before & After Scenarios

BEFORE					
Row Labels	**EB**	**NB**	**SB**	**WB**	**Grand Total**
No Stop	15169	65608	42120	10101	132998
Stop	10259	15541	11503	5982	43285
Grand Total	**25428**	**81149**	**53623**	**16083**	**176283**
AFTER					
Row Labels	**EB**	**NB**	**SB**	**WB**	**Grand Total**
No Stop	17277	72079	46366	12006	147728
Stop	10997	19322	14441	6234	50994
Grand Total	**28274**	**91401**	**60807**	**18240**	**198722**

Table 11. Vehicle Counts – Stopped vs No Stop, by Approach

Red Light Violations

With constant signal timing changes to extend or shorten green times by direction to respond to LRV presence, there could be a concern that vehicle red light violations can increase. The data shown in Figures J and K do not support an increase in red light violations as the violation percentage is similar in the before and after scenarios. The first chart shows violations (noted when a vehicle has crossed the geographic threshold of the pedestrian crosswalk) of all types, specifically through and right turning vehicle movement violations. However, since right turning vehicles can make a legal right turn after stopping at a red light, we wanted to filter out these movements through the second chart that isolates the red-light violations by only through movements. Future studies could potentially use the time stamped GPS data to determine if vehicles came to a complete stop at a red light prior to making the right turn.

