INNOVATE 680
IMAGINE THE POSSIBILITIES

I-680 ADVANCED TECHNOLOGY PROJECT
COORDINATED ADAPTIVE RAMP METERING (CARM)

DRAFT Concept of Operations (Con Ops)

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1 Introduction

1.1 Program Overview

The Contra Costa Transportation Authority (CCTA), in cooperation with the California Department of Transportation (Caltrans) District 4, and the Federal Highway Administration (FHWA) proposes to address congestion on Interstate 680 (I-680) through the deployment of the Innovate 680 Advanced Technologies (AT) Coordinated Adaptive Ramp Metering (CARM) Project. The Innovate 680 AT CARM Project is intended to replicate the CARM strategy integral to the Australian Managed Motorways concept (also known as managed freeways or smart freeways) to control traffic flows and alleviate recurrent chronic congestion. The primary goal of the project is to provide more efficient, productive, and reliable freeway traffic flows through the project corridor using advanced transportation management technologies and Intelligent Transportation System (ITS) devices, without the expense and disruption of constructing additional roadway capacity.

The first phase of the AT CARM Project (Segment 1) will occur on northbound I-680 in Contra Costa County, between Alcosta Blvd and Olympic Blvd. This segment was selected as part of a CARM feasibility study, and I-680 corridor evaluation described later in this section.

First developed and deployed successfully in Australia by the Victoria Department of Transportation (VicDOT), the Australian Managed Motorways strategy operates a range of ITS installations as a comprehensive, coordinated network to manage traffic flows on a proactive basis. A foundational element of the Australian Managed Motorways approach is the utilization of a CARM strategy featuring a comprehensive advanced traffic management system running a suite of algorithms to balance the demand for freeway access from ramps throughout the entire corridor on a dynamic, real-time basis. This approach enables the system to manage and optimize freeway traffic flows while also balancing ramp queues and wait times, distinguishing the Australian CARM concept from other coordinated ramp metering and integrated corridor management (ICM) strategies.

The success of the implementation in Victoria has led to subsequent Smart Freeway deployments with various other state road agencies in Australia including the Queensland Department of Transport and Main Roads and Main Roads Western Australia. The CARM concept was also successfully piloted in the U.S. by the Colorado Department of Transportation (CDOT) on the I-25 corridor in Denver, Colorado.

The complexity of the proposed CARM system requires a robust deployment of advanced traffic detection, available ramp storage and discharge capacity, and other ITS devices to fully understand and control for real-time traffic conditions. This Concept of Operations (ConOps) will detail the desired vision for the Innovate 680 AT CARM Project, as well as articulate the proposed ITS technologies and locations, configuration of the freeway management system, and operational practices.

At the time of this writing, Caltrans has initiated a State Highway Operation and Protection Program (SHOPP) project (EA 04-1Q720) proposing ramp metering installations at multiple service interchanges along I-680 in Contra Costa County, as well as adjacent freeway segments in Alameda and Solano Counties. The Caltrans SHOPP Fiber/Traffic Operations System (TOS)/Ramp Metering project proposes to install a fiber-optic cable communication trunk line, upgrade the traffic-operations system, install ramp metering equipment, and widen selected ramps to provide high occupancy vehicle (HOV) preferential lanes along I-680 in Contra Costa County. It is currently expected that the Innovate 680 AT CARM Project improvements would be additive to the Caltrans SHOPP Fiber/TOS/Ramp Metering Project. As such, the Innovate 680 team has been and will continue to coordinate closely with Caltrans staff on project design, requirements, and system operation.

The sequencing and activation of AT CARM and SHOPP ramp metering deployments along I-680 will need to be carefully managed and sequenced to avoid any issues with public and stakeholder acceptance. Specifically, CCTA has worked extensively with local jurisdictions along the I-680 corridor to explain the unique operational characteristics of AT CARM to build support for deployment of the system and to appease preconceived concerns regarding ramp metering operations within the I-680 corridor. Consistent with these outreach efforts and the expectations of local jurisdictions, it is critical that the AT CARM operational strategy is integral to any ramp metering deployment in the Segment 1 AT CARM corridor along northbound I-680 from Alcosta Blvd to Olympic Blvd, in order to minimize public and stakeholder acceptance challenges and to avoid a drastic shift in community expectations and driver experience.

It should also be noted that CCTA intends to implement advanced technology, including CARM, as one of the multiple components of its larger Innovate 680 program. The Innovate 680 Program will include CARM, in addition to the I-680 Express Lanes Completion and Part-time Transit Lanes/Transit Bus on Shoulder (TBOS) projects, and the Coordinated Adaptive Traffic Signals (CATS) project involving adjacent arterial traffic signals. As such, AT CARM Project development will occur concurrently to these related efforts, and project teams will coordinate on overall system design, integration, and deployment.

As described throughout this document, the Innovate 680 AT CARM Project will be delivered through a phased implementation throughout the Contra Costa I-680 corridor. The initial phase of AT CARM deployment (Segment 1) will occur on northbound I-680 in Contra Costa County, between and including Alcosta Blvd and Olympic Blvd. The Segment 1 AT CARM Project represents an initial deployment of CARM on I-680, that will be evaluated after two years of operations to determine the efficacy of this concept and suitability for permanent deployment. The evaluation is expected to include before and after comparison of a range of performance measures, as well as possible comparison to the performance of Caltrans traditional ramp metering deployed along other corridors in the Bay Area region, subject to data availability.

It should be noted that successful CARM operations requires a comprehensive freeway management system for managing the various components of system operations, as well as an advanced suite of ramp metering algorithms capable of responding to real-time traffic conditions to simultaneously manage both freeway mainline and ramp conditions on a corridor-wide basis. The STREAMS® platform developed by Transmax is currently the only commercial system capable of meeting the needs of the CARM concept, and authorized to use the ALINEA and HERO suite of algorithms. As such, the Transmax STREAMS® freeway management platform has been selected for the Innovate 680 AT CARM Project. At the time of this writing, CCTA is coordinating with Caltrans to execute a Public Interest Finding (PIF) for the use of STREAMS® for the initial Segment 1 AT CARM deployment on I-680.

Project delivery of Innovate 680 AT CARM Project can be divided into multiple stages over the life of the project. These are summarized below:

- **Feasibility:** The *I-680 Advanced Technology Project Coordinated Adaptive Ramp Metering – Corridor Evaluation* was conducted from 2020-2022. This effort evaluated the feasibility of applying the CARM concept in Contra Costa County, and the I-680 corridor was confirmed as a viable CARM corridor as part of that process. In addition, the viability of existing corridor ramp configurations and ITS devices were evaluated for CARM, and initial recommendations were made on ramp improvements and technology. This evaluation also identified northbound I-680 between Alcosta Blvd and Olympic Blvd as the most viable segment for the first phase of AT CARM deployment (AT CARM Segment 1). This segment was selected due to presence of isolated peak-period bottlenecks, corridor geometry, and available right-of-way (ROW). The Segment 1 AT CARM Project could also be funded based on committed sources and delivered concurrently with the Caltrans SHOPP Fiber/TOS/Ramp Metering project.

- **Programming Document:** A Project Study Report (PSR) for the AT CARM Project was completed in 2021. The PSR document described I-680 corridor conditions, purpose and need, and proposed AT CARM Project elements, development process, and funding and schedule assumptions at a high level. The PSR includes a request for programming within the State Transportation Improvement Program (STIP).

- **Project Approvals:** The project approval phase of the Segment 1 AT CARM Project is currently underway and involves the analysis and documentation necessary for approval of the Project prior to final design. Project approvals will adhere to the Caltrans Project Development Process (PDP) and will incorporate preliminary design and cost estimates presented in a Project Report, and documentation to support environmental clearance. A Categorical Exclusion/Categorical Exemption (CE/CE) with associated technical studies is the anticipated level of environmental document due to the minor anticipated construction impacts within state-owned right-of-way (ROW). The previously completed Systems Engineering Management Plan (SEMP) and this ConOps also falls within the project approval phase as part of the early systems engineering process.

- **Final Design:** The preparation of Plans, Specifications, and Estimates (PS&E) will commence at the conclusion of the Project Approval Phase. This phase will include the preparation of final design sheets and specifications for both civil ramp improvements, and the installation of ITS devices. This phase will also involve the preparation of a Requirements Traceability Matrix, that will link user needs, ConOps elements and system requirements as part of the systems engineering process.

- **Construction & Installation:** The construction phase follows the completion of the design phases and includes physical modifications to selected entrance ramps, installation of new vehicle detectors, and installation and/or configuration of ITS cabinets, signals and signage. These construction improvements are considered prerequisites to the deployment of the CARM concept. At the time of this writing, it is assumed that construction and installation of the Phase 1 CARM segment will be delivered as an integrated part of the Caltrans SHOPP Fiber/TOS/Ramp Metering project planned for the I-680 corridor.

- **Integration & Testing:** The integration and testing phase of project development will occur in the later stages of construction during the ITS device commissioning process. As part of this phase, individual devices and communications infrastructure will be tested and commissioned following acceptance testing. This phase will also involve the set-up, configuration and testing of the STREAMS® operating environment for CARM operations.

- **Operations:** This phase will involve the day-to-day operations of the Innovate 680 AT CARM Project within the Segment 1 CARM limits. Operations of CARM will be managed through the STREAMS® platform and supplemented by CCTV and field observations. Prior to the commencement of STREAMS® CARM operations, at least 12 weeks of existing traffic conditions data will be collected using the newly installed detection devices to serve as a baseline to support tuning and calibration of the system as well as subsequent performance evaluations. Ongoing system tuning and performance monitoring will occur with the commencement of STREAMS® operations. The AT CARM system is proposed to be the first ramp metering system to operate along the I-680 corridor within Contra Costa County to manage public and stakeholder expectations and driver experience, as CARM will operate substantially different than standard Caltrans ramp metering.

- **Maintenance:** This phase will occur in perpetuity and will ensure that the ATMS and individual ITS devices installed for the Segment 1 AT CARM Project remain operational. During CARM operations, the STREAMS® software will be maintained by Transmax as part of their normal product hosting and support. ITS devices, including vehicle detectors, field processors and ramp signals, will be maintained by a dedicated ITS Maintenance Contractor through a performance-based maintenance contract.

- **Evaluation:** Regular performance monitoring and reporting will be conducted during operations of the Segment 1 CARM project (as well as subsequently deployed segments). At the conclusion of the first three months of operations, a preliminary assessment memorandum will be completed summarizing the performance of the Innovate 680 AT CARM Segment 1 Project and comparing conditions in the I-680 corridor before and after the activation of the system. The assessment memorandum will be updated on an annual basis to document and compare conditions in the I-680 corridor within Contra Costa County before and after activation. After two years of operation, the performance evaluation will be expanded to compare the level of traffic improvement along the Segment 1 CARM project corridor to the performance of Caltrans traditional ramp metering deployed along other corridors in the Bay Area region, subject to data availability.

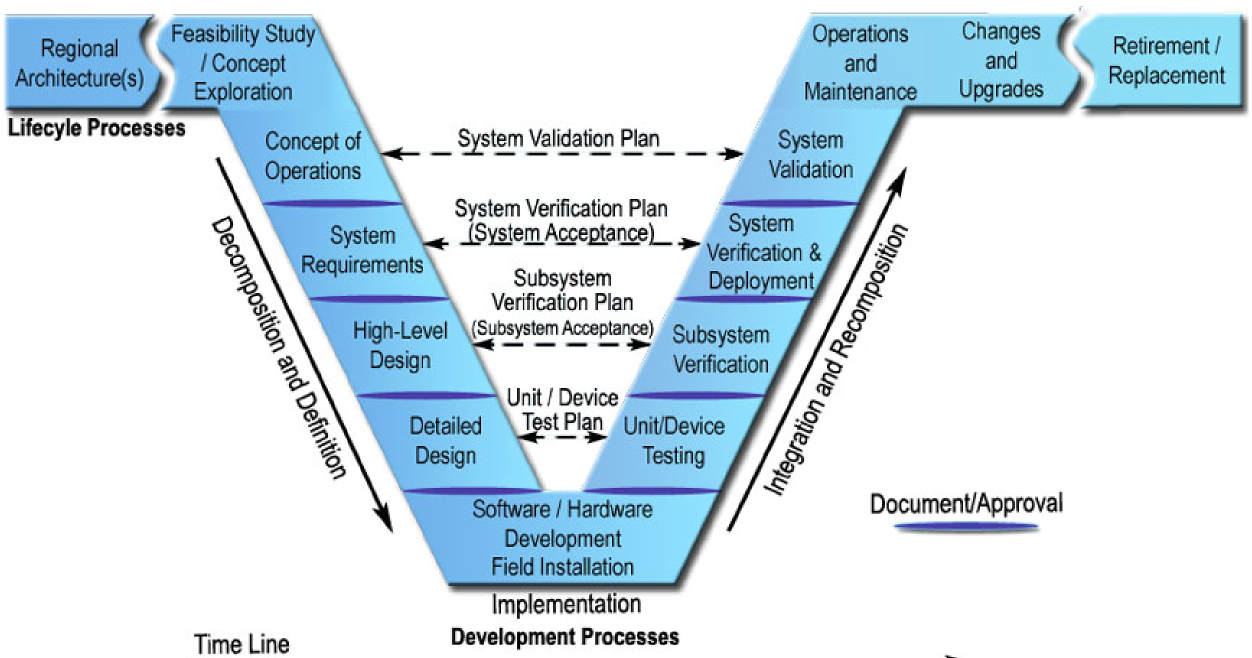
- **Potential Expansion:** Based on the results of Segment 1 AT CARM operations, and the availability of project funding, CARM is anticipated to be expanded to other segments of I-680. CCTA intends to deploy CARM incrementally, using a systematic approach focused on the identification of recurrent bottlenecks and the complexity and cost of installing the required improvements, with the eventual goal of CARM operations on all of I-680 (and potentially other freeway corridors) within Contra Costa County.

1.2 Systems Engineering Process

This ConOps is a formal document within the Systems Engineering Analysis (SEA) process, whereby the system lifecycle from planning and deployment through management and operations is documented. The ConOps provides the initial documentation towards providing system requirements used to design the system that can be traced to documented stakeholder needs, goals and objectives.

The ConOps is identified within the Systems Engineering "V" diagram (Figure 1-1), and typically follows the successful feasibility study and concept exploration stages. Given the specific function and progress to date on the Segment 1 AT CARM Project, this ConOps has been developed concurrent with preliminary design and project approval activities.

Figure 1-1 Systems Engineering V Diagram



Source: Federal Highway Administration, 2007.

The purpose of this document is to describe how the Innovate 680 AT CARM Project will operate from a user perspective and to set the framework for the design and operational characteristics of the system. The functions of the ConOps include:

- Establishing the rationale for the deployment of CARM following the Australian Managed Motorways or Smart Freeways approach;
- Identifying the goals, objectives, and measures of effectiveness for the system;

- Providing operational scenarios which illustrate the function of the system; and
- Articulating the expectations of stakeholders.

The ConOps focuses broadly on benefits that can be obtained from the deployment of CARM. The document defines CCTA and Caltrans' vision of how the system will work and informs the design of the technology, such as vehicle detection devices, signalization and operations improvements, and other technical requirements that are used to design, develop and deliver the system.

As an early document as part of the SEA, this ConOps is not intended to specify detailed design requirements, nor unique considerations for each point of interaction with the system. Subsequent efforts include the description of system requirements and initiation of a traceability process to ensure the deployed system is linked to the concept as described here.

1.3 Organization of Document

The subsequent sections of the ConOps are organized as below:

- **Section 2: Definitions & References** - This section provides an overview of commonly used acronyms, terminology and reference documents that were used to develop the ConOps.
- **Section 3**: **Project Scope** - This includes a description of the project and corridor, goals and objectives, and a list of agencies engaged in the development and operation of the system.
- **Section 4: Existing Conditions** - This section identifies the existing traffic, safety and infrastructure conditions within the project corridor.
- **Section 5: User Needs** - This section identifies key user needs that govern the development of the Segment 1 AT CARM Project and will eventually serve as the basis for system requirements.
- **Section 6: Justification for CARM Program** - This section describes the current conditions and factors warranting the implementation of the Segment 1 AT CARM Project and provides an overview of the desired changes offered by the proposed program, relative to the existing condition.
- **Section 7: CARM Concept & System Description** - This section provides a high-level operational description of the Innovate 680 AT CARM system proposed for the I-680 corridor.
- **Section 8: Operational Scenarios** - This section describes how the AT CARM system would operate under various operational scenarios, providing a general understanding of roles for all stakeholders.
- **Section 9: Summary of Anticipated Impacts** - This section summarizes the potential impacts of the Segment 1 AT CARM Project, including anticipated changes to operations, traffic benefits and the metrics that will be used to measures these impacts.

2 Definitions & References

2.1 Commonly Used Acronyms, Abbreviations, & Terminology

- **AHS** – ALINEA & HERO suite of algorithms
- **ATM** – Active Traffic Management
- **ATMS** – Advanced Traffic Management System
- **CARM** – Coordinated and Adaptive Ramp Metering
- **CCTA** – Contra Costa Transportation Authority
- **CCTV** – Closed-Circuit Television
- **CDOT** – Colorado Department of Transportation
- **CE** – Categorical Exclusion
- **CHP** – California Highway Patrol
- **ConOps** – Concept of Operations
- **Caltrans** – California Department of Transportation
- **FHWA** – Federal Highway Administration
- **HCM** – Highway Capacity Manual
- **ICM** – Integrated Corridor Management
- **ITS** – Intelligent Transportation Systems
- **LOS** – Level of Service
- **LUMS** – Lane Use Management System
- **MOE** – Measure of Effectiveness
- **MPO** – Metropolitan Planning Organization
- **MTC** - Metropolitan Transportation Commission
- **MUTCD** – Manual on Uniform Traffic Control Devices
- **NCHRP** – National Cooperative Highway Research Program
- **PeMS** – Performance Monitoring System
- **ROW** – Right-of-Way
- **SEA** – Systems Engineering Analysis
- **SEMP** – Systems Engineering Management Plan
- **STREAMS®** – STREAMS® is a comprehensive freeway management system for managing various components of traffic services and operations. STREAMS® is currently the only commercial system authorized to use the ALINEA and HERO suite of algorithms.
- **TCD** – Traffic Control Device
- **TMC** – Transportation Management Center

- **TSMO** – Transportation System Management & Operations
- **TRANSMAX** – TRANSMAX is the system implementor of the STREAMS® freeway management system and is a wholly-owned public enterprise of the State of Queensland, Australia.
- **USDOT** – United States Department of Transportation
- **VicDOT** – Victoria Department of Transportation. VicDOT is the designer, implementer and operator of the Australian Managed Motorways concept in Melbourne.
- **VDS** – Vehicle Detection System

2.2 References

2.2.1 Intelligent Transportation Systems Reference Documentation

- *Intelligent Transportation System Architecture and Standards – Final Rule*, 23 CFR Parts 655 and 940, Federal Register, Vol. 66, No. 5, January 2011.
- *ITS 2015-2019 Strategic Plan*, Joint Program Office, FHWA-JPO-14-145, U.S. Department of Transportation, December 2014.
- *Systems Engineering for Intelligent Transportation Systems: An Introduction for Transportation Professionals*, Federal Highway Administration, FHWA-HOP-07-069, U.S. Department of Transportation, January 2007.
- *Systems Engineering Guidebook for Intelligent Transportation Systems, Version 3.0.*, Federal Highway Administration, U.S. Department of Transportation, November 2009.

2.2.2 Caltrans Reference Documentation

- *Ramp Metering Design Manual*, California Department of Transportation Division of Traffic Operations, October 2022.

2.2.3 Australian Managed Motorways Reference Documentation

- *STREAMS ITS Platform Product Description*, Transmax, November 2014.
- *STREAMS Managed Motorways Product Description*, Transmax, February 2016.
- *Managed Motorway Design Guide Volume 2: Design Practice, VicRoads, Oct 2019.*
- *TCS 048 2018 Specification for the Supply of Freeway Data Stations, VicRoads, Dec 2018.*
- Vincent Vong and John Gaffney, *Monash-Citylink-West Gate Upgrade Project: Implementing Traffic Management Tools to Mitigate Freeway Congestion*, VicRoads, 2012.

3 Project Scope

3.1 Project Overview

I-680 is a major interstate highway facility within Contra Costa County carrying interstate, interregional, and intraregional traffic. This area is projected to experience substantial growth for goods movement and passenger vehicle traffic. I-680 is one of the major north-south corridors in Contra Costa County and is listed by the Metropolitan Transportation Commission (MTC) as one of the ten most congested freeways in the San Francisco Bay Area. The corridor experiences significant delays and unstable flow of traffic in both directions, and these delays are expected to continue in the foreseeable future.

Severe recurrent congestion is present along I-680 during typical weekdays, and saturated stop-and-go conditions can be experienced in both southbound and northbound directions. The Innovate 680 AT CARM Project seeks to demonstrate the effectiveness of the Australian CARM concept to control traffic flows, alleviate recurrent chronic congestion, and improve travel time and reliability along the I-680 corridor in Contra Costa County.

3.2 Smart Freeways Context

The Innovate 680 AT CARM Project will deploy a CARM system following the approach that is a fundamental component of the Australian Managed Motorways concept on the I-680 corridor in Contra Costa County. Segment 1 of the AT CARM Project will occur on northbound I-680 in between Alcosta Blvd and Olympic Blvd, south of SR-24. The Segment 1 AT CARM Project will also feature the installation of enhanced vehicle detection systems (VDS) along the I-680 mainline and ramps.

Smart Freeways CARM system, referred to as Managed Motorways in Australia, was first pioneered by VicDOT on the M1 Motorway in Melbourne, Victoria. The initial implementation of Smart Freeways on the M1 resulted in a significant reduction in recurring congestion during peak-periods. A before and after evaluation of the initial M1 trial[1] showed that peak-period flows increased between 5% (AM peak) and 8% (PM peak). Furthermore, traffic speeds improved between 35% and 59% during peak-periods, while overall reliability, as measured by the variability in traffic speeds during the peak period, improved between 149% during the AM peak-period and over 500% during the PM peak-period.

Results from the recently completed Smart 25 Pilot Project conducted by the Colorado Department of Transportation on northbound I-25 south of downtown Denver demonstrated similar benefits on the first U.S. deployment of the CARM following the VicDOT approach. PM peak-period travel times were reduced by 14% over the base conditions, while PM peak-period reliability was improved by over 20%. Furthermore, total delay in the corridor was reduced by almost 50% during the PM peak-period and over 40% for the full day.

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[1] Vincent Vong and John Gaffney, *Monash-Citylink-West Gate Upgrade Project: Implementing Traffic Management Tools to Mitigate Freeway Congestion*, VicRoads, 2012.

The performance of Australian Smart Freeways is determined primarily by the ability of the CARM system to minimize or prevent flow breakdown, to adapt and respond to influxes of volume and occupancy, and to recover as soon as possible in the event of congestion occurring. This entails designing the infrastructure and the ramp metering system to minimize the potential for flow breakdown and operating the system to manage flow within the freeway's sustainable operational capacity.

The general principle of the Smart Freeways CARM strategy is to control and regulate all traffic entering a managed freeway from entrance ramps along the corridor. The CARM system is able to manage flow to an optimum level along the whole route and coordinate the operation at all ramps to balance ramp queues and waiting times. This allows the system to prevent, minimize, or delay the breakdown of mainline traffic flow, while preventing ramp queues from backing up onto any given arterial roadway.

The Innovate 680 AT CARM Project objectives support the following desirable outcomes for I-680 corridor users:

- Achieving maximum safety and productivity from the freeway infrastructure to facilitate the movement of general traffic, freight and on-road public transport;
- Improving transportation outcomes for road users in terms of travel safety, efficiency and reliability;
  Preventing the occurrence of, and facilitating recovery from, flow breakdown and congestion, as these have detrimental effects on the freeway as well as the wider arterial and local road network.

3.2.1 Coordinated and Adaptive Ramp Metering

Traffic control with CARM following the VicDOT approach manages freeway occupancy and traffic flow along the freeway mainline to optimize safety and minimize the potential for flow breakdown and congestion. This is achieved by:

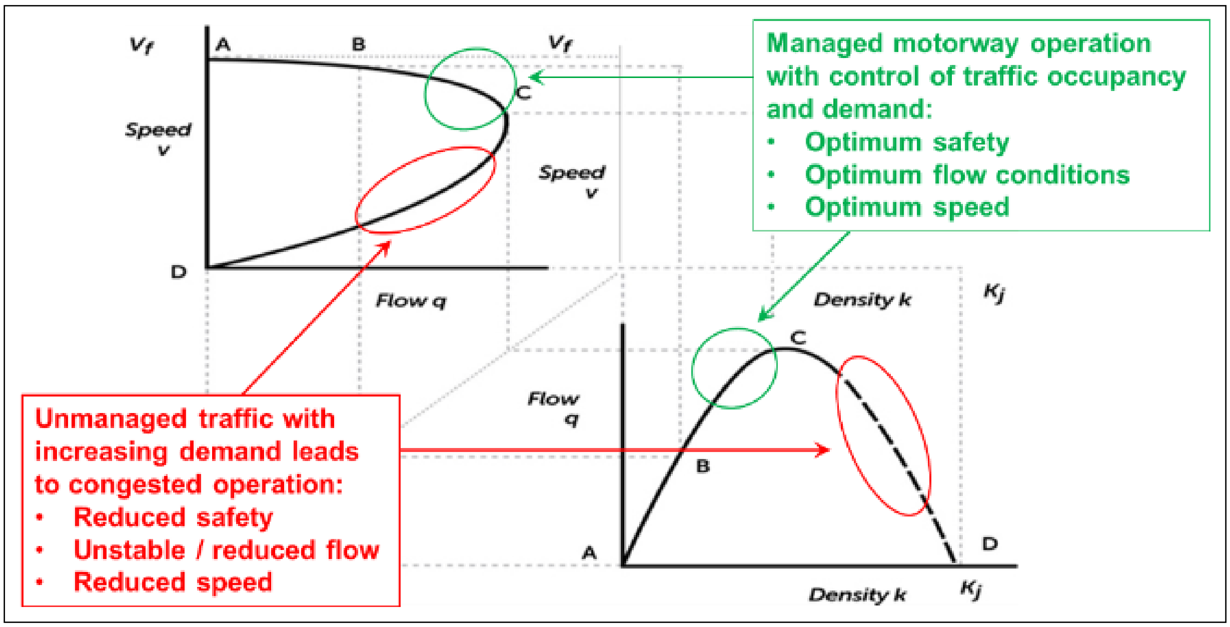
- Using ramp metering to break up platoons of vehicles entering from the arterial network;
- Adjusting the entry flows based on the available capacity of the freeway;
- Finding the moving bottleneck locations and calculating their dynamic capacity; and
- Balancing the workload and queues across all available ramps

Where traffic demands are high, CARM is most effective when implemented on a corridor-wide basis to provide full management of the freeway corridor, together with control of all entrance ramps (including freeway-to-freeway connectors) to balance queues, balance wait times and prevent back-ups from ramps onto adjacent roadways.

The central principle of freeway management for optimum safety, flow and travel speed is that traffic demand entering the freeway must be controlled to minimize the risk of flow breakdown and resultant congestion on the freeway mainline. The traffic theory that underpins this principle is shown in Figure 3-1. The exhibit highlights how sections of freeway corridors each have maximum sustainable flow rates, beyond which traffic flow becomes unstable and unmanageable, and the risk of traffic flow breakdown into congested conditions increases substantially. These maximum flow rates are typically much lower than the theoretical throughput maximums described in the Highway Capacity Manual (HCM)[2].

By using the CARM approach, and by providing ramp signals at all entrance ramps along a corridor to control demand, the system has the ability to increase operational freeway throughput by optimizing and stabilizing traffic flows and preventing flow breakdown while also managing ramp queues and wait times to avoid impacts to adjacent roadways. Even if mainline demand exceeds sustainable flow rates at times, the CARM system can prevent the freeway operation from degrading to the point of corridor-wide flow breakdown and assist with recovery of the system to more manageable conditions.

Figure 3-1 Traffic Flow Fundamental Diagrams



Source: WSP

The CARM system manages flow to an optimum level along the freeway corridor as well as at localized mainline areas near each entry ramp. The CARM system controls all freeway entry ramps, as necessary, to:

- Keep mainline flows within critical occupancy and density values, while simultaneously managing ramp wait times and queue lengths within the constraints of all available ramp storage;
- Manage multiple bottlenecks occurring at any location along the freeway corridor based on real-time information; and
- Assist with recovery of flow to stable conditions if unstable conditions or flow breakdown do occur, including after an incident.

[2] *Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis*, Transportation Research Board, September 2020

3.2.2 Complementary Active Traffic Management Tools

CARM is considered by the developers and operators of Smart Freeways to be its core component and the most effective means to reduce recurring congestion. However, contemporary Smart Freeways corridors throughout Australia have incorporated additional complimentary Active Traffic Management (ATM) tools. With CARM as its key feature, elements such as Variable Speed Limits (VSL), Lane Use Management Systems (LUMS), and Variable Message Signage (VMS) displaying estimated ramp travel times have been added to Smart Freeways corridors. These tools are intended to further enhance safety and flow management on corridors by addressing items unaffected by CARM, such as more orderly and less disruptive vehicle merging behavior upstream of lane closures or major roadway junctions. In addition, arterial VMS signage installed near ramps can communicate travel times and other mainline information to motorists. This can lead to more efficient routing decisions and greater understanding of the CARM concept. All complimentary ATM elements can be managed by the same central freeway management system to refine operations and continually improve system functionality over time.

As mentioned previously, the AT CARM Project is one component of the larger Innovate 680 Program. As such, the development of the AT CARM project will coincide with the development of the CATS and TBOS components of Innovate 680, and efforts will be made to coordinate closely with the various project teams. If deemed necessary, this document and subsequent system requirements may be modified to specify more direct integration between the CARM, CATS, and TBOS systems.

3.3 CARM Deployment

The Innovate 680 AT CARM Project will feature the installation of a CARM system and associated ramp modifications on I-680 throughout Contra Costa County. The first CARM segment will be deployed on northbound I-680 south of SR-24, from Olympic Blvd to Alcosta Blvd. The CARM project will also feature the installation of various ITS infrastructure to support the CARM system, including installation of additional vehicle detection devices to enhance data accuracy and coverage. The Segment 1 CARM Project will include the following northbound service interchanges:

- Alcosta Boulevard Interchange;
- Bollinger Canyon Road Interchange;
- Crow Canyon Road Interchange;
- Sycamore Valley Road Interchange;
- Diablo Road Interchange;
- El Cerro Boulevard Interchange;
- El Pintado Road Interchange;
- Stone Valley Road Interchange;
- Livorna Road Interchange;
- Rudgear Road Interchange; and
- Olympic Boulevard Interchange.

Segment 1 was selected for the first phase of the Innovate 680 AT CARM Project based on the findings of the *I-680 Advanced Technology Project Coordinated Adaptive Ramp Metering – Corridor Evaluation,* which was conducted from 2020-2022. The feasibility evaluation analyzed the entirety of I-680 through Contra Costa County based on viability for a CARM based solution. The evaluation included analysis of the existing traffic conditions, and the existing and planned physical configuration of the corridor. The segment 1 corridor was selected for an initial CARM implementation based on existing mainline lane geometry and ramp configurations, which can accommodate proposed project improvements within existing Caltrans ROW without significant environmental impacts. The estimated Segment 1 CARM implementation cost also aligns with the $25 million in available STIP funding. In addition, the expected implementation schedule would allow for Segment 1 CARM construction to be integrated with the concurrent Caltrans SHOPP Fiber/TOS/Ramp Metering project. Segment 1 CARM operations will offer functional utility to provide discernable benefits, while also allowing for CCTA and Caltrans to garner lessons learned that can be applied as more complex CARM implementations are deployed in future phases of the project.

The Segment 1 CARM project will build upon ITS systems and communication infrastructure already present along the I-680 corridor or planned as part of the Caltrans SHOPP Fiber/TOS/Ramp Metering project and integrated with the Caltrans District 4 Transportation Management Center (TMC). The Segment 1 AT CARM Project represents an initial deployment of CARM on I-680, that will be evaluated after two years of operations to determine the efficacy of this concept and suitability for permanent deployment. However, as discussed, previously, the AT CARM system is proposed to be the first ramp metering system to operate along the I-680 corridor within Contra Costa County to best manage public and stakeholder expectations and driver experience.

The primary components of the Segment 1 CARM project include:

- **Coordinated & Adaptive Ramp Metering.** The coordinated and adaptive ramp metering system involves controlling all the entrance ramps of I-680 within the Segment 1 project limits to operate as a single system. This will allow for freeway flow to be monitored along the entire corridor to identify locations where flows are becoming unstable. As a single management system, the system responds by activating ramp meters and adapting the metering rates as needed along the corridor to maximize the storage and flow management capabilities of each entrance ramp to best meet the needs of the entire corridor.

- **Extensive Vehicle Detection Systems.** As a part of the project, detection devices will be installed throughout the corridor along the freeway mainline and ramps. The devices will be spaced along the mainline at critical control points to ensure real-time lane occupancy (a proxy for traffic density), vehicle speed and volume information are continuously available throughout the corridor. Detection will also be installed along entrance and exit ramps to ensure real-time data on ramp queues, and entry and exit flows. In all locations, detection should be available at a high level of accuracy as required for successful CARM operations.

- **Responsive Flow Management.** Another element of the Smart Freeway system involves the deployment of an advanced traffic management program with the capability of utilizing the ALINEA and HERO suite of algorithms to coordinate and adapt ramp metering to respond to corridor conditions, control mainline traffic flows, and managed ramp queues and wait times. As discussed previously, the Transmax STREAMS® platform has been selected to meet this need. Transmax is the only authorized provider of the ALINEA and HERO suite of algorithms in North America [CCTA and Caltrans are currently working to secure a PIF document for the use of STREAMS®].The STREAMS® system will use real-time freeway occupancy, speed and volume data to optimize flow rates throughout the corridor and apply the appropriate metering rates recalculated every 20 seconds across the system to optimize traffic flows and prevent flow breakdown within the corridor. The system also uses ramp occupancy and volume data to monitor ramp queues and wait times to maintain queues within the available ramp storage and to keep maximum wait times within prescribed limits.

- **Optimizing vehicle storage.** The configuration of freeway entrance ramps is an important consideration for effective CARM operation. Ramp storage and discharge capacity may be expanded to ensure the operational flexibility necessary to support coordinated ramp metering.

3.4 Institutional Setting & Governance

3.4.1 Contra Costa County Transportation Authority (CCTA)

CCTA is the lead agency overseeing the funding, development, implementation, integration, operation, maintenance, and evaluation of the Innovate 680 AT CARM Project improvements, as well as the greater Innovate 680 program. CCTA will coordinate with additional regional and state agencies, FHWA and local stakeholders on issues relating to CARM development and operations. Through the Innovate 680 program, CCTA will also maintain the various project entities responsible for guidance, oversight and stakeholder engagement throughout project development and operations. These include the Corridor Management Team (CMT), CARM Integrated Team, Project Development Team (PDT), Strategic Development Team (SDT) and the Technical Advisory Committee (TAC).

3.4.2 California Department of Transportation (Caltrans)

Caltrans manages more than 50,000 miles of highway and freeway lanes throughout California, and is the ultimate owner responsible for the maintenance, operations and improvement of the state highway system. Caltrans District 4 is responsible for the maintenance and operation of ITS devices and assets within the Bay Area, including along the I-680 corridor. As such, Caltrans District 4 will be a key project partner for the delivery of the AT CARM project. District 4 is also leading the development of the Caltrans SHOPP Fiber/TOS/Ramp Metering project on I-680.

3.4.3 California Highway Patrol (CHP)

The CHP will be the lead enforcement agency for the Innovate 680 AT CARM Project. Enforcement agencies will play a vital role in the success of the CARM project, which is in part dependent on vehicles adhering to ramp metering signals.

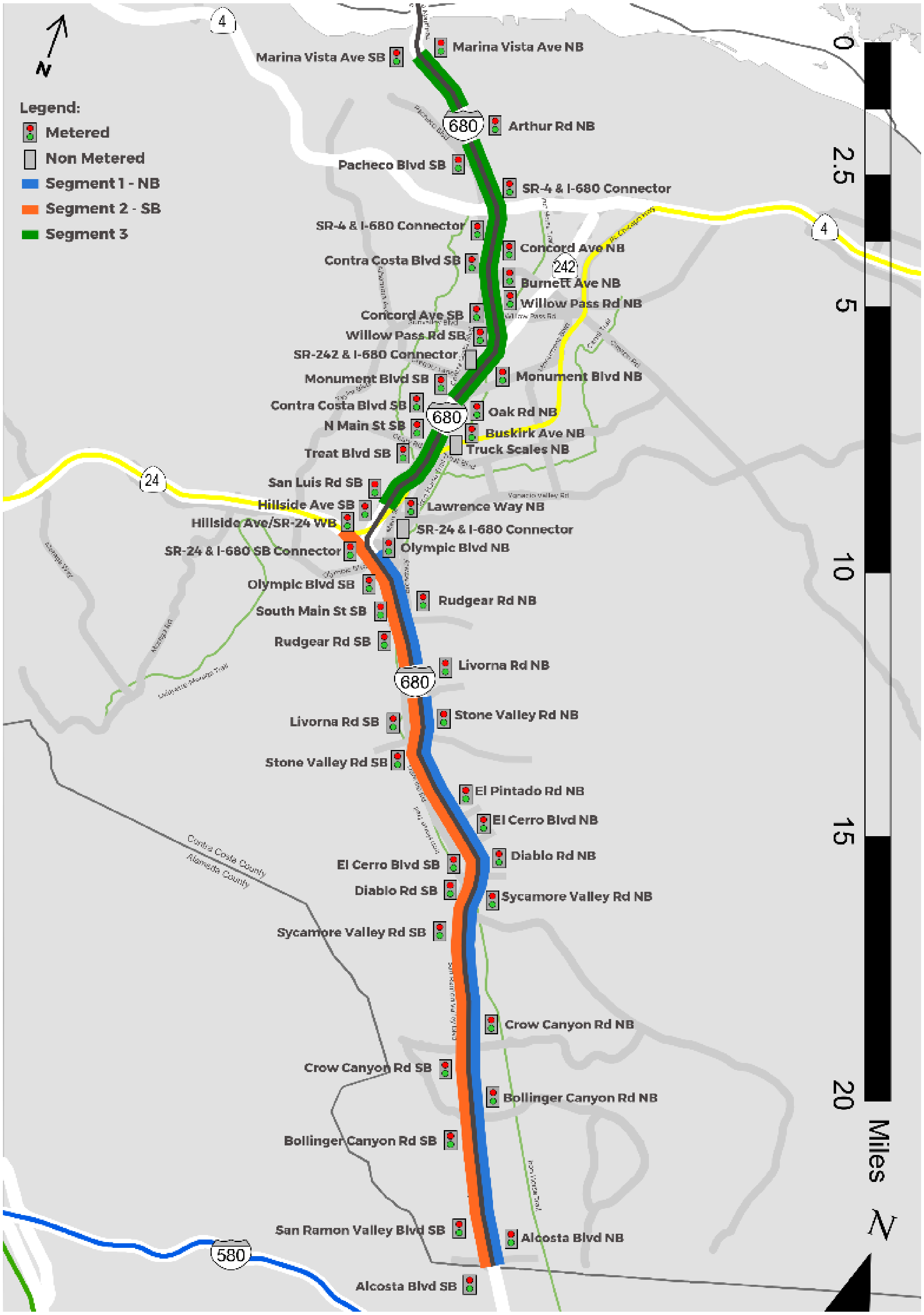
3.4.4 Local Jurisdictions

The Innovate 680 AT CARM Project corridor traverses multiple local jurisdictions, including the City of Dublin, City of San Ramon, Town of Danville and the City of Walnut Creek, as well as unincorporated areas of Contra Costa County. Local jurisdictions maintain the arterial network infrastructure adjacent to the Segment 1 I-680 CARM corridor, including the eleven intersecting routes, and parallel frontage roads and arterials. Local agencies will provide input on CARM system project development, with participation facilitated through the Innovate 680 TAC. More direct local stakeholder involvement may be required in the event that the Innovate 680 CATS project is directly integrated with the Segment 1 AT CARM project. However, the timing of this integration is unknown at the time of this writing and may not be applicable until future phases of CARM deployment along I-680.

3.5 Corridor Boundaries

I-680 is a heavily traveled commuter route between the East Bay and the South Bay. In Contra Costa County, I-680 stretches from the Contra Costa County/Alameda County line to the Benicia-Martinez Bridge (Figure 3-2) at the Contra Costa County/Solano County line. The I-680 corridor provides high-capacity connections to SR-24 in Walnut Creek, SR-242 in Concord, and SR-4 in Martinez. As described previously, Segment 1 of the Innovate 680 AT CARM project will be deployed in the northbound direction only between Alcosta Blvd and Olympic Blvd. The additional segments shown in Figure 3-2 are slated for future implementation following the initial operations of the Segment 1 CARM corridor as additional funding becomes available.

Figure 3-2 Innovate 680 CARM Corridor Map



Source: WSP

3.6 Project Purpose and Need

The purpose and need of the Innovate 680 AT CARM project were defined during the *I-680 Advanced Technology Project Coordinated Adaptive Ramp Metering – Corridor Evaluation*, and further refined during the Innovate 680 CARM PSR process. These are explained further below.

3.6.1 Purpose

The purpose of the Innovate 680 AT CARM project is to is to add system functionality and complement the ramp metering elements of the State Highway Operation and Protection Program (SHOPP) Project 04-1Q720 to:

- Proactively manage both recurrent and non-recurrent congestion in a coordinated, real-time manner to improve operational efficiency and reliability of the I-680 corridor.
- Optimize mainline performance and balance ramp queues.
- Improve traffic and incident detection to support CARM implementation.
- Encourage collaboration with local agencies for further implementation of ITS elements.
- Replace the existing Type 50 median barrier with Type 60 median barrier to meet current standards.

3.6.2 Need

The recurrent and non-recurrent congestion on weekdays and weekends along the I-680 corridor in Contra Costa County results in traffic delays, reduction in traffic throughput and inconsistent travel-time reliability. In some instances, this reportedly leads to natural diversion of freeway traffic onto the local street network. This will require that the following needs to be addressed by the proposed project:

- There is currently congestion in the northbound direction beginning at El Pintado Road during the AM peak period and at Treat Boulevard during the PM peak period, with both areas of congestion propagating and ultimately extending south to Sycamore Valley Road. The CARM system will work to address this need.
- Current ramp meter system does not automatically operate in response to crashes and lane blocking events on the freeway, coordinate metering rates across multiple ramps, and distribute queues on the ramps. The proposed AT CARM project will introduce new tools and technology to meet this need.
- The proposed AT CARM project will introduce new tools and technology to meet this need;
- Current traffic monitoring infrastructure provides lower resolution information on mainline traffic performance and incident identification, which will be approved through CARM.
- Existing median barriers in the southerly segment of the project limits do not meet current Caltrans requirements. Barrier in this section will be updated through the AT CARM and SHOPP projects.

4 Existing Conditions

4.1 Roadway Configurations

I-680 within Contra Costa County is generally an eight-lane freeway providing 23 interchanges northbound and 27 interchanges southbound, including freeway-to-freeway connections with SR-24, SR-242, and SR-4. Single-lane high occupancy toll (HOT) lanes extend 11 miles between Alcosta Boulevard and Livorna Road northbound, and 25 miles from Marina Vista Avenue to Alcosta Boulevard southbound.

The portion of I-680 selected for the initial phase of the Innovate 680 AT CARM Project (Segment 1) is 14 miles long in the northbound direction only. The Segment 1 CARM corridor includes 11 arterial interchanges with 14 individual northbound entrance ramps onto I-680. These entrance ramp locations are listed in Table 4-1 below along with basic ramp characteristics.

Table 4-1 Innovate 680 AT CARM Segment 1 Ramp Conditions

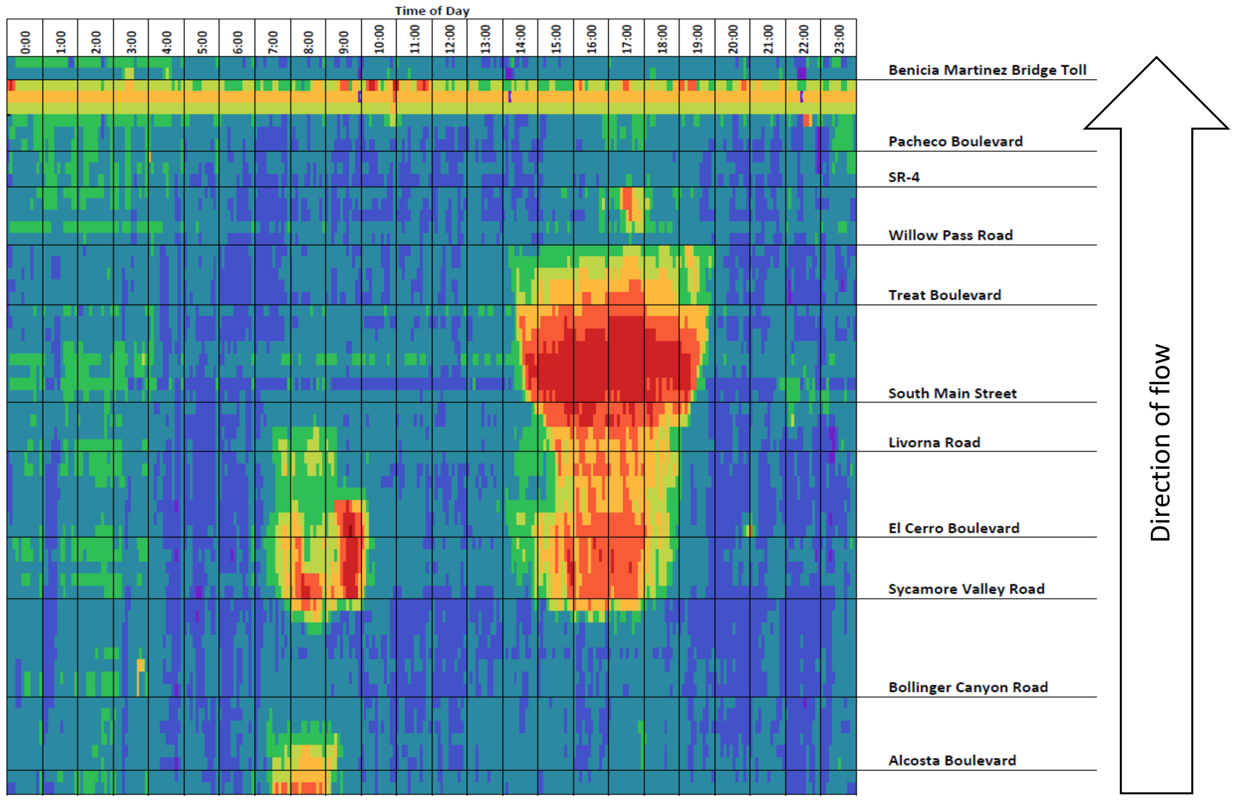
Existing Ramp Location [South to North]	Existing Lanes on Ramp	Existing Ramp Vehicle Storage [Lane Feet]
Alcosta Blvd	2	2,500 ft
Bollinger Canyon Rd [Loop]	1	570 ft
Bollinger Canyon Rd [Direct]	2	2,464 ft
Crow Canyon Rd [Loop]	1	1,550 ft
Crow Canyon Rd [Direct]	2	1,650 ft
Sycamore Valley Rd	1*	1,610 ft
Diablo Rd [Loop]	1	700 ft
Diablo Rd [Direct]	1	670 ft
El Cerro Blvd	1	800 ft
El Pintado Rd	1	420 ft
Stone Valley Rd	1	890 ft
Livorna Rd	1	440 ft
Rudgear Rd / Danville Blvd	1*	1,290 ft
Olympic Boulevard	2	1,675 ft

*Two lanes at ramp entrance merge to one lane

4.2 Existing Corridor Performance

The I-680 corridor experiences severe recurrent congestion in the northbound and southbound direction, as documented in the *I-680 Advanced Technology Project Coordinated Adaptive Ramp Metering – Corridor Evaluation (2022)*. The corridor evaluation during the feasibility stage included a spatial analysis, where daily speed heat plots were prepared for each day during the representative month of October 2018 (pre-COVID) using data from INRIX. Figure 4-1 shows the speed heat plot in five-minute averages from the typical day of Wednesday, October 17, 2018. In the figure, the location along the corridor is represented in the vertical axis, while time of day is shown in the horizontal axis. Slow speeds of less than 20 mph are represented by red colored cells, while free-flow speeds of over 60 mph are represented in shades of blue.

Figure 4-1 I-680 Northbound Speed contour Heat Plots

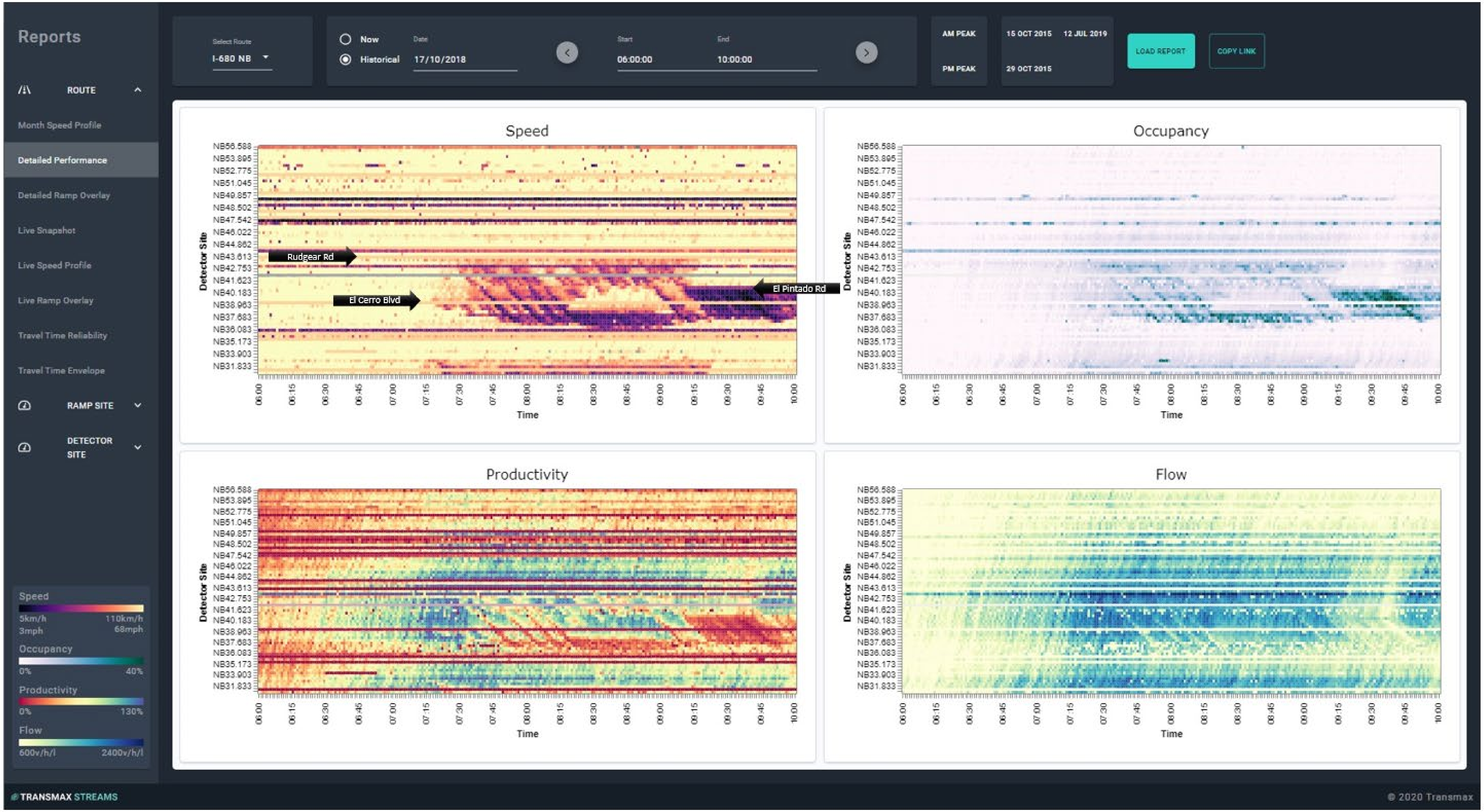


Source: INRIX, Wednesday, Oct 17, 2018.

Recurrent congestion in the northbound direction can be characterized by an isolated area of AM peak-period congestion in the southern third of the corridor, and a more prominent area of congestion in the northern half of the corridor during the PM peak. The northern bottleneck eventually propagates upstream and spreads into the southern half of the corridor reaching the same bottleneck observed in the AM peak period. This level of recurrent congestion in this area contributes significantly to degraded travel times and travel time reliability for the traveling public, as well as a critical loss of corridor efficiency and productivity that impacts the surrounding transportation network.

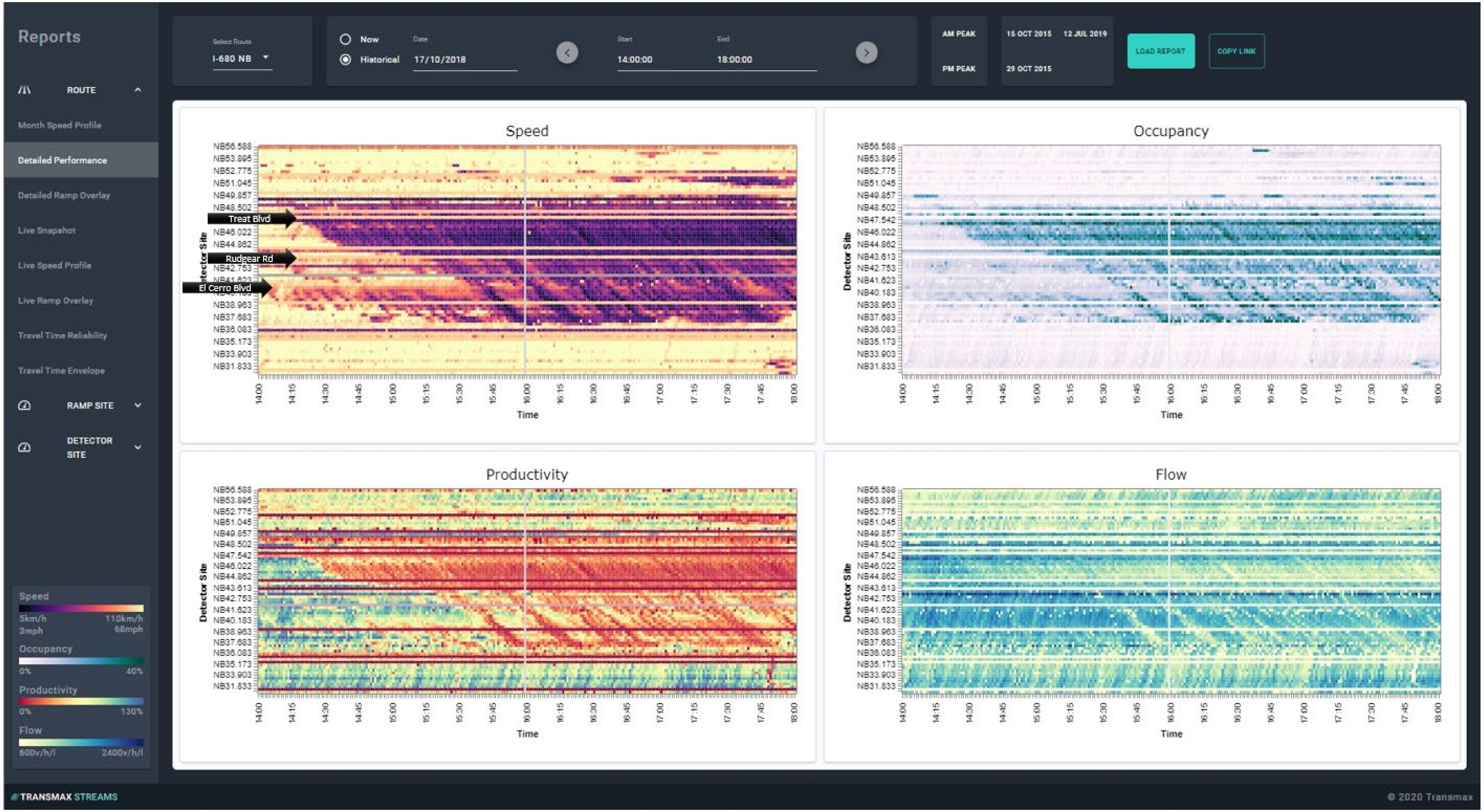
A more detailed investigation of existing traffic conditions was also undertaken in the feasibility stage using raw data obtained from PeMs, which is sourced from existing loop vehicle detection sites along the I-680 corridor. The Transmax STREAMS® Smart Motorways Dashboard was then used to process the raw loop detector data and generate reports for the same representative day of October 17, 2018. This process resulted in a set of more detailed heat plots showing speed, lane occupancy, productivity (product of speed and flow), and flow (volume) at a one-minute resolution. Figure 4-2 shows this information for the northbound I-680 corridor during the four-hour period from 6:00 AM to 10:00 AM on October 17, 2018, while Figure 4-3 shows the four-hour period from 2:00 PM to 6:00 PM.

Figure 4-2 I-680 Northbound - Congestion Characteristics – AM Peak-Period



Source: PeMS, Wednesday, Oct 17, 2018, 6:00 AM to 10:00 AM.
Transmax STREAMS® report dashboard

Figure 4-3 I-680 Northbound - Congestion Characteristics – PM Peak-Period



Source: PeMS, Wednesday, Oct 17, 2018, 2:00 PM to 6:00 PM.
Transmax STREAMS® report dashboard

These figures similarly illustrate the various performance measures along the corridor with each detection location represented in the vertical axis, while time of day is shown in the horizontal axis. As with the prior exhibit, the direction of travel in the corridor is illustrated on the vertical axis up the page from bottom to top. The colors in the upper two images in each figure illustrate Speed and Occupancy (a proxy for traffic density), respectively, transitioning from darker, indicating slow speeds and increased occupancy (very congested conditions) to lighter, representing high speeds and lower occupancy (free-flow conditions). In the lower left images illustrating Productivity, darker shades of red correlate to lowest productivity (congested conditions) while darker shades of blue correlate to highest productivity (free-flow conditions at higher flows). The lower right images illustrate Flow (a proxy for traffic volume) with darker shades indicating the highest flows and lighter shades indicating the lowest flows. A legend in the lower left of each figure specifies the color ranges used in the different heat plots. It should be noted that there are data gaps at several locations in the plots, which are indicated by light-gray colors. These represent vehicle detectors that were not reporting data because of device malfunction, communications loss, or another unknown reason. Horizontal bands of the same or very similar shade in the exhibits typically indicate a vehicle detector that has malfunctioned and was reporting errant or incomplete data.

As shown most prominently in the Speed exhibit in Figure 4-2, traffic flow breakdown is observed at two separate bottleneck locations in the northbound direction during the AM peak period. Traffic flow instability is first observed around 7:15 AM near El Cerro Blvd, with waves of congestion extending diagonally upstream along the corridor and to the right over time. A second area of traffic flow breakdown forms soon afterward in the vicinity of Rudgear Rd, with the waves of congestion eventually extending several miles upstream. Around 8:15 AM, traffic flow breaks down completely in the vicinity of Sycamore Valley Rd. This condition effectively meters the traffic flow downstream clearing the bottleneck previously observed in the vicinity of El Cerro Boulevard. Around 9:00 AM, the bottleneck at Sycamore Valley Rd clears, but soon afterward traffic flow breaks down completely in the vicinity of El Pintado Rd. The breakdown of traffic at this location is likely the result of an increase in traffic flow that exceeds the maximum sustainable flow rate (MSFR) at the El Pintado Rd bottleneck location. The effective metering of traffic at the El Pintado Road bottleneck allows the downstream bottleneck at Rudgear Rd to dissipate. However, traffic remains congested at this third bottleneck location until after 10:00 AM when demand in the corridor appears to fall sufficiently for the remaining bottleneck to dissipate and free-flow conditions to resume.

The isolated nature of these AM peak-period bottlenecks makes these locations desirable for the application of CARM, which can improve the management of traffic flows and balance demand along the corridor, substantially reducing the observed effects of congestion. Furthermore, strategic improvements at the various ramp locations to accommodate CARM would likely assist in resolving the turbulent traffic flows that contribute to the formation of these bottlenecks.

As shown in Figure 4-3, northbound traffic flows in the PM peak period are dominated by a substantial bottleneck and resulting reduced speeds, flow and productivity in the vicinity of Treat Boulevard, approximately 2-½ miles north of the I-680/SR-24 system interchange. The influence of this bottleneck extends into the northbound Segment 1 focus area, and eventually results in waves of congestion extending almost twelve miles to the vicinity Sycamore Valley Road. There are also secondary bottlenecks that form upstream of Sycamore Valley Road during the PM peak hour that could benefit from the implementation of CARM to reduce the effects of traffic flow breakdown. Furthermore, the application of CARM could also better manage traffic flowing into the I-680/SR-24 system interchange and potentially reduce the magnitude of disruption caused by the Treat Boulevard bottleneck. It should be noted that the planned Innovate 680 Express Lane Completion Project (EA: 04-0Q3100) will also contribute to reduced congestion at the Treat Boulevard interchange.

As shown in the charts in Figure 4-3, traffic flow instability is observed in the vicinity of El Cerro Boulevard as early as 2:00 PM, eventually resulting in waves of congestion extending upstream. This condition progressively worsens for approximately 90 minutes until the effects of the Treat Boulevard bottleneck reaches this location. Similarly, unstable traffic flows are observed in the vicinity of Rudgear Road as early as 2:15 PM, with isolated waves of congestion continuing to form for approximately 45 minutes until the effects of the downstream congestion reach this vicinity. It is anticipated that the implementation of CARM could substantially resolve the instability at these secondary bottleneck locations to prevent to onset of congestion until downstream influences reach the focus area.

The critical locations identified as part of the spatial analyses were further evaluated through a detailed flow characteristics analysis. This analysis process detailed the relationships between traffic flow (volume), speed, and lane occupancy (density) using 60-second data intervals from individual mainline vehicle detectors. This analysis provides a greater understanding of each problem area, indicates the typical loss of throughout and duration of flow breakdown, and provides additional background to the level of system control necessary in each location. Analysis was performed for October 17, 2018, for various critical locations in the study corridor.

Figure 4-4 shows flow characteristic results for I-680 northbound near El Cerro Blvd (PeMS detector site 401112 at PM 39.813). Based on the review of the heat plots in the previous sections, this location appears to be a critical bottleneck that provides the earliest indication of traffic flow disruption. As shown in the line graph, flow/volume (indicated by the blue line) gradually increases after 6:00 AM reaching a peak flow rate of near 1,800 vehicles per hour per lane (vphpl) around 7:15 AM. At that time, speeds (indicated by the magenta line) begin to drop indicating the onset of unstable flows.

Figure 4-4 I-680 Northbound at El Cerro Blvd – Traffic Flow Characteristics

Source: PeMS, Wednesday, Oct 17, 2018, 6:00 AM to 10:00 AM.
Transmax STREAMS® report dashboard

By 7:45 AM, traffic flow breaks down and waves of congestion become evident with speeds and flow dropping substantially, and lane occupancy (indicated by the teal line) increasing. Under this congested condition, flow rates average between 1,400 and 1,500 vphpl, which is 12% to 17% below peak flow rates, and roughly 25% to 30% below the typical capacity of similar freeway segment. The congestion continues until 8:20 AM when speeds recover. However, flow rates remain near 1,400 vphpl until breaking down further around 9:00 AM. At that point, downstream congestion backs up to this location with speeds and flows dropping substantially and lane occupancy spiking to over 50%, indicating that traffic queues are nearly stationary.

A review of the scatter plots included on Figure 4-4 shows well defined curves closely resembling the fundamental diagrams of traffic flow. The scatter plots demonstrate the expected pattern with traffic flows, speeds, and occupancy gradually increasing until unstable flows are observed at the peaks of the curves. This is followed by traffic flows falling into a congested state, characterized by a more scattered array of points indicative of repeated waves of congested flow and momentary recovery.

4.3 Existing Transportation Management Assets

4.3.1 ITS & Transportation Management Programs

The Caltrans District 4 TMC, located in Oakland, California, provides oversight over the region's state highway traffic and incident management services. Caltrans District 4 TMC coordinates existing traveler information, ATM activities and incident response capabilities for the state highway system within Bay Area counties.

District 4 also operates the existing ramp meter system within the district, and forwards information to the Caltrans PeMS. Key functions include:

- Collection and processing of traffic data from field data sensors;
- Access to video feeds from CCTV cameras;
- Management of messages displayed on VMS signs;
- Coordination with CHP dispatch; and
- Event response decision support system.

4.3.2 ITS Field Systems

The Segment 1 I-680 CARM corridor currently features a combination of ITS components:

- **CCTV Cameras:** The CCTV cameras are used for monitoring travel conditions in the corridor, such as weather conditions, collisions and other traffic disruptions and traffic congestion. The video images are also shared with the public and television news agencies via the internet at the following link: https://cwwp2.dot.ca.gov/vm/iframemap.htm?long=-117&lat=34.55168&zoom=24

- **Vehicle Detection Systems:** Inductive loop vehicle detector sites are at several locations along the Segment 1 I-680 CARM corridor. Detector sites are used to measure volume, occupancy, speed and vehicle classification to inform PeMS and other Caltrans District 4 systems. Radar vehicle detection systems are also present in the corridor as part of the tolling systems for high-occupancy toll lanes in the I-680 corridor. Caltrans also has two existing TIRTL demonstration sites located along southbound I-680 near N. Main Street and S. Main Street, respectively. These sites are co-located with existing loop detector sites as the basis for providing comparative analysis of VDS data.

- **Communications Network:** Caltrans maintains a fiber communications network from field devices to the Caltrans District 4 TMC. Each device cabinet is connected to a network node. A fiber backbone connects each network node back to the Caltrans District 4 TMC. The MTC also maintains fiber optic communications in the I-680 corridor to support the toll collection system for the I-680 Express Lanes.

5 User Needs

This section identifies key user needs that govern the development of the Innovate 680 AT CARM Project. User needs were determined based on the *I-680 Advanced Technology Project Coordinated Adaptive Ramp Metering – Corridor Evaluation (2022)*, as well as discussions with the AT CARM PDT. These needs will form the basis for the development of functional requirements, which will be documented later in the project development process.

5.1 Categories of Participants

Expected participants in the I-680 AT CARM system are identified in Table 5-1. As shown in the table, there are three separate types of participants, classified based on how each group would interact with the system:

- **Active Users:** For Segment 1 operations, CCTA Operations Staff will be the most active users of the solution during the operation of the Segment 1 AT CARM system. The Transmax Configuration and Tuning (C&T) Team will be most heavily involved during the setup and implementation of Segment 1, and the Transmax Support Team will provide continuing system support during CARM operations.

- **Primary Stakeholders:** Project participants that are immediately responsible or accountable for some aspect of the project delivery. These stakeholders are typically also users of the AT CARM system.

- **Secondary Stakeholders:** Indirect users who do not actively participate in the operation of the system, but either travel the corridor, have keen interest in the system performance, or are otherwise impacted by CARM operations.

Table 5-1 Innovate 680 AT CARM System Participants

Active Users	Primary Stakeholders	Secondary Stakeholders
CCTA Operations Staff	Caltrans District 4 TMC Operators	Local Emergency Response
Transmax C&T Team	Caltrans ITS Engineering	ITS Device Vendor
Transmax Support Team	Caltrans Traffic Engineering	Agency Managers
	Caltrans Network and Infrastructure (N&I) Specialists	Local Drivers
	ITS Installation Contractor	Public Information Officers
	ITS Maintenance Contractor	Commercial Fleet Operators
	CCTA Project Staff	
	CCTA Management	
	Local Jurisdictions	
	Caltrans Management	
	CHP Officers	
	BAIFA	

A summary of activities performed by each of the system participants is outlined in the Responsible/Accountable/Supporting/Consulted/Informed (RASCI) summary in Table 5-2.

Table 5-2 RASCI Summary

Activity	Responsible	Accountable	Supporting	Consulted	Informed
Civil Engineering	Caltrans and/or Civil Design Team	Caltrans Management	CCTA Project Staff	CCTA Management	Transmax C&T Team
ITS Design	Caltrans and/or ITS Design Team	Caltrans Management	CCTA Project Staff; Transmax C&T Team	Transmax C&T Team; Caltrans N&I Specialists; ITS Device Vendor; ITS Installation Contractor	Caltrans Maintenance
Inter Project Coordination	Caltrans Management	CCTA Management	Caltrans Traffic Engineering	Transmax C&T Team; Corridor Manager Team	None
ITS Device Installation	ITS Installation Contractor	Caltrans ITS Engineering	ITS Device Vendor	Transmax C&T Team	Caltrans Managers
ITS Device Installation Acceptance	Transmax C&T Team	Caltrans ITS Engineering	ITS Installation Contractor; ITS Device Vendor	Caltrans ITS Maintenance; Caltrans Management;	CCTA Management; Caltrans District 4 TMC
System Configuration and Tuning	Transmax C&T Team	Transmax C&T Team	ITS Installation Contractor; ITS Device Vendor	Caltrans ITS Engineering; Caltrans Traffic Engineering; Transmax Support Team	Caltrans Management; CCTA Management; Transmax Support Team
Collecting and Processing Data	Transmax C&T Team	Transmax C&T Team	Caltrans Traffic Engineering; Transmax Support Team	Caltrans Management; CCTA Management	None
Monitoring Ramp Metering	CCTA Operations Staff	CCTA Management	Caltrans Ramp Metering Team; Caltrans ITS Maintenance; Transmax Support Team	Transmax Support Team	Transmax Support Team; Caltrans ITS Maintenance
Emergency Access and	Caltrans District 4 TMC	Caltrans District 4 TMC	Caltrans ITS Maintenance;	None	Caltrans Management

Activity	Responsible	Accountable	Supporting	Consulted	Informed
Incident Management			Transmax Support Team		
Data Retrieval from STREAMS® Gateway	Caltrans Traffic Engineering	CCTA Engineering	Transmax C&T (Project) Team	Caltrans Management	Transmax Support Team; Corridor Manager Team
Monitoring ITS Device Status	CCTA Operations Staff	CCTA Management	Caltrans District 4 TMC; Caltrans ITS Maintenance; Transmax Support Team	ITS Device Vendor	Caltrans Management
Freeway Performance Observation and Reporting	Corridor Manager Team	CCTA Management	Transmax C&T Team	CCTA Project Staff	Caltrans District 4 TMC
Smart Freeway Performance Assessment	Corridor Manager Team; CCTA Project Staff	CCTA Management	Transmax C&T Team	Caltrans Traffic Engineering	Caltrans District 4 TMC; Caltrans Management
CCTV Video Management	Caltrans District 4 TMC	CCTA Management	Transmax C&T Team; Caltrans ITS Maintenance	Caltrans N&I Specialists	CCTA Operations Staff; Transmax Support Team
ITS Network Management	Caltrans N&I Specialists	Caltrans Management	Transmax Support Team	Caltrans District 4 TMC	Caltrans ITS Maintenance
System Security	Caltrans Management; Transmax C&T Team	CCTA Management	Caltrans N&I Specialists; Transmax Support Team	None	Caltrans District 4 TMC
System Device Maintenance	ITS Maintenance Contractor	Caltrans Management	Transmax Support Team; Caltrans District 4 TMC; Caltrans ITS Maintenance	ITS Device Vendor	Caltrans District 4 TMC
Public Outreach	Emergent Transportation Concepts Outreach Team	CCTA Management	Caltrans Traffic Engineering; Transmax C&T Team	CCTA Project Staff	Caltrans District 4 TMC; Local Police Depts; Agency

Activity	Responsible	Accountable	Supporting	Consulted	Informed
					Managers; Public Information Officers; Local Drivers; Commercial Fleet Operators
Enforcement	CHP Officers	CHP Officers	Caltrans District 4 TMC	CCTA Management Caltrans Management	Caltrans District 4 TMC; Local Police Depts
STREAMS® Maintenance and Upgrades	Transmax Support Team	Transmax Support Team	Transmax C&T Team	Caltrans District 4 TMC	Caltrans Management; CCTA Management; Corridor Manager Team
Integration from ITS Field Network to STREAMS®	Caltrans N&I Specialists; Transmax C&T Team	Caltrans Management	Transmax Support Team	Caltrans District 4 TMC	Caltrans ITS Maintenance

5.2 System Management Needs

5.2.1 Operating Platform

A freeway management operating system provides the Transmax C&T Team with a central software platform for system configuration and calibration, including mainline geometry and ramp storage parameters, as well as location and functionality information for all detection and signal devices associated with the system. This enables the application of CARM theory to be applied to the unique geometry and requirements of the I-680 AT CARM corridor. The platform will also provide the means by which metering rates are communicated to devices in the field. The software platform also provides the ability for CCTA Operations Staff (and/or Caltrans District 4 TMC Operators, if assigned) to monitor and verify system status and performance, as well as calibrate and adjust system settings during CARM operations.

For the purposes of the Innovate 680 AT CARM Project, the Transmax STREAMS® freeway management platform has been selected to fill this need. At the time of this writing, CCTA is coordinating with Caltrans to prepare a Public Interest Finding PIF) for the use of STREAMS® for the initial Segment 1 AT CARM deployment on I-680.

5.2.2 Professional Capability

Innovate 680 CARM operations will rely on the Transmax C&T Team to configure and calibrate the freeway management system, and the CCTA Operations Staff to monitor the system. Operators will need sufficient professional capabilities to perform the daily operation of the system. Professional capability includes the necessary technical knowledge to set-up and maintain the freeway management operating system, configure, and adjust system parameters, and monitor/refine system performance. In addition, operators will need to have open communication with Caltrans District 4 TMC to coordinate for incidents or other events.

5.2.3 Operating Environment

An appropriate system configuration and working environment is needed to facilitate remote monitoring and control for the Transmax C&T Team and CCTA Operations Staff. Secured remote network connections will need to be established to allow the Transmax C&T Team as well as the CCTA Operations Staff to remotely change ramp meter parameter settings along the corridor, and to access and monitor I-680 CCTV footage with pan, tilt, and zoom control. Given likely communication needs between the Transmax C&T Team, CCTA Operations staff and Caltrans District 4 TMC staff, communication protocols will also need to be established to aid in incident detection and response, potentially including the need for system override.

5.3 System Monitoring Needs

5.3.1 Collect and Process Mainline Data

The Innovate 680 AT CARM system must monitor and process mainline traffic data in real-time. This information will be used to measure traffic conditions throughout the corridor and adjust ramp meter signal timings every 20 seconds to optimize mainline traffic flows and prevent the formation of congestion. Data will need to be provided through VDS devices installed at specific locations and spacing throughout the Segment 1 AT CARM corridor. VDS will also need to provide real-time speed, volume and occupancy at a level of accuracy required by CARM standards.

5.3.2 Collect and Process Entrance Ramp Data

The AT CARM system must also monitor and process entrance ramp performance data in real-time. This data will be used to inform the system on the number of vehicles entering the corridor mainline at any given time. The system calculates the number of vehicles waiting at every entrance ramp meter and estimates the total entrance ramp storage available through the corridor. It also estimates the associated waiting times. This information will then provide a basis for the system to balance ramp queues throughout the corridor, and prevent or minimize queues from impacting arterials, through the continual manipulation of ramp meter signal timings. Entrance ramp information will need to be sourced from vehicle detectors installed at specific locations along the I-680 Segment 1 corridor mainline and entrance ramps, and will also need to provide volume, speed and occupancy information at a level of accuracy required by CARM standards.

5.3.3 Monitor Ramp Metering Functionality

The Transmax C&T Team and the CCTA Operations Staff need to monitor the status and functionality of all ramp meters in real-time. As such, the CARM system needs to provide real-time data on the active ramp metering rate in each location, along with the operating status of all ramp meters. This information will be used by the system to inform needed changes to ramp signal timing, and to indicate any functionality issues.

5.3.4 Monitor ITS Device Status

The CARM system will need to monitor the status of all critical ITS devices and equipment utilized as part of system operations. These items include ramp meter controllers and signals, vehicle detectors, and field processors. The real-time status of all devices and equipment will be needed to indicate malfunctioning items to the Transmax Support Team. The status of CCTV cameras will need to be manually verified by TMC staff and, BAIFA staff, and the Transmax Support Team through a separate interface.

5.3.5 Reporting Capability

In order to facilitate the provision of real-time I-680 corridor and system performance, the CARM operating platform will need to have real-time reporting capabilities. The operating platform needs to quickly communicate mainline traffic performance, entrance ramp performance and ITS device status. This real-time information will be needed by the system and operators for successful CARM operations and evaluation. Also, all performance data from system operations will need to be archived to facilitate later analysis.

5.3.6 CCTV Video

The Transmax C&T Team, CCTA Operations staff, and the Transmax Support Team will require pan, tilt, and zoom (PTZ) access to live CCTV video feeds of the I-680 Segment 1 CARM corridor, currently available to TMC staff. The provision of live footage and camera control is important to assist in the real-time monitoring of the corridor's mainline and ramp conditions, to observe impacts to changes in system parameters, and to assist in incident response. TMC operators will also need override capability to have ultimate control of CCTV cameras during emergency situations. CCTV coverage is required for all controlled ramps along the Segment 1 CARM corridor and is desired to cover all locations where vehicle detection has been installed.

5.4 Ramp Metering Control Needs

5.4.1 Ramp Meters

To effectively manage the mainline operations of the AT CARM Project, the system will need the ability to control every entrance ramp included along the northbound I-680 Segment 1 CARM corridor through ramp metering. In order to provide this level of control, the installation of new ramp meters will be needed at each northbound entrance ramp within Segment 1. These ramp locations include Alcosta Blvd, Bollinger Canyon Rd, Crow Canyon Rd, Sycamore Valley Rd, Diablo Rd, El Cerro Blvd, El Pintado Rd, Stone Valley Rd, Livorna Rd, Rudgear Rd, and Olympic Blvd.

At all ramp meters, STREAMS requires the ability to release of vehicles simultaneously at the stop-bar in order to maximize control of the system and to effectively monitor and control ramp wait times and queues. Simultaneous release of vehicles at the stop bar is not typically used by Caltrans District 4 but is used by the department at locations in Caltrans District 7 and other districts. Simultaneous release is also used universally on all CARM projects in Australia and was used successfully without any reported incidents for the nine-month duration of the CDOT Smart 25 CARM Pilot Project in Denver. In addition, new ramp meters will need to be constructed to Caltrans standards in order to facilitate the possible future reversion of the system to standard Caltrans District 4 operations. Ramp meter control is informed by vehicle detection information extending downstream and upstream from ramp entrances.

5.4.2 Ramp Storage

In order to enable the system to respond to real-time traffic conditions, entrance ramps within the corridor need to provide an adequate level of vehicle storage and vehicle discharge capacity. Vehicle storage is necessary to temporarily store vehicles on entrance ramps without impacting adjacent arterials, while discharge capacity is needed to quickly release vehicles when they can be accommodated on the mainline. As such, several ramp improvements will be included as part of the Innovate 680 AT CARM Project. Ramp storage improvements will also need to be exempted from providing HOV priority lanes, in order to maximize ramp storage, discharge capacity and operational flexibility in accordance with CARM standards. At some on ramp locations, storage will be provided within a part-time shoulder lane that will be open to traffic only when the ramp meter is activated. This is described further in section 7.5.5.

5.4.3 Incident Ramp Signal Control

The I-680 CARM system will need to incorporate parameters that enable independent control of ramp meter signals. Note, in this context, “independent” refers to segregation of ramp control from other coordinated ramps based on local conditions, not independence from STREAMS® control. Independent ramp signal control should consider real-time information on ramp queue, waiting time and downstream bottleneck conditions to adjust ramp meter signal timings. When required, independent control of ramp signals will better enable the system to respond to real-time traffic conditions and prevent ramp queues from impacting adjacent roadways.

5.4.4 Coordinated System Control

The CARM system will also need the ability to coordinate ramp meter signals throughout the I-680 Segment 1 corridor. Coordinated ramp control is needed in order to respond to real-time mainline traffic conditions and ramp conditions on a corridor-wide basis. Specifically, the system will need the ability to manage multiple bottlenecks, while coordinating ramp meter signal timing at each entry ramp in order to balance ramp queues and waiting time among all ramps. Coordinated control of ramp signals will better enable the system to prevent the breakdown of corridor traffic flow, balance ramp meter wait times throughout the corridor, and prevent ramp queues from impacting adjacent roadways.

5.4.5 Queue Warning

In order to prevent potential safety concerns, the CARM system needs to incorporate a means to warn drivers of upcoming queues on corridor entrance ramps. Queue warning should be accomplished by a combination of static signs and flashing electronic beacons consistent with the Caltrans RMDM to signal that ramp meters are active and stopped traffic may be ahead. Adequate queue warning devices are needed to prevent potential rear-end collisions and increase driver awareness as part of CARM system operations.

5.4.6 Emergency Access

The Innovate 680 CARM system will need to accommodate emergency vehicle access as part of operations. The CCTA Operations Staff, Caltrans District 4 TMC, and the Transmax Support Team will need the ability to temporarily override system control and deactivate individual ramp meter signals at locations where shoulders are inadequate to allow emergency vehicles to pass. This manual override ability will be needed to assist in incident or emergency response by allowing emergency vehicles to enter the I-680 mainline without waiting through a queue during normal ramp metering. In practice, this deactivation of individual signals should only be implemented by the CCTA Operations staff including by request from CHP, local emergency services, or Caltrans TMC staff.

5.4.7 Adaptive Flow Management

As part of CARM operations, the system will need to incorporate the ability to respond and adapt to traffic conditions as they approach saturated conditions and the potential breakdown of corridor traffic flow. This ability will need to be informed by real-time traffic conditions provided from vehicle detectors throughout the corridor and individual parameters built into the system. Real-time information will be used by the CARM system to dynamically apply appropriate metering rates throughout the corridor and adjust flow rates every 20 seconds to prevent corridor breakdown.

5.4.8 Parameter Flexibility

The CARM system will need to be flexible in order to accommodate issues that may arise during system implementation. Specifically, the system and Transmax C&T team must have the ability to adjust existing parameters based on unforeseen impacts, such as greater than expected ramp queues at a particular location, new bottleneck locations, etc. Flexibility in parameters will better enable the CARM system to respond to real-time traffic conditions.

5.5 Data Management Needs

5.5.1 Data Archiving

The data collected by the Innovate 680 CARM system during its daily operations needs to be stored to support future offline analyses and evaluations. Satisfying this need implies that a database for historical data storage needs to be incorporated as part of the system. Archived data should include data from corridor traffic detectors, ramp meter queue estimates, speed, volume, and occupancy data from all ramp detectors necessary for future analyses and evaluations. Historical traffic performance and CARM system traffic performance will serve as the basis for the assessment of Segment 1 CARM operations.

5.5.2 Data Reporting

The system will need to have the ability to report corridor traffic and system data when necessary. Data reporting abilities will need to include high resolution data that can quickly communicate summary traffic conditions from a given time period. This reporting capability will be needed in order to support ongoing performance assessments and stakeholder communication.

5.5.3 Data Sharing Interface

In order to facilitate real-time system performance data sharing to various audiences, a dashboard web interface is needed as part of CARM system operations. The dashboard would be available to stakeholders on a read-only web interface. The dashboard will also allow for stakeholders to observe real-time conditions and offer the ability to display historic performance data. The dashboard will highlight both mainline and ramp conditions, including volumes, speed, occupancy, ramp wait times, queue information and metering rates. In addition, nominated individuals (e.g., CCTA Operations staff) will receive privileged access to the dashboard enabling them to place overrides to discontinue metering on individual ramps in response to extreme circumstances, such as in the event of a vehicle breakdown near the ramp meter stop bar.

5.5.4 Internal Data Communication

The Innovate 680 AT CARM system needs to include an appropriate internal communication network in order to monitor and respond to corridor traffic conditions in real-time. The internal communication network will need to include communications between the system operating platform, servers, vehicle detectors and ramp signal controllers. For the purposes of Segment 1 CARM operations, part of this network is anticipated to be located within an online cloud environment. A high-speed and reliable communications network is essential for successful CARM system functionality and operations. The internal data communication network (between a field processor in the roadside cabinet, and the STREAMS® Application Server in AWS) is required to maintain:

- Minimum of 100MB/s bandwidth;
- Maximum 250ms latency.

5.5.5 External Data Communication

Although the CARM system is proposed to have a cloud-based configuration for the purposes of Segment 1 operations, certain vehicle detection and ramp metering data will still need to be made available to Caltrans. This data will be in raw or near-raw format with minimal or no processing having been applied. Hence no proprietary information related to system algorithms will be exposed in its provision. This data feed is proposed to flow from the cloud environment to the Caltrans District 4 TMC data center.

5.5.6 Arterial Data Communication

The operations and performance of the arterial roadways that intersect the I-680 CARM corridor will have direct impact on the system operations and vice versa. To gauge the impact of CARM operations on adjacent roadways, arterial performance data will need to be included as part of system operations. Arterial performance information will be obtained from readily available sources such as local municipalities and/or third-party data providers. Arterial information will be helpful for the Transmax C&T Team during system calibration phases to avoid any queue impacts. The arterial data need may be further defined through Innovate 680 CATS system development.

5.5.7 System Security

The successful operation and performance of the Innovate 680 AT CARM Project is dependent on a functional and secure communications network. As such, the system communications network will need to have adequate security features to prevent outside persons from hacking into CARM systems to disrupt ramp metering operations.

5.6 Maintenance & Enforcement Needs

5.6.1 Enforcement

The success of Segment 1 CARM operations is dependent on the ability of the ramp metering system to control and coordinate the entry of vehicles onto the I-680 mainline. As such, system operations need to include an adequate amount of enforcement resources in order to prevent drivers from ignoring ramp meter signals. At the time of this writing, it is anticipated that CHP will provide enforcement as a part of existing I-680 patrol activities. Any infringement notices will be justified based upon CHP observation of non-compliance rather than system data. If an exceptionally high number of violators are observed in the corridor potentially impacting the ability of the system to manage traffic flows, CCTA staff will engage with CHP staff to determine what additional enforcement actions are needed to achieve greater compliance.

5.6.2 System Device Maintenance

The successful operation of individual ITS devices and equipment are critical to the success of CARM operations. The greater the amount of time that individual devices are malfunctioning or otherwise unavailable, the greater the impact on the system to monitor and react to real-time traffic conditions and prevent the breakdown of traffic flow. As such, the system needs to include adequate maintenance resources to respond to malfunctioning devices and equipment within an appropriate timeframe. During Segment 1 CARM operations, this could include the need for maintenance resources to respond to issues within as little as 24 hours.

5.7 Potential Constraints

In addition to the various needs outlined in the previous section, there are certain potential constraints that should be considered during system development. The following items include examples of known constraints that could impact the success of the Innovate 680 AT CARM Project.

5.7.1 Operational Constraints

- **Driver Compliance:** Success of the AT CARM Project is dependent on the ability of the ramp metering system to control throughput of vehicles onto the I-680 freeway. If there are a high number of ramp meter violators, the ability of the system to reduce congestion will be hindered. This puts an emphasis on the need for adequate public outreach and education regarding CARM operations, as well as enforcement.

- **Traffic Volumes:** Feasibility analysis of the I-680 project corridor relied on existing traffic data from limited existing vehicle detector locations. More reliable data will not be available until after new detectors have been installed as part of the project. Since the feasibility study data is based on existing conditions and standard forecasts, unforeseen increases in future volumes could impact the ultimate performance of the system.

- **Uncontrolled Entry:** The proposed CARM system will only control the entry of vehicles from entrance ramps within the Segment 1 corridor limits along I-680. Therefore, increased northbound volumes entering from the southern end of the corridor can have a negative impact on the system's ability to control congestion.

- **Downstream Bottlenecks:** Along with uncontrolled entry volumes, the CARM system will only be able to manage conditions within the project corridor where there is sufficient mainline detection and coordinated ramp meters to respond to bottleneck formation. If a bottleneck forms downstream of the Segment 1 corridor, such as near the merge with traffic entering from SR-24 or near Treat Blvd back-ups could lead to degraded conditions in the I-680 Segment 1 AT CARM corridor.

- **Maintenance Constraints:** As mentioned previously, the successful operation of individual ITS devices and equipment are critical to the success of Innovate 680 AT CARM operations. Malfunctioning or non-responsive equipment could have a significant impact on system performance. Therefore, the success of the CARM system could rely on the ability of maintenance resources to quickly respond to problems.

- **Arterial Impacts:** As mentioned previously, the operations and functionality of the arterial roadways that intersect I-680 have a direct impact on those of the Segment 1 I-680 corridor, and vice-versa. Although the project is being designed to contain all metering operations within the ramps and will mitigate impacts to arterials through ramp improvements, and issues are not expected, the impact of operations on the greater roadway network is unknown.

5.7.2 Public Acceptance Constraints

- **Public Acceptance:** The operation of the CARM system will impact typical peak-period travel on the corridor relative to the existing condition, most notably through the introduction of new ramp meters. Although these changes are expected to improve overall travel times and reduce delay along the Segment 1 CARM corridor, these new practices may not initially be popular among or fully understood by all drivers and may result in political or public acceptance challenges.

- **Public and Stakeholder Outreach:** The Innovate 680 AT CARM Project is intended to demonstrate the effectiveness of a traffic management strategy that is new to Northern California. While some of the key elements of the project, like the use of ramp meters, may be familiar to drivers in the California Bay Area, specific aspects of the traffic management strategy including the use of STREAMS®, ramp metering operational characteristics (e.g., time of day, coordinated metering, simultaneous vehicle release, etc.) may be unfamiliar. Targeted public and stakeholder outreach to educate on the purpose of CARM and unique aspects of the operations, as well as regular dissemination of performance monitoring observations, will be necessary to build understanding and support.

6 Justification for CARM Program

This section describes the existing conditions and factors along the Segment 1 I-680 corridor that warrant implementation of the Innovate 680 AT CARM Project. This section also contains an overview of the desired changes offered by the proposed CARM system, relative to the existing condition.

6.1 Current Conditions Warranting Implementation

The Segment 1 I-680 CARM corridor was selected for the first phase of CARM system implementation and further project development based on findings from the *I-680 Advanced Technology Project Coordinated Adaptive Ramp Metering – Corridor Evaluation (2022)*, as described earlier in this document. That feasibility analysis determined the northbound I-680 Segment 1 corridor to be a viable option for initial CARM implementation for two main reasons: regular freeway flow breakdown during peak-periods which has been shown to trigger recurring and severe congestion; and the physical configuration of the corridor, which can accommodate CARM operations without significant construction. As such, Segment 1 is appropriate as an initial implementation to be evaluated against standard Caltrans metering on other corridors in the region after two years of operation. Additionally, the estimated Segment 1 CARM implementation cost also aligns with the $25 million in available STIP funding, and the expected implementation schedule would allow for Segment 1 CARM construction to be integrated with the concurrent Caltrans SHOPP Fiber/TOS/Ramp Metering project. It should be noted that the Caltrans SHOPP Ramp Metering project will be sequenced in order to enable CARM operations on all ramps included as part of the Segment 1 AT CARM project.

6.1.1 Peak-Period Congestion Conditions

As described in section 4.2, feasibility analysis of the CARM system included a detailed corridor evaluation of the I-680 corridor that identified critical bottleneck locations where recurring congestion typically begins. AM peak-period northbound flow characteristics for the identified bottleneck at Sycamore Valley Rd are shown in Figure 6-1. As shown in the traffic flow chart, the average flow per lane increases steadily until around 7:30 AM, when a maximum flow of ~1,600 vphpl is reached. At that point, traffic flow is shown to breakdown, as demonstrated by the drastic reduction in average speed, decreased lane flow, and increase in lane occupancy. Due to this breakdown, volumes in this location average closer to ~1,200 vphpl for the remainder of the AM peak period, representing approximately 400 vphpl in lost throughput. In addition, speeds drop from near 75 mph to closer to 20 mph after flow breakdown, indicating saturated slow-moving conditions at this location.

This phenomenon represents a major loss in freeway productivity at a time when freeway demand is at its highest. Alleviating this sort of volatility and major flow breakdown is the ultimate goal of the Innovate 680 AT CARM system. The pattern illustrated in Figure 6-1 is not unique to the specific location. As documented in 4.2, the pattern of freeway breakdown, and the associated loss of productivity, is witnessed at several bottleneck locations during the AM and PM peak-periods. By automatically adapting to conditions in real-time to minimize this type of freeway breakdown, the CARM system can be expected to greatly reduce the impact of recurring bottlenecks, and result in greater operational capacity, increased speeds, and travel time reliability.

Figure 6-1 I-680 Northbound at Sycamore Valley Rd – Traffic Flow Characteristics

Source: PeMS, Wednesday, Oct 17, 2018, 6:00 AM to 10:00 AM.
Transmax STREAMS® report dashboard

6.1.2 Physical Factors

As noted previously, the Innovate 680 Segment 1 CARM corridor was selected for the first phase of CARM implementation as part of a regional feasibility concept analysis. In addition to traffic conditions, the northbound I-680 corridor between Alcosta Blvd and Olympic Blvd was selected because of existing ramp characteristics.

- **Existing Ramp Storage:** The existing entrance ramps within the proposed Segment 1 CARM corridor are constructed with an existing footprint and configuration to offer a fair amount of vehicle storage, relative to many other entrance ramps in the region. However, these ramps were constructed following traditional Caltrans ramp design principles. Although adequate in terms of typical freeway design, current ramp configurations offer limited flexibility and ramp discharge capacity for CARM operations. As such, the Innovate 680 CARM Project will include ramp modifications to install ramp meters, restripe lane markings within the existing footprint, perform minor pavement widening, and/or combine existing separate loop and direct ramps using minimal barrier placements.

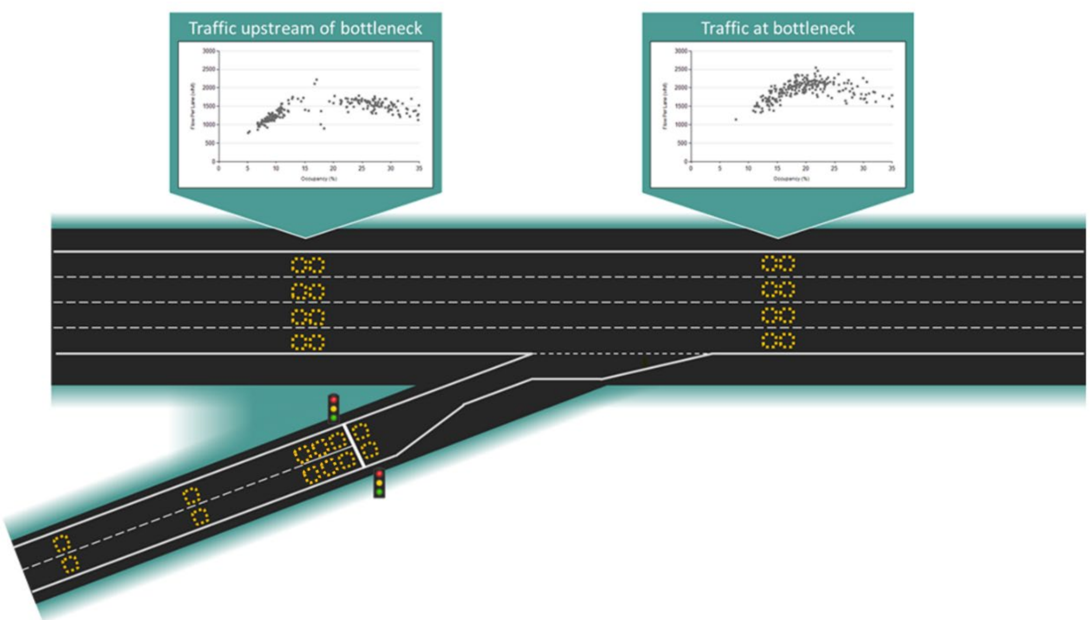
6.1.3 Operational Factors

In addition to recurring traffic congestion and physical conditions, there are several operational factors that also merit the implementation of the Innovate 680 CARM Segment 1 Project.

- **Existing Traffic Detection:** The existing traffic detection devices and detection configuration in the northbound Segment 1 I-680 corridor provide only a limited ability to monitor traffic conditions in real-time. There are several inductive loop installations along the I-680 mainline in the Segment 1 corridor. However, many of the existing mainline loops are located immediately upstream of entrance ramp locations consistent with existing Caltrans ramp metering practices. Additional detector locations along the mainline, especially at the critical entrance ramp merge locations, will be needed in order to provide a complete picture of real-time mainline conditions throughout the corridor (Figure 6-2).

  Inductive loops are also planned for installation as part of the Caltrans SHOPP Fiber/TOS/Ramp Metering Project under concurrent development in the same corridor. However, the installation of these detectors is expected to follow standard Caltrans installations along entrance ramps, which are currently limited to passage and occupancy detectors near the ramp meter stop bar, and back of queue detectors at the top of entrance ramps. Additional loop detectors will be needed within each lane at the mid-ramp location for the CARM system to be able to accurately estimate the number of waiting vehicles and the approximate wait-time each vehicle is experiencing. In addition, an additional detector location can be installed on corridor exit ramps in order to have a detailed understanding of the number of vehicles exiting the corridor in real-time.

Figure 6-2 Significance of Vehicle Detection Placement



Source: GHD

- **Planned Ramp Metering:** The ramp metering system proposed as part of the Caltrans SHOPP Fiber/TOS/Ramp Metering Project is controlled using standard Caltrans District 4 metering practices. Essentially this involved using information from limited vehicle detectors on the freeway mainline as well as vehicle detectors on the entrance ramp near the ramp meter stop-bar. Mainline traffic information and the number of vehicles on the ramp are used to determine the ramp's local metering rate. Although this system meets the needs for locally responsive metering, it has been shown to have limited functionality when compared to modern CARM systems. Furthermore, the recurring peak-period congestion and breakdown of traffic within the corridor underscores the inability of the ramp metering system to address existing traffic conditions.

- **Freeway Management Capability:** There is currently a limited ability to successfully manage and respond to issues on the I-680 corridor due to the existing tools available to TMC operators. As discussed previously, data on existing traffic conditions is not always reliable. Caltrans District 4 TMC operators currently rely on CCTV camera feeds, reports, or communications from law enforcement in order to detect incidents or major events. There is no ability for the existing system to identify traffic abnormalities and indicate a possible issue to operators. Furthermore, if an issue is detected, there is no means to dynamically adjust the ramp metering system in order to prevent compounding the problem, or to assist with the recovery of traffic flow.

6.1.4 Financial & Environmental Factors

Several additional financial and resource realities also reinforce the desire to demonstrate the CARM concept on northbound I-680:

- **Limited Available ROW:** There is limited ROW available along the northbound I-680 corridor. Traditional highway improvements, including possible lane expansion and associated widening of existing structures, would likely require the acquisition of private property, demolitions and large amounts of funding. In addition, the contemporary understanding of the long-term environmental impacts of lane expansion may make that option untenable. The I-680 corridor also abuts the San Ramon Creek and other sensitive environmental resources, further constraining freeway expansion. This underscores the need for corridor improvements to be implemented within the existing ROW, and within the existing freeway footprint, where possible.

- **Limited Funds for Large-Scale Capital Infrastructure:** As with many agencies, CCTA and Caltrans operate with a constrained budget and have limited ability to make major investments in infrastructure. This reality makes it difficult for an agency to justify new civil infrastructure mega projects and produces a need to find more creative solutions that can be implemented with minimal changes to maximize the productivity of existing infrastructure. This reality is one enabler for the Innovate 680 AT CARM Project.

6.2 Desired Project Changes

The Innovate 680 AT CARM Project will introduce new devices, tools, and management practices in the northbound Segment 1 I-680 CARM corridor. The following summary includes a set of components desired for inclusion as part of the CARM system, to address the existing conditions and factors described previously in this section. As described previously, these changes will be delivered in coordination with the Caltrans SHOPP Fiber/TOS/Ramp Metering project.

- **New ramp meters:**
  - Install new ramp meters at all northbound entrance ramps from Alcosta Blvd to Olympic Blvd meeting CARM standards;
  - Allow greater control of the corridor through new corridor-wide metering capability; and
  - Enable the system to have greater response capability to real-time traffic conditions.
- **Optimized ramp vehicle storage and discharge capacity:**
  - Modify entrance ramp configurations, where appropriate, for greater storage and discharge capability;
  - Offer greater operational flexibility to respond to real-time traffic conditions. This includes eliminating the use of HOV priority lanes in order maximize the benefit of the system for all travelers;
  - Better enable ramp queues to be coordinated and balanced throughout the corridor; and
  - Provide the ability to release more vehicles more quickly by releasing vehicles simultaneously at the ramp meter stop bar.
- **Improved traffic detection:**
  - Add new traffic detection technology along corridor to provide more accurate and reliable data for advanced systems;
  - Install traffic detection in additional locations to provide real-time traffic data for entire corridor; and
  - Better enable freeway management and ramp metering systems ability to respond to real-time traffic conditions.
- **Enhanced ramp metering system:**
  - Modernize functionality of meters through deployment of proven, more flexible and sophisticated control logic;
  - Provide complete coordination of ramp meters throughout Segment 1 corridor; and
  - Better enable the ability of central system to respond to real-time traffic congestion.
- **Dynamic freeway management:**
  - Improve freeway management system to provide accurate real-time traffic conditions to operators; and
  - Provide dynamic response capability to CARM system to prevent compounding the impacts of incidents or events, and to better assist in the recovery of traffic flow.

- **Physical impact:**
  - Offer solutions to corridor traffic issues that require only minimal changes to existing infrastructure; and
  - Deploy technology-based tools to address current conditions at limited expense relative to major civil infrastructure investment.

7 CARM Concept & System Description

7.1 Innovate 680 CARM Vision

The Innovate 680 AT CARM Project will demonstrate the effectiveness of the CARM concept to control traffic flows and alleviate recurrent chronic congestion along northbound I-680, as outlined in the Program Overview section 1.1. The Innovate 680 AT CARM Project will be delivered through a phased implementation throughout the Contra Costa I-680 corridor. The Segment 1 AT CARM Project represents an initial deployment of CARM on I-680 that will be evaluated after two years of operations to determine the efficacy of this concept and suitability for permanent deployment. The evaluation is expected to include before and after comparison of a range of performance measures, including changes in travel time, throughput and level of delay, as well as possible comparison to the performance of Caltrans traditional ramp metering deployed along other corridors in the Bay Area region, subject to data availability.

CCTA and the Innovate 680 team will coordinate with Caltrans to determine the appropriate sequencing for activating ramp metering operations along the I-680 corridor. This sequencing will be essential to manage public and stakeholder expectations and the driver experience by avoiding issues that may arise from a drastic change in ramp metering performance due to variations in the effectiveness of different ramp metering approaches.

As discussed previously, the CARM concept being proposed for the I-680 CARM Project was pioneered on the Melbourne M1 Freeway by VicDOT. The initial implementation on the M1 resulted in a significant reduction in peak-period congestion and has now become commonplace in metropolitan freeway corridors throughout Australia. CCTA and Caltrans intend to replicate this CARM concept for the purpose of replicating its success, and to meet the objectives and needs of the northbound Segment 1 I-680 project corridor. To that end, the Innovate 680 AT CARM Project system requirements will closely follow those that have been deployed and documented in Australia. SMART 25 was the first application of the Australian CARM concept in the United States with pilot operations concluding in late July 2022. The SMART 25 Pilot Project has resulted in many lessons learned that can be applied to I-680 to further the success of the proposed AT CARM system.

It should be emphasized that at the time of this writing, CCTA is coordinating with Caltrans t to prepare a PIF for the use of STREAMS® for the initial Segment 1 AT CARM deployment on I-680. The STREAMS® platform developed by Transmax is currently the only commercial system capable of meeting the needs of the CARM concept, and authorized to use the ALINEA and HERO suite of algorithms. As such, the Transmax STREAMS® freeway management platform has been selected for the Innovate 680 AT CARM Project.

The proposed AT CARM concept and system will also closely align with the Riverside County Transportation Commission (RCTC) I-15 Smart Freeways Project in Riverside County, California. The RCTC I-15 Smart Freeways Project is currently in final design stages. Due to the similarities between the RCTC Smart Freeways Project and the proposed Innovate 680 AT CARM system, including scope and key stakeholders (including Caltrans), the proposed operational framework and system configuration for both projects will be related.

7.2 Operational Framework

Management of the Australian CARM system utilizes a software platform that provides modules to control traffic on, through and off the freeway using a suite of algorithms specific to CARM. The Segment 1 AT CARM system proposes to use the same control platform and CARM algorithms as those in use in Australia, used on the SMART 25 Pilot in Colorado, and proposed for the RCTC I-15 Smart Freeways Project. The proposed control platform is known as STREAMS®. The proposed CARM suite of algorithms include adapted versions of the ALINEA and HERO algorithms. The ALINEA and HERO suite (AHS) was originally developed by the Technical University of Crete in Greece, and further refined by VicDOT in Australia over 20 years of CARM development and operation. Transmax is currently the only authorized distributor of AHS in the United States. Although other coordinated ramp metering systems are commercially available, the desire to replicate the Australian CARM principles for I-680 Segment 1 operations requires the use of STREAMS® and its AHS components. To best replicate the results of other CARM systems, the project's system configuration, tuning and support will be performed by Transmax. Transmax staff have detailed experience configuring, tuning, operating, and supporting systems both in Australia and on I-25 in Colorado.

The design and configuration of the AT CARM freeway management system and operating platform is proposed as a remote cloud-based configuration. This is intended to demonstrate the effectiveness of the CARM system as part of Segment 1 operations, without overly disrupting District 4 ramp metering operations on other corridors. A cloud deployment:

- Enables best-in-class physical security, availability, reliability and accessibility;
- Enables scaling and reconfiguration of the system, as required, without constraints imposed by computing power or other limitations on premise; and
- Enables Transmax access for pro-active and re-active system maintenance.

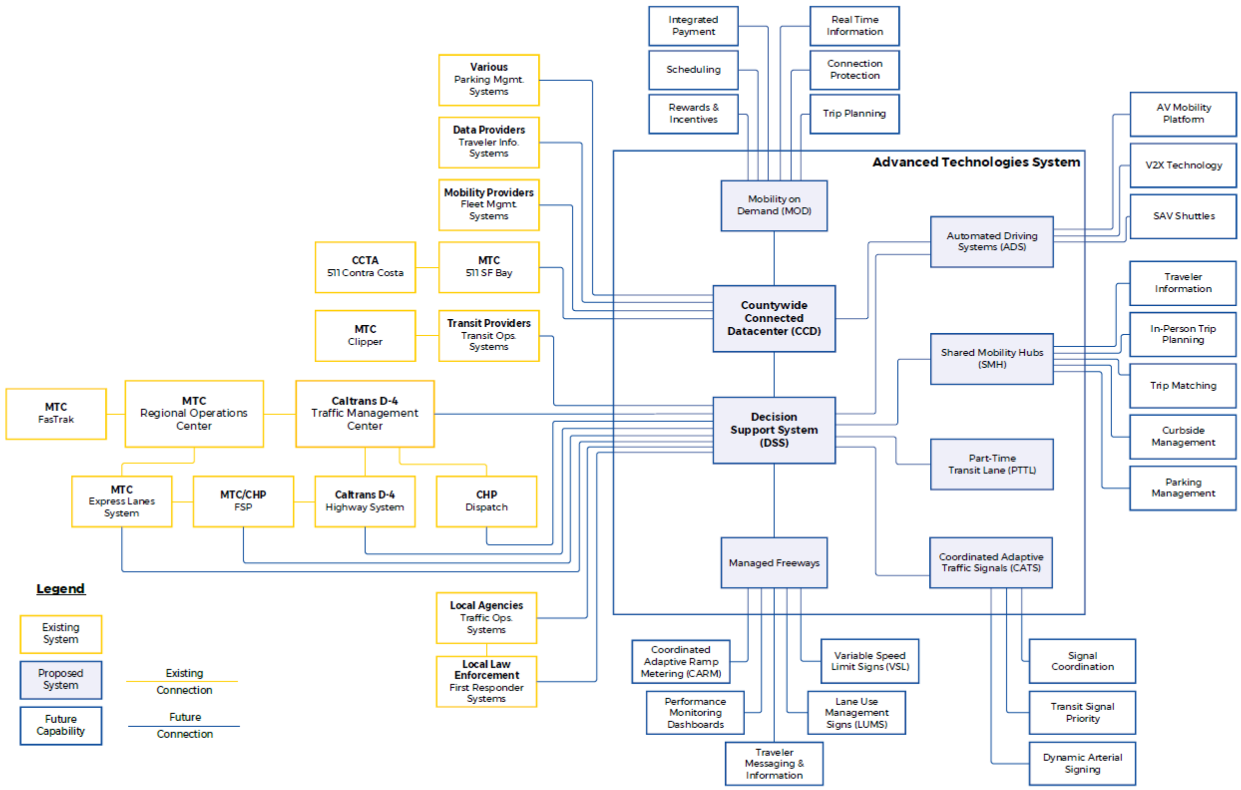
Future phases of the Innovate 680 AT CARM system may require a more substantial integration with existing Caltrans District 4 TMC systems and practices and require training of staff or procurement of dedicated resources to equip the TMC with the skills and equipment necessary to operate an expanded CARM system. However, initial I-680 Segment 1 CARM operations intend to demonstrate the ability of the CARM system to improve corridor performance and provide CCTA and Caltrans with an indication of the level of investment necessary for permanent and expanded operations.

It should also be noted that during Segment 1 CARM operations, other ITS devices in Contra Costa County along I-680 and other freeway corridors within or adjacent to the Segment 1 CARM corridor, including ramp meters, VDS, CCTV, mainline VMS signage and other ITS assets, will continue to operate under the purview of Caltrans District 4.

7.2.1 Innovate 680 Program System Integration

The greater Innovate 680 program is compiled of several individual projects, as described in section 1.1. Each of these disparate systems are envisioned to function cooperatively on a holistic, corridor-wide basis. The program envisions an overarching "system-of-systems" that ties together the various proposed program components and management systems. The planning level architecture of the proposed program system is summarized in Figure 7-1 below, and further detailed in the *Innovate 680 – Program Concept of Operations* document.

Figure 7-1 Innovate 680 Program System Architecture



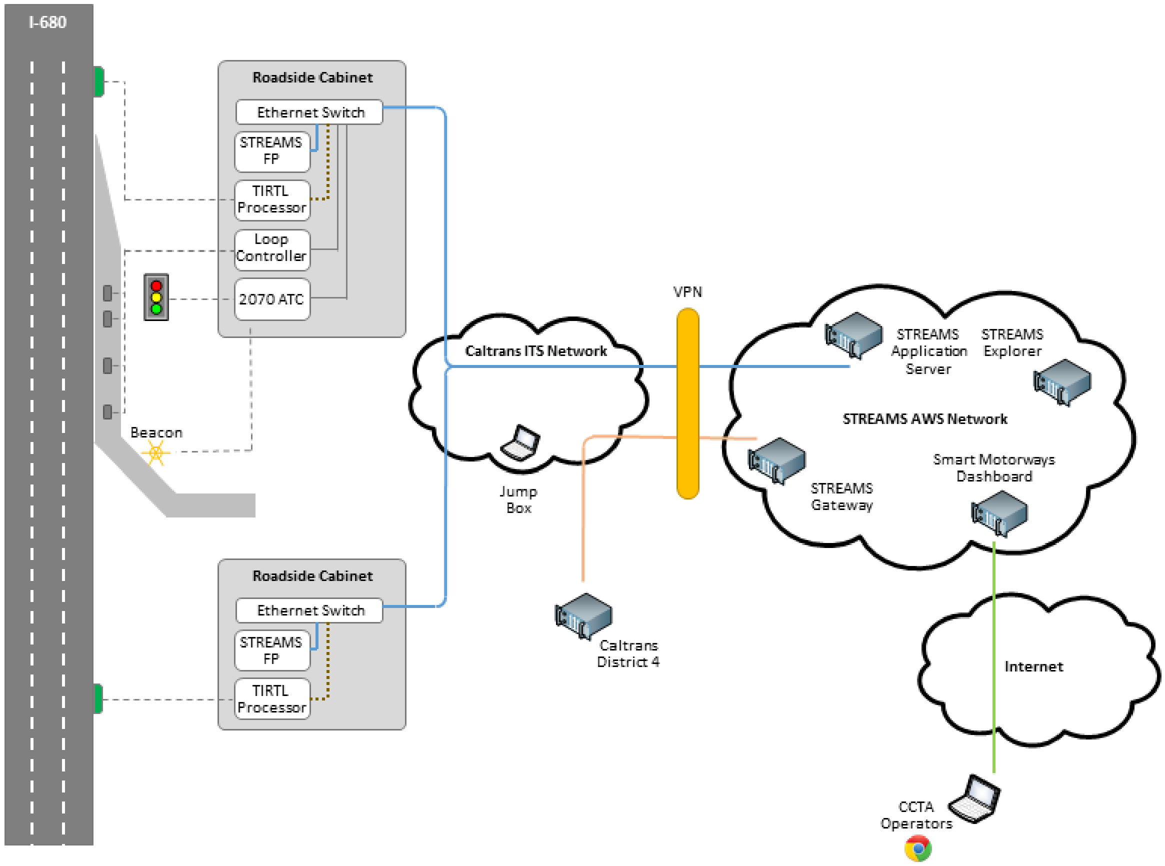
Source: WSP, 2021

The proposed Segment 1 CARM system is envisioned to eventually integrate and operate as part of the program system architecture. However, it should be noted that the program architecture presents an idealized version of system and subsystem components to support the operational concept of the Innovate 680 program. Certain program elements are not currently funded, and Segment 1 CARM operations are expected to initially operate without direct integration to other program elements.

7.2.2 Conceptual CARM System Architecture

The proposed Segment 1 CARM system will utilize a cloud-based production environment. Transmax C&T and Support teams will be physically located in Australia during operations, although onsite visits by team members may be required during initial system testing and calibration activities. It is anticipated that CCTA (and/or Caltrans) will also contract a separate entity to provide operations monitoring and adjustment for initial Segment 1 CARM operations. It is anticipated that the CCTA Operations staff will be based within the United States but may work remotely to provide oversight of the system operations. The proposed conceptual CARM system architecture is shown Figure 7-2.

Figure 7-2 Conceptual Model of CARM System Architecture



Source: Transmax

System traffic condition management requires capturing real-time speed, volume and occupancy information sensed by corridor vehicle detectors along the mainline and entrance ramps. The vehicle detection devices proposed for use as part of CARM operations, and which meet VicRoads standards documented in this section, include:

- Inductive loop detectors on corridor entrance and exit ramps;
- The Infrared Traffic Logger (TIRTL) detectors on the I-680 mainline.

The STREAMS® Application Server (AS) is responsible for processing vehicle detection data, applying the collection of AHS algorithms, and subsequently instructing the ramp signal controller to meter at the calculated optimal metering rate. This central processing of vehicle detection information by the STREAMS® AS, rather than the ramp signal controller, is imperative for the coordination of metering rates between the ramps in the corridor.
In the field, the STREAMS® Field Processor (FP) is responsible for integration with individual vehicle detectors and ramp signal controllers, and for managing communication with the STREAMS® AS. Communication between the STREAMS® AS and STREAMS® FP is protected using a secure tunnel connection. In this model, all information from corridor vehicle detectors is routed through STREAMS®, and there is no direct integration between the ramp

signal controller and vehicle detectors. Information and instructions are sent to, or received from, the STREAMS® AS via the STREAMS® FP.

Ramp signal controllers are responsible for actuating ramp signals and advance warning flashing beacons. The ramp signal management function provides for configuration, control and monitoring of ramp signal controllers to achieve the continuous calculation and setting of ramp metering rates.

The Transmax C&T Team utilize the STREAMS Explorer client application as a user interface to STREAMS to deliver the following services:

- Infrastructure data specification and configuration (to allow communication and control of ITS devices);
- Geographic data specification and configuration (configuring the local transportation network model);
- Control data specification, scheduling and scripting (such as time of day ramp metering schedules employed as a failure mode in the event of hardware faults and/or communication loss); and
- Specifying parameters used by the AHS suite of algorithms.

The system will utilize all of the above information to measure, calculate and instruct ramp metering activation and deactivation, and set optimal metering rates at each ramp. Additional services that the STREAMS Explorer client provides to the Transmax C&T Team include:

- Support and maintenance reporting (such as the system availability of field processors);
- Data viewers (map, street directory and spreadsheet/list) to facilitate set up and management of ITS devices;
- Reports (real time/historical) to support testing and tuning of ramps;
- Fine grained user access control for the appropriate management of system security;
- Application management (to ensure the STREAMS AS software and services are continuously available);
- Scripting interpreter (to provide customized data processing) where required;
- Data management (to control data retention, aggregation and sharing);
- Determination and specification of critical bottleneck locations and measures from this site; and
- Platform management (to monitor server infrastructure and associated hardware for available capacity and reliability).

The user interface for monitoring and overriding ramp signals in the system is accessed remotely by the CCTA Operations staff via the Smart Motorways Dashboard using a web browser. Key services provided via this interface include:

- Monitoring the operational state of the ramp metering sites;
- Monitoring travel time, average vehicle speed and flow on the mainline;
- Monitoring wait time and queueing on ramps;
- Monitoring the health of vehicle detectors on ramps and the mainline;
- Comparison between the current travel time for the corridor vs. historical averages;

- Presentation of heat plots for the corridor showing speed, volume and density (as measured by occupancy) in near real time, and historically;
- Presentation of daily heat plots allowing simultaneous comparison of individual days over four weeks;
- Presentation of snapshots showing metering behavior and queuing across the corridor in near real time;
- Charting of minute speed, flow and density (as measured by occupancy) readings across user specified time periods;
- Historical review of ramp metering rates and queuing; and
- Override of ramp signal controllers to discontinue metering.

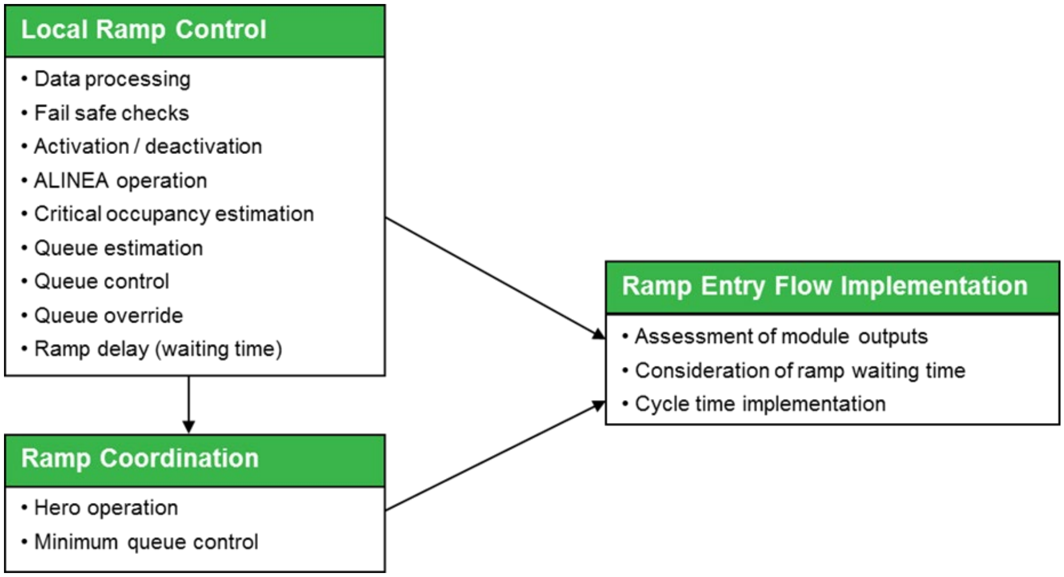
7.2.3 Ramp Metering System Functionality

AHS provides the suite of algorithms that powers the proposed CARM system as part of the I-680 Segment 1 operations, and provides for the following:

- Dynamic start-up and shut-down algorithms that ensure the system (and associated metering at each ramp location) only operates when required;
- Application of contemporary traffic theory for optimizing freeway flow;
- Control logic based on feedback from downstream conditions in real-time;
- Dynamic adjustment to signal cycle times at each ramp (individually);
- Use of lane occupancy from freeway bottleneck locations detected in real-time as the primary optimizing measure;
- Fully configurable parameters;
- Integrated operation of isolated ramp control within a dynamic coordinated system based on refined operating rationale;
- Management of flow at interchanges by linking upstream ramps;
- Ability to manage bottlenecks detected anywhere in the corridor regardless of proximity to the nearest ramp;
- Consideration of mainline performance at multiple detected mainline bottleneck locations simultaneously to determine the critical bottleneck; and
- Simultaneous release of vehicles at the ramp meter stop-bar.

AHS manages the ramp traffic flow entering the freeway by monitoring and controlling the freeway flow at each ramp merge as well as other critical bottleneck locations. Ramp discharge flow calculations are based on various modules providing outputs for isolated and coordinated operation as shown in Figure 7-3. The central ramp metering control system calculates the appropriate actions determined by the algorithms and passes the adjustments to the ramp signals. This process is continually re-calculating every 20 seconds to reevaluate corridor conditions and revise ramp metering logic and signal timings to prevent mainline flow break-down while also balancing ramp queuing and wait-times.

Figure 7-3 ALINEA & HERO Suite (AHS) CARM Algorithm Module



Source: Transmax

7.2.4 Data Collection

CARM operations rely upon a detailed digital representation of freeway ramps and associated devices. A summary of key configuration activities is presented in Table 7-1. The data required for CARM will be collected directly from VDS devices and does not require information exchange between STREAMS® and other centralized ITS systems. Vehicle detection information exchange (via proprietary protocols) includes volume, occupancy and speed. Ramp signal controller information exchange (via NTCIP protocol) includes ramp metering rate and status monitoring.

Table 7-1 Configuration Data for Ramp Management

Item	Required Configuration Data
Maps	• Raster maps for visualization of the road network • Geographic Information System (GIS) based vector maps • Roadway network specification based on GIS Maps and project design drawings
Technical Drawings	• Placement of static and electronic signs (x,y) • Placement of ITS devices (x,y) • Line markings, gore on ramps and mainline • Mile point markers (x,y)
Ramp	• Ramp name, type and description • Number of metered lanes • Length of the ramp.
Ramp Metering site (from to-scale drawings with coordinates)	• Ramp metering site name and description • Type of ramp signal controller • Distance from the ramp stop line to the start of the freeway movement • X & Y coordinates of roadside cabinet, stop bar, passage detectors, stop bar detectors, mid queue detectors, ramp entrance detectors and upstream arterial detectors

	• Ramp storage capacity under normal stand-still spacing and bumper-to-bumper spacing. • Name and location of cameras from which RSC, signals and stop bar are visible
Ramp Signal Controller (RSC)	• RSC make, model, firmware, firmware version • RSC IP address • Name and IP address of local network switch in the roadside cabinet • Port number (assumed 161) • Details of associated warning beacons and ramp condition signs • Mile point and x,y coordinates • Minimum and maximum permitted metering rates • Vehicles per green per lane
Ramp Signal Groups	• The ramp metering site at which the signal group is located. • A short name, hardware ID and owner of the ramp signal group • The type of lamp technology used in the lanterns in the ramp signal group. • A description of where the ramp signal group is positioned on the ramp.
Vehicle Detectors	• Name, description, type • IP address and port number for controller • Username and password • X & Y Coordinates • Chainages to stop bar • Default Speed Limit • Lane ID • Detector length • Name, location and IP address of the network switch to which it connects
Other Devices	• Required configuration of any other ITS devices

7.3 Standards & Specifications

Requirements for CARM are based on two seminal guidance documents produced by VicDOT (formally known as VicRoads) in Victoria, Australia. The first is the *VicRoads Managed Freeways: Freeway Ramp Signals Handbook (July 2013)*, which was published by VicRoads as documentation of the Managed Freeways concept for the M1. The second is the *VicRoads Managed Motorways Framework (March 2017)* which provides the rationale and supporting evidence behind the active management of Melbourne's motorways. The documents concur on the requirements for vehicle detection and the importance of reliable and accurate traffic data at appropriate locations to obtain real-time lane-level information. Two key requirements are considered in design and cost development:

- Number and placement of detection devices; and
- Required vehicle detection device accuracy.

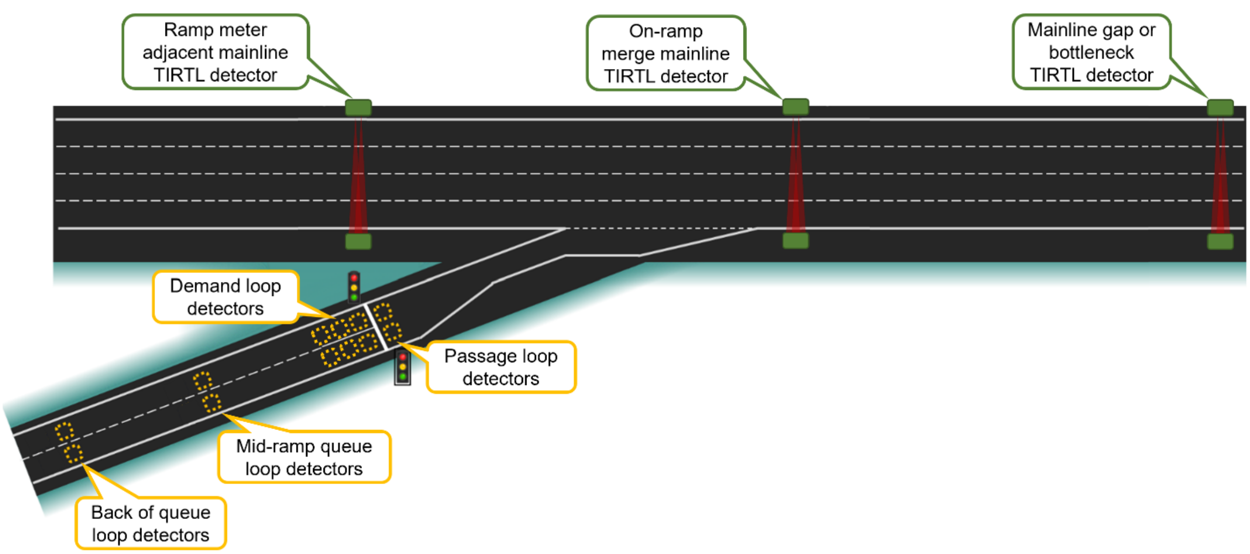
Vehicle detection devices should be installed on the mainline to cover the full length of the freeway corridor with detectors providing data for all lanes at each point. This would generally include the following locations as listed below and illustrated in Figure 7-4.

1. Corridor Mainline
    (a) At the end of the on-ramp merge, approximately 1,000 feet downstream of the gore point of a single lane merge. This location is often the primary mainline site for ramp metering control where a merging bottleneck may occur.
    (b) Just upstream of the on-ramp gore point, typically abeam the ramp metering stop bar. This location is typically the primary detector site for legacy feed-forward ramp metering algorithms and would be required for Caltrans to revert CARM sites to legacy metering if desired.
    (c) Just downstream of the exit ramp gore point.
    (d) Potential bottleneck locations where traffic flow needs to be managed, such as weaving areas, just downstream of lane drops, on steep upgrades, around tight curves and in areas where the freeway mainline is narrowed (e.g., areas with reduced shoulders, narrowed lanes and close proximity to structural objects like barriers, bridge abutments, retaining walls or sound walls).
    (e) Remaining locations typically to ensure not more than approximately 1/3 mile spacing along the full length of the freeway corridor.

2. Corridor Ramps
    (a) Demand (upstream) and passage detectors (downstream) of the on-ramp meter stop-bar
    (b) Back of queue detectors at entrance/s of the on-ramp
    (c) Mid-ramp queue detectors near center of the length of the ramp storage area

Coordination of detection locations with other ITS assets should also be considered to facilitate constructability and minimize costs, e.g., for provision of power, communication connections, maintenance, etc. However, when this is being considered in design it should not compromise adoption of locations required for operational control.

Figure 7-4 CARM Freeway Detector Configuration



Source: GHD

The *VicRoads TCS 048-2018 Specifications for the Supply of Freeway Data Stations (2018)* summarizes the accuracy requirements for data collection on CARM corridors, shown in

Table 7-2 and Table 7-3. Based on these placement and accuracy requirements developed by VicDOT, the Innovate 680 AT CARM Project will require additional detection along the mainline and on corridor entrance and exit ramps. The TIRTL detector is proposed for mainline detection on the Segment 1 CARM corridor. TIRTL detection devices exceed the accuracy standards for mainline detection and have become standard for contemporary Smart Freeways deployments by VicDOT. Caltrans standard inductive loop detectors are commonplace on existing metered ramps within Caltrans District 4. The Segment 1 AT CARM Project will continue the use of inductive loops on ramps but will supplement typical Caltrans District 4 detection placement with additional loops at the midpoint of entrance ramps and on exit ramps to meet VicDOT guidelines and CARM system needs.

Table 7-2 CARM Traffic Data Accuracy Requirements (Mainline)

Data per Vehicle	Range	Accuracy	Maximum Response Time
Speed	6-100 mph	±2%	0.3 s
Presence Event	On-Off	±2%	0.3 s
Length	6-115 feet	±2% or 9 inches	0.3 s

Table 7-3 CARM Traffic Data Accuracy Requirements (Ramp)

Data per Vehicle	Range	Accuracy	Maximum Response Time
Speed	6-81 mph	±2%	0.3 s
Presence Event	On-Off	±2%	0.3 s
Length	6-115 feet	±2% or 9 inches	0.3 s

7.3.1 System Performance

The STREAMS® freeway management system reporting function will conduct the following:

- Produce a list of freeway routes;
- Produce a list of freeway ramps;
- Produce a list of ramp metering sites;
- Produce a list of ramp signals;
- Produce a list of ramp metering algorithms;
- Produce a freeway ramp real-time performance report; and
- Produce a freeway mainline real-time performance report

Transmax C&T Team will review historical and real-time freeway performance outputs to optimize the performance of the STREAMS® AHS system of CARM by modifying parameters as needed. System performance summaries will also be shared with project stakeholders through the provision of a read-only web platform. The web-based platform will allow stakeholders to view real-time and historical system performance and functionality.

7.3.2 System Availability

As a real-time system, CARM is heavily reliant upon continuous network connectivity and service continuity. In addition to the vehicle detection accuracy requirements defined in Table 7-2 and Table 7-3, service level targets for key system and device components will also be stipulated during later project development.

Periodic scheduled outages may be required for STREAMS® upgrades and security patching. These can be negotiated in advance and are typically performed outside of peak-periods for durations of less than one hour per month. The STREAMS® AS is responsible for processing vehicle detection information and calculating optimal metering rates. During an outage to the STREAMS® AS, ramps may fall back to time-of-day metering rates. The STREAMS® AS is monitored by Transmax and deemed to be available if a STREAMS® Explorer workstation can connect to the AS and display a list of configured ITS devices. The STREAMS® AS is not directly accessible by stakeholders other than Transmax C&T, CCTA Operations Staff and Transmax Support Teams. Should an event occur resulting in an outage to the STREAMS® AS, Transmax seeks to have the service restored promptly, within hours, to minimize data loss.

An availability target for the AWS Direct Connect/VPN connection will also be specified later in project development to lessen the impact of unplanned outages. The selection between an AWS Direct Connect service or a conventional IPSec tunnel redundant pair will be determined nearer to time of implementation. The AWS Direct Connect/VPN link is responsible for integrating the STREAMS® AS with the Caltrans ITS network. The availability of the link will be monitored by both Caltrans N&I Specialists and the Transmax Support Team. In the event of an outage, the two teams will collaborate to promptly identify the root cause and instigate corrective actions.

Periodic scheduled outages may be required for STREAMS® Dashboard upgrades and security patching. These can be negotiated in advance and are typically for durations of less than one hour per month. The STREAMS® Dashboard is the component responsible for Caltrans and CCTA's browser-based access to reports and schematics. During an outage to the STREAMS® Dashboard, ramp metering management may continue, but will not be visible or controllable by Caltrans or CCTA. The STREAMS® Dashboard is monitored by Transmax and deemed to be available if an external user is able to connect to the Dashboard and display the Current Travel Time report. Should an event occur resulting in an outage to the STREAMS® Dashboard, Transmax also seeks to have the service restored quickly to maintain the provision of system performance information and reduce data loss.

Individual network devices include network switches, media converters and radios responsible for enabling communication between ITS devices in the field and the end points for AWS Direct Connect connection. Field network devices are deemed to be available if more than one upstream device and more than one downstream device is visible on the network from the STREAMS® AS (assuming the AWS DirectConnect connection is also available) and all necessary network services are provided upstream and downstream of the device (e.g., DNS, NTP). During an outage to an individual ITS field network device, one or more ITS devices will be unreachable or inoperable from the STREAMS® AS. Field ITS network devices will be monitored by CCTA Operations Staff with support from Caltrans N&I Specialists, as needed. Availability targets for individual field network devices will be further defined in later stages of project development.

Individual ITS devices include ramp signal controllers, ramp signals, beacons, field processors, TIRTLs, loops, and all the associated controllers and ancillary devices necessary for them to continue operation in a production capacity. Individual ITS devices are collectively responsible for sensing and controlling traffic flows on the freeway. Outages to individual ITS devices can severely impede or entirely prevent ramp management control. ITS device status will be pro-actively monitored by the CCTA Operations staff using the STREAMS® Dashboard and reactively monitored by the Transmax Support Team. Should an ITS device become unavailable, corrective measures are to be managed by CCTA Operations staff with direction to the ITS Maintenance Contractor and other parties identified in Table 5-2.

7.3.3 System Execution

Granular operational monitoring and control for the CARM system will be conducted by qualified and trained traffic management specialists to:

- Monitor the activation and de-activation of ramp meters;
- Identify ITS device faults and failures and initiate corrective actions;
- Explicitly discontinue metering at individual ramp sites should it be required; and
- Contribute to the determination of critical bottleneck sites and review performance outcomes post tuning.

7.4 CARM Operational Perspectives

This section contains general descriptions of the different operational viewpoints of the proposed Innovate 680 AT CARM system, in terms of how the system will function and how benefits will be realized from a user perspective.

7.4.1 System Users

System users consist of the secondary stakeholders identified in Table 5-1 who travel some or all of the I-680 AT CARM corridor, including:

- Local Emergency Response;
- Transit Operators;
- Local Drivers (both commuters and other motorists); and
- Commercial Fleet Operators.

7.4.2 System Operators

The roles and responsibilities for entities contributing to the operation of the Segment 1 CARM system are outlined in the RASCI model in section Table 5-1. At an organizational level, these are summarized below:

- **CCTA:** CCTA operations responsibilities will be focused on the management of contractors engaged in the provision of project management, direct operations and maintenance resources. CCTA will oversee general operations of the Innovate 680 AT CARM system, facilitate local stakeholder input on operations, and oversee the evaluation of system operations.

- **Caltrans:** Caltrans District 4 responsibilities during Segment 1 CARM operations, which are focused on continuing their normal freeway operations, include:
    - Management and maintenance of its infrastructure;

- Management of ITS devices and network infrastructure, including CCTV, VMS, and PeMS;
- Incident management on infrastructure under its control; and
- Managing stakeholder and external inquiries on general freeway operations.

It is also anticipated that Caltrans District 4 will identify staff to be trained in the operation of the CARM system during Segment 1 operations, including the use of the STREAMS operator's dashboard. This training will be conducted in anticipation of Caltrans potentially being tasked with operating the CARM system on an ongoing basis during later Innovate 680 project stages.

- **CARM Project Team:** The CARM consulting team will manage day-to-day oversight of the I-680 AT CARM system under the direction of CCTA. Specific oversight responsibilities include:
    - Day-to-day management and oversight of project operations;
    - Stakeholder engagement and public outreach;
    - Performance evaluation reporting; and
    - Facilitating coordination between Transmax, Caltrans, CCTA, and CCTA Operations staff.

- **Transmax:** Transmax responsibilities during Segment 1 CARM operations, which are focused on hosting, operations and technical support for the CARM system, include:
    - Setting up and maintaining the road network GIS base in STREAMS® using the Transport Network Specification (TNS), including ways, intersections, links, freeway routes, ramps, etc.;
    - Creating devices in STREAMS®, including field processors, detectors and detector sites, ramp metering sites, etc.;
    - Configuring and checking accuracy and availability of detectors and other devices;
    - Configuring all data stations correctly;
    - Identifying all field device faults on a regular basis and initiating rectification or communicating problems to the CCTA Operations Staff or Caltrans, as appropriate:
    - Setting up all initial ramp metering parameter values in STREAMS®, including default ramp properties, algorithm configurations for ramps and mainline, and time of day defaults;
    - Reviewing and adjusting all default settings of ramp metering parameter values in STREAMS®, including ramp properties, algorithm and configurations for initial switch on and progressive implementation for ramps and mainline, etc. This includes multi-bottleneck arguments and switch on and coordination configuration;
    - Provide first, second and third level technical support to the STREAMS® software components of the solution;
    - Analysis, adjustment and refinement of the system operation from time to time to ensure optimum on-going operations;
    - Running real-time and historical reports to demonstrate performance of the freeway and ramp metering operation; and.

  - Setting up and maintaining STREAMS® Dashboard web platform to facilitate sharing of corridor operations and performance to interested stakeholders.

- **CCTA Operations Staff:**
  - Operation of the CARM system including ramp meters and associated ITS devices;
  - Day-to-day monitoring, management and adjustment of the CARM system;
  - Escalation to Transmax for identified system configuration, tuning and device connectivity information requests;
  - Coordination with Caltrans and ITS Maintenance Contractor to diagnose and troubleshoot device and communications faults; and
  - Initiating actions in emergency situations when requested by Caltrans (e.g., switching off/on ramp metering during an incident or when system or device faults occur, if available, although general practice is to leave all ramp meters switched on during incidents as it has been shown to provide a safer and more efficient outcome);

7.4.3 Interaction Framework

The channels for communication and interaction are to be maintained at three levels during CARM system operations:

1. Day-to-day interaction, as necessary, between Caltrans, CCTA, Transmax, and CARM consulting team, particularly regarding managing incidents, faults, and other projects. This includes:
   - Communication and sharing of intelligence relating to operations during events (congestion and/or incidents);
   - Collaboration on the operation of ramp metering to address traffic management needs during events;
   - Consultation and agreement regarding planned maintenance which would generally be outside of peak-periods; and
   - Change management of any system components (using an appropriate change management framework).

2. Periodic interaction in relation to performance monitoring and outcomes.

3. Management oversight of general arrangements to ensure collaboration and good working relationships, as well as satisfactory resolution of any concerns.

E-mail addresses and contact phone numbers to facilitate two-way communication are to be provided for day-to-day interaction. The STREAMS® Dashboard will also be enabled to respond to operational requests, during incidents, and/or other information sharing situations. Jira ServiceDesk is proposed for logging and managing system support tickets.

7.4.4 Communication of Device Status

The STREAMS® Dashboard platform will provide an easily accessible reference to confirm working status of critical devices. In addition, the operational status of a device can also be checked by the Transmax Support Team via the IT Service Management product.

7.5 Traffic Management Devices

CARM operations proposed as part of the Innovate 680 AT CARM Project will use ramp meter signals and a number of associated ITS devices to manage traffic flows.

7.5.1 Ramp Meter Signals

Traffic signals are displayed to control traffic on each of the entrance ramps. A typical example of a ramp meter signal installation following the *Caltrans Ramp Metering Design Manual (2022)* is pictured in Figure 7-5. The signals are supplemented with static signs indicating 'STOP HERE ON RED' and 'ONE VEHICLE PER GREEN EACH LANE.' New ramp meter installations as part of the Segment 1 AT CARM project will replicate the signal configuration shown in the photograph below, with overhead three-section (red, amber and green) signals mounted over each lane using an overhead mast arm. Signals will also be placed on side mount pedestal poles (left and right), with upper three-section signals and lower two-section (red and green) signals. Signs are also proposed to be modified to remove HOV priority lanes in order to provide for general-purpose use in all lanes to maximize storage, discharge capacity and operational flexibility.

Figure 7-5 Typical Ramp Meter Signals

Source: WSP

7.5.2 Flashing Beacons and Ramp Status Warning Signs

Warning signs with a flashing beacon as shown in Figure 7-6 are provided on each side of the ramp near the ramp entrance to warn drivers that the ramp metering signals are on or switching on. As the static warning signs can be seen at all times, they also reinforce to motorists that the signals are present on the ramp and may commence operation at any time. Activation of the flashing beacon is typically linked to the ramp metering signal controller to initiate flashing in conjunction with the activation of ramp signals.

To supplement the Caltrans standard ramp signal advanced warning signs and flashing beacons, small VMS signs will be located on each arterial approach to on ramps. These signs will follow a VicDOT format to provide ramp status information to drivers as shown in the example in Figure 7-7. The inset in Figure 7-7 shows potential MUTCD compliant display options consistent with the standard display options used by VicDOT to indicate ramp status. These include warnings with messages stating 'RAMP METER AHEAD' and 'RAMP CLOSED', as well as the ability to generate and display other specified messages.

Figure 7-6 Ramp Signal Advanced Warning Sign and Beacon

Figure 7-7 Example Supplemental Ramp Status VMS

7.5.3 Vehicle Detectors

The availability of high-quality traffic data (flow, speed and lane occupancy) in locations to suit system operation is crucial to effective operation of the CARM ramp metering system.

- **Mainline Data:** The mainline detectors will be placed upstream and downstream of corridor entrance and exit ramps, at critical bottlenecks, and at other locations to create corridor-wide detection nominally every 1/3rd-mile along the freeway. These detectors are used for real-time speed, flow and lane occupancy data. TIRTL detectors are proposed for mainline detection for Segment 1 CARM operations. As shown in Figure 7-8, TIRTL detectors work as a transmitter and receiver pair and can be installed within cabinets in several configurations.

Figure 7-8 Typical TIRTL Installations

Source: WSP

- **Ramp Data:** Detectors are also provided at the following locations along corridor ramps to calculate queue lengths, manage queues and waiting times, and detect exiting vehicles:
    - In each lane downstream of the entrance ramp stop bar (passage detectors);
    - In each lane immediately upstream of the entrance ramp stop bar (demand detectors);
    - In each lane roughly at the mid-point of the entrance ramp (mid-queue detectors);
    - In each lane immediately downstream of the entrance to the ramp (back of queue detectors); and
    - On exit ramps immediately downstream of the gore point.

  Ramp detectors are proposed to be inductive loops configured to follow the *Caltrans Ramp Metering Design Manual (2022)*, including installation of the optional mid-queue detectors and exit ramp detectors.

7.5.4 CCTV Cameras

CCTV camera coverage with pan, tilt, zoom (PTZ) functionality will be provided by Caltrans District 4 and BAIFA to select CCTA Operations Staff and Transmax Support Team participants to facilitate surveillance of the freeway and ramps. CCTV access is required to provide 100% coverage of corridor ramps as well as the corridor mainline. Existing CCTV coverage of the corridor will be reviewed during the preliminary design phase to determine if installation of additional CCTV cameras will be required to provide full coverage of the corridor.

7.5.5 Part-Time Shoulder Use and Lane Use Management System Signage

The Sycamore Valley Road interchange direct ramp and the Olympic Boulevard interchange direct ramp will both be striped to provide part-time shoulder lanes open to traffic only when the ramp meter is on. The shoulder lanes will be equipped with an overhead Lane Use Management System (LUMS) VMS and accompanying pole-mounted VMS and static signs to advise on the status of the shoulder for use by traffic. These VMS are proposed to have full-color, full-matrix capability. An additional pole-mounted static sign with the message 'SHOULDER DRIVING PERMITTED ON ARROW' in black font on a white background will be placed beneath the pole-mounted VMS. Figure 7-9 depicts an example part-time shoulder LUMS sign assembly on I-405 near Seattle that includes the overhead LUMS VMS, the accompanying pole-mounted VMS and the pole-mounted static sign. The example in Figure 7-9 indicates the shoulder is open to traffic. Figure 7-10 illustrates the messaging to be provided on the LUMS sign and accompanying VMS when ramp metering is on (i.e. the shoulder is open to traffic) and when ramp metering is off (i.e. the shoulder is closed to traffic and the right lane ends), respectively.

During periods when ramp metering is on, the overhead LUMS sign, which will be centered over the shoulder lanes , will display a downward pointing green arrow indicating the shoulder area is open to traffic. The accompanying pole-mounted VMS sign will simultaneously display 'SHOULDER OPEN TO TRAFFIC'. These displays will be activated by the ramp metering system as part of the start-up procedure described in section 8.2.2.

During periods when ramp metering is off, the overhead LUMS sign will display a red 'X' indicating the shoulder area is closed. The pole-mounted VMS sign will simultaneously display a 'Right Lane Ends' symbol with black symbols on a yellow background, consistent with the Manual on Uniform Traffic Control Devices (MUTCD) Type W4-2 sign.

Figure 7-9 Example Part-Time Shoulder Lane Use Management System, I-405 near Seattle, Washington

Image source: Wikipedia

Figure 7-10 Proposed Message Concept for Part-Time Shoulder Use Lane Use Management System Signage and Associated VMS

Ramp Metering On		Ramp Metering Off	
Overhead LUMS Sign	Pole-Mounted VMS	Overhead LUMS Sign	Pole-Mounted VMS

8 Operational Scenarios

This section describes how the proposed Innovate 680 AT CARM system would operate under typical operational scenarios. The intent of these scenario descriptions is to clearly outline system practices, major stakeholder roles and responsibilities, and anticipated actions under different conditions. Operational descriptions are not wholly comprehensive but are meant to illustrate what could trigger specific actions or practices, whether the system, CCTA Operations Staff, Caltrans District 4 TMC, or Transmax Support Team is responsible for the action, and what communications are anticipated between stakeholders.

8.1 Typical Off-Peak Operations

The default condition for the Segment 1 AT CARM system is for ramp meter signals to be turned off. Since the intent of the CARM system is to respond to traffic flow disturbances caused by increases in lane occupancy observed in real-time, it is anticipated that ramp meters will be inactive during lower-volume off-peak times of day. Off-peak times are considered as the periods in between peak AM and PM periods, both in the late evening and overnight, as well as midday (mid-morning to early afternoon). During these periods of lower traffic demand, lane occupancy is expected to remain below critical thresholds and therefore I-680 CARM operations will be limited to the monitoring and recording of real-time traffic conditions. Additionally, these times may be used for system analysis and adjustment, as well as equipment and device maintenance. If the Segment 1 AT CARM system detects increases in lane occupancy reaching critical thresholds during off-peak periods, the system can automatically enable typical CARM operations, as described later in this section. Specific tasks associated with Segment 1 CARM operations during off-peak periods are described below.

8.1.1 Monitoring and Reporting of Real-Time Corridor conditions

During off-peak operations of the Segment 1 AT CARM system, real-time corridor conditions will be continuously monitored and recorded for later analysis. Real-time information will also be available via the proposed Smart Freeways web dashboard. Recorded information will include:

- Traffic volumes from corridor mainline and entrance ramp detectors;
- Lane occupancy from corridor mainline and entrance ramp detectors; and
- Average speed information from mainline vehicle detectors.

In the event that real-time monitoring indicates increases in lane occupancy reaching critical thresholds during off-peak periods, the system can automatically respond by initiating typical CARM operations.

8.1.2 System Analysis and Refinement

During off-peak operations of the Segment 1 AT CARM system, when ramp meters are inactive, the Transmax C&T Team and/or the CCTA Operations Staff may utilize this time to analyze performance data from previous peak-period operations and investigate adjustments to system parameters. It is anticipated that these activities would likely take place during midday or late evening periods, in between the PM and AM peak periods. Possible refinements to the system may include, but are not limited to:

- Adjustments of control algorithms to better prevent the formation of specific bottlenecks;
- Adjustments of metering rate minimum and maximum settings of individual ramps to better anticipate the length of queues at any given entrance; and
- Operator overrides on specific ramps to account for damaged or malfunctioning equipment.

8.1.3 Planned System Maintenance

As described previously, the Segment 1 AT CARM system must monitor and respond to traffic conditions in real-time. Any non-responsive or malfunctioning equipment could have a major impact on the functionality of the I-680 system, and therefore will require readily available maintenance resources to quickly respond to any problems. It is anticipated that maintenance activities will take place during off-peak periods, in order to prevent impacts to peak-period traffic conditions, and in accordance with existing Caltrans policies for I-680.

Table 8-1 describes the key roles and responsibilities of individual Segment 1 AT CARM stakeholders during typical off-peak operations.

Table 8-1 Role & Responsibilities – Typical Off-Peak Operations

Stakeholder	Roles & Responsibilities
Transmax C&T Team	• Monitor and record real-time corridor traffic conditions for later analysis. It is anticipated that this would be mainly an automated function of the STREAMS® freeway management system. • Periodically analyze system performance. • Investigate augmentations to STREAMS® system parameter settings when needed.
CCTA Operations Staff	• Monitor corridor performance and complete adjustments as necessary. • Identify any maintenance issues or needs. • Coordinate response to maintenance issues/equipment faults.
TMC Operators	• Monitor corridor performance and assist in incident response, as normal. • Supply information when requested to the CCTA Operations Staff, Transmax Support team and the Transmax C&T team.
Maintenance Resources	• Respond to issues in the field within given timeframe. • Respond to maintenance issues/equipment faults in the field, when requested by CCTA project managers, CCTA Operations Staff or Transmax Support team.

8.2 Typical Peak-Period Operations

The Segment 1 AT CARM system will continuously monitor corridor traffic conditions in real-time. When the onset of congestion is detected, the I-680 CARM system will activate and begin typical peak-period operations. It is anticipated that peak-period operations will occur on weekdays during the AM and PM peak commute periods, when northbound congestion is known to occur. Additional analysis of existing traffic conditions will be necessary before peak-periods are able to be defined. However, ramp meters are anticipated to be active roughly between 6:00 AM – 10:00 AM in the morning, and 2:00 PM – 8:00 PM in the evening. The Segment 1 AT CARM system may also operate to alleviate traffic problems at other times of the day (refer to section 8.1). Specific tasks associated with I-680 CARM operations during typical peak-periods are described below.

8.2.1 Monitoring and Reporting of Real-Time Corridor conditions

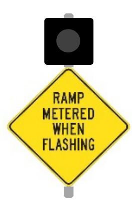
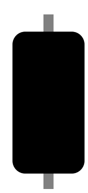
During peak period operations of the Segment 1 AT CARM system, real-time corridor conditions will be continuously monitored and stored for later analysis. Read-only information will also be available on the STREAMS® web dashboard. Recorded information will include:

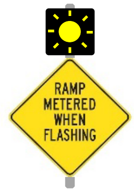
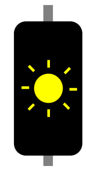
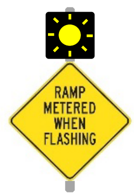
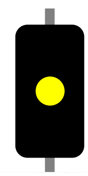
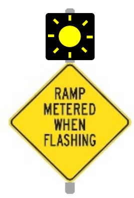
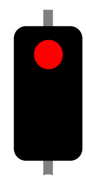
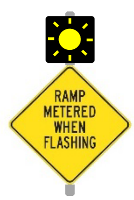
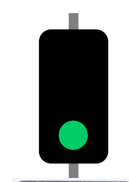
- Traffic volumes from corridor mainline, entrance ramp, and exit ramp detectors;
- Lane occupancy from corridor mainline and entrance ramp detectors;
- Average speed information from mainline vehicle detectors;
- Entrance ramp queue size;
- Entrance ramp metering source; and
- Entrance ramp metering rate.

8.2.2 Activation and Start-Up

The I-680 Segment 1 AT CARM system will be activated automatically when real-time monitoring indicates lane occupancy is exceeding critical thresholds. Activation is anticipated to occur in advance of the peak-periods, as warranted by corridor conditions. There are various predetermined tunable procedures for flashing beacons, traffic signals, signal timings, and LUMS signage associated with system activation. The proposed control sequence for ramp metering start-up as part of Segment 1 AT CARM operations is outlined in Figure 8-1.

Figure 8-1 Proposed Start-Up Control Sequence

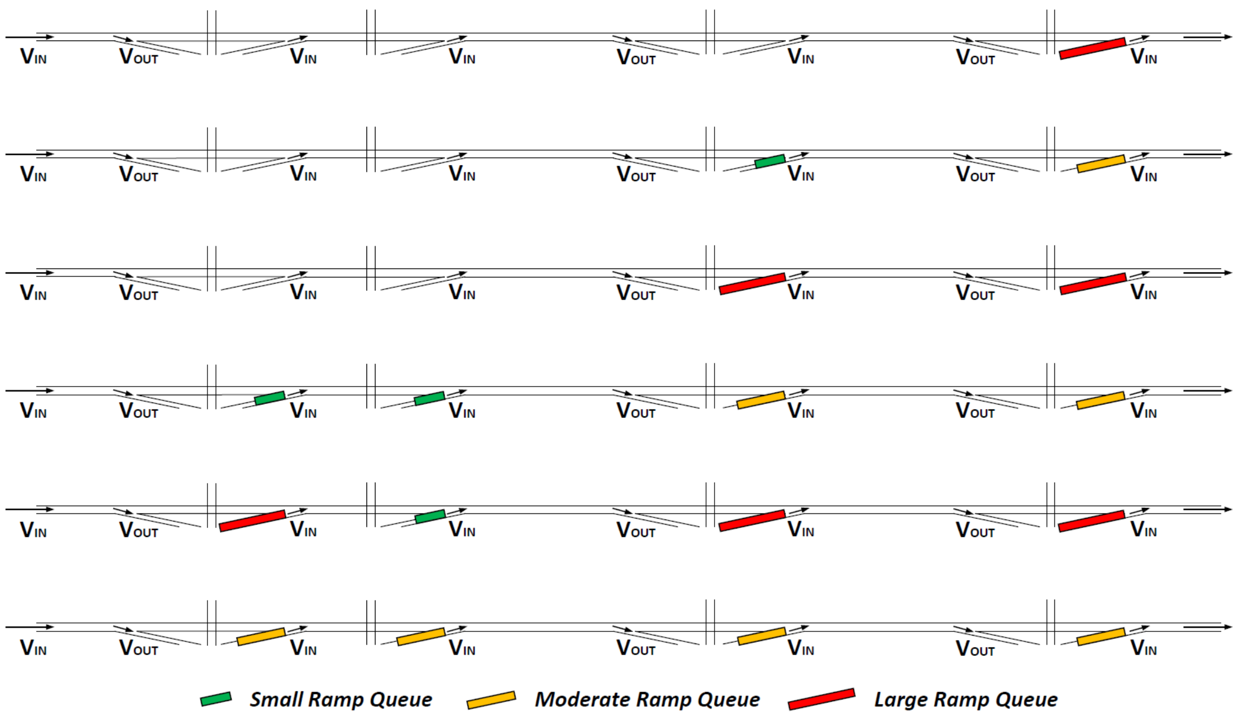
Time	Flashing Beacon	Traffic Signals	Sycamore Valley Road & Olympic Boulevard Ramp Shoulder LUMS and VMS
Prior to 'Start Up' Signals and Flashing Beacon are off.	 Off	 Off	 Shoulder Closed to Traffic Lane Ends

'Start up' Period (10 seconds) Activate a flashing yellow at traffic signals. Activate the Flashing Beacon.	 Flashing	 Flashing Yellow	 Shoulder Closed to Traffic Lane Ends
'Start up' Period (next four seconds) Activate a steady yellow at traffic signals. Continue the Flashing Beacon.	 Flashing	 Steady Yellow	 Shoulder Closed to Traffic Lane Ends
'Start up' Period (next six seconds) Activate a steady red at traffic signals. Continue the Flashing Beacon.	 Flashing	 Steady Red	 Shoulder Open to Traffic
Signals Metering Traffic Signals cycle to control traffic. Continue the Flashing Beacon.	 Flashing	 Green-Red cycle	 Shoulder Open to Traffic

8.2.3 CARM Operation

Once activated, the CARM system will work to coordinate ramp meter signals at all entrance ramps along the northbound I-680 Segment 1 AT CARM corridor. All entrance ramps will work together to share and address operational needs. The ramp metering system will operate using the same automated principles whether traffic is light, moderate, or heavy. In all conditions, the system will work to optimize mainline and ramp performance outcomes. The anticipated progression of Segment 1 AT CARM corridor ramp metering is outlined below and illustrated in Figure 8-2. As volumes steadily increase along the corridor and the onset of congestion is detected, individual arterial ramp meters will start-up independently based on conditions in and around the entrance ramp (local conditions). As volumes increase more and congestion is detected downstream, pairs of arterial ramp meters may begin working together (coordinating) to control entry flows and balance the number of vehicles/ wait times on the arterial ramps. During peak periods, when lane occupancy is expected to be at its highest, all ramp meters will activate and coordinate in order to manage the highest travel demand and the multiple associated bottlenecks that are likely to be observed along the corridor. This enables the system to better manage the freeway corridor as a whole to optimize mainline traffic flows and to balance ramp queues throughout the corridor.

Figure 8-2 Coordinated and Adaptive Ramp Metering Diagram



Source: GHD

8.2.4 Entrance Ramp Queue Management

The management of entry ramp queues is considered as an essential component of Innovate 680 AT CARM system. As part of STREAMS® system operations, queue length of each ramp will be estimated and managed every 20 seconds, in parallel with calculations associated with mainline performance, based on VicDOT standards. The automated system will consider the following items when determining ramp signal cycle times:

- Traffic volumes;
- Rate of queue development;
- Balancing of queues between coordinated ramps along the corridor;
- Queue length as it reaches the ramp entrance from adjacent roadway; and
- Waiting time for vehicles in the queue.

The operational intent for ramp metering under typical circumstances is to manage queues within known storage parameters. In this way, every reasonable effort will be made to manage queues within the ramp footprint, and to avoid any queue from impacting the traffic flow on an arterial road, upstream freeway mainline or other ramp connections within an interchange.

During a queue override situation when a long ramp queue is detected near the entrance of a ramp from an adjacent roadway, the cycle time will be reduced by the system to increase the ramp flow and reduce the number of waiting vehicles. However, this will only occur to the extent that it will not trigger flow breakdown on the mainline, as a breakdown of the mainline typically results in longer queues on ramps, lost productivity and more network delay for customers, and longer overall travel times throughout the system.

8.2.5 Signal Cycle Times

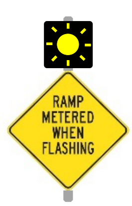
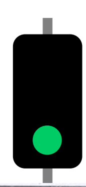
The Segment 1 AT CARM system will dynamically operate the cycle times at each entrance ramp to manage the freeway mainline, traffic demand and ramp queues. Ramp signal timing will be adjusted every 20 seconds, as determined by the STREAMS® freeway management system. Ramp cycle timing generally ranges from 4 seconds minimum to 18 seconds maximum (equivalent to hourly metering rates of between 900 vphpl and 200 vphpl for each lane provided at the ramp meter). The signal times within each cycle based on one vehicle per green per lane are:

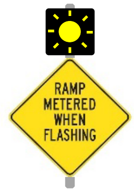
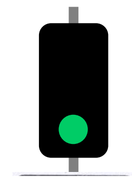
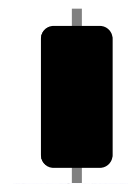
- Red: Variable - typically within the range 2.5 to 16.5 seconds
- Green: 1.5 seconds

8.2.6 System Shutdown

The Segment 1 AT CARM system will automatically deactivate individual ramp meters when real-time monitoring indicates reduced traffic flows at the conclusion of typical peak-periods. There are various predetermined procedures for flashing beacons, traffic signals, and LUMS signage associated with system deactivation. The proposed control sequence for ramp metering shutdown is outlined in Figure 8-3.

Figure 8-3 Proposed Shut-Down Control Sequence

Time	Flashing Beacon	Traffic Signals	Sycamore Valley Road & Olympic Boulevard Ramp Shoulder LUMS and VMS
Signals Metering Traffic Signals cycle to control traffic. Flashing Beacon.	 Flashing	 Green-Red cycle	 Shoulder Open to Traffic

'Shutdown' Commences (10 seconds) Activate steady green at traffic signals. Continue the Flashing Beacon.	 Flashing	 Steady Green	 Shoulder Closed to Traffic Lane Ends
Shut-down complete Switch off Signals and Flashing Beacon.	 Off	 Off	 Shoulder Closed to Traffic Lane Ends

Key roles and responsibilities of individual Innovate 680 AT CARM system stakeholders during typical peak-period operations are shown in Table 8-2.

Table 8-2 Role & Responsibilities – Typical Peak-Period Operations

Stakeholder	Roles & Responsibilities
CCTA Operations Staff	• Monitor and analyze corridor performance and complete adjustments as necessary. • Perform overrides of specific metering sites when needed based on real-time data. • Identify and log any maintenance issues or needs to be addressed.
Transmax C&T Team	• Monitor and record real-time corridor traffic conditions for later analysis. It is anticipated that this would be mainly an automated function of the STREAMS® freeway management system. • Regularly analyze system performance. • Investigate augmentations to STREAMS® system parameter settings when needed.
TMC Operators	• Monitor corridor performance and assist in incident response, as normal. • Supply information when requested to CCTA Operations Staff, the Transmax Support team and the Transmax C&T Team
California Highway Patrol	• Patrol I-680 CARM corridor, as normal. • Enforce ramp meter signal violations, as normal.

8.3 Incident Event

As part of typical Innovate 680 AT CARM operations, it is anticipated that there will be occasional abnormal events that are generally outside of the control of CCTA, Caltrans or the Transmax Support team. These situations are considered those that are caused by an event or combination of events that prevents the CARM system from managing the freeway mainline or ramp queues as normal. These events can include, but are not limited to:

- Traffic incidents or crashes;
- Other incidents such as debris on roadway, oil spill, inclement weather, etc.; and
- Unplanned maintenance

It is anticipated that incident events will be unique and will vary based on location, severity, and other circumstances. Therefore, the following tasks related to incident events are intended to reflect general principles and response actions, which may vary depending on the situation. It should be noted that in most instances, allowing the CARM system to continue to operate can provide optimal benefits in terms of managing traffic during an incident, as well as expediting recovery from an incident, and therefore disabling the system should be discouraged and viewed as a last resort in extreme circumstances. In all incident events Caltrans, TMC operators, CHP and local emergency agencies will have ultimate control over incident response.

8.3.1 Incident on Freeway Mainline

In certain incident situations, the Segment 1 AT CARM system may be used to assist in managing traffic demand during incident events in order to assist in flow recovery. Therefore, the system will continue dynamic coordinated ramp metering during incident events, unless directly instructed to deactivate the system at the request of Caltrans TMC staff, CHP or local emergency response representatives. If necessary, deactivation would include CCTA Operations Staff overriding default or automated system operation to disable individual or multiple ramps to assist with emergency access and response.

8.3.2 Incident on Controlled Ramp

As with an incident on the freeway mainline, the Segment 1 CARM system may be able to mitigate the impact of an incident on a controlled ramp by continuing regular metering operations at that location. However, if requested by Caltrans TMC staff, CHP or local emergency response representatives, CCTA Operations Staff can disable ramp metering at specific locations.

8.3.3 Emergency Vehicle Access

At times when agencies require emergency vehicle access to the freeway during regular metering operations, agencies will be able to coordinate with CCTA Operations staff to arrange the clearing of ramp queues that may obstruct emergency response. A particular focus would be any ramp where the shoulders are inadequate to allow emergency vehicles to pass. When required by emergency services, CCTA Operations staff would be notified and they would immediately override normal operations in the requested location and post a

'RAMP CLOSED' message to the ramp status VMS sign as described in Section 7.5.2. After the entry of emergency response vehicles, the operator would then remove the override so that dynamic metering could continue. Alternatively, a timed override could be applied.

Table 8-3 describes the key roles and responsibilities of individual Segment 1 AT CARM stakeholders during an incident event.

Table 8-3 Role & Responsibilities – Incident Condition

Stakeholder	Roles & Responsibilities
Transmax Support Team	• Assist with post incident performance reporting.
CCTA Operations Staff	• Monitor real-time corridor traffic conditions for indications of incident. • Disable individual ramp meters to clear ramp queues (as a last resort, if required). • Notify Transmax Support team when a request to disable individual ramp meters is received.
TMC Operators	• Monitor real-time corridor traffic conditions for indications of incident. • Assist in incident response.
California Highway Patrol	• Patrol I-680 CARM corridor, as normal. • Assist with incident response, as normal. • Notify TMC if individual ramp meters should be disabled for emergency vehicle access.
Local Emergency Response	• Assist with incident response, as normal. • Notify TMC if individual ramp meters should be disabled for emergency vehicle access.

9 Anticipated Impacts

This section summarizes the potential impacts of the Innovate 680 AT CARM Project, specifically Segment 1 CARM operations. Individual elements include a summary of anticipated changes to the corridor and operations, and anticipated traffic benefits. This section also includes a discussion of metrics that will be used to gauge the performance of the proposed CARM system.

9.1 Summary of Operational & Physical Impacts

The previous sections of this document have described the concept and components of the Innovate 680 AT CARM Project that will be deployed as part of the greater Innovate 680 program on the I-680 corridor. The following summary briefly describes the operational impacts anticipated as part of the Segment 1 CARM operations. The items listed include both physical changes to the corridor, along with changes to operational tools and capabilities provided by the CARM system. As described previously, all proposed improvements will be closely coordinated with the concurrent Caltrans SHOPP Fiber/TOS/Ramp Metering Project.

- **Ramp Meter Signals**: New ramp meter signals will be installed along the northbound I-680 Segment 1 CARM corridor at the entry ramps listed below:
    - Alcosta Boulevard;
    - Bollinger Canyon Road;
    - Crow Canyon Road;
    - Sycamore Valley Road;
    - Diablo Road;
    - El Cerro Boulevard;
    - El Pintado Road;
    - Stone Valley Road;
    - Livorna Road;
    - Rudgear Road: and
    - Olympic Boulevard.

  These new meters, along with proposed ramp modifications described below, will enable STREAMS® a greater degree of control over the corridor, and better enable the system to respond to real-time traffic conditions.

- **Ramp Modifications**: A number of the new ramp meter installations described above as part of Segment 1 CARM operations will also undergo physical modifications to better accommodate the CARM system. These improvements will involve restriping entrance ramp lanes and/or minor widening to accommodate additional lanes at the ramp meter stop bar to temporarily store vehicles or quickly release vehicles based on the real-time needs of the CARM system. These ramp modifications will offer greater storage and ramp discharge capacity along the corridor, which will provide greater operational flexibility to balance queues and respond to real-time conditions. All ramp meters will release vehicles simultaneously in order to provide greater flexibility and queue clearance from arterial ramps. Proposed CARM improvements will also be coordinated with the concurrent Caltrans SHOPP Fiber/TOS/Ramp Metering Project as not to duplicate efforts and perform redundant construction activities. As such, some ramp modifications may be delivered through the Caltrans Ramp Metering Project while others may be constructed under a separate Segment 1 CARM contract.

- **Traffic Detection:** Additional traffic detection technology will be installed throughout the corridor to provide more accurate information on real-time traffic conditions. New TIRTL detector devices will be installed along the corridor mainline (nominally every 1/3rd-mile). In addition, new inductive loops will be installed on entrance and exit ramps. Additional detection will provide a clearer picture of traffic conditions throughout the entire corridor at any given time.

- **Coordinated and Adaptive Ramp Metering:** The new CARM system will be deployed on all individual entrance ramps within the Segment 1 CARM corridor**.** Coordination between all meters will allow for the freeway mainline and ramp flow to be monitored and optimized in real-time throughout the entire corridor.

- **Dynamic Freeway Management:** During I-680 Segment 1 CARM operations, the STREAMS® freeway management system will be used to provide CCTA Operations Staff a platform to observe and respond to real-time traffic conditions. The platform will use traffic data to detect abnormalities in corridor traffic behavior. The management system will also include a dynamic response capability, to enable the CARM system to prevent compounding the impacts of incidents or events, and to better assist in the recovery of traffic flow.

- **Maintenance:** Operations of the Innovate 680 AT CARM Project will include the provision of dedicated maintenance staff. Maintenance resources will need to be available to respond to device faults and/or other issues in as little as 24 hours in order to address malfunctioning or unresponsive equipment.

- **Corridor Environment:** All physical improvements included as part of the Innovate 680 Segment 1 AT CARM Project will occur within the existing I-680 footprint and within Caltrans ROW.

9.2 Anticipated Traffic Impacts

This section describes the mobility impacts that can be anticipated as part of the Innovate 680 AT CARM Project. Content includes high-level performance goals for Segment 1 CARM operations, documented results from previous Australian CARM implementations, and summary findings from the Colorado CDOT SMART 25 Managed Motorways CARM Pilot project in Denver, Colorado.

Based on the existing conditions of the I-680 corridor, the proposed CARM components and functionality, and the performance of other CARM projects in Australia and Colorado, notable improvements in corridor mobility are anticipated as part of Segment 1 AT CARM operations. By improving the flow of vehicles onto the Segment 1 corridor, minimizing the formation of mainline bottlenecks, and facilitating greater overall trip reliability, Segment 1 AT CARM operations are intended to improve:

- Vehicle Throughput

- Average Travel Time
- Travel Time Reliability
- Corridor Productivity
- Management of arterial ramp queues
- Number of vehicle crashes

Results from the M1 Motorway in Melbourne and the SMART 25 Managed Motorways Pilot Project are detailed in section 9.2.1 and section 9.2.2 respectively. Anticipated mobility benefits for the Segment 1 AT CARM corridor are further detailed in section 9.2.3.

9.2.1 Melbourne M1 Motorway Results

The initial implementation of the Australian CARM system or "managed motorways" occurred on a 9-½ mile segment of the M1 Motorway east of downtown Melbourne, Australia. The corridor was selected based on pre-existing ramp storage and the existing placement of highly accurate traffic vehicle detection. As part of a temporary one-year pilot project, six existing ramp meters were upgraded from a fixed-time system to a fully coordinated dynamic CARM system using the ALINEA and HERO suite of algorithms. As a result of the piloted CARM system, VicDOT reported the following performance results during peak-periods[3]:

- Increase in average traffic flow (vphpl):
  - +4.7% during AM Peak; and
  - +8.4% during PM Peak.

- Increase in average travel speed (mph):
  - +34.9% during AM Peak; and
  - +58.7% during PM Peak.

- Increase in travel time reliability [Less than 20% Speed Variation (%)]:
  - +148.7% during AM Peak; and
  - +516.4% during PM Peak.

9.2.2 Denver SMART 25 Results

As mentioned previously, the CDOT SMART 25 Managed Motorways CARM Pilot recently concluded in Denver, Colorado. The SMART 25 CARM project operated 18 individual ramp meters on a 14-mile corridor of northbound I-25 south of downtown Denver. Construction of the SMART 25 pilot included similar components to those proposed for the Innovate 680 AT CARM system, including targeted ramp improvements and the installation of additional highly accurate vehicle detection. The STREAMS® freeway management system was also used for SMART 25 pilot operations.

The Draft SMART 25 Performance Evaluation Report was completed in late 2022, which compared corridor traffic performance between three months of baseline CDOT legacy ramp

[3] Vincent Vong and John Gaffney, *Monash-Citylink-West Gate Upgrade Project: Implementing Traffic Management Tools to Mitigate Freeway Congestion*, VicRoads, 2012.

metering operations to five months of full CARM operations in STREAMS®. Understanding that the pilot and evaluation is being conducted during COVID recovery, particular care was given to the impacts of overall demand changes on the I-25 corridor. A review of historical volumes found that although congestion was present during the baseline data collection (July 2021 to October 2021), volumes had increased in 2022 by the start of full CARM operations in March 2022.

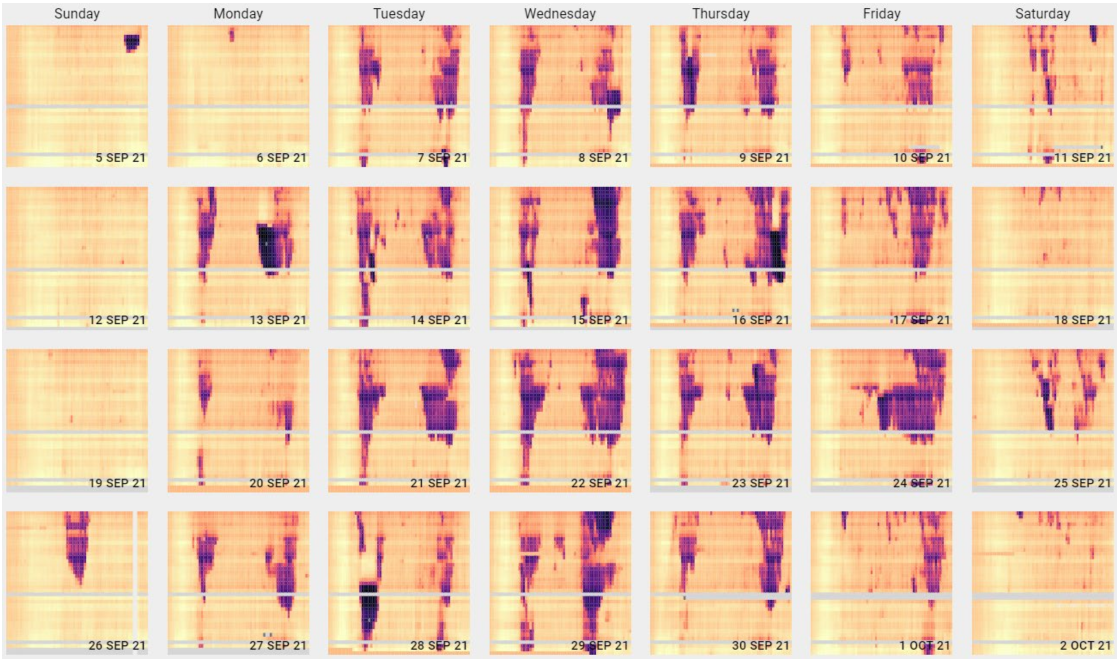
Despite the increase of corridor volumes, a comparison of baseline to full CARM operations provides the following results:

- AM Peak Period:
    - Corridor-wide travel times have been reduced slightly (2%) overall despite increases in volumes.
- Midday Off-Peak:
    - Off-peak congestion during the midday has been effectively eliminated, with a minimal improvement in average travel time (0.7%).
- PM Peak Period:
    - Corridor-wide average travel times in the PM peak-period have improved by more than 14% over Baseline conditions.
    - Corridor-wide average travel times improve by more than 19% at the height of the PM peak-period.
    - Reliability (measured by a comparison of 95^{th} percentile average travel times) has improved by over 20% in the PM peak period compared to Baseline conditions, and by over 24% during the height of the PM peak-period.
    - Total delay in the corridor has been reduced by over 40% for the whole day and almost 50% during the PM peak period.
    - The maximum sustainable flow of traffic through known bottleneck locations has increased, indicating traffic flows are more stable and resilient to breakdown.

During all times of the day, ramp queues have been able to be effectively managed without any impacts to adjacent arterials. Wait times averaged up to two minutes and rarely exceeded four minutes.

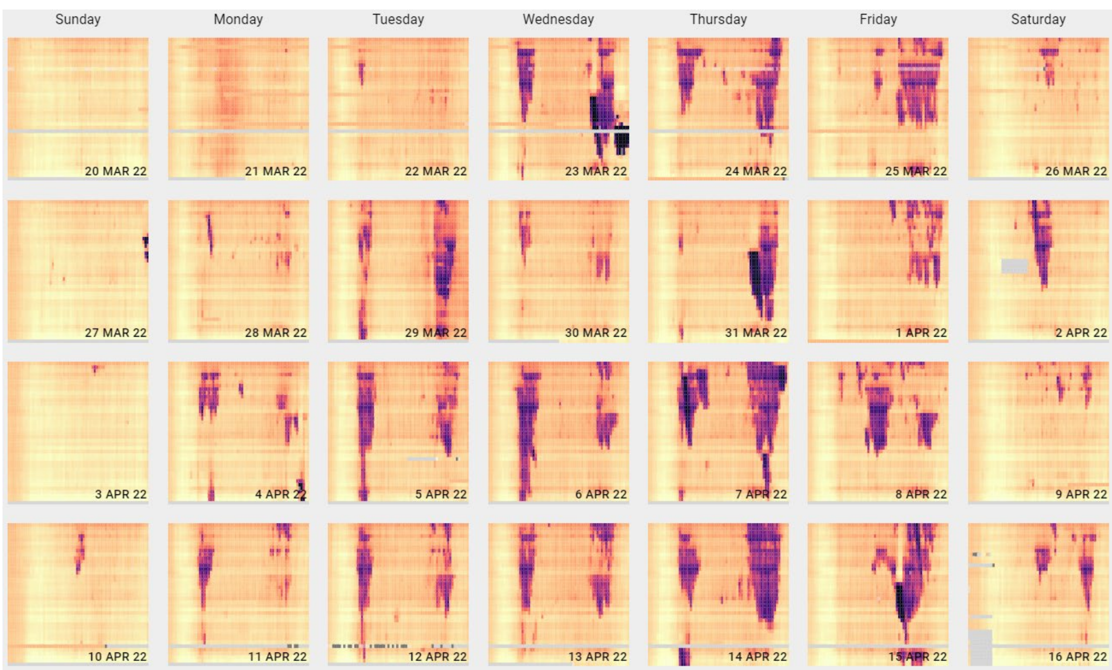
Speed contour plots were also generated for each day during the baseline and full CARM operations periods, using similar tools to those described in section 4.2 earlier in this document. As shown in Figure 9-1 and Figure 9-2, distinct AM and PM peak-period congestion can be recognized during most days during both the baseline and CARM operations as indicated by dark colored 'bruising' representing time periods with slow speeds. However, when visually comparing the level of congestion between baseline and full CARM operations, there are noticeable differences in the duration of peak-periods and the severity of congestion during those periods. Figure 9-1 and Figure 9-2 demonstrate how CARM has generally been able to shorten peak-period congestion, while also reducing the severity of congestion during both the AM and PM.

Figure 9-1 SMART 25 – Baseline Operations (September 2021) I-25, Denver, Colorado



Source: Transmax

Figure 9-2 SMART 25 – CARM Operations (March/April 2022) I-25, Denver, Colorado



Source: Transmax

9.2.3 Associated Mobility Benefits

Based on the documented results of the CARM pilot implementation on the M1 Motorway in Melbourne, and the summary results of the SMART 25 Pilot Project in Colorado, notable improvements in mobility are expected as part of the Innovate 680 AT CARM Project. The following benefits are anticipated as part of the Segment 1 I-680 CARM implementation during peak-periods:

- **Vehicle Throughput:** Increases in traffic flow within known bottleneck locations during peak-periods are expected, as with the results of the Colorado SMART 25 Pilot Project.

- **Average Travel Time:** Peak-period average travel time is also expected to decrease, along with a shortening of observed peak-period congestion.

- **Travel Time Reliability:** Due to the effective management of critical recurring bottlenecks, travel time variability is expected to be reduced significantly during peak-periods, similar to the results of the SMART 25 project in Colorado.

- **Vehicle Crashes:** An additional benefit of the reduction in recurring bottlenecks is the associated reduction in rear-end and side-swipe collisions. As such, reduction in total peak-period crashes is also anticipated during Segment 1 CARM operations.

Although the implementation of CARM concepts on the M1 and I-25 provide an idea of the type of results that can be possible through Segment 1 CARM implementation, it is important to recognize that each corridor is unique. The M1, I-25, and I-680 have different underlying demand patterns, lane geometry, drivers, and number of controlled entrance ramps.

Although the Innovate 680 AT CARM team is confident in the ability of the system to improve I-680 corridor performance, the extent to which this can be achieved is unknown at this time. However, given the similarities in the scale of proposed CARM system implementations, and the lessons learned from the SMART 25 project in Colorado, the I-25 CARM Pilot results will be considered as performance expectations for the Innovate 680 Segment 1 CARM implementation. Concept performance will be thoroughly evaluated as part of regular Segment 1 CARM performance assessments as described in section 9.3.

9.3 Associated Performance Measures

The ability of the Innovate 680 AT CARM Project to produce corridor improvements satisfying all stakeholders will depend on the metrics used to assess corridor operations. The following list of measures were selected to gauge the effectiveness of the Segment 1 CARM operation to improve existing deficiencies and to deliver benefits to system users and stakeholders. These measures will be used as part of regular comparative performance assessments as part of the Innovate 680 AT CARM system. In addition, the metrics will be used to evaluate the performance of Caltrans traditional ramp metering deployed along other corridors in the Bay Area region, subject to data availability.

This analysis will utilize high-resolution data from new vehicle detectors planned for installation along the corridor mainline, as well as existing and new vehicle detectors installed on corridor entrance and exit ramps. Data from these devices will be used to assess both existing traffic conditions and conditions during Segment 1 CARM operations, in order to provide an appropriate comparison.

Additionally, most measures will assess before and after performance during peak periods, when the Segment 1 CARM system is anticipated to be active. An initial review of performance data from new traffic detectors will be necessary before the extent of the AM and PM peak-periods can be defined for further analysis.

- **Average Travel Time:** A comparison of average travel times during peak-periods (weekdays AM/PM) for before and during CARM operations indicating the ability for the system to better manage traffic flows and reduce congestion.

- **Travel Time Index (TTI):** A comparison of actual travel time during peak-periods (weekdays AM/PM) to free-flow travel time, indicating the level of travel delay.

- **Planning Time Index (PTI):** A calculation of the 95th percentile travel time during peak-periods (weekdays AM/PM), divided by the free-flow travel time. This value is an important measure of travel time reliability, one of the most significant anticipated benefits of the Innovate 680 AT CARM Project.

- **Traffic Flow:** Recorded values during peak-periods (weekdays AM/PM), reported as vehicles per hour per lane. This measure is an indication of the efficiency of the freeway corridor. The measure will be used to assess corridor wide efficiency. However, particular attention will be paid to the change in volumes at and downstream of existing bottleneck locations.

- **Average Speed:** Recorded speed values during peak-periods (weekdays AM/PM), weighted by individual lane volumes to gauge the average speeds of vehicles passing individual points over a period of time. In application, these values will be represented through heat-plots, similar to those shown in Figure 9-1 and Figure 9-2. This process will offer a visual indication on the impact of the system on specific bottleneck locations.

- **Crashes:** Number of total crashes (including serious injuries, fatalities, and property damage only) reported during Segment 1 CARM system operations. This total value, and reported locations, will then be compared to the same period from previous years. Although the number of crashes will be reported as part of regular performance assessments, it should be recognized that it will be difficult to draw statistically relevant conclusions based on early samples of data, as crashes are typically reported over 3- to 5-year periods.

- **Productivity:** An illustration of the relationship between speed and traffic flow during peak-periods (weekdays AM/PM). The measure is calculated by multiplying average speed by hourly lane flow in order to gauge the level of freeway optimization offered by the CARM system. In practice, the system may seek to optimize for speed early in the peak-period, while peak flow at a slightly lesser speed will be optimized during the highest demand of the peak-period.

In addition to these individual measures, outputs from these metrics may be used to conduct a Benefit Cost Analysis (BCA) of the Segment 1 CARM system during initial performance assessments. This calculation can help gauge the high-level economic impact of the Segment 1 CARM program, relative to capital and operations costs. This information can be used to communicate the level of benefit the CARM system can offer to corridor stakeholders.