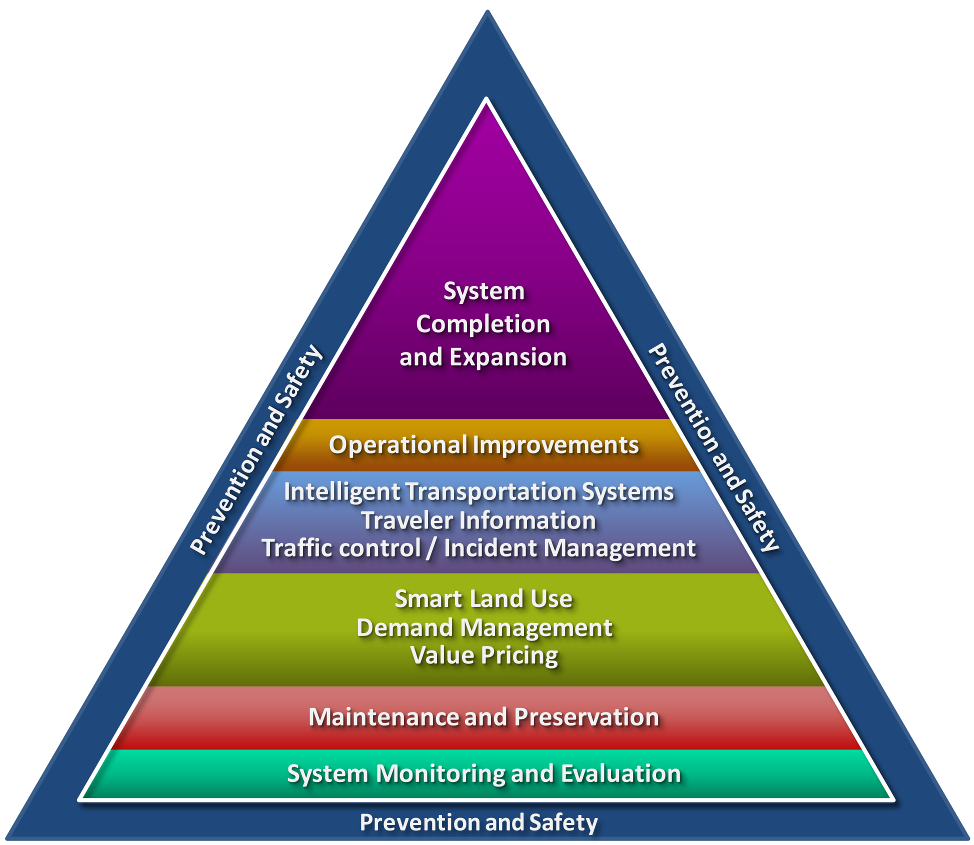
Connected Corridors Program Overview

August 2011 - July 2015

Connected Corridors
Vehicles
Infrastructure
People

California PATH (Partners for Advanced Transportation Technology)
University of California, Berkeley

Contents



Caltrans Mobility Pyramid

Connected Corridors Program Overview: Introduction and Summary

Four years ago a contract titled "Research and Innovation for Traffic Operations: Researching and Implementing Technical Solutions to Improve Mobility across California" began at UC Berkeley PATH. Now known as the "Connected Corridors" program, this project plays a central role in Caltrans' evolution toward a Transportation Systems Management and Operations (TSM&O)-based culture. According to Caltrans personnel, the Connected Corridors program is a direct response to the issues raised in "The California Department of Transportation: SSTI Assessment and Recommendations."

The Connected Corridors program is focused on establishing Caltrans' statewide leadership in the area of multi-modal, multi-jurisdictional integrated corridor management (ICM). The program has been officially announced and is actively supported by the Caltrans Directorate. It embodies the Caltrans mission to "Provide a safe, sustainable, integrated and efficient transportation system to enhance California's economy and livability" as well as the System Performance Goal: "Utilize leadership, collaboration and strategic partnerships to develop an integrated transportation system that provides reliable and accessible mobility for travelers."

PATH, a leader in Intelligent Transportation System implementation, with a proven ability to deliver transformative programs, was asked to lead the effort. Caltrans realized that engaging a respected, vendor-neutral organization would ensure the final recommendations for a statewide ICM program would incorporate the best of existing and new technologies. Utilizing these recommendations, proven through a pilot implementation, Caltrans would be positioned to unite and lead California's MPOs in the implementation and operation of ICM in 50 congested urban corridors.

The program, tasked with the large and challenging task of planning for, conducting, and fanning out next-generation ICM in California, is progressing well on the three main contract deliverables:

1) Managing, with Caltrans and our regional stakeholders, the selection of a corridor (success: we have chosen the I-210 in LA) and the coordination and implementation on that corridor of a full-lifecycle, multi-jurisdictional, multi-modal ICM pilot/field test that will be scalable to multiple locations in the state.

2) Establishing and facilitating the use and understanding of a knowledge base of educational materials, assessments of past and recent ICM activities, reusable methods, new organizational structures, architectural models, cultural change, documentation of existing/planned operations, and standardized tools for use in planning for, implementing, and operating ICM in multiple urban corridors.

3) Performing applied research and development in support of new techniques for system management and decision support tools applicable to ICM planning and real-time corridor operations.

In two summary paragraphs:

- **By the results**: We have engaged multiple cities and regional stakeholders in LA with fundamental success as measured by both their full participation in the pilot implementation and in the positive statements made by their members, boards, and city councils. We have developed several systems engineering documents, planned and assisted with the allocation of 18 million dollars for corridor improvements, have begun the development of a corridor-wide simulation using new macro modeling tools, established improved communications between D7 and Caltrans, have created and populated an online state of practice and tool repository, and by next year will deliver a macro modeling tool suite using new and existing data sources. We have combined our efforts with other Caltrans- and Metro-funded programs for efficiency and are supporting D7 and headquarters in the implementation of a new organizational structure with new job roles needed to support Caltrans' role as a leader in the management and operation of Integrated Corridors.
- **By the numbers**: We have held over 75 meetings with public organizations around the state, developed an expanding website with 366 web pages, 257 supporting documents, and 10,000 data files, published over 40 research papers, raised (with Caltrans) 18 million dollars for corridor improvements, are preparing to ask for 5 million more from Metro, designed multiple software systems with over 100 database tables, and built an extended sustainable organization composed of over 30 public and private partners focused on the ongoing success of Caltrans.

Additional high-level information is provided below with details on outreach, systems engineering, system design, and applied research following in subsequent sections of the document.

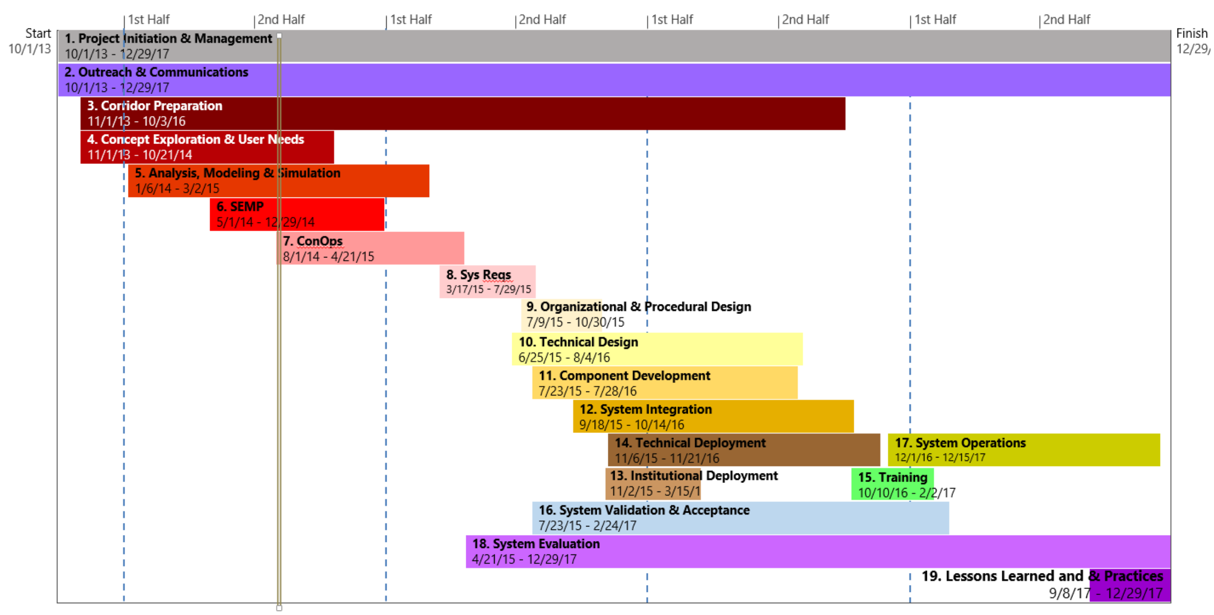
Implementing a Pilot/Field Test on the I-210 Corridor in Los Angeles

Implementation of Integrated Corridor Management involves planning, agreements, organizational changes, systems and new operational and maintenance paradigms. As such, a pilot project is essential for ensuring correct recommendations are made before fanning out ICM to other urban corridors.

After over a year of organizational canvassing and detailed site study and selection, the I-210 in Los Angeles was chosen as the pilot site for Connected Corridors. The site begins in the city of Pasadena and continues through Arcadia, Monrovia, and Duarte. A highly detailed study of the corridor can be found on our website.

The response from our stakeholders has been highly supportive, with LA Metro and LA County signing on as full-fledged participants with Caltrans in this effort.

The pilot is a significant effort in education, planning, implementation, and operations. The schedule is shown below. We are on schedule to complete the Concept of Operations early next year. FHWA is monitoring our progress and has expressed satisfaction and pleasure with the project thus far. We have local governing agencies, consultants, and industry partners on board.



For over three years the Connected Corridors program has worked with Caltrans, public agencies, academia, and private partners to develop the strong supportive relationships, long-term commitments, and simple trust required to overcome the inevitable challenges arising in programs seeking to accomplish an effort as challenging as the I-210 ICM. A number of our friends and partners have indicated that this is a once-in-a-lifetime opportunity to bring about the transportation and societal improvements they have dreamed about for decades. They have expressed a deeply personal commitment to the success and the goals of the Connected Corridors program.

This extended organization is composed of transportation engineers, electrical engineers, researchers, system engineers, software developers, communication specialists, public relation experts, policy analysts, and project and program managers. The organization is the result of long-range planning, partnerships formed through years of careful relationship-building, and studies of related organizations around the world. This is an organization that Caltrans can rely on for years to come, planned to survive the organizational, personnel, and focus changes that inevitably occur in large organizations when they work on a long-term program.

The organization is composed of seven distinct groups:

1) Core personnel working at Berkeley PATH – (40+ personnel) Program Management, Research, Outreach, Communication, Systems Engineering, AMS (Analysis, Modeling, and Simulation), Systems Development, and Evaluation. This includes multiple professors, researchers, communication personnel, engineers, management, and administrative support.

2) Connected Corridors operations team working at Caltrans HQ – The Connected Corridors HQ team and their staff provide program management and focus on organizational change, funding, prioritization, and overall program visibility and support.

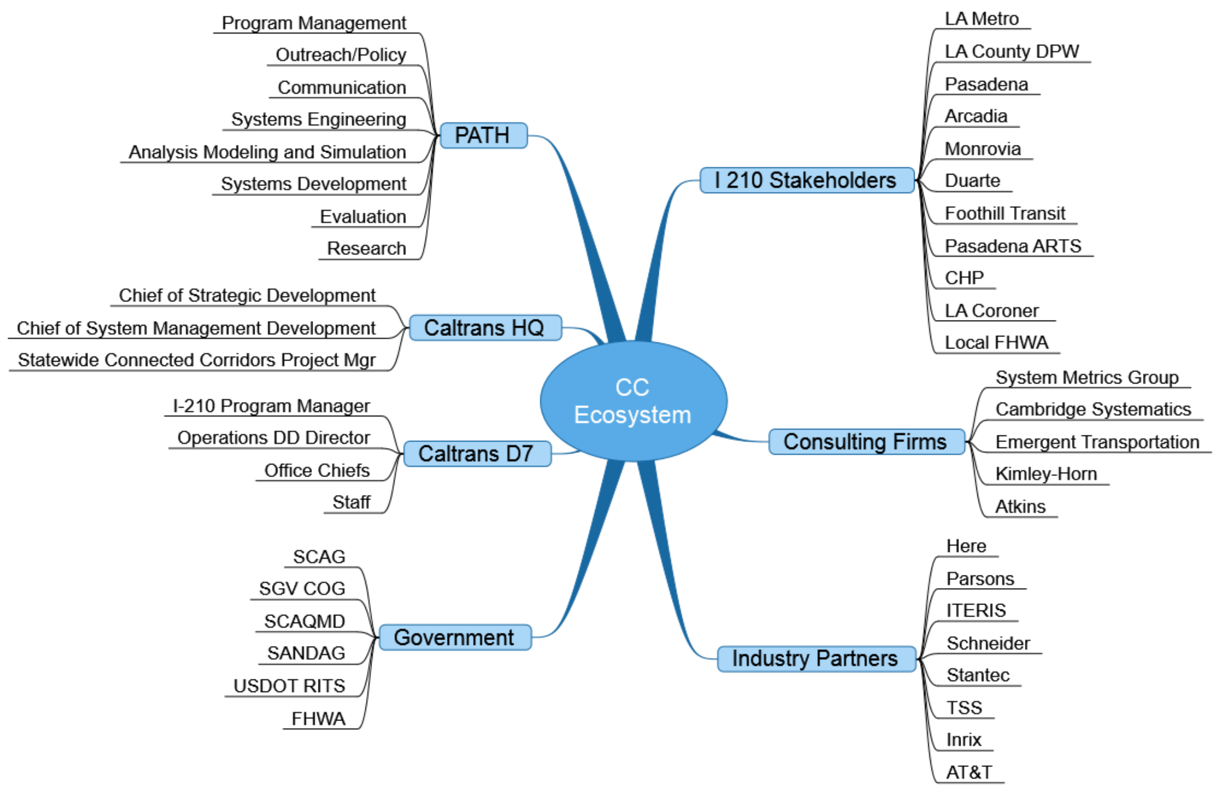
3) I-210 pilot team working at Caltrans D7 – The deputy of operations and the 210 corridor manager lead the team at D7. A number of the office chiefs and their staff also provide support. The PR department is also participating in our outreach efforts.

4) I-210 stakeholder organizations – LA Metro, LA County, Cities of Pasadena, Arcadia, Monrovia, and Duarte, other groups including Foothill Transit, Pasadena ARTS, CHP, Coroner's Office, local FHWA office

5) Government organizations not directly related to the I-210 Pilot – FHWA, USDOT RITA, SANDAG, SCAG (Southern CA Association of Governments), San Gabriel Valley Council of Governments, South Coast Air Quality Management District

6) Consulting firms – Systems Metrics Group, ITERIS (including the former BTS), Cambridge Systematics, Emergent Technologies, Iteris, Kimley-Horn, Atkins

7) Industry Partners – Delcan, Schneider, Stantec, Here (Nokia), Inrix, TSS



The outreach efforts needed to build, educate, and maintain this ecosystem have been extensive. We have made over 70 trips to Sacramento and Los Angeles and held over 75 public meetings attended by individuals from throughout the state, country, and world. For each of these meetings we have prepared materials, researched important points, and followed up with meeting notes.

These trips do not include the 3-4 weekly standing calls we have each week with our pilot participants to ensure good information exchange and a well-managed program.

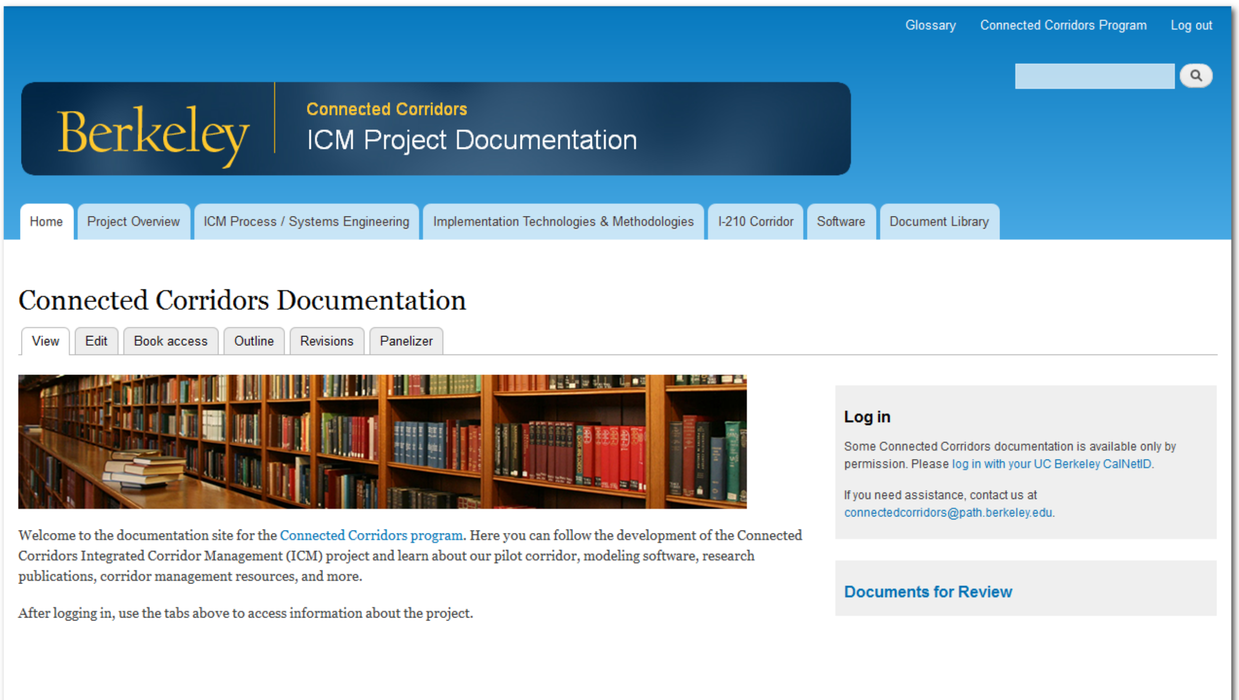
Please see the Connected Corridors/I-210 Pilot Outreach Timeline and Process section on page 11 for more information on our extensive outreach efforts and a listing of all of our public meetings.

Performing Applied Research and Development

Applied Research is an integral component of the Connected Corridors Program. The program developed from three previous/ongoing Caltrans efforts initially carried out by PATH at UC Berkeley: PEMS, TOPL, and Mobile Millennium. Connected Corridors brings the data-gathering and estimation functions provided by PEMS (loops) and Mobile Millennium (mobile data) together with the macro modeling capabilities provided by TOPL. Connected Corridors carries each of these forward in an integrated way, adding aspects of demand data and demand management. An example of a research area where strong interest is being shown by the practitioner community is the work being done on real-time origin-destination determination using cell tower data. This has the potential to revolutionize aspects of traffic management.

Specifically, in the last several years the Connected Corridors program has investigated areas of highway and arterial estimation and modeling, demand management, corridor-level control (ramp metering, signal synchronization, rerouting), safety, route change incentivization, security, and a number of other areas. The professors and researchers have submitted 50 Papers, spoken at 20 conferences, and received numerous awards. Please see the Summary of ICM Research Achievements section on page 31 for more details on our research results and a listing of each paper.

Knowledge Base, Methods, and Tools for ICM



The mission of the Connected Corridors Knowledge Management Function is to gather knowledge, synthesize and combine it with new ideas, formalize those ideas as methods, automate those methods as tools, and build a communication infrastructure for presenting and disseminating the knowledge, ideas, methods, and tools.

Two Websites

We developed and maintain two websites:

- One is public and contains general information about the Connected Corridors program. Its URL is http://connected-corridors.berkeley.edu.
- The other, pictured above, is password-protected and contains all of the data, documents, and tools being developed by the Connected Corridors program. It is located at: http://ccdocs.berkeley.edu.

Overall we have 366 web pages, 257 supporting documents (systems engineering docs, research publications, presentations, etc.), and over 10,000 data files.

For information on connecting to the website please see the Connected Corridors ICM Project Documentation Website section on page 22.

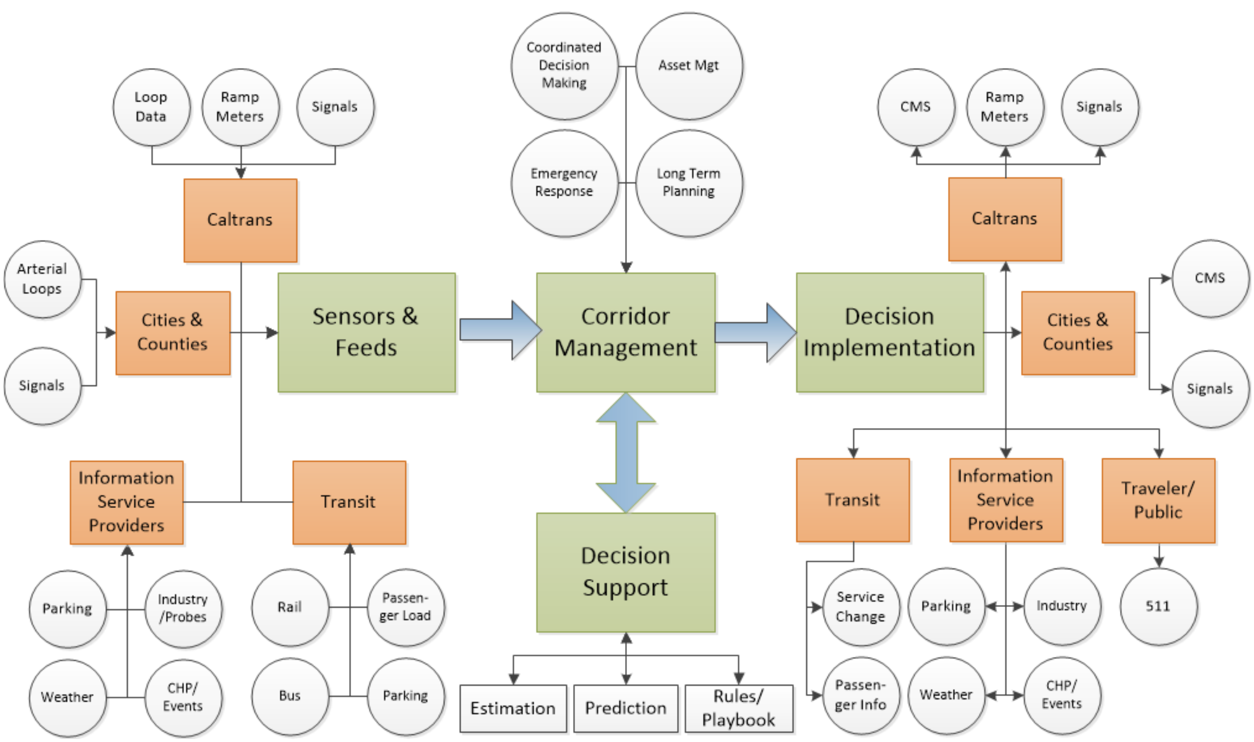
Knowledge Gathering and Education

We have gathered information on ICM, ATM, and ATDM efforts from around the world and presented it in numerous meetings and presentations. We have held workshops and seminars on ICM, Decision Support Systems, and Analysis, Modeling, and Simulation.

Tools

We primarily design software-based frameworks and tools (as opposed to hardware systems). Our goal is to be able to immediately move into development and procurement once the requirements are finalized and our next contract, permitting limited tool development, is approved.

These frameworks permit the integration of heterogeneous data, the fusion of this data for use in state estimation, the feeding of state estimation to calibrated models for prediction of future state. The future state prediction is combined with corridor rules and potential intervention scenarios to determine the best course of action to follow to maximize corridor metrics such as throughput, travel time, and GHG emissions. These interventions are translated into control messages to ramps, signals, and signs and to recommendations for agencies (such as transit modifications) and travelers through advanced traveler information systems. The following diagram illustrates this process:



We have studied existing ICM, ATMS, and decision support systems as we built out our designs. We have prototyped certain modeling algorithms for use in our Analysis, Modeling, and Simulation efforts. We have focused on networks, experimenting with multiple ways to represent them and load them from different map sources. We have developed three different UI solutions for scenario generation and worked with both Oracle and Postgres data repositories. We have also studied the possibilities of integrating our macro models with existing micro and meso models so that all aspects of a corridor may be properly simulated and predicted. We have designed over 100 database tables.

Timeframe and Finances

The overall mission of the Connected Corridors program is to ensure Caltrans' lead in integrated corridor management is established in 50 congested urban corridors within the next 10 years. The Connected Corridors program started three years ago. Assuming that support will be required after the next 10 years, we envision that Connected Corridors is a 15-year program.

During the period of July 2011 through June 2014 (3 Years) the program has spent 6 million dollars. The mission and importance of the organization has resulted in numerous professors, students, interns, and industry partners joining the organization without pay. Additionally, the program has attracted contributions by professors and students who are paid by other grants. The value of this extended support is worth nearly 2 million Dollars (12 students, 20 interns, industry in kind).

These numbers do not include the synergy with the Caltrans-funded TOPL program which has been a concurrent program executed in close cooperation with the Connected Corridors program for two years.

Connected Corridors/I-210 Pilot Outreach Timeline and Process

Initial Outreach Activities

Prior to starting outreach for the Connected Corridors/I-210 Pilot, the outreach and communications team led and/or participated in the following activities, primarily in 2012:

- Conducted background research and analysis on various potential corridors in the state and specific research on corridors in the Los Angeles area
- Studied other ICM projects in the state, US, and abroad in order to understand the corridor, the technology and/or infrastructure to be deployed, the outreach strategies, etc.
- Researched the I-210 corridor (after the corridor criteria were developed, corridors were analyzed, and the I-210 was selected)—its attributes, stakeholders, potential project leaders, the political landscape, the deployed technology, the region's demographics, the current working relationship between the corridor stakeholders and Caltrans, etc.
- Developed short-, medium-, and long-term plans for outreach and communications for the CC/Pilot for approximately the next three years
- Prepared communications goals:
    - Build awareness of CC/Pilot and the consortium of participants
    - Provide information in multiple formats to clearly articulate the who, what, where, when, and why of the program
    - Promote CC, the Pilot, and the consortium
    - Engage all stakeholders and keep them educated and informed; produce materials in multiple languages if needed
    - Generate support for the CC/Pilot
    - Obtain positive media coverage
- Prepared communications objectives:
    - Proactively communicate regarding the CC/Pilot
    - Provide timely, relevant information for either general or specific purposes
    - Support decision-makers by providing clear, concise messaging and detailed communications materials
    - Build a strong community/corridor-oriented foundation of public support and positive media coverage based upon local concerns and input

- Mapped out a specific strategy for Pilot stakeholder meetings, publications (newsletters, fact sheets, etc.), websites, social media, public announcements, conference participation, agency agreements, etc.
- Wrote, circulated, and confirmed the vision statement for the project: “Developed with a consortium of partners, Connected Corridors is a multi-modal, integrated, tested, replicable, and sustainable corridor transportation program created for California. It uses technology, instrumentation, communications, software, and operational/system innovations to build a framework for a modern traffic management system. The goals: better traveler mobility, improved safety, less congestion, higher efficiency, and sustainable environmental benefits that can be implemented state-wide.”

Outreach Summary

Since approximately 2013, the following outreach efforts have been undertaken:

Meetings and Activities

- Held initial meetings with Caltrans Headquarters and leadership at Caltrans D7 for project initiation and mutual understanding, and to get buy-in from the local Caltrans district
- Expanded outreach with primary partners: the Los Angeles County Metropolitan Transportation Agency (“LA Metro”) and the Los Angeles County Department of Public Works (“LACDPW”)
- Participated in two meetings with each of the corridor cities (Pasadena, Arcadia, Monrovia, Duarte) – one meeting to introduce the project to the staff and one technical meeting to review the existing data, communications equipment, signal controllers and software, etc.
- Prepared a CC Outreach and Communications Work Plan
- Assisted with drafting the “ICM Deployment Planning Grant” submitted to the Federal Highway Administration
- Held a User Needs Workshop with the cities, LACDPW, Metro, Caltrans D7, and Headquarters to discuss and document stakeholder needs which will be a component of the Concept of Operations document
- Met with the San Gabriel Valley Council of Governments (the largest and most diverse sub-regional council of governments in Los Angeles County) staff, Traffic Forum, and Transportation Committee
- Met with the Metropolitan Planning Organization (the Southern California Association of Governments) – the largest MPO in the nation – who are very interested in the project and future collaboration
- Met with the California Highway Patrol and the LA County Coroner’s office regarding coordinated incident response; interest in attending a First Responder’s User Needs Workshop with local police and fire, the Sheriff’s Department, etc.

- Made presentations to the Pasadena and Arcadia City Councils; Duarte is scheduled for September 9th; Monrovia likely will be scheduled this fall
- Held meetings with transit providers: Foothill Transit, Metro Bus, and Metro Rail; a separate Transit User Needs Workshop has been scheduled for August 27, 2014
- Have ongoing bi-monthly CC Project Management team meetings at D7 in Los Angeles and weekly CC conference calls

Outreach Materials

- Prepared and distributed Connected Corridors Fact Sheets
- Wrote the CC Summary for the UC Berkeley/PATH Biennial Report
- Prepared the CC Poster for the 2014 Transportation Research Board mid-year meeting in Irvine, CA
- Initiated the Connected Corridors website: www.http:\\connected-corridors.berkeley.edu
- Posted the Connected Corridors Digest on an ongoing basis – a compendium of links to articles, research papers, conferences, newsletters, etc. specifically related to ICM
- Prepared speaking points regarding the Connected Corridors/I-210 pilot for various speakers

Conference Presentations

- ITS California Southern California Lunch Meetings – Connected Corridors has been presented at two ITS California lunch meetings in Southern California, once by Greg Merritt and once by Sam Esquenazi.
- 2014 TRB Mid-Year Meeting in Irvine – Connected Corridors was well-represented at the 2014 TRB Mid-Year meeting. Caltrans Director Dougherty prominently discussed Connected Corridors during his keynote address and the project had a poster during the "poster session" where the project components and stakeholders were highlighted. Several other posters related to Connected Corridors were also at the poster session.
- ITS California Annual Meeting in October 2014 in Santa Clara – Connected Corridors is a session at this year's ITS California Annual Meeting in October. Connected Corridors will have several speakers (to be determined) in the session.
- Participation in Federal DSS Workshop in San Diego – Connected Corridors team members from Caltrans D7, Caltrans HQ, UC Berkeley, and LA Metro participated in a two-day DSS workshop in San Diego in August 2014.
- Analysis, Modeling, and Simulation Workshop at D7 - The Connected Corridors staff from UC Berkeley are organizing and participating in the AMS Workshop at CT D7 on August 13th.
- TRB (Transportation Research Board) Presentations.

Moving Forward into the Future

- Draft, present to the stakeholder agencies, and execute interagency agreements
- Start quarterly CC newsletter in the fall 2014
- Outreach with other business, professional, and/or community organizations
- Initiate speaker's bureau, quarterly webinars, and social media (Facebook and/or Twitter)
- Plan and implement a videoconference series in lieu of initial press release
- Develop a CC brochure
- Plan and implement an annual CC/ICM Conference

Chronology of Outreach Meetings

Meeting/Date	***Attendees***	***Hotel/# of Nights***	***Flight***	***Meeting Type***
August 30, 2012	Lisa		X	CC Project Meeting with D7 & Metro
November 1	Lisa, Francois		X	CC Project Meeting with D7 & Metro
November 8	Lisa		X	Meeting with CT HQ and MTC in Oakland
Jan. 12-18, 2013	Joe	6	X	Transp. Research Board (TRB) in Washington, DC
January 22- 23	Joe	1	X	Meeting at CT D7
February 19	Joe, Francois, Lisa	1	X	CC Project Meeting with D7 & Metro
February 20	Joe, Francois, Lisa		X	Meeting at SANDAG and tour of TMC
February 28	Lisa			ITS CA Workshop at MTC (Oakland)
April 15-16	Joe, Francois, Lisa	2	X	CC Project Meeting with D7 & Metro
April 17	Joe, Francois, Lisa		X	Meeting at SANDAG
April 19-23	Joe	4	X	ITS America 23rd Annual Meeting and Exposition in Nashville, TN
May 30	Joe		X	Meeting in Seattle, WA with INRIX
June 9-11	Joe, Lisa	Joe-1; Lisa-2	X	Meeting with Jane White, LA County DPW and CC Project Meeting with D7 & Metro
July 8-9	Joe, Francois, Lisa	1	X	CC Project Meeting with D7 & Metro
July 18	Joe, Lisa			Presentation to CT management (Sacramento)

July 29-30	Joe, Francois	1	X	Meeting with CT D7
August 12	Lisa		X	Outreach meeting at D7
August 14-15	Joe	1	X	Meeting with CT D7
August 20	Joe, Francois, Lisa	1	X	CC Project Meeting with D7 & Metro
August 21	Joe, Francois, Lisa		X	Meeting with SANDAG
September 5	Joe			Meeting at Caltrans HQ (Sacramento)
Sept. 8-10	Joe, Francois	2	X	CC Meetings at D7
September 18	Joe, Alex B.	1	X	Meeting with INRIX in Seattle, WA
September 22-24	Joe	2	X	Meetings In LA with Caltrans D7
September 25	Joe			Meeting at Caltrans HQ (Sacramento)
September 30-Oct. 2	Lisa	2	X	ITS CA in San Diego
October 14-15	Joe, Francois, Lisa	1	X	CC Project Meeting with D7 & Metro
October 29	Joe			CC Project Meeting with System Metrics Group (San Francisco)
October 31	Joe, Francois, Lisa	1	X	Meeting with City of Pasadena staff
November 12	Lisa, Francois		X	Meeting with City of Arcadia staff
November 19-20	Joe, Francois, Lisa	1; Lisa-0	X	CC Project Meeting with D7 & Metro
December 3-4	Joe, Francois	1	X	Meeting with CT D7
December 10	Joe			Meeting at Caltrans HQ (Sacramento)
December 10	Francois, Lisa		X	Meeting with City of Duarte staff
January 8, **2014**	Lisa		X	Meeting with City of Monrovia staff
January 12-16	Joe	4	X	TRB in Washington, DC
January 21	Joe, Francois	1	X	Duarte technical meeting
January 22	Joe, Francois		X	CC Project Meeting with D7 & Metro
January 27	Joe			Meeting at Caltrans HQ (Sacramento)
February 18	Joe			Meeting at Caltrans HQ (Sacramento)
February 26-27	Joe, Francois, Lisa	1	X	User Needs Workshop- Duarte and Monrovia
February 27	Alex B.		X	User Needs Workshop- Duarte and Monrovia
March 3	Joe			Caltrans/CC Meeting in Sacramento
March 10	Joe			Caltrans CC Meeting in Sacramento
March 10-11	Joe, Francois, Lisa	1; Lisa-2	X	CC Project Meeting with D7 & Metro
March 12	Lisa		X	Meeting in LA re: Project launch
March 18	Lisa, Francois		X	San Gabriel Valley COG meeting

				(staff)
March 19	Joe, Francois, Lisa			Technical Workshop at UC Berkeley
March 28	Joe			Caltrans/CC Meeting in Sacramento
April 15	Joe, Francois, Lisa			Presentation at UCB by CT Director Dougherty
April 15-16	Joe	1	X	Meeting at CT D7
April 17	Francois, Lisa		X	San Gabriel Valley COG Transportation Committee
April 21-22	Francois, Lisa	Francois-1; Lisa-2	X	Monrovia and Pasadena data collection
April 23	Lisa		X	Meeting with Southern CA Assoc. of Governments
May 5	Francois, Lisa	1	X	Pasadena City Council meeting
May 6	Lisa		X	Meeting with Metro bus staff; meeting with CT PIO
May 22	Joe		X	Meeting with LA Metro and CT
May 28-29	Joe	1	X	Caltrans meetings
June 2-4	Joe, Francois, Lisa	Joe-1; Lisa/Francois-2	X	Meeting with CHP and Coroner's office; CC Project Meeting; and Arcadia City Council Meeting
June 3	Alex B.		X	Meeting with CHP and Coroner's office; CC Project Mtg.
June 4	Joe			Caltrans CC Meeting in Sacramento
June 18	Francois, Lisa		X	Meeting with Foothill Transit
June 22-25	Joe, Lisa	Joe -3, Lisa - 2	X	TRB Mid-Year meeting in Irvine
July 1	Lisa		X	Meeting with Metro Rail
July 14-15	Joe, Francois, Lisa	1; Lisa-0	X	CC Project Meeting with D7 & Metro
July 22-23	Joe	1	X	Meeting with CT D7 re: AMS Workshop planning
July 24	Francois		X	Meeting with Pasadena Technical Advisory Committee
August 4-5	Joe, Francois	1	X	DOT DSS Workshop in San Diego
August 12-13	Joe, Francois, Lisa	1; Lisa-0	X	AMS Workshop at CT D7
August 27	Lisa	1	X	Transit User Needs Workshop
September 9	Joe, Francois, Lisa		X	CC Project Meeting with D7 & Metro

Systems Engineering Summary

Corridor Selection

- Conducted a general review of the geometry and traffic management needs of various freeway corridors within California and the Los Angeles area. This included compiling statistics from 22 freeway corridors in District 7, 7 in District 8, 5 in District 12, and 6 within District 11.
- Conducted a suitability analysis of the I-710 freeway as a pilot ICM implementation corridor. This three-month analysis involved assessing traffic flow patterns and congestion hotspots on the freeway using PeMS data, assessing available capacity along the surrounding arterials using data that could be extracted from traffic impacts studies, inventorying existing transit services and park-and-ride lots, and assessing the feasibility of implementing various traffic management strategies. This analysis led to the identification of several issues that precluded its selection for an ICM pilot deployment. Among key issues were the extent to which congestion problems along the freeway are caused by heavy trucking activities and roadway geometry factors, political issues associated with the option of pushing trucks on nearby arterials, the financial stability of cities along the I-710 corridor, the distance to reach light-rail stations from the freeway, and the lack of park-and-ride lots within the corridor.
- Following the elimination of the I-710 as a pilot candidate, conducted a detailed analysis of the traffic management needs and suitability of the I-210 freeway for a pilot ICM implementation. This analysis also involved assessing freeway and arterial flow patterns based on available data that could be retrieved, inventorying existing transit services and park-and-ride facilities, and assessing the feasibility of implementing various traffic management strategies. The presence of congestion problems to solve, several parallel arterials, light-rail service in close proximity to the freeway, and several park-and-ride facilities within the corridor led to the selection of the I-210 corridor as the site for the pilot deployment of an ICM system.

Systems Engineering

- Project Work Plan
  - Helped define over the course of a month key project tasks, key deliverables for each task, and overall project schedule.
  - Developed in Microsoft Project a detailed Gantt chart covering the entire project, from conception to design, implementation, and evaluation, and showing the interactions and interdependencies between the various tasks.
  - Have periodically revised the Microsoft Project file to reflect changes in project activities or activity scheduling.

- Project Management Plan (PMP)
  - Helped the project team develop over the course of two months a Risk Registry and Risk Management Plan.
  - Developed and wrote the Project Management Plan (PMP). This plan, which required meeting repeatedly with various project team members, was developed over five months. It identifies the project management approach, the change management process, the scope management plan, the schedule management plan, the plan for managing communication between project team members, the processes by which cost and staffing needs will be managed, the quality management plan, the risk management plan, and the procurement management plan.
- Systems Engineering Management Plan (SEMP)
  - Helped the project team understand the application of systems engineering principles to the I-210 Pilot project.
  - Helped developed a preliminary draft of the Systems Engineering Management Plan (SEMP).
  - Currently working on finalizing the content and write-up of the SEMP.
- Identification of User's Needs
  - Helped the project team identify and engage key corridor stakeholders.
  - Developed general high-level user needs for a generic ICM system.
  - Currently finalizing the identification of high-level specific user needs for the I-210 Pilot.
- Concept of Operations (ConOps)
  - Helped the project team define the project scope and goals.
  - Developed over a 12-month period a detailed inventory of existing systems within the I-210 corridor. This includes an inventory of traffic detection systems (traffic sensors, CCTV camera systems, Bluetooth travel time monitoring systems), traffic management systems (signal controller types, type of signal operations, centralized traffic signal control systems), traveler information systems (changeable message signs, 511 systems, etc.), transit systems (light-rail systems, express commuter buses, commuter rail), and parking systems (park-and-ride lots, general parking facilities). While some information could easily be retrieved from existing reports, the retrieval of a significant portion of the collected information was a time-consuming process. All collected data samples needed to be reviewed to assess data quality and data gaps. Some information required spending time measuring or visually assessing geometrical information from maps and aerial pictures. In some cases, significant time also had to be spent reaching out to the appropriate contact persons within each agency and following up with them.

- Conducted a high-level operational corridor analysis focusing on the identification of congestion and safety hotspots on the I-210 freeway and surrounding arterials. This activity required three persons to conduct detailed flow pattern and roadway capacity analyses over a three-month period.
- Developed a list of potential ICM strategies that may be considered in a generic ICM implementation. This list is to be used as the basis of discussion with I-210 corridor stakeholders for the determination of specific strategies to consider for the I-210 Pilot.
- Developed a preliminary list of relevant standards that may affect the development of an ICM system.
- Developed a high-level operational framework for a generic ICM system, identifying key system components and key interactions between them.
- Currently assessing detection and operational gaps within the I-210 corridor.
- Currently working on the development of operational scenarios for the I-210 Pilot.

- System Requirements
  - Initiated the compilation of information that may affect the development of system requirements (technical constraints, institutional constraints, user needs, desired system features, etc.).

Data Collection

- Identified data collection needs for the operational characterization of freeways, arterials, transit, and parking systems.
- Established a connection with the Arcadia TransSuite traffic signal control system, enabling the project team to get real-time access to signal status data from all city-operated signals, five-minute traffic counts from about two thirds of the city-operated intersections, and one-minute travel time data from the city-operated Bluetooth sensor network.
- Currently working on the development of a potential link to LA County's Information Exchange Network (IEN), a communication system that was developed by LA County to support the exchange of information on traffic signal operations.
- Collected information:
  - Geometry of intersection approaches (number of lanes, lane markings, length of turning bays, turn restrictions) for approximately 525 intersections. This information was generally retrieved from maps or aerial photos from Google Maps. This effort required the involvement of four persons over a three-month period. The most time-consuming effort was to measure the length of turning bays using a Google Maps application.
  - Location of traffic sensors on the freeway mainline, freeway ramps, and individual intersection approaches. While sensor layout diagrams were provided for most of the

corridor intersections, these diagrams did not always indicate the exact location of sensors on each approach. The location of sensors had to be visually verified and extracted from Google aerial and street view photos for approximately 300 intersections. In these cases, a Google Maps measuring tool was used to determine the location of each sensor relative to the downstream stop line. This was a time-consuming effort that fully involved two persons over a one-month period.

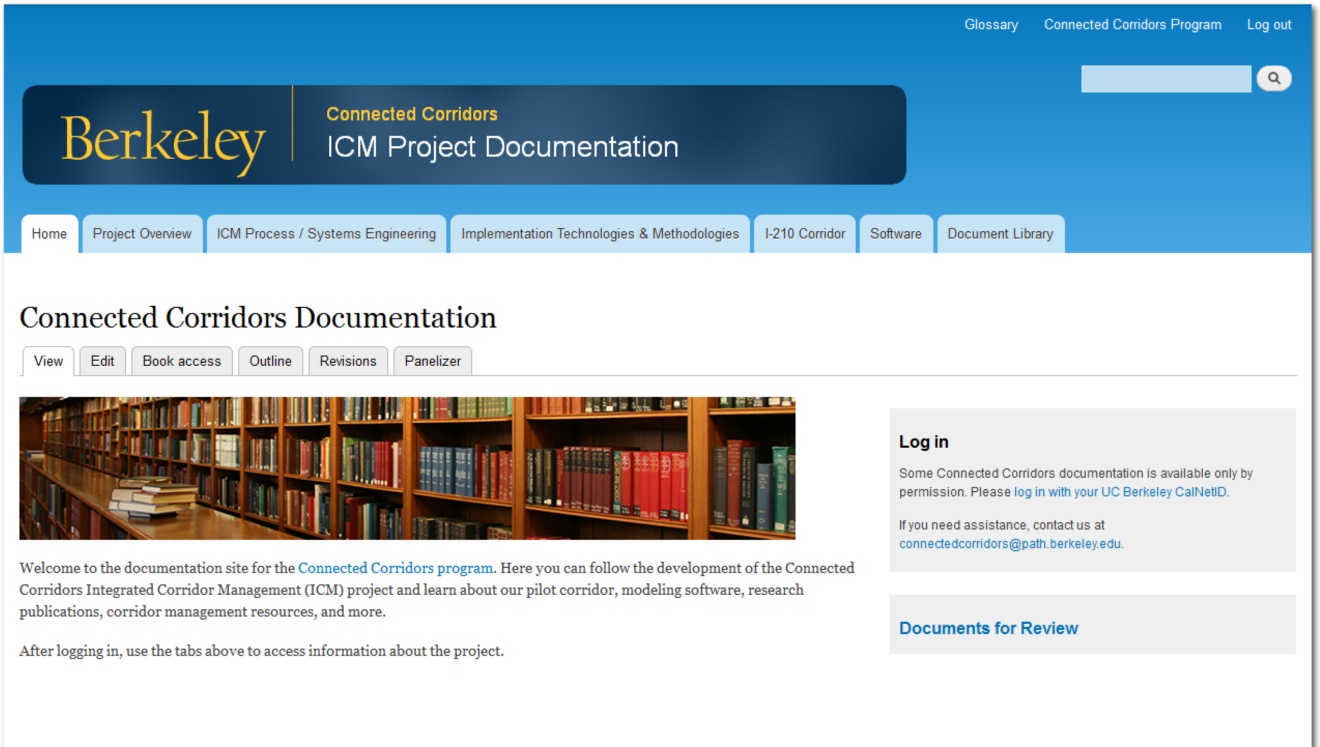
  - Available signal timing sheets from Caltrans, LA County, and local jurisdictions.
  - Available intersection detection layout diagrams from Caltrans, LA County, and local jurisdictions.
  - Available five-minute traffic counts from the Arcadia TransSuite system from December 2013 to present.
  - Available vehicle detections from the Arcadia Bluetooth sensor network from December 2013 to present.
  - One-week sample of signal timing and 15-minute traffic flow data from the Pasadena i2 centralized traffic signal control system.
  - Reports on traffic impact studies that have been conducted for proposed projects within the I-210 corridor over the past 8 years.
  - Synchro model developed by Iteris covering a significant portion of the city of Pasadena.

- Data analysis efforts
  - Developed several maps of corridor systems. While many maps already existed, these maps generally only covered a specific system. What was needed in the corridor were maps including in a single document all the existing systems. Efforts were thus required to transpose data from one mapping system to another.
  - Conducted various analyses on the Arcadia real-time data to assess their quality, identify typical daily flow profiles, and determine how the available data could be used to determine flow patterns at individual intersections and through the city. This required reviewing detailed timing data from 51 intersections and sensor data from 367 detection stations covering a six-month period.
  - Conducted a preliminary analysis of the quality of traffic flow data sample that was obtained from the city of Pasadena. This required reviewing and analyzing data from over 500 sensors across 70 intersections covering a seven-day period.
  - Assessed how vehicle counts from existing traffic detection locations may be used to determine traffic flow patterns along specific arterials and within the corridor. This is a complex analysis that required several weeks to process data from various arterial segments and, for each arterial segment considered, data from various periods.

Corridor Modeling

- Modeled arterials within the I-210 corridor in Synchro, a commonly used signal optimization software. This model currently models nearly 500 signalized intersections. While half of this modeling re-used a Synchro model that was developed by Iteris for the city of Pasadena, information from the source model had to be reviewed to correct several inaccuracies and code several missing intersections. Coding of the remaining intersections, particularly the signal timing information for each intersection, required a three-month effort. This modeling will eventually be used to assess the operational effectiveness of existing traffic signal control plans under existing flow patterns, as well as existing and proposed control plans under assumed traffic conditions. It is also used to assess data gaps and needs.

Connected Corridors ICM Project Documentation Website



Welcome to the documentation website for Connected Corridors' Integrated Corridor Management (ICM) project. This website documents the effort to design, develop, and implement an ICM system for use on transportation corridors in California. An important part of this effort involves piloting the system on a section of the I-210 freeway in Southern California.

As the state's transportation agency, Caltrans is leading the effort to plan, build, and deploy ICM systems on fifty corridor segments in California over the next ten years. Called "ICM California," this plan is part of Caltrans' strategic response to the State of California's objectives of improving transportation systems to enhance the livability, sustainability, and economic performance of the state. The I-210 Pilot is the first corridor segment in that effort.

What You'll Find on the Site

The site includes information on:

- The project's background, purpose, scope, and components
- The ICM development process and the Systems Engineering approach used to guide it
- The process of selecting a corridor, engaging stakeholders, and developing a detailed understanding of the transportation environment
- The technologies and methodologies used in building the ICM system, including:
    - Decision support
    - Analysis, modeling, and simulation
    - Theoretical and mathematical concepts
    - Applied research and development
    - System architecture
    - Software development and tools

Please note that the ICM project is still in development, and the website is continuing to grow along with it. Not all sections are complete, and others will be added, expanded, or revised over time.

About this Guide

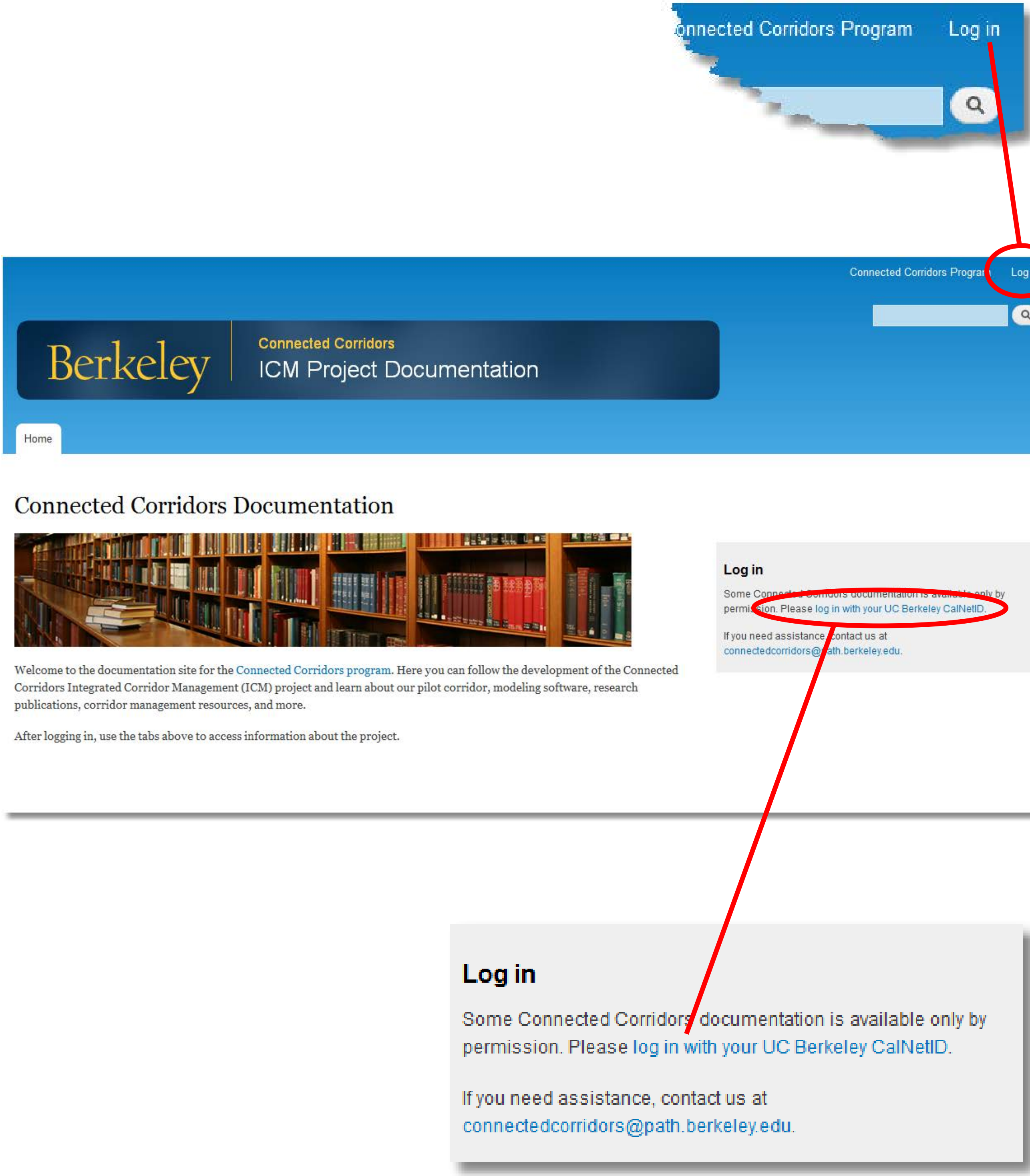
This guide will help you access the website and get started using it. It will guide you through:

- Logging In
- Understanding how the site is organized
- Finding your way around and locating the information you want
- Generating a printer-friendly version of the web topics

Logging In

To log in to the Connected Corridors project documentation site:

1. Point your browser to http://ccdocs.berkeley.edu.
2. Click either **Log in** link.
3. Enter your CalNet ID and passphrase.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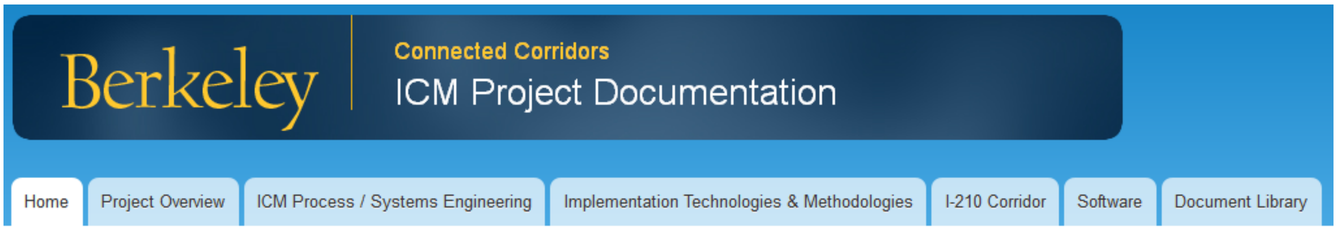
Berkeley
Connected Corridors
ICM Project Documentation
Home
Connected Corridors Documentation
Welcome to the documentation site for the Connected Corridors program. Here you can follow the development of the Connected Corridors Integrated Corridor Management (ICM) project and learn about our pilot corridor, modeling software, research publications, corridor management resources, and more.
After logging in, use the tabs above to access information about the project.
Log in
Some Connected Corridors documentation is available only by permission. Please log in with your UC Berkeley CalNetID.
If you need assistance, contact us at connectedcorridors@path.berkeley.edu.

Quick Guide to the Tabs

After logging in, you'll see a row of tabs that lets you access different categories of information about the Connected Corridors ICM project:



Here's what the tabs contain:

This tab	Contains this	And includes this information
Project Overview	Summary of the project: its background, purpose, scope, and components	• Project motivation • Background • Current state of ICM • Project definition • Corridor boundaries • Transportation systems under consideration • Problems to be addressed • Intended cost/benefit of the study • Contractual deliverables and organization of the website
ICM Process / Systems Engineering	A high-level view of the ICM process and its relation to systems engineering	• Stages of an ICM project and typical activities at each stage • Guiding the project with systems engineering • Systems engineering documentation
Implementation Technologies and Methodologies	The concepts and technologies used to build the Connected Corridors ICM system	• ICM data flow • Decision Support System • Analysis, modeling, and simulation • System architecture

This tab	Contains this	And includes this information
		• Theory and applied research
I-210 Corridor	Information focusing on the I-210 corridor	• Corridor selection • Stakeholder engagement • Corridor description and system inventory • Data collected about the corridor
Software	Software development and tools supporting research and corridor management	• Outline of development process • Links to the tools
Document Library	Quick access to project documents and supporting materials	• Systems engineering documents • Presentation materials • Research publications • Additional project documents

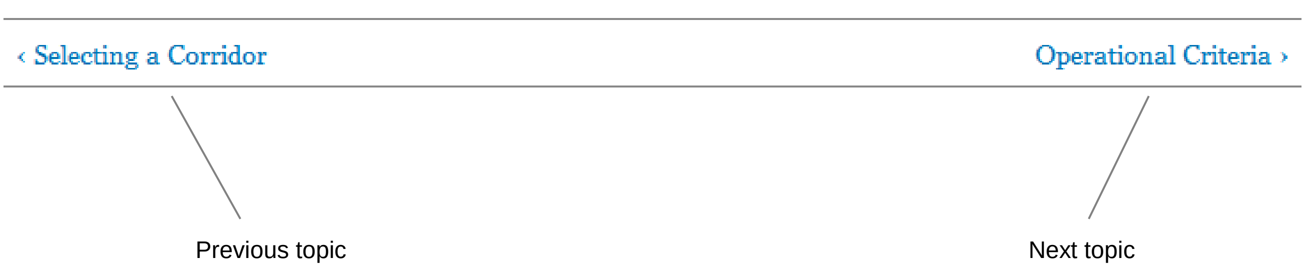
Finding What You Want

Table of Contents

Most pages on the website have a table of contents in the left sidebar to give you easy access to the information available:

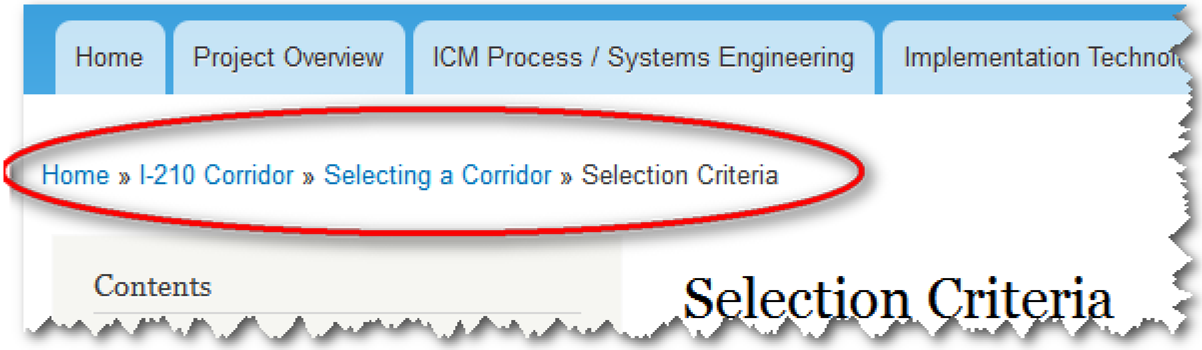
Browsing through Topics

In addition to the table of contents, you'll find links at the bottom of most pages that let you click forward or backward through the list of topics:



Breadcrumbs

So-called “breadcrumbs” show the path leading to the current topic, so you can quickly see where you are:

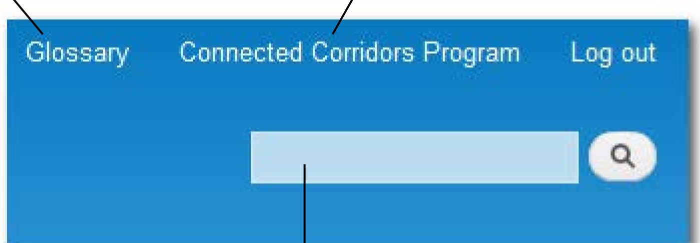


Search Tool, Glossary, Program Website

A cluster of features at the top right of the window help you find additional information, no matter what page you're on:

Click the **Glossary** link for a list of the acronyms used on the website.

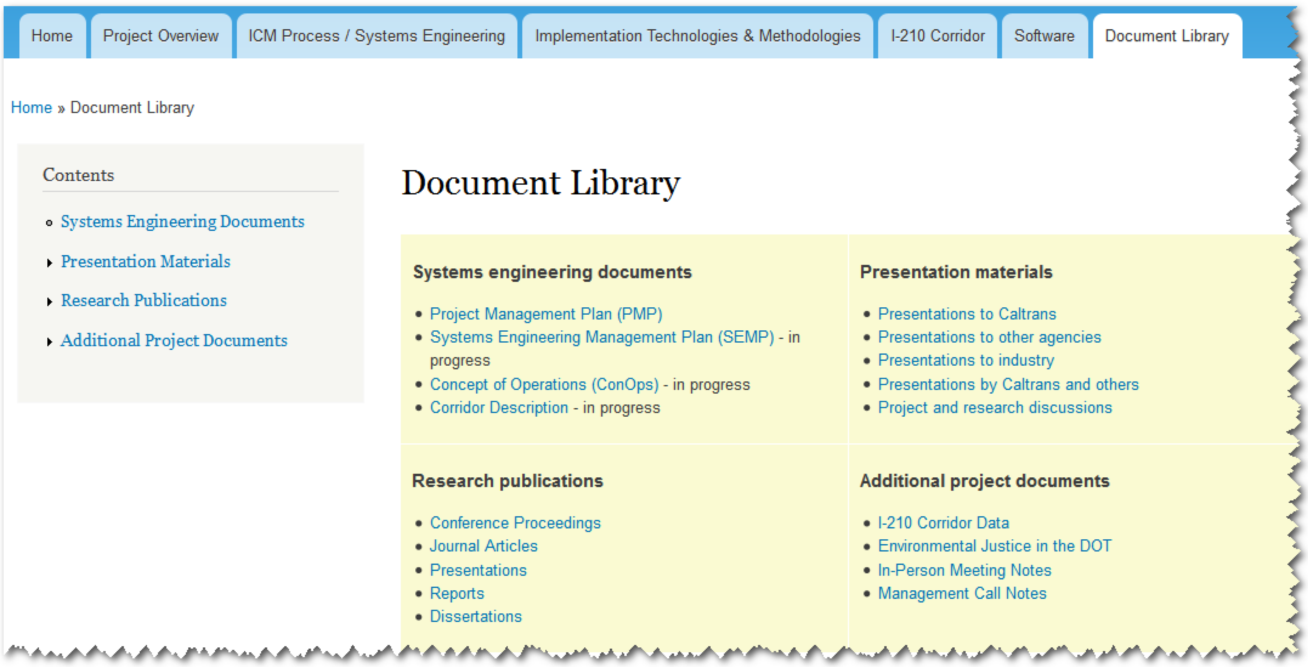
To view the public site for Connected Corridors, click the **Connected Corridors Program** link. **Note:** This link takes you *away* from the ICM Project Documentation site to the public Connected Corridors site. (To remain in the Project Documentation site, *right-click* the **Connected Corridors Program** link and open it in a new tab or window.)



The search tool lets you search for specific content. Type the word or phrase you're looking for in the text box and press Enter, or click the magnifying glass for advanced search features.

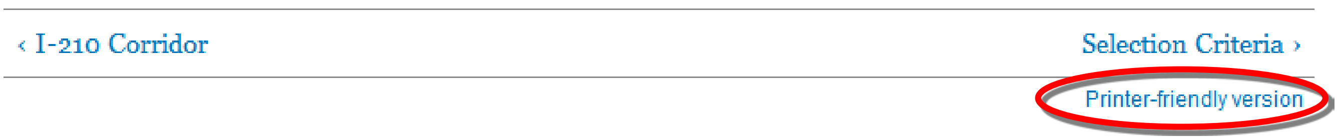
Document Library

The Document Library tab gives you quick access to the documents and other materials available on the site, including research publications, systems engineering documents, presentations, corridor data, and more:



Printing Website Topics

While you can, of course, print individual web pages directly from your browser, the documentation website includes a feature that lets you print multiple topics within a tab so they are output as a single document. You'll find the link at the bottom right of most web pages:



When you click the link, it generates a printable version of the topic you're viewing *plus any subordinate topics as well*, in one continuous web page.

For example, suppose you're viewing the topic “Selecting a Corridor.” The table of contents in the sidebar shows that there are several subordinate topics under it:

If you click the **Printer-friendly version** link, the site generates a single printable page containing “Selecting a Corridor” plus “Selection Criteria,” “Deciding on a Corridor,” and “Considering Alternatives.”

Summary of ICM Research Achievements

Modeling, Simulation, Analysis, and Control of Traffic Corridors

The ultimate and overriding goal of our research in this field is to develop means to intelligently manage and coordinate mobility in a large urban corridor, in order to maximize environmental sustainability, productivity, convenience, and livability. To this end, the Connected Corridors research program was initiated in July 2011 at UC Berkeley's Partners for Advanced Transportation Technology (PATH) to research, develop, and test a framework for future corridor traffic management in California. Connected Corridors was established by unifying the research and development efforts of two major PATH projects: Tools for Operational Planning (TOPL) and Mobile Millennium. The TOPL project, which Professors Horowitz and Varaiya established and direct, focused on the development of traffic analysis, modeling, prediction, and decision support tools for freeway traffic corridors. Mobile Millennium, which Professor Alex Bayen established and directed, focused on the use of mobile and hybrid data for traffic estimation and travel time prediction. A key aspect of Connected Corridors, which sets it apart from previous PATH efforts in this field, is the inclusion of a large-scale pilot deployment that is planned to take place during the next four years in the I-210 freeway corridor in Los Angeles. If this pilot deployment proves successful, it will set a framework and initial blueprint for further Caltrans-led corridor management deployments in other sites throughout California.

A key component of the Connected Corridors program is the development of a macroscopic/mesoscopic simulation prediction-based Decision Support System (DSS) for active traffic management of the I-210 corridor. The envisioned Decision Support System utilizes self-calibration, traffic estimation, demand prediction, and model-based traffic management tools to run a series of short-term (e.g., one-hour) rolling horizon simulations, in order to (a) forecast future traffic conditions under different expected likely scenarios and different traffic management strategies and (b) determine the strategy that will most likely meet traffic management performance objectives if deployed.

To achieve this goal, we have been developing traffic flow simulation models that not only run very quickly, but are also able to adapt quickly and frequently to changing traffic supply and demand conditions, based on current and historical heterogeneous traffic data, and produce traffic forecasts whose reliability can be verified. We have also been synthesizing traffic management strategies that optimize corridor performance, under a set of predicted model parameters and traffic demands and scenarios forecasts, in order to quickly and reliably estimate the best possible performance gain of a management strategy under consideration. Finally, we are working to ensure that a selected traffic management strategy is deployable in a robust manner, subject to frequent traffic sensor and communication faults.

Freeway Modeling, Simulation, Analysis, and Control

Research during this period has addressed several critical elements of freeway corridor traffic forecasting decision support systems:

1) The development of automated statistical-learning techniques for calibrating the capacity and supply characteristics of the roadway segments, based on heterogeneous historical traffic data [1, 2].

2) The development of model-based learning algorithms for accurately imputing (i.e., reconstructing) unavailable on-ramp input flow demands and off-ramp flow turning proportions at ramps that lack detection, using mainline traffic flow data [3].

3) The development of model-based sensor fault detection, exclusion, and model reconfiguration techniques to achieve robust model calibration in the presence of frequent mainline traffic sensor and communication faults, even when unavailable on-ramp demand flows and off-ramp turning ratios must be imputed using sporadically faulty mainline traffic flow detection [4, 5].

4) The development of boundary demand prediction algorithms that are able to forecast the boundary mainline or on-ramp traffic flows that are expected to enter the network and the turning ratios of the off-ramp flows that will exit the network during the forecasting period, based on historical and currently available traffic data [6, 5].

5) The development of model-predictive coordinated on-ramp metering and variable speed limit control algorithms that can determine, in a computationally efficient manner, the traffic management strategy that globally minimizes the total vehicular travel time spent on the roadways [7, 8] or locally decreases mainline traffic flow immediately upstream of a bottleneck section that experiences significant capacity drop [9], for a given set of calibrated supply characteristics and boundary demand predictions.

   Other traffic management strategies, model-based freeway-to-arterial traffic detouring, freeway-arterial coordination, and arterial signal control traffic management strategies are currently under development.

6) The formulation and experimental verification of new queue estimation techniques, based on vehicle re-identification using wireless magnetometer sensor arrays, in order to reliably estimate vehicle queues at the freeway on-ramps and signalized arterial intersections [10, 11, 12]. Monitoring queues at freeway on-ramps and signalized arterial intersections is necessary to effectively manage freeway corridors.

Results in [5, 3] show that the developed calibration, sensor fault detection and handling, and ramp flow imputation techniques can produce traffic flow models that accurately reproduce observed traffic behavior in large freeway network segments for an entire 24-hour simulation period, utilizing only the measured or imputed on-ramp flows and off-ramp turning ratios as inputs to the model. For example, it was shown in [3] that a calibrated macroscopic cell transmission model of a 26-mile long section of I-

210E is able to accurately reproduce observed traffic congestion behavior, while producing relatively small overall density and flow errors (2.63% and 3.58%, respectively) and satisfying most of the fidelity performance benchmarks that are used to evaluate microscopic models by the Federal Highway Administration and many state DOTs. Results in [6, 5] show that the developed boundary demand prediction algorithms can effectively and in a computationally efficient manner forecast mainline and on-ramp traffic flow demands one hour ahead of time, even during days with unusual traffic flow demands, such as a Super Bowl Sunday. Results in [7] show that the developed model-predictive freeway coordinated ramp metering and variable speed limit freeway traffic management schemes can be implemented in a computationally efficient manner, on a large-scale freeway corridor (e.g., a 23-mile segment of the I-80 freeway in the Bay Area) over a ½-1–hour rolling time horizon, in order to determine the traffic management strategy that will minimize total travel delay, including time spent on the on-ramp queues, for a given set of freeway calibration parameters and boundary demand predictions.

Further details are included in the subsections below.

Freeway Modeling, Analysis, and Calibration

A key feature in TOPL and Connected Corridors is the automated, empirical calibration of corridor traffic flow models from traffic data, as originally introduced in [13]. Five-minute traffic flow and density data, obtained at each section of the freeway via the PeMS database system, is used to estimate the key parameters of the Cell Transmission Model (CTM), including free-flow speed, maximum flow capacity, critical density, congestion-wave speed, and jam density. [1] and [2] each present a statistical learning methodology for improving the characterization and identification of these parameters. [1] explores the use of probabilistic graphical models to represent the joint probability distribution of section capacities located along a freeway. [2] explores the statistical learning estimation of the flow-versus-density fundamental diagram as a probability density distribution in both the free-flow and congested traffic regimes. Such distributions can be used either to estimate the expected values of the parameters, in order to conduct deterministic traffic flow simulations, or to conduct statistical simulation studies in decision support systems.

Ramp Flow Imputation

Accurate access to on-ramp flow demands and off-ramp flow data is essential for a traffic flow model to reproduce actual traffic behavior and perform accurate traffic forecasting. In particular, during peak periods when freeway mainline flows are near capacity, small increases in on-ramp demands or small decreases in off-ramp split ratios can trigger congestion, resulting in large increases in travel time and producing large deviations in the resulting density and speed. Unfortunately, data from freeway ramps, particularly off-ramps and freeway-to-freeway interconnection ramps, are often missing or incorrect. A key innovation introduced in TOPL is the model-based imputation (e.g., generation) of missing on-ramp flows and off-ramp flow split ratios using neighboring mainline traffic flow data.

[3] analyzes the convergence properties and presents experimental results of an iterative learning algorithm introduced in [14] for imputing on-ramp flows and off-ramp turning ratios, based on the Link Node Cell Transmission Model (LN-CTM) [15]. This imputation algorithm no longer requires the 24-hour periodicity assumption that was required in our previous algorithm ([14]); hence, it can be used to

impute on-ramp flows and turning ratios during any segment of time. Moreover, it can be used in a decision support system to perform imputation of missing ramp flow data in "real time." In the first step of the imputation procedure presented in [14, 3], a discrete-time adaptive iterative learning algorithm is used to estimate the effective input flow demand to each cell of the model. In the second step of the imputation procedure, on-ramp flows and off-ramp split ratios are uniquely determined through the solution of a linear program that minimizes the error between modeled and observed mainline flows. The papers illustrate the application of the imputation algorithm to determine missing on-ramp and off-ramp flow measurements in a 26-mile long section of the I-210 freeway in Pasadena. It is shown that the calibrated LN-CTM with imputed missing on-ramp and off-ramp data is able to accurately reproduce observed traffic congestion behavior, while producing relatively small overall density and flow errors (2.63% and 3.58%, respectively) and satisfying most of the fidelity performance benchmarks that are used to evaluate microscopic models by the Federal Highway Administration and many state DOTs.

Sensor Fault Detection and Handling

A frequently encountered problem with freeway traffic data is that it is often faulty, due to sensor damage, transmission errors, vandalism, etc. This problem is aggravated when unknown on-ramp demands and split ratios must be imputed in order to perform traffic forecasts, since the ramp imputation algorithms heavily rely on mainline traffic data.

[4] presents an innovative model-based fault detection and exclusion scheme that implements a decision logic to automatically identify faulty or misallocated freeway traffic sensors in the presence of unknown on-ramp and off-ramp flows. This algorithm is currently being implemented within the TOPL and Connected Corridors frameworks in the form of a fault detection and handling tool that automatically excludes faulty detection stations and reconfigures the calibration, imputation, estimation, and prediction systems accordingly.

[5] presents a case study of the use of the TOPL and Connected Corridors calibration, ramp imputation, and fault detection and handling tools in the calibration of a link-node cell transmission model for the I-680 freeway in Northern California, under severe mainline sensor faults (60% of the mainline vehicle detection stations (VDS) were faulty).

Coordinated Ramp Metering and Variable Speed Limits

On-ramp flow metering is one of the most effective means of decreasing congestion and travel-time delays on a freeway. In ramp metering, traffic entering the freeway through the on-ramp is regulated, while often preventing the resulting on-ramp queue from significantly overflowing onto the neighboring arterials, with the objective of allowing the freeway to operate at maximum efficiency. Speed control (variable speed limits) is primarily used for improving safety, but it has also has been found to be useful for congestion alleviation when ramp metering is insufficient, particularly when it is deployed in a freeway segment immediately upstream of a bottleneck section that experiences a heavy flow capacity drop during the onset of congestion. These traffic control schemes are part of the suite of traffic management options that are being incorporated into the TOPL/Connected Corridors traffic management decision support system under development. [9, 16, 17] describe two novel approaches for implementing Variable Speed Limits (VSL) and Coordinated Ramp Metering (CRM) on freeways.

[9] presents a heuristic but effective VSL/CRM control scheme, specifically designed to decrease mainline traffic flow immediately upstream of a bottleneck section that experiences significant capacity drop, such as the infamous Powell St. bottleneck on the I-80 freeway in Emeryville. [16, 17] present a new class of computationally efficient model-predictive CRM/VSL congestion controllers for freeways that are based on the Link-Node Cell Transmission Model (LN-CTM) used in the TOPL/Connected Corridors framework. In [16] the standard LN-CTM model without capacity drop is considered, while in [17] a modified LN-CTM with congestion-induced capacity drop is considered. It is shown in [16] that the minimization of the total travel time (or total travel delay) in a freeway segment (including time spent at the on-ramp queues) under combined CRM and VSL control can be cast, under a relaxation process, as a solution to a linear program (LP). An approach is proposed to map the LP solution back to the solution of the original optimal control problem, and it is proven that the solution derived from this approach is optimal. A model-predictive framework is used to demonstrate the feasibility of the proposed methodology, even when VSL is disabled, via a realistic freeway-modeling exercise. In [17] the model-predictive methodology presented in [16] is extended for the case when congestion-induced capacity drop and ramp weaving effects are included in the LN-CTM model. Since the resulting optimal control formulation is non-convex, a heuristic solution approach is proposed by partitioning the freeway into segments and placing realistic restrictions on solution trajectories, based on the results of [44]. This allows the computation of the control strategy to be performed as a small sequence of linear programs.

[18] summarize a newly developed model capable of handling the coupled effects of on-ramp queue dynamics and freeway dynamics. These have subsequently been used to derive a set of ramp control algorithms capable of regulating traffic, based on efficient uses of the so-called adjoint-based method [8]. In this article the algorithm is implemented on a model of I-15, based on an original Aimsun simulation.

Freeway-Arterial Coordination and Rerouting

The adjoint-based method was also used in [19] to formulate controllers capable of rerouting flows based on the congestion level on the freeway. The corresponding algorithms figure out the proper split ratios to apply at selected off-ramps to optimize overall throughput when part of the flow is fed to the arterial network and the other part stays on the freeway. To complement this approach, a few other modeling directions have been investigated, in particular the modeling of creeping flow (i.e., smaller vehicles using the space between larger vehicles to overtake them in traffic jams) [20], or the use of a “viscosity term” in the conservation of vehicles to understand how to smooth shocks in traffic and control the corresponding flows (through the Hamilton-Jacobi equations) [21].

In parallel, the problem of routing in traffic networks has been investigated quite thoroughly, in the context of stochastic routing (and the problem of stochastic on-time arrival). The problem there is to understand how one can maximize the chance of arriving on time given a deadline, which is different from minimizing the expected travel time. Several acceleration mechanisms for these algorithms have been developed. [22] It is expected that this line of research will ultimately feed the travel information part of the DSS.

[23] examines the issue of cybersecurity: What would happen if an intruder took over the control infrastructure of the freeway (i.e., metering), as recently demonstrated through the attack on the Sensys network. The corresponding papers show the ability to create "congestion on demand," i.e., the ability to selectively create traffic jams at a user-specified location and time frame.

Queue Estimation Using Vehicle Re-Identification

As discussed in a previous section, ramp metering is an effective traffic control strategy for managing freeway congestion. However, in most instances it is critical to maintain the on-ramp queues to within the lengths of the on-ramps, in order to prevent their spillback onto neighboring arterial traffic. Frequent on-ramp queue spillback onto neighboring arterials is one of the major sources of conflict between freeway and city traffic managers. Unfortunately, it is extremely difficult to obtain reliable queue length estimates based on existing on-ramp and arterial traffic flow detectors, particularly when the traffic on top of the detection station is congested.

[10] reports on a field test that was conducted on the Hegenberger Road loop on-ramp to I-880 southbound to evaluate traditional and novel on-ramp queue length estimation methods. It was found that a novel queue length estimation method, which relies on counting vehicles entering and leaving the on-ramp but corrects for offset errors using vehicle re-identification algorithms based on wireless Sensys detector arrays, offered the best estimation performance. However, it was also found that the existing vehicle re-identification algorithms underperformed during congested traffic conditions, when vehicles stop and move slowly over the detectors, at the on-ramp entrance.

[11] describes how vehicle re-identification algorithms that are based on magnetometer arrays need to be modified in order to improve their performance under congested traffic conditions. The modified algorithm was tested on the Hegenberger Road loop on-ramp to I-880 southbound and compared to the existing algorithm. It was found that the proposed algorithm modifications not only significantly improve the vehicle re-identification rate but also significantly decreased the vehicle mismatch rate, particularly during congested traffic conditions. The modifications also resulted in accurate on-ramp queue estimations, even under congested traffic conditions, when vehicles stop and move slowly over the detectors, at the on-ramp entrance. [12] presents an arterial traffic travel time estimation field test using vehicle re-identification techniques. It is shown in this study that the modified vehicle re-identification algorithm introduced [11] also outperforms the original algorithm in arterial travel time estimation applications.

Demand Estimation, Prediction, and Management

The traffic corridor decision support system that is being developed in the Connected Corridors program requires demand-prediction tools that are able to forecast the amount of traffic that is expected to enter the network during the prediction horizon, to run a series of short-term rolling horizon traffic flow simulations, in order to forecast future traffic conditions under different expected likely scenarios and different traffic management strategies.

[24] presents a boundary flow prediction method that combines the most recent traffic data with historical traffic data. For each ramp flow in the network, historical data are aggregated to flow profiles

that represent a typical day, one for each day of the week. Using the nominal historical profile as a deterministic input and the actual traffic flow as the noise-contaminated measured output, the parameters of an autoregressive moving average with exogenous input (ARMAX) model that best describes this input/output relation are identified in a real-time recursive fashion. Based on the results of the ARMAX identification process, the optimal multi-step ahead predictor model of the traffic flow, which utilizes the flow measurements up to the current time, is determined. [5] provides a more sophisticated and adaptable demand-prediction scheme by first clustering the historical sensor data using the K-means method to obtain the representative data pattern of the sensor. In this case, instead of using only a single flow profile to represent a typical day, multiple flow profiles are considered, each being the centroid of a K-means cluster. Based on the identified ARMAX model, a D-step ahead optimal predictor is generated for each cluster and its associated estimated error prediction variance calculated. The cluster and its associated ARMAX estimate that produces the smallest estimated D-step ahead error prediction variance is selected at each sampling time instant to generate the optimal D-step ahead predictor of the sensor output. Due to their simplicity and robustness, these methods are useful in practical applications. Results obtained using empirical freeway mainline and on-ramp data show that these methods outperform methods that rely only on the historical average of the data to perform a prediction, especially during days with unusual traffic flow demands, such as a Super Bowl Sunday.

A part of the work has focused on understanding the value of time and the proper pricing structure to incentivize commuters to change their patterns. For example, how much should one person receive in order to accept a change to their routes and take a longer path? Preliminary findings are available in the article [25]. More work is needed on pricing.

Based on this initial work, routing games have been studied, i.e., a setting in which a portion of users are indeed changing their routes for the common good (against some rewards) to decrease congestion. The first problem studied is the Nash Stackelberg problem, in which a set of commuters change their pattern and the rest of the commuters readjust themselves selfishly. This was published in [26]. Then the problem of learning these equilibria was studied, i.e., to understand how, day after day, a population making choices learns from their choices based on the outcome of the previous day. This phenomenon is important and enables us to understand how the population will react to incentivization, should it be given the opportunity to gain some reward for good behavior. [27]

More recent work has focused on the problem of understanding mobility patterns (in particular, OD estimation and the route assignment and route flow inference problems) based on cell tower records. This work is still in its infancy, and partnerships with AT&T and Verizon are just starting. However, the preliminary results are promising and show that we will be able to estimate OD, link density, and volumes, as well as estimate typical routes and flows along them from cellular data [28]. The methods account for demographic and coverage biases, and solve flow inference problems via convex optimization from data without involving traditional modeling assumptions (such as user equilibrium). Under the present-day cellular coverage density in the I-210 region, the methods provide 90% accuracy in route flow estimation. These findings give promise for the use of cellular data sources in operational coordinated re-routing at the corridor scale.

Freeway Model Modifications

After the completion of the I-680 CSMP Project [56], recommendations were made as to how the freeway traffic model could be improved. Two major requirements were:

1. Modify the junction model to better handle multiple incoming flows when output links are congested.
2. Extend the existing HOV model to the separated HOV lane configuration with gated access.

We have introduced a new node model [57], which (1) incorporates user-adjustable input link priorities and (2) relaxes the First-In-First-Out (FIFO) condition for diverging flows. The FIFO condition means that at junctions with multiple output links a jam in one of the output links blocks the whole flow through the junction. The consequence of that is a completely blocked freeway mainline flow in case of an off-ramp spillback. Relaxing the FIFO condition results in partial (not complete) blocking of flows that are directed to free output links, a behavior that is more realistic. Monotonicity and mixed monotonicity properties of a system with relaxed FIFO at junctions are analyzed in [58].

In [57] we introduced the macroscopic model components needed to adequately represent a traffic network with managed lanes: multi-commodity traffic flow, policy for junctions with multiple input and multiple output links, and local traffic assignment, where vehicles of certain types may choose between multiple downstream links. Then, we applied this theory to modeling of freeways with HOV and HOT lanes, and introduced techniques that reproduce phenomena inherent to HOV/T traffic [59]: the inertia effect and the friction effect. The inertia effect reflects drivers' inclination to stay in their lane as long as possible and switch only if this would obviously improve their travel condition. The friction effect reflects the empirically observed drivers' fear of moving fast in the HOV lane while traffic in the adjacent GP links moves slowly due to congestion.

The upgraded traffic model is being implemented in the Berkeley Advanced Traffic Simulator (BeATS) [60] and tested with freeway configurations I-680N (full access HOV lane) and I-210E (separated HOV lane with gated access) in [61].

Freeway Density Estimation Using Probe Data

In an age of ever-increasing penetration of GPS-enabled mobile devices, the potential of real-time "probe" location information for estimating the state of transportation networks is receiving growing attention. Much work has been done on using probe data to estimate the current speed of vehicle traffic (or equivalently, trip travel time). While travel times are useful to individual drivers, the state variable for a large class of traffic models and control algorithms is vehicle density. In this research we derived a method for using probe data to enhance density estimates that had been obtained using roadside sensors, based on Rao-Blackwellized particle filters, a sequential Monte Carlo scheme. Subsequently, we present numerical results showing the utility of our scheme in using probe data to improve vehicle density estimation, with high performance in simulation and good performance with real data collected from a freeway in Los Angeles, California [62].

Loop Detector Fault and/or Bias Identification

Loop detection data that is received through the Caltrans Performance Measurement Systems (PeMS) in the form of flow, density, and speed information is critical for calibrating models, predicting inflow demands, and running model-based decision support systems. Unfortunately, loop detector data often contains biases, and the detectors are subject to frequent faults, which may lead to inaccurate calibrations and predictions if not properly handled.

We have developed a new model-based and multi-step procedure for analyzing loop detector data, in order to identify faulty and/or biased detectors:

1. Perform flow balance tests across freeway links, to pinpoint groups of detectors that include one or more biased or faulty detectors. Although this first test cannot pinpoint the actual biased or faulty detectors, it pinpoints the group of detectors that require further fault identification analysis.
2. Run a model-based fault detection algorithm that imputes ramp flows, in order to match mainline data density measurements, and subsequently identifies faulty or biased mainline freeway loop detectors utilizing an error signature parity match. This step successfully identifies the mainline detectors that are faulty or biased among the group of detectors flagged by the first step of the procedure.
3. Run the same ramp imputation and error signature parity match algorithm as in the second step, but use measured on-ramp and off-ramp flows, in order to respectively flag biased or faulty off-ramp or on-ramp loop detectors.

This fault identification procedure was tested using loop detector data from Interstate 210-W in Los Angeles, California, obtained from PeMS. Results obtained from a particular day's analysis indicate that the developed loop detector fault and/or bias identification procedure is working reliably. To test the algorithms, the fault identification algorithms in the second and third steps of the procedure were run independently from the first step. Most of the mainline and ramp loop detectors that were identified as faulty or biased by the second and third steps were also flagged as being part of a group of faulty detectors by the first (flow balance) step of the procedure, and were correctly diagnosed as being faulty by further human analysis. Additional loop detectors were identified as being faulty and/or biased by the second and third steps of the fault detection algorithm, which were not flagged by the first (flow balance) step. However, a subsequent human analysis involving the local flow values of the regions surrounding each of these detectors show that the flagged detectors were indeed faulty and/or biased. These flow imbalances, however, were of low enough values to not be registered by the first (flow balance) step of the identification procedure. Additional numerical analysis is in progress, and a complete progress report is in preparation.

Arterial Modeling, Simulation, Analysis, and Control

Research during this period has addressed the following critical elements of arterial traffic modeling, calibration estimation, and forecasting in decision support systems.

Arterial CTM Model Calibration and Testing

The Cell Transmission Model (CTM) and its extended models have been applied in both traffic simulation and control design, for both freeway traffic and urban street traffic. However, to date there have been very few studies that analyze the accuracy of Cell Transmission Models when they simulate urban street traffic. [29, 30] discuss the calibration and evaluation of an arterial Link-Node Cell Transmission Model (LN-CTM) developed under TOPL using the Lankershim data set generated by the Next Generation Simulation (NGSIM) project of the Federal Highway Administration (FHWA). The Lankershim NGSIM data contains detailed vehicle data on a segment of Lankershim Boulevard that is close to Universal Studios in Los Angeles. The segment has four signalized intersections and intersects, from north to south, with one off-ramp from US-101, Universal Hollywood Dr., and James Stewart Ave/Valleyheart Dr. In total, there are 11 entering roads and 10 exiting roads in this network. The NGSIM vehicle trajectory data was generated by video from five cameras and real-time signal timing data. The vehicle trajectory data was processed to obtain the model parameters, demands, and exit flow split ratios, as well as link vehicle densities and vehicle queues and flows at the intersections.

Simulation results showed that the link-node cell transmission model (CTM) is able to simulate arterial traffic with relative error flows on the order of those obtained in CTM freeway models. However, a CTM arterial model may require significantly more calibration parameters than a CTM freeway model (e.g., signal timing plans and turning ratios at all intersections) and, more important, the arterial NGSIM traffic data used in this study is seldom available in most arterial networks. Arterial traffic inhomogeneity and other exogenous effects, such as pedestrian crossing traffic and right-turn-on-red vehicle flow, make modeling accuracy more challenging. The model accuracy can be improved if such events are modeled in more detail. In this simulation study presented in [29, 30], demand and split ratios were updated at an interval of 10 seconds. Unfortunately, such data quality is seldom available in most arterial networks.

Development of the Vertical Cell Model (VCM)

[38] attempts to adapt the Cell Transmission Model (CTM) to make it work in the arterial network. While CTM is generally accepted as a standard representation of traffic flows on freeways with long links and uninterrupted flows, less is known about the accuracy of CTM or other macroscopic queueing models on urban road networks with short links and frequent flow blockages due to signal control. In fact, almost all existing validations of CTM focus on modeling freeways. In this work done on the Connected Corridors deployment site, we aimed to provide evidence toward selecting the appropriate queueing model dynamics for use in analysis and control of a large-scale network of signalized traffic intersections. We introduce a new vertical queueing dynamics called the Vertical Cell Model (VCM) that incorporates a representation of link transit time and finite queue capacity. The linear link model of VCM provides an attractive new alternative to CTM for practical network-wide estimation and control procedures. We then compared the link outflow and density outputs of both VCM and CTM to a set of

high fidelity ground-truth observations on a multi-intersection segment of an existing urban roadway. Ultimately we provided a validation of both CTM and VCM for use in arterial networks which have minimal observed over-saturation. The development and validation of VCM is a first step toward a new control-theoretic approach to the operations of signalized intersections in a large-scale network.

Arterial Point Queue (PQ) Model and the Max Pressure Controller

[31, 32] presents a groundbreaking approach to both modeling and control of arterial traffic networks.

A novel mesoscopic Point Queue (PQ) model is introduced, which described the evolution of arterial networks as controlled store-and-forward (SF) queuing networks. In this modeling paradigm, vehicles at the links independently make turns at intersections with fixed probabilities or turn ratios and leave the network upon reaching an exit link. There is a separate queue for each turn movement at each intersection. These are point queues with no limit on storage capacity. Arterial network demand is modeled by vehicles entering the network at a constant average rate with an arbitrary burst size and moving with pre-specified average turn ratios.

A new max-pressure approach for controlling the signalized intersections of an arterial network is also introduced in [31, 32]. The control formulation assumes that at the beginning of each cycle, a controller selects the duration of every stage at each intersection as a function of all queues in the network. The max-pressure differs from other network controllers analyzed in the literature in three respects. First, max-pressure requires only local information: the stage durations selected at any intersection depend only on queues adjacent to that intersection. Second, max-pressure is provably stable: it stabilizes a demand whenever there exists any stabilizing controller. Third, max-pressure requires no knowledge of the demand, although it needs turn ratios. The analysis presented in the paper provides guaranteed bounds on queue size, delay, and queue clearance times.

[33] studies the simulation and control of a network of signalized intersections using the ”point queue” (PQ) simulation model. Vehicles are assumed to arrive at entry links from outside the network in a continuous Poisson stream, independently make turns at intersections, and eventually leave from exit links. There is a separate queue at each intersection for each turn movement. The control at each intersection determines the amount of time that each queue is served within each cycle. A vehicle arriving at an intersection joins the appropriate queue, waits there until it is served (its ”green light” is operated), then travels over the downstream link and joins the next queue or leaves if it is an exit link. The performance of the control scheme that is modeled using the PQ simulator is measured in terms of the length of each queue, the queue waiting time, and the travel time from entry to exit. Two sets of control policies are modeled and compared via PQ simulations for a fairly complex arterial network near the I-15 freeway in San Diego, California. The first is “fixed time” (FT) control, which generates an open loop periodic sequence of green light operations. The second is the “max pressure” (MP) in which the turn movement that is operated is a function of the queue lengths adjacent to the intersection. The simulations confirm the theoretical property of MP, namely that it maximizes throughput, whereas FT does not. The simulation study provides more details concerning the queue length distribution and the behavior of MP as a function of how frequently it is invoked. These details are critical in evaluating the

practicality of MP. The study shows that the PQ simulator is a versatile tool in the design of signal control.

In [34] different modifications of the max-pressure controller are analyzed and compared under the same demand scenarios. The mesoscopic model used for the simulation experiments is an extended version of the point queue (PQ) model introduced in [31, 32]. The results obtained demonstrate the efficiency of max-pressure algorithms, which, under certain conditions, can stabilize all queues of the system. The PQ mesoscopic simulation model was validated using the same the NGSIM Lankershim Los Angeles data that was used to calibrate and validate the CTM model in [29, 30].

In [53] we calibrate the PointQ for data from a small portion of the Huntington-Colorado I-210 arterial network, and again show the superiority of MP over the existing fixed time controller.

Signalized Intersections

[35] simulates a network of signalized intersections as a queuing network, and intersections are assumed to be regulated by fixed time (FT) controls, all with the same cycle length or period. It is shown in this paper that the state of the network evolves according to a delay-differential equation and that there exists a unique periodic trajectory to which every state trajectory converges. Moreover, if vehicles do not follow loops, the convergence occurs in finite time. This unique periodic trajectory determines the performance of the entire network.

This insight is used in [54] to propose an algorithm for calculating the optimum offsets in an arbitrary network. The algorithm is illustrated for the 13-intersection Huntington-Colorado I-210 arterial network. The performance of the ”optimum” offsets is compared with the existing offsets and decreases peak and average queues by 27 percent and travel time by 9 percent. The optimum offsets are calculated in 0.37 seconds on a standard laptop.

Traffic Management

[55] is addressed to transportation economists. It argues, based on many years of work in the TOPL and Connected Corridors projects, that congestion is due as much to ineffective management as it is to excess demand. Economists generally ascribe all congestion to excess demand.

Origin-Destination Estimation

[36] presents an approach to estimate Origin-Destination (OD) flows and their path splits, based on link traffic counts in the network. The approach called Compressive Origin-Destination Estimation (CODE) is inspired by Compressive Sensing (CS) techniques. Even though the estimation problem is underdetermined, CODE recovers the unknown variables exactly when the number of alternative paths for each OD pair is small. Noiseless, noisy, and weighted versions of CODE are illustrated for synthetic networks, and with real data for a small region in East Providence. CODE’s versatility is suggested by its use to estimate the number of vehicles and the Vehicle-Miles Traveled (VMT) using link traffic counts.

Queue Estimation and Modeling

In [37] an algorithm was developed to estimate queue length based on loop detector data, using the Hamilton-Jacobi framework. However, this approach was found not to be practical given the noise level in the data. In [38] a discrete-time point queue (DTPQ) model was developed and compared to an arterial cell transmission. In addition, a common framework was developed to analyze both CTM and DTPQ models. In order to feed this model with the proper boundary conditions (i.e., split ratios at the intersections), an algorithm was developed to estimate split ratios in real time. This algorithm was tested and provides good results even with aggregate data [39].

Facilitating Implementation of Traffic Responsive Plan Selection Operations

Typical traffic controllers can be operated with plan selection based either on time of day (using time-of-day or TOD mode) or on observed conditions (using a traffic responsive plan selection or TRPS mode). TRPS mode will enable a signal controller to use immediate feedback from local volume and/or occupancy sensors to choose a timing plan optimized for current conditions from a pre-programmed set of existing plans. While most of the implementation-oriented research performed to date on TRPS has focused on either small networks of less than five intersections or on artificial (theoretical) networks, several studies have shown that operating in a TRPS mode often has large potential for achieving delay reductions in highly varying or abnormal traffic conditions.

[52] proposes a new method for rapidly configuring TRPS system parameters for global delay reduction using only the set of signal timing plans that is already encoded in network controllers. This methodology is model-independent and therefore easy to implement on any network given reasonable knowledge of sensor placements and critical intersections. The “constraint” of using only existing signal plans makes this method more immediately useful than previous proposals, as it skirts the need for long and costly re-timing processes—but can still incorporate new plans as they become available. We believe that this will make the methodology very attractive to municipalities hoping to improve the efficiency of their existing automated signal control procedures without the expense of re-timing procedures or the need to acquire new hardware.

The work built procedures that could be implemented to calibrate this mechanism, and provide a proof-of-concept demonstration of the procedure which improves the theoretical performance of a real signal in terms of a simple estimation of intersection delay. Even without any real effort to tune or “optimize” the tools implemented in the proposed calibration procedure, the resulting controller was shown to achieve a delay reduction that was very close to the optimal performance possible with the set of existing signal plans. Because the concept was designed to be applied on existing hardware using the set of signal plans already available, the algorithm is something that could be implemented practically immediately.

Additional Work

In addition to traffic flow management, part of the efforts devoted to the work have focused on estimation of traffic conditions on arterials, in particular using probe data. Topics covered include:

- Evaluation of variations of travel time in slow varying traffic conditions, based on LASSO algorithms. [40]

- Path inference filter, a new technique developed at Berkeley to integrate probe data into travel time estimation algorithms. This algorithm has been parallelized and implemented in the cloud using various computational platforms, in particular Spark. [41]
- Probabilistic formulation of queuing problems (i.e., understanding the expected lengths of queues rather than their instantaneous values). [42]
- Map attribute inference problems (learning the features of a map, such as stop signs, from probe data). [43]

References

[1] Ajith Muralidharan, Gunes Dervisoglu, and Roberto Horowitz. “Probabilistic Graphical Models of Fundamental Diagram Parameters for Simulations of Freeway Traffic.” Transportation Research Record: Journal of the Transportation Research Board, No. 2249, pp. 78-85. Dec. 2011.

[2] Dongyan Su, Roberto Horowitz and Xiao-Yun Lu, “Real-Time Estimation of Intersection Turning Proportions from Exit Counts,” Transportation Research Board 93rd Annual Meeting (TRB), (14-3095), Session: 706 - Prediction, Estimation, and Real-Time Traffic Signal Systems (18). Washington, D.C., January 12-16, 2014.

[3] Ajith Muralidharan and Roberto Horowitz, “Analysis Of An Adaptive Iterative Learning Algorithm For Freeway Ramp Flow Imputation,” 2011 ASME Dynamic Systems and Control Conference, DSCC2011-6178, 2011.

[4] Gunes Dervisoglu and Roberto Horowitz, “Model Based Fault Detection of Freeway Traffic Sensors,” 2011 ASME Dynamic Systems and Control Conference, DSCC2011-6177, 2011.

[5] Cheng-Ju Wu, Thomas Schreiter and Roberto Horowitz, “Multiple Clustering ARMAX-Based Predictor and Its Application to Freeway Traffic Flow Prediction,” 2014 American Control Conference (ACC), Portland, Oregon, USA. June 4-6, 2014.

[6] Cheng-Ju Wu, Thomas Schreiter, Roberto Horowitz and Gabriel Gomes, “Fast Boundary Flow Prediction for Traffic Flow Models using Optimal Autoregressive Moving Average with Exogenous Inputs (ARMAX) Based Predictors.” Accepted for publication in the Transportation Research Record: Journal of the Transportation Research Board. (March 2014).

[7] Ajith Muralidharan, Roberto Horowitz and Pravin Varaiya, “Model Predictive Control of a Freeway Network With Capacity Drops,” 2012 Joint ASME Dynamic Systems and Control Conference and MOVIC, Cambridge, Massachusetts, USA, September 13-15, DSCC2012-MOVIC2012-8851, 2012.

[8] Reilly, J.; Krichene, W.; Delle Monache, M. L.; Samaranayake, S.; Goatin, P.; and Bayen, A. M. “Adjoint-based optimization on a network of discretized scalar conservation law PDEs with applications to coordinated ramp metering. Journal of Optimization Theory and Applications” (under review). 2014.

[9] Xiao-Yun Lu, Pravin Varaiya, Roberto Horowitz, Dongyan Su, and Steven E. Shladover. “Novel Freeway Traffic Control with Variable Speed Limit and Coordinated Ramp Metering.” Transportation Research Record: Journal of the Transportation Research Board, No. 2229, pp. 55-65. Sept. 2011.

[10] Rene O. Sanchez, Roberto Horowitz and Pravin Varaiya . “Analysis of Queue Estimation Methods Using Wireless Magnetic Sensors.” Transportation Research Record: Journal of the Transportation Research Board, Vol. 2229, No. 4 pp. 34-45, Sept. 2011.

[11] R. O. Sanchez,, G. Flores, R. Horowitz, R. Rajagopal and P. Varaiya, “Vehicle Re-Identiffication Using Wireless Magnetic Sensors: Algorithm Revision, Modiffications andPerformance Analysis,” 2011 IEEE International Conference on Vehicular Electronics and Safety (ICVES), July 2011.

[12] R. O. Sanchez,, G. Flores, R. Horowitz, R. Rajagopal and P. Varaiya, “Arterial TravelTime Estimation Based On Vehicle Re-Identiffication Using Magnetic Sensors: Performance Analysis,” 2011 14th IEEE Conference on Intelligent Transportation Systems (ITSC), pp.997 -1002, Oct. 2011.

[13] Dervisoglu, D., Gomes, G., Kwon, J.,Horowitz, R. and Varaiya, P. “Automatic Calibration of the Fundamental Diagram and Empirical Observations on Capacity.” 88th Annual Meeting, of the Transportation Research Board, Washington, D.C. January 2009.

[14] Muralidharan, A. and Horowitz R.. “Imputation of Ramp Flow Data for Freeway Traffic Simulation”, Transportation Research Record (TRR), the Journal of the Transportation Research Board. No. 2099, pp. 58-64. Sept. 2009.

[15] Kurzhanskiy, A. “Modeling and Software Tools for Freeway Operational Planning.” PhD thesis, University of California, Berkeley, 2007.

[16] Ajith Muralidharan and Roberto Horowitz, “Optimal Control Of Freeway Networks Based On The Link Node Cell Transmission Model,” 2012 American Control Conference, Montreal Canada, June 2012.

[17] Ajith Muralidharan, Roberto Horowitz and Pravin Varaiya, “Model Predictive Control of a Freeway Network With Capacity Drops,” 2012 Joint ASME Dynamic Systems and Control Conference and MOVIC, Cambridge, Massachusetts, USA, September 13-15, DSCC2012-MOVIC2012-8851, 2012.

[18] Delle Monache, M. L.; Reilly, J.; Samaranayake, S.; Krichene, W.; Goatin, P.; and Bayen, A. M. “A PDE-ODE Model for a Junction with Ramp Buffer,” SIAM Journal on Applied Mathematics 2014, Vol. 74, No. 1, pp. 22-39.

[19] Samaranayake, S.; Reilly, J.; Krichene, W.; Delle Monache, M.L.; Goatin, P.; Bayen, A. “Multi-commodity real-time dynamic traffic assignment with horizontal queuing”, submitted to Operations Research. 2014.

[20] (1) Fan, S. and Work, D. “A heterogeneous multiclass traffic flow model with creeping.” Submitted to the SIAM Journal on Applied Mathematics, July 2014. (2) Fan, S. and Work, D. “A cell transmission model for heterogeneous multiclass traffic flow with creeping.” Submitted to the Transportation Research Board, 94th Annual Meeting, August 2014.

[21] (1) Bekiaris-Liberis, N.; and Bayen, A. M. “Nonlinear stabilization of a viscous Hamilton-Jacobi PDE”, IEEE Conference on Decision and Control, 2014. (2) Bekiaris-Liberis, N.; and Bayen, A. M. “Nonlinear local stabilization of a viscous Hamilton-Jacobi PDE”, IEEE Transactions on Automatic Control, provisionally accepted.

[22] (1) Samaranayake, S.; Blandin, S.; Bayen, A. “A Tractable Class of Algorithms for Reliable Routing in Stochastic Networks.” in Proceedings of the 19th International Symposium on Transportation and Traffic Theory (ISTTT), July 18-20 2011, Berkeley, California. (2) Borokhov, P.; Blandin, S.; Samaranayake, S.; Goldschimdt, O.; Bayen, A. “An adaptive routing system for location-aware mobile devices on the road network.” in Proceedings of the 14th International IEEE Conference on Intelligent Transportation

Systems (ITSC) , October 5-7 2011, Washington, DC. (3) Samaranayake, S.; Blandin, S.; Bayen. A. “A Tractable Class of Algorithms for Reliable Routing in Stochastic Networks.” Transportation Research Part C: Emerging Technologies, Volume 20, Issue 1, Pages 199-217, February 2012. (4) Samaranayake, S.; Blandin, S.; Bayen. A. “Speedup Techniques for the Stochastic on-time Arrival Problem.” in Proceedings of the 12th Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems , September 13, 2012, Ljubljana, Slovenia. (5) Sabran, G.; Samaranayake, S.; Bayen, A. “Pre-processing algorithms for the stochastic on-time arrival problem.” Proceedings of the 16th SIAM Workshop on Algorithm Engineering and Experiments (ALENEX), pp 138-146, January 5, 2014, Portland, Oregon.

[23] (1) Reilly, J.; Martin, S.; Payer, M.; Song, D.; and Bayen, A. M. On Cybersecurity of Freeway Control Systems: Analysis of Coordinated Ramp Metering Attacks. Transportation Research - Part B: Methodological (under review). 2014. (2) Reilly, J.; Martin, S.; Payer, M.; Song, D.; and Bayen, A. M. On Cybersecurity of Freeway Control Systems: Analysis of Coordinated Ramp Metering Attacks. Transportation Research Board (under review). 2015.

[24] Dongyan Su, Xiao-Yun Lu, Roberto Horowitz and Zhongren Wang. “Coordinated Ramp Metering and Intersection Signal Control.” International Journal of Transportation Science and Technology, Vol. 3, No. 2, pp. 179-19. 2014. To appear.

[25] Leblanc, R. and Walker, J.L. “Which Is the Biggest Carrot? Comparing Nontraditional Incentives for Demand Management,” 92nd Annual Meeting of the Transportation Research Board, January 2013, Washington DC.

[26] (1) Krichene, W.; Reilly, J.; Amin, S.; and Bayen, A. “On the characterization and computation of Nash equilibria on parallel networks with horizontal queues,” 2012 IEEE 51st Annual Conference on Decision and Control (CDC), vol., no., pp.7119, 7125, 10-13 Dec. 2012 doi: 10.1109/CDC.2012.6426543. (2) Krichene, W.; Reilly, J.; Amin, S.; and Bayen, A. “On Stackelberg routing on parallel networks with horizontal queues,” 2012 IEEE 51st Annual Conference on Decision and Control (CDC), vol., no., pp.7126,7132, 10-13 Dec. 2012. doi: 10.1109/CDC.2012.6426526. (3) Jebbari, Y.; Krichene, W.; Reilly, J.D.; Bayen, A.M., “Stackelberg thresholds on parallel networks with horizontal queues,” IEEE 52nd Annual Conference on Decision and Control (CDC), vol., no., pp.268, 274, 10-13 Dec. 2013. doi: 10.1109/CDC.2013.6759893. (4) Krichene, W.; Reilly, J.; Amin, S.; and Bayen, A. “Stackelberg Routing on Parallel Networks with Horizontal Queues,” Automatic Control, IEEE Transactions on, vol.59, no.3, pp.714, 727, March 2014. doi: 10.1109/TAC.2013.2289709.

[27] (1) Drighes, B.; Krichene, W.; and Bayen, A. “Stability of Nash equilibria in the congestion game under replicator dynamics.” 53rd IEEE Conference on Decision and Control (CDC), accepted. (2) Krichene, W.; Drighès, B.; and Bayen, A. “Learning Nash equilibria in congestion games.” SIAM journal on Control and Optimization (SICON), submitted

[28] (1) Wu C., Yadlowsky S., Thai J., Pozdnoukhov A., Bayen A., “Cellpath: fusion of cellular and traffic sensor data for route flow estimation via convex optimization.” Int Symp on Transportation and Traffic Theory (ISTTT) and Transportation Research: Part C, 2015, in print. (2) Yadlowsky S., Thai J., Wu C.,

Pozdnoukhov A., Bayen A., “Link Density Inference from Cellular Infrastructure.” Transportation Research Board (TRB) 94th Anuual Annual Meeting, Transportation Research Record (TRR), 2015.

[29] Dongyan Su, Alex Kurzhanskiy, and Roberto Horowitz. “Simulation of Arterial Traffic Using Cell Transmission Model.” In Transportation Research Board 92nd Annual Meeting, no. 13-2387. 2013.

[30] D. Sun, “Modeling, Estimation and Control of Traffic,” Ph.D. Dissertation, University of California, Berkeley 2014.

[31] Pravin Varaiya, “Max pressure control of a network of signalized intersections.” Transportation Research Part C, 36 (2013) 177–195. 2013.

[32] Pravin Varaiya, “The Max-Pressure Controller for Arbitrary Networks of Signalized Intersections.” In Advances in Dynamic Network Modeling in Complex 27 Transportation Systems, Complex Networks and Dynamic Systems 2, DOI 10.1007/978-1-4614-6243-9 2, S.V. Ukkusuri and K. Ozbay (eds.). Springer Science+Business Media, New York 2013.

[33] Jennie Lioris, Alexander A. Kurzhanskiy, Dimitrios Triantafyllos and Pravin Varaiya. “Control experiments for a network of signalized intersections using the ‘.Q’ simulator.” 12th IFAC - IEEE International Workshop on Discrete Event Systems (WODES 2014), Cachan, France. 2014.

[34] Anastasios Kouvelas, Jennie Lioris, Alireza Fayazi and Pravin P. Varaiya. “Max-pressure Controller For Stabilizing The Queues In Signalized Arterial Networks.” In Transportation Research Board 93rd Annual Meeting, no. 14-5440. 2014. To appear in TRR 2015.

[35] Ajith Muralidharan, Ramtin Pedarsani and Pravin Varaiya, “Analysis of Fixed Time Control.” Submitted to the Transportation Research Board 94th Annual Meeting, 2015.

[36] Borhan M. Sanandaji and Pravin Varaiya, “Compressive Origin-Destination Estimation.” Submitted to the Transportation Research Board 94th Annual Meeting, 2015.

[37] Anderson, Leah A.; Canepa, Edward S.; Horowitz, Roberto; Claudel, Christian G.; and Bayen, Alexandre M.. “Optimization-Based Queue Estimation on an Arterial Traffic Link with Measurement Uncertainties.” 93rd Annual Meeting of the Transportation Research Board, Washington, D.C. January 2013.

[38] Anderson, Leah A; Gomes, Gabriel; and Bayen, Alexandre. “Evaluation of horizontal and vertical queueing models in relation to observed trajectory data in a signalized urban traffic network.” Transportation Research Board, 2014/11/12.
http://bayen.eecs.berkeley.edu/sites/default/files/conferences/evaluation_of_horizontal.pdf

[39] Grappin, Antoine; Anderson, Leah; and Bayen, Alexandre. “Assessment of the Effect of Time Aggregation in Vehicle Count Measurements on Accuracy of Intersection Turn Ratio Estimations” submitted to the 94th Annual meeting of the Transportation Research Board in August 2014.

[40] (1) Hofleitner, A.; Rabbani, T.; Rafiee, M.; El Ghaoui, L.; and Bayen, A. "Learning and estimation applications of an online homotopy algorithm for a generalization of the LASSO," Discrete and Continuous Dynamical Systems, to appear, 2014. https://www.aimsciences.org/journals/displayArticlesnew.jsp?paperID=9594. (2) Hofleitner, A.; Rabbani, T.; Rafiee, M.; Rosat, S.; El Ghaoui, L.; and Bayen, A. "Online homotopy algorithm for a generalization of the LASSO with applications to online learning, "IEEE Transactions on Automatic Control, in press, 2013. http://ieeexplore.ieee.org/application/enterprise/entconfirmation.jsp?arnumber=6506951&icp=false

[41] (1) Hunter, T.; Abbeel, P.; and Bayen, A. "The Path Inference Filter: Model-Based Low-Latency Map Matching of Probe Vehicle Data," IEEE Transactions on Intelligent Transportation Systems, to appear 2014. (2) Hunter, T.; Abbeel, P.; and Bayen, A. "The path inference filter: model-based low-latency map matching of probe vehicle data". In the 10th International Workshop on the Algorithmic Foundations of Robotics (WAFR)}, 2012, doi:10.1007/978-3-642-36279-8-36. (3) Hunter, T.; Das, T.; Zaharia, M.; Abbeel, P.; and Bayen, A. "Large Scale Estimation in Cyberphysical Systems using Streaming Data: a Case Study with Smartphone Traces," IEEE Transactions on Automation Science and Engineering, October 2013, 10(4), pp.884-898, doi:10.1109/TASE.2013.2274523.

[42] Hofleitner, A.; Claudel, C.; and Bayen, A. "Probabilistic formulation of estimation problems for a class of Hamilton-Jacobi equations," 51st IEEE Conference on Decision and Control, 2012, pp. 3531-3537, doi:10.1109/CDC.2012.6426316.

[43] Hofleitner, A.; Come, E.; Oukhellou, L.; Lebacque, J-P; and Bayen, A. "Automatic signal detection leveraging sparsely sampled probe vehicles," IEEE Conference on Intelligent Transportation Systems (ITSC), Anchorage, AK, pp. 1687-1692, September 2012, doi:10.1109/ITSC.2012.6338641.

[44] Gomes G, Horowitz R., Kurzhanskiy AA, Varaiya P and Jaimyoung Kwon. "Behavior of the cell transmission model and effectiveness of ramp metering." Transportation Research Part C: Emerging Technologies, vol.16, no.4, Aug. 2008, pp. 485-513

[45] Brian T. Phegley, Roberto Horowitz and Gabriel Gomes, "Fundamental Diagram Calibration: A Stochastic Approach to Linear Fitting", Transportation Research Board 93rd Annual Meeting (TRB), (14-4928), Session: 841 - Advances in Traffic Flow Theory and Characteristics, Part 2. Washington, D.C., Jan., 2014.

[46] Nianfeng Wan, Gabriel Gomes, Ardalan Vahidi and Roberto Horowitz, "Prediction on Travel-Time Distribution for Freeways Using Online Expectation Maximization Algorithm", Transportation Research Board 93rd Annual Meeting (TRB), (14-3221), Session: 841 - Advances in Traffic Flow Theory and Characteristics, Part 2. Washington, D.C., January 12-16, 2014.

[47] Gabriel Gomes, "Bandwidth Maximization For Pretimed and Actuated Arterials. An Approach Based On Relative Offsets." Submitted for publication, under review. 2014

[48] (1) Thai, J.; Bayen, A., “State Estimation for Polyhedral Hybrid Systems and Applications to the Godunov Scheme for Highway Traffic Estimation”, IEEE Transactions on Automatic Control, 2014. (2) Thai, J.; Bayen, A., “State estimation for polyhedral hybrid systems and applications to the Godunov scheme”, Hybrid Systems: Computation and Control (HSCC), 2013. (3) Thai, J.; Prodhomme, B.; Bayen, A. “State Estimation for the discretized LWR PDE using explicit polyhedral representations of the Godunov scheme”, American Control Conference, 2013.

[49] (1) Pumir, Thomas; Anderson, Leah; Triantafyllos, Dimitrios; and Bayen, Alexandre. “Stability of Modified Max Pressure Controllers with Application to Signalized Traffic Networks” Submitted to IEEE Transactions on Control Systems Technology, May 2014. (2) Varaiya, Pravin. “Max Pressure Control of a Network of Signalized Intersections.” Transportation Research Part C: Emerging Technologies V.36 2013 pp 177-195.

[50] Lioris, Jennie; Kurzhanskiy, Alexander A.; and Varaiya, Pravin. “Control experiments for a network of signalized intersections using the ‘.Q’ simulator” submitted to WODES December 2013.

[51] Merritt, Greg; Bailey, Nathaniel; and Bayen, Alexandre. “Recommendations to the New Cities Foundation Task Force on Connected Commuting” http://www.newcitiesfoundation.org/wp-content/uploads/UCBerkeley_NCF_Report_Final.pdf. August 2012.

[52] Leah Anderson, “Data-Driven Methods for Improved Estimation and Control of an Urban Arterial Traffic Network,” Ph.D. thesis, UC Berkeley, 2015.

[53] F.Y. Tascikaraoglu, J. Lioris, A. Muralidharan, M. Gouy and P. Varaiya, PointQ model of an arterial network: calibration and experiments, submitted to Transportation Research Part B: Methodological, 2015.

[54] Samuel Coogan, Gabriel Gomes, Eric S. Kim, Murat Arcak, Pravin Varaiya, Offset Optimization For a Network of Signalized Intersections via Semidefinite Relaxation, IEEE CDC, 2015.

[55] A.A. Kurzhanskiy and P. Varaiya, Traffic management: An outlook, Economics of Transportation (2015) http://dx. doi.org/10.1016/j.ecotra.2015.03.002i

[56] I-680 CSMP Project: http://dot.ca.gov/hq/tpp/corridor-mobility/CSMPs/d4_CSMPs/D04_I680_CSMP_Final_Revised_Report_2015-05-29.pdf

[57] M. Wright, G. Gomes, R. Horowitz and A.A. Kurzhanskiy. A new model for multi-commodity macroscopic modeling of complex traffic networks. Online: http://arxiv.org/abs/1509.04995

[58] S. Coogan, M. Arcak and A.A. Kurzhanskiy. On the Mixed Monotonicity of FIFO Traffic Flow Models. Online: http://arxiv.org/abs/1511.05081

[59] M. Wright, G. Gomes, R. Horowitz and A.A Kuurzhanskiy. Macroscopic Modeling of Freeway Networks with HOV/T Lanes. Online: http://doqqa.com/keeppies/b235ab83bb9dee58

[60] Berkeley Advanced Traffic Simulator: https://github.com/calpath/beats

[61] Calibration software: https://github.com/akurzhan/L0-planning

[62] Wright, M. and Horowitz, R. Fusing Loop and GPS Probe Data to Estimate Freeway Density. Submitted to the IEEE Transactions on Intelligent Transportation Systems (under review). http://arxiv.org/abs/1510.06702

Connected Corridors Software Development in Support of Research and Corridor Management

Executive Summary

PATH's Connected Corridors program has made significant progress in the areas of systems engineering and software development. This effort continues to support the development of macro traffic modeling for corridor operations and prepare for the design and development of a decision support system capable of a live, full-scale demonstration program.

Connected Corridors has created two primary development environments, designated L0 and L1. L0 supports early research with a fast-changing, low-barrier-to-entry system that allows a "fail fast and often" entrepreneur approach to validate and improve new research techniques. L1 provides an environment to take the best traffic modeling techniques in L0 and incorporate them into a pre-production macro modeling engine that can be used in a Connected Corridors demonstration program.

The L1 environment is now transitioning to a corridor-capable system, with primary emphasis on four configurations supported by a common set of subsystems:

- A prototype corridor decision support system suitable for use within a demonstration project
- A research system providing support for ongoing research and a vehicle for incorporating new research efforts and advancing the state of the art in traffic modeling
- A publicly available planning tool suitable for use in transportation planning efforts by local and state transportation planners and consultants
- A CTM engine that can be incorporated into commercially available transportation products

There has also been significant work to develop the tools necessary to build the complex models required for running a macro traffic simulation, estimation, or prediction. These tools provide the ability not only to build the model, but also to visualize the results.

The work to date has been instrumental in supporting the decision making required as the program moves forward. The efforts to date will be critical in informing the correct selection of technologies and system design decisions to be made as the program now moves to the next phase – creating a system capable of supporting the demonstration of Connected Corridors on the I-210 corridor.

Traffic Macro Model Development

The development of software to implement the macro model research is the core of the system development efforts. The current macro cell transmission model (CTM) engine, ccFramework, is based primarily on two past research programs: the Freeway CTM engine from the Mobile Millennium (MM) program, and BEATS from the TOPL program. ccFramework is a collaborative effort to take the best of both programs and create a CTM engine that would perform at the level required by a corridor and provide the basis for future research and improvements.

Initial work in ccFramework was to ensure that the CTM engine could provide accurate estimation and prediction of freeway traffic, under both normal conditions and during an event such as a typical incident. The software now provides capabilities to run integrated freeway and arterial simulations with predictive ramp meter controllers and arterial fixed-time intersection signals. Work continues to progress to improve these capabilities to adequately estimate and predict current and future conditions on the corridor.

Database Development

In order to provide a basis for early prototype production-level operations, the Postgres database used by the Mobile Millennium program and file-based persistence used by BEATS was replaced in ccFramework with an Oracle database. The Oracle database provides significant advantages in supportability, geospatial capabilities, scalability, and performance, specifically with the large data volumes and high-performance requirements of the system. This is a major shift in design and a significant achievement of the program.

The database consists of 245 tables to store the network elements (nodes and links), traffic characteristics (e.g., traffic demand profiles, split ratios, boundary flows), CTM model characteristics (e.g., fundamental diagrams), real-time and historical traffic data (e.g., PeMS loop sensor data, probe data), and system data (e.g., user information). It also contains numerous Oracle packages and procedures used to ensure relational integrity and access control, and support high-speed data processing and model development.

Data Processing, PeMS, and Future Data Opportunities

Development efforts for the Connected Corridors program have focused on ensuring reliable, fast PeMS data processing. However, future operations will require additional capabilities to adequately estimate and predict arterial performance and improve freeway capabilities. Future efforts will be to incorporate additional data sources, particularly from past research efforts with probe data, cell tower data, and vehicle-to-central-server data. Additionally, efforts are underway to gather and incorporate arterial data from the IEN network on the 210 corridor in the modeling efforts.

The PeMS filter and data processing components provide three basic services:

- Fetch PeMS data from the PeMS FTP site
- Load the raw PeMS data
- Filter and post process the PeMS data for use by the CTM engine

The software and database provide these services at a speed required for real-time estimation of a corridor. This system has been operated against the four most heavily instrumented Caltrans districts simultaneously, proving its ability to process PeMS data at a speed required by corridor operations.

L0 and L1 Development Environments

The L0 development environment has been instrumental in providing an environment where research and new approaches can be implemented quickly. This includes algorithm development and research as well as new approaches to developing and implementing network and model elements and approaches to processes such as model calibration and imputation. L0 has proven to be the testing ground and pathway to implementation of L1 in areas such as model predictive control for ramp metering and signal implementation for arterials within the CTM model.

The L1 development environment has made significant progress as well with the development of a robust Oracle database to support the data capture, data processing, running of the model, and processing of results at speeds approaching those required for corridor operations. In addition, the work done to run the L1 environment to provide estimation, prediction, and simulation of freeway and arterials, incorporating the initial steps to ramp meter and arterial traffic signal control, has been extremely successful.

Freeway and Arterial Modeling

Software development for CTM modeling has accomplished the following goals:

- Ability to run a freeway model with specified demand profiles, split ratios and fundamental diagrams in estimation, simulation, and prediction modes
- Ability to incorporate model predictive control on ramp meters
- Ability to dynamically adjust and predict splits and demands on ramps based on real-time ramp sensor measurements
- Ability to run an arterial model with specified demand profiles, split ratios, fundamental diagrams, and fixed-time signal plans
- Ability to calibrate freeway and arterial models
- Ability to run combined freeway and arterial models

This has confirmed the basic design of the system. Further efforts are currently underway to improve these capabilities, extend our ability to model more complex environments and situations, ensure the scalability of the design, and wrap the necessary supporting elements required for operations within a corridor.

Research Support/Tool Development

While software development of a pre-production L1 CTM engine (ccFramework) and supporting elements has progressed, research as well as software development has required significant tools both to create the models and to analyze results. With a very small development team, it has proved a constant challenge to balance the development and research needs of the CTM engine and the legitimate needs for tools to make it possible to build the road networks and model components required for calibrating, running, and analyzing the results.

This has led to a significant effort to use student-developed tools for building and maintaining the networks and models, as well as the reuse of tools used in past projects, both in the L0 and L1 development environments.

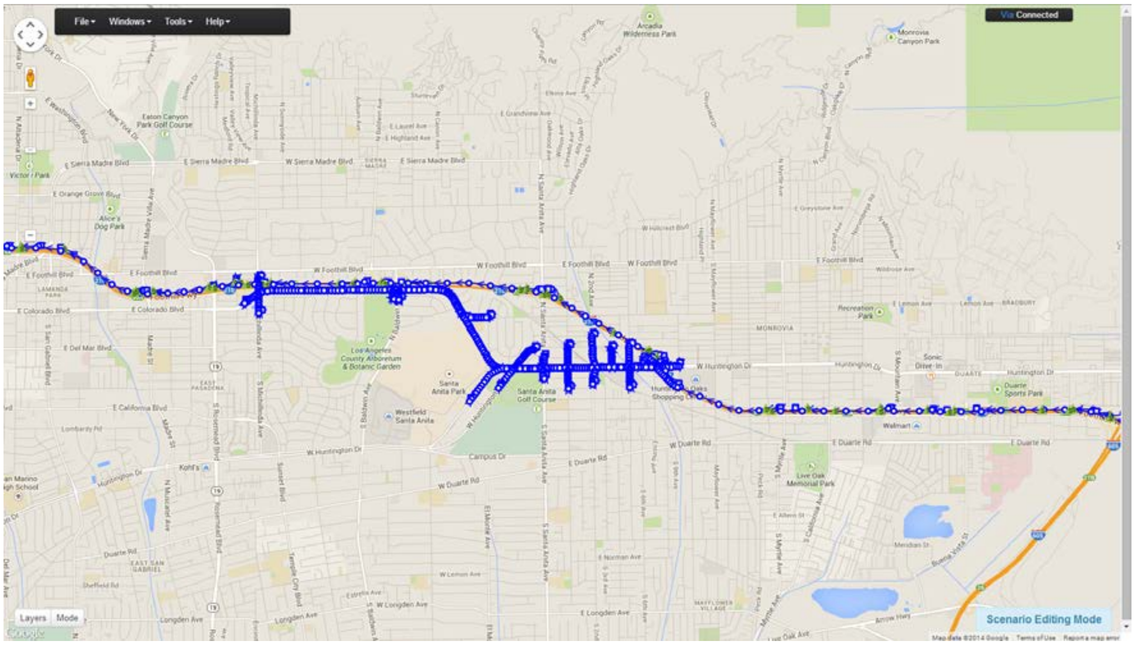
Research-Level Tools and Data Analysis

A number of research-level tools have been developed for the following:

- Editing networks generated from Navteq base maps that are appropriate for the model
- Visualizing information and results from both L0 and L1 environments, including:
    - Map-based velocity and density displays
    - Contour plots of traffic density in space and time
    - Route, space and time plots of delay (person or vehicle), travel time, vehicle miles traveled, vehicle hours traveled, and other corridor metrics
    - Model information such as FD, demand, split, and initial density profiles
- Imputing flows where data is not available
- Calibration of the models
- Generation of model characteristics (FD, demand, splits, initial densities)
- Input of model information such as signal plans

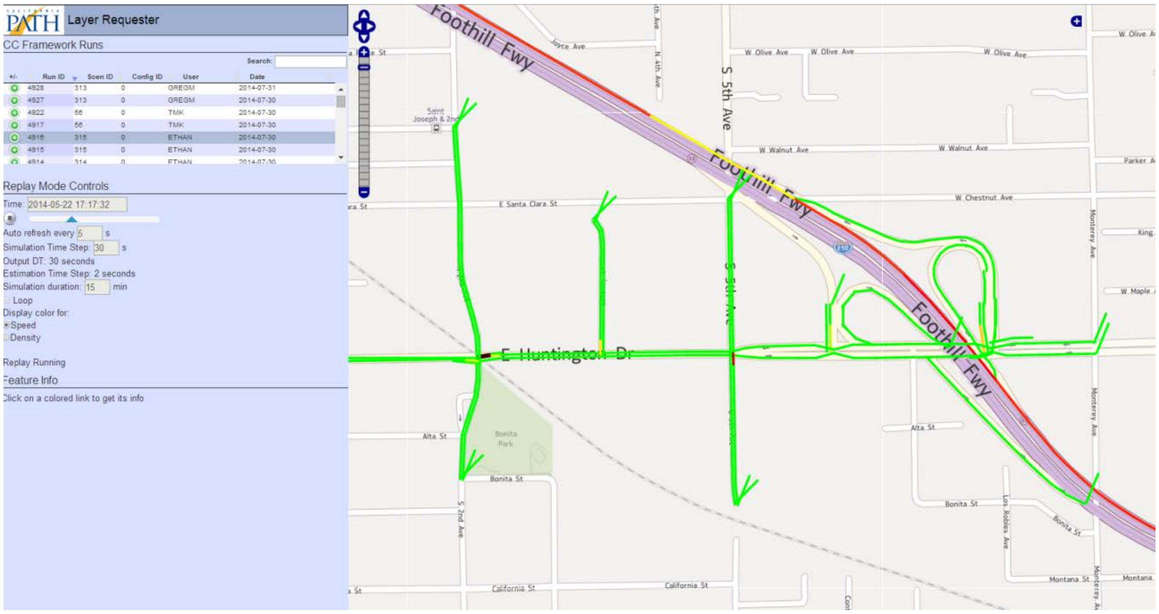
These research-level tools are often developed by students quickly and with extremely limited expenditures in a variety of development languages including PL-SQL, Matlab, and Java. While not suitable for corridor operations or use by Caltrans or other personnel, they are critical to model development while more appropriate tools are being developed that will provide both efficient and effective model development and corridor operations.

Scenario Editor



Early development included a tool known as Scenario Editor to assist developers in network and model development. Scenario editor was initially successful, allowing researchers to create networks by hand without the help of a base map (like those provided by Navteq), add scenario elements (FDs, splits, boundary conditions), and transfer those models between the L0 and L1 development environments. This early tool was important to getting the initial efforts started, but has proved unable to scale to corridor-size networks and models.

Diva

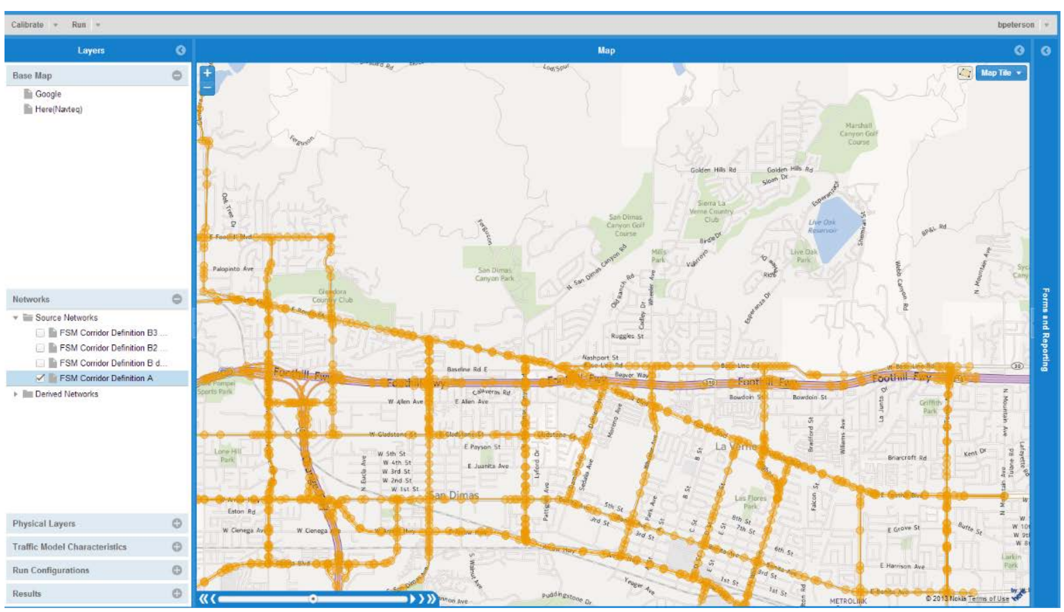


Diva is a tool used to display the traffic velocity, and more recently traffic density, results provided by ccFramework against the backdrop of map tiles from commercial or open-source providers. This tool has been extremely successful, being brought from the Mobile Millennium project and converted for use at minimal expense. It has been an effective tool in displaying and analyzing results as well as informing researchers of the benefits of improved UI design.

The Next Generation of Tools – Scaling from Research to Corridor

Both Diva and Scenario Editor have taught the Connected Corridors team much about the requirements for building a prototype system capable of serving corridor operations. As a result, the team has begun developing a replacement for both tools with significant improvements in performance, scalability, and functionality. The new tool will provide the following capabilities:

- Improved user interface designed for more efficient development of networks and models using the experience gained in developing the first corridor-level networks and models
- Significant improvements in performance, with faster display of significantly larger networks and data volumes
- Improved data input capabilities for larger networks
- Improved map display
- Improved tools for network editing
- Data analysis and plotting capabilities
- Single application interface for full network and model development, model run management, and data analysis



Improved Toolset

This effort has already made significant gains in the areas of performance. The technology stack selected has made orders of magnitude improvement in the display of large networks and their associated data.

Proof-of-Concept System Planning and Development / System Requirements and Design Investigations

Connected Corridors has now begun to move from an investigative and modeling stage to a corridor operations readiness stage, creating a high-level design to support four configurations of software:

- A prototype corridor decision support system suitable for use within a demonstration project
- A research system providing support for ongoing research and a vehicle for incorporating new research efforts and advancing the state of the art in traffic modeling
- A publicly available planning tool suitable for use in transportation planning efforts by local and state transportation planners and consultants
- A CTM engine that can be incorporated into commercially available transportation products

In order to do this, a plan has been developed to provide subsystems that can be reused and configured to address each of these configurations. Actions include:

- Developing high-level requirements for each of the four system configurations (see Appendix)
- Developing a high-level architecture detailing major subsystems, interactions between subsystems, and major system supporting layers (e.g., data access, persistence, messaging, service layers) required by a corridor-level operational system
- Developing preliminary requirements and designs for each subsystem, the subsystem APIs, and the communication protocols to be used within each subsystem
- Developing external interfaces to data feeds and other components such as ATMS systems capable of implementing control strategies selected and agreed upon by users of the decision support system

Progress Summary

System development for Connected Corridors is now at a crossroads. In the past it has focused on developing a CTM engine that can be used by research to improve the state of the art in macro modeling of traffic, laying the foundation for managing traffic at a corridor level. It is now beginning a new stage of both continuing that effort and incorporating that effort into a system with the reliability, scalability, functionality, and performance required for corridor operations. To meet these needs, design and development is beginning to create four configurations (research, planning, corridor decision support, and commercialized CTM engine) based on a common suite of subsystems. This effort will include in-house development for subsystems and components central to the macro modeling and its use within a decision support system, as well as integration points to external commercial or open-source components outside of the core competencies of the Connected Corridors program.

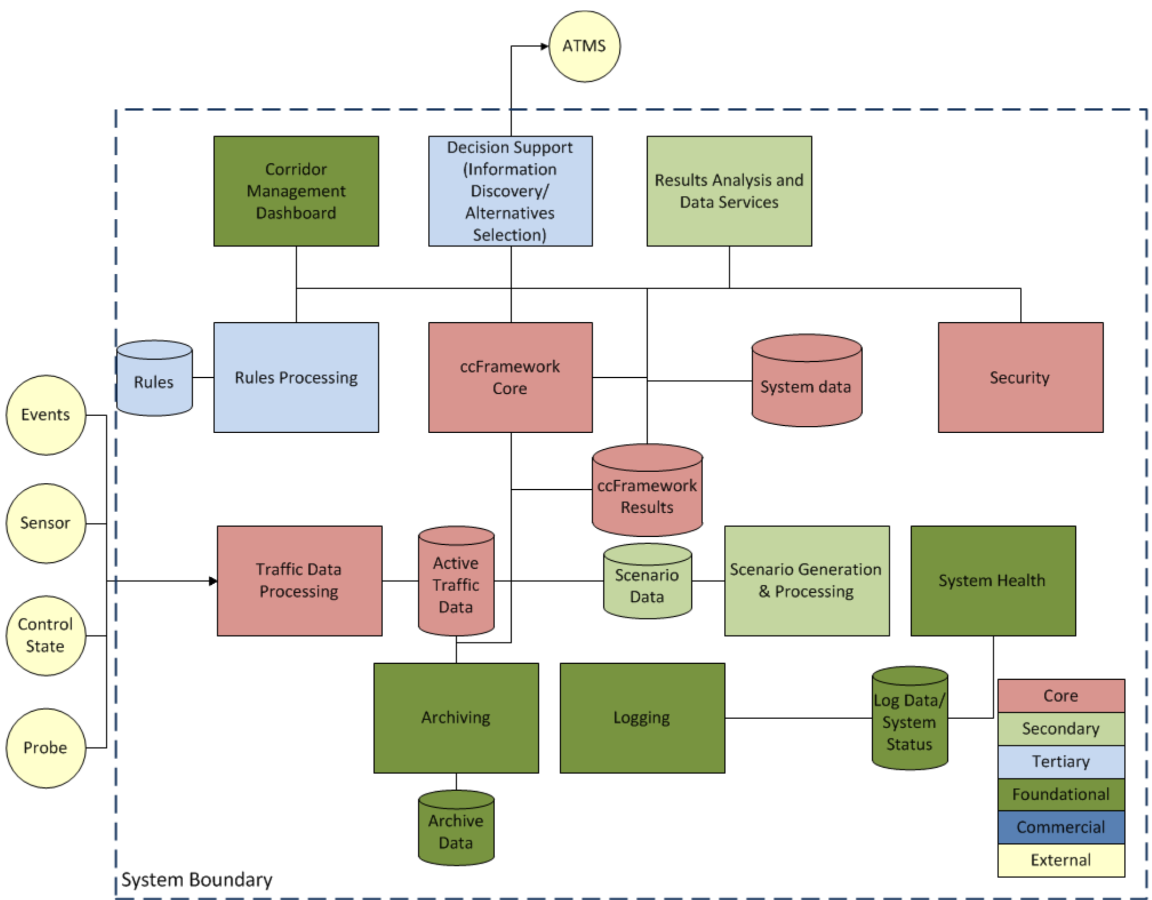
Appendix

High-Level Software Architecture

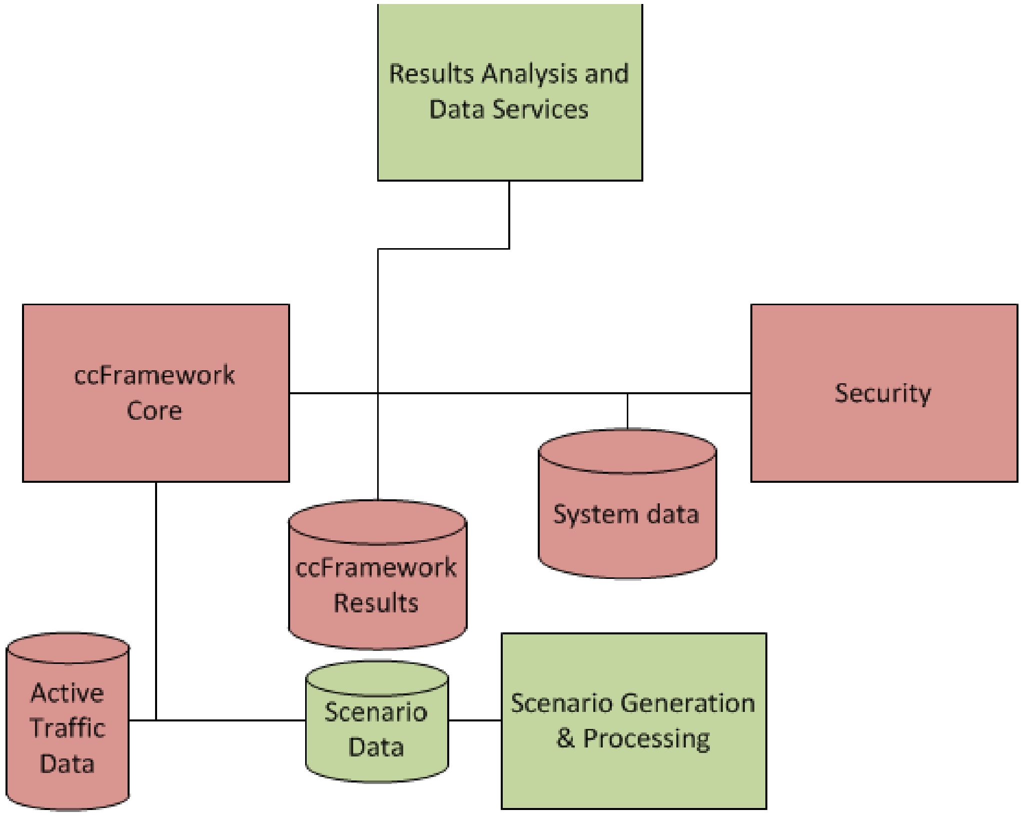
High-level architecture for each of the four primary configurations:

- Decision support
- Research
- Planning
- CTM engine commercialization

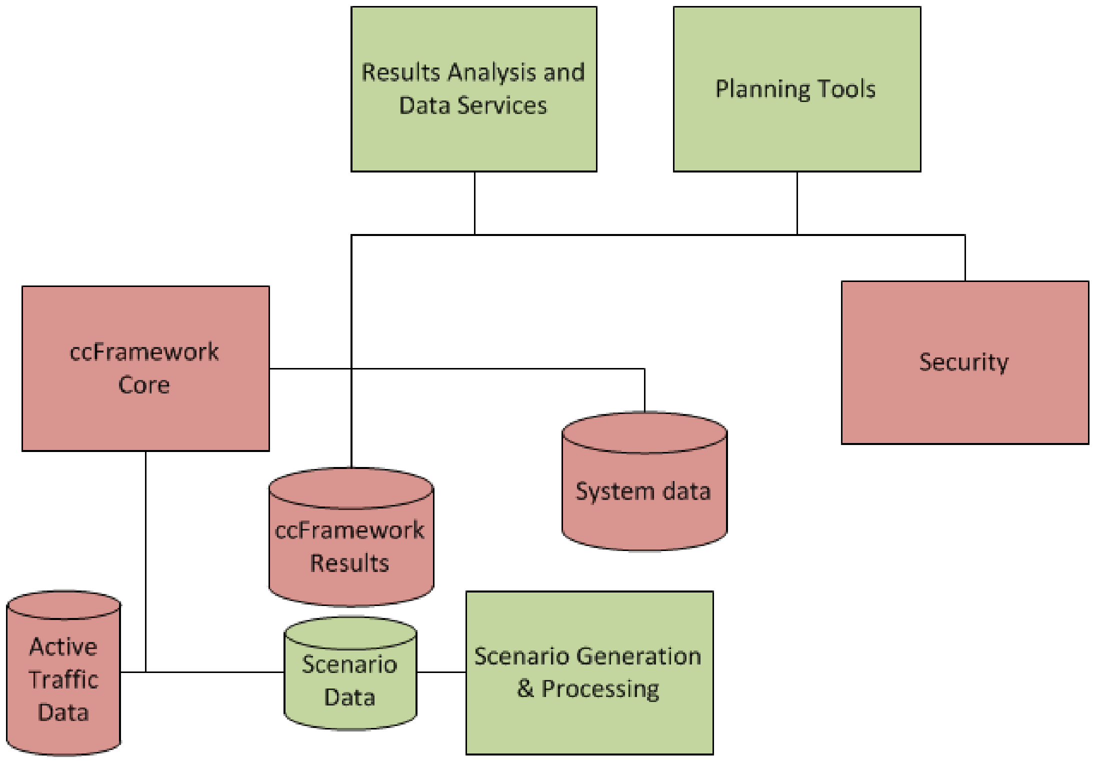
Decision Support Configuration



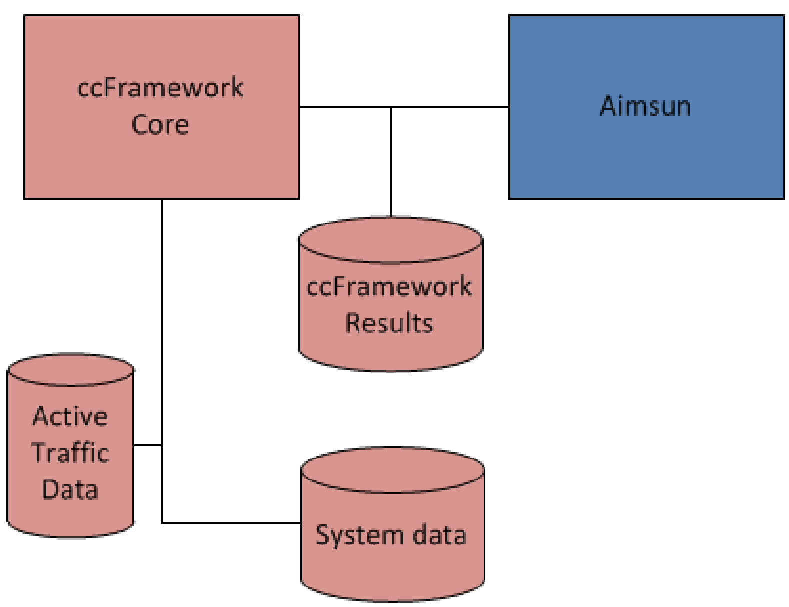
Research Configuration



Planning System Configuration

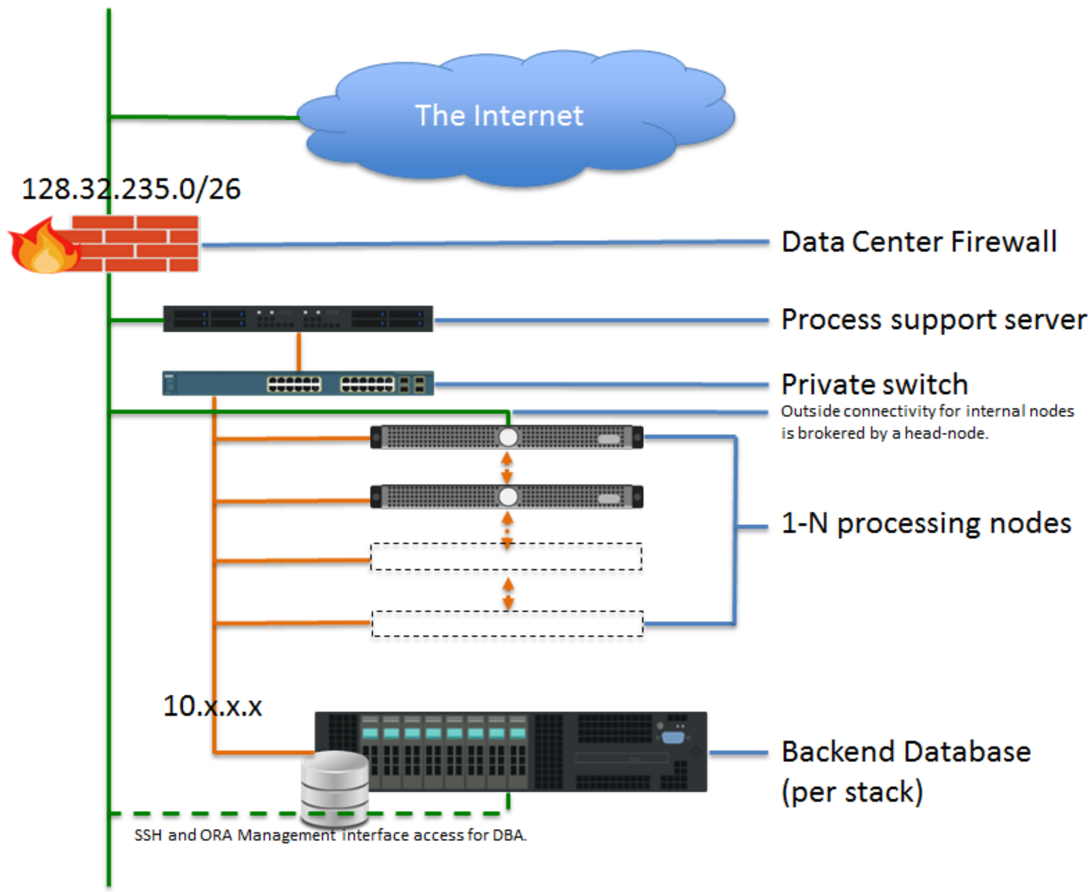


CTM Engine Commercialization Configuration

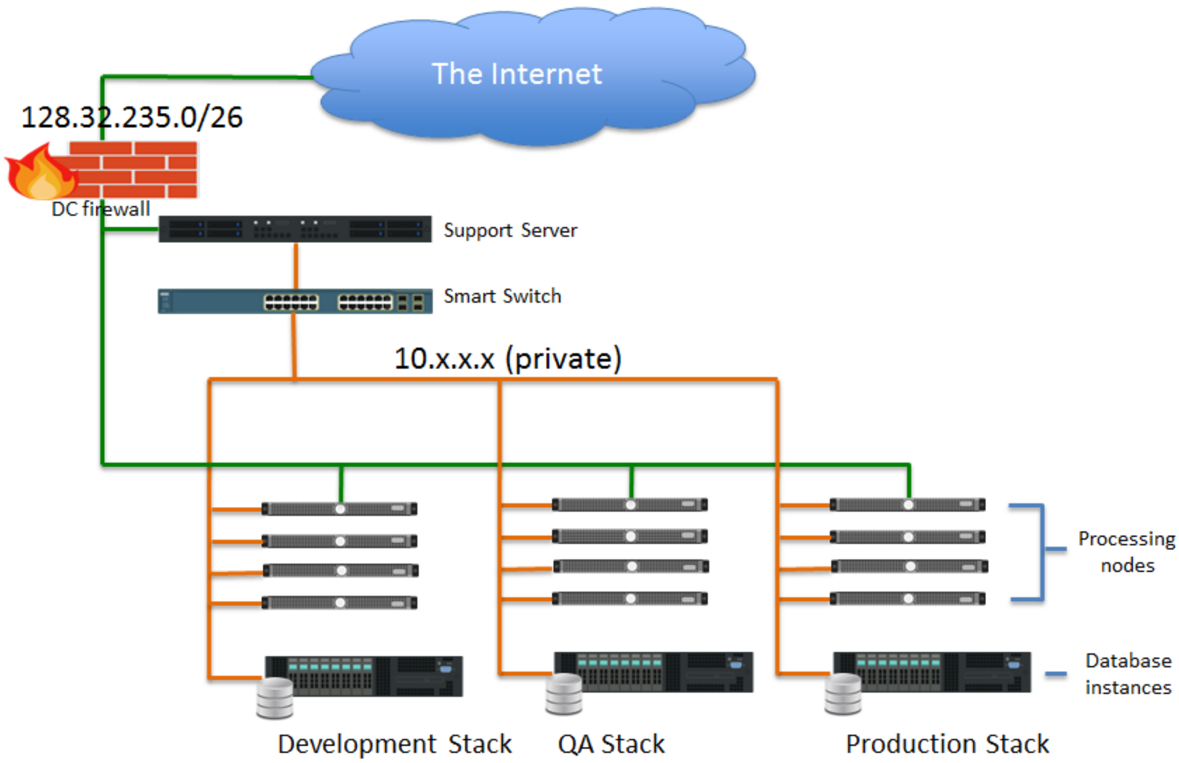


Build/Development, Test, Research, Production Target Hardware Platforms

Scalable Single Stack Configuration



Dev/Test/Production Environments



Database Table Listing

ACTUATORS
ACTUATOR_ELEM_TYPES
ACTUATOR_SETS
ACTUATOR_TYPES
ACTUATOR_USAGE_TYPES
AGGREGATION_TYPES
AIMSUN_ACTUATOR_DATA
AIMSUN_LINK_IMP

AIMSUN_NODE_IMP
AIMSUN_SENSOR_IMP
APPLICATION_TYPES
CALIB_ALG_TYPES
CMS_DATA
CMS_DEBUG
CMS_RAW
CMS_RAW_ARCHIVE
CMS_SIGNS
CNTLR_TABLE
CNTLR_TAB_DATA
CNTLR_TAB_DATA_KEYS
CONTROLLERS
CONTROLLER_SETS
CONTROLLER_TYPES
DBMSHP_FUNCTION_INFO
DBMSHP_PARENT_CHILD_INFO
DBMSHP_RUNS
DEF_ENKF_PARAMS
DEF_ESTIM_SETTINGS
DEF_SIM_SETTINGS
DEMANDS
DEMAND_PROFS
DEMAND_SETS

DEST_NETWORKS
DEST_NETWORK_LINKS
DEST_NETWORK_SETS
DS_BNDRY_CAPS
DS_BNDRY_CAP_PROFS
DS_BNDRY_CAP_SETS
DYN_DEMANDS
DYN_DEMAND_PROFS
DYN_DEMAND_SETS
DYN_INIT_DENS_SETS
DYN_PREDICTIONS
DYN_SPLIT_RATIOS
DYN_SPLIT_RATIO_PROFS
DYN_SPLIT_RATIO_SETS
ENKF_NP
ENKF_NP_SETS
ENKF_PARAMS
ESTIMATION_RUNS
EVENTS
EVENT_SETS
EVENT_SPLIT_RATIOS
EVENT_TABLE
EVENT_TAB_DATA
EVENT_TAB_DATA_KEYS

EVENT_TYPES
FUND_DIAGRAMS
FUND_DIAG_PROFS
FUND_DIAG_PROF_HOLD
FUND_DIAG_SETS
FUND_DIAG_TYPES
FW_CONFIG
FW_CONFIG_ENUM_VALUES
FW_CONFIG_KEYS
FW_CONFIG_KEY_TYPES
FW_CONFIG_TYPES
FW_CONFIG_VALID_KEYS
INIT_DENS
INIT_DENS_SETS
JOBS
JOB_HISTORY
JOB_PARAMETERS
LDT_ROLLUP
LINKS
LINKS_HOLD
LINKS_TEMP
LINK_DATA_DETAILED
LINK_DATA_TOTAL
LINK_DATA_TOTAL_DEBUG

LINK_DATA_TOTAL_HOLD
LINK_DETAIL_TYPES
LINK_LANES
LINK_LANE_OFFSET
LINK_NAMES
LINK_PERFORMANCE_DETAILED
LINK_PERFORMANCE_TOTAL
LINK_TURN_REST
LINK_TYPES
LINK_TYPE_DET
LPT_ROLLUP
LRS_TEST
MDRT_101E3FA_
MDRT_10EF5D8_
MDRT_10F76EB_
MDRT_110997D_
MDRT_110D971_
MDRT_13149BB_
MDRT_1316C74_
MDRT_131B794_
MDRT_131BB87_
MDRT_131CACD_
MDRT_131CD2C_
MDRT_131CD33_

MDRT_F3D5D9_
METRICS_TEMP_ONE
METRICS_TEMP_TWO
MLINKS
MNODES
NETWORKS
NETWORK_SETS
NET_CONNS
NET_CONN_SETS
NODES
NODES_HOLD
NODES_TEMP
NODE_NAMES
NODE_TYPES
NODE_TYPE_DET
PEMS_1DAY
PEMS_1HOUR
PEMS_30SEC_FILT
PEMS_30SEC_FILT_HIST
PEMS_30SEC_FILT_TEST
PEMS_30SEC_RAMP_RAW
PEMS_30SEC_RAMP_RAW_TEST
PEMS_30SEC_RAW
PEMS_30SEC_RAW_HOLD

PEMS_30SEC_RAW_TEST
PEMS_30_RAW_IMPORT
PEMS_5MIN
PEMS_AGG_DATA
PEMS_AGG_DATA_TEST
PEMS_AGG_RUNS
PEMS_AGG_RUNS_TEST
PEMS_CALTRANS_DIST
PEMS_CA_PM_CODES
PEMS_CLUSTER_RUNS
PEMS_LOADER_CONFIG
PEMS_LOADER_CONFIG_HOLD
PEMS_LOADER_STATUS
PEMS_RT_LAST_OP
PEMS_SIMPLE_CVG
PEMS_SIMPLE_CVG_RUNS
PEMS_TO1TO2_RAW_IMP
PEMS_TRACK
PEMS_UNFILT_TS
PEMS_VDS_ACTIONS
PEMS_VDS_CLUSTERS
PEMS_VDS_FILTERS
PEMS_VDS_FILTER_DETAIL
PEMS_VDS_NET_LINKS

PEMS_VD_STATIONS
PEMS_VD_STATIONS_CITIES
PEMS_VD_STATIONS_COUNTIES
PEMS_VD_STATIONS_FW_TYPE
PEMS_VD_STATIONS_HOLD
PEMS_VD_STATIONS_IMP
PEMS_XFER_TEMP
PIF_PROBE_COORD
PIF_PROBE_COORD_TEST
PLSQL_PROFILER_DATA
PLSQL_PROFILER_RUNS
PLSQL_PROFILER_UNITS
POSTMILES
POSTMILE_HIGHWAYS
PROBES_NEW
PROBES_RAW
PROBE_DATA_SOURCES
PROBE_DS_TRGTS
PROCESSOR_NODES
PROJECTS
QUANTITY_TYPES
Q_CONTROLLERS
Q_CONTROLLER_TYPES
REFERENCED_SCENARIO_ELEMENTS

ROUTES
ROUTE_LINKS
ROUTE_METRICS
ROUTE_METRIC_TYPES
ROUTE_PERFORMANCE_TOTAL
ROUTE_SETS
SCENARIOS
SCENARIO_ELEM_PARAMS
SCENARIO_ELEM_TYPES
SCENARIO_LOCK
SCENARIO_SET_TYPES
SENSORS
SENSOR_SETS
SENSOR_TABLE
SENSOR_TAB_DATA
SENSOR_TAB_DATA_KEYS
SENSOR_TYPES
SENSOR_USAGE_TYPES
SFEC_TABLES
SFEC_TAB_DATA
SFEC_TAB_DATA_KEYS
SIG_PHASE_ELEM_TYPES
SIG_PHASE_MVMNTS
SIG_PLANS

SIG_PLAN_PHASES
SIG_PLAN_SCHEDULES
SIG_PLAN_SCHED_ACTION_TYPES
SIG_PLAN_SCHED_ELEMS
SIG_PLAN_SCHED_SET
SIG_PLAN_SETS
SIG_TIMINGS
SIG_TIMING_SETS
SIG_TIMING_TYPES
SIMULATION_RUNS
SIM_SENSOR_30SEC
SPLIT_RATIOS
SPLIT_RATIO_PROFS
SPLIT_RATIO_SETS
SYS_AA_TABLES
SYS_COLUMN_META_DATA
SYS_DB_READER_TEST
SYS_DB_WRITER_TEST
SYS_ERROR_CLOBS
SYS_ERROR_STRINGS
SYS_FRWY_CONFIG
SYS_FRWY_CONFIG_DET
SYS_FRWY_PARAMS
SYS_FRWY_PARAM_TYPES

SYS_FRWY_PARAM_VALUES
SYS_GEN_TYPE_TABLE
SYS_LINKLIST
SYS_LINK_WALK
SYS_MONITOR_CONN
SYS_PEMS_MOVER
SYS_PUBLIC_PKG
SYS_PUBLIC_SP
SYS_SETTINGS
SYS_TABLE_META_DATA
SYS_TEMP_VALUES
SYS_TYPETABLE_TEMPLATE
SYS_TYPE_TABLES
SYS_WEB_CNTRL_TYPES
TO1_TO2_PROBE_ARCHIVE
USERS
VEH_SET_DET
VEH_TYPES
VEH_TYPE_SETS
WEAVE_SETS
WEAVING_FACTORS