CALIFORNIA PATH PROGRAM

Biennial Report 2018-2020

University of California, Berkeley
Institute of Transportation Studies

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Message from the Directors – *Trevor Darrell & Thomas West*

The last two years have been as dynamic as any we have seen, including an unprecedented pandemic, raging wildfires, and social unrest that has widely disrupted daily life for millions of Californian citizens. As a result, we have quickly adapted with changed daily habits, work environs, and a focus on what it will take to return to some semblance of normal. The PATH team has proven to be as resilient as any, and while there are still many unknowns, the team has renewed its focus on how it will help our fellow citizens in the coming years. Whether adapting to new statewide priorities aimed at leading climate action, ensuring equitable transportation options for all Californians, or enhancing and connecting the state's multi-modal transportation network, the PATH team stands ready to conduct the necessary research, pilot demonstrations, and deployment assistance that would lead to successful execution of these worthy goals.

A recent and major accomplishment this year was the development of a strategic plan for Caltrans regarding Connected and Automated Vehicles (CAV) including a list of actions to ensure that California continues to support and guide this nascent industry to the benefit of all Californians. Related, a separate study is underway to understand Automated Vehicle (AV) industry needs that might benefit from close collaboration with Caltrans including potential infrastructure improvements that would ensure the safest possible operation.

As a national leader in the development, testing, and demonstration of truck platooning technology, California PATH continues to support the increased economic and social prosperity that e-commerce has brought to Californians' while fully attending to the reduction of negative impacts of a growing freight industry. Recently, PATH was selected as the sole recipient of a major federal award to implement and test platooning technology across a small fleet of trucks in California, consistent with our goal to leverage federal and private sector transportation funding and consistent with the goals of the draft California Freight Mobility Plan 2020.

Reducing congestion and emissions, improving travel reliability, and fully utilizing California's multi-modal transportation network is at the heart of the longstanding Connected Corridors Interstate 210 Integrated Corridor Management (ICM) project. Billed as the most sophisticated ICM to date, exceptional commitment and coordination between state and regional transportation stakeholders together with the most innovative tools and techniques will offer a glimpse into the future of transportation agency cooperation and network operation in fiscal year 2021/22.

Finally, California PATH continues to conduct leading research in Artificial Intelligence and Deep Reinforcement Learning for vehicle automation through the affiliate Berkeley Deep Drive program. Through funding derived from an associated private sector consortium, BDD brings forward cutting-edge developments in automated vehicle driving techniques, safety awareness, and the consideration and protection of vulnerable road users. With a portfolio of nearly 100 projects and over 35 faculty experts, this program stands alone in its support to both industry and California travelers.

There is much to be done in the coming year, including a redoubling of efforts to ensure that California can mitigate the impacts of our changing world while promoting livability, equality, and economic and social prosperity. Whether this translates to improvement of transit ridership in the face of an ongoing pandemic, the improved resiliency of transportation networks during times of stress, or simply attending to a shifting workforce, technology and scientific know-how will drive California and California PATH to new heights in transportation leadership.

Message from Caltrans - *Dara Wheeler*

I am honored to provide a message from Caltrans, to reflect upon the joint activities of California Partners for Advanced Transportation Technology (PATH) and Caltrans over the last two years, and to talk briefly about the future of transportation in California.

As the Chief of the Division of Research, Innovation and System Information (DRISI), my colleagues and I take great pride in promoting and implementing innovation in order provide a safe, sustainable, integrated and efficient transportation system for all travelers in California. DRISI works with partners like PATH to discover, develop, and deliver technological solutions that solve some of California's most intractable transportation issues. This work involves guiding each project through various stages of development including advanced research, prototype development, prototype field testing, and deployment in order to quickly achieve the benefits of the proposed innovation.

It is with great pleasure to suggest that PATH possesses the capabilities to assist Caltrans with each and every stage of this development process, something unique in transportation research and development. This is not accidental, as for nearly a quarter century, Caltrans and PATH have honed their relationship to ensure the efficient delivery of innovation, and to rapidly adjust to changing statewide priorities. I deeply appreciate the level of partnership interactions between our organizations and the responsiveness of both PATH and DRISI to each other, in order to ensure the most efficient working relationship.

This year we were confronted with unprecedented challenges. COVID-19 has disrupted our social and economic order at lightning speed and on a scale that we have not seen in living memory. Despite these and other challenges, DRISI and PATH showed an unwavering commitment to keep the joint research and development activities moving forward with few disruptions.

An example of this commitment has been the development of the Caltrans Connected and Automated Vehicle (CAV) Strategic Plan. This effort will instruct how Caltrans can best support CAV deployment in California by considering California's enduring leadership in the development of connected and automated vehicle technology as well as changing statewide priorities. Another related example is the ongoing effort to upgrade and support the nation's first Connected Vehicle (CV) test facility called the California Connected Vehicle Testbed. This unique facility is located in the heart of the Silicon Valley and provides the opportunity to industry and academia to test new, break-through innovations that hold promise to greatly improve traveler safety and efficiency. These include those that walk, ride bikes, take transit, or drive vehicles.

PATH has always been on the forefront of improved multi-modalism, and this recent period is no exception. PATH has thoughtfully worked with many of the Bay Area transit agencies to understand how best to encourage mode-shift by ensuring reliable and safe transit service. No project better illustrates this than the cooperative work of Tri-Delta Transit and PATH in the development of a sixty-bus demonstration that helped transit users protect their connection to adjoining transit services, in this instance between BART and first/last mile bus service.

There are of course too many projects to mention here but let me sum up by saying that I am quite proud of the PATH and DRISI affiliation as well as the partnering efforts that carefully assess and select the research that will make a difference in California and is capable of rapid field implementation. For with this final step, we ensure that we will make progress in improving the safety and efficiency of California's transportation system, while at the same time provide more choices to California travelers.

Historic Perspective

The California PATH Program was founded in 1986 as the first research program in North America focused on the subject now known as Intelligent Transportation Systems (ITS). The major growth in California's famous network of freeways occurred during the 1950s to 1970s. By the mid-1980s, the California Department of Transportation (Caltrans) realized that they needed to look ahead and determine how they were going to be able to meet the continually growing transportation needs of a state with a rapidly growing population and economy. Traffic congestion was becoming an increasingly acute public concern as well as being recognized as an impediment to the future economic health of the state.

In 1986, the University of California and Caltrans jointly established the PATH program as the academic research arm for Caltrans in the area of Intelligent Transportation Systems. Designated a multi-campus program, research efforts occurred primarily at the Berkeley campus with early attention focused on how emerging technology could readily assist in reducing congestion, improving safety, and improving air quality.

The initial impetus for using information technology to improve road transportation operations came from California, but the program founders at Caltrans and the University of California knew from the start that this was not something that California could do on its own. A national program would be necessary - to ensure nationwide interoperability of vehicles and to provide a large enough market for the new products and services that would be needed. Consequently, as soon as the program was created, extensive efforts of missionary work (in Washington DC as well as other states and universities) was conducted.

Since PATH was the only active research program in the field at the time, we were starting with a clean sheet of paper and had a great deal of latitude to identify the most important research issues. We were particularly conscious that we were starting something new - that was meant to lead to large changes in transportation. This pointed toward research topics that represented significant departures from the mainstream of transportation research at the time.

From the start, the PATH program focused on navigation, automation, and electrification. Navigation research focused on issues related to how enhanced information could lead to more intelligent traffic management and traveler route choice decisions. Automation research initially focused on the technical feasibility and transportation system impacts of automated highway systems. Electrification research focused on the inductive charging of transit buses at stops or at speed to extend range and thus improve overall air quality. From the start, the highest priority in California was to determine how to achieve a highway capacity increase large enough to get ahead of the growth in population and economic activity, without requiring such huge civil infrastructure additions that it would be unaffordable and environmentally unacceptable.

Many of the themes from the early days, especially automation and national collaboration, can be found in today's PATH Program.

California's Transportation Priorities

In this section we present a view of the future of transportation in California and technology needs, envisioned by its stakeholders, necessary to manage its performance and mitigate any deleterious impacts in 2050.

From its inception, PATH was founded to address highway performance issues anticipated to be encountered in the future. Much of the challenges envisioned in 1986 have come to pass, along with new Intelligent Transportation Technologies to help manage the challenges. Change, however, is the only constant. California's population and economy will continue to grow, and an increasingly sophisticated highway and arterial infrastructure will be needed to manage demand, safety, and congestion as well as ameliorate the deleterious impacts of transportation. The CTP 2050 describes societal trends and resultant challenges that California will face – and that PATH is addressing today.

About the California Transportation Plan (CTP 2050)

California's transportation system exists to serve its people and our communities. It connects California's 39+ million residents to jobs, housing, services, and recreation; and facilitates trade to and from the world's 5th largest economy. But transportation does far more than this – transportation plays a central role in our economic opportunities, cost of living, environmental quality, health, and quality of life.

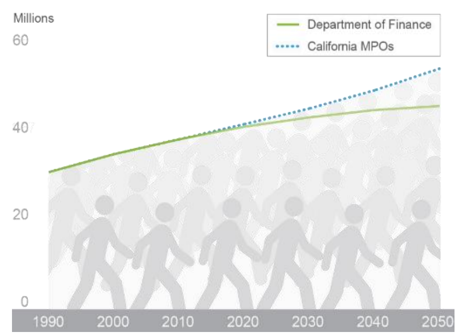
California's priorities for transportation, below, were extracted from a long-range plan known as the California Transportation Plan 2050 (CTP 2050). The following provides selected insights and the implications for transportation in 2050. This is not a complete summary of CTP 2050, but focuses on foundational topics relative to PATH research.

The CTP 2050 is guided by a unified, forward-looking vision for California's future transportation system that was developed with the input of hundreds of stakeholders from all corners of the state. It reflects the breadth of regional planning efforts, including evaluation and review from California's 18 Metropolitan Planning Organizations (MPO). An MPO is a federally mandated and federally funded transportation policy-making organization in the United States that is composed of representatives from local government and governmental transportation authorities.

Challenging Societal Trends

Population Growth

Changes in population is what drives change in California. Population forecasts have a considerable impact on estimated future vehicle travel, delay, and emissions.



- Today
  - There are 39 million people that call California home. Thirty years ago, in 1990, the state's population was about 30 million people.
- 2050
  - By 2050, according to the Department of Finance (DOF) California will be home to six million new residents (45 million total). The 2050 population forecasted by California's MPOs, at 53 million, is significantly greater than the DOF's forecasts.
  - Approximately a quarter of the population will be over 65 in 2050. Mobility needs are different for older populations.
  - Growing travel demand from new drivers on the road in 2050 will add to congestion, emissions, safety concerns, and roadway maintenance needs.

Economy

- Today
  - California's economic success is due in no small part to a robust transportation network. This network supports thousands of jobs, enables access to jobs, goods, and services, and ensures that goods can move efficiently between businesses, residents, and the global marketplace.
  - California's economy is made up of a diverse set of industries including technology, aerospace, tourism, agriculture, and entertainment - all of which have unique transportation needs.
    - Freight-intensive sectors, such as manufacturing, construction, trade, and utilities make up about a third of our GSP (Gross State Product).

        - Service and professional sector industries such as technology, finance, education, and health care, which make up the remainder of GSP, rely on the transportation system for shipments and deliveries, and to keep commuters moving safely and efficiently.
    - Before COVID-19, California's economy grew at about three percent per year - faster than any other state.
    - The transportation sector is also a job generator itself, with 1.2 million jobs in transportation and material moving occupations in 2018 - not to mention supporting engineering and construction jobs.
    - An increasing number of Californians are participating in the gig economy. These jobs have potential to change travel patterns in California cities – for the better or for the worse.
- 2050
    - Over the long-term, statewide employment is expected to grow by 37 percent by 2050, to 23 million jobs. The Sacramento Region, Inland Empire, and San Joaquin Valley are expected to experience the highest rate of job and population growth, with urban areas retaining most of the state's jobs.
    - Trends in automation and reshoring will also have drastic implications for job growth, wages, workforce training, and education by 2050.

Geographic Imbalance between housing growth and job growth

- Today
    - There is an imbalance between where the jobs are and where the housing is; this causes lower and middle income families to endure long commutes. Because of this imbalance, transportation is now the second-highest household expenditure in California - only after housing.
- 2050
    - Approximately 1.8 million new housing units are needed by 2025 to meet the MPO projected population and household growth, significantly greater than was seen in the last decade.
    - If current trends continue, housing will continue to be a distance from the core city. VMT will grow as will fuel consumption, emissions and congestion.

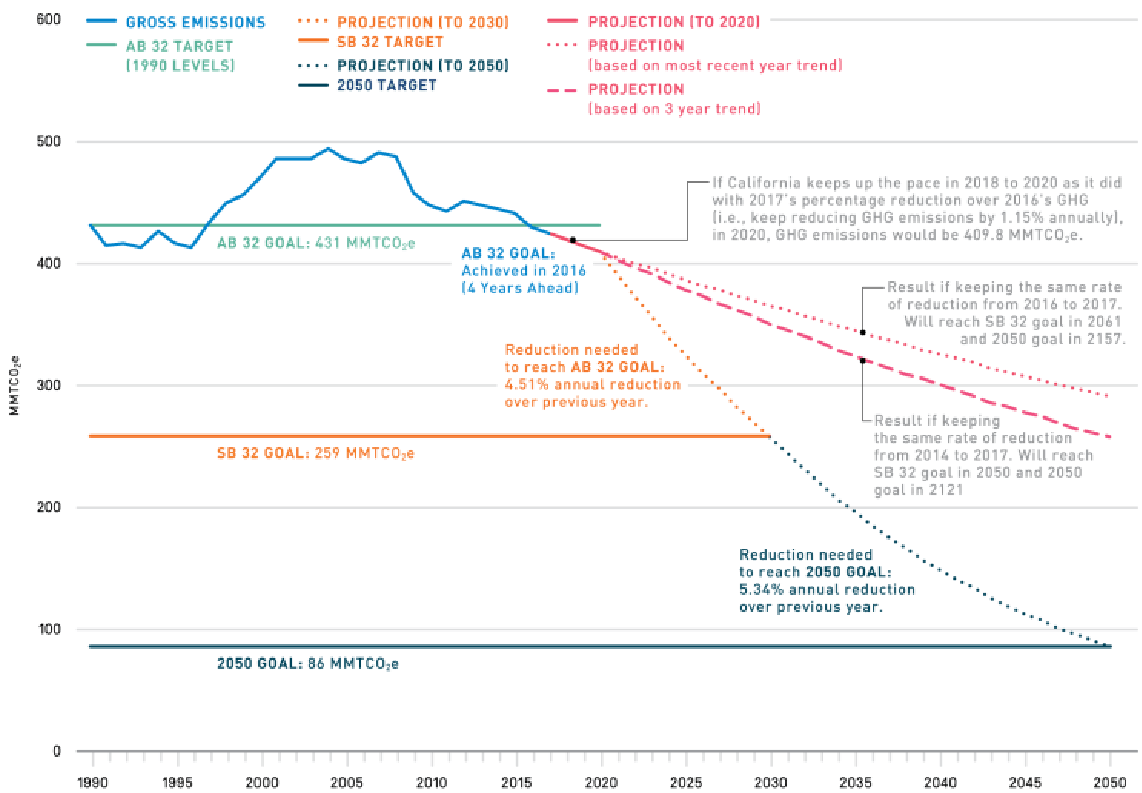
Production of Greenhouse Gasses from Transportation Sources

- Today
    - Transportation is the largest contributor to statewide greenhouse gas (GHG) emissions, accounting for 41 percent in 2017.
    - On September 20, 2019, Governor Newsom issued Executive Order N-19-19[1], proposing an agenda that directs the State Transportation Agency (STA) to help reverse the trend of increased fuel consumption and reduce GHG emissions. More specifically, Governor Newsom's guidance to his agencies is to (1) reduce vehicle miles travelled; (2) reduce congestion; (3) fund transportation options that contribute to Californians' improved

[1] https://www.gov.ca.gov/wp-content/uploads/2019/09/9.20.19-Climate-EO-N-19-19.pdf

health; and (4) mitigate transportation cost increases for lower-income residents of the state.

  - Senate Bill (SB) 391 requires the state to achieve an 80 percent reduction below 1990 levels in GHG by 2050. The Executive Order (EO) -B-55-18 calls for carbon neutrality by 2045.
  - Under SB 375, the development and implementation of Sustainable Communities Strategy (SCS)'s, which link transportation, land use, housing, and climate policy, are designed to reduce per capita GHG emissions.
  - For land development projects, with implementation of SB 743, Caltrans will measure vehicle miles traveled (VMT) rather than level of service (LOS). Using VMT puts focus on the likely change in the number and length of car trips associated with new projects. Measuring VMT forecasts whether a new development is located close to jobs, businesses, and services that enable short trips and travel choices besides driving alone. Projects that create facilities for pedestrians and about half of housing projects will not need to analyze VMT. When VMT assessment is required, it could cost 80 percent less than it previously cost to do LOS analysis and mitigation.
  - Climate change is leading to growing frequency of fires, floods, sea level rise and other natural disasters.
- 2050
  - According to the CTP 2050, California is not on track to meet its target of reducing statewide GHG emissions to 80 percent below 1990 levels by 2050 (despite current legislation to achieve these goals).
  - The CTP for 2050 identifies a goal to achieve statewide GHG emission reduction targets and increase our resilience to climate change as well as minimizing the adverse impacts of the transportation system.
  - In order to achieve these goals, collaboration will be needed between the Air Resources Board (ARB), Metropolitan Planning Organizations (MPOs), California Energy Commission (CEC), and California Transportation Commission (CTC). Implemented tactics may require significant redesign of the transportation network, speed control of the highways, and eco-integrated corridor management (Eco-ICM).
  - Research in active traffic management, vehicle connectivity, and human factors will all be necessary to successfully change the operations of California's extensive transportation network.



