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California Energy Commission
Clean Transportation Program

FINAL PROJECT REPORT

The Port of Los Angeles Advanced Yard Tractor Deployment and Eco-Drive Freight Advanced Traveler Information System Drayage Truck Efficiency Project

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance, and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued Grant Funding Opportunity GFO-15-604 to demonstrate freight transportation projects for medium- and heavy-duty vehicle technologies, demonstrate intelligent transportation systems and technologies, and deploy natural gas vehicles. In response to GFO-15-604, the recipient submitted an application which the CEC proposed for funding in its notice of proposed awards dated May 19, 2016, and the agreement was executed as ARV-15-069 on January 30, 2017.

ABSTRACT

The Port of Los Angeles Advanced Yard Tractor Deployment and Eco-Drive Freight Advanced Traveler Information System Drayage Truck Efficiency Project consists of the demonstration of advanced heavy-duty cargo handling equipment technologies and the demonstration of intelligent transportation systems and technologies to reduce freight-induced environmental impacts while improving mobility and congestion in and around the Port of Los Angeles. Everport Terminal Services demonstrated 20 liquified natural gas-fueled and five battery-electric yard tractors. The Eco-Drive and Freight Advanced Traveler Information System integrated two mature and proven technologies for the intelligent transportation systems demonstration.

Keywords: California Energy Commission, Port of Los Angeles, liquid natural gas, renewable natural gas, battery-electric, intelligent transportation systems, petroleum displacement, greenhouse gas, emission reduction, drayage truck, yard tractor, Freight Advanced Traveler Information System, FRATIS, optimization, turn time, fuel consumption, connected vehicle, eco-driving, traffic signal, zero-emission, medium- and heavy-duty

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EXECUTIVE SUMMARY

The Port of Los Angeles' "Advanced Yard Tractor Deployment and Eco-Drive Freight Advanced Traveler Information System Drayage Truck Efficiency Project" demonstrated two types of advanced technology yard tractors together under the same duty cycles in a rigorous port container terminal setting and tested innovative intelligent transportation systems technologies for this project.

Everport Terminals, Inc., a Port of Los Angeles container terminal operator, tested and evaluated 20 renewable natural gas-fueled yard tractors certified to the optional standard of 0.02 grams per brake horsepower-hour oxides of nitrogen and five zero-emission, battery-electric yard tractors. Capacity Trucks designed and built the renewable liquified natural gas units, with support from Cummins Westport (the engine supplier) and Agility Fuels (the fuel tank system integrator), with fueling support from Clean Energy Fuels. BYD Motors, Inc. designed and built the battery-electric yard tractors and also supplied the charging equipment to support the demonstration units.

The renewable natural gas fleet achieved significant reductions in key criteria, toxic and greenhouse gas pollutants. The zero-emission fleet achieved a 100 percent reduction in all tailpipe emissions. These emission reductions provided a direct benefit to the local disadvantaged communities surrounding the Port of Los Angeles. Key findings include (1) the importance of designing fueling infrastructure to meet local permitting requirements, (2) advanced technology equipment operation should mimic as much as possible existing operations, and (3) the rigorous nature of the Port operating environment should not be underestimated.

The Eco-Drive Freight Advanced Traveler Information System Drayage Truck Efficiency Project is the other major effort undertaken by this project. In this effort, the project team integrated proven technologies designed to reduce traffic congestion, fuel consumption and emissions by improving the efficiencies of logistics, cargo movements, and driver behavior. The project was designed to improve mobility in and to and from the Ports of Los Angeles and Long Beach via reduced: truck trips, truck-miles travelled, truck-hours travelled, truck idling, which all thus reduces emissions and fuel consumption. Most of the emission reductions would occur in state designated Disadvantaged Communities and Low Income Communities, and the state's highest ranked communities in the California Communities Environmental Health Screening Tool, CalEnviroScreen 3.0. The project consisted of two components—Freight Advanced Traveler Information System and Eco-Drive—that individually as well as collectively attained the aforementioned performance measures. Productivity Apex, Inc. and Infomagnus performed the Freight Advanced Traveler Information System component of the project, while the University of California at Riverside under the guidance of and with the support from the Port of Los Angeles, conducted the Eco-Drive portion of the project. The technologies in both project components were successfully developed, demonstrated, and evaluated, showing the readiness of the technologies for broader market adoption.

The Freight Advanced Traveler Information System tool utilized a sophisticated optimization algorithm that incorporates such factors as time windows, traffic information, customer appointment systems, etc. associated with drayage moves. The system enabled coordination

of moves between parties to maximize loaded container drayage moves and minimize unproductive moves. In this project, Freight Advanced Traveler Information System integrated real-time truck travel time and terminal turn time from the GeoStamp platform in the planning of trucking company daily orders' execution sequence for each truck/driver. In evaluation of 243 days of operational data generated by the participating drayage company, use of the Freight Advanced Traveler Information System tool yielded an 11.6 percent reduction in daily miles-traveled and an increase of 11.5 percent in productivity. Additionally, the use of optimization technology demonstrated a potential reduction of greenhouse gas emissions of up to 11.6 percent and a potential reduction of over 4.51 metric-tons of non-greenhouse gas emissions. In addition, the analysis yielded a decrease of up to 418 gallons of fuel use per year, per truck.

The Eco-Drive system used real-time traffic signal phase and timing data, enabled by connected vehicle technology, along with the information about the equipped truck and traffic conditions, to determine the optimal speed profiles for the driver to follow. The results from a real-world performance evaluation on two corridors near the Port of Los Angeles showed that driving with Eco-Drive resulted in less fuel consumption and greenhouse gas emissions than driving without it by six percent to 15 percent. On one of the connected corridors, driving with Eco-Drive also resulted in 29 percent to 32 percent fewer number of stops at signalized intersections, which helped reduce the overall travel time by seven percent to 11 percent. As an unexpected co-benefit, the Eco-Drive also helped the truck driver better comply with the speed limit of the road, which could improve safety for all motorists. As a portable system with only a tablet and an optional camera-based range sensor onboard, Eco-Drive can be easily adapted for use in other vehicle platforms such as passenger cars and transit buses.

Overall, this project combined technologies that directly reduced emissions at the tailpipe with efficiency improvement strategies to provide an overall benefit to the Port of Los Angeles operators and adjacent communities.

CHAPTER 1:
Purpose and Approach

1.1 Purpose of the Project

The Port of Los Angeles (POLA, port) "Advanced Yard Tractor Deployment and Eco-Freight Advanced Traveler Information System Drayage Truck Efficiency Project" was developed to address the high greenhouse gas (GHG) and criteria and toxic pollutant emissions from off- and on-road vehicles that operate in and around the Port of Los Angeles (POLA). In addition to the use of conventional diesel-fueled internal combustion engines in the heavy-duty equipment that move goods, the increasing volume of goods moving through the port, the emergence of larger ships, and the evolving supply chain management practices of end-customers have increased the demands and pressure placed on the port complex. Congestion has a significant negative impact on the local and the broader economy, as it leads to lost revenue for the companies importing or exporting goods and increased shipping costs to offset the inefficiencies. Local communities suffer as commuter traffic conditions are negatively impacted by freight congestion, air quality is degraded by emissions from idling vehicles or those equipped with conventional propulsion systems, and safety is compromised by increasingly congested roads. Port equipment and vehicles operate adjacent to disadvantaged communities that experience a majority of the adverse environmental impacts from port operations. A secondary problem addressed by this project is the large amount of petroleum fuel consumption required to operate port-related vehicles region wide. The proposed project addressed these problems by utilizing a suite of advanced technologies that eliminates or significantly reduces petroleum consumption and exhaust emissions. These technologies included:

- Integration of engines certified to the optional standard of 0.02 grams per brake horsepower-hour (g/bhp-hr) oxides of nitrogen (NOx) fueled by renewable liquefied natural gas (RNG), demonstrated for the first time in an off-road yard tractor manufactured by Capacity Trucks.
- Zero-emission battery-electric yard tractors from BYD Motors (BYD), a new manufacturer of zero-emission equipment in this market.
- An intelligent transportation systems (ITS) project that involves the integration of two established systems that will lead to an enhanced, efficient flow of freight through well-organized planning by stakeholders.

1.1.1 Project Goals

The goal of this project was to enhance market acceptance of advanced vehicle and information technology in yard tractor and drayage truck applications by successfully demonstrating two advanced vehicle technologies (renewable liquefied natural gas (LNG) and battery-electric yard tractors) and two newly integrated ITS technology suites, freight advanced traveler information system (FRATIS), and Eco-Drive. These technologies were used in equipment and vehicles that transport freight in and around POLA. A comprehensive one-year demonstration was conducted to collect and analyze real-world operating data to assess the effectiveness of these technologies in freight transportation applications. These data were used to assess project benefits including GHG and criteria pollutant emission reductions, reduced petroleum fuel use, and improvements in mobility and congestion in and around POLA and Port of Long Beach (POLB), providing a direct benefit to the local disadvantaged communities surrounding the port.

1.1.2 Project Objectives

The objectives of this Agreement were to support accelerated market acceptance of near zero-emission, zero-emission and ITS technology while achieving measurable reductions in port equipment and diesel fuel consumption and emissions in accordance with the broader objectives of the Clean Transportation Program. Specific measurable objectives include demonstration of:

- Design and build 20 low-NOx (near-zero) emission and 5 zero-emission yard tractors for field demonstration in order to verify operational performance and to collect in-use operation data.
- Design and build RNG fueling and electric charging infrastructure to support the daily fuel needs of the yard tractor demonstration units.
- Document significant reduction in GHG and criteria pollutant emissions compared with conventional diesel yard tractors performing similar terminal work.
- Document energy costs and the reduction in petroleum fuel consumption, compared to cost and fuel used in comparable diesel yard tractors in operation at the terminal.
- Document the displacement of petroleum diesel fuel, measured as the amount of diesel gallons saved as a result of the ITS technology suite utilization.
- Deployment of an integrated ITS system to reduce fuel consumption by trucks, reduce freight related emissions, increase driver productivity defined as number of orders per truck, reduce unproductive (bobtail) travel time, and decrease waiting time at marine terminals.

1.2 Project Approach

POLA assembled a strong team for the 12-month demonstration project. POLA’s approach to team with original equipment manufacturers (OEMs) for this project facilitated OEM experience with new near-zero and zero-emission platforms to support the long-term viability of these designs as production equipment in the commercial market.

For the ITS project, POLA teamed with providers of mature ITS systems to combine commercial packages into an integrated suite of tools to improve freight operations around POLA.

1.2.1 Advanced Yard Tractor Demonstration

The project team demonstrated 25 OEM advanced technology yard tractors, a first for POLA. For the 20 RNG yard tractors, Capacity Trucks teamed with Cummins Westport and Agility Fuels to integrate the certified low-NOx LNG engines into their commercial diesel fueled yard tractor. Clean Energy Fuels provided the RNG fueling infrastructure for the Capacity units. For the battery-electric yard tractors, Everport Terminals Inc. (Everport) teamed with BYD for the demonstration of five first-generation battery-electric yard tractors. Capacity and BYD worked with Everport toward demonstration unit designs that would meet terminal operational requirements. The electric vehicle supply equipment (EVSE) to charge the yard tractors was also designed and built by BYD.

1.2.2 ITS Demonstration

For this innovative project, the Freight Advanced Traveler Information System (FRATIS) team integrated intelligent transportation systems technologies to improve goods mobility in and out of the Ports of Los Angeles and Long Beach. The project components included the FRATIS and Eco-Drive systems, supported by the real-time truck travel time and terminal turn time from the GeoStamp platform, which plans the trucking company daily orders' execution sequence for each truck.

1.3 Project Tasks

Overall, the project was organized into four key tasks: project administration; design, build and commission the yard tractors (including fueling infrastructure); plan, design, integrate and commission the ITS systems; and implementation of the 12-month demonstration with associated data collection and analysis. Below is an overview of each task.

1.3.1 Task 1: Project Administration

Task 1 encompassed Project Administration. During implementation of this project, POLA executed subrecipient agreements and coordinated progress meetings and reports with the project team. This included periodic tele-meetings (weekly or monthly as needed), monthly progress reports to CEC, two Critical Project Review (CPR) reports and meetings and development of this Final Report. The first CPR was held on August 24, 2017, with a focus on the ITS project scope, and the second CPR was held on October 31, 2018, with a focus on the advanced yard tractor scope. The Commission Agreement Manager (CAM) approved the project to proceed upon completion of each CPR. POLA's project manager also worked with the project team to monitor the project schedule and ensure that the Schedule of Products and Due Dates was maintained or updated/reviewed with the CAM, as necessary. Project deliverables such as approved permits, design specifications, and reports were managed under this administration task. An important element of the administration task was also to manage project invoicing and payments and document match funding commitments.

1.3.2 Task 2: Design, Build and Commission Yard Tractors

Under Task 2, the project team planned, designed, built and commissioned 20 low-NOx emission yard tractors and 5 first-generation battery-electric zero-emission yard tractors for demonstration at Everport. Specifically, this task encompassed the following key activities:

- Review equipment build specifications and functional requirements.
- Determine location for RNG equipment fueler and chargers.
- Finalize engineering bill of materials and order components for each vehicle.
- Design, fabricate, and build vehicles, components, systems, and subsystems.
- Provide skid-mounted mobile natural gas tank to refuel vehicles.
- Conduct tests, certifications, quality checks, and validations for vehicle components, systems, subsystems, and safety elements.
- Conduct drivability testing, visual quality assurance, final road test, and pre-delivery test.
- Obtain sign-off authorization to release trucks, commission the demonstration vehicles, and deliver vehicles to the demonstrator.

Capacity and BYD designed and built their respective demonstration units and delivered the project equipment to Everport in accordance with Task 2. Each of the RNG units have identical design specifications and functional capabilities. Similarly, the five battery-electric yard tractors also have identical design specifications and functional capabilities.

1.3.3 Task 3: Plan, Design, Integrate and Commission ITS

Under Task 3, the project team planned, designed and integrated the FRATIS, Eco-Drive and GeoStamp suite of ITS applications. Specifically, this task encompassed the following key activities:

- Identify, plan, map processes and protocols, and secure participants for demonstration, provide a list of participants, and identify the number of trucks participating by company.
- Customize and integrate the FRATIS application, and design and integrate FRATIS back-office application, subsystems, software, hardware, communication technologies, and infrastructure.
- Test and validate the FRATIS application.
- Identify and list each demonstration site and the list of equipment upgrades needed at each site.
- Upgrade traffic signal controllers at the demonstration sites and create a place for receiving, storing, and disseminating traffic signal phase and timing information.
- Design, develop, test, validate and integrate the Eco-Drive application and GeoStamp engine.
- Provide a technical memorandum on:
    - Traffic signal controller upgrade, traffic signal phase and timing information.
    - Eco-Drive algorithms, application design, software architecture, testing of the Eco-Drive mobile application, and test results.
    - GeoStamp information on integration solution, integration platform for applications, security system to process requests, and turn time data.
- Procure 70 Android tablets, cellular service, and truck navigation with traffic service for truck deployment and install the driver mobile application and all the other supporting applications.

1.3.4 Task 4: Demonstration, Data Collection and Analysis

Task 4 was the heart of the project: to collect operational data for a 12-month demonstration and use these data to assess the environmental and economic impacts of the technology demonstrations. Key metrics were collected in order to assess throughput, usage, and operations data for the project equipment during the 12-month demonstration period.

For the Advanced Yard Tractor Demonstration, hours of advanced yard tractor operation, and gallons of diesel fuel displaced (estimated based on hours of operation) were collected to estimate expected GHG and air pollutant emissions reductions, including carbon dioxide equivalent (CO_2e), diesel particulate matter (PM), fine particulate matter ($PM_{2.5}$), oxides of nitrogen (NOx), and hydrocarbons (HC). Additionally, an estimate of the project's reduction in carbon intensity was undertaken.

During the ITS demonstration, total execution time per truck, total waiting time per truck, turn time per truck, total vehicle utilization time, total vehicle utilization reduction, operational cost improvement, total miles reduction and unproductive miles reduction, fuel consumption reduction and emission reductions, were documented.

CHAPTER 2:
Advanced Yard Tractor Deployment Project

2.1 Advanced Yard Tractor Deployment Project Overview

This project was developed to aid marine terminal operators interested in adopting advanced cargo handling equipment technology to assess and overcome key obstacles that inhibit the deployment of advanced yard tractor technologies, including:

- Marine terminal operator uncertainty regarding advanced technology yard tractor performance (can it do the job?),
- The current "price premium", i.e., the incremental cost of alternative fuel and battery-electric vehicles as compared to conventionally-fueled vehicles, and
- A lack of experience and knowledge in the marine terminal industry regarding the operation, refueling, and maintenance of advanced technology cargo handling equipment.

Grant funding from CEC for this project provided Everport and POLA the opportunity to address these obstacles. The advanced yard tractor deployment project provided early experience with each of the technologies and their performance in a rigorous marine terminal environment, while substantially mitigating the marine terminal's financial risk and potential loss of productivity. Importantly, the demonstration allowed Everport to gain experience in the operation and maintenance of advanced technology yard tractors, and this experience was generally positive.

For the Advanced Yard Tractor Deployment Project effort, POLA, Capacity Trucks, Cummins Westport, Clean Energy and Everport Terminals teamed to demonstrate 20 yard tractors equipped with the commercially available Cummins Westport near-zero engine certified to the optional low-NOx standard, 0.02 gram per brake horsepower per hour (g/bhp-hr.) NOx. This is the first time the Cummins' low-NOx natural gas engines were integrated into an off-road yard tractor application. Agility Fuels installed the natural gas fuel systems in the yard tractors. To further maximize project benefits, Clean Energy provided a temporary fueling system that provides RNG, marketed as REDEEM by Clean Energy. Natural gas is a commercially successful alternative fuel used in small and large on-road fleets throughout the world. This project undertook the transfer of this commercial technology to the off-road yard tractor application as a near term solution to reduce environmental impacts for this off-road equipment. In the longer term, additional reductions are needed to meet air quality and climate goals, which is why POLA teamed with BYD Motors and Everport Terminals to demonstrate five yard tractors equipped with BYD's first-generation zero emission propulsion technology.

2.2 Demonstration Fleet

Throughout the transportation industry, Capacity Trucks has been and remains a respected global leader in the design and manufacture of durable, reliable terminal tractors that can get the job done in warehouses, distribution centers, intermodal terminals and ports around the world. Capacity's headquarters are in Longview, TX and all yard tractors are manufactured in the USA. The Capacity truck chassis provided a stable, proven platform for evaluation and demonstration of the Cummins Westport RNG engines and Agility fuel systems installed for this project.

Cummins Westport formed in 2001 as a joint venture between Cummins Inc. and Westport Innovations. Cummins Westport has approximately 80 employees, with engineering and customer support staff located in Columbus, IN. Sales, marketing, and management staff are based in the USA and Canada. More than 60,000 Cummins Westport natural gas engines are in service worldwide. Designed to meet the most stringent emissions regulations, they provide efficient and reliable service. The new low-NOx Cummins Westport engine builds on that reputation and, when fueled by RNG, has the potential to provide a game-changing combination of near-zero emissions of criteria pollutants and greenhouse gases.

BYD is an original equipment manufacturer of battery technologies, with operations in every developed country in the world, and with more than $9 billion in revenue and 180,000 employees worldwide. BYD has achieved wide-scale commercialization of 100 percent battery electric transit buses and taxis—more than 50 million operating miles in both categories. BYD is a vertically integrated company that manufactures every major component, starting with the batteries and battery management system (BMS), and including the inverters and traction motors.

Below is a discussion of the efforts undertaken to plan, design and fabricate 20 yard tractors equipped with the Cummins 8.9L low-NOx natural gas engine and 5 BYD battery-electric zero-emission yard tractors for demonstration at Everport.

2.2.1 Capacity RNG Yard Tractors

For this project, Capacity planned, designed and fabricated 20 yard tractors equipped with the Cummins 8.9L low-NOx natural gas engine for demonstration at Everport. Since the 20 yard tractors have identical functional capabilities and technical design specifications, the below discussion pertains to all Capacity units.

2.2.1.1 Technical Specifications and Functional Requirements (RNG)

The Capacity low-NOx yard tractors were designed to operate identically to a typical diesel-powered yard tractor, except for the change from diesel to RNG fuel. The range, lifting capacity, and maximum speed requirements were the same as a comparable diesel-powered terminal tractor. Previous "port spec" trucks, ordered by Everport, were used to establish a detailed list of requirements for these low-NOx yard tractors.

Below are the functional requirements of the Capacity yard tractors. These requirements are comparable to conventional diesel fueled technology and there were no deviations from the base performance requirements for the low-NOx design. During Task 2, Capacity reviewed and confirmed these requirements.

Key technical specifications and functional requirements for the low-NOx yard tractor are listed below.

- Engine power of 250 horsepower (hp) @ 2200 revolutions per minute (RPM)
- 60 DGE (diesel gallon equivalent) LNG fuel capacity
- 70,000 lifting capacity of fifth wheel boom
- 16-inch maximum lift height of fifth wheel boom
- 25 mile per hour (mph) maximum vehicle speed
- 12.28:1 planetary rear axle
- Rigid rear suspension

- 72-inch rear cab door height
- Rubber dock bumpers on front bumper
- Reinforced RH mirror mount
- Headache rack behind cab
- Beavertail rear skid ramp on frame

2.2.1.2 Design Challenges for the Capacity RNG Yard Tractors

The design of the low-NOx yard tractors, built for this project, began as a derivative of a Capacity truck design that utilized a compressed natural gas fueled propulsion engine. The design was then adapted for the specific RNG engine, technical specifications, and functional requirements of this project. The length of the RNG storage tank, and the distance required for this tank between the front and rear tires, limited the wheelbase of the truck to a minimum 150-inch wheelbase. This also limited possible frame entry/exit step locations to the right side of the truck since the fuel tank occupied all frame space on the left side of the truck. Other design challenges included cooling system design, coolant and air pipe routing, fuel system mounting, fuel tank rub protection, and tailpipe support provisions.

This truck design placed higher demands on the engine cooling system because natural gas engines have higher heat rejection requirements than diesel engines. Additionally, the L9N engine platform is a natural gas conversion from a diesel platform. This means that the coolant pump provided with the engine was sufficient for diesel operation, but not for natural gas operation. Increasing either the air flow through the radiator or the size of the radiator will compensate for reduced coolant flow. Increasing radiator size was not an option, so the team decided to increase the power and efficiency of the engine-driven fan that pulls air through the radiator. This pulled enough air though the radiator to achieve the necessary heat rejection required by the engine. The downside to the higher-powered fan was that it required 40 horsepower to operate. This reduced the engine power output available to the rest of the truck by 40 horsepower.

The location of the coolant and charge air ports on the engine and the location of the corresponding ports on the radiator and charge air cooler was another design challenge. The coolant and charge air pipes are large diameter rigid steel pipes that usually require careful planning for their routing to ensure that they have a clear path with as few bends as possible. The location of the turbocharger outlet port and the charge air inlet port required modification to a long pipe, more than once, to prevent interference with the cab and engine. The size of other ports on the engine, radiator, and charge air cooler required the design of special reducing coolant and charge air pipes to make the required connections.

The frame was designed and fabricated with mounting provisions for the RNG fuel tank based on dimensions of the fuel tank mounting bracket provided by the fuel system integrator (Agility Fuels, now Hexagon Agility). Unfortunately, when the fuel system was delivered, the mounting brackets for the fuel system were not the same as the original mounting brackets. This meant that the frame rails, on previously fabricated frames, had to be modified to fit the new bracket and the design of the frame rail had to be revised for any future frames.

After the trucks were delivered, another design challenge was encountered. The operator requested installation of a rub guard on the trucks, for protection of the RNG tanks. This meant that the guard was designed and fabricated based only on 3D models of the truck, since none of the trucks were still at the factory to be used for prototyping. Once designed, the guards were shipped to the trucks and installed. Additional bolt holes were drilled in the frame and RNG tank brackets in order to mount the guard. Once the guards were installed and the trucks were operational, it was discovered early on that the design of the interface between the tank guard and the tank mounting bracket needed to be revised. The original tank guard brackets were developing cracks and failing. After some reevaluation of the design, revised mounting brackets were fabricated and installed to resolve this issue.

The final design challenge involved the exhaust system mount. The design of this mount was based on previous exhaust mount designs. However, after the trucks began operation, the tailpipe required additional supporting structure. Due to the weight of the tailpipe and horizontal forces applied to the tailpipe during operation, the outlet of the engine aftertreatment developed cracks and failed at the interface between the aftertreatment body and the tailpipe flange. The aftertreatment systems were shipped back to Capacity for repair. A tailpipe support structure was designed, fabricated, and shipped to the trucks for installation. This prevented further issues from occurring in the future.

The last RNG yard tractor demonstration unit was placed in service on October 30, 2019, and the 12-month demonstration period began on November 1, 2019. Table 1 documents the commissioning date for each demonstration unit and Figure 1 provides a photo of each unit.

Table 1: Commissioning Dates for Capacity LNG Demonstration Units

Unit ID	In-Service Date	Vehicle Identification Number
LN0321	10/17/2019	4LMPJ2113HL026776
LN0322	10/11/2019	4LMPJ2115HL026777
LN0323	10/12/2019	4LMPJ2117HL026778
LN0324	10/24/2019	4LMPJ2119HL026779
LN0325	10/12/2019	4LMPJ2115HL026780
LN0326	10/12/2019	4LMPJ2117HL026781
LN0327	10/11/2019	4LMPJ2119HL026782
LN0328	10/12/2019	4LMPJ2110HL026783
LN0329	10/23/2019	4LMPJ2112HL026784
LN0330	10/17/2019	4LMPJ2114HL026785
LN0331	10/23/2019	4LMPJ2116HL026786
LN0332	10/23/2019	4LMPJ2118HL026787
LN0333	10/11/2019	4LMPJ211XHL026788
LN0334	10/17/2019	4LMPJ2111HL026789
LN0335	10/21/2019	4LMPJ2118HL026790
LN0336	10/23/2019	4LMPJ211XHL026791
LN0336	10/26/2019	4LMPJ2111HL026792
LN0338	10/12/2019	4LMPJ2113HL026793
LN0339	10/12/2019	4LMPJ2115HL026794
LN0340	10/30/2019	4LMPJ2117HL026795

Source: Everport Terminal Services

Figure 1: Capacity’s RNG Demonstration Units

Credit: Everport Terminal Services

2.2.2 Battery-Electric Yard Tractors

For this project, BYD planned, designed and fabricated five yard tractors equipped with BYD's battery-electric propulsion system. Since the five yard tractors have identical functional capabilities and technical design specifications, the below discussion pertains to each of the five units.

2.2.2.1 Technical Specifications and Functional Requirements (Battery-Electric)

The BYD battery-electric yard tractors were designed to operate identically to a typical diesel-powered yard tractor, except for the accommodation for overnight charging. The range, lifting capacity, and maximum speed requirements were designed to be the same as a comparable diesel-powered terminal tractor. BYD worked with Everport to finalize the BYD Model 8Y technical specifications and functional requirements, including customer-specific requirements unique to Everport's operation.

Below are key technical specifications and functional requirements for the battery-electric yard tractors, BYD's Model 8Y:

- Maximum power @ 241 hp, rated power @ 201 hp
- Battery capacity @ 209 kilowatt-hour (kWh)
- Charging power @ 100 kilowatt (kW) Alternating Current (AC)
- 2.5 hour charge time
- Minimum 10 hour runtime
- 70,000 lifting capacity of hydraulic fifth wheel
- 16.97-inch nominal
- lift height of fifth wheel boom
- 33 mph maximum speed
- Rigid rear (solid mount) suspension
- Gradeability exceeds 15 percent

2.2.2.2 Design Challenges for the BYD Battery-Electric Yard Tractors

The BYD demonstration units were first delivered to Everport mid-June 2019 based on a successful pre-delivery inspection to ensure that all terminal-specific requirements were met. Unfortunately, the equipment sat idle for several months due to prolonged delays for the certification of the EVSE (see Section 2.3.2 for more discussion); final permit approval of the EVSE was issued February 27, 2020, and the yard tractors were deployed on March 10, 2020.

During the initial deployment of the trucks in March 2020, Everport identified that when a bomb cart[1] connected to the kingpin[2], the front wheels would lift off the ground slightly. A BYD technician, dispatched to the site to evaluate the issue, determined that the power take-off (PTO) ramp was interfering with the bomb cart and the area around the fifth wheel required modification to resolve the issue. Accordingly, the units returned to the BYD Lancaster facility for modification. BYD made the appropriate modifications and the units were returned to Everport in late June. Thus began several ongoing issues requiring periodic transport of the

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[1] A bomb cart is the term used for a heavy-duty chassis that carries a twenty-foot equivalent unit (TEU) container.

[2] The kingpin is the pivot mechanism connected to the fifth wheel coupling.

units back to Lancaster that adversely impacted in-service demonstration with these zero-emission units, including:

- Safety issue related to the door hydraulics, temporarily trapping an operator inside the cab.
- Safety modifications identified in the field including fifth wheel support brackets, breakaway glad hands[3] and Emergency Exit stickers for the front windshields.
- Structural issues with the steel plate covering the drive motor, exposing the electrical cables, that in one case resulted in structural collapse of the battery bank support.

Additional discussion related to the challenges experienced with the battery-electric units is provided below in Section 2.4.2 (Operational Experience). Table 2 documents the commissioning date for each demonstration unit and Figure 2 provides a photo of each BYD demonstration unit.

Table 2: Commissioning Dates for BYD's Battery-Electric Demonstration Units

Unit ID	In-Service Date	Vehicle Identification Number
E313	3/10/2020	LA9TYG881H1LC0026
E314	3/10/2020	LA9TYG883H1LC0027
E315	3/10/2020	LA9TYG885H1LC0028
E316	3/10/2020	LA9TYG887H1LC0029
E317	3/10/2020	LA9TYG883H1LC0030

Source: Everport Terminal Services

Figure 2: BYD's Battery-Electric Demonstration Units

Credit: Everport Terminal Services

2.3 Infrastructure

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[3] Glad hands are coupling devices used to connect the service and emergency air lines from the truck or tractor to the trailer. The couplers have a rubber seal, which prevents air from escaping.

Support of the demonstration fleet required infrastructure for two alternative fuels. Clean Energy Fuels provided RNG for the Capacity low-NOx yard tractors, and BYD and POLA coordinated the installation of five BYD chargers to support the battery-electric yard tractors.

2.3.1 RNG Yard Tractor Fueling Infrastructure

Clean Energy is a leading provider of natural gas for transportation in North America. As a vertically integrated company, Clean Energy designs, builds, operates and maintains compressed natural gas (CNG), liquefied natural gas (LNG), liquefied to CNG (L/CNG) and renewable natural gas (RNG) fueling stations throughout North America. Clean Energy has over two decades' experience in developing and implementing natural gas fueling solutions for high volume fleet customers including transit agencies, refuse operators, recycling and trucking companies, airports, transportation providers, educational institutions, utility companies and government agencies.

Clean Energy partnered with Everport to provide 100 percent renewable liquified natural gas to fuel the Capacity low-NOx demonstration fleet. While Everport had originally envisioned the use of wet-hose fueling[4] for the RNG demonstration units, local permitting challenges were significant and an alternative approach was undertaken for this project. Clean Energy designed and built a temporary fueling skid, referred to as the "Harpoon". The Harpoon fueler was purpose-built to Clean Energy specifications and previously deployed at various customer locations. The Harpoon is an RNG storage tank mounted on a trailer chassis that allows for movement to multiple locations. The Harpoon includes all the equipment needed for receiving and dispensing RNG to vehicles including pumps, controls, electronics, and safety systems. The Harpoon design includes an integrated secondary containment for RNG spills so that external secondary containment is not required, which simplifies deployments. The Everport project was a good fit for the Harpoon in that the temporary nature of a limited demonstration is well suited to Harpoon deployment. Modifications were made to the unit to meet the terminal's operational requests, including k-rail safety barriers around the Harpoon.

POLA's Electrical Engineering and Construction and Maintenance Departments worked with Clean Energy and Everport Facilities Management to establish the best site location for the Harpoon based on the facility's electrical power supply locations, yard operations, traffic flow and safety considerations. The team worked together to select a dedicated area for the tanker that allowed for a safe fueling location for both the Capacity fleet and Harpoon refills that minimized exposure to foot traffic. Figure 3 shows the RNG Harpoon and Figure 4 depicts Clean Energy refueling the Harpoon from a mobile supply.

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[4] Wet-hose fueling brings the fuel to the parked units and is standard practice for the diesel yard tractors.

Figure 3: Clean Energy's RNG Fuel Harpoon

Credit: Everport Terminal Services

Figure 4: Refueling the Clean Energy RNG Harpoon

Credit: Everport Terminal Services

Authorities Having Jurisdiction (AHJ) require electrical components be certified, or listed[5], and all components of the Harpoon met this requirement. However, the City of Los Angeles Building Department, the AHJ for the Everport project, required certification of the entire Harpoon as complete system – a first-time requirement for Clean Energy. Clean Energy undertook a significant effort, at their cost, to achieve electrical certification of the Harpoon as a whole system. This effort involved hiring a consultant to inspect the system and identify required changes, and then uninstalling this fueling system and returning it to Clean Energy's shop to make the required modifications. The certification was received after inspection, upon completion of final modifications. This was an expensive undertaking because the Harpoon is a unique and uncommon piece of equipment and contains many electrical components. There were also significant costs incurred for site modifications such as berms, barriers and signage to satisfy permitting requirements.

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[5] Underwriters Laboratory, or equivalent.

2.3.2 Battery-Electric Yard Tractor Charging Infrastructure

For this project, BYD provided five 100 kW BYD AC chargers for use with the five battery-electric yard tractors. BYD's 100 kW AC chargers provided for this project were designed and fabricated according to BYD's standard design. There were few, if any, high speed DC chargers available when BYD was introducing heavy duty commercial vehicles, so BYD developed high power, three-phase AC charging equipment, including the 100 kW AC charger designed and fabricated based on industry reference standards. When BYD introduced the three-phase AC charger into the US market for BYD buses, and then for trucks, there was still no DC charging standard available. Now, however, like much of the rest of the market, BYD has since switched to the DC charging standard for use in later designs.

The primary issue that arose during the commissioning of the system was that the City of Los Angeles would not issue a permit for the charger installation because the BYD chargers were not UL listed. Over several months, BYD and Everport worked with the City of Los Angeles toward a permitting solution. Ultimately, stakeholders agreed that BYD would hire Technischer Überwachungsverein[6] (TUV) Rheinland of North America – a nationally recognized testing laboratory – to perform a field evaluation to determine if the BYD chargers could meet UL and other electrical safety standards. As part of this process, BYD research and development made the design changes to fulfill the UL and other safety standard requirements identified by TUV and BYD then purchased all of the relevant materials, provided labor, and hired certain contractors to perform the charger modifications on-site. Upon final evaluation, TUV approved the design changes in its final report. This report was subsequently submitted to and accepted by the City of Los Angeles and the project was ultimately approved for final permit approval.

POLA's Electrical Engineering and Construction and Maintenance Divisions worked with BYD and Everport Facilities Management to establish the best site location for the EVSE based on the facility's electrical power supply locations, yard operations, traffic flow and safety considerations. The team worked together to select the closest convenient location from the electrical substation source to minimize trenching and vehicle traffic challenges. Table 3 provides key specifications for BYD's 100kW EVSE and Figure 5 provides a photo of a charger.

Table 3: BYD EVSE Specifications

Description	Specification
Charger	100 kW
Charging Mode	AC
Input Voltage	480V 3-phase
Operating Voltage Range	432V-528V 3-phase
Input Current	120A
Input Power	100kW

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[6] English translation: Technical Inspection Association. TÜV Rheinland of North America is accredited as a Nationally Recognized Testing Laboratory, by the Occupational Safety and Health Administration in the United States, and as a Product Certification Body by Standards Council of Canada in Canada.

Description	Specification
Frequency	60Hz
Output Voltage	432V-528V 3-phase
Output Current	120A
Output Power	100kW
Charging Coupler Type	IEC62196-2
Number of Coupler(s)	1
Charging Cable Length	118.11in
Mounting Method	Floor-mounted
Certification	CQC/TUV
Reference Standard	IEC61851/IEC62196
Enclosure Protection	IP54

Source: Everport Terminal Services

Figure 5: BYD EVSE

Credit: BYD

2.4 In-Use Demonstration Experience

The RNG and battery-electric demonstrations experienced vastly different project outcomes. The RNG units were able to achieve nearly 50 percent of projected low-emission operation, in spite of a number of challenges experienced throughout the demonstration. The battery-electric demonstration struggled through the project term to accrue minimal operating hours due to design issues that arose during the demonstration, as well as external conditions.

A significant adverse impact to the demonstration project began in late February 2020. Work at the Everport terminal slowed dramatically, due to China’s Lunar New Year celebration followed closely by the spread of COVID-19 and subsequent quarantine restrictions. Several ships were held in the Far East for the 14-day quarantine period. Throughput volume at the terminal was reduced by nearly half, drastically cutting the day and night shift operations during that time. The project demonstration was adversely impacted by the subsequent slowdown in throughput in the first half of 2020 as a result of the global pandemic. Table 4 documents the significant reduction in total twenty-foot equivalents (TEUs) moved at the port from January through July 2020 compared to 2019.

Table 4: 2020 Port of Los Angeles Container Statistics[7]

Month	Total TEUs	Prior Year Change
January	806,144	-5.43 percent
February	544,037	-22.87 percent
March	449,568	-30.94 percent
April	688,999	-6.45 percent
May	581,665	-29.81 percent
June	691,475	-9.58 percent
July	856,389	-6.11 percent
August	961,833	11.7 percent

Source: Port of Los Angeles

The pandemic also closed BYD's Lancaster, California facility and caused significant parts supply issues due to the COVID-19 global pandemic. The below discussion elaborates on the many challenges experienced during this demonstration project.

2.4.1 RNG Yard Tractor Operational Experience

The Capacity low-NOx yard tractors were fully commissioned by Everport on October 31, 2019. At the beginning of the demonstration, the equipment experienced some initial mechanical issues, including cracked catalytic converters, engine shutdowns, check engine lights and other minor issues that were quickly addressed under warranty. The entire fleet was retrofitted with a mounting bracket that prevented the exhaust tailpipe from banging against the catalytic converter, which resolved the initial crack catalyst events.

Once these issues were fully addressed, the demonstration fleet was commissioned and in-service from November 1, 2019, through October 31, 2020. The RNG demonstration fleet accrued 17,681 hours during the 12-month demonstration, averaging 884 hours each, operating in two 8 to 10 hour shifts of 10 tractors each. Each yard tractor averaged 74 hours per month, moving about 35 containers per shift. The units were deployed in rail, marine, and yard operations.

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[7] https://www.portoflosangeles.org/business/statistics/container-statistics/historical-teu-statistics-2020 (Accessed October 2021).

In order to satisfy permitting conditions for the fueling infrastructure, unexpected constraints limited accessibility to the RNG fuel trailer. Without a mobile wet-hose unit (as originally envisioned for this project), the gearmen were required to drive each yard tractor to the Harpoon, park it in a space approved by the Fire Department, fuel the equipment, and drive the yard tractor back to the corral location. Although timing for this process decreased with experience, from the originally reported 20 to 25 minutes per unit down to a 10 to 15 minute average, the time expended necessitated scheduling adjustments. The units operated on a rotating duty cycle, with half on the day shift, while the other half fueled, and then switched the process for the night shift. This challenging situation meant that the units were not able to operate double shifts, as is the case with diesel-fueled yard tractors that are able to be wet-hose fueled during shift breaks. This fueling limitation decreased the anticipated hours of operation by half for the demonstration since the units could only conduct one shift per day. A few other noteworthy issues were experienced during the demonstration:

- The RNG Harpoon encountered a problem; the Coriolis meter needed to be replaced. The lead time for the replacement meter was three weeks, however, Clean Energy was able to locate the part on another unit in the field and to minimize downtime, the Harpoon was repaired and operational two weeks later.
- Oil began to leak into the coolant reservoir on some of the units. This became an ongoing issue, repaired under warranty by Harbor Diesel Industries (Capacity’s local representative) as it presented, and units were modified with a redesigned fan shroud, fan blades and stainless-steel oil coolers, as needed.
- Midway through the demonstration, several units experienced a problem with the fuel tank brackets. The nuts and bolts were loosening, causing the bolts to sheer and crack the bracket holding the RNG fuel tank, resulting in partial collapse. Everport’s mechanics repaired four of the yard tractors, but once it became an ongoing problem, Capacity designed and fabricated replacement bracket sets that were retrofit by Agility Fuels under warranty.

Some foremen were reluctant to issue the RNG yard tractors to temporary drivers, due to the wheelbase differentiation between the RNG and diesel counterparts; the RNG units have a larger turning radius. Measurement of each yard tractor type’s wheelbase, axle to axle, are as follows: diesel 114”; RNG 154”; battery-electric 114”.

2.4.2 BYD Yard Tractor Operational Experience

As discussed in Section 2.2.2.2 above, the BYD zero-emission yard tractors experienced significant downtime throughout the demonstration. The initial delay of eight months for certification and permit approval of the EVSE was a major setback. Then, once the EVSE was fully permitted in late-February 2020, the official demonstration period began.

Unfortunately, outside circumstances interfered with BYD’s ability to address initial issues experienced with the demonstration units once placed in service. Compounding the challenges of permitting the EVSE, the battery-electric yard tractors had the added circumstance of overlapping with the COVID-19 global pandemic. COVID-19 restrictions closed the BYD Lancaster factory on March 20, 2020, and it did not reopen until its staggered reopening on May 18, 2020. The factory was not fully operational until June 2020. This delayed addressing issues that arose with the demonstration units during this time. Once BYD was fully operational, the project team worked on the following issues:

- During the initial deployment of the units, it was identified that when a bomb cart was connected to the kingpin, the front wheels would lift off the ground slightly. A BYD technician was dispatched to Everport to evaluate the issue, but ultimately it was determined that the power take-off (PTO) ramp was interfering with the bomb cart and the area around the fifth wheel required modification to resolve the issue. Accordingly, the trucks returned to the BYD Lancaster facility for modification and returned to service in late-June 2020.
- Subsequently, a serious issue arose with respect to the demonstration unit doors. During operation on August 6, 2020, an incident occurred involving air bag deployment and door hydraulics that trapped a longshoreman inside the cab, posing a serious safety issue and "red-tagging" all five units (i.e., removing them from service). Accordingly, a technician was dispatched to Everport, where it was determined that the trucks would need to be returned to BYD's Lancaster facility for a modification to the cab. Upon receipt of the units, BYD determined that when there was no air in the cab air suspension, the cab position would drop too low, causing the sliding door frame to sit on the battery protective panel. The BYD team resolved to fix the issue by adding one 20 millimeter (mm) cab spacer and one 5mm cab spacer to the cab support bracket, which created a 10 mm to 15 mm gap between the door rail and the battery protective panel; this measurement is taken when the truck released as much air as possible from the system. The first modified unit was returned to the terminal in mid-November 2020; the final yard tractor was returned in late March 2021.
- Later in 2020, based on experience with the units, Everport requested three additional safety modifications: installation of fifth wheel support brackets, installation of breakaway glad hands, and placement of an Emergency Exit sticker on the front windshield. These modifications began at the end of September 2020 but took some time to complete, due to lack of availability for fifth wheel support brackets and breakaway glad hands for all five vehicles. The COVID-19 pandemic adversely impacted lead-times.
- It is noteworthy that unit #316 was the last unit returned to Everport from Lancaster in late March 2021, but remained out of commission for fabrication and installation of a headache rack to protect the door and an overhead rack for cab protection, hence this unit never logged demonstration hours.
- Toward the end of March 2021, two units experienced an issue with the steel plate covering the drive motor. The kingpin was hitting the metal as it extended, bending and cutting the metal plate until it broke off entirely, exposing the electrical cables, and in one case, resulting in structural collapse of the battery bank support. All five units remain at the BYD facility in Lancaster as of the writing of this report.

Overall, just 336 hours of in-service operation accrued in between visits to Lancaster to address these ongoing issues with the battery-electric units.

2.4.3 Operator Surveys

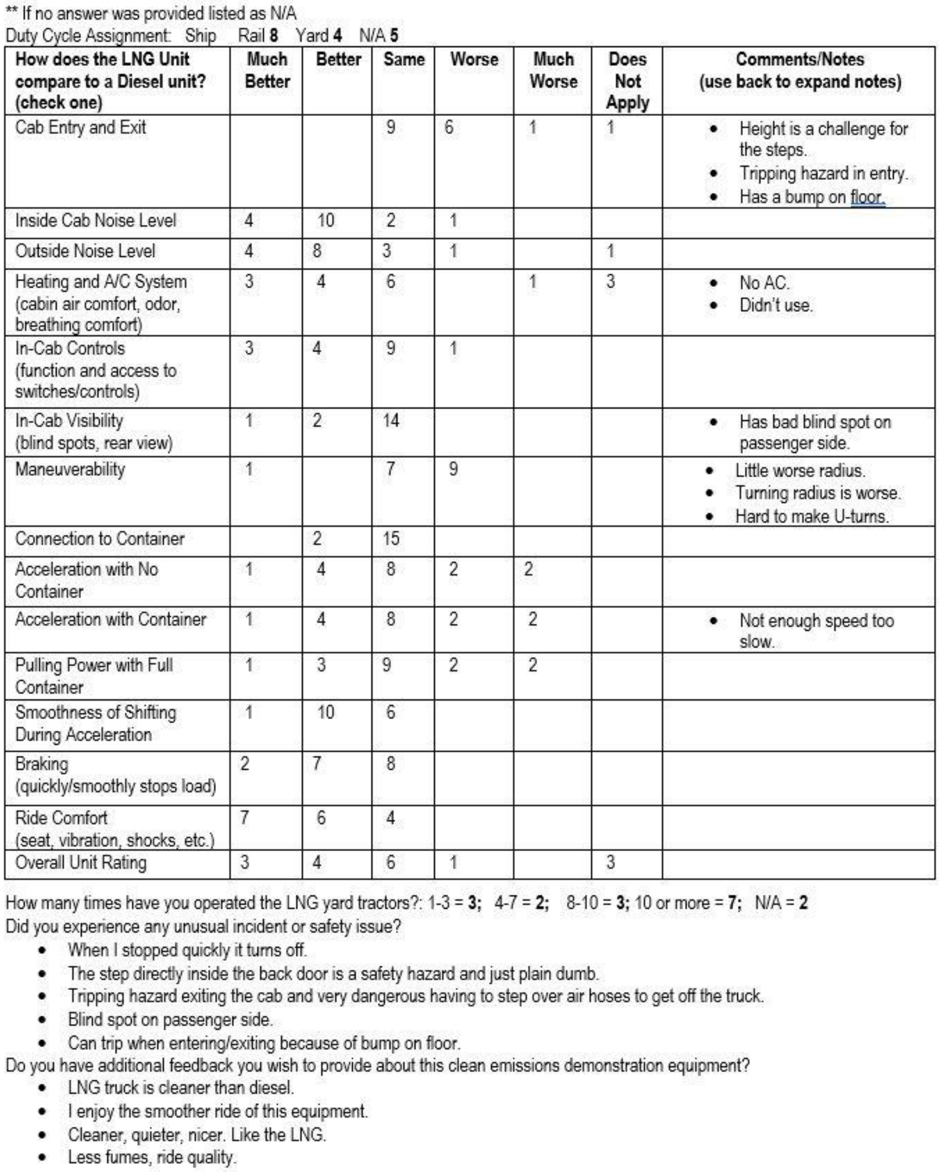
Everport collected seventeen operator surveys to document equipment operator feedback regarding their experience with the project equipment. Generally, feedback on the RNG units was positive and many of the experienced operators requested the RNG units because they preferred them over the diesel yard tractors. As a result of so few operating hours for the BYD units, operator surveys were not conducted for the battery-electric units.

Nearly every survey category indicated that the units were the same or better than the diesel counterparts, noting in particular the decreased noise inside the cab. One operator survey commented, “Cleaner, quieter, nicer.” Another operator commented, “Less fumes, ride quality.” Smoothness of shifting during acceleration received high positive marks, as did braking and ride comfort.

Opportunities for improvement indicated equipment maneuverability; nine operators categorized the maneuverability to be “worse” than the diesel counterpart. This seems to be largely due to the extended wheel base noted in sections 2.2.1.2 and 2.4.1. Six operators commented on the tripping hazard with cab entry and exit rating “worse.” One survey reported a blind spot on the passenger side. Several operators reported on the lack of air conditioning in the cab, which is a common complaint for most cargo handling equipment (CHE). Once the operators became more accustomed to the equipment, responses were extremely positive.

Figure 6 represents a compilation of the operator survey results collected during the demonstration.

Figure 6: Compilation of Operator Surveys



** If no answer was provided listed as N/A

Duty Cycle Assignment: Ship Rail **8** Yard **4** N/A **5**

How does the LNG Unit compare to a Diesel unit? (check one)	**Much Better**	**Better**	**Same**	**Worse**	**Much Worse**	**Does Not Apply**	**Comments/Notes (use back to expand notes)**
Cab Entry and Exit			9	6	1	1	• Height is a challenge for the steps. • Tripping hazard in entry. • Has a bump on floor.
Inside Cab Noise Level	4	10	2	1			
Outside Noise Level	4	8	3	1		1	
Heating and A/C System (cabin air comfort, odor, breathing comfort)	3	4	6		1	3	• No AC. • Didn't use.
In-Cab Controls (function and access to switches/controls)	3	4	9	1			
In-Cab Visibility (blind spots, rear view)	1	2	14				• Has bad blind spot on passenger side.
Maneuverability	1		7	9			• Little worse radius. • Turning radius is worse. • Hard to make U-turns.
Connection to Container		2	15				
Acceleration with No Container	1	4	8	2	2		
Acceleration with Container	1	4	8	2	2		• Not enough speed too slow.
Pulling Power with Full Container	1	3	9	2	2		
Smoothness of Shifting During Acceleration	1	10	6				
Braking (quickly/smoothly stops load)	2	7	8				
Ride Comfort (seat, vibration, shocks, etc.)	7	6	4				
Overall Unit Rating	3	4	6	1		3	

How many times have you operated the LNG yard tractors?: 1-3 = **3**; 4-7 = **2**; 8-10 = **3**; 10 or more = **7**; N/A = **2**

Did you experience any unusual incident or safety issue?

- When I stopped quickly it turns off.
- The step directly inside the back door is a safety hazard and just plain dumb.
- Tripping hazard exiting the cab and very dangerous having to step over air hoses to get off the truck.
- Blind spot on passenger side.
- Can trip when entering/exiting because of bump on floor.

Do you have additional feedback you wish to provide about this clean emissions demonstration equipment?

- LNG truck is cleaner than diesel.
- I enjoy the smoother ride of this equipment.
- Cleaner, quieter, nicer. Like the LNG.
- Less fumes, ride quality.

Credit: Everport Terminal Services

2.5 Data Collection and Analysis

Below are the project results from the 25-unit advanced yard tractor demonstration. The RNG demonstration period began on November 1, 2019, and ended on October 31, 2020. The battery-electric demonstration period began on April 1, 2020, and ended on March 31, 2021. As discussed in the GFO Application for this project, the "baseline" yard tractor annual usage, fuel consumption and emissions derived from the 2014 POLA Emissions Inventory (EI), the most recent available at time of POLA's GFO application submission. The 2014 POLA EI indicates that the average model year yard tractor operating at POLA in 2014 was from 2009; the Port derived its emission factors for the EI from CARB's Off Road Model[8].

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[8] Mobile Source Emissions Inventory – Off Road Model: https://ww2.arb.ca.gov/our-work/programs/mobile-source-emissions-inventory/msei-road-documentation-0

The emissions of the certified optional low-NOx Cummins Westport ISL G NZ engine derived from its CARB certification Executive Order, and the emissions of the BYD battery electric yard tractor are zero at the tailpipe.

2.5.1 Yard Tractor Duty Cycle

As detailed in Section 2.2, the project objective was to demonstrate advanced technology yard tractors that would perform identically to a typical diesel-powered yard tractor. The range, lifting capacity, and maximum speed requirements were the same as a comparable diesel-powered terminal tractor. Specifically, the following minimum duty cycle performance metrics were targeted:

- One 8-hour shift (no opportunity charging/fueling assumed)
- Two 8-hour shifts with opportunity charging/fueling
- 70,000 freight load capacity (loaded container plus chassis)
- 25 mph at 0 percent grade
- Gradeability at vehicle launch: 20 percent grade at 81,000 GCW
- Gradeability at vehicle launch: 15 percent grade at 81,000 GCW

2.5.2 Yard Tractor Demonstration Data

2.5.2.1 RNG Yard Tractor Operation Data

The RNG yard tractor fleet accrued a total of 17,681 hours of operation for this demonstration. Table 5 documents monthly operation of the 20-unit fleet. Everport's gearmen are responsible for fueling the equipment and collecting these data by recording fueling totals on a paper log after filling each tractor and recording the hour-meter readings on a monthly basis.

Table 5: Capacity RNG Yard Tractor Operation (20 units)

Month, Year	Hours/Month	LNG Gallons/Month	Average LNG Gallons/Hour
Pre-Commission	1,120	5,618	5.02
November, 2019	1,171	5,815	5.79
December, 2019	1,150	5,074	4.72
January, 2020	1,532	7,735	4.93
February, 2020	837	7,042	12.46
March, 2020	536	3,718	8.38
April, 2020	1,386	6,787	5.17
May, 2020	1,632	8,480	5.32
June, 2020	1,736	7,857	4.66
July, 2020	1,540	8,774	5.75
August, 2020	1,521	7,198	5.02
September, 2020	1,958	10,083	6.62
October, 2020	1,562	7,869	7.84

Month, Year	Hours/Month	LNG Gallons/Month	Average LNG Gallons/Hour
Total:	**17,681**	**92,050**	**5.21**

Source: Everport Terminal Services

The fuel economy recorded by Everport during the demonstration was an average of 5.21 LNG gallons per hour. There are 1.73 diesel gallon equivalents (DGE) in a gallon of LNG, so the average fuel economy experience by Everport during the demonstration was 3.0 DGE/hour based on data collected at the fueler. According to Capacity, the expected fuel economy for a similar RNG unit they studied was 2.15 DGE/hour and a special eight day study conducted by Everport on the RNG fleet indicated fuel economy was just under 2.0 DGE/hour, in line with manufacturer expectations.

Review of the RNG fuel purchase records indicated a disconnect between the observed fuel economy during the demonstration and the actual fuel purchased by Everport for its RNG fleet. According to Everport's fuel purchase records, 134,966 DGE were delivered to operate 18,475[9] hours, or 7.31 DGE/hour, far above operational records or what the equipment manufacturer indicates as the engines fuel economy. Even discounting lost fuel when the Harpoon was removed from service for recertification, and other times when the units would lose fuel due to maintenance and repair events, the fuel economy experienced by Everport is estimated to be over 3.5 DGE/hour.

Everport conducted a second check to assess fuel economy of the RNG fleet by collecting the lifetime hours of all the RNG units on May 31, 2021, which totaled 30,222 hours. Everport purchased 187,013 DGE of RNG, based on the invoices from Clean Energy for all RNG fuel purchased up through that same date. This total fuel divided by the total operational hours as read by the equipment hour-meters is 6.19 DGE/hour from commissioning to May 31, 2021, for the RNG fleet, more than twice the fuel consumption indicated by field records. The project team continues to investigate this issue, which remains unresolved as of this writing.

A meter was installed in May 2020 that allowed Everport to track the RNG fuel Harpoon's electric power consumption. Table 6 presents the monthly electricity consumption from June 2020 through the end of the demonstration.

Table 6: RNG Fueling Harpoon Electric Power Consumption

Month, Year	kWh
June, 2020	432
July, 2020	751
August, 2020	454
September, 2020	447
October, 2020	333

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[9] Note that during the time of this demonstration, Everport operated two other LNG yard tractors with the smaller Cummins Westport 6.7L engine, the additional hours above our demonstration hours reflects the fuel used by those two units (which are not part of our demonstration).

Month, Year	kWh
Total:	2,417
Average:	483 kWh/month

Source: Everport Terminal Services

2.5.2.2 Battery-Electric Yard Tractor Operation Data

The battery-electric yard tractors accrued a total of 336 hours of operation for this demonstration, well below expectations due to the challenges experienced with the unique port terminal environment. As noted above, after the initial delivery, additional modifications were made to the trucks. Section 2.4.2 details numerous incidents and issues encountered for these units, resulting in very limited in-service operation. The shortfall was exacerbated by closures and parts delays resulting from the COVID-19 global pandemic.

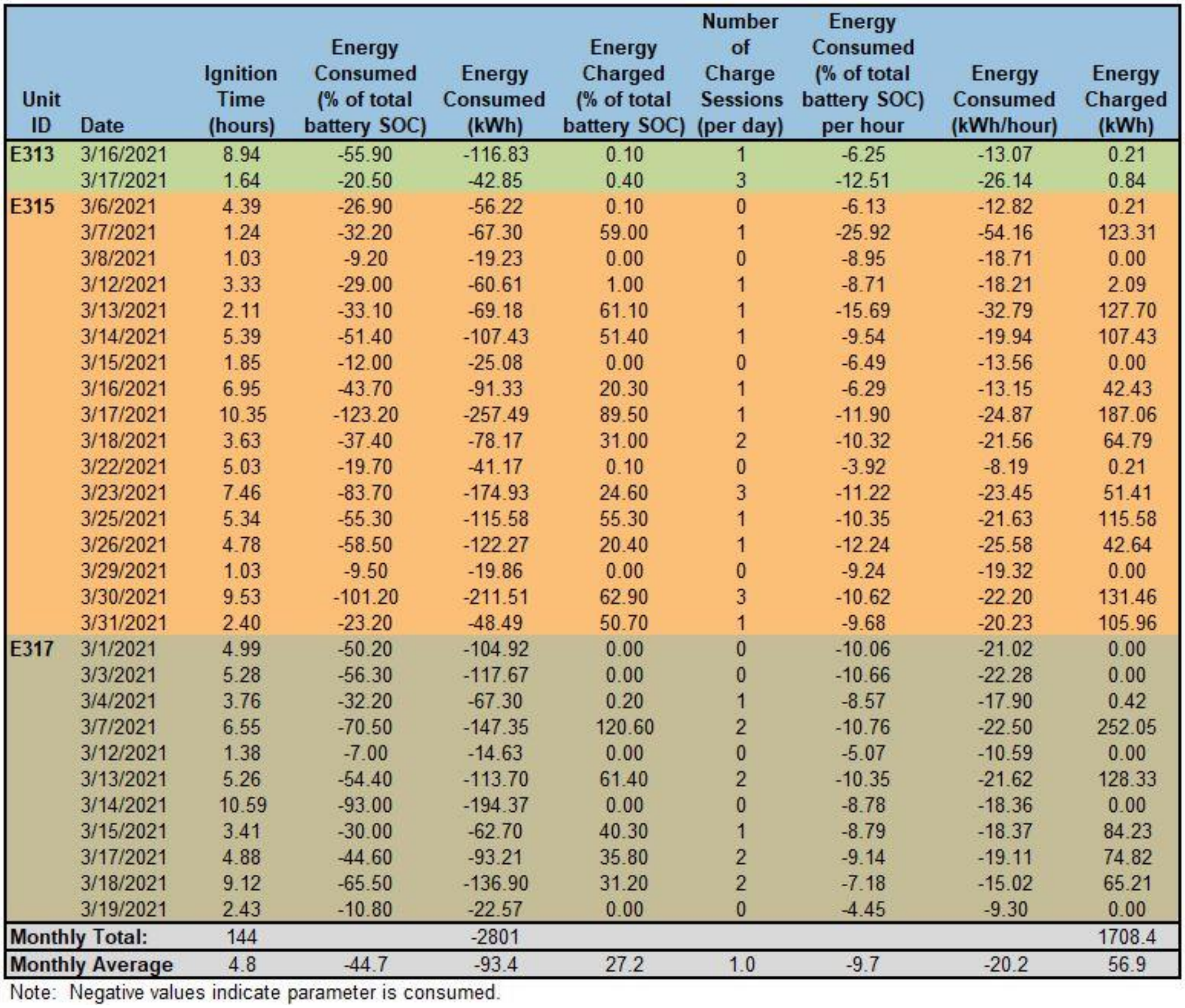
Table 7: BYD Battery-Electric Yard Tractor Operation (5 units)

Month, Year	Hours	Average kWh
April, 2020	0	
May, 2020	0	
June, 2020	0	
July, 2020	0	
August, 2020	0	
September, 2020	0	
October, 2020	0	
November, 2020	0	
December, 2020	30	583
January, 2021	84	1,633
February, 2021	78	1,517
March, 2021	144	2,800
Total:	**336**	**6,533**

Source: Everport Terminal Services

In preparation for the demonstration, GeoTab data loggers were installed on July 14, 2020, but it was determined in August that these data loggers would not interface with the BYD yard tractors. BYD ordered HEM data loggers, which were expected to be installed in September, but then BYD engineers developed a work-around to utilize the original GeoTab data loggers, which was finalized in October. The data loggers were expected to collect data once the yard tractors resumed operational status. Unfortunately, challenges continued for BYD with the GeoTab data loggers. Finally, in March 2021, the issues with the GeoTab data loggers were resolved and the loggers were mostly functional during this last month of demonstration. Over the previous months, operator timecard records were determining equipment hours of operation. Figure 7 provides a GeoTab download of the data logged for March 2021, the best (and last) month of the demonstration. Units 314 and 316 were not in service during March due to battery balancing issues and 316 was further delayed in order to fabricate its headache rack.

Figure 7: BYD Data Logger Results for March, 2021



Unit ID	Date	Ignition Time (hours)	Energy Consumed (% of total battery SOC)	Energy Consumed (kWh)	Energy Charged (% of total battery SOC)	Number of Charge Sessions (per day)	Energy Consumed (% of total battery SOC) per hour	Energy Consumed (kWh/hour)	Energy Charged (kWh)
E313	3/16/2021	8.94	-55.90	-116.83	0.10	1	-6.25	-13.07	0.21
	3/17/2021	1.64	-20.50	-42.85	0.40	3	-12.51	-26.14	0.84
E315	3/6/2021	4.39	-26.90	-56.22	0.10	0	-6.13	-12.82	0.21
	3/7/2021	1.24	-32.20	-67.30	59.00	1	-25.92	-54.16	123.31
	3/8/2021	1.03	-9.20	-19.23	0.00	0	-8.95	-18.71	0.00
	3/12/2021	3.33	-29.00	-60.61	1.00	1	-8.71	-18.21	2.09
	3/13/2021	2.11	-33.10	-69.18	61.10	1	-15.69	-32.79	127.70
	3/14/2021	5.39	-51.40	-107.43	51.40	1	-9.54	-19.94	107.43
	3/15/2021	1.85	-12.00	-25.08	0.00	0	-6.49	-13.56	0.00
	3/16/2021	6.95	-43.70	-91.33	20.30	1	-6.29	-13.15	42.43
	3/17/2021	10.35	-123.20	-257.49	89.50	1	-11.90	-24.87	187.06
	3/18/2021	3.63	-37.40	-78.17	31.00	2	-10.32	-21.56	64.79
	3/22/2021	5.03	-19.70	-41.17	0.10	0	-3.92	-8.19	0.21
	3/23/2021	7.46	-83.70	-174.93	24.60	3	-11.22	-23.45	51.41
	3/25/2021	5.34	-55.30	-115.58	55.30	1	-10.35	-21.63	115.58
	3/26/2021	4.78	-58.50	-122.27	20.40	1	-12.24	-25.58	42.64
	3/29/2021	1.03	-9.50	-19.86	0.00	0	-9.24	-19.32	0.00
	3/30/2021	9.53	-101.20	-211.51	62.90	3	-10.62	-22.20	131.46
	3/31/2021	2.40	-23.20	-48.49	50.70	1	-9.68	-20.23	105.96
E317	3/1/2021	4.99	-50.20	-104.92	0.00	0	-10.06	-21.02	0.00
	3/3/2021	5.28	-56.30	-117.67	0.00	0	-10.66	-22.28	0.00
	3/4/2021	3.76	-32.20	-67.30	0.20	1	-8.57	-17.90	0.42
	3/7/2021	6.55	-70.50	-147.35	120.60	2	-10.76	-22.50	252.05
	3/12/2021	1.38	-7.00	-14.63	0.00	0	-5.07	-10.59	0.00
	3/13/2021	5.26	-54.40	-113.70	61.40	2	-10.35	-21.62	128.33
	3/14/2021	10.59	-93.00	-194.37	0.00	0	-8.78	-18.36	0.00
	3/15/2021	3.41	-30.00	-62.70	40.30	1	-8.79	-18.37	84.23
	3/17/2021	4.88	-44.60	-93.21	35.80	2	-9.14	-19.11	74.82
	3/18/2021	9.12	-65.50	-136.90	31.20	2	-7.18	-15.02	65.21
	3/19/2021	2.43	-10.80	-22.57	0.00	0	-4.45	-9.30	0.00
Monthly Total:		144		-2801					1708.4
Monthly Average		4.8	-44.7	-93.4	27.2	1.0	-9.7	-20.2	56.9

Note: Negative values indicate parameter is consumed.

Source: BYD

2.5.3 Criteria Pollutant and Greenhouse Gas Emissions Reduced

Table 8 summarizes the projected and actual GHG and air pollutant emission reductions for the RNG yard tractors, including CO2e in short tons and metric tons, DPM, $PM_{2.5}$, NOx, HC, and SO_2 emissions. The projected emission reductions were provided in the original GFO application and based on a total of 1,816 hours of operation per demonstration unit, or a total of 36,320 hours of RNG unit operation and 9,080 hours of zero-emission unit operation. Note that diesel engines emit inherently low HC emissions, especially compared to natural gas engines, which accounts for the increase in HC emissions for the RNG demonstration.

Table 8: GHG and Criteria Pollutant Reductions for the RNG Yard Tractors

Scenario	CO2e (tons)	CO2e (metric tonnes[10])	DPM (tons)	$PM_{2.5}$ (tons)	NOx (tons)	HC (tons)	SO_2 (tons)
Originally projected emission reductions (based on 1,816 hours operation per unit, 36,320 total fleet hours)	263	238	0.084	0.076	3.67	-7.49	0.023
Estimated emission reductions based on actual hours of operation (17,681 RNG yard tractor hours)	128	116	0.041	0.037	1.79	-3.65	0.011

Source: Port of Los Angeles

The quantification methodology used to derive the air quality benefits of the advanced technology yard tractors compared the emissions of a baseline yard tractor to those of the near-zero Capacity/Cummins Westport and BYD zero-emissions yard tractors.

For the purpose of this assessment, the baseline yard tractor emissions were derived from the 2014 POLA Emissions Inventory (EI), the most recent EI available at the time of GFO application. The 2014 POLA EI determined that the average model year yard tractor operating at POLA is 2009. Emission factors derived from CARB's Off-Road Model that correspond to this model year were then used as the baseline for comparison. The emissions of the Cummins Westport natural gas engine were derived from the CARB certification Executive Order, and the emissions of the BYD battery electric yard tractor are zero at the tailpipe.

Note that this project was conceived in 2015 with project benefits benchmarked to the available baseline data at that time, when the average yard tractor age was the 2009 model year. According to the 2019 POLA EI, the average yard tractor age is now 2011, indicating that the fleet is getting younger. Potential project benefits will diminish over time as the fleet continues to grow cleaner. This has an adverse effect on the cost-effectiveness of implementing advanced technologies.

Table 9 summarizes the battery-electric demonstration emissions reduction estimates, which are based on 336 hours of zero-emission operation. These reductions are significantly below projections due to the reduced operation achieved during the demonstration, as addressed in Section 2.4.2.

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[10] 1 short tonne = 0.907185 metric tons

Table 9: GHG and Criteria Pollutant Reductions for the Zero-Emission Yard Tractors

Scenario	CO2e (tons)	CO2e (metric tonnes)	DPM (tons)	$PM_{2.5}$ (tons)	NOx (tons)	HC (tons)	SO_2 (tons)
Originally projected emission reductions (based on 1,816 hours of operation per unit, or 9,080 total fleet hours)	554	503	0.021	0.019	0.931	0.07	0.006
Estimated emission reductions based on actual hours of operation (336 zero-emission yard tractor hours)	21	19	0.0008	0.0007	0.0346	0.0025	0.0002

Source: Port of Los Angeles

2.5.4 Petroleum Fuel Displaced

As is common practice at port terminals, Everport does not track diesel fuel consumption for each unit in their fleet on an individual basis because diesel fuel is purchased in large bulk orders to supply its CHE fleet's wet-hose fuel truck. The wet-hose truck drives around the terminal to fuel the parked equipment, instead of the equipment driving individually to a fueling station. In order to estimate the annual diesel fuel displacement for this advanced yard tractor demonstration, the CO2e emissions from POLA 2014 Inventory of Air Emissions for Everport were used to back-calculate diesel fuel consumption. Table 10 provides step-by-step documentation of this approach.

Table 10: Diesel Fuel Displacement Calculation

Calculation Step	Value	Units
Diesel yard tractor fleet (865 units @ 1,816 hours each) total annual CO2e metric tonnes per POLA 2014 Emissions Inventory, Table 5.6	79,274	metric tonnes/year
Convert to short tons CO2e (1 short ton = 0.907185 metric tonne)	87,385.6	tons/year
Calculate tons CO2e per hour (divide total tons by 865 units and 1,816 hours)	0.0556	tons/hour of diesel operation
Convert to pounds per hour (multiply by 2,000 pounds per ton)	111.3	pounds/hour of diesel operation
Apply CO2e Emissions Coefficient for diesel (22.46 pounds of CO2e per gallon of diesel) to calculate the gallons per hour of a baseline diesel yard tractor.	4.95	diesel gallons/hour

Calculation Step	Value	Units
Multiply gal/hr by 17,681 total RNG yard tractor hours of operation to estimate the reduction in diesel fuel consumption for the demonstration from the operation of 20 RNG yard tractors.	87,586	diesel gallons
Multiply gal/hr by 336 total battery-electric yard tractor hours of operation to estimate the reduction in diesel fuel consumption for the demonstration from the operation of five (5) battery-electric yard tractors.	1,668	diesel gallons
Total gallons displaced during this demonstration (sum the RNG and battery-electric diesel gallons displaced)	**89,254**	**diesel gallons**

Source: Everport Terminal Services

The project originally projected that nearly 180,000 diesel gallons would be displaced by the full-time operation of the RNG yard tractors. As a result of the fueling operation changes that were required for the RNG fleet discussed above, Everport was only able to displace just under 50 percent of these diesel gallons. For the battery-electric yard tractors, 1,668 diesel gallons were displaced, far below expectations due to the many technical issues with the units addressed in Section 2.4.2. Both technologies demonstrated in this project were also adversely impacted by the COVID-19 global pandemic, due to enhanced sanitizing practices, manufacturing facility shutdowns and parts delivery delays.

2.5.5 Energy Efficiency Measures

There are no energy efficiency measures used in the facility that may exceed Title 24 standards in Part 6 of the California Code Regulations.

2.5.6 Job Creation and Economic Development

For this project, Everport tracked the specific labor assigned to the demonstration equipment. The job counts provided are based on individual union employees that were hired for a single shift. Jobs at the Everport site can consist of a single, 1-day shift or run for multiple consecutive days.

The RNG yard tractor demonstration accounted for 2,099 individual jobs/shifts and the BYD battery-electric yard tractor demonstration accounted for 165 individual jobs/shifts. Translating this shift labor count to a traditional, fixed labor force, Everport estimates the following job creation to manage the demonstration and ongoing operation of the 20 RNG yard tractors and the 5 BYD zero-emission yard tractors on an annual basis:

- Eight Operator positions (7 RNG and 1 battery-electric)
- One Mechanic position
- One Management position

For design and manufacture of the Capacity low-NOx yard tractors Capacity did not see an initial job growth. Yard tractors are Capacity’s core business; the alternative fuel LNG was a new design for the team. Installation of the alternative fuel components was subcontracted to

Agility Fuel Solutions and performed at the Capacity factory in Texas. Agility provided training into the installation efforts and Capacity has added LNG to their product offering. These builds are complicated and will slow down the normal assembly line unless run separately. These builds will require two-to-three key trained assembly technicians; thus, Capacity anticipate a two-to-three-person job growth in 2022. As commercialization evolves Capacity expects to add staff as demand for product increases.

As California transitions to a zero-emission goods movement economy, Everport's early introduction and experience with the BYD zero-emission yard tractors will position the terminal to grow its fleet to process more throughput using a zero-emission pathway. This will ensure the terminal remains competitive with companies that strive to minimize their carbon footprint.

2.5.7 Alternative Fuel and Renewable Energy Use at Everport

POLA's electrical power is provided by the Los Angeles Department of Water and Power (LADWP). According to LADWP's Power Content Label for 2019[11], just over 34 percent of the utility's power is from eligible renewable sources. Solar provides 12.5 percent, wind and geothermal provide a combined 18.7 percent with hydroelectric and biomass/biowaste covering the balance. Any growth in the renewable energy content of Everport's electricity is solely dependent on LADWP's ongoing efforts to increase its renewable energy content.

In addition to the renewable energy content of the electricity consumed by Everport and as a result of this demonstration project, the terminal operates 20 yard tractors that are fueled with RNG provided by Clean Energy Fuels (Clean Energy). This fuel is Clean Energy's REDEEM, which is 100 percent renewable. Everport plans to continue to operate these natural gas units for their full useful life, though there are no current plans to procure additional RNG units at this time.

2.5.8 Carbon Intensity Improvement

California's Low Carbon Fuel Standard (LCFS) regulation provides the benchmark for the average diesel fuel carbon intensity of 92.92 gCO_{2e}/MJ for the year 2020. This year was selected as the benchmark because the demonstration was conducted a majority of the time during 2020.

REDEEM is Clean Energy's RNG brand that can be delivered and dispensed at any natural gas fueling station. It is sourced from renewable feedstocks such as agricultural waste, food waste, wastewater treatment plants and landfills. Clean Energy currently has 50 fuel pathways approved under the LCFS regulation. Details on the specific pathways can be viewed on CARB's Current Fuel Pathways spreadsheet at this website[12]. In 2019, Clean Energy delivered 143 million gallons of Redeem into its fueling network. At the end of 2019, REDEEM's Carbon Intensity was 48.96 gCO2e/MJ based on the average portfolio carbon intensity for fuel delivered in 2019 as reported to the California Air Resources Board, Low Carbon Fuel Standard regulation.

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[11] Los Angeles Department of Water and Power website (https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-power/a-p-powercontentlabel?_adf.ctrl-state=wgufh5clh_4&_afrLoop=179676638453161)

[12] California Air Resources Board website (https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities)

Per CARB's grid electricity pathway ELC000L00072021[13], the current certified carbon intensity for grid electricity is 75.93 gCO_{2e}/MJ. This is an 18.3 percent reduction in carbon intensity for this project's zero-emission yard tractors. As California's grid electricity increases its renewable fuel source mix, the use of zero-emission port terminal equipment will continue to improve (i.e., lower) its carbon intensity.

2.5.9 Alternative Fuel Costs

According to Everport's 2020 and 2021 diesel fuel purchase records, the average price paid for diesel was $2.02 per gallon and $2.80 per gallon, respectively. The weighted average for diesel fuel purchased during the RNG demonstration period was $2.69 per gallon. According to Table 10, the advanced yard tractor demonstration offset 87,586 diesel gallons from the RNG demonstration and 1,668 diesel gallons from the battery-electric demonstration. Had the demonstration vehicles operated on diesel fuel instead of the project's alternative fuels RNG and electric power, Everport would have spent $235,606 and $4,487, respectively, on diesel fuel. Also, per Table 10, the average fuel consumption for the conventional diesel-fueled yard tractor fleet is 4.95 diesel gallons per hour. At $2.69 per gallon, the baseline fleet fuel cost would have been $13.32 per operating hour.

For the RNG demonstration, Clean Energy invoiced Everport $507,239 for 134,966 DGE, or $3.76 per DGE (average price of RNG during the demonstration, with taxes, which were between 11 percent and 17 percent depending on the month for California state and Federal excise taxes). This is a 115 percent increase in the price of fuel during the demonstration if you compared the amount of RNG purchased to the offset diesel fuel that would have otherwise been purchased. The RNG yard tractor operating hours associated with this total fuel purchase was 18,475 (including the two extra units not part of this demonstration), resulting in an average fuel economy of 7.3 DGE per operating hour. At $3.75 per DGE, the hourly cost to operate the RNG based on actual Clean Energy invoices was $27.46 per operating hour.

In addition to the RNG fuel cost, the RNG fueling Harpoon also consumes electricity at about average of 483 kWh per month (see Table 6). This adds a little over $100 per month for electricity to power the Harpoon.

For the battery-electric demonstration, Everport electric utility invoices indicate an average cost of $0.02122 per kWh of electricity purchased. Per Table 7, 6,533 kWh of electricity were consumed during the limited battery-electric demonstration, for a total estimated cost of $1,386, or $4.12 per operating hour.

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[13] *Ibid.*

CHAPTER 3:
Eco-FRATIS Drayage Truck Efficiency Project

3.1 Introduction

POLA's Eco-FRATIS Drayage Truck Efficiency Project tested ITS technologies to improve mobility in and to and from POLA and POLB) via reduced: truck trips, truck-miles travelled, truck-hours travelled, truck idling, which all thus reduces emissions and fuel consumption. Most of the emission reductions would occur in state designated disadvantaged communities and low income communities, and the state's highest ranked communities in the California Communities Environmental Health Screening Tool (CalEnviroScreen 3.0). The project consisted of two components—FRATIS and Eco-Drive—that individually as well as collectively attained the aforementioned performance measures. The FRATIS component of the project was performed by Productivity Apex, Inc. (PAI) and Infomagnus, while the Eco-Drive portion of the project was conducted by the University of California at Riverside under the guidance of and with the support from POLA. The technologies in both project components were successfully developed, demonstrated, and evaluated, showing the readiness of the technologies for broader market adoption. The project achievements and technology evaluation results are summarized below.

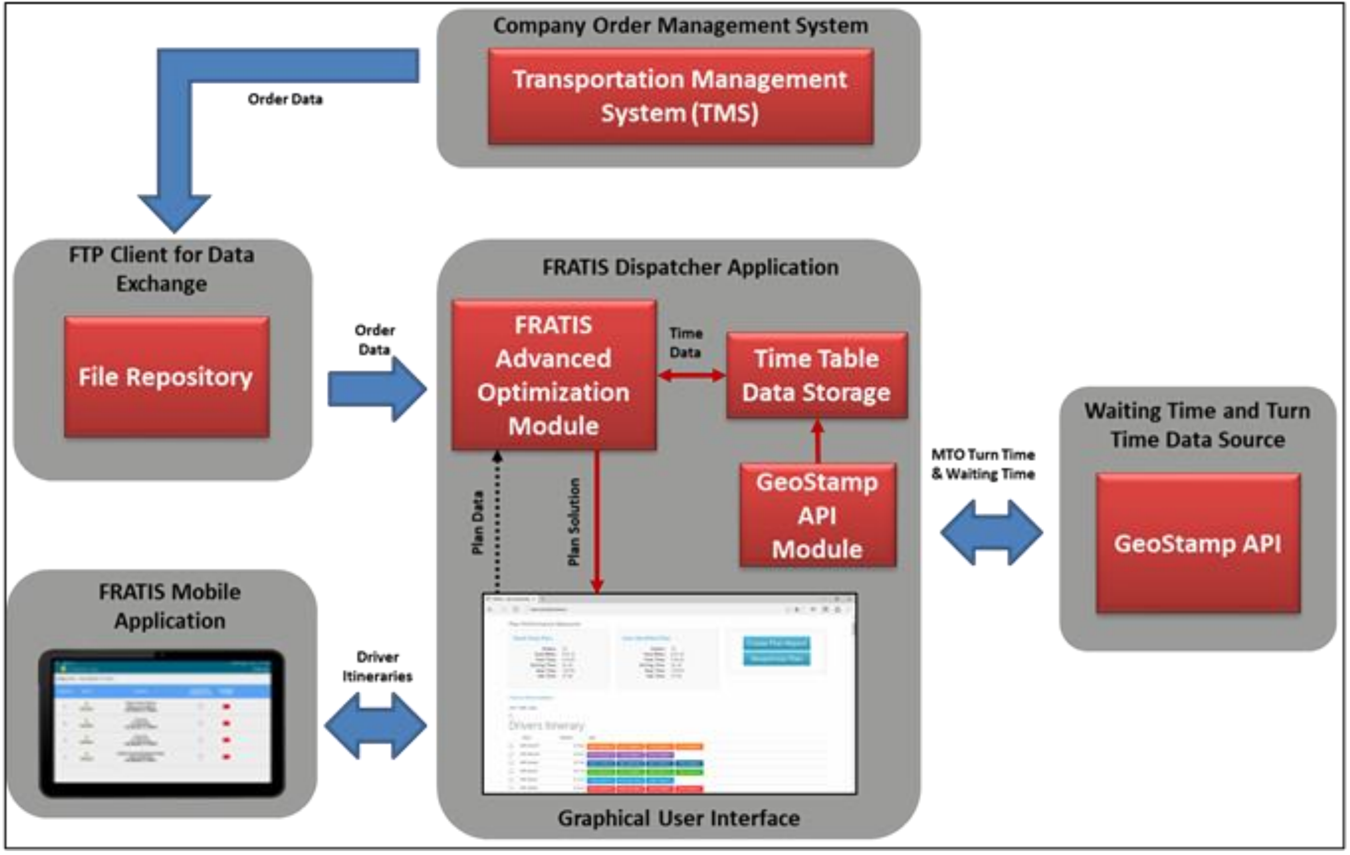
The FRATIS component of this CEC demonstration project represents further advancement of the technology. Between 2013 and 2018, the United States Department of Transportation (USDOT) retained PAI to develop and test the FRATIS tool in the POLA and POLB, in two separate projects. The two technologies are summarized below.

FRATIS (intermodal logistics information technology)

- Optimized sequencing of container delivery and pick-up with a drayage company and 100 trucks
- Real-time roadway traffic data via the Los Angeles County Metropolitan Transportation Authority (LA Metro) Regional Integration of ITS
- Real-time container terminal visit times via GPS-based system, GeoStamp
- Accounts for terminal appointments

Figure 8 provides a depiction of the Eco-FRATIS high level architecture.

Figure 8: Eco-FRATIS High-Level Architecture



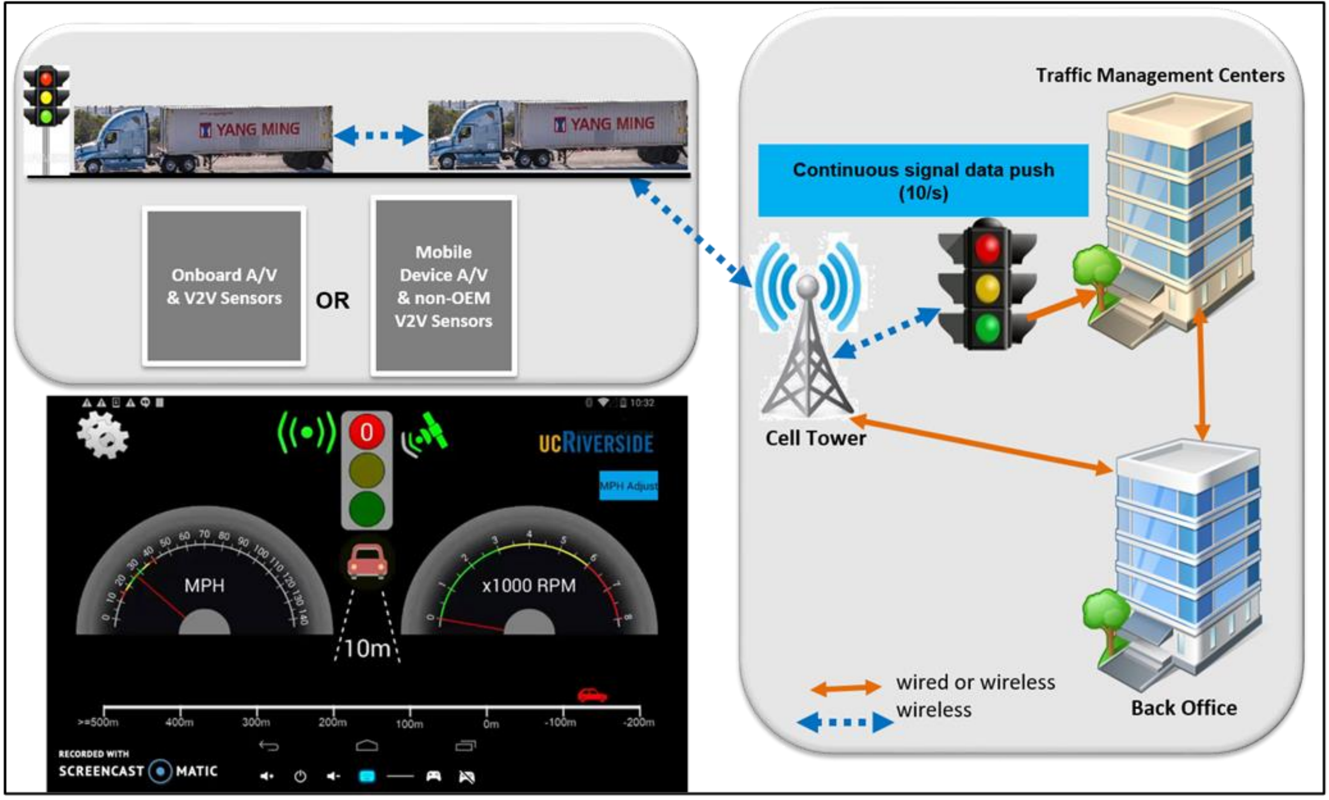
Credit: Productivity Apex, Inc.

<u>Eco-Drive</u>

- University of California Riverside's Eco-Drive application, which is a connected-truck (vehicle-to-infrastructure) demonstration project at 15 adjacent intersections along Harry Bridges Avenue and Alameda Street
  - Audio/visual (via tablet) speed advisory to drivers on route, using real-time traffic signal phase and timing obtained wirelessly, to: minimize signal delay & optimize acceleration/deceleration

Figure 9 provides a depiction of the Eco-Drive high level architecture.

Figure 9: Eco-Drive High-level Architecture



Credit: University of California, Riverside

3.1.1 FRATIS

The Eco-FRATIS project was implemented with scope that integrates the mature technologies of FRATIS and GeoStamp to improve the efficiencies of logistics and freight movement. Trucking company Southern Counties Express was asked to participate in this project and specific user requirements were recorded. To meet the requirements of POLA and Southern Counties Express, development was required for FRATIS and the key enhancements are listed below:

- Integration with GeoStamp
- Development of automatic use of files from the directory
- Development of automatic order change detection in the directory
- Development of a Mobile Application Notification system
- Enhancement of the algorithm to consider priority orders
- Enhancement of the algorithm to match equipment size between jobs when creating routes

Following development and implementation of these enhancements, organizational issues at Southern Counties Express interfered with their ability to fully use the system consistently. Therefore, the project team worked on securing operational data to allow for comparisons of performance with and without the use of the FRATIS application. This method of assessment resolved any operational concerns and provided a means to assess the impact of the enhanced FRATIS tool on daily freight movement. The resulting analysis yielded a consistent 11.6 percent reduction in miles traveled and an increase of 11.5 percent in productivity when utilizing the FRATIS tool for planning.

The Eco-FRATIS project presented new functionalities and technologies developed to fill operational gaps identified from its original technologies and prominent stakeholder. It allowed for a more comprehensive understanding of operational challenges and opportunities in the drayage industry. Analysis of live operational data showed that the use of a planning and optimization system like FRATIS can yield numerous benefits such as an 11.6 percent reduction in CO_2 emissions and significant reductions in non-greenhouse gasses emissions and fuel consumption. Most of the emission reductions would occur in state designated disadvantaged communities and low income communities, and the state's highest ranked communities in CalEnviroScreen 3.0.

The FRATIS development for this CEC project provided invaluable lessons learned and insight for on-going, continued advancement and demonstration of this type of technology. LA Metro is currently developing and testing an advanced version through a grant from USDOT.

3.1.2 Eco-Drive

The Eco-Drive system used signal phase and timing (SPaT) information from downstream traffic signals, that was enabled by connected vehicle technology, along with the information about the equipped truck and preceding traffic to determine the optimal speed profiles for the driver to follow. The key innovations of this component of the project include:

- Deployment at 15 intersections near the POLA with 4G/LTE cellular communication
- Development of Traffic Signal Information System (TSIS) server to collect and archive real-time SPaT messages
- Development of deep learning based SPaT prediction algorithms for actuated signals
- Development of trajectory planning algorithms for conventional diesel trucks that are applicable to actuated signals
- Innovative design of the driver-vehicle interfaces (DVIs) of an Eco-Drive application on Android platform
- Experiment and performance evaluation of Eco-Drive with an equipped truck in real-world traffic

The successful deployment of the connected signalized intersections was a result of the collaboration among a number of public agencies and private entities. It exemplified the public-private partnerships needed to enable travel and energy efficiency improvements as well as GHG and criteria pollutant emission reductions through Connected Vehicle technology. The Eco-Drive system was initially demonstrated with two equipped trucks prior to the formal CEC project demonstration, at an event in Carson, California, on March 6, 2019. This event had more than 100 attendees that included stakeholders from both the public and the private sectors.

The results from the real-world Eco-Drive performance evaluation on two connected corridors near the POLA showed that driving with Eco-Drive resulted in less fuel consumption and GHG emissions than driving without it by 6 percent to 15 percent. These emission reductions occurred in state designated disadvantaged communities and low income communities, and the state's highest ranked communities in CalEnviroScreen 3.0. On one of the connected corridors, driving with Eco-Drive also resulted in 29 percent to 32 percent fewer number of stops at signalized intersections, which helped reduce the overall travel time by 7 percent to 11 percent. As an unexpected co-benefit, it was found that Eco-Drive also helped the truck driver better comply with the speed limit of the road, which improves safety for all motorists. As a portable system with only a tablet and an optional camera-based range sensor onboard, Eco-Drive can be easily adapted for use in other vehicle platforms such as passenger cars and transit buses.

3.2 Freight Advanced Traveler Information System Overview

The Eco-FRATIS team was composed of Productivity Apex, Inc. and Infomagnus. The Eco-FRATIS system entails the enhancement and the previously demonstrated FRATIS system, and its integration with Infomagnus' commercially available and used GeoStamp system. The integration of these technologies was used to demonstrate improving truck operations in the Southern California region, which contains the largest logistics system in North America. Significant enhancements were made during the CEC project to FRATIS, which included enhanced application protocol interface (API) communications and data retrieval from the GeoStamp system.

As part of this effort, a mode of comparison was necessary to evaluate the integrated tool's effectiveness in solving the issues presented above. For this, the participation of the company Southern Counties Express was gained. Southern Counties Express is a Compton-based logistics company that provides transportation, warehousing and distribution services in California, Arizona, Nevada, and other mid-western states. The company was founded in 1990 and was built from servicing the Ports of Los Angeles and Long Beach. The company volunteered to use the final integrated tool to allow the team to obtain one year of usage data as discussed further in this report.

3.2.1 Drayage Operations

The POLA-POLB is largest container port complex in the entire Western Hemisphere, and handled about 17 million twenty-foot equivalent units (TEUs) in 2020. By 2035, the POLA-POLB is projected to handle about 35 million TEUs, which will generate about 115,000 truck trips per day (from 63,000 in 2018), and further strain the nation's most important freight gateway. To put this volume in perspective, the volume of truck trips alone requires about 14 lanes of freeways. Hence, multimodal solutions, such as ITS, are needed to accommodate expected cargo volumes.

Drayage moves are usually defined as short hauls. Drayage firms receive container requests for pick up and delivery to and from: port terminals, empty container storage yards, railyards, and logistics facilities located throughout Southern California. Some of these drayage moves may have appointments at the receiver side, and based on this information and other parameters discussed throughout this report, companies determine the routing and schedules for assigning orders to drivers. Trucks are then dispatched to these facilities where, if they arrive with an export container, they will proceed to a drop-off location and wait for yard cranes to load containers onto cargo ships. Trucks arriving with an empty chassis or as bobtails with no chassis are first processed and then directed to a container pick-up location. Bobtail trucks would proceed to a chassis pick-up location before being loaded on an import container. Drivers would then take the import containers to their receivers where they would wait for cargo to be unloaded from the truck, or perform what is known as a "drop and pick" where trucks will drop the trailer and pick it up at a later time. After dropping import containers, drivers usually pick-up empty boxes from previous moves to be returned to specific locations determined by the shipping lines.

3.2.2 System Evolution

3.2.2.1 FRATIS

The FRATIS platform has evolved from USDOT's previously deployed systems like the Cross-Town Improvement Project (C-TIP) (an early deployed versions of the FRATIS) and the Corridor Optimization for Freight, known also as FRATIS Phase two. These systems were developed and deployed with the common purpose of improving freight operations given the range of challenges that different local environments experience, like congestion, insufficient communication among parties, among others, and constitute the base of what would be the new Corridor Optimization for Freight.

The C-TIP was deployed in Memphis, Tennessee in 2013 with the participation of one motor carrier and its main objective was to develop a solution to minimize unproductive freight moves. During this pilot project an optimization algorithm was developed that allowed for the assignment and sequencing of freight orders in a way that minimized driven miles, given operational constraints such as order appointment time, driving and duty hour limits for drivers, starting location and earliest start time of drivers, etc.

Other deployments involved the implementation of a similar prototype tool in the Los Angeles and Long Beach area, South Florida, and Dallas, Texas. Given the specific characteristics found in these environments, the tool was modified and enhanced to consider some of the most important constraints encountered in those locations. The Los Angeles deployment was the most complex pilot study where a communication mechanism had to be developed between a marine terminal and a trucking company to exchange information and real-time updates for order and container status. In addition, traffic information, marine terminal waiting times, and turn times had to be integrated with the optimization algorithm when generating a solution to account for the heavy congestion presented in the area. Integration with weather services and improvements in the overall performance of the algorithm were also accomplished in the Los Angeles deployment.

In South Florida, as well as in Dallas, the major accomplishment was the integration with the participating company order management system to eliminate the double data entry problem encountered in the previous deployments. In South Florida data migration was scheduled for automatically populating the order management system multiple times a day to provide the participating trucking company with the latest order status on their prototype interface. On the other hand, in Dallas, the integration was accomplished by the manual upload of a flat file. These two approaches provided a better understanding of the pros and cons of the different mechanisms available for performing a more thorough integration of FRATIS with third party systems.

In each previous deployment, enhancements were made based on lessons learned and were implemented in the follow-on pilots. The following list describes the major features and the state of the system prior to this development:

- The dispatcher dashboard allows users to upload comma-separated value (CSV) and Excel formatted files to input orders into the system, as well as manually create new orders.
- The dispatcher dashboard allows users to modify and delete existing orders in the system.
- The dispatcher dashboard allows users to create, modify, and delete drivers in the system.

- The dispatcher dashboard allows users to run the optimization algorithm to create plans for specific dates that reduce unproductive miles and total execution time taking into consideration the following constraints:
  - Driver total driving and duty time
  - Driver earliest start time
  - Driver start location
  - Driver skills or certification (hazmat, overweight permit, etc.)
  - Order appointment time windows
  - Estimated travel times between locations based on historical traffic information per day of the week and time of the day
  - Order specific required driver
  - Order scheduled shift
- The dispatcher dashboard allows two-way communication of order information and orders updates into the system mobile application
- The mobile application allows drivers to login using their mobile tablets and access route and order information for the day
- The mobile application allows drivers to navigate to their selected destination using the co-pilot mobile application with real time traffic information
- The mobile application notifies drivers of route changes

3.2.2.2 GeoStamp

GeoStamp is a software as a service product designed to help trucking companies track and monitor wait time at given facilities. GeoStamp uses a combination of API integration with global positioning system (GPS) providers and home-built geofencing technology to provide accurate reporting of queues, wait time, delay time, and bread crumb map reporting.

GeoStamp's core features contain:

- Dashboard – where dispatchers, customer service representatives, and executives can manage the performance of their fleet and track wait time in real time. From here, users can click on certain moves and review them as a map report.
- Tracts - where end users can create and manipulate their own geofences to track wait time at facilities they want to, enabling complete control over a given fleet.
- Vehicles/Drivers – where end users manage their fleet of vehicles and their list of drivers.
- Invoice – where end users can find specific reports over a given amount of wait time and download them for invoicing.

The GeoStamp Analytics product is designed to help marine terminals, port authorities, trucking associations, and industry partners (like GPS providers and transportation management systems (TMS)) see and review average performance and wait times. It is mostly used to help poor performing facilities improve their performance over time.

The Analytics core features contain:

- Up-to-date subtabs that report on terminal and facility performance that are updated every 2 hours. There subtabs include average queue time, terminal time, and out queue time calculated using all trucks calling and being tracking in GeoStamp

- Real time dashboards that update every 2 minutes or every 30 minutes that show real time averages of wait time tracked at given facilities. These reports allow for real time adjustments from marine terminals and rail yards – among other industry stakeholders.

3.2.3 System Enhancement and Integration

Every new feature and improvement to the FRATIS application was based on the seamless integration of FRATIS with the Infomagnus system GeoStamp and capturing of user requirements from Southern Counties Express.

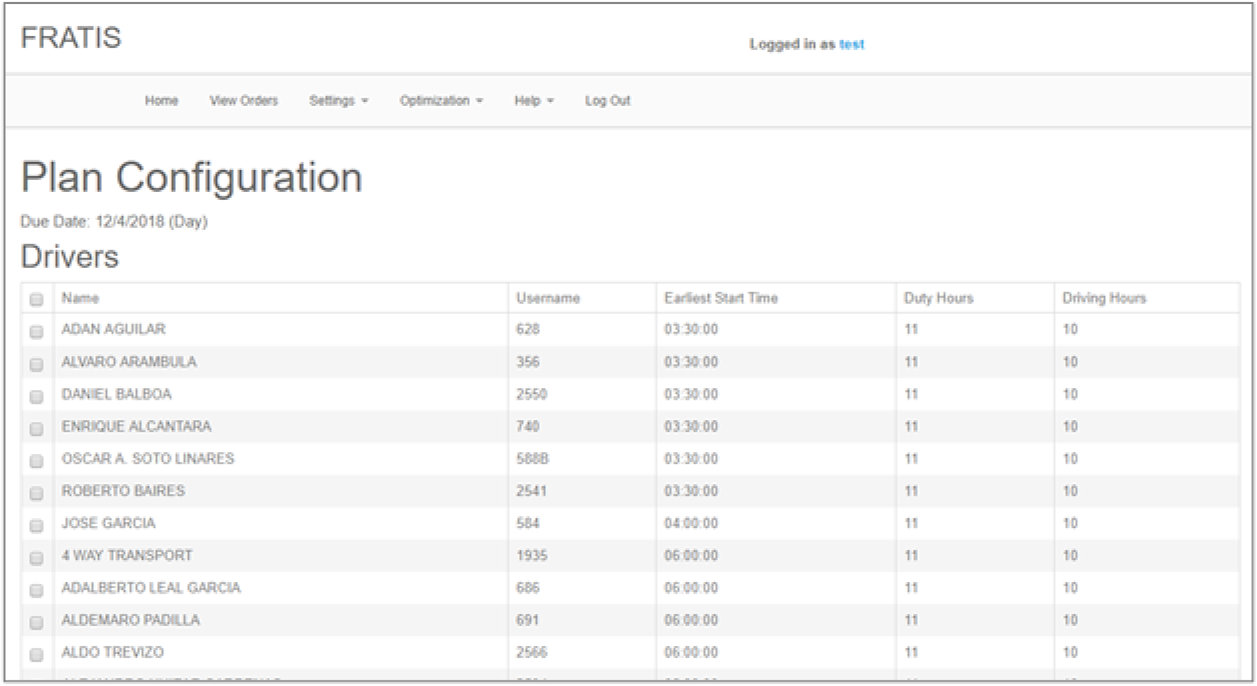
3.2.3.1 Integration with GeoStamp

One of the main objectives of this project was the integration of mature ITS systems to improve freight operations in and around POLA. GeoStamp's database allowed for retrieval of historical wait-time and turn-time information for use within the FRATIS optimization. The new turn-time module retrieved the turn-time data and wait-time data for each marine terminal from GeoStamp/Infomagnus servers. The data were analyzed and processed to provide the optimization algorithm the turn-time and wait-time by day of the week and time of the day. The optimization algorithm used the data provided to find near-optimum solutions to schedule trips to and from marine terminals. These data were used to schedule visits based on the minimum amount of wait time at any given marine terminal, in turn decreasing truck idling time and reducing fuel consumption and emissions. Overall, this integration provides the potential for improved fleet productivity and increased marine terminal throughput. The integration of FRATIS with GeoStamp was meticulously tested to confirm successful delivery of data into the FRATIS tool and its use within the optimization algorithm.

3.2.3.2 Data Exchange between Southern Counties Express TMS and FRATIS

A file transfer protocol (FTP) client was setup to transfer order data from Southern Counties Express TMS to the FRATIS route optimization tool with a frequency of one-hour intervals. Every hour a flat file was shared through the client containing not only new orders entered in the system but updates in location, assignments, and appointments for existing orders. This allowed the system to be updated throughout the day with the latest information. Figures 10 and 11 below show part of the tool interface.

Figure 10: FRATIS Dashboard Screenshot with List of Available Drivers



Plan Configuration

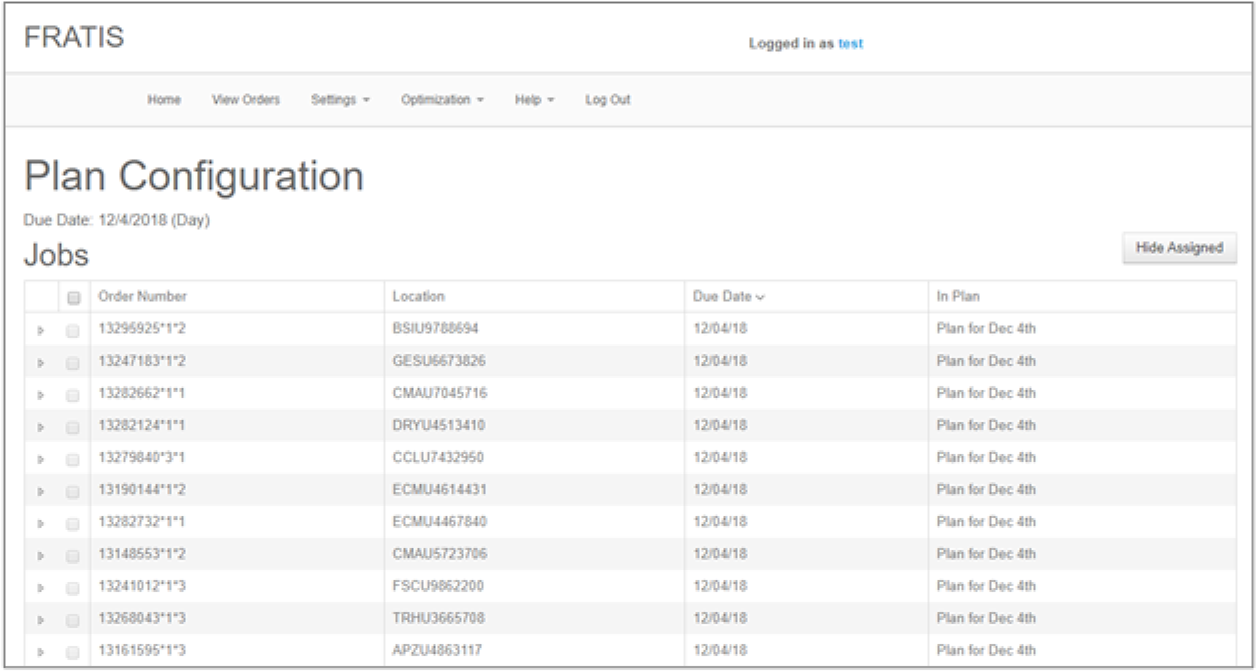
Due Date: 12/4/2018 (Day)

Drivers

☐	Name	Username	Earliest Start Time	Duty Hours	Driving Hours
☐	ADAN AGUILAR	628	03:30:00	11	10
☐	ALVARO ARAMBULA	356	03:30:00	11	10
☐	DANIEL BALBOA	2550	03:30:00	11	10
☐	ENRIQUE ALCANTARA	740	03:30:00	11	10
☐	OSCAR A. SOTO LINARES	588B	03:30:00	11	10
☐	ROBERTO BAIRES	2541	03:30:00	11	10
☐	JOSE GARCIA	584	04:00:00	11	10
☐	4 WAY TRANSPORT	1935	06:00:00	11	10
☐	ADALBERTO LEAL GARCIA	686	06:00:00	11	10
☐	ALDEMARO PADILLA	691	06:00:00	11	10
☐	ALDO TREVIZO	2566	06:00:00	11	10

Screen capture of FRATIS application dashboard with list of available drivers.
Credit: Productivity Apex, Inc.

Figure 11: FRATIS Dashboard Screenshot with List of Available Orders



Plan Configuration

Due Date: 12/4/2018 (Day)

Jobs

	☐	Order Number	Location	Due Date	In Plan
▸	☐	13295925*1*2	BSIU9788694	12/04/18	Plan for Dec 4th
▸	☐	13247183*1*2	GESU6673826	12/04/18	Plan for Dec 4th
▸	☐	13282662*1*1	CMAU7045716	12/04/18	Plan for Dec 4th
▸	☐	13282124*1*1	DRYU4513410	12/04/18	Plan for Dec 4th
▸	☐	13279840*3*1	CCLU7432950	12/04/18	Plan for Dec 4th
▸	☐	13190144*1*2	ECMU4614431	12/04/18	Plan for Dec 4th
▸	☐	13282732*1*1	ECMU4467840	12/04/18	Plan for Dec 4th
▸	☐	13148553*1*2	CMAU5723706	12/04/18	Plan for Dec 4th
▸	☐	13241012*1*3	FSCU9862200	12/04/18	Plan for Dec 4th
▸	☐	13268043*1*3	TRHU3665708	12/04/18	Plan for Dec 4th
▸	☐	13161595*1*3	APZU4863117	12/04/18	Plan for Dec 4th

Screen capture of FRATIS application dashboard with list of available order.
Credit: Productivity Apex, Inc.

3.2.4 Development of FRATIS Tool from User Requirements

New features incorporated to the FRATIS tool were a result of numerous interactions with Southern Counties Express where they detailed their requirements as users of the tool.

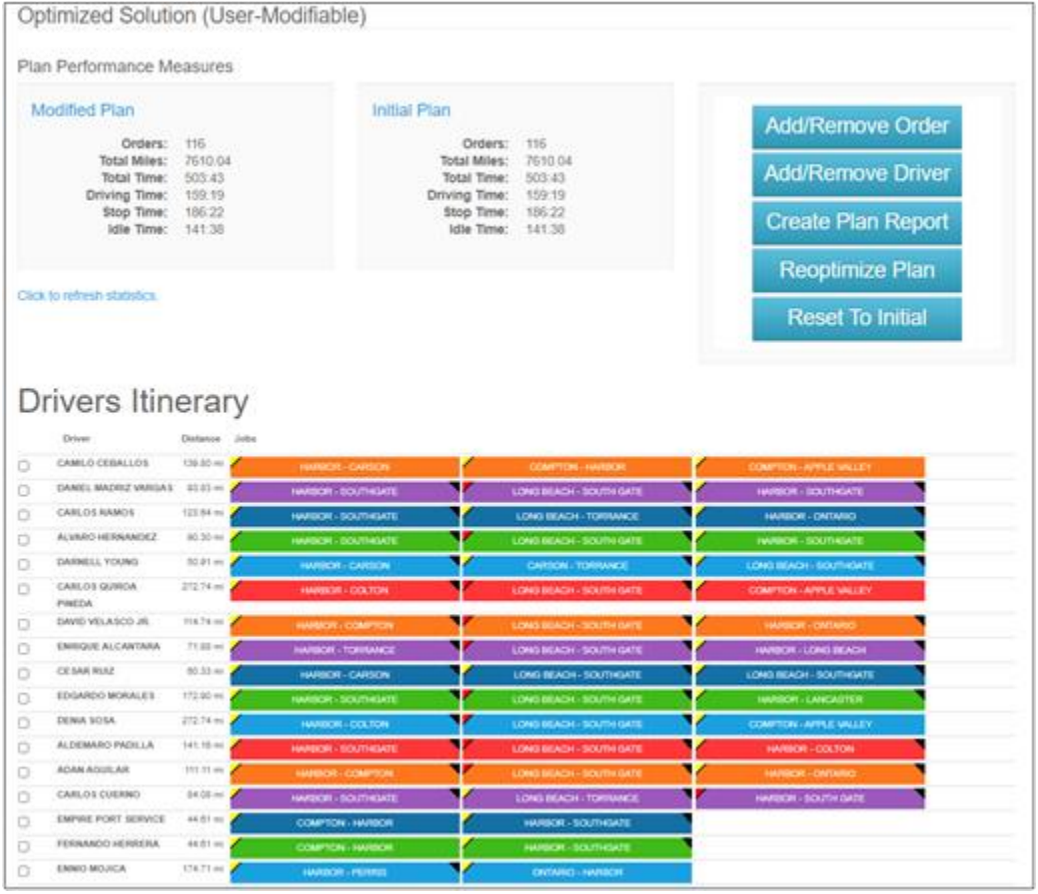
The following list represents the enhancements made to the original system:

- The tool allows users to run the optimization algorithm for plans with up to 80 drivers.

- The tool allocates enough space in the database storage for usage by multiple subscribers with up to 80 drivers total for a period of one year.
- The tool makes calls to the GeoStamp API to get wait-time and turn-time values to use when running the optimization algorithm.
- The tool caches or stores GeoStamp wait-time and turn-time values locally to facilitate data retrieval.
- The tool automatically replaces marine terminal default stop-time with updated turn-time from GeoStamp while running the optimization algorithm.
- The tool populates specific location wait-time during the route creation per marine terminal with wait-time from GeoStamp while running the optimization algorithm.
- The tool considers updated stop-time and wait-time in the calculation of route statistics.
- The algorithm uses default values in the absence of marine terminal data from GeoStamp.
- The tool automatically makes calls to the GeoStamp API to get wait-time data at selected marine terminals.
- The tool automatically makes calls to the GeoStamp API to get turn-time data at selected marine terminals.
- The tool allows users to upload FRATIS formatted files when entering orders into the system.
- The tool automatically consumes order files from a directory via the FTP client.
- The tool automatically detects when new order files have been saved to the directory.
- The tool notifies users of any failed attempts for file processing from the directory.
- The tool allows users to upload FRATIS formatted filed files to update the status of the orders in the system.
- The mobile application notified users of any change in order status caused by file uploads.
- The algorithm matches chassis ownership and size when creating routes for plan solution.
- The tool identifies owned chassis graphically when displaying final route solutions.
- The algorithm shall consider last-free-day priority when creating routes for plan solution.

Figure 12 below shows a screenshot of the FRATIS interface with an optimized plan containing all orders assigned to drivers and different statistics for that day’s plan.

Figure 12: FRATIS Dashboard Screenshot of Optimized Plan



	Modified Plan	Initial Plan
Orders:	116	116
Total Miles:	7610.04	7610.04
Total Time:	503:43	503:43
Driving Time:	159:19	159:19
Stop Time:	186:22	186:22
Idle Time:	141:38	141:38

	Driver	Distance	Jobs		
☐	CAMILO CEBALLOS	139.80 mi	HARBOR - CARSON	COMPTON - HARBOR	COMPTON - APPLE VALLEY
☐	DANIEL MADRIZ VARGAS	93.83 mi	HARBOR - SOUTHGATE	LONG BEACH - SOUTH GATE	HARBOR - SOUTHGATE
☐	CARLOS RAMOS	123.84 mi	HARBOR - SOUTHGATE	LONG BEACH - TORRANCE	HARBOR - ONTARIO
☐	ALVARO HERNANDEZ	80.30 mi	HARBOR - SOUTHGATE	LONG BEACH - SOUTH GATE	HARBOR - SOUTHGATE
☐	DARNELL YOUNG	50.81 mi	HARBOR - CARSON	CARSON - TORRANCE	LONG BEACH - SOUTHGATE
☐	CARLOS QUIROA PINEDA	272.74 mi	HARBOR - COLTON	LONG BEACH - SOUTH GATE	COMPTON - APPLE VALLEY
☐	DAVID VELASCO JR.	116.74 mi	HARBOR - COMPTON	LONG BEACH - SOUTH GATE	HARBOR - ONTARIO
☐	ENRIQUE ALCANTARA	71.88 mi	HARBOR - TORRANCE	LONG BEACH - SOUTH GATE	HARBOR - LONG BEACH
☐	CESAR RUIZ	80.33 mi	HARBOR - CARSON	LONG BEACH - SOUTHGATE	LONG BEACH - SOUTHGATE
☐	EDGARDO MORALES	172.90 mi	HARBOR - SOUTHGATE	LONG BEACH - SOUTH GATE	HARBOR - LANCASTER
☐	DENIA SOSA	272.74 mi	HARBOR - COLTON	LONG BEACH - SOUTH GATE	COMPTON - APPLE VALLEY
☐	ALDEMARO PADILLA	141.16 mi	HARBOR - SOUTHGATE	LONG BEACH - SOUTH GATE	HARBOR - COLTON
☐	ADAN AGUILAR	111.11 mi	HARBOR - COMPTON	LONG BEACH - SOUTH GATE	HARBOR - ONTARIO
☐	CARLOS CUERNO	84.08 mi	HARBOR - SOUTHGATE	LONG BEACH - TORRANCE	HARBOR - SOUTH GATE
☐	EMPIRE PORT SERVICE	44.61 mi	COMPTON - HARBOR	HARBOR - SOUTHGATE	
☐	FERNANDO HERRERA	44.61 mi	COMPTON - HARBOR	HARBOR - SOUTHGATE	
☐	ENNIO MOJICA	174.71 mi	HARBOR - PERRIS	ONTARIO - HARBOR	

Screen capture of FRATIS application showing display of optimized plan.
Credit: Productivity Apex, Inc.

3.3 Data Analysis

The data analysis performed during this project is intended to measure the impact and potential benefits that the integration and extension of these mature technologies could have on freight operations in POLA. The project team collected daily orders and execution data for one year of operations to perform a comparison between optimized plans generated by FRATIS and the actual execution of daily orders by the trucking company. With the data available it was possible to perform statistical analysis to determine potential efficiencies achieved using the optimization tool. This provided a clear picture of the impacts for freight movements when utilizing these technologies.

3.3.1 Scope Revision

FRATIS was originally customized for Southern Counties Express to run optimized plans of their daily operations and monitor executions; managing any changes to orders and moves, allowing for re-optimization and adjustments mid-day as required. However, since the deployment of the tool several factors have affected its intended use. Among these, Southern Counties Express had an increase to their workload during certain months of 2019 delaying the original deployment date, they had technical issues with their system where it was down for multiple weeks causing interruptions, and they experienced multiple changes in staff causing consistent re-training. Additionally, Southern Counties Express went through a change in ownership during the period of deployment causing further disruptions due to introduction of new personnel with a lack of project familiarity, and a significant change in the level of commitment to this endeavor.

Ultimately, a revision to the data capture approach for the project was implemented that provided a feasible approach to demonstrating the advantages of using the project technologies in drayage operations. This new methodology, developed in coordination with POLA, consisted of the project team running the optimization algorithm using the daily order files shared by the participating company. Daily optimized plans were generated using the available pending orders corresponding to each day in the original deployment schedule from March 2019 to March 2020 and compared against the company's execution of those same orders during the same period of time. Below is a more detailed description of this approach.

3.3.2 Data Analysis Assumptions

In order to compare the results obtained from running the optimization algorithm with the actual execution data provided by Southern Counties Express, the following assumptions needed to be made:

- All drivers from the drayage company start and end their routes at the headquarters main location.
- All drivers from the drayage company start their route at 6:00 AM and have a driving and duty time limit of 12 hours maximum.
- The number of drivers with assignments for each day in the actual execution data corresponds to the total number of drivers available for that given day.
- Stop times at customer locations are estimated to be an average of 30 minutes for the purpose of creating a daily plan.
- Stop times at marine terminals are provided by GeoStamp based on the day of the week and the time of the day. However, if data were not available for a particular location at a particular time, a default of 90 minutes is used for the purpose of creating the daily plan by running the optimization algorithm.

3.3.3 Data Analysis Methodology

The project team CSV files from Southern Counties Express for the period of March 2019 to March 2020 through a shared folder via an FTP client. These files were sent on a daily basis every hour between 6:00 AM and 7:00 PM Eastern Time from Mondays to Fridays. They would only contain day shift orders and would include data related to: order identifiers, pick-up and delivery appointment time windows, empty last free days and demurrage, order status, assigned driver numbers, due dates, pick-up and delivery locations, priority level, container size, and chassis ownership.

Each of these files was subsequently stored for analysis and became the basis for creating the optimized plans. In order to run the optimization algorithm and create daily plans, the first file containing available orders for each given day was selected to create what would have been the initial plan for that day. Additionally, the number of drivers to assign each day was selected based on the number of drivers assigned in the actual execution data for the same corresponding date. Following these selection parameters, the optimization would be run and route plan statistics and reports would be stored for analysis.

A total of 266 days of data were received from Southern Counties Express. The project team screened out data for days with insufficient data or where the data were affected by holidays, so that 243 days were used in the final analysis.

Additionally, the participating company provided their actual execution data corresponding to the same period in which data were captured to run the FRATIS optimization algorithm from

March 2019 to March 2020. This data consisted of all the completed orders by all drivers working for the company during this period. It included completion date, assigned driver, pickup and delivery locations, sequence of execution per day and driver, move type, equipment size and type, and mileage per order leg.

In order to accurately compare the two sets of data, the execution dataset had the following data items screened out: records completed during the night shifts, weekend, or holidays; records with zero mileage, order records associated with subcontractor carriers, and any long hauls and interstate orders.

When both datasets were prepared, the same dates and order records were matched in order to ensure an appropriate comparison between the actual execution data and the optimized data built by the tool.

Critical performance measures were compared in preparation of this report, including:

- Total number of orders scheduled
- Total Number of routes scheduled
- Average number of orders scheduled per day
- Average number of orders assigned per driver
- Average number of drivers with assignments per day
- Average miles per day
- Average miles per order
- Average daily miles per driver

3.3.4 Impact of Fuel Consumption of Vehicle Emissions

According to the Inventory of United States Greenhouse Gas Emissions and Sinks[14], emissions from transportation activities, in aggregate, accounted for the largest portion of total U.S. greenhouse gas emissions in 2018 with 28.4 percent across all sectors of the economy. Within the transportation sector, medium and heavy-duty vehicles account for the second largest producer of GHG emissions with 23 percent. Light vehicles like cars, pickup trucks and large vans represent the largest producer with 59 percent of the total transportation sector.

Carbon dioxide (CO_2) accounts for over 81 percent of all greenhouse gas emissions and makes up roughly 99 percent of the total greenhouse gases emitted from the tailpipe. GHGs can stay in the atmosphere for over 100 years and have great impact on earth's climate, raise sea levels, and result in dangerous effects to human health and welfare, and to ecosystems.

Because of this the United States Environmental Protection Agency (EPA) and the United States Department of Transportation's National Highway Traffic Safety Administration (NHTSA) have issued rules and standards to reduce GHG emissions. Table 11 below shows the Model Year 2017 combination tractor standards.

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[14] Inventory of United States Greenhouse Gas Emissions and Sinks
(https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks)

Table 11: Model Year 2017 Combination Tractor Standards

Category	EPA CO_2 Emissions			NHTSA Fuel Consumption		
	grams per ton-mile			gallons per 1,000 ton-mile		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Day Cab Class 7	104	115	120	10.2	11.3	11.8
Day Cab Class 8	80	86	89	7.8	8.4	8.7
Sleeper Cab Class 8	66	73	72	6.5	7.2	7.1

Source: Productivity Apex, Inc.

Additionally, heavy-duty trucks use diesel fuel which emissions include PM, NOx, carbon monoxide (CO), and other health pollutants that are associated to serious health and environmental issues. Combination trucks consume an average of 5.9 miles per gallon according to the 2018 National Transportation Statistics.

Table 12 below shows the estimated U.S. average vehicle emissions rates per vehicle for heavy-duty vehicles using diesel from 2000 to 2018.

Table 12: Estimated U.S. Average Vehicle Diesel Emission Rates per Heavy-Duty Vehicle, 2008 to 2018 (grams per mile)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total HC	1.064	1.059	1.070	1.031	0.973	0.917	0.835	0.781	0.732	0.687	0.645
Exhaust CO	3.908	3.848	3.851	3.651	3.392	3.151	2.804	2.570	2.361	2.171	1.994
Exhaust NOx	13.585	12.955	12.461	11.535	10.532	9.665	8.812	8.008	7.287	6.612	5.971
Exhaust PM2.5	0.614	0.583	0.564	0.512	0.462	0.418	0.357	0.317	0.280	0.246	0.213

Source: Bureau of Transportation Statistics (https://www.bts.gov/content/estimated-national-average-vehicle-emissions-rates-vehicle-vehicle-type-using-gasoline-and)

These standards are used to determine the potential impact in GHG emissions and other air pollutants based on the performance measures resulted from the use of the optimization tool.

3.3.5 Data Analysis Results

The objective of the FRATIS tool is to reduce the number of unproductive moves and distance traveled for drayage trucks operations using an optimization algorithm that considers operational constraints such as appointment times, driver's driving and duty time allotments, driver's staring location and time, and marine terminal wait-times through the GeoStamp integration. The following data illustrates the possible improvements achieved if the FRATIS tool had been implemented into the daily operations of Southern Counties Express.

Table 13 shows the data sets used in the analysis.

Table 13: Data Sets Analyzed

Data parameters	Optimized Data	Actual Execution Data
Number of days studied	243	243
Total number of orders scheduled/completed	44,099	33,995
Total number of routes scheduled/completed	23,890	20,543

Source: Productivity Apex, Inc.

As shown in Table 13 above, both datasets were based on 243 days of operation between March 2019 and March 2020, with atypical day types removed as discussed above. Also as shown in Table 13, there is a difference in the number of orders and routes scheduled and completed between the two datasets. This is due to the nature of the data collection for optimization versus actual execution: while the actual execution data comprises records of completed orders, the optimization data contains records of orders to be completed, thus the optimization data may have multiple entries for the same order if it was not completed on the day initially assigned. The analysis below normalizes these differences.

Table 14 shows a comparison for the daily performance measures between the optimized and actual execution data.

Table 14: Comparison of Daily Measures Between Optimized and Execution Data

Performance Measure	Optimized Data	Actual Execution Data
Average number of drivers with assignments per day	98.31	84.54
Total avg. number of orders scheduled/completed per day (productivity)	181.48	139.90
Total avg. number of orders assigned per driver (productivity rate)	1.85	1.65

Source: Productivity Apex, Inc.

Taking into consideration the previously calculated performance measures, three scenarios were developed to measure the impact in operational performance when the integrated optimization tool is used and when is not.

Scenario 1:

The number of daily drivers needed to complete 44,099 orders in the same time period and at an assignment rate of 1.65 orders per driver. This value corresponds to the assignment rate of the actual execution data.

Number of total routes needed to complete 44,099 Orders	26,649 routes
Number of daily driver assignments needed to complete 44,099 Orders	110 drivers/day

When compared to the 98 drivers per day needed to complete the same amount of orders when using the optimization tool, the value of 110 drivers per day represents an increase of 11.5 percent. This not only represents an increase in drivers but an increase in the number of vehicles used to complete the same amount of work.

Scenario 2:

The number of days needed to complete 44,099 orders assuming a level of productivity equal to 139.9 orders per day. This value corresponds to the level of productivity achieved without the use of the integrated optimization tool.

Number of days needed to complete 44,099 Orders	315 days

This value of 315 days represents an increase of 29.2 percent in the number of days needed to complete the same amount of work that was able to be scheduled in 243 days using the integrated optimization tool. This measure suggests that vehicle usage could have been avoided for 72 days, additionally to what all this represents in terms of operational logistics and personnel.

Scenario 3:

The number of orders to be completed assuming a fixed number of total routes at 20,453 and a daily assignment rate equal to 1.85 orders per driver. The number of total routes was obtained from the actual execution data and the daily assignment rate was the level resulted from the use of the optimization tool.

How many orders could have been done in 243 days	37,920 orders
Number of orders per day (productivity)	156 orders/day

By using the optimization tool, an identified improvement of up to 11.5 percent in the productivity levels can be obtained when compared to productivity levels of 140 orders per day resulting from the analysis of the actual execution data provided.

3.3.6 Monthly Performance Metrics Comparison

Tables 15 and 16 below show the performance metrics resulting from the analysis of the actual execution data provided by the drayage company and the use of the optimization tool on the daily files provided.

Table 15: Actual Execution Data Monthly Performance Metrics

Month	Number of days studied	Number of orders executed	Avg. number of drivers assigned per day	Total number of routes scheduled	Avg. number of orders executed per day	Avg. daily number of orders executed per driver
March 2019	12	367	25.83	310	30.58	1.18
April 2019	22	3716	108.23	2381	168.91	1.56
May 2019	6	1304	127.33	764	217.33	1.71
June 2019	13	1295	76.08	989	99.62	1.31
July 2019	22	3492	101.05	2223	158.73	1.57
August 2019	22	3593	99.86	2197	163.32	1.64
September 2019	21	4292	112.00	2352	204.38	1.82
October 2019	23	6145	132.91	3057	267.17	2.01
November 2019	20	2522	78.65	1573	126.10	1.60
December 2019	18	381	18.67	336	21.17	1.13
January 2020	22	2519	78.55	1728	114.50	1.46
February 2020	20	2385	74.20	1484	119.25	1.61
March 2020	22	1984	52.23	1149	90.18	1.73

Source: Productivity Apex, Inc.

Table 16: Optimized Data Monthly Performance Metrics

Month	Number of days studied	Number of orders scheduled	Avg. number of drivers scheduled per day	Total number of routes scheduled	Avg. number of orders scheduled per day	Avg. daily number of orders assigned per driver
March 2019	12	985	33.33	400	82.08	2.46
April 2019	22	4745	115.14	2533	215.68	1.87
May 2019	6	1720	149.17	895	286.67	1.92
June 2019	13	1805	87.46	1137	138.85	1.59
July 2019	22	3920	109.05	2399	178.18	1.63
August 2019	22	4313	115.27	2536	196.05	1.70
September 2019	21	5167	129.38	2717	246.05	1.90
October 2019	23	7400	153.22	3524	321.74	2.10
November 2019	20	4249	101.05	2021	212.45	2.10
December 2019	18	926	22.72	409	51.44	2.26
January 2020	22	3566	94.41	2077	162.09	1.72
February 2020	20	3060	92.90	1858	153.00	1.65
March 2020	22	2243	62.91	1384	101.95	1.62

Source: Productivity Apex, Inc.

The average number of orders scheduled per day can also be referred to as the productivity level. A comparison can be made by calculating the potential monthly productivity values using the average daily number of orders assigned per driver from the optimized data and the actual days and routes scheduled per month from the actual execution data.

Table 17 shows the comparison between the actual and the potential monthly productivity values.

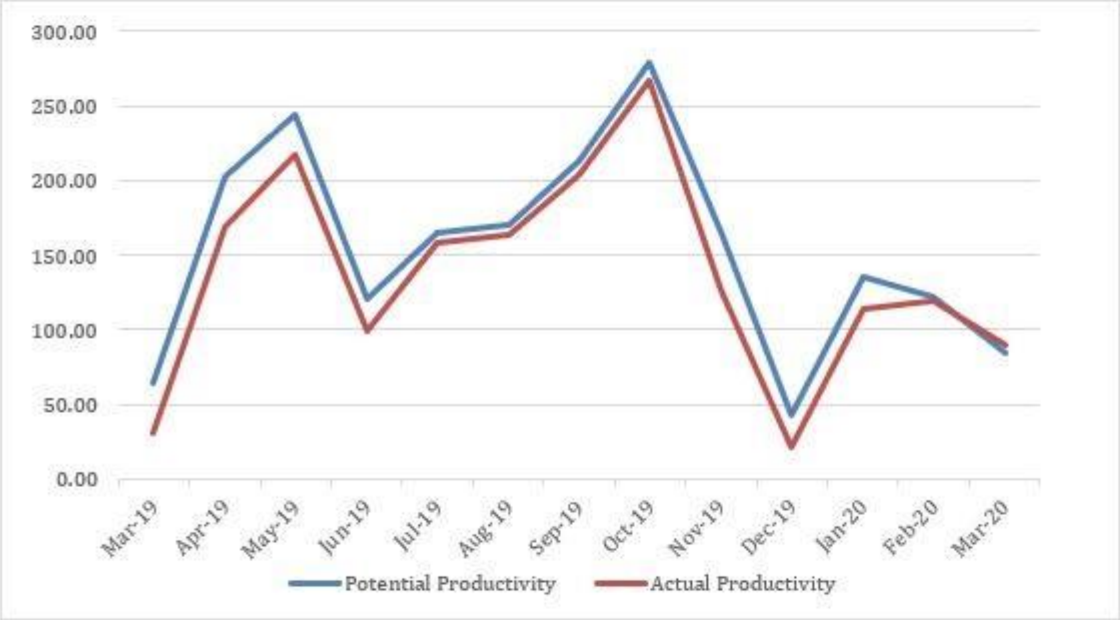
Table 17: Comparison of Actual and Potential Monthly Productivity

Month	Days per Month	Actual Productivity	Calculated Potential Productivity
March 2019	12	30.58	63.61
April 2019	22	168.91	202.74
May 2019	6	217.33	244.71
June 2019	13	99.62	120.77
July 2019	22	158.73	165.11
August 2019	22	163.32	169.84
September 2019	21	204.38	212.99
October 2019	23	267.17	279.10
November 2019	20	126.10	165.36
December 2019	18	21.17	42.26
January 2020	22	114.50	134.85
February 2020	20	119.25	122.20
March 2020	22	90.18	84.64

Source: Productivity Apex, Inc.

Figure 13 shows the graphical representation of the previous table. In the graphic it can be observed that the potential productivity acquired by using the optimization tool is greater in 12 out of the 13 months evaluated.

Figure 13: Comparison of Actual and Potential Monthly Productivity



Line graph representing productivity over time of potential and actual monthly plan.
Credit: Productivity Apex, Inc.

3.3.7 Traveled Distance Comparison

Although the data provided by the trucking company only contained the mileage within the stops in a leg or job and did not include the distance in between the executed jobs, nor the sequence in which they were completed, it was possible to find estimations of this distance in the available literature. These segments of the driver's daily route are also known as deadheading or empty miles in the freight industry.

According to the United States Census Bureau's 2002 Vehicle Inventory and Use Survey[15] (VIUS) – the most recent year the Census Bureau conducted the survey – mid-size and large asset-based carriers have a percentage of empty miles equal to 34 percent. Additionally, when analyzing the types of moves based on route distance, the survey shows that trucks that worked primarily short hauls (typical range of operation between 100 miles and 200 miles) drove about 36 percent of their miles empty; and those that worked primarily local hauls (typical range of operation within 100 miles of their home base) drove about 33 percent of their miles empty. The participating trucking company in this report falls in the category of mid-size and large asset based carrier and performs mostly short hauls and local hauls; hence, the value of 34 percent seemed fitting.

Table 18 below shows the original distance values obtained from the actual execution data, including its adjustment based on the percentage of estimated empty miles and from the results of the optimization tool.

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[15] United States Census Bureau Vehicle Inventory and Use Survey (https://www.census.gov/programs-surveys/vius.html)

Table 18: Adjusted Execution Miles to Include Empty Miles

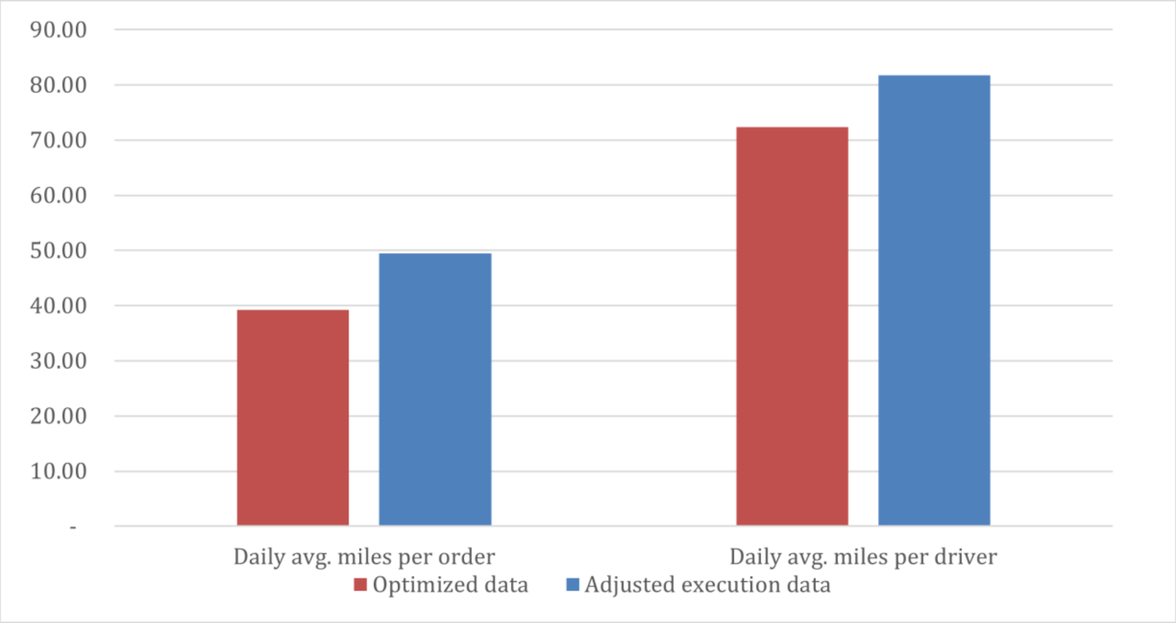
Performance Measure	Optimized data	Actual Execution data	Adjusted Execution data (based on 34 percent empty miles)	Percent Change Optimized vs. Adjusted Execution
Number of Orders	44,099	33,995	33,995	+ 29.7 percent
Total avg. miles per day:	7,112	5,161	6,916	+ 2.8 percent
Daily avg. miles per order:	39.2	36.9	49.4	- 20.7 percent
Daily avg. miles per driver:	72.3	61.1	81.8	- 11.6 percent

Source: Productivity Apex, Inc.

It is important to highlight from the previous table that the mileage values for the optimized data correspond to a set of 44,099 orders versus the 33,995 orders from the actual execution data. That is 29.7 percent more orders. However, the percentage increase in miles in the optimized data is only 2.8 percent compared to the adjusted execution data for a corresponding increase in orders of 29.7 percent.

Figure 14 shows a comparison between the adjusted execution data and the optimized data for daily average miles per order and daily average miles per driver.

Figure 14: Comparison of Optimized and Adjusted Execution Data



Bar graph comparing daily average miles per order and per driver for optimized vs adjusted execution data. Credit: Productivity Apex, Inc.

The previous figure shows that when using the optimization tool, it identified improvements of up to 20.7 percent when averaging the miles per order and an 11.6 percent in the average number of daily miles traveled by drivers can be obtained. This represents great potential savings in vehicle emissions and idling time.

3.3.8 Fuel Consumption and Emissions Reduction

Estimation on the reduction of air pollutants and greenhouse gases can be calculated using some of the results obtained from the use of the optimization tool.

Results from the previously presented Scenario 1 showed us that, by not using the optimization tool, at least 11 additional drivers and vehicles were needed to execute the same workload scheduled by the tool within the same period of time. For this, the following rates were calculated by averaging emissions rates between the year 2000 and 2018 from table 2 to account for multiple vehicle year models. The results are presented in Table 19 below.

Table 19: Average Emissions per Vehicle

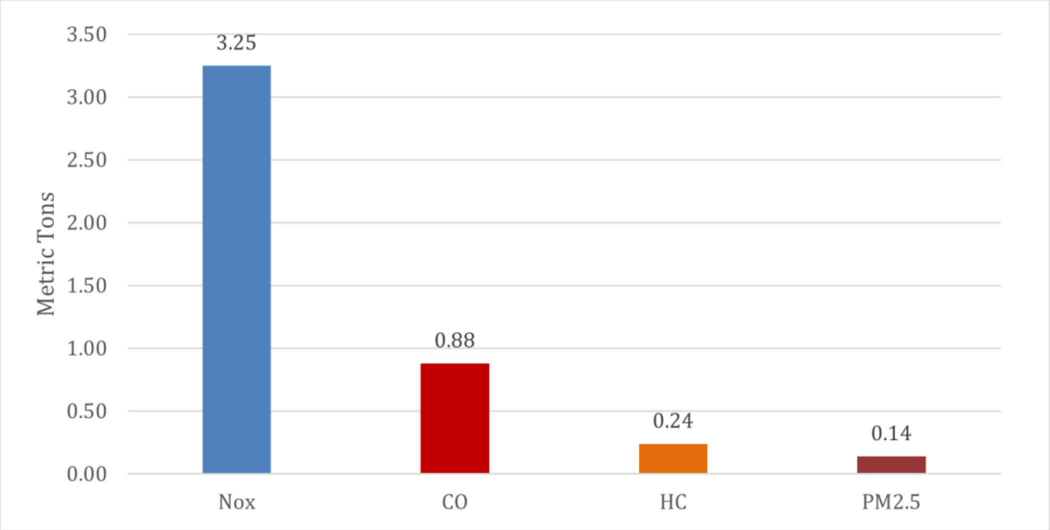
	Average Emissions per Vehicle 2000-2018 (grams per mile)
Total HC	1.01
Exhaust CO	3.73
Exhaust NOx	13.84
Exhaust PM2.5	0.61

Source: Productivity Apex, Inc.

As a result, these additional 11 vehicles needed represent 3.25 metric tons of NOx, 0.88 metric tons of CO, 0.24 metric tons of HC, and 0.14 metric tons of PM2.5 a year, assuming they operate 261 days a year (this correspond to number of weekdays in a year) at an average of 81.8 miles a day.

Figure 15 shows the potential reduction in Non-GHG emissions based on the proposed scenario.

Figure 15: Potential Reduction of Non-GHG Emissions



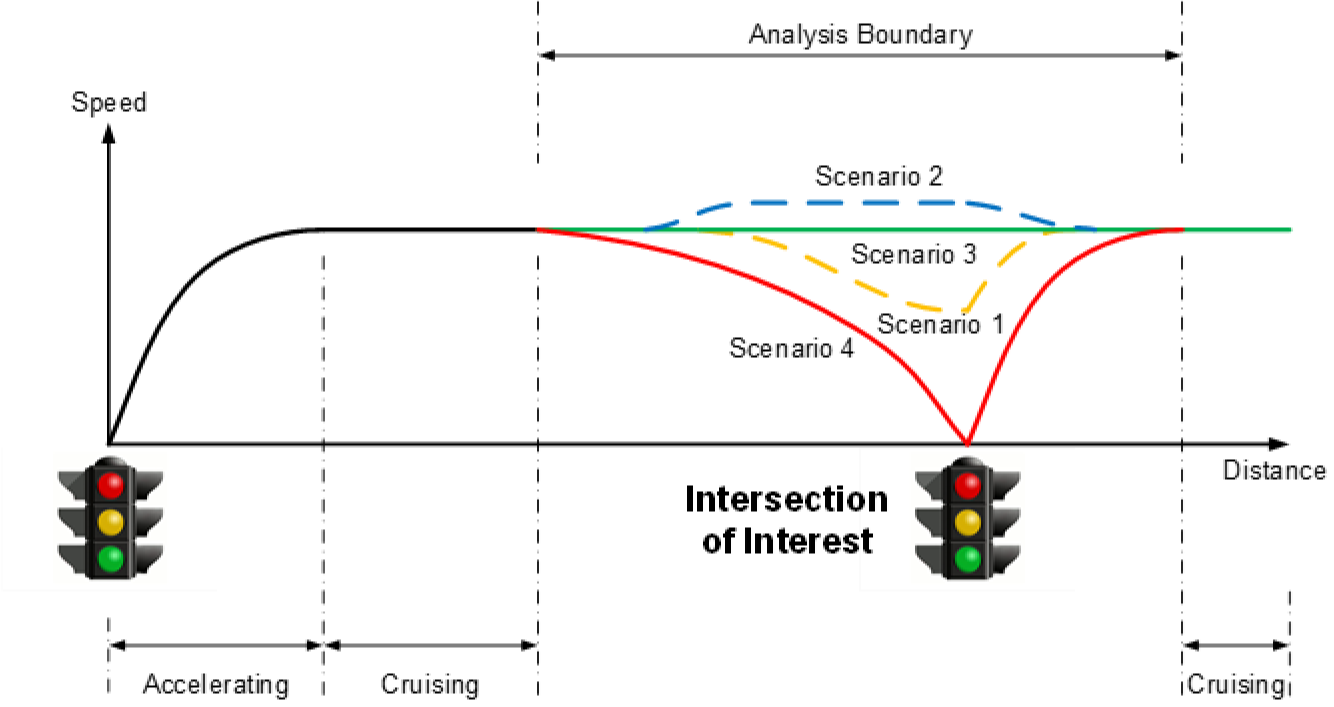
Bar graph comparing the potential reduction of Non-GHG emissions from proposed plan.
Credit: Productivity Apex, Inc.

Additionally, the use of the optimization tool showed an improvement of 11.6 percent in the number of daily miles traveled per driver, which in this study corresponded to nearly 9.46 miles a day. This would directly translate to a decrease of 11.6 percent in CO2 emissions and, assuming an average fuel consumption of 5.9 miles per gallon, a reduction of up to 418.5 gallons of fuel per year per vehicle.

3.4 Eco-Drive Overview

As part of the project, the University of California at Riverside (UCR) was responsible for developing and demonstrating the Eco-Drive system at the San Pedro port complex. The key underlying technology of Eco-Drive is the Eco-Approach and Departure (EAD) algorithm, which uses SPaT information from the upcoming traffic signal along with the information about the equipped truck and preceding traffic to determine the best course of action from one of the four possible scenarios shown in Figure 16. These are: 1) slowing down in advance so that the vehicle reaches the intersection just when the signal turns green; 2) speeding up (while staying under the speed limit) to pass through the intersection before the signal turns red; 3) cruising through the green light; or 4) coasting to a stop if the red light is truly unavoidable.

Figure 16: Scenarios when driving through an intersection with traffic signal

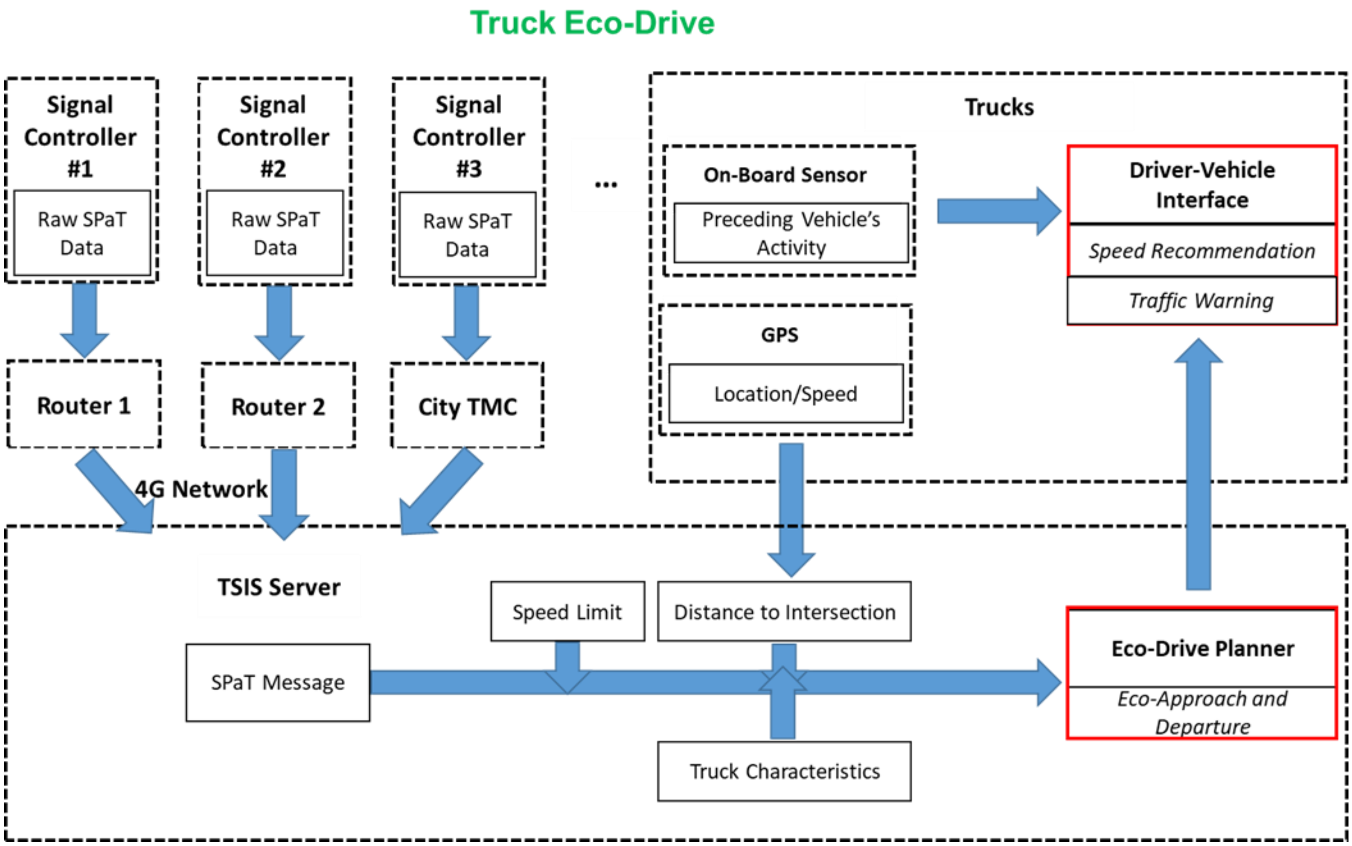


Curves representing four possible speed profiles when driving through a signalized intersection. Credit: University of California, Riverside

Previous studies showed that with well-designed trigonometric speed profiles, the driver would travel through the intersection in an eco-friendly manner which effectively minimizes stops and avoids unnecessary acceleration and deceleration [Barth et al., 2011]. The EAD system was first applied to the scenario with fixed time signals without any other traffic, and validated in microscopic traffic simulation and field experiment showing 10-20 percent reduction in fuel consumption. Based on the initial model, multiple variations have been developed to adapt to different signal and traffic conditions, such as actuated signals [Hao et al., 2019], signalized corridor [Barth et al., 2011], and congested traffic [He et al., 2015].

Once EAD has determined the best course of action, it then designs the optimal driving speed profile that would minimize delay and fuel consumption without compromising safety. This information can be delivered to drivers via visual display and/or voice notification to perform eco-approach and departure at the signalized intersection. In this project, the Eco-Drive system architecture and developed Eco-Drive algorithms were designed specifically for drayage trucks. Figure 17 illustrates the block diagram of the truck Eco-Drive system, which consists of several components as described briefly below.

Figure 17: Block Diagram of Truck Eco-Drive System



Block diagram showing system architecture of the truck Eco-Drive system. Credit: University of California, Riverside

1. *Traffic signal information*: This includes real-time SPaT messages from all connected signals. It can be acquired from the traffic signal operator's traffic management center if one is available. Otherwise, this information needs to be acquired from the traffic signal controller directly. The information is sent to the TSIS server over a cellular network.

2. *Global Positioning System (GPS) and map matching*: GPS is the source for vehicle location and instantaneous speed information. The digital map on the TSIS server is used, in conjunction with the vehicle location information from the GPS, to determine whether the truck is within the vicinity of a connected signalized intersection where SPaT is available. If so, the distance-to-intersection and road grade of the roadway are determined and used by the Eco-Drive Planner.

3. *Eco-Drive Planner*: This is the key component of the EAD system. Vehicle trajectory planning algorithms are developed to provide speed recommendation based on the state of the vehicle and the traffic signal. The Eco-Drive Planner receives and processes data inputs

from other system components, performs the calculation of the algorithms, and sends the resulting outputs to the on-board display.

4. *On-board sensor*: A camera-based range sensor is installed on top of the dashboard to detect preceding vehicles and monitor their activities. Sensor data is sent to the on-board tablet for use in the display state machine algorithm for governing the display of the recommended speed based on vehicle detection by the sensor.

5. *On-board display*: This can be in the form of either a tablet or a smartphone. The advisory driving speed range, preceding vehicle warning, and road speed limit information are displayed to the truck driver through DVIs.

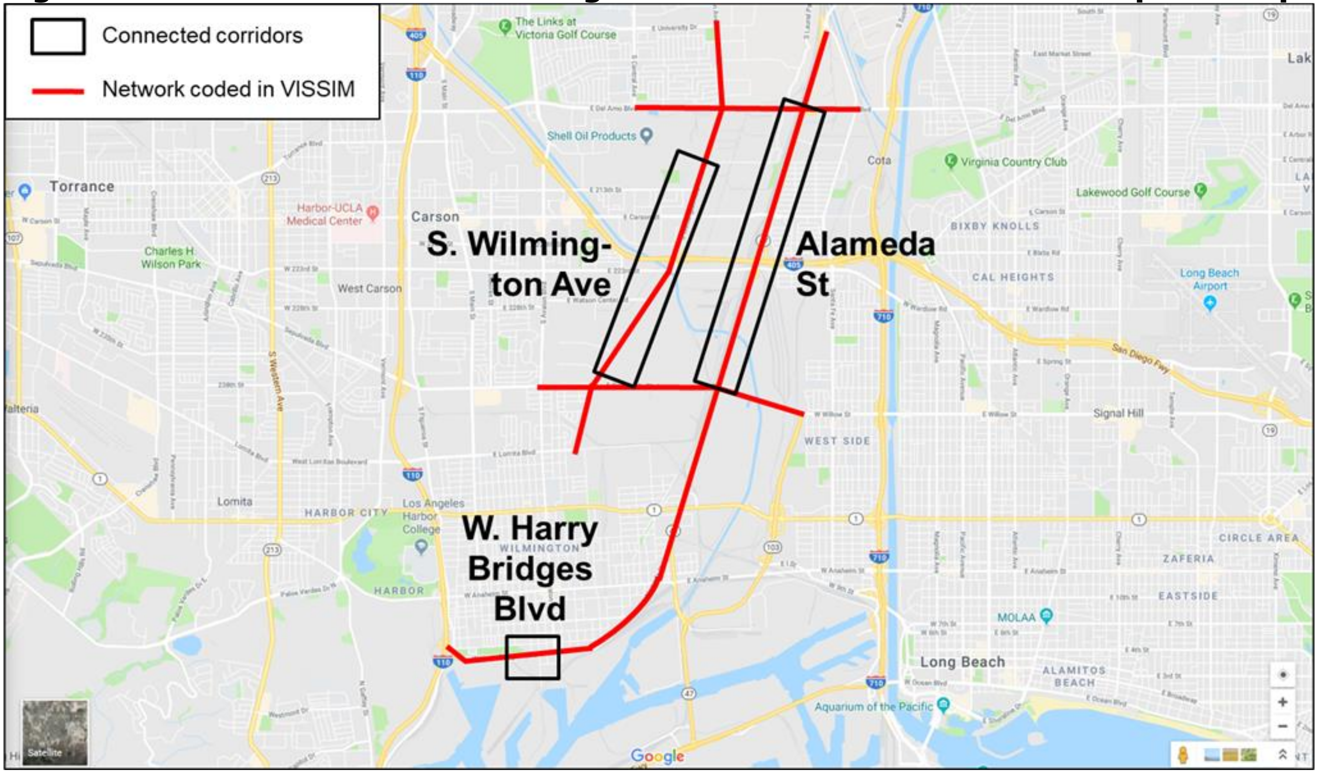
In the following sections, more technical details of the Eco-Drive system are provided, including the Eco-Drive infrastructure in Section 3.5, the Eco-Drive application in Section 3.6, and the evaluation of Eco-Drive in Section 3.7.

3.5 Eco-Drive Infrastructure

3.5.1 Connected Signalized Intersections Setup

The UCR team worked with POLA, LA Metro, Los Angeles County Department of Public Work, City of Carson, and City of Los Angeles Department of Transportation (LADOT) to deploy 15 connected signalized intersections nearby the San Pedro port complex to support a variety of connected vehicle applications. The 15 connected signalized intersections are located on three urban freight corridors, which carry a high volume of truck traffic: 1) Alameda Street, 2) S. Wilmington Avenue, and 3) W. Harry Bridges Boulevard Figure 18 shows the locations of the three connected signalized corridors.

Figure 18: Locations of connected signalized corridors near San Pedro port complex



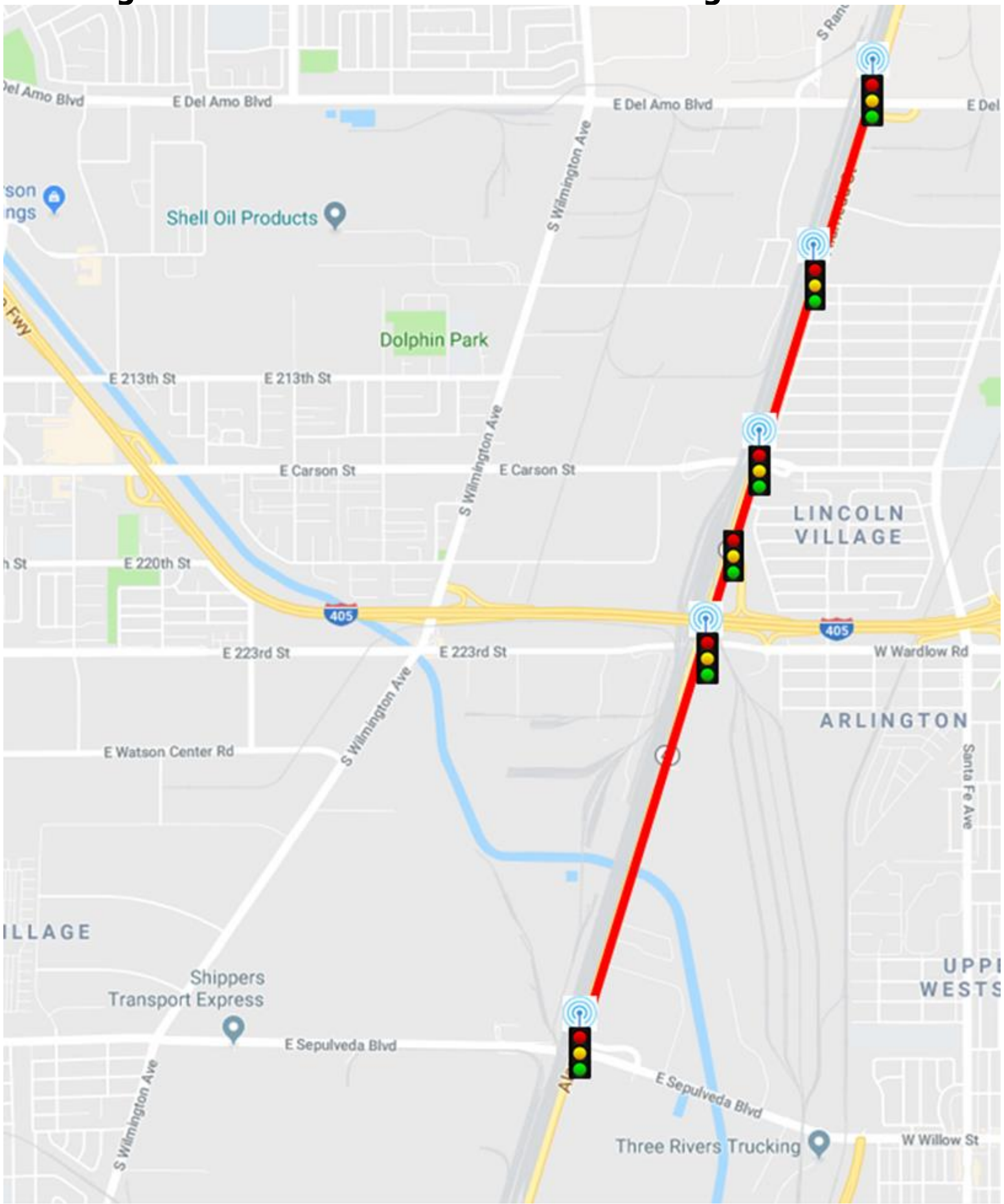
Map showing locations of connected signalized corridors near San Pedro port complex Credit: University of California, Riverside

Some characteristics of the corridors and the locations of the connected intersections are given in Figure 19 through Figure 21.

As shown in Figure 19, the connected corridor along Alameda Street is a 3-mile segment with 2-3 lanes per direction. The speed limit is 45 miles per hour (mph). There are six signalized intersections in the segment where five of them are connected (shown with the antenna sign in the figure). The five connected intersections include:

1. Alameda Street & E. Del Amo Boulevard
2. Alameda Street & E. Dominguez Street
3. Alameda Street & E. Carson Street
4. Alameda Street & 223rd Street
5. Alameda Street & E. Sepulveda Boulevard

Figure 19: Connected intersections along Alameda St.

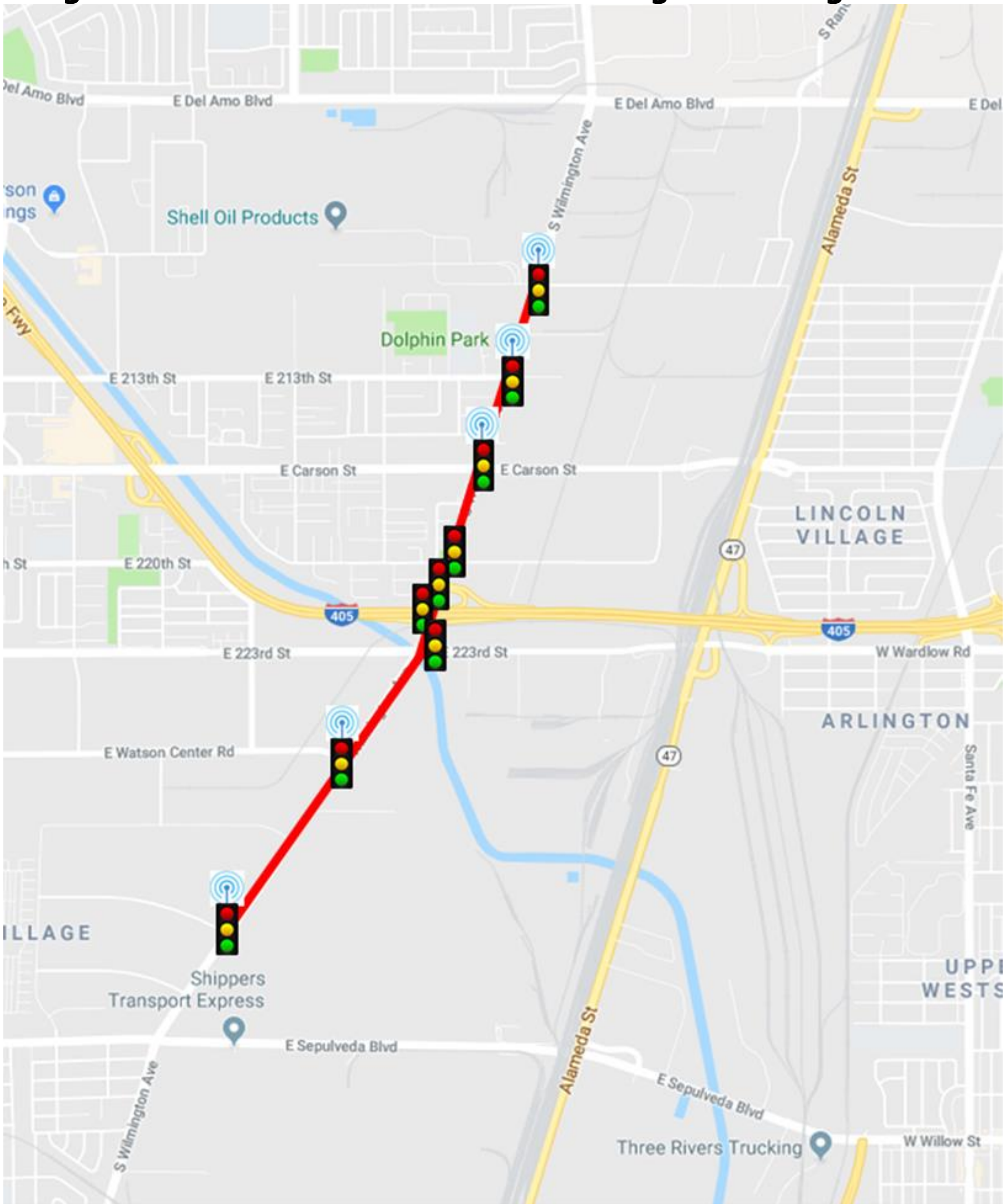


Map showing locations of connected signalized intersections along Alameda St.
Credit: University of California, Riverside

In Figure 20, the connected corridor along S. Wilmington Avenue is a two-mile segment with two lanes per direction. The speed limit is 40 mph. There are nine signalized intersections in the selected segment, with five of them being connected:

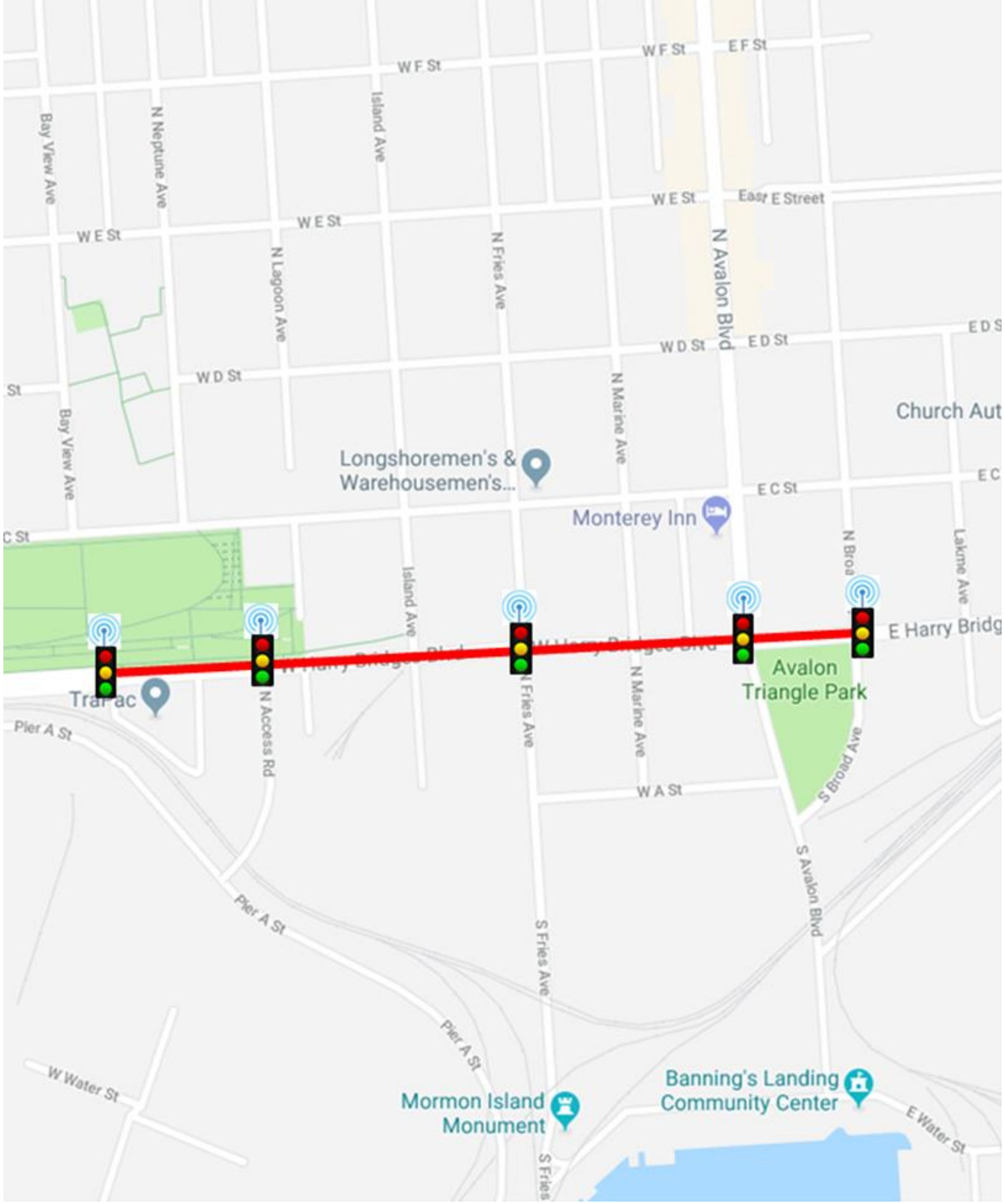
1. S. Wilmington Avenue & E. Dominguez Street
2. S. Wilmington Avenue & E. 213th Street
3. S. Wilmington Avenue & E. Carson Street
4. S. Wilmington Avenue & E. Watson Center Road
5. S. Wilmington Avenue & E. 233rd Street

Figure 20: Connected intersections along S. Wilmington Ave.



Map showing locations of connected signalized intersections along S Wilmington Ave
Credit: University of California, Riverside

Figure 21: Connected intersections along W. Harry Bridges Blvd



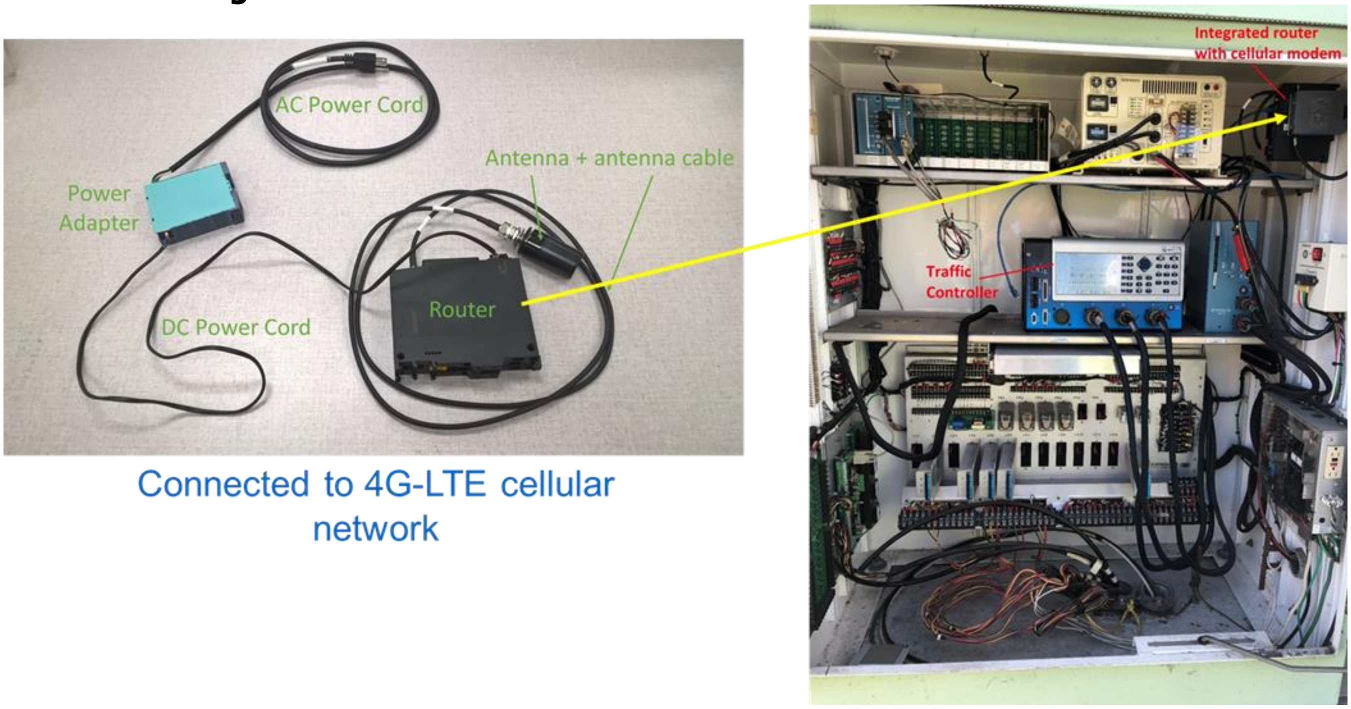
Map showing locations of connected signalized intersections along W Harry Bridges Blvd
Credit: University of California, Riverside

In Figure 21, the connected corridor along W. Harry Bridges Boulevard is a 0.5-mile segment with two lanes per direction. The speed limit is 35-40 mph. There are five signalized intersections, all of which are connected:

6. W. Harry Bridges Boulevard & Bay View Dr.
7. W. Harry Bridges Boulevard & N. Access Road
8. W. Harry Bridges Boulevard & N. Fries Avenue
9. W. Harry Bridges Boulevard & N. Avalon Boulevard
10. W. Harry Bridges Boulevard & Broad Avenue

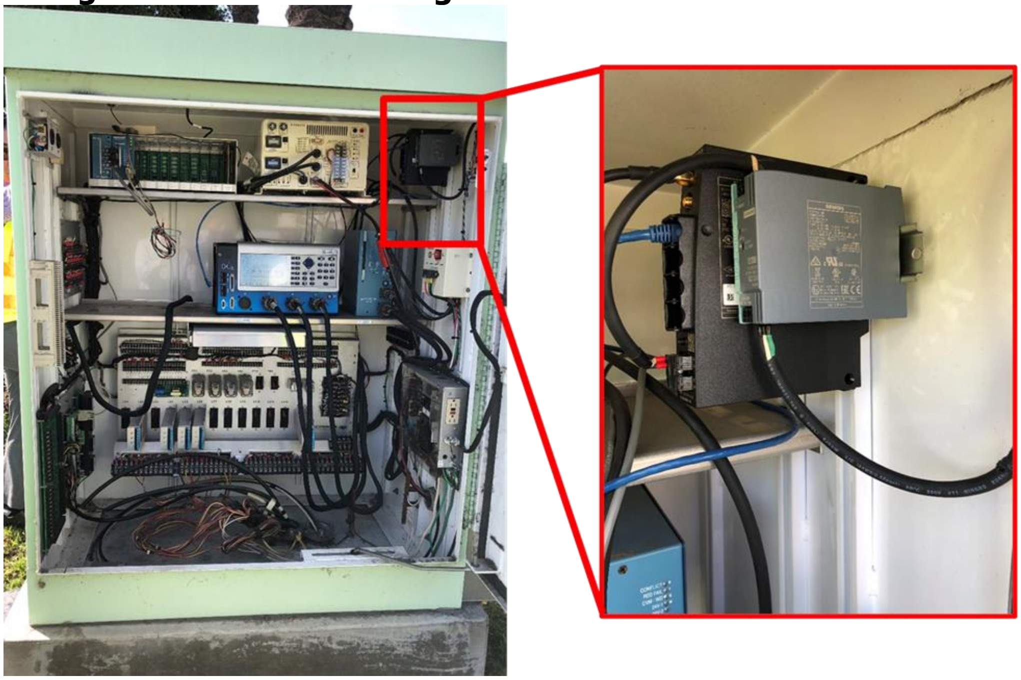
For the five connected intersections on W. Harry Bridges Boulevard, real-time SPaT data were obtained from the traffic management center of LADOT. On the other hand, the connectivity of the 10 connected traffic signals on Alameda Street and S. Wilmington Avenue is enabled by 4G/LTE where real-time SPaT data is sent to the TSIS server at UCR via cellular communication. Figure 22 shows the hardware configuration inside the controller cabinet at one of the intersections. The router mounted in the cabinet is a rugged, industrial-graded router that can withstand temperature of up to 160 degree Fahrenheit. After connecting to the traffic controller, the cellular modem forwards SPaT messages from the traffic controller to the TSIS server over 4G/LTE cellular network. The latency varies, but is usually around 1-2 seconds. This level of latency is acceptable for Eco-Drive, which is a non-safety critical application. Figures 23 and 24 shows the different cabinet configurations to connect a router with the traffic signal controller from Econolite and McCain, respectively.

Figure 22: Communication devices in the controller cabinet



Photos showing the communication devices in the controller cabinet at one intersection
Credit: University of California, Riverside

Figure 23: Cabinet configuration with Econolite controller