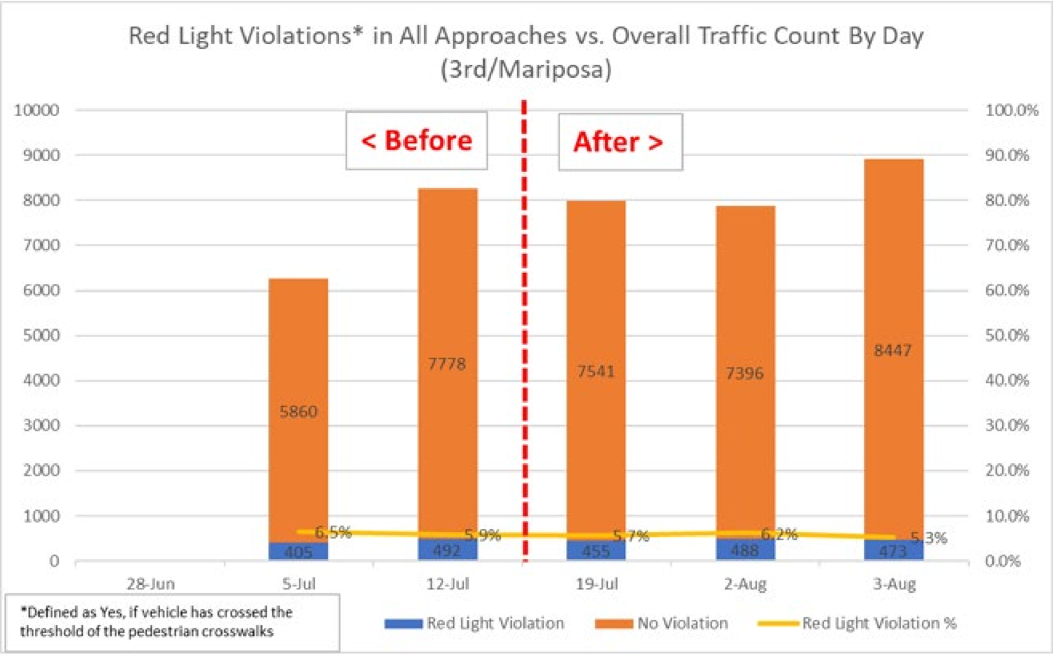


Figure J. Red-Light Violations in All Approaches vs Overall Traffic Count

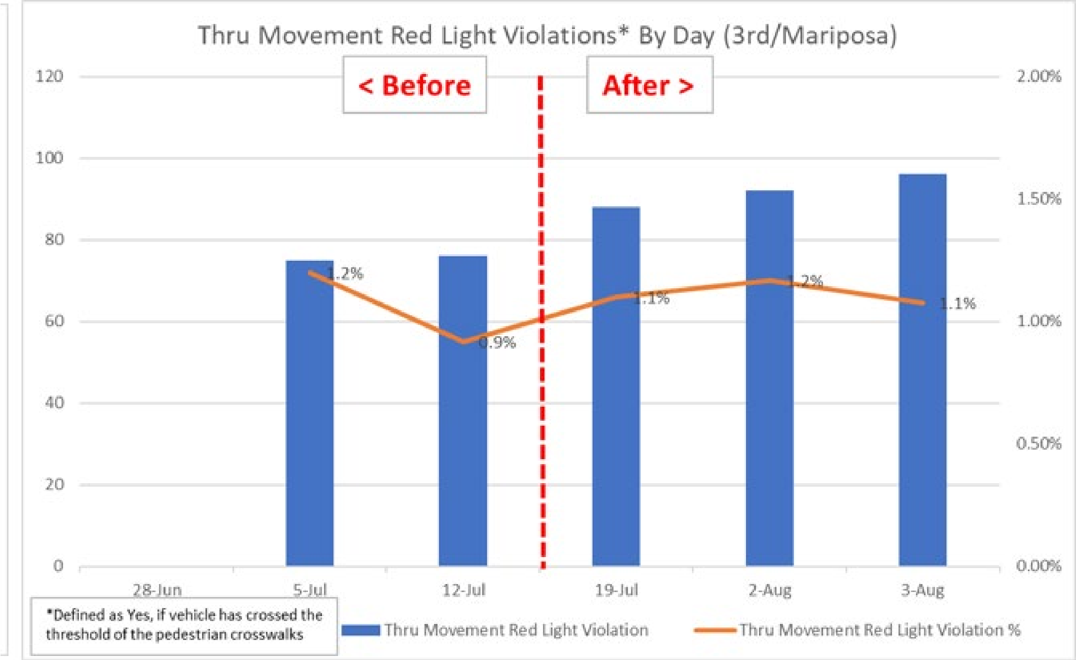


Figure K. Through Movement Only Red-Light Violations

Pedestrian Impacts

Pedestrians attempting to cross the street in the direction opposite the transit movement can often see increased wait times due to the prioritization of the transit street. There were some impacts in this category - the odds that a pedestrian did not have to wait at all went from about 70% in the Before scenario to about 50% in the After scenario. As shown in the cumulative frequency distribution graph, wait times would normalize around the 50-60 seconds wait time bucket, meaning there was no noticeable difference in waiting times for pedestrians beyond this time bucket in the two scenarios. Through this metric the project team would classify the overall impacts to pedestrians as non-significant.

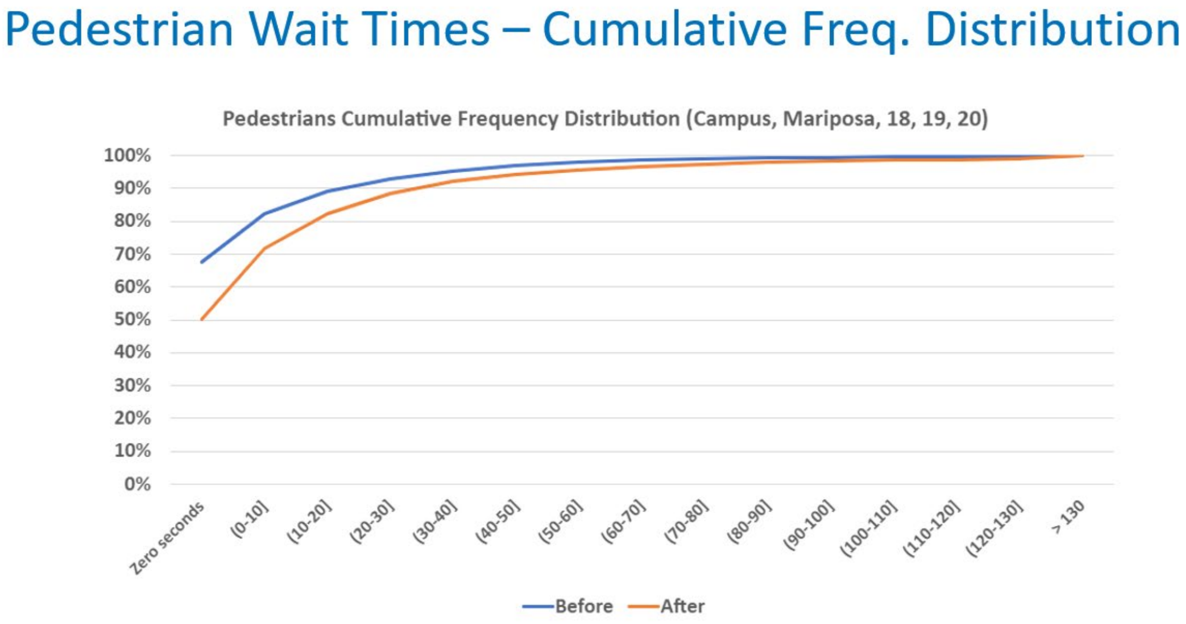


Figure L. Pedestrian Wait Time Cumulative Frequency Distribution

Near Misses

The project team sought to evaluate the accuracy of near miss collision events via the selected hardware and software configuration. Near misses are calculated via the projected path of each vehicle or pedestrian over the course of their next 5 seconds. A collision would be flagged if the paths of these 2 objects would intersect within a 1.5 second interval. The data generated by the LiDAR sensors was compared to analysis of video footage (4 hours) to determine accuracy and the results were that many false positives were generated – LiDAR flagged more near misses than actual near misses.

	Recorded Near Misses	**LiDAR False Positives**	**LiDAR False Negatives**
Video Reviewed Counts	3	N/A	2
LiDAR Produced Counts	34	33	N/A

Table 12. Comparison of Video Recording Near Misses vs LiDAR Identified Near Misses

Three near misses were observed in that 4-hour period via recorded video however the LiDAR produced a count of 34 recorded near misses. Thirty-three of the 34 Lidar produced near misses are false positives, which means it was incorrectly labeled as a near miss. The LiDAR produced counts failed to pick up 2 of the near misses that were observed through video, identified in the table above as a false negative.

The observed inaccuracy in classifying near misses is one of the drawbacks of using our designed LiDAR setup as a detection method. Compared to video observed counts there were variances from +3% to -53% in LiDAR vehicle counts at various intersections. LiDAR counts for the combined category of motorcycles, bicycles, and scooters had larger variances ranging from 0% to +493% at various intersections. Pedestrian counts observed via LiDAR had variances of +9% to -68% compared to video observed counts. The inaccuracy in classifying near misses is a notable drawback of using our designed LiDAR setup for detection.

The quality of the near-misses count output can be unreliable as it is determined by the quality of the vehicle, pedestrian and other vehicle count. There is room for improvement in this area as the project had to make multiple tweaks to sensor placement to achieve a balance of accurately identifying various object types. Sensor quality for both LiDAR and video will continue to improve, and the project team plans to incorporate these advancements in future work.

Benefit Cost Analysis

The multiple PoCs demonstrate that there is potential to provide measurable transit travel time savings. Travel time savings can reduce operational costs while maintaining comparable levels of service, such as maintaining service frequencies while also reducing the number of LRVs in service. SFMTA provided 562,303 light rail revenue service hours in 2023 per the Federal Transit Administration National Transit Database. A travel time reduction of 15%, as demonstrated by our PoC, would save up to 84,360 revenue service hours. SFMTA light rail vehicle operating expenses in 2023 were $383.56 per revenue service hour and saving 84,000 revenue service hours could lead to over $32 million in annual savings if the promising returns from the PoC can be sustained over the entire system for a year duration.

ATCMTD Project Goals

San Francisco's vision of the ATCMTD program sought to achieve 11 goals across the 4 different projects. The Connected Corridor Project was designed to address 10 of those goals. The goals and results from the Connected Corridor Project are presented in Table 12.

#	Goal
1	Environmental benefits from congestion management and streamlined traffic flow
	Outcome: Further study needed The Pilot increased a slight increase in vehicles approaching signalized traffic intersections on a green light therefore reducing emissions from idling by a slight amount. The project team would like to extend the pilot period to better assess whether the results of the optimized signal timing system can be sustained over time before drawing conclusions about impacts on environmental benefits.
2	Measurement and improvement of transportation networks operations
	Outcome: Success The pilot demonstrated that data can effectively capture the impacts of signal timing changes on transportation network operations generated by the optimization software.
3	Reduction of traffic crashes and increase in personal safety
	Outcome: Further study needed The traffic signal optimization software was turned on for a limited 3-day duration. While there were no crashes during this period, the project team would want a larger sample size to make any definite conclusions that traffic crashes were reduced as a result of using traffic signal optimization software.

#	Goal
4	Real time information to improve mobility, reduce congestion and provide for more efficient and accessible transportation
	Outcome: Further study needed The Project sought to disseminate real time information through two separate channels – via (1) DSRC to connected vehicles and (2) providing transit riders with more accurate real time arrival predictions by improving transit travel time reliability. Phase 1 of our Proof of Concept captured less than 1% of vehicles with DSRC equipped capabilities which led us to pivot to a different method to disseminate real time information to reach a larger market share and make a larger impact. The 2nd method sought to improve transit arrival predictions (broadcast through a 3rd party) through more reliable travel times. Using camera platform data, we trained a model to assign variable dwell time values based on the number of passengers present at the platform and detect whether a person in a wheelchair or strollers were present. The updated dwell times were factored into predicted arrival time for the train (sent to the downstream signal controller) at the next signal. With a large enough data set accumulated over time the 3rd party may adjust their bus stop-to-bus stop arrival predictions.
5	Access to safe, reliable, and affordable connections to employment, education, healthcare, freight facilities, and other services
	Outcome: Further study needed The project team would like to extend the pilot period to better assess whether the results of the optimized signal timing system can be sustained over a longer timeframe and larger area before drawing conclusions about its safety and reliability.
6	Monitoring transportation assets to improve infrastructure management, reduce maintenance costs, prioritize investment decisions, and ensure a state of good repair
	Outcome: Success Data collected from the Pilot allows the agency to monitor performance of all travel options at the intersection level and provides the tools needed to make informed decisions on signal timing adjustments to align with agency priorities.
7	Economic benefits from reduced delays, improved system performance, and throughput, and the efficient and reliable movement of people, goods and services
	Outcome: Further study needed. The project team would like to extend the pilot period to better assess whether the results of the optimized signal timing system can be sustained over a longer timeframe and larger area before drawing conclusions about impacts on economic health.
9	Advanced technologies integrated into transportation system management and operations
	Outcome: Success The pilot demonstrated successful integration of new technologies into existing traffic signal infrastructure and processes.

#	Goal
10	Demonstration, quantification, and evaluation of the impact of advanced technologies
	Outcome: Success The pilot was able to quantify various performance measures from the implementation of advanced technologies.
11	Reproducibility of successful systems and services for technology and knowledge transfer to other locations facing similar challenges
	Outcome: Success. The two project PoC phases successfully demonstrated that measurable improvements to transit reliability and traffic flow can be achieved and are scalable to corridor wide operations in future project phases. Through project documentation, the knowledge gained from the effort can be shared with others to learn and build upon.

Table 13. Connected Corridor Project Goal Outcomes

Lessons Learned and Future Studies

Technology evolves rapidly and future work that builds upon the existing foundation established by the two PoCs will be dependent on improvements in the technology space, such as detection sensor quality and capabilities, to achieve the desired outcomes of optimizing public transit and improving safety over a sustained longer duration. The selected LiDAR sensors required a mounted sensor on each of the 4 corners of a typical signalized intersection which required extensive labor to pull wire through conduits and ongoing site location visits to adjust sensor angles and mounts to improve roadway image quality. A key lesson learned from this deployment is that future installations would need to reduce maintenance commitments and maintenance needs should play a larger role in the decision making on how a product is selected for implementation.

LiDAR technology as it stands does not provide the level of accuracy needed to move away from video detection for the purpose of actuating a traffic phase. In our case we had LiDAR recorded traffic counts that were off by as much as 53%. The next generation sensors will also need to have improved abilities to distinguish individuals from groups as our PoC would at times count individuals that are closely spaced next to each other as 1 entity. From a maintenance and upkeep angle we would also like to reduce the number of sensors from 4 to 1-2 while also providing a larger field of view to reduce the equipment count needed to be serviced or adjusted. Furthermore the City & County of San Francisco maintains existing video detection sensors across the city and there is a preference to manage a streamlined set of devices, such as relying on video instead of LiDAR for future studies/deployments, to reduce the need for introducing additional products to troubleshoot, stock in the warehouse and on trucks where space is limited, and pay for extended product and customer support packages.

If we choose to select video as the preferred sensor technology given the discussed tradeoffs, additional scope to explore as part of the next PoC could include:

- Measuring "frustration levels" to see if there is a threshold time limit for pedestrians or vehicles to receive their green light as a tradeoff to further extend and hold greens for transit or other prioritized modes

    - As a subset of the above, study whether cars will more likely take right turns on red after queuing for an amount of time with the original intention of proceeding straight if they think the signal is not timed or working properly
- Further explore integration of more accurate dwell time predictions at platforms based on the present rider population types to feed information to signal controller on how to best prioritize signal timing

While adding scope can be useful and merits further study, the main goal for any future deployment should focus on improving overall safety and optimizing transit efficiency.

Next Steps

The Proof of Concept delivered very promising results primarily through reduced travel times and red-light delays to light rail vehicles without causing significant impacts to other parties. The project team will seek other funding opportunities to build upon the PoC and determine whether the benefits of a dynamic traffic signal optimization system can be sustained over an extended period and over a longer corridor through a separate follow up pilot project.