Source: Next 10 California Green Innovation Index (based on CARB Greenhouse Gas Inventory) Dec 2020

Impact of Societal Trends on Transportation

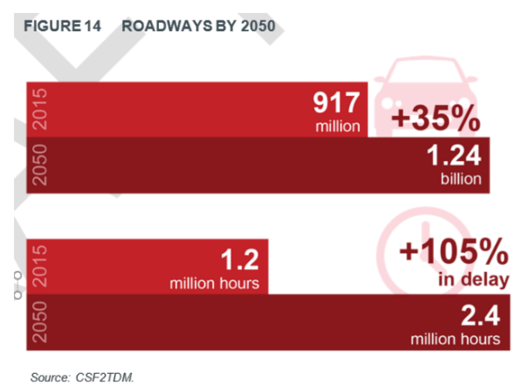
Transportation Safety

- Today
  - Transportation directly affects Californians' health and safety. In California, over 3500 people die each year in traffic crashes and more than 13,000 people are severely injured. Collectively, these traffic crashes cost California over $53.5 billion.
  - Exposure to air pollution from vehicle travel is linked to increasing rates of respiratory and cardiovascular diseases, which are heightened within low-income communities and children.
  - Safety is a primary goal. In 2015 California committed to eliminating fatalities on the transportation system – with the Toward Zero Deaths (TZD) campaign. Fatality rates among bicyclists and pedestrians are disproportionately high, representing 16 percent of all fatalities - but only a small share of total collisions.
  - In addition to the tragic loss of life, traffic incidents cost California $28 billion annually and are responsible for 50% of all non-recurring traffic delays.
- 2050
  - The CTP 2050 aims to reduce transportation-related fatalities and serious injuries to zero, confront environmental injustices head-on, and expand access to safe, healthy, and affordable mobility options.

- Opportunities
    - CV's and automated vehicles have the potential to improve transportation safety – significantly. Safety improvements will be realized first through vehicle connectivity (vehicle-to-vehicle [V2V] and vehicle-to-infrastructure [V2I]). In the long-term, vehicle automation holds promise to further improve safety.

Congestion & Its Reduction

- Today
    - Between 2001 and 2017, auto travel (VMT) on California's roadways increased by 14%, leading to growing traffic congestion, delay, and rising emissions.
    - The suburbs have been designed with the automobile in mind. Most suburbs have little access to transit and are plagued by congestion and growing travel times.
    - California's urban areas, particularly Los Angeles and the Bay Area, have some of the worst congestion in the nation.

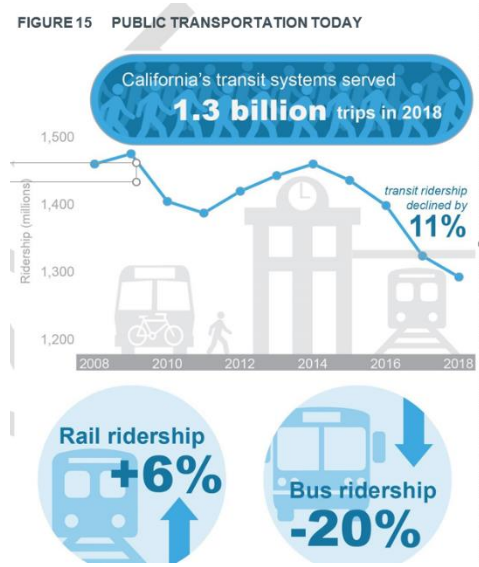


    - Growing congestion is leading to delay and inefficiencies in goods movement and causing commuters to spend more time in traffic (estimated to be 40 hours annually in 2017) which costs Californians $28 billion in wasted fuel and lost time each year.
    - In 2015 Californians used an auto for 88% of all travel in the state, and in many communities, there is no other option.
- 2050
    - Travel increases as our population grows. If current trends continue, driving will remain the dominant mode of transportation and people will live farther away from jobs, school, shopping, and recreation.
    - Growth in VMT (expected to be 13% by DOF estimates and 35% by MPO estimates [between 2015 and 2050]) will result in increased crashes, fatalities, fuel use, and emissions.
    - Based on the MPO population estimation of 53 million residents by 2050, delays from congestion are expected to increase by 105%.
- Opportunities
    - To maximize accessibility for future generations California must address our growing traffic congestion problem and optimize system performance across all modes of travel. It has become abundantly clear that we cannot continue to build our way out of traffic congestion.
    - Travel Demand Management Plan (TDMP) strategies can reduce the number of vehicles on the road, particularly those that expand non-auto options.
    - Intelligent transportation systems (ITS) can support deployment of CV's (and later, connected automated vehicles [CAV's]) leading to more efficient use of the roadway system and the implementation of travel demand strategies.
    - New tools and technologies can advance modeling, simulation, and data collection; monitoring tools can help manage multimodal assets more effectively.

- Improved emergency preparedness, response, and recovery on the transportation system can build transportation resilience.

Public Transportation

- Today
  - Public transportation provides a vital role in California's transportation system, with over 200 local agencies. By providing an affordable alternate to driving, these systems stimulate economic growth, reduce congestion, and help reduce GHG emissions.



  - California's public transportation systems are under stress. For example, as currently configured, buses cannot effectively compete with the services offered by Mobility as a Service (MaaS) networks. (These networks, it should be noted, have been operating at a loss. This 'market launching strategy' has facilitated their growing presence in the transportation service market, but such an approach is not sustainable.)
  - Modal connectivity barriers (both physical and logistical) continue to make transit an infeasible option for many Californians.

- 2050
  - Efficient and effective public transportation services are key for California's future, improving health, quality of life, and access to opportunities.
- Opportunities
  - Increase the competitiveness of transit, shared mobility, and active transportation options.
  - Mobility as a Service (MaaS) could improve the first and last mile connectivity, if paired with transit.
  - Dedicated right-of-way and ITS solutions for rapid bus transit could improve the reliability and convenience of transit.
  - Seamless integration of transit modes routing, booking, and payment could improve convenience and reliability of transit services.
  - Transit ITS, including signal priority, passenger counters, and real-time traveler information systems could make transit more efficient and reliable.
  - MaaS has options that could connect people to traditional bus and rail services in urban and suburban settings, and has the potential to replace public transit in rural settings.

Freight

- Today

    - California exported $178 billion worth of goods in 2018, a value equal to 10.7 percent of the nation's overall exports, making it the second-largest exporter.
    - Approximately $441 billion worth of goods (about 2.5 times greater than the value of exports) entered through California's transportation gateways in 2018. This represents about 48% of all loaded US import container trade.
    - More than 1.3 million people are employed in commercial and industrial activities, which are supported by California's freight network.
    - Trucking is the primary mover of freight in California, carrying about 3.8 million tons per day – 88% of all manufactured tonnage in the state. Nearly every commodity shipped to, from, or within California is transported by truck at some point.
    - Seven of the nation's top ten freight bottlenecks are located in California. These bottlenecks cause congestion, delay, and lead to increased travel time.
    - Last mile connectivity is a growing concern, as ecommerce and same and next day deliveries put additional stress on last mile connectors.
- 2050
    - As our population grows so will grow the demand for goods. By 2050, truck trips are expected to increase by 40%. This equates to an increase in truck VMT of 90%. This negatively impacts every goal for improvement in transportation.
- Opportunities
    - Opportunities to improve our freight systems include autonomous trucking and platooning, which could significantly improve freight operations and highway capacity (from the CFMP and Sustainable Freight Action Plan).
    - Advances in freight intelligent transportation systems could improve goods movement on California roads.
    - Alternate last mile deliveries (drones, and other automated delivery technologies) could reduce truck traffic on local roads.

Navigating the uncertain impacts of emerging technologies.

- Connected and autonomous vehicles (CAV), transportation network companies (TNCs), dock-less bikes and scooters, and emerging technologies such as drones, artificial intelligence, blockchain, and 5G internet are rapidly transforming how people and goods can travel. These technologies could enable improvements in transportation or create deleterious impacts if their deployment is not thoughtfully managed. Ensuring that these emerging technologies help rather than hinder California's transportation vision is a priority of the CTP.
- Managing congestion and expanding transit were priorities before the arrival of COVID-19 and remain essential to achieving a sustainable recovery.
- Since the onset of COVID-19, ride-hailing and micro-mobility companies such as Lyft and Uber have seen an immediate decline in users. Because of increased concern over the spread of the virus, Transportation Network Companies (TNCs) and ride-hailing services suspended the option of cheaper shared carpooling. Consumer data indicates that spending for ride-sharing services is down nearly 83 percent.
- Mobile devices are increasingly becoming vital to everyday needs. They collect massive amounts of data which is transforming how transportation systems and services are being planned and implemented.

- Connected and automated vehicles could offer important safety and network performance benefits such as congestion relief, optimization of roadway capacity, less demand for parking, and improved safety.
- E-commerce, 3D printing, same-day deliveries, automation, and electrification are drastically impacting freight transportation. Warehouses are becoming smaller, more automated, and with less workers.

Vision of transportation in 2050 (from CTP 2050)

By 2050, California's transportation system will provide nearly 45 million residents with convenient and reliable access to jobs, education, health care, services, and more. It will offer a range of high-quality, safe, and affordable mobility options, connecting urban, rural, coastal, mountain, and inland regions into an integrated multimodal network. Urban centers such as Los Angeles, the San Francisco Bay Area, San Diego, and Sacramento will build sufficient housing to meet demand. The majority of new housing will be built in transit-supportive areas and be affordable to low-and-middle income Californians, ensuring that residents have viable alternatives to the automobile, and that those who need to drive can do so amid minimal congestion.

> The 2050 transportation system will aim to reduce transportation-related fatalities and serious injuries to zero. It will be high-tech, high-quality, and resilient to the impacts of climate change, earthquakes, pandemics, and other disruptions, ensuring protection of our invaluable natural and cultural resources. It will power the expansion and diversification of California's world-class economy, with a modernized and sustainable freight system that supports local economic growth. Our future transportation system will be carbon-neutral, enhancing public health and quality of life for all Californians, regardless of race, ethnicity, income, age, gender, sexual orientation, or ability. Our future system will advance quality-of-life and economic opportunity for people of color and low-income communities, who have long endured the greatest burdens of our transportation system - building economic opportunity and mobility for those who need it most.

Caltrans Mission and Goals

Caltrans manages more than 50,000 miles of California's highway and freeway lanes, provides inter-city rail services, permits more than 400 public-use airports and special-use hospital heliports, and works with local agencies to address transportation issues. Caltrans carries out its mission of providing a safe, sustainable, integrated, and efficient transportation system to enhance California's economy and livability.

Mission

- Provide a safe, sustainable, integrated, and efficient transportation system to enhance California's economy and livability.

Vision

- A performance-driven, transparent, and accountable organization that values its people, resources, and partners, and meets new challenges through leadership, innovation and teamwork.

Goals

- **Safety and Health**
  Provide a safe transportation system for workers and users and promote health through active transportation and reduced pollution in communities.
- **Stewardship and Efficiency**
  Money counts. Responsibly manage California's transportation-related assets.
- **Sustainability, Livability, and Economy**
  Make long-lasting, smart mobility decisions that improve the environment, support a vibrant economy, and build communities, not sprawl.
- **System Performance**
  Utilize leadership, collaboration, and strategic partnerships to develop an integrated transportation system that provides reliable and accessible mobility for travelers.
- **Organizational Excellence**
  Be a national leader in delivering quality service through excellent employee performance, public communication, and accountability.

Current PATH Program Areas

Traffic Operations Research

PATH Traffic Operations Research focuses on advancing state-of-the-art traffic management, while producing results for near-term, real-world implementation. Whether integrating new data sources into traditional traffic management systems or developing new technologies to improve traffic flow, PATH's research continues to advance the tools available to traffic operations and fundamentally change and enhance traffic management. Traffic operations is a broad discipline. Major near-term themes include performance evaluation, ramp metering, control of high occupancy lanes, safety improvement, hybrid data, and operations planning. Larger, integrated research themes like corridor management or connectivity and automation, for example, are described in more detail below.

Projected Benefits

- Improvements in travel-time reliability and a reduction in incident-related delays.
- Likely reductions in secondary incidents, leading to improvements in safety.
- Enhanced coordination between Caltrans, local traffic management agencies, first responders, and traffic management centers.
- Creation of new decision-making tools to improve corridor operations for the freeways, arterials, and transit.
- Reduced GHG emissions and criteria pollutants, resulting in improved quality of life for the region.

Traffic Operations Research: ICM & Connected Corridors

Connected Corridors is a collaborative effort to research, develop, test, and deploy a framework for the management of transportation corridor systems in California. Using this approach, Caltrans aims to change the way it manages its transportation challenges for years to come. Connected Corridors was initiated a decade ago with theory, modeling, and stakeholder collaboration. Caltrans, its stakeholders, and the PATH research team will soon launch a pilot on Interstate 210 in the San Gabriel Valley. Success will lead to larger scale deployments of Connected Corridors' concepts.

A Cohesive System

As an Integrated Corridor Management (ICM) program, Connected Corridors looks at the entire multi-modal transportation network and all opportunities to move people and goods in the most efficient and safest manner possible. Previous efforts to reduce congestion along the I-210 corridor have made incremental improvements; today however, a cohesive system does not exist. The Connected Corridors pilot will integrate the entire transportation system to capture the greatest improvement in operational performance. The Connected Corridors team is working closely with corridor stakeholders to build consensus on how to address the overall transportation needs of the corridor rather than the needs of specific elements or agencies alone. Connected Corridors offers a continued opportunity for the implementation of Caltrans traffic operations research.

The Partnership

The project involves a multi-jurisdictional partnership along the corridor with the County of Los Angeles, the cities of Pasadena, Arcadia, Monrovia, Duarte, the San Gabriel Valley Council of Governments, the Southern California Association of Governments, and Foothill Transit. The leadership team includes Caltrans, LA Metro, and PATH.

Projected Benefits

- Improvements in travel-time reliability and a reduction in incident-related delays.
- Reduced incident-response times, including response to the incidents themselves and the implementation of travel mitigation plans.
- Likely reductions in secondary incidents, leading to improvements in safety.
- Enhanced coordination between Caltrans, local traffic management agencies, first responders, and traffic management centers.
- Increased attractiveness of transit services.
- Improved traveler experience.

- New decision-making tools to improve corridor operations for the freeways, arterials, and transit.
- Reduced GHG emissions and criteria pollutants, resulting in improved quality of life for the region.

Traffic Operations Research: Connectivity and Automation

The Connected Automated Vehicle (CAV) technology provides a powerful tool for the Infrastructure Owner Operator (IOO) to perceive traffic-flow states and implement advanced traffic-management strategies. USDOT research has shown that more than 90 percent of traffic-related fatalities are caused by human error[2]. Research results demonstrated that connectivity between vehicles has the ability to mitigate 80% of these driver errors. Combining communication with automation (of vehicles, roadway infrastructure and highway control systems) has the capacity to prevent the remaining driver errors and save lives on a scale that is beyond all other risk and incident countermeasures. In fact, the impact that communication and computing technologies has had, and will continue to have, is a transformational influence on transportation.

The PATH Program focuses on connectivity and automation to develop new concepts, methods, and technologies to improve safety and freeway capacity, reduce traffic congestion and emissions, and improve the reliability and efficiency of transportation.

Connectivity

Communication technologies have been transforming industry and society for many decades. In transportation, this revolution has taken the form of basic information being shared, wirelessly, between vehicles (V2V communications) as well as between vehicles and roadside equipment (vehicle-to-infrastructure [V2I] communications). V2V technologies transfer basic information about vehicles. Vehicles that receive this data use it to execute on-board safety applications such as collision avoidance. V2I technologies facilitate cooperation between vehicles and the execution of corridor control strategies. These strategies can be used by ICM systems installed at traffic control centers (such as Connected Corridors) to improve roadway capacity and travel reliability as well as reduce energy consumption and emissions.

Projected Benefits of PATH's Connectivity Research

- Enable safer vehicles and roadways by developing better crash avoidance for all road vehicles and other road users, as well as mechanisms to protect consumer privacy, commercial motor vehicle safety considerations, and infrastructure-based and cooperative safety systems. This includes exploring how V2V and V2I technologies can help people avoid crashes through new safety advisories, warnings, messages, and ultimately, automated responses, in addition to exploring ways to enhance traffic-incident management and responder safety when a crash does occur.
- Enhance mobility by exploring methods and management strategies that increase system efficiency and improve individual mobility. This will be achieved through a variety of programs and applications, including improved traffic management, work zone and incident

[2] https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

management, transit management, freight management, and road weather management, among others. It further leverages the full potential of CVs, travelers, and infrastructure to provide additional information and technologies that better facilitate mobility for all users of the surface transportation system.

- Limit environmental impacts by better managing traffic flow, speeds, and congestion and using technology to address other vehicle and roadway operational practices. Explore how to reduce the environmental impacts of each trip by assisting system users and operators with "green" transportation alternatives and options such as avoiding congested routes, taking alternate routes, using public transit, or rescheduling a trip — all of which can make trips more fuel-efficient and eco-friendlier.

PATH has been working on development of a cooperative adaptive cruise control (CACC) system for the platooning of heavy trucks in collaboration with the Volvo Group and other partners since 2015, under the sponsorship of USDOT and Caltrans.

Automation

Automated vehicle (AV) technologies provide a pathway to achieving the TZD initiative by enabling the control of steering, acceleration, and braking by the vehicle control system. In the late 1990's California PATH demonstrated fully automated vehicles on the I-15 freeway in San Diego. These vehicles utilized magnets embedded in the road to effect longitudinal and lateral control. Since that time research has focused on the installation of on-board sensors to create situational awareness, which in turn is used to for lateral and longitudinal control. Depending on its intended functionality – from partial to full automation – the automated driving system (ADS) includes the elements of sensing, communicating, monitoring, navigating, decision-making, behavior, and driving control that is required for its progression in traffic. The term AV covers a very broad range of automated functions, both in terms of the extent to which it replaces functions of the human driver as well as the intended operating environment.

Automation will have a significant influence on driving safety, personal mobility, energy consumption, operating efficiency, environmental impact, and land use. In addition to the possibilities that automation offers, it also poses new technical and policy challenges. The entirety of the transportation system can best serve the vital needs of the community when it is using technology to its fullest potential and enabling transportation system managers to effectively "connect the dots" of information from various factors that affect transportation operations.

Projected Benefits of PATH's Connectivity & Automation Research

- Reduce the number and severity of crashes caused by drivers or by other conditions, which communication technologies can provide.
- Increase transportation equity and accessibility by expanding the reach of transportation modes to disabled and older users.
- Increase multi-modality and reduce VMT by providing "first & last mile" connectivity service for all transit users.
- Increase the efficiency and effectiveness of existing transportation systems.
- Reduce greenhouse gas emissions and improve resilience of the transportation system to climate change.

Traffic Operations Research Program Area: Simulation

Simulation models continue to play an important role in the multi-modal planning activities of Caltrans and other transportation agencies in California. These models are used to predict the performance of the transportation system under different, alternative scenarios (including the deployment of new technologies). Hence, simulations are an integral part of the resource allocation process.

California's transportation environment is dynamic - the economy, our environmental challenges, and our transportation system continues to grow both in size and complexity. In addition to these continuous changes, we will soon face multiple disruptive changes to our transportation system. These include the impacts of partial automation, CVs, and AVs. We also expect that recent disruptions from ride hailing and shared vehicles will continue to evolve. All of these changes will need to be addressed in planning, infrastructure investment, and operation. In support, existing simulation models will need to be updated and new models will need to be created that address new factors never previously considered by planning, infrastructure investment, and operations.

In addition to changes to our environment, traffic simulation models are changing. The amount and variety of data available for calibrating traffic models has increased substantially in recent years. New techniques in the areas of data science and machine learning now allow us to apply large datasets to the general task of building models. These new techniques are only now finding their way into the realm of traffic modeling. Operational aspects of simulation models also need to change. Currently, the process of model maintenance is extremely labor intensive, requiring the expertise and continued efforts of traffic-modeling professionals. The areas of data science and machine learning offer tremendous opportunities for reducing this burden and streamlining the model building and maintenance tasks.

The Planning and Simulation Program at PATH seeks to develop simulation and data assimilation tools that will help Caltrans effectively manage a complex and ever-changing transportation system. We do this by adapting cutting-edge techniques in **traffic modeling**, **data science**, and **machine learning** to the specific needs of Caltrans modelers and planners.

Over the years, there have been many fruitful collaborations between Caltrans and U.C. Berkeley in this area, including the development of FREQ (a frequency table that can be used to analyze and summarize one or more categorical variables), the Tools for Operations Planning (TOPL) project, and the Connected Corridors Program, among many others.

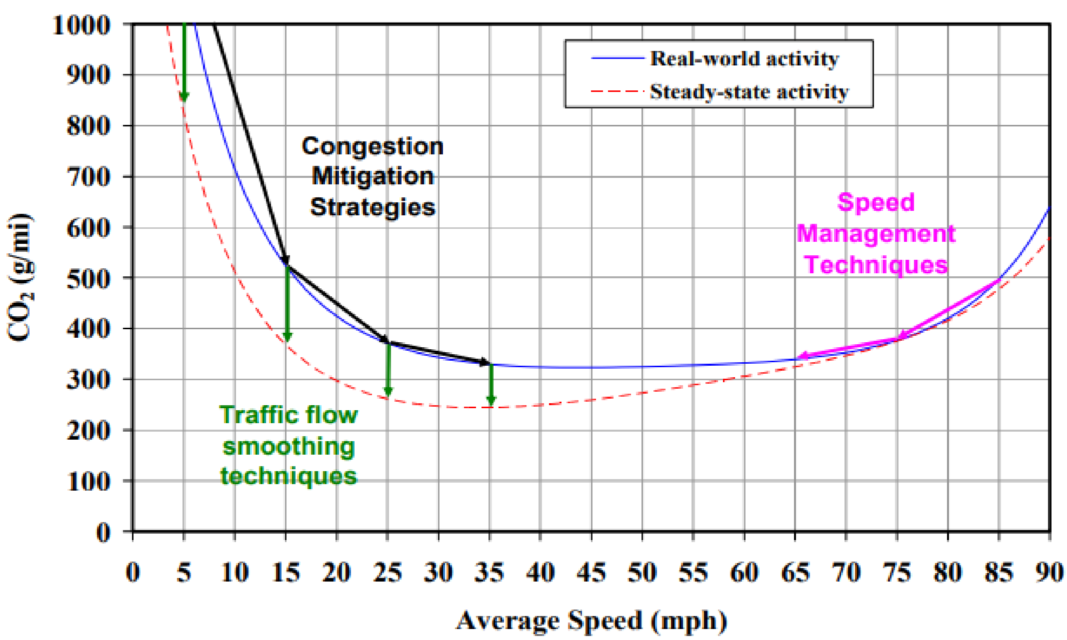
Benefits of Traffic Simulation Research

- One of the greatest benefits of traffic simulations is the ability to implement and evaluate traffic management strategies and new modes of traffic at an extremely low cost compared to a real-world implementation. This is important during the period of dynamic change that now exists.
- Simulation can be applied to quantify different infrastructure designs and control strategies.
- In addition to their use as a standalone tool, simulation sub-models can be embedded in other tools such as a decision support system (DSS) (as was done in the Connected Corridors Project).
- Simulations can be used in the context of real-time laboratories to train Traffic Management Center operators.

Traffic Operations Research: Greenhouse Gas Reduction

The impacts of GHG on the environment, originating from the transport sector, are widely reported by researchers around the globe. Climate change, air pollution, health problems, and degradation of water and soil quality are among the most important impacts, with climate change being of high interest.

International treaties (such as the Kyoto Protocol [2005] and the Paris Agreement [2016]) are in force to enhance the fight against global warming. The European Union enacted legislation in 2009 that set goals for the reduction in CO2 emissions. In the US, California is at the forefront with its adoption of CO2 reduction legislation in 2006 (AB32). California has further advanced its initial goals, through a multitude of legislative initiatives that now establish a 2050 CO2 emission level at 80% below 1990 emissions levels.



Source: “Real-World CO2 Impacts of Traffic Congestion”, Barth/Boriboonsomsin; January 2008

Extensive study of light duty vehicle emissions production, at UC Irvine, illustrated that energy consumption and gas emissions are strongly influenced by a vehicle's speed as well as stop-and-go cycling that is characteristic of congestion. Specifically, fuel consumption and emissions are high at low speeds, as well as in case of traffic congestion, they flatten out at average speeds, and then rise up again when vehicles are moving at higher speeds. The primary conclusion of the UC Irvine studies, as well as several from Europe, is that several different advanced connected-vehicle traffic control strategies can significantly reduce emission. Based on that fact they estimate that there are three possible ways to reduce both energy consumption and gas emission:

(1) Reduce traffic congestion, so as to allow vehicles to move at average speeds.

(2) Vehicle platooning, so as to reduce aerodynamic drag forces, and consequently reduce fuel consumption and gas releases.

(3) Traffic smoothing, by eliminating stop-and-go driving behavior.

Energy and emission savings strategies

Eco-driving is associated with automated acceleration and braking technologies applied on CAVs. Such technologies have the ability to reduce fuel consumption and could result in a fuel consumption (and emission) reduction. An estimate of carbon dioxide reduction, which varies based on vehicle and situational specifics, is between 4% and 10%.

Platooning is also expected to increase fuel savings by reducing air resistance (air drag) for vehicles following the leader car of the platoon. Platooning gains are greater for the vehicles in the middle of the platoon 'string' and become significantly smaller for the vehicles at the front or at the end. Studies such as the European Union's Social Attitudes to Road Traffic Risk in Europe (EU SARTRE) project estimate a possible reduction of up to 20% of fuel consumption due to platooning. PATH's own estimate of truck platooning energy savings (and thus emission reductions) documented 5% savings for the lead vehicle, 15% savings for following vehicles and 10% savings for the last vehicle in the truck platoon.

Another indirect effect on the environment is through maximizing routing efficiency. CAVs provided real-time information on congestion levels, accidents, and more could select routes that avoid traffic congestion and thus reduce emissions. One estimate that utilizes algorithms for route selection in a simulation projected a 12% emissions reduction.

One of the most widely mentioned benefits of CAV implementation is the potential to reduce traffic congestion. As GHG emissions and fuel consumption rise due to congestion, a decrease in traffic congestion could result in a (situationally dependent) decrease in fuel consumption varying between 15% and 60%.

The transportation sector accounts for about 41% of California's total GHG emissions, while light-duty vehicles make up 70 percent of the sector's Green House Gas (GHG) emissions. Additionally, approximately 80 percent of the smog in California comes from vehicle emissions' criteria pollutants.

Greater emission reduction benefits may be achieved when a combination of measures is implemented and these measures are currently being pursued by the Integrated Corridor

Management (ICM) program. New tools are needed to predict CAV implementation impacts, their energy consumption, and the emissions reduction potential to facilitate their application by MPOs.

Projected Benefits of Environmental Research

- Improved information for data-driven decision making.
- Informed policy through better understanding of traffic flow and the resultant transportation emissions.
- Identifying and quantifying the emission reduction potential of different traffic management strategies.

Modal Applications Research

The PATH Modal Applications Program focuses on developing new concepts, methods, and technologies for offering more reliable and efficient transit options, for better balancing the demand and supply of the entire transportation system, and to solve passenger mobility problems that affect the safety, accessibility, convenience, connectivity, user friendliness, and affordability of the State's public transportation systems.

Mass transit faces a multitude of challenges and recent ridership decline has recently accelerated due to car hailing applications and has been seriously exacerbated by COVID-19 and the subsequent shelter-in-place orders. Despite mass transit’s positive contributions to mobility equality, congestion elimination, energy saving, and producing job opportunities, today, transit services are being outcompeted by other transportation modes. Here is a summary of challenges:

Low Density & Intra-Connectivity

In California’s suburban regions, transit agencies face enormous challenges for delivering cost-effective transit operations because the traveling population is distributed over large geographic areas. Transit operators typically assign a limited number of buses on the maximum number of routes possible in order to offer wide geographic coverage. As a result, the headway of each bus route is long, and many passengers need transfers among such routes in order to reach their destinations. Consequently, travel using transit takes much longer than the driving alternative. The longer travel time significantly discourages choices to take transit. Rural and suburban transit agencies need tools to be able to innovate transit operations.

Safety

According to FTA, after 2008 the number of road incidents involving bus transit has increased by 3.8%, number of injuries by 1% and number of fatalities by 1.1% per year. The proportion of fatalities involving cyclists, pedestrians, scooter riders, and motorcyclists represents more than half of the total deaths. Most of these events occur at merge areas and at intersections. Intersections are challenging because of complex interactions between pedestrians, bicycles, and vehicles, the absence of lane markings to guide vehicles, split phases that prevent determining who has the right of way, obstructions from stopped vehicles, and illegal movements.

Sustainability

Transit ridership was already lagging prior to the COVID-19 outbreak and is now at critically low levels. There are concerns about budget-driven reduction of transit services and, possibly, the workforce. Transit services to riders are rapidly being redefined – both by COVID-related constraints and by rapidly evolving technology in other aspects of mobility. Presently, a faster reaction and adaption to a constantly changing environment as well as readiness for unconventional solutions is required of transit agencies. Transit recovery and roadway congestion management (as well as the reduction of emissions and VMT) go hand in hand. Transit can benefit from gains in roadway technology and infrastructure with co-benefits of collision avoidance, pedestrian safety, and congestion relief.

Approach

- Research on Dynamic and Flexible Transit Operation

The conventional transit system was established upon the framework of fixed routes, fixed schedules, and almost-fixed ticket prices. To improve the transport service in order to attract travelers from private driving, transit systems are substantially required to be flexible and dynamic. The traveler-centric and demand-responsive concept of Dynamic Transit Operation offers flexible operations as well as multi-mode linkages.

- Research on Restoring and Innovation

The goals are to restore and attract transit ridership as well as develop transit infrastructure. These objectives are tightly linked. PATH is engaged in working with transit agencies and municipalities to cooperatively adopt new practices and implement new solutions. Innovation plays a key role in this picture.

- Research on bus transit routes characteristics

We focused on bus operation at and near signalized traffic intersections. Intersections are dangerous: 40% of crashes, 50% of serious collisions, and 20% of fatalities occur at intersections.

Table 1 Intersection properties.

Intersection configuration properties obtained from Open Street Maps				
Number of approaches	Number of exits	Number of lanes for each approach	Number of lanes for each exit	Number of right-side bicycle approaches
Number of right-side bicycle exits	Number of center bicycle approaches	Number of center bicycle exists	Number of railway approaches	Number of railway exits
Number of crosswalks	Presence of signal	Presence of pedestrian signal	Number of transit stops at approaches	Number of transit stops at exits

Number of tram/train stops at approaches	Number of tram/train stops at exits	Number of pedestrian railway crossings	Separation of railway and road traffic	Presence of a subway station
Road class of each approach	Road class of each exit	Speed limit at each approach	Speed limit at each exit	Presence of road dividers
Intersection properties obtained from additional geometry analysis				
Curvature of each approach	Intersection size	Number of lane merges	Number of conflict zones of each type	Number of potential blind zones for each conflict zone type

This table filled out for all city intersections enables a classification of intersections into families based on various subsets of parameters. It can be used to analyze the dependency of incident data on intersection properties based on the intersection configuration and geometry analysis; and, if available, signal configuration and traffic volumes. This highlights the combination of intersection parameters affecting the intersection safety for each family of intersections.

We have performed this analysis for all California intersections.

Benefits of Modal Research

- To improve the transport service by making it more flexible and dynamic - in order to attract travelers from private driving and expand the value that public transit delivers to the traveling public.
- To accelerate innovation in public transit through cooperative partnerships.
- To improve safety of transit operations.

Automation: Artificial Intelligence, Machine Learning and Vision Systems

Artificial Intelligence (AI) is now prevalent in many aspects of our daily life. Transportation is a field that has great potential to leverage the power of AI technologies, and its use is already facilitating progress in many aspects of transportation.

- Navigation on personal mobile devices is greatly enhanced by features enabled by AI. New methods of traffic modeling, prediction, and forecasting outperform conventional algorithms.
- A suite of functions, including object recognition, classification, vehicle counting, incident detection, and traffic pattern recognition is handled by machine learning (ML) techniques.
- Particularly noticeable over the last decade is the adoption of AI technologies for automated driving.
- AI and ML are transforming many functionalities, including data sourcing, in-vehicle technologies, data processing, traffic modeling, traffic signal control, route optimization, and system management.

The list of potential AI applications can be expected to grow as the technologies continue to evolve.

Berkeley has a long history of world-renowned research leadership in Artificial Intelligence, which is currently centered at Berkeley Artificial Intelligence Research (BAIR). Berkeley DeepDrive (BDD), formed within PATH in 2016, is a sister organization of BAIR with the mission to merge deep learning with automotive driving and bring computer vision technologies to the forefront. BDD brings together a consortium of (private industry) partners with faculty and researchers from multiple departments and centers to develop new and emerging technologies with real-world applications for intelligent automation. The applicable domains include automated driving, robotics, traffic systems, and data analytics. The research itself can be described as pre-competitive basic research. Consortium members select research topics, and the results provide foundational knowledge that is further expanded within BDD or individually within the consortium members.

Industrial Sponsors

The BDD sponsors, during the 2019 and 2020 fiscal years, in alphabetical order, include:

Allstate, AutoBrain, Baidu, Continental, Didi Chuxing, Ford Motors, FutureWEI, General Motors, HoloMatic, Honda Research Institute, Huawei, Hyundai Motors, Luminar, Mapillary, Meituan-Dianping, Nexar, Nvidia, NXP, Panasonic, Qisda, Samsung, SF Motors, Sony, Toyota Research Institute, UISEE, Zenuity, and ZF.

Projected Benefits of PATH's Artificial Intelligence, Machine Learning, and Vision Systems

- Increase the efficiency and effectiveness of existing transportation systems.
- Reduce the number and severity of crashes caused by drivers or by other conditions, which the above communication technologies can provide.
- Reduce GHG emissions and improve resilience of the transportation system to climate change.

Human Factors and Safety

Human factors research applies psychological and physiological principles to the design of systems, tasks, and environments in order to establish their successful and safe use. In transportation, the goal of human factors research is to reduce the probability and consequences of human errors through the creations of these systems, tasks and environmental designs that recognize all road users' characteristics and limitations.

Successful roadway safety depends on the consideration and integration of three fundamental components - the roadway, the vehicle, and the user. Because driver error is a key contributor to crashes (and roadway fatalities), a more driver-centered approach to highway design and highway operation will promote improved highway safety.

Safety

In order to achieve California's goal of Towards Zero Fatalities (TZD), stakeholders identified 16 safety challenge areas on which to focus resources, illustrated below.

Human factors issues are a common thread throughout all of the safety challenges. Research on how road users perform as a component in the transportation system can play a critical role in identifying how they cause injuries and fatalities. This role recognizes that driver performance is influenced by many environmental, psychological, and vehicle design factors. The focus of the human factors research is to determine which aspects of road or traffic management devices should be modified to improve driver performance and reduce unsafe behaviors.

Congestion

It is evident that no singular solution can solve the congestion problem. Strategies for mitigating congestion include: new or expanded facilities, intelligent transportation systems (variable speed limits, coordinated ramp metering, and managed lanes), information display technologies (to provide travelers with travel choices and alternative routes), and in-vehicle messaging as part of connected and automated vehicles. Any effective solution will depend on driver compliance as well as acceptance by other road users. Human factors knowledge and principles are needed in the design, deployment, and evaluation of these solutions.

Connected and Automated Vehicles

CAV technologies offer the potential to achieve goals that are extraordinarily important to the state of California. The PATH team has identified the following areas of human factors research which could mitigate the impacts of environmental concerns, increase safety, and bring advances in traffic management and CAV implementation. Further investigation and collaborative decision-making within city, state, and federal agencies to address these topics would tackle these specific issues in moving this technology forward.

- Shaping the design of road infrastructure and traffic management systems (e.g., signs, signals) to mitigate the associated safety challenge areas.
- Evaluating drivers' compliance behaviors and effectiveness of signage for congestion mitigation and emission reduction.

- Evaluating driver behavior in the context of human-driven and mixed traffic at varying degrees of market penetration of CAV.
- Assessing the safety of drivers and other road users with connected and automated driving systems (ADS).

Benefits of Human Factors Research

Human factors research enhances safety, reduces congestion, mitigates climate change, and facilitates the deployment of new technologies. It reduces likelihood and consequences of human errors through designs that respect all road users' characteristics and limitations. It can also identify limitations of (and deeded modifications to) current road or traffic management devices to improve driver performance. The outcome is reduced congestion and emissions as a result of improved understanding of (and compliance with) new dynamic traffic control measures that utilize messaging.

Active Projects (being executed during 2018/19 and 2019/20)

PATH's applied research projects are built upon three pillars – **data, simulation,** and **testing & evaluation**. We begin with the end in mind, and how the implementation of new processes or technologies relies on the results of an evaluation of data produced from a pilot implementation (or field test). The pilot implementation itself is designed through simulations of the existing situation and potential changes that new technologies and processes might enable. The simulation, of course, requires a detailed set of (real world) data that captures the current situation and characterizes the challenge. Configuring the simulation to quantify an expected outcome produces performance metrics that support decision-making and management. Any individual pillar can be the central focus of an individual research project, and many projects are interconnected with other pillars that were conducted in the past or are planned for the future.

Data

Data involves sensors, measurement, and generating useful performance metrics to support decision-making and management. Data related projects involve capturing data from existing sensors. Often existing data are fused with data from new sources. Frequently the source of new data is from emerging connected vehicle communications which can often involve new roadside equipment.

In total, data projects create large volumes of data, creating new possibilities and avenues of managing traffic flow and infrastructure. Large volumes of data create new challenges in data storage and retrieval, as well as generate a need to manage data quality (through automation) and to analyze the data with new, innovative tools (using data science). PATH's data projects touch on all of the above themes.

Simulation

A simulation of a transportation network is a mathematical model of the infrastructure and the vehicles that use it and exist in the form of computer software. Simulations are used for network planning, design, and the analysis of existing and emerging alternatives. Simulation tools are important, because they enable studies (and the use of models) on situations that are too complicated for analytical or numerical treatment. PATH employs simulations in our experimental studies, to quantify existing conditions, to evaluate future (new technology enabled) scenarios, and to create metrics with which to evaluate experimental outcomes.

PATH's projects that incorporate simulations span a wide range of application areas. They investigate environmental effects, freeway and corridor operations, and HOT lane operation including the behavior of HOT lane violators. PATH employs conventional tools as well as purpose-built tools to:

(1) simulate mixed traffic with both connected and automated vehicles (CAV) and manually driven vehicles
(2) simulate transportation network company (TNC) vehicles and evaluate their impact during pick-up and drop-off
(3) simulate new ideas for mobile traffic control (i.e., using a few vehicles as traffic controllers via CAV technology) to improve the energy efficiency of traffic flow.

Testing and Evaluation

Theory and modeling lead to testing in real-world settings and evaluation of the resultant data and information. The PATH Traffic Operations Program maintains a portfolio of projects that evaluate operations, impact studies, and pilot deployments. Example application areas include ICM, complete streets, ramp metering, transit operations, and freeway service patrol (FSP) operations.

Methodologies are created for evaluating the traffic performance of alternative designs. For example, "complete streets" provides safe mobility for all users, including bicyclists, pedestrians, transit vehicles, truckers, and motorists.

Highlight of Selected Projects

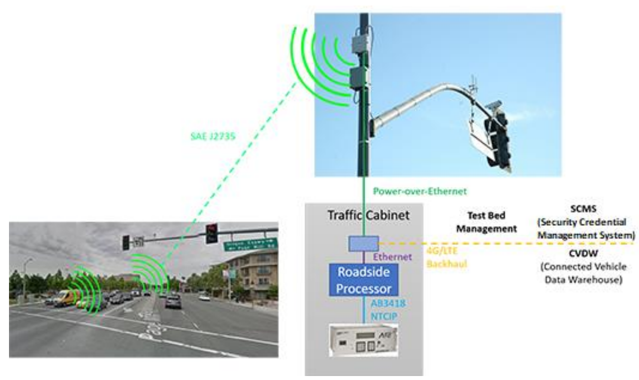
Below we provide a detailed description of the results from several research projects.

Palo Alto – Connected Vehicle Test Bed

In 2005, Caltrans collaborated with the Metropolitan Transportation Commission (MTC) and the California PATH program at UC Berkeley to create the nation's **first public Connected Vehicle Test Bed** on El Camino Real (State Route 82). El Camino is a signalized arterial roadway that serves more than 50,000 vehicles traveling each day between San Francisco and San Jose.

In 2018, Caltrans and PATH worked with the United States Department of Transportation (USDOT) to update the equipment in the Test Bed so that it now complies with the latest connected vehicle standards and implementation architecture. These improvements were recently used to successfully demonstrate Multi-Modal Intelligent Traffic Signal System (MMITSS), including CV-based traffic signal control and signal priority for transit, freight, pedestrians, and Environmentally Friendly Driving.

Caltrans is currently working with PATH to expand its size from the original 11 intersections to 31 intersections in Palo Alto and Mountain View. This connected vehicle corridor will serve as a model deployment that can be duplicated on similar corridors in other urban regions of California. Caltrans is working with PATH and ProspectSV to ensure that the Test Bed is available to all developers to test how connected vehicle technologies perform under real-world conditions.



Coordinated Ramp Metering

Ramp metering is the most widely-used tactic in California to mitigate freeway traffic congestion. Ramps interconnect freeways with their arterials. Currently, a freeway ramp meter operates independently from an adjacent arterial intersection traffic signal that feeds traffic onto this ramp. This situation often causes queue spillback (from the ramp back on to the arterial) as well as the activation of queue override, which negates the benefits of ramp metering by introducing platoons of vehicles on to the freeway. This is due to the lack of coordination between the two traffic control systems which are usually operated by different agencies. Field measurements at a real-world test site show that queue override reduces the freeway bottleneck capacity by 10%.

A control strategy for coordinating freeway ramp metering and arterial traffic signals was developed, field implemented, and evaluated in this study. The algorithm takes available on-ramp storage into account and dynamically reduces the cycle length of the feeding intersection signal control in order to avoid on-ramp queue spillback and mitigate unnecessary delay in the conflicting directions. The proposed algorithm was tested in the morning peak during a four-month period. Observations in the field suggest that the proposed control was able to reduce travel time and delay on freeways while preventing on-ramp queue spillback to arterials.

Operations Planning Toolbox

On November 6, 2020, the Operations Planning Toolbox (OPT) Alpha version was released (Figure below). It is a fully functional traffic planning and analysis tool with the following features:

- A configuration module with an intuitive user interface that allows building the road network, specifying input demands and outgoing traffic flows, modeling different types of traffic (e.g., single-occupancy vehicles [SOV's], trucks), defining policies for managed lanes (including high-occupancy vehicle [HOV] lanes and high-occupancy toll [HOT] lanes), and setting ramp metering policies for HOV and low-occupancy vehicle (LOV) traffic.
- A simulation module that handles multimodal traffic, implements lane changing behavior, and accepts outgoing flows in two formats – as off-ramp flows and as split ratios that determine the portions of traffic to be directed to off-ramps.
- Reporting of simulation results in the form of pie charts for summaries, time series charts, and contour plots for spatial-temporal data. Simulation results can be exported to Excel.
- Users can set their preferences about simulation setup, duration, and reporting granularity.

OPT employs Open Traffic Models (OTM) as its computational core. OTM is a traffic simulation engine recently developed by PATH researchers, for the purpose of advancing research in areas that are currently beyond the reach of most commercial simulators. OTM is a *hybrid* simulation framework, in the sense that it supports a wide variety of traffic models, including microscopic, mesoscopic, and macroscopic models – all acting simultaneously on a single network. OTM is also the first *macroscopic* simulator to be deployed in modern high-performance computing clusters. Tests of OTM on the Cori supercomputer at Lawrence Berkeley National Laboratory (LBNL) have demonstrated record simulation speeds for a macroscopic simulation [Gomes et. al. 2020]. Finally, OTM is an open-source project. This will enable the wider community of traffic engineers and theorists to cooperate in developing tools that advance the state of traffic planning and real-time traffic management.

Simulation Model Development and Case Studies for Mixed Traffic FlowCAV technology provides a powerful tool for the Infrastructure Owner Operator (IOO) to perceive the traffic flow states and implement advanced traffic management strategies. To fully take advantage of this new technology, it is essential to understand the mobility and vehicle energy impacts of CAVs on mixed-traffic flow under various traffic scenarios. However, it is not economically feasible to explore the CAV impacts via large-scale field tests. Tackling such a challenge calls for the development of a high-fidelity simulation framework that can accurately capture the dynamic interactions between CAV and other vehicles in mixed-traffic streams. To build this simulation framework, PATH has adopted a technical approach that begins with generating car-following models of CAV based on datasets from small-scale CAV driving in real traffic. The CAV models are then integrated into a simulation platform that contains a well-calibrated model of manually driven vehicles (MDV). With such an integration, the simulation platform is able to depict microscopic car-following and lane-changing behaviors of CAV and their interactions with MDVs. In addition, the modeling framework also contains functions to model the cooperation of CAVs and infrastructure. This further enhances the capability of the simulation framework for depicting various traffic scenarios.

The development of the PATH simulation model has been supported by USDOT and Department of Energy (DOE) via multiple research grants. The USDOT projects mainly focus on the freeway modeling and analysis on mobility impacts, whereas the DOE projects cover both the freeway and the intersection studies with analysis in both mobility and energy saving benefits. Details regarding the model development and application are summarized as follows:

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Simulation Model Development via USDOT Funded Projects

USDOT supported PATH's simulation model development via two major projects: *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams* and *Developing Analysis, Modeling, and Simulation (AMS) Tools for Connected and Automated Vehicle (CAV) Applications*. The two projects resulted in a simulation framework capable of modeling corridor-level freeway traffic operations under the influence of traffic management strategies including CAV dedicated lane and Vehicle Awareness Device (VAD) implementations. Notably, the simulation framework not only captures the interaction between CAVs and MDVs, but also between Connected Manually Driven Vehicles (CMDV) and MDVs. This simulation model allows the PATH team to perform extensive freeway capacity and vehicle energy analyses of isolated freeway bottlenecks and complicated freeway corridors. Highlights are listed below:

- The PATH team built a CACC model and extended it to describe the interactions among the CACC vehicles and manually driven vehicles in mixed traffic. The modeling framework adopts a vehicle dispatching model to generate the high-volume traffic flow expected to exist due to the CACC string operation. The framework also includes lane changing rules and automated speed control algorithms. This ensures realistic CACC vehicle behaviors at freeway on/off-ramp areas where traffic disturbances might frequently interrupt the CACC string operations. The modeling capability of the presented framework has been verified via case studies on a simple 4-lane freeway segment with an on-ramp and an off-ramp as well as the complex 18 kilometer freeway corridor State Route (SR)-99 northbound (NB) in California.
- PATH investigated the impact of CACC vehicle string operation to determine the capacity of isolated multilane freeway merge bottlenecks. Simulation experiments were conducted using CACC car-following models derived from field test data, along with lane-changing models of CACC vehicles and manually driven vehicles, as well as a maximum CACC string length and inter-string time gap constraint. Simulation results reveal that the freeway capacity increases quadratically as the CACC market penetration increases, with a maximum value of 3080 vehicle/hour/lane at 100% market penetration. The disturbance from the on-ramp traffic causes the merge bottleneck and can reduce the freeway capacity by up to 13% but the bottleneck capacity still increases in a quadratic pattern as CACC market penetration becomes larger.
- PATH examined the impacts of CACC vehicle string operations on vehicle speed and fuel economy on the 13-mile SR–99 corridor NB from Elk Grove to SR–50 near Sacramento, CA. The case study revealed that the average speed of the corridor over the simulated morning peak period increased by 70% when the CACC market penetration increased from 0 to 100 percent. The highest average fuel economy expressed in miles per gallon (MPG) was achieved under the 50 percent CACC scenario where MPG was 27. This was 10 percent higher than the baseline scenario. When CACC market penetration reached 100 percent, the corridor allowed 30 percent more traffic to enter the network without experiencing reduced average speed.
- With the simulation framework PATH identified the impact of vehicle connectivity and users' acceptance on the performance of a feedback variable speed advisory (VSA) system. It adopted a simulation approach in order to conduct scenario analyses to estimate the performance of the VSA algorithm under various connected manually driven vehicle (CMDV) market penetrations. The analysis results indicate that the VSA control could have substantial effects on the freeway corridor when the CMDV market penetration was 10 to 40 percent. With the advisory speed, vehicle fuel efficiency increased two to six percent. These results suggest that the speed adaptation of a few connected drivers could change the traffic flow pattern, leading to more energy-efficient traffic flow. In addition, the full compliance brought about two to three percent extra benefit on vehicle fuel efficiency.

Simulation Model Development via DOE Funded Projects

DOE supports PATH's simulation model development via the Energy Efficient Mobility Systems (EEMS) Program in Task 7A.1.2 of *Traffic Microsimulation of Energy Impacts of CAV Concepts at Various Market Penetrations*. The task resulted in a simulation framework capable of modeling the performance of urban intersections with an advanced signal control and trajectory guidance for CAVs. In addition, it provided vehicle energy analysis results for isolated freeway bottlenecks. Highlights of those works are listed below:

- The PATH team developed a cooperative signal control algorithm that adopts the CACC datasets and the datasets collected by the traditional fixed traffic sensors to predict the future traffic conditions. The prediction allows the signal controller to assign signal priority to the intersection approach that accommodates the most CACC strings. Such a control strategy can significantly enhance the CACC string operation, which ultimately improves the overall intersection performance. This algorithm also provides reference trajectories to CAVs, letting them pass the intersection without stopping. Such proactive driving patterns are expected to improve the safety, mobility, and energy efficiency of the CAVs themselves, as well as the general traffic that follows. The effectiveness of the algorithm has been tested in a simulated four-way signalized intersection. The algorithm substantially outperforms a typical actuated controller and fixed signal controller.
- PATH adopted a state-of-the-art traffic flow modeling framework to explore the impacts of CACC on vehicle fuel efficiency in mixed traffic. The analyses at a freeway merge bottleneck indicated that the CACC string operation resulted in a maximum of 20% reduction in energy consumption compared to the human-driver-only case. At 100% market penetration, CACC equipped vehicles consume 50% less fuel than adaptive cruise control (ACC) vehicles without V2V communication and cooperation. This implied the importance of incorporating the V2V cooperation component into the automated speed control system. In addition, the CACC string operation could substantially improve freeway capacity without degrading the vehicle fuel efficiency. At 100% CACC market penetration, the capacity increased by 49% while the vehicle fuel consumption rate per vehicle mile traveled remained the same as the rate observed in the human driver only case.

Complete Summary of PATH's Active Project Portfolio

Traffic Operations

Field Test of Coordination of Freeway Ramp Meters and Arterial Traffic Signals (Phase II-B), PI: Alexander Skabardonis; Description: Arterial signals that feed freeway ramps contribute to freeway congestion. Currently ramp control and arterial signal control systems operate independently. During high demand periods ramps control traffic flow to avoid congestion on the mainline. In contrast, arterial control systems lengthen green phase signals - to lessen arterial congestion. Unfortunately, this floods the ramp - triggering queue override that creates considerable mainline congestion. This project will test in the field an approach that coordinates both signals and implements a new control algorithm for ramp timing. Project Sponsor: Caltrans 65A0605; Funding: $249,969; End Date: December 2018.

Meeting the SB 1 Transportation Systems Performance Goals, PI: Alexander Skabardonis; Description: The research team evaluated the Caltrans performance-based methodology to achieve the SB 1 (California's Road Repair and Accountability Act) ten-year (2027) performance goals. The team found that the Caltrans Transportation Asset Management Plan (TAMP) follows Federal Highway Administration (FHWA) guidance as well as published Asset Management Best Practices and will meet the SB 1 target; some additional recommendations were offered. Project Sponsor: UCB-ITS SB-1; Caltrans PM: Brian Simi; Funding: $25,000; End Date: December 2018. Final Report: https://escholarship.org/uc/item/32t4p6h0.

Review of the Project Resourcing and Schedule Management (PRSM) System used by Caltrans, PI: Ben McKeever; Description: This project conducted a complete, post-implementation review of the Project Resourcing and Schedule Management (PRSM) information technology system upgrade completed by the USDOT. The PRSM system referenced is Commercial-Off-The-Shelf (COTS) software deployed at Caltrans in 2014. Project Sponsor: UCB-ITS SB-1; Funding: $400,000; End Date: December 2018; Final Report: https://escholarship.org/uc/item/20t4r81t.

Modeling and Control of HOT Lanes – Phase II., PI: Alexander Kurzhanskiy; Description: HOT lanes become congested when LOV drivers evade the toll and use the lane during periods of peak demand. To address this problem, a multimodal macroscopic freeway simulation model was developed to capture the phenomena of a HOT lane operation, including the behavior of HOT lane violators, for their efficient evaluation. It was implemented and tested with I-10 West HOT data. Project Sponsor: Caltrans Traffic Operations; Caltrans PM: Asfand Yar Siddiqui; Funding: $123,000; End Date: June 2019.

Workforce Challenges in Implementing Transportation System Management and Operations within Caltrans, PI: Alexander Skabardonis (lead) and Joe Butler; Description: Caltrans has traditionally focused on designing, building, and maintaining California's large freeway network. Lately, a stronger focus is being placed on real-time transportation network operation which requires the use of real-time data and decision-support software tools. This transition represents a cultural shift for Caltrans, and its organizational structures and staffing processes are not yet in place to support the effort. Project Sponsor: UCB-ITS SB-1; Funding: $19,400; End Date: June 2019; Final Report: https://escholarship.org/uc/item/4j3023xk.

Generation and Mitigation of Hazardous Scenarios at Traffic Intersection, PI: Alexander Kurzhanskiy; Description: The goal of the project is to create a simulation-driven methodology for automatic generation of hazardous scenarios at traffic intersections and use the results to design information sharing and cooperation between the autonomous vehicle and infrastructure. Achieving this goal will address the stated problems (1) by focusing the simulation effort on the most safety-critical situations, and (2) through systematic design of intelligent intersections that cooperate with autonomous driving systems. Project Sponsor: BDD; Funding: $50,000; End Date: June 2019; Final Report: https://deepdrive.berkeley.edu/project/generation-and-mitigation-hazardous-scenarios-traffic-intersections.

Monitoring the Cost Effectiveness of the Caltrans Freeway Service Patrol (FSP) SB 1 Funded Expansion, PI: Alexander Skabardonis; Description: This research project performed a near-term cost effectiveness evaluation of the SB 1- funded FSP program expansion and found that in its first year of implementation

(Fiscal Year 2018-19), the SB 1-funded FSP program expansion provided over 118,000 assists to California's motorists. The SB 1-funded FSP expansions provided almost $47 million in benefits to motorists, while costing the State under $9 million. On average, the SB 1-funded FSP expansions provided five times as much benefit to California's motorists as these expansions cost the State. Project Sponsor: UCB-ITS SB-1; Funding: $79,523; End Date: June 2019; Final Report: https://escholarship.org/uc/item/63k7d9tx.

I210 Barrier Simulation, PI: Joe Butler; Description: The objective of this project was to identify the impact of construction lane closures on I-210 traffic. The Aimsun model was used to simulate eight different freeway lane closure scenarios to replace the barrier separating traffic from Gold Line light-rail trains along I-210 in Pasadena. Project Sponsor: Jacobs; Funding: $160,000; End Date: January 2020.

Improve Traffic Census and Highway Performance Monitoring Programs, PI: Alexander Skabardonis; Description: The objective of the study is to support the Traffic Census and Highway Performance Monitoring System (HPMS) Programs in identifying locations for motorized traffic data collection on all public roads in California. The study will analyze the traffic census maps for each District to reevaluate count locations on the State Highway System (SHS) based on FHWA requirements. At the same time, the Highway Performance Monitoring System (HPMS) needs a similar effort to evaluate count locations for motorized traffic data collection on non-SHS routes as part of FHWA requirements. The study will also evaluate the statistical accuracy of count locations in meeting FHWA requirements for all public roads in California and provide guidance on the technologies the University could use to collect data by location and count type. Project Sponsor: Caltrans Traffic Operations 74A1119; Caltrans PM: Nick Compin, Ph. D; Funding: $250,000; End Date: June 2020.

Research Support for the Freeway Service Patrol (FSP) Program, PI: Alexander Skabardonis; Description: The FSP is an incident-management program to assist disabled vehicles and reduce non-recurring congestion along the freeway during peak commute hours. This project has three objectives: develop standardized FSP data management and reporting procedures, provide district-specific requested research support, and develop Statewide and District Annual Reports. Project Sponsor: Caltrans Traffic Operations 51A0494; Caltrans PM: Lisa Davies; Funding: $300,000; End Date: September 2020.

Evaluation of Different Coordinated Ramp Metering Systems in Caltrans, PI: Alexander Skabardonis; Description: This project will evaluate the performance of three different CRM approaches to corridor ramp metering, which have been implemented by Caltrans in three different operating districts. Using field data, the study will identify which has the best overall performance – considering system throughput, corridor time travel, and queue reduction. Project Sponsor: Caltrans 65A0693; Caltrans PM: Hassan Aboukhadijeh; Funding: $270,940; End Date: November 2020.

Hybrid Data Research Project, PI: Anthony Patire; Description: The objective of this project is to evaluate and demonstrate how third-party probe data can be used to extend, enhance, and replace traditional point source data that is the backbone of the Caltrans Performance Measurement System (PeMS). The resultant performance measurement system will provide broader coverage at lower costs. Project Sponsor: 65A0739 Caltrans; Caltrans PM: Melissa Clark; Funding: $249,999; End Date: November 2020.

Operations Planning Toolbox, PI: Alexander Kurzhanskiy; Description: This project will develop a user-friendly, well-documented, open-source, multi-modal transportation modeling software. This new software, a mesoscopic simulator, will support the fast execution of the analysis of freeway and corridor operations as well as highways and multi-lane road analysis. It will be simple to learn and use, and serve to replace the legacy simulation application FREQ12, also developed by UC Berkeley. Project Sponsor: Caltrans 65A0713; Caltrans PM: Diane Jacobs; Funding: $560,000; End Date: December 2020.

Graphical User Interface Development for Coordinated Ramp Metering System, PI: Xiao Yun Lu; Description: The goal of this project is to develop a Graphical User Interface (GUI) software (e.g., a Linux or Windows-based) application to enable the implementation of a Coordinated Ramp Metering (CRM) system on any freeway corridor by Caltrans District engineers. Ramp-metering (RM) is the most widely-used tactic in California to mitigate freeway traffic congestion. Under a previous study, prevailing RM control strategies have been revised and tested. The GUI will allow widespread application of the new RM approach by Caltrans. Project Sponsor: Caltrans 65A0689; Caltrans PM: Hassan Aboukhadijeh; Funding: $356,187; End Date: March 2021.

Field Test of Combined Coordinated Ramp Metering and Variable Speed Advisory for Freeway Traffic Control, PI: Xiao Yun Lu; Description: The UC Berkeley PATH project team has developed a simple, practical VSA algorithm that should improve bottleneck flow and reduce shockwaves along the freeway. The objective is to field implement, test, and evaluate the performance of combined CRM and VSA data learned from previous Caltrans projects on SR 99 NB corridor in Caltrans District 3 in Sacramento. During a 12-month field test stage, dynamic interactions of CRM and VSA in a real-world freeway corridor will be investigated. The radar speed data from these VSA signs and the speed data collected from the dual loop detectors/2070 controllers will be used to evaluate the driver compliance rate. Performance improvements for joint functions of CRM and VSA will be quantified using river compliance. Project Sponsor: Caltrans - 65A0743; Caltrans PM: Hassan Aboukhadijeh; Funding: $550,000; End Date: April 2021.

Erroneous HOV Degradation, PI: Anthony Patire; Description: The proposed research explores the application of data science to improve the accuracy of highway performance measures, specifically measurement of HOV lanes. The main goal is to develop automated means to identify configuration errors associated with loop measurement of HOV lanes - leveraging the latest research in data science. Project Sponsor: Caltrans 65A0759; Caltrans PM: Melissa Clark; Funding: $150,000; End Date: June 2021.

Mobile Device Data Analytics to Support Next-Generation Traffic Management, PI: Jane Macfarlane; Anthony D Patire; Description: This project will apply data science techniques on GPS-based point-speed data and associated transportation infrastructure data to generate an inventory of observed driver paths in the I-210 Corridor. This will be the first large-scale driver response study - both temporally and geospatially - to establish a consistent methodology for processing GPS-based trajectory data that can be used to augment efforts of transportation system performance measurement, evaluation, and optimization. Project Sponsor: UCB-ITS SB-1; Funding: $76,083; End Date: June 2021

Development of a Model to Evaluate Policy Approaches for Transportation Network Companies and the Private Vehicle to Address Congestion and Promoting Equity in San Francisco, PI: Pravin Varaiya; Description: The project will evaluate the impact of regulations on Transportation Network Companies (TNC) and private vehicles on congestion and equity in San Francisco. TNCs like Uber and Lyft are popular with the public and growing in use. Unfortunately, TNCs have disrupted traffic and increased congestion in San Francisco. Between 2010 and 2016, daily TNC vehicle miles travelled (VMT) increased by 630,000 miles, accounting for 51% of increased delay and 25% of total delay. With 45,000 drivers, TNCs are the city's largest employer. Project Sponsor: UCB-ITS SB-1; Funding: $70,000; End Date: June 2021.

Traffic Operating System, PI: Roberto Horowitz; Description: Our growing population is impacting the limited capacity of our roadways. Each year commuters experience hundreds of hours of lost time. Congestion reduction can only be achieved by through emerging technologies (CAV, ITS, car sharing, ride on demand, last mile delivery services). This project will develop, simulate, and test a traffic operating system over a three-year period, July 2017 through June 2020, that is based on these new technologies to minimize congestion, enhance safety, and minimize the number of vehicles on the road. Project Sponsor: NSF 1545116; Funding: $1,099,914; End Date: June 2021.

Improved Analysis Methodologies and Strategies for Complete Streets, PI: Alexander Skabardonis; Description: A complete street is a transportation facility that is planned, designed, operated, and maintained to provide safe mobility for all users including bicyclists, pedestrians, transit vehicles, truckers, and motorists (appropriate to the function and context of the facility). The objectives of this project are 1) development of improved methodology for evaluating the traffic performance of alternative designs for complete streets, and 2) development of signal control strategies to improve the travel experience at signalized intersections for all users. Project Sponsor: Caltrans 65A0723; Caltrans PM: Pradeepa Pannirselvam, P.E.; Funding: $236,000; End Date: June 2021.

Policy Recommendations for Reducing the Damage of Overweight Trucks on Public Roads by Improving California's Weigh-in-Motion (WIM) System, PI: Wei-Bin Zhang; Description: Many of California's public roads, highways and bridges are in poor condition. Overweight vehicles are responsible for about 60% of road network damage, and studies revealed that the extremely low overweight detection rate is caused by technological gaps of the WIM sensors used in California. Project Sponsor: UCB-ITS SB-1; Funding: $25000; End Date: July 2021.

Richmond-San Rafael Bridge Access Improvements Projects Before/Mid-Term Study Evaluation and Report, PI: Francois Dion; Description: The Richmond San Rafael (R_SR) Bridge improvement project is a four-year pilot of changes to east and west bound lanes to alleviate congestion. These changes include the elimination of breakdown lanes, the installation of a moveable barrier and the addition of bike lanes as well as general purpose (GP) travel lanes. There is some uncertainty as to whether the changes will be effective, as breakdown lanes themselves have a congestion-mitigating function. The objective of this project is to document the operational characteristics of the bridge prior to the modifications. This study has been completed. Project Sponsor: Caltrans - 65A0529 TO 036; Funding: $364,637; End Date: July 2021; Final Report: https://tinyurl.com/y4e4gtv6.

Richmond-San Rafael Bridge After Study, PI: Francois Dion; Description: This is the second phase of the R-SR improvement study, where operational characteristics of the bridge are going to be quantified subsequent to modifications. Improvements have been installed and the operational characteristics are under study to determine if the changes should remain in place. Project Sponsor: Caltrans 65A0684; Funding: $346,500; End Date: July 2021.

Research Support for the SB-1 funded Expansion of FSP, PI: Alexander Skabardonis; Description: The purpose of this project is to evaluate the expansion of the Caltrans FSP program funded by SB-1. The tools used and the operational performance measures will significantly contribute to the agencies' efforts to continuously improve the FSP program. Project Sponsor: Caltrans Traffic Operations 51A0525; Caltrans PM: Lisa Davies; Funding: $300,000; End Date: February 2022.

Richmond San-Rafael Bridge and Sir Francis Drake Pilot (Phase II) "Bikeways", PI: Francois Dion; Description: The primary objective of this project is to evaluate the impacts associated with the conversion of an existing one-way Class II bikeway on the I-580 overpass featuring non-standard design features. PATH is being asked to assess the operational, maintenance, and safety impacts of the resulting traffic/bikeway lane configuration. Data gathered through this project will help Caltrans determine whether the bikeway should be maintained as-is or if changes may be warranted to improve its operations and safety. Project Sponsor: Caltrans Traffic Operations; Funding: $450,000; End Date: June 2024.

Toolbox for Managed Lane Operational Planning, PI: Roberto Horowitz; Description: The objective of this project is to develop a toolbox for efficient quantitative assessment of operational scenarios on freeways with managed lanes in terms of VMT, vehicle hours traveled (VHT), delay, travel time, and toll revenue. This toolbox will include data analysis and modeling components that would explore the impact of HOT policy violations on the operation of the GP and the HOT lanes. Project Sponsor: Caltrans 65A0626; Funding: $123,396; End Date: December 2018.

Traffic Operations: Integrated Corridor Management

Connected Corridors - Tools, Methods and Pilot Implementation (ICM 2), PI: Alexandre Bayen; Description: Connected Corridors is an ICM program that looks at an entire transportation system and all the opportunities to move people and goods in the most efficient manner possible and to ensure that the greatest potential gains in operational performance will be achieved. The goals for this phase are to establish institutional agreements needed to implement ICM, develop the systems engineering processes for the ICM pilot, optimize traffic control strategies for corridor operation, and develop and pilot the DSS. Project Sponsor: Caltrans Traffic Operations 51A0479; Caltrans PM: Nick Compin, Ph.D.; Funding: $6,599,998; End Date: December 2019.

ICM3 Data Hub and Decision Support System Pilot, PI: Alexandre Bayen; Description: The primary objective is to develop a database system that processes and cleans all the data that arrives from different sources. Data from field elements must be validated for completeness and data quality prior to use by downstream system components (the DSS). With such a variety of data sources, often for the same type of field elements, data must be transformed into a common set of data semantics. The Data Hub will process all incoming data into a standardized format. Project Sponsor: Caltrans Traffic Operations 51A0501; Caltrans PM: Nick Compin, Ph. D; Funding: $4,299,911; End Date: June 2019.

I-210 Pilot Deployment and Operation (ICM4), PI: Joe Butler; Description: The Connected Corridors Program is an integral component of Caltrans's commitment to transportation systems management. The objective of this phase is to implement the DSS, conceive an operational structure for corridor management, and demonstrate the benefits of a system management approach. Project Sponsor: Caltrans Traffic Operations 51A0514; Caltrans PM: Nick Compin, Ph.D.; Funding: $2,136,208; End Date: January 2020.

I-210 Hard Pilot Deployment and Operation ICM 5 - Revised, PI: Alexandre Bayen; Description: The Connected Corridors Program is an integral component of Caltrans's commitment to transportation systems management. The objective of this phase is to develop and demonstrate key elements of Connected Corridors research. This includes completion of the technical design, implementation of the estimation function, system integration, and the launch and operation of the I-210 pilot. Project Sponsor: Caltrans Traffic Operations 51A0522; Caltrans PM: Nick Compin, Ph. D; Funding: $7,000,000; End Date: December 2021.

Management of Multiple Integrated Corridor Management (ICM) Corridors, PI: Anthony Patire; Description: ICM success depends on understanding and mitigating the impacts of incidents in one corridor upon other interconnected corridors. This project will provide foundational tools to understand large-scale traffic patterns and considerations for the design of future interconnected ICMs. Ultimately, interconnected ICMs should support each other's objectives. Better traffic management decisions will translate to better environmental outcomes and improved livability. Project Sponsor: Caltrans; Caltrans PM: Hassan Aboukhadijeh; Funding: $250,000; End Date: September 2021.

Traffic Operations: Connected and Automated Vehicles

Modeling & Evaluation of Intersection Infrastructure for Connected Vehicles, PI: Alexander Kurzhanskiy; Description: Intersections present a very demanding environment and unsurprisingly, most demonstrations of AVs are on freeways; but the full potential of automated vehicles can only be realized when AVs can safely and efficiently maneuver through intersections. AVs are equipped with an array of sensors but situations exist in which additional information about the upcoming traffic environment would be beneficial to better inform the vehicles' built-in tracking and navigation algorithms. A potential source for such information is from in-pavement sensors at an intersection that can be used to differentiate between motorized and non-motorized modes and track road user movements and interactions. Project Sponsor: UCB-ITS SB-1; Funding: $70,000; End Date: December 2018.

Intelligent Intersection, PI: Alexander Kurzhanskiy; Description: The objective of this research is to design intelligent intersection infrastructure and evaluate its performance in terms of safety and mobility benefits. This project seeks to remove one important cause of intersection accidents: drivers, pedestrians, and cyclists that make mistakes because they lack sufficient information about the movement of others as they proceed through an intersection. This missing information can be supplied by an "intelligent intersection". The intelligent intersection broadcasts this information via radio and can be received by a connected vehicle or anyone in the intersection with a smartphone or Bluetooth device. Project Sponsor: BDD; End Date: December 2018.

Safe Operation of Automated Vehicles in Intersections, PI: Pravin Varaiya; Description: Worldwide Research and Development (R&D) activity in AVs is accelerating, led by California. This is a source of pride as well as a matter of concern since California will be the first to make mistakes in the deployment of AVs. Using advanced sensing platforms to proactively monitor safety-critical events of multi-modal road users provides an opportunity to supplement the traditional assessment of the safety performance of these facilities. Sensor perspective can be exploited to alert AVs about the presence of other oncoming modes in advance of their arrival into their detection zones, thus potentially gaining critical time in taking better decisions. Project Sponsor: Caltrans 65a0529 TO 052.7; Caltrans PM: Asfand Yar Siddiqui; Funding: $150,000; End Date: December 2018.

Introducing an Intelligent Intersection, PI: Pravin Varaiya; Offer Grembek; Description: In the U.S., approximately 40% of all crashes, 50% of serious collisions, and 20% of fatalities occur in intersections. Intersections are challenging due to complex interactions among pedestrians, bicycles and vehicles, absence of lane markings, difficulty in determining who has the right of way, blind spots, and illegal movements (e.g., vehicles running red lights). AVs find intersections especially challenging; 58 of 66 (88%) AV crashes reported to the California DMV occurred in intersections. The objective of this project is to identify intersection risks and then analytically design an intelligent intersection that mitigates these risks. In addition, this project identified then developed a methodology to priority-rank intersections where the installation of instrumentation would ensure safe and efficient AV operations. Project Sponsor: UCB-ITS SB-1; Funding: $100,000; End Date: December 2018. Final Report: https://escholarship.org/uc/item/2qm9h8jb.

Early Opportunities to Apply Automation to Managed Lanes, PI: Xiao Yun Lu; Description: California has the largest network of HOV and HOT managed lanes as well as one of the largest concentrations of automotive R&D in the country. This project proposes to identify the specific opportunities to capitalize on the state's managed lane network as early experimental and deployment sites for connected automated vehicles. The managed lanes network provides a means of concentrating equipped vehicles in close proximity to each other (with some degree of separation from other traffic) so that they can interact with each other as if they represented a larger fraction of the vehicle population than they really do. Project Sponsor: Caltrans 65A0595; Caltrans PM: Asfand Yar Siddiqui; Funding: $150,000; End Date: December 2018.

Connected Automated Vehicle Platform, Integrated Prototype I, PI: Xiao Yun Lu; Description: The object of this project is to develop experimental control system for the DOT Carma platform that incorporates V2V communication. Project Sponsor: Leidos, Inc; Funding: $35,380; End Date: December 2018.

Evaluation of Innovative Platform Track Intrusion Detection System, PI: Wei-bin Zhang; Ching-Yao Chan; Description: The objective of this project is to evaluate the performance and effectiveness of a radar-based detection system to identify people on passenger railroad tracks. In addition, a comprehensive analysis will be conducted to evaluate the safety improvement in terms of false alarm reduction, reduced response time, reduced schedule delay, improvement of operation, etc. The evaluation results will also allow analysis on the efforts on partnership, knowledge sharing, and national applicability analysis. Project Sponsor: LA Metro; Funding: $99,950; End Date: December 2018.

DOE-LBL Connected Automated vehicles (Eco Driving), PI: Joshua Meng; Description: The objective of this project is to develop and demonstrate a V2I communication system that provides information to drivers as they approach a signalized intersection. This facilitates smoother arrivals and departures through the intersection, which in turn reduces energy consumption and emissions production. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $300,000; End Date: December 2018.

CAV Standards, PI: Steve Shladover; Description: The objective of this project is to identify gaps in CAV standards that are, or may, prevent CAV deployment Project Sponsor: US DOE Vehicle Technologies Office; Funding: $139500; End Date: December 2018.

Arterial Traffic Estimation Using Field Detector and Signal Phasing Data, PI: Alexander Skabardonis; Description: Intersection performance computed from the state-of-the-practice Highway Capacity Manual (HCM) method is not reliable under heavy traffic conditions. This project developed a novel approach to estimate the traffic states on arterial road links controlled by signalized intersections. The parameters used to compute performance are closely related to road geometry, detector layout, signal settings, and vehicle dynamics (which can be obtained from the field data). The proposed trapezoidal fundamental diagram was validated using a dataset with six months of detector data. Project Sponsor: UCB-ITS SB-1; Funding: $79,851; End Date: March 2019; Final Report: https://escholarship.org/uc/item/7g5532jh.

Smart Mobility – Simulating the traffic impacts of CACC (and similar cooperative automation systems), PI: Steve Shladover; Description: The driving behaviors of automated vehicles operating in platoons will impact traffic in new ways. The objective of the project is to simulate the behavior of platooning on freeway traffic to quantify both negative and positive impacts. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $350,611; End Date: March 2019.

Technical Support to California DMV on Automated Vehicle Regulations, PI: Steve Shladover; Description: Assist CA DMV in their development of regulations that permit testing of autonomous vehicles on California roadways. Project Sponsor: CA DMV; Funding: $200,000; End Date: March 2019.

Automated Driving of Ground Vehicle - French Autonomous Vehicle Consortium, PI: Ching-Yao Chan; Description: This international collaboration supports basic research that will: 1) expand knowledge of self-driving vehicles, 2) develop intelligent onboard systems, and 3) get self-driving vehicles on the road in Asia, Europe and the United States. Project Sponsor: 00VDN9 Mines ParisTech Foundation; Funding: $125,260; End Date: March 2019.

One California Deployment Support, PI: Kun Zhou; Description: The objective of this project is to refine the development of CV applications (MMITSS, Real Time Corrections Messages [RTCM]) and then field test them to see what improves traveler safety, mobility, and the productivity of goods movement (through intersections), all while improving California's environment. These applications include intelligent signal control, intelligent signal priority, and connected eco-driving. Project Sponsor: Caltrans 65A0601; Caltrans PM: Asfand Yar Siddiqui; Funding: $450,000; End Date: June 2019.

Inference of Drivers' Intent at Intersections, PI: Pravin Varaiya; Description: This basic research project is developing new algorithms for the safe interaction of pedestrians and automated vehicles at intersections. Project Sponsor: BDD; End Date: June 2019.

Which Intersections Need I2V and When? PI: Alexander Kurzhanskiy; Description: Intersections present a demanding environment for AVs. Challenges arise from interactions among pedestrians, bicycles, and vehicles, complex vehicle trajectories, absence of lane markings to guide vehicles, split phases that prevent determining who has the right of way, invisible vehicle approaches, and illegal movements. The objective of this project is to use a simulation-based toolbox that will perform quantitative evaluation of effectiveness of an I2V system at a given intersection. Project Sponsor: BDD; Funding: $50,000. End Date: June 2019; Final Report: https://deepdrive.berkeley.edu/project/which-intersections-need-i2v-and-when.

Topic 1E: Partial Automation for Truck Platooning, PI: Xiao-Yun Lu; Description: The objective of this program is to implement partial automation in a Class 8 truck in the form of CACC to enable its operation on public highways. The CACC design will be built on the experience from the earlier PATH truck platooning control project and PATH's more recent CACC developments for passenger cars. The program includes development, testing, and a demonstration. Subsequent phases of this program will include expanded testing. Project Sponsor: USDOT Federal Highway Administration & Caltrans 65A0521; Caltrans PM: Matt Hanson; Funding: $2,863,000; End Date: September 2019.

Interactive Simulation of CACC Matching, PI: Xiao Yun Lu; Description: This project will execute new methods for simulating CACC driving through a combination of networked and microscopic traffic simulation. This tool will then be used to facilitate the clustering of CACC equipped vehicles to enable the on-road use of CACC. This initiates a strategic approach for more efficient freight transport in California. Project Sponsor: Caltrans 65A0682; Caltrans PM: Asfand Yar Siddiqui; Funding: $225,000; End Date: December 2019.

Truck Cooperative Adaptive Cruise Control Technical Performance Improvement, PI: Xiao Yun Lu; Description: The objective of this project is to improve the low-speed performance of CACC systems deployed on trucks. This can be done by passing the engine torque and the internal service brake control modules – facilitated by the use of the Society of Automotive Engineers (SAE) J1939 interface. PATH, with Volvo's support, will investigate and implement the new communication protocol and then test the performance of the resulting system. Project Sponsor: Caltrans 65A0733; Caltrans PM: Matt Hanson; Funding: $200,000; End Date: March 2020.

Industry Affiliation: Vehicle-Infrastructure Technology Affiliates Laboratory (VITAL) Membership, PI: Tomizuka; Description: In the current era of ubiquitous connectivity, wireless communication technologies have enabled a kaleidoscopic array of applications that revolutionize many aspects of commercial activities and public services. This revolution, redefining the landscape of user experience and business models, is encroaching into the next frontier - automobiles. The objective of the VITAL lab is to explore the feasibility and benefits of providing safety, mobility, efficiency, and environment-friendly services to users based on the concept of CVs. The exploitation of wireless communication for automobiles, and for transportation, presents exciting opportunities as well as intriguing challenges. Project Sponsor: ITRI; Sandax; Funding: $486,500; End Date: March 2020.

Autonomous Vehicles Industry Survey of Transportation Infrastructure Needs, PI: Ching-Yao Chan; Description: The objective of this project is to prepare for the introduction of fully autonomous vehicles, expected by 2025. Today there are a number of recognized issues that may require new investment in roadway infrastructure to facilitate AV acceptance. This project will initiate a meaningful interchange between the AV industry and government, leading to the identification and priority ranking of roadway modifications for AVs. Project Sponsor: Caltrans 65A0735; Caltrans PM: Asfand Yar Siddiqui; Funding: $100,000; End Date: June 2020.

Streamlining Connected Automated Vehicle (CAV) Test Data Collection and Evaluation in the Hardware-in-the-Loop Environment, PI: Xiao-Yun Lu; Description: The proposed research aims to develop a test tool that integrates into experimental on-vehicle CAV systems that were developed by ITS Berkeley. The tool will provide a user-friendly interface that executes the functions of individual CAVs and establish communication channels for real-time control message interchange. The tool will also capture CAV operational data and store it in a database. Project Sponsor: UCB-ITS SB-1; Funding: $79,901;End Date: June 2020.

Cooperative Adaptive Cruise Control Development and Test of Heavy Duty Truck for Self Driving, PI: Alexandre Bayen; Xiao Yun Lu; Description: Due to its strategic location by connecting three continents, the Kingdom of Saudi Arabia (KSA) is a developing epicenter of trade to the world. Growing trade, increased communications, and connectivity infrastructure is creating an opportunity for automation to accelerate freight and mobility modernization. The objective of this project is to develop and demonstrate two-truck CACC in Saudi Arabia with the first truck driven completely manually in steering control and acceleration/braking control. Project Sponsor: King Abdulaziz City for Science and Technology; Funding: $974,773; End Date: July 2020.

Development of Cooperative Automation Capabilities: Integrated Prototype II, PI: Xiao Yun Lu; Description: The objective of this project is to develop control and communication systems that facilitate cooperative driving. Cooperative driving enables emissions reduction, fuel savings, and safety improvements. Project Sponsor: Leidos; Funding: $235,292; End Date: August 2020.

Maintenance, Operations, and Enhancement of DSRC Communications Infrastructure Phase II, PI: Kun Zhou; Description: The objective of this project is to continually update the dedicated short-range communications (DSRC) hardware and software of the experimental testbed to maintain compliance with evolving federal standards. Project Sponsor: Caltrans 65A0696; Caltrans PM: Asfand Yar Siddiqui; Funding: $139,995; End Date: September 2020.

Experimental Evaluation of Eco-Driving Strategies (LBNL) [Task 7A.3.2], PI: Wei-Bin Zhang; Description: The goal of this project is to analytically and experimentally evaluate the energy-saving benefits (to both the subject vehicle and vehicles following behind) and impacts on efficiency and safety of surrounding traffic. We investigated a broad set of eco-driving strategies in order to fully understand the potential energy-related benefits and impacts of each. Furthermore, we analytically and experimentally quantified the benefits and impacts of intersection Eco-Approach and Departure (EAD) assistant strategies. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $333,393; End Date: September 2020; Final report: page 121 of https://tinyurl.com/y4zbpy58.

Red Light Violation Warning, PI: Kun Zhou; Description: The goal of this project is to compare how two different communications technologies (DSRC and 4G/LTE cellular) are able to support a specific CV application utilizing the California CV Test Bed in Palo Alto. Red Light Violation Warning (RLVW) aims to warn the drivers of the danger of potentially violating an upcoming red signal based on their speed, distance to the signalized intersection, and intersection signal phase and timing (SPaT) information. The California CV Test Bed is compliant with the latest CV standards and is broadcasting SPaT and Map data (MAP) over DSRC. Each test bed intersection has 4G/LTE backhaul for supporting this proposed project by simultaneously streaming SPaT and MAP over 4G/LTE. Project Sponsor: Caltrans 65A0704; Caltrans PM: Asfand Yar Siddiqui; Funding: $120,000; End Date: October 2020.

CACC Development for Passenger Cars with Different Powertrains (LBNL) [Task 7A.3.1 Part II], PI: Xiao-Yun Lu; Description: The work proposed here for DOE Vehicle Technologies Office (VTO) will develop the CACC string with at least three power types: 1) IC engine (gasoline and/or diesel), 2) hybrid electric, and 3) fully electric, which offers many new possibilities. With this CAV string platform, DOE/VTO can conduct extensive R&D and field test for data collection for energy-saving and emission-reduction studies in the long run. The collected data from real-world traffic can be used for calibration of microscopic simulation models for more accurate meso-and-macroscopic-level energy consumption and emission-change evaluation. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $400,000; End Date: December 2020; Final Report: See page 91 of https://tinyurl.com/y4zbpy58.

Smart Mobility – Simulating the traffic impacts of CACC (and similar cooperative automation systems), PI: Xiao-Yun Lu; Description: This project will employ a suite of traffic simulation tools to estimate the impacts to traffic flow and energy consumption resulting from different levels of CAV deployment. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $269,000; End Date: December 2020.

Smart Mobility – Test track experiments to measure the performance and fuel economy of cars using CACC, PI: Xiao Yun Lu; Description: The objective of this project is to perform an experimental verification of fuel consumption reduction (and thus emissions reduction) of light-duty vehicles under CACC control. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $100,000; End Date: December 2020.

Truck CACC operation at signalized intersections [Task 7A.3.1: Part I], PI: Xiao-Yun Lu; Description: Work accomplished under this task includes two aspects related to CACC trucks. First, field test data will be analyzed to quantify performance and performance limits. Second, a simulation environment will be developed from data obtained from an experimental intersection. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $751,000; End Date: December 2020; Final Report: See page 84 of https://tinyurl.com/y4zbpy58.

Enabling Research on Interactions between Traffic & Vehicle Control (micro and roadrunner), PI: Xiao-Yun Lu; Description: This project will analyze vehicle and traffic dynamics under CAV control. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $90,000; End Date: December 2020.

Connected Vehicle Application Development, PI: Kun Zhou; Description: The objective of this program is to physically expand the CAV test bed in Palo Alto (an additional 20 intersections) and to expand its functionality (at each intersection) to include some of the recent USDOTCAV applications. In addition, this project will support the implementation of Smartmicro sensors (deployed in a parallel project) and evaluate their efficacy in expanding intelligent control strategies at low DSRC implementation. Project Sponsor: Caltrans 65A0714; Caltrans PM: Asfand Yar Siddiqui; Funding: $475,000; End Date: January 2021

Collect Data using Connected Vehicle (CV) for Real-Time and Future Use, PI: Kun Zhou; Description: The goal of this research is to address an existing technology gap in the gathering of useful information from CV data for its integration with Transportation Management System (TMS) operations. Specific data that a transportation management plan (TMP) needs include real-time vehicle speed/travel times, origin and destination data, vehicle classification, and vehicle lane position (which lane is the vehicle in). The Basic Safety Message (BSM) and Probe Vehicle Data (PVD) message are most important sources of this data. Project Sponsor: Caltrans 65A0776; Caltrans PM: Asfand Yar Siddiqui; Funding: $100,000; End Date: February 2021.

DMV - Autonomous Vehicle field evaluation, PI: Shladover; Description: The objective of this project is to provide technical assistance to the CDMV in their evaluation of third party field AV field testing on the streets of California. This included the development of a performance data performance framework and data evaluation of the resultant information. Project Sponsor: California DMV; Funding: $750,000; End Date: April 2021.

Caltrans Connected and Automated Vehicle (CAV) Strategic Plan, PI: Ben McKeever; Description: The purpose of this project is to define a vision and tactical strategy Caltrans leadership in preparation for CAV deployment. A number of transformational CAV technologies promise to have a profound impact on traffic operations and safety. At the same time, the research, development, and market penetration of these technologies are accelerating rapidly. Caltrans has a strong interest in preparing for the fast-moving evolution in CAV. Project Sponsor: Caltrans-65A0756; Caltrans PM: Gurpit (Pete) Hansra; Funding: $400,000; End Date: June 2021.

Assessment of Infrastructure Needs for Deployment of Connected Vehicle Technologies, PI: Wei-Bin Zhang; Description: This white paper will assess the current state of development of CV technologies, particularly those that involve cooperation with the infrastructure, and will analyze the gaps, needs and requirements of CV technologies and applications from the perspectives of system level safety, efficiency, reliability and resilience. The study will also provide predictions on the timing of commercially available CV technology and provide recommendations for California infrastructure owners and operators regarding necessary preparation efforts. Project Sponsor: UCB-ITS SB-1; Funding: $25,000; End Date: May 2021.

Smart Mobility: Validate Workflow, PI: Xiao Yun Lu; Description: The SMART Mobility modeling workflow has been developed to evaluate new transportation technologies such as connectivity, automation, sharing, and electrification through multi-level systems analysis that captures the dynamic interactions between technologies. Through integration of multiple models across different levels of fidelity and scale (i.e., individual vehicles to entire metropolitan areas), the workflow yields insights about the influence of new mobility and vehicle technologies at the system level Argonne and LBNL will validate workflow across multiple tools (RoadRunner, AimSum, POLARIS) into one technology (Task 6). Project Sponsor: US DOE Vehicle Technologies Office; Funding: $150,000; End Date: September 2021.

System Impact of Connected and Automated Vehicles: An Application to the I-210 Connected Corridors Pilot, PI: Qijian Gan; Description: Using advanced sensing platforms to proactively monitor safety-critical events of multi-modal road users provides an opportunity to supplement the traditional assessment of the safety performance of these facilities. Sensor perspective can be exploited to alert AVs about the presence of other oncoming modes in advance of their arrival into their detection zones, thus potentially gaining critical time in taking better decisions. Project Sponsor: Caltrans 65A0757; Caltrans PM: Pradeepa Paanirselvam; Funding: $200,000; End Date: December 2021.

CPS: TTP Option: Medium: Collaborative Research: CIRCLES: Congestion Impact Reduction via CAV-in-the-loop Lagrangian Energy Smoothing, PI: Alexandre Bayen; Description: This proposal focuses on the development of mobile traffic control (i.e., using a few vehicles as traffic controllers via connected and automated vehicle (CAV) technology), to (1) improve the energy efficiency of traffic flow; (2) integrate mobile automation with static infrastructure to further optimize energy efficiency. The demonstrated technology will result in energy gains of up to 10% for all vehicles on the road, through automation of less than 5% of the vehicles in the flow. Project Sponsor: NSF; Funding: $4,866,021; End Date: December 2021.

Support Deployment of Real-Time Broadcasts, PI: Kun Zhou; Description: The goal of this project is to provide a one-stop source for the deployment of Real-Time Kinematic (a new GPS positioning technique) broadcasts. These broadcasts have the potential to deliver free lane-level vehicle positioning solution for CV's, therefore improving the effectiveness of CV applications and providing better safety and mobility for all modes of travel. Project Sponsor: Caltrans; Funding: $150,000; End Date: December 2021.

MMITSS Phase III Extension for Additional Enhancements, PI: Kun Zhou; Description: The goal of this Phase III effort is to make deployment readiness enhancements to the MMITSS prototypes that were developed and field tested in Phase II. The readiness enhancements are focused on creating improved and "cleaned up", or mature application code that is hardware agnostic and interoperable or transferable regardless of the hardware vendors or products. Project Sponsor: University of Arizona; Caltrans PM: Asfand Yar Siddiqui; Funding: $304,590; End Date: February 2022.

Utilizing Connected and Automated Vehicles as Floating Sensors for Cooperative Traffic Control and Road Condition Monitoring, PI: Kun Zhou; Description: The long-term objective of this program is to integrate data collected by CAV's with CV data that is communicated via the Basic Service Message – and to use both for intelligent traffic signal control. The first phase of the research on this project will focus on the development of a fused CV-CAV data stream that can be produced and communicated in real-time from a modified CAV. Project Sponsor: Caltrans 65A0783; Caltrans PM: Asfand Yar Siddiqui; Funding: $400,000; End Date: February 2022.

Truck Platooning Early Deployment Assessment - Phase 2 Proposal, PI: Xiao Yun Lu; Description: The objective of this project is to quantify the costs and benefits of truck platooning, their impact on other road users. and quantify policy, operational, and safety impacts. The PATH team will install the previously developed CACC technology on four new Volvo model VNL-64T760 trucks and have Roly's Trucking integrate these trucks into their daily operations along the I-10 corridor between California and Texas. All of the trucks will be driven by Roly's drivers - three in a platoon, and the other one independently - to serve as a control in the experiment. Project Sponsor: FHWA & Caltrans; Caltrans PM: Matt Hanson; Funding: $675,000 - including $375,000 from Caltrans DRISI and $300,000 from USDOT. End Date: January 2023.

Smart Mobility – Truck Platooning, PI: Xiao Yun Lu; Description: This project will investigate drivers' responses when using eco-driving applications. It will study the effects on fuel savings, emission reduction, and the associated safety impacts through a simulated driving experiment involving a local roadway with signalized intersections and freeway stop-and-go traffic. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $725,000; End Date: December 2020.

Truck CACC Platooning Testing, PI: Xiao Yun Lu; Description: The objective of this project is to perform an experimental verification of fuel consumption reduction (and thus emissions reduction) of heavy-duty vehicles (Class 8 trucks) under CACC control. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $300,896.63; End Date: December 2019.

Connected Vehicle Pool Fund Study RFP for Connected Traffic Control System, PI: Kun Zhou; Description: The objective of this project is the development of an application for traffic control at signalized intersections that would be utilized by CAV technologies. Project Sponsor: University of Arizona; Caltrans PM: Asfand Yar Siddiqui; Funding: $400,000; End Date: December 2020.

MMITSS Phase 3, PI: Kun Zhou; Description: Under this UVA contracted (Pool Fund Study award) project, Smartmicro sensors will be installed on three test bed intersections. These sensors emulate DSRC-equipped vehicles that provide input data for MMITSS. This enables intelligent control strategies at low levels of DSRC implementations. Project Sponsor: University of Arizona; Caltrans PM: Asfand Yar Siddiqui; Funding: $310,000; End Date: January 2021.

Traffic Operations: Simulation

General Microsimulation to Meso-simulation (LBNL, ANL), PI: Xiao Yun Lu; Description: This project contains two areas of work: (1) *Micro-to-Meso*: building the link between the micro-simulation and meso-simulation of mixed traffic with manually-driven vehicles and CAVs, and (2) *TNC Simulation*: preliminarily developing a microscopic traffic simulation with TNC vehicles and evaluating their impact on other traffic while picking-up and dropping-off passengers. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $700,000; End Date: December 2020; Final report: See page 289 of https://tinyurl.com/y4orgsar.

Developing Analysis, Modeling, and Simulation (AMS) Tools for Connected and Automated Vehicle (CAV) Applications, PI: Xiao Yun Lu; Alexander Skabardonis; Description: The objective of this program is to develop the tools that will enable the evaluation of CAV traffic impact upon their deployment. CAV deployment will require that transportation agencies quantify which application best addresses their unique transportation problems. It is necessary to adapt and re-engineer the existing set of tools available to agencies, validate these models/tools, and provide a mechanism to share these models/tools with public agencies. Project Sponsor: Leidos; Funding: $193,191; End Date: December 2020.

Traffic Microsimulation of Energy Impacts of CAV Concepts at Various Market Penetrations (LBNL) [Task 7A.1.2.], PI: Xiao-Yun Lu; Description: This project is to develop and apply traffic microsimulation tools to predict the impacts that CAV systems are likely to have on traffic, energy consumption, and emissions reduction. The transportation sector accounts for almost 50 percent of California's total GHG emissions, according to the data from the California Air Resources Board (CARB); while light-duty vehicles make up 70 percent of the sector's GHG emissions. Additionally, approximately 80 percent of the smog in California comes from vehicle emissions. Project Sponsor: US DOE Vehicle Technologies Office; Funding: $681,000; End Date: December 2020; Final report: see Page 60 of http://tinyurl.com/y4orgsar.

Traffic Operations: Greenhouse Gas Reduction

Environmental Impacts of Congestion Management Strategies, PI: Alexander Skabardonis; Description: This project described congestion management strategies, implemented in, or relevant to California – as well as their environmental impacts. The findings are based on a critical literature review and supplemented by interviews with key staff members at agencies that are implementing new strategies. The congestion strategies investigated typically reduce GHG emissions in the range of 5% to 15%. Greater benefits may be achieved when a combination of measures is implemented as currently pursued by the ICM program. Project Sponsor: California Air Resources Board; End Date: December 2019; Funding: $75,000; Final Report: [https://ww3.arb.ca.gov/research/single-project.php?row_id=68590.](https://ww3.arb.ca.gov/research/single-project.php?row_id=68590)

Modal Applications Research

Integrated Dynamic Transit Operations System, IDTO 2, PI: Joshua Meng; Description: Suburban transit agencies face enormous cost challenges due to the large geographic areas they serve. Integrated Dynamic Transit Operation (IDTO) applications are expected to have great potentials to support these agencies by introducing new flexibilities to their operations – facilitating real-time changes to routes, reducing wait times, and facilitating first and last mile shared rides. This project's objectives are to conduct the analysis, planning, and IDTO system development that will enable a completely new operation strategy for suburban transit operations. Project Sponsor: Caltrans-65A0685; Caltrans PM: Nathan N Loebs; Funding: $800,000; End Date: July 2020.

Development and Implementation of Integrated Dynamic Transit Operations System, Phase II+, PI: Joshua Meng; Description: Transit system were established upon the framework of fixed routes, fixed schedules, and almost-fixed ticket prices. To attract travelers from private driving, transit systems need to be flexible and dynamic. Integrated Dynamic Transit Operation (IDTO) applications show great potentials to improve transit service – offering reduced travel time and improved connectivity. This project, an extension of prior Caltrans sponsored work, will test a fully functional IDTO system that delivers improvements to suburban transit services. The IDTO algorithms and user apps are developed to allow holding at bus stops to meet with connecting passengers (Connection Protection or T-CONNECT). Project Sponsor: Caltrans 65A0800; Caltrans PM: Nathan N Loebs; Funding: $400,000; End Date: May 2021.

Monitoring Public Transit COVID-19 Recovery Efforts and Ridership Trends and Assessing Opportunities for Deploying Dynamic Transit Routes, PI: Alexander Kurzhanskiy; Description: Mass transit is in crisis. Recent ridership decline has been seriously exacerbated by COVID-19 and the subsequent shelter-in-place orders. This project will provide a better understanding of the impact of COVID-19 and its recovery on transit. In addition, it will evaluate the tactics used by different transit agencies to mitigate COVID-19 -19 challenges as well as develop approaches to share key information between agencies. Project Sponsor: UCB-ITS SB-1; Funding: $50,000; End Date: June 2021.

AI, Machine Learning and Vision

Model-Independent Automated Driving Strategy Based on Meta-Learning, PI: Ching-Yao Chan; Description: Machine Learning can potentially contribute to the implementation of AV's when applied to object detection, autonomous perception, decision making, trajectory planning, and control strategies. The primary objective of this project is to conduct a study of deep learning for automated driving applications, to serve as a basis for further implementation of machine learning technologies in ADS. Project Sponsor: Denso; Funding: $180,000; End Date: July 2020.

Agent Behavior Understanding in Crowds – Predicting Future Trajectories and Activities, PI: Ching-Yao Chan; Description: The objective of this proposal is to provide an end-to-end, multi-task, machine-learning system utilizing rich visual features about human behavioral information and their interaction with surroundings. A machine-learning network will be trained to predict future activities from its location using large-scale camera data of human interactions. Previous work on crowd-behavior analysis, future forecasting, activity recognition, and unsupervised embedding of camera images will be leveraged. Project Sponsor: UCB-ITS SB-1; Funding: $50,794; End Date: June 2021.

Uncertainty-Aware Reinforcement Learning for Interaction-Intensive Driving Tasks, PI: Pieter Abbeell, Ching-Yao Chan; Description: In daily driving, drivers often need to deal with various types of uncertainties, among which is the critical factor of the intrinsic uncertainty of road users' behaviors. In this project, we propose to develop uncertainty-aware decision-making algorithms for interaction-intensive driving tasks, e.g., performing maneuvers in dense traffic and negotiating with surrounding vehicles with highly variant behaviors. We will exploit and improve current methods to address aleatoric (road user behavior) and epistemic (knowledge gaps) uncertainties. Project Sponsor: UCB-ITS SB-1; Funding: $46,000; End Date: June 2021.

Uncertainty-Aware Meta-Learning and Safe Adaptation, PI: Sergey Levine; Description: Project Sponsor: Berkeley DeepDrive; Funding: $622,000; End Date: June 2020.

Infrastructure Acquisition and Related Research, PI: Ching-Yao Chan; Description: This project creates and manages the shared resources utilized by BDD – primarily the vehicles, data and models. The experimental vehicle platform at BDD includes three vehicles: a 2017 Lincoln MKZ, a 2013 Lincoln MKS, and a 2017 Hyundai Genesis. The vehicles are equipped with cameras, GPS, LiDAR (Light Detection And Ranging), radar, and IMU (inertial measurement unit). The MKZ and Genesis are equipped with drive-by-wire systems and are used as self-driving vehicles. The models include a "global" intention-prediction model which relies on a comprehensive set of factors, such as pedestrian motion dynamics (e.g., position, velocity, head pose), contextual information (e.g., distance to curb), traffic interaction (e.g., relative distance to oncoming traffic), and social awareness (e.g., whether neighboring individuals are crossing). Project Sponsor: BDD; Funding: $2,560,000; End Date: June 2021.

Off-Policy Reinforcement Learning for Learning from Logged Data, PI: Sergey Levine; Description: In this basic research project, we aim to develop a simple and scalable reinforcement learning algorithm that uses standard supervised learning methods as subroutines. Our goal is an algorithm that utilizes only simple and convergent maximum likelihood loss functions, while also being able to leverage off-policy data. Project Sponsor: Berkeley DeepDrive; Funding: $622,000; End Date: June 2020.

3D Object Detection Using Temporal LIDAR Data, PI: Avideh Zakhor; Description: 3D object detection is a fundamental problem in the space of autonomous driving, and pedestrians are some of the most important objects to detect. In this basic research project, we modify PointPillars to become a recurrent network, using fewer LiDAR frames per forward pass. With this modification, we observe an 8% increase in pedestrian detection and a slight decline in performance on vehicle detection in coarse settings. Project Sponsor: Berkeley DeepDrive; Funding: $125,000; End Date: June 2020.

A Comprehensive Trajectory Dataset for Driving on Unstructured Under-Regulated Roads, PI: Alexandre Bayen; Description: In this basic research project we address driving on unstructured, under-regulated roads for autonomous vehicles. A main source of difficulty comes from the uncertainties in surrounding human drivers' behaviors, as it is difficult to predict drivers' trajectories, which is essential for motion planning. This project's goal is to see if there is a dataset of driver behavior that is based on etiquette (not regulation) by recording extensive top-down drone videos of traffic in dense rural/urban areas of China. Project Sponsor: Berkeley DeepDrive; Funding: $62,500; End Date: June 2020.

A Flow Disturbance Estimation and Rejection Strategy Of Multirotor With Round Trip Trajectories, PI: Michael Mueller; Description: In this basic research project, we examine a round-trip strategy of a multirotor with unknown flow disturbances. The method is designed to decrease flight time for return trips while safety is maintained. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

A Programmatic and Semantic Approach to Explaining and Debugging Neural Network Based Object Detectors, PI: Sanjit Seshia; Description: In this basic research we present a programmatic and semantic approach to explaining, understanding, and debugging the correct and incorrect behaviors of a neural network-based perception system. Our approach is semantic in that it employs a high-level representation of the distribution of environment scenarios that the detector is intended to work on. It is programmatic in that the representation is a program in a domain-specific probabilistic programming language using which synthetic data can be generated to train and test the neural network. Project Sponsor: Berkeley DeepDrive; Funding: $75,000; End Date: June 2020.

Adversarial Inverse Reinforcement Learning for Decision Making in Autonomous Driving, PI: Ching-Yao Chan; Description: In this basic research projects, we examine Generative Adversarial Imitation Learning (GAIL) as an efficient way to learn sequential control strategies from demonstration. Adversarial Inverse Reinforcement Learning (AIRL) is similar to GAIL but also learns a reward function at the same time and has better training stability. In previous work, however, AIRL has mostly been demonstrated on robotic control in artificial environments. In this paper, we apply AIRL to a practical and challenging problem – the decision-making in autonomous driving - and also augment AIRL with a semantic reward to improve its performance Project Sponsor: Berkeley DeepDrive; Funding: $50,000; End Date: June 2020.

An End-to-End Visual-Audio Attention Network for Emotion Recognition in User-Generated Videos, PI: Kurt Keutzer; Description: Emotion recognition in user-generated videos plays an important role in human-centered computing. In this basic research project, we propose to recognize video emotions in an end-to-end manner based on convolutional neural networks (CNNs). Specifically, we develop a deep Visual-Audio Attention Network (VAANet), a novel architecture that integrates spatial, channel-wise, and temporal attentions into a visual 3D CNN and temporal attentions into an audio 2D CNN. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

Automated Lane Change Strategy using Proximal Policy Optimization-based Deep Reinforcement Learning, PI: Ching-Yao Chan; Description: Lane-change maneuvers are commonly executed by drivers to follow a certain routing plan, overtake a slower vehicle, adapt to a merging lane ahead, etc. However, improper lane change behaviors can be a major cause of traffic flow disruptions and crashes. In this basic research project, we propose an automated lane change strategy using proximal policy optimization-based deep reinforcement learning, which shows a great advantage in learning efficiency while maintaining stable performance. The trained agent is able to learn a smooth, safe, and efficient driving policy to determine lane-change decisions (i.e., when and how) even in dense traffic scenarios Project Sponsor: Berkeley DeepDrive; Funding: $50,000; End Date: June 2020.

BADGR: An Autonomous Self-Supervised Learning-Based Navigation System, PI: Surgey Levine; Description: In this basic research project, we investigate how to move beyond these purely geometric-based approaches (for AV navigation) using a method that learns about physical navigational affordances from experience. Our approach, which we call BADGR, is an end-to-end learning-based mobile robot navigation system that can be trained with self-supervised off-policy data gathered in real-world environments, without any simulation or human supervision. Project Sponsor: Berkeley DeepDrive; Funding: $125,000; End Date: June 2020.

Combining Deep Learning and Model Predictive Control for Safe, Effective Autonomous Driving, PI: Francesco Borrelli; Trevor Darrell; Description: We present a system-level modeling and control framework which allows investigating different vehicle parking strategies while considering path planning and collision avoidance. The proposed approach decouples the problem into a centralized parking spot allocation, path generation, and a decentralized collision-avoidance control. This paper presents the hierarchical framework, algorithmic details, and extensive simulations. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

Efficient Model for Large-Scale Point Cloud Perception, PI: Masayoshi Tomizuka; Kurt Keutzer; Description: In this basic research project, we investigate multi-source domain adaptation for semantic segmentation. Specifically, we design a novel framework, termed Multi-source Adversarial Domain Aggregation Network (MADAN), which can be trained in an end-to-end manner. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

Efficient Neural Networks Through Systematic Quantization, PI: Kurt Keutzer, Michael Mahoney; Description: In this basic research project, we expand the application of Quantization. We propose a novel Zero-shot Quantization (ZEROQ) framework. ZEROQ allows post-training, mixed-precision quantization without any access to the training data. In particular, we solve an optimization problem to generate input data that minimizes the mismatch between produced statistical moments and the moments from batch normalization layers. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

Few Shot Learning for Point Cloud Data Using Model Agnostic Meta Learning, PI: Avideh Zakhor; Description: Current deep-learning approaches suffer from poor sample efficiency - in stark contrast to human perception. In this basic research project, we extend the MAML algorithm to point cloud data using a PointNet Architecture. We construct N × K-shot classification tasks from the ModelNet40 point cloud dataset to show that this method performs classification as well as supervised deep learning methods with the added benefit of being able to adapt after a single gradient step on a single N × K task. Project Sponsor: Berkeley DeepDrive; Funding: $62,500; End Date: June 2020.

Heavy-Tailed Universality Predicts Trends in Test Accuracies for Very Large Pre-Trained Deep Neural Networks, PI: Michael Mahoney; Description: In this basic research project, we show how to use a new theory of Heavy-Tailed Self-Regularization (HT-SR), showing that the correlations in the layer weight matrices can be fit to a power law with exponents that lie in common Universality classes. Rather than considering small toy NNs, we examine over 50 different large-scale pre-trained DNNs ranging over 15 different architectures and trained on ImagetNet, each of which has been reported to have different test accuracies. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

Human-like Decision Making for Autonomous Driving via Adversarial Inverse Reinforcement Learning, PI: Ching-Yao Chan; Description: To make human-like decisions under a complex driving environment is a challenging task for autonomous agents. In this basic research project, we augment AIRL by concatenating semantic reward terms into the learning framework to improve and stabilize its performance, and then extend it to a more practical but challenging situation, such as a decision-making scenario in a highly interactive driving environment. Project Sponsor: Berkeley DeepDrive; Funding: $50,000; End Date: June 2020;

Improving Adversarial Robustness Through Progressive Hardening, PI: David Wagner; Description: Adversarial training (AT) has become a popular choice for training robust networks. In this basic research project, we propose Adversarial Training with Early Stopping (ATES). The design of ATES is guided by principles from curriculum learning that emphasizes on starting easy and gradually ramping up on the difficulty of training. We do so by stopping the adversarial example generation step early on in AT, progressively increasing difficulty of the samples the network trains on. Project Sponsor: Berkeley DeepDrive; Funding: $60,000; End Date: June 2020.

Inter-Level Cooperation in Hierarchical Reinforcement Learning, PI: Alexandre Bayen; Description: In this basic research project, we develop a novel algorithm for promoting cooperation between internal actors in a goal-conditioned hierarchical reinforcement learning (HRL) policy. Within this setting, we hypothesize that improved cooperation between the internal agents of a hierarchy can simplify the credit assignment problem from the perspective of the high-level policies, thereby leading to significant improvements to training in situations where intricate sets of action primitives must be performed to yield improvements in performance. Project Sponsor: Berkeley DeepDrive; Funding: $43,750; End Date: June 2020.

Learning Representations for Multi-Vehicle Spatiotemporal Interactions with Semi-Stochastic Potential Fields, PI: Ching-Yao Chan; Description: Reliable representation of multi-vehicle interactions in urban traffic is pivotal but challenging for AV's due to the volatility of the traffic environment, such as roundabouts and intersections. This basic research project describes a semi- stochastic potential field approach to represent multi-vehicle interactions by integrating a deterministic field approach with a stochastic one. Project Sponsor: Berkeley DeepDrive; Funding: $50,000; End Date: June 2020.

MADAN: Multi-source Adversarial Domain Aggregation Network for Domain Adaptation, PI: Kurt Keutzer; Description: Domain adaptation aims to learn a transferable model to bridge the domain shift between one labeled source domain and another sparsely-labeled or unlabeled target domain. In this basic research project, we propose a novel multi-source domain adaptation (MDA) framework to design an end-to-end Multi-source Adversarial Domain Aggregation Network (MADAN). Project Sponsor: Berkeley DeepDrive; Funding: $258,000; End Date: June 2020.

Minimum-Norm Adversarial Examples on KNN and KNN-Based Models, PI: David Wagner; Description: In this basic research project, we study the robustness against adversarial examples of k-nearest neighbors (kNN) classifiers and classifiers that combine kNN with neural networks. The main difficulty lies in finding an optimal attack on kNN that is intractable for typical datasets. In this work, we propose a gradient-based attack on kNN and kNN-based defenses. Project Sponsor: Berkeley DeepDrive; Funding: $62,500; End Date: June 2020.

Multi-source Distilling Domain Adaptation, PI: Kurt Keutzer; Description: Deep neural networks suffer from performance decay when there is domain shift between the labeled source domain and the unlabeled target domain. In this project, we propose a novel multi-source distilling domain adaptation

(MDDA) network, which not only considers the different distances among multiple sources and the target, but also investigates the different similarities of the source samples to the target ones. Project Sponsor: Berkeley DeepDrive; Funding: $258,000; End Date: June 2020.

Multi-source Domain Adaptation in the Deep Learning Era: A Systematic Survey, PI: Kurt Keutzer; Description: In many practical applications, it is often difficult and expensive to obtain enough large-scale labeled data to train deep neural networks to their full capability. In this survey, we define various MDA strategies and summarize available datasets for evaluation. We also compare modern MDA methods in the deep learning era, including latent space transformation and intermediate domain generation. Finally, we discuss future research directions for MDA. Project Sponsor: Berkeley DeepDrive; Funding: $258,000; End Date: June 2020.

Orthogonal Convolutional Neural Networks, PI: Stella Yu; Description: In this basic research project, we examine the instability and feature redundancy in CNNs, which hinders their further performance improvement. Using orthogonality as a regularizer has shown success in alleviating these issues. Previous works only considered the kernel orthogonality in the convolution layers of CNNs, which is a necessary but not sufficient condition for orthogonal convolutions in general. We propose orthogonal convolutions as regularizations in CNNs and benchmark its effect on various tasks. Project Sponsor: Berkeley DeepDrive; Funding: $31,250; End Date: June 2020.

ParkPredict: Motion and Intent Prediction of Vehicles in Parking Lots, PI: Francesco Borrelli; Description: Despite the rapid advancement in autonomous driving technologies, there remain many challenges due to the uncertainty in behaviors of neighboring human drivers. In this basic research project, we investigate the problem of predicting driver behavior in parking lots - a domain which is less structured than typical road networks and features complex, interactive maneuvers in a compact space. Using the CARLA simulator, we develop a parking lot environment and collect a dataset of human demonstrations. Project Sponsor: Berkeley DeepDrive; Funding: $125,000; End Date: June 2020.

Point Cloud Segmentation Using RGB Drone Imagery, PI: Avideh Zakhor; Description: In recent years, the ubiquity of drones equipped with RGB (red, green, and blue light band) cameras has made aerial 3D model generation significantly more cost effective than traditional aerial LiDAR-based methods. Most existing aerial 3D point cloud segmentation approaches use geometric methods and are tailored to 3D LiDAR data. In this basic research project, we propose a pipeline for semantic segmentation of 3D point clouds obtained via photogrammetry from aerial RGB camera images. Our basic approach is to directly apply deep learning segmentation methods to the very RGB images used to create the point cloud itself, followed by back projecting the pixel class in segmented images onto the 3D points. Project Sponsor: Berkeley DeepDrive; Funding: $100,000; End Date: June 2020.

Principled Defenses Against Adversarial Attacks on Deep Learning, PI: Dawn Song; Description: In this basic research project, we propose REFIT, a unified watermark removal framework based on fine-tuning, which does not rely on the knowledge of the watermarks and even the watermarking schemes. Firstly, we demonstrate that by properly designing the learning rate schedule for fine-tuning, an adversary is always able to remove the watermarks. Furthermore, we will conduct a comprehensive study of a realistic attack scenario where the adversary has limited training data. Project Sponsor: Berkeley DeepDrive; Funding: $147,500; End Date: June 2020.

PyHessian: Neural Networks Through the Lens of the Hessian, PI: Michael Mahoney; Description: In this basic research project, we perform an extensive analysis of conventional neural-network training architectures by directly measuring the Hessian spectrum. In particular, we compute the top eigenvalue, trace, and full Hessian eigenvalue density throughout training. This analysis leads to fine-scale insight, suggesting that in some cases conventional wisdom is validated, but in other cases we demonstrate that the opposite is true. Project Sponsor: Berkeley DeepDrive; End Date: June 2020.

Quadratic Q-network for Learning Continuous Control for Autonomous Vehicles, PI: Ching-Yao Chan; Description: In this basic research project, we propose a hybrid model by combining Q-learning with the classic Proportion Integration Differentiation (PID) controller for handling continuous vehicle control problems under a dynamic driving environment. Project Sponsor: Berkeley DeepDrive; Funding: $50,000; End Date: June 2020.

REACH: Reducing False Negatives in Robot Grasp Planning with a Robust Efficient Area Contact Hypothesis Model, PI: Ken Goldberg; Description: In this basic research project, we examine the use of the REACH (Robust Efficient Area Contact Hypothesis) model in robotics. The REACH model computes the contact profile using constructive solid geometry intersection and barycentric integration, and then estimates the contact's ability to resist external wrenches (e.g., gravity) under perturbations in object pose and material properties. Project Sponsor: Berkeley DeepDrive; Funding: $193,750; End Date: June 2020.

Real World Traffic Smoothing Demonstration with Deep-RL Trained CAVs, PI: Alexandre Bayen; Description: In this basic research project, we successfully trained a set of two autonomous vehicles to lead a fleet of vehicles onto a round-about and then transferred this policy from simulation to a scaled city without fine-tuning. We used Flow, a library for deep reinforcement learning in micro simulators, to train two policies, (1) a policy with noise injected into the state and action space and (2) a policy without any injected noise. In simulation, the autonomous vehicles learned an emergent metering behavior for both policies which allowed smooth merging. Project Sponsor: Berkeley DeepDrive; Funding: $62,500; End Date: June 2020.

Rectangular Pyramid Partitioning using Integrated Depth Sensors (RAPPIDS): A Fast Planner for Multi-copter Navigation, PI: M. Mueller; Description: In this basic research project, we present a novel multi-copter trajectory planning algorithm (RAPPIDS) that is capable of quickly finding local collision-free trajectories given a single depth image from an onboard camera. The algorithm leverages a new pyramid-based spatial partitioning method that enables rapid collision detection between candidate trajectories and the environment. Project Sponsor: Berkeley DeepDrive; Funding: $125,000; End Date: June 2020.

Regularization Matters in Policy Optimization, PI: Trevor Darrell; Description: Conventional regularization techniques in training neural networks have been largely ignored in RL methods. In this basic research project, we present the first comprehensive study of regularization techniques with multiple policy optimization algorithms on continuous control tasks. Project Sponsor: Berkeley DeepDrive; Funding: $125,000; End Date: June 2020.

Safe and Near-Optimal Policy Learning for Model Predictive Control using Primal-Dual Neural Networks, PI: Francesco Borrelli; Description: In this basic research project we propose a novel framework for approximating the explicit Model Predictive Control (MPC) law for linear parameter-varying systems using supervised learning. In contrast to most existing approaches, we not only learn the control policy, but also a "certificate policy" that allows us to estimate the sub-optimality of the learned control policy online during execution time. We learn both these policies from data using supervised learning techniques, and also provide a randomized method that allows us to guarantee the quality of each learned policy measured in terms of feasibility and optimality. Project Sponsor: Berkeley DeepDrive; Funding: $250,000; End Date: June 2020.

Superposition of many models into one, PI: Bruno Olshausen; Description: In this basic research project, we present a method for storing multiple models within a single set of parameters. Models can coexist in superposition and still be retrieved individually. In experiments with neural networks, we show that a surprisingly large number of models can be effectively stored within a single parameter instance. Furthermore, each of these models can undergo thousands of training steps without significantly interfering with other models within the superposition. Project Sponsor: Berkeley DeepDrive; Funding: $187500; End Date: June 2020.

Systematic Study of Neural Network Robustness Against Adversarial Attacks, PI: Kurt Keutzer; Joseph Gonzalez; Michael Mahoney; Description: In this basic research project we examine the non-robustness of trained neural network models. We show that one can easily generate synthetic datasets, process natural datasets, or change the training procedures. We present a taxonomy on adversarial examples, and we show that they can arise due to non-robust features and for other different reasons. Project Sponsor: Berkeley DeepDrive; Funding: $125,000; End Date: June 2020.

Training Data Augmentation for Autonomous Driving, PI: Kurt Keutzer; Description: In this basic research project, we examine the application of new algorithms for use in LiDAR, an essential and widely adopted sensor for autonomous vehicles. To reduce the data-intensive nature of current applications, we propose LATTE, an open-sourced annotation tool for LiDAR point clouds. LATTE features several innovations (sensor fusion, one-click annotation, tracking). Project Sponsor: Berkeley DeepDrive; Funding: $93,750; End Date: June 2020.

Trust Region Based Adversarial Attack on Neural Networks, PI: Michael Mahoney; Description: In this basic research project, we present a new family of trust region based adversarial attacks, with the goal of computing adversarial perturbations efficiently. We propose several attacks based on variants of the trust region optimization method. We test the proposed methods on Cifar-10 and ImageNet datasets using several different models including AlexNet, ResNet-50, VGG-16, and DenseNet-121 models. Project Sponsor: Berkeley DeepDrive; Funding: $341,250; End Date: June 2020.

Tuning Algorithms and Generators for Efficient Edge Inference, PI: Vladimir Stojanovic; Description: In this basic research project, we address edge-computing complexities in Deep Neural Networks by creating a cross-layer software/hardware design framework that encompasses network training and model compression that is aware of and tuned to the underlying hardware architecture. Project Sponsor: Berkeley DeepDrive; Funding: $406,000; End Date: June 2020.

Unified Neural Architecture Search Framework for Computer Vision, PI: Kurt Keutzer; Description: In this basic research project, we study the fine-grained regression problem of visual emotions based on CNNs. Specifically, we develop a Polarity-consistent Deep Attention Network (PDANet), a novel network architecture that integrates attention into a CNN with an emotion polarity constraint. Project Sponsor: Berkeley DeepDrive; Funding: $93,750; End Date: June 2020.

Human Factors Research

Information Display Board for Corridor Management in California, PI: Ching-Yao Chan; Description: The primary goal of this project is to develop the data and findings required for FHWA evaluation of a new Information Display Board. To facilitate the evaluation, the project will assess the comprehensibility, legibility, and effectiveness of each of the text and graphical messages designs for drivers' perception and experience. Project Sponsor: Caltrans 65A0637; Caltrans PM: Asfand Yar Siddiqui; Funding: $449,958; End Date: June 2020.

Safety Effect of Yellow Alert CMS, PI: Ching-Yao Chan; Description: California PATH, on behalf of Caltrans, conducted an independent research project using human-factors approaches in order to identify and evaluate the safety effects of the Yellow Alert CMS (changeable message sign). Project Sponsor: Caltrans-65A0683; Caltrans PM: Asfand Yar Siddiqui; Funding: $302,978; End Date: February 2020.

Assessing Drivers' Responses to Eco-driving Applications, PI: Peggy Wang; Description: Eco-driving applications are designed to change a person's driving behavior by providing real-time, vehicle-specific information and advice such as to accelerate slowly and to reduce speed (to optimize vehicle speed, reduce fuel consumption, and reduce emissions). It is not known how effective real time information will be under dynamic traffic conditions. This project will investigate drivers' responses when using eco-driving applications, the effects on fuel savings and emission reduction, and the associated safety impacts through a simulated driving experiment involving a local roadway with signalized intersections and freeway stop-and-go traffic. Project Sponsor: UCB-ITS SB-1; Funding: $70,254; End Date: June 2021.

Safety-Critical Requirements of External Communication for Automated Vehicle-Pedestrian Interactions, PI: Peggy Wang; Description: In this project, we will explore the interaction between highly automated vehicles and pedestrians. This project has the following objectives: identify safety critical scenarios of vehicle-pedestrian interaction, develop a prototype AV communication system for pedestrians, and experimentally evaluate the efficacy of the proposed AV communication systems. Project Sponsor: UCB-ITS SB-1; Funding: $80,000; End Date: June 2019; Final Report: https://escholarship.org/uc/item/82n7043g.

User Acceptance and Public Policy Implications for Deployment of Automated Driving Systems, PI: Ching-Yao Chan; Description: The objective of this project is to understand public perception of ADS and to develop acceptance models that can help understand users' intentions to use fully automated driving system, in all its forms. Findings from this study show that safety, vehicle control and compatibility, and trust are the three most critical factors that have influence on users' acceptance of the fully automated driving systems. Project Sponsor: UCB-ITS SB-1; Funding: $75000; End Date: August 2018; Final Report: https://escholarship.org/uc/item/5570537f.

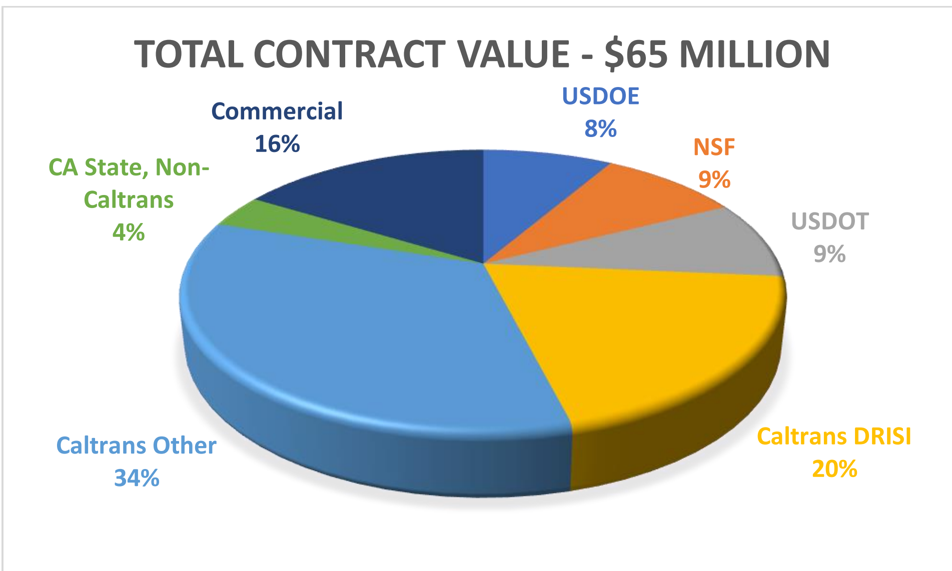
The BDD projects listed above are only a sample of the total projects undertaken; more information about this research can be found at: https://deepdrive.berkeley.edu/

Financial Data for 2018/19 and 2019/20

The backbone of the California PATH program is the support provided by Caltrans. California is the most populous state and the state with the largest highway network in the nation. It is strategically positioned for freight transport from Asia. California also leads the nation in its innovative thinking and innovative actions. As a result, California's transportation research priorities are on the leading edge and others seek out our experience and involvement. This places California PATH in a position to leverage our experience and Caltrans involvement in other national research efforts.

Total Contract Value

The total value of the contracts being executed by California PATH, from June 2018 to June 2020, is approximately $65 million. This exceeds the cumulative annual expenses (which were $16.4 million for FY 2019 and $16.9 million for FY 2020). Most contracts have a performance period that begin before - or end - after the current two-year period of interest. The contract value, however, illustrates the sources of funding, and their relative proportions.



Caltrans Division of Research and Innovation

During the 2019 and 2020 fiscal years Caltrans DRISI sponsored about 34 different projects and the contract value of these projects was about $12.8 million.

Caltrans, Other

PATH is also engaged by other Caltrans divisions, principally Traffic Operations. During the 2019 and 2020 fiscal years the contract value of these nine projects (mostly the Connected Corridor Program) was about $22.2 million.

US Department of Transportation

During the 2019 and 2020 fiscal years the USDOT sponsored 2 separate projects at California PATH. These projects focused on truck platooning and the contract value was $5.8 million.

National Science Foundation

During the 2019 and 2020 fiscal years the NSF sponsored two projects at PATH, with a contract value of $5.9 million.

US Department of Energy

During the 2019 and 2020 fiscal years the DOE sponsored 12 projects, with a contract value of $5.4 million.

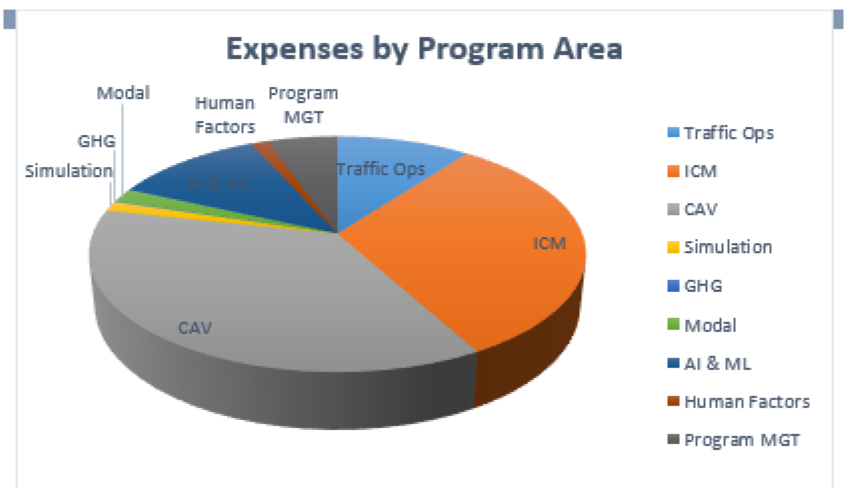
Commercial Sponsors

The Berkeley DeepDrive program is completely sponsored by commercial firms. During the 2019 and 2020 fiscal years the combined sponsorship of these firms was $7.5 Million. In addition, PATH also received another $3.1 million from other commercial sponsors. The total support from commercial firms was $10.6 million during the 2019 and 2020 fiscal years.

California State Funding

The final category of research sponsorship non-Caltrans state funding. The principal source of this funding is the SB-1 Highway bill. This program is administrated by UC Berkeley ITS, in collaboration with the CA State legislature (Transportation Committee). Projects are identified in collaboration with this committee annually. During the 2019 and 2020 fiscal years PATH executed 19 projects that were supported by SB-1.

Expenses by PATH Program Area



Program Management

During fiscal years 2018/9 and 2019/20 the overall program expenses for PATH were about $40 Million. Management expenses of the PATH program, during this same period, were $3,518,494. One important goal is to attract non-DRISI support for research that targets solving California's transportation challenges. During this period 80% of program expenses (of about $40 Million) was from non-DRISI sources.

Artificial intelligence, Machine Learning and Visions Systems (Berkeley Deep Drive)

This basic research program had expenses of $7,570,000 during the 2018/9 and 2019/20 fiscal years. It was entirely supported by commercial sources of funding.

Human Factors Research

PATH executed several research projects in the Human Factors category, the expenses of these projects were about $860,000.

Modal Applications Research

PATH executed several large projects in this program area, for total expenses of $1,250,000.

Traffic Operations: Greenhouse Gas Reduction

This topic area emerged with a scoping study sponsored by the California Air Resources Board, in the amount of $75,000. We expect that interest in this area will grow as connectivity and automation can make a significant impact on emissions reduction. Further, by CARB's own analysis, California is not on target to attain state mandated emission reductions by 2050. So, additional strategies are necessary.

Traffic Operations: Simulation

Simulation is an important component of the PATH research program. We executed a variety of projects for multiple sponsors. Total expenses for these projects were $893,191 during fiscal years 2018/9 and 2019/20.

Traffic Operations: Connected and Automated Vehicles

Research into connectivity and automation as it applies to vehicles, highways, and arterials is the largest single component of the PATH Program. Total expenses for these projects were $23,821,963 during fiscal years 2018/9 and 2019/20.

Traffic Operations: Integrated Corridor Management and Connected Corridors

Research in this discipline represents large-scale, technology-enabled collaborative improvement in highway capacity management, particularly during incidents. PATH expenses were $20,736,075 during fiscal years 2018/9 and 2019/20. An additional $20 million was expended for infrastructure by our partners during this same period.

Traffic Operations Research

A large number of projects in different disciplines were executed to produce near-term improvement in highway operations, such as through improved ramp metering. Total expenses for these projects were $6,712,152 during fiscal years 2018/9 and 2019/20.

PATH Publications- Reports and Presentations - 2018-2020

PATH Reports and presentation may be accessed through the PATH website - https://path.berkeley.edu/publications/research

Reports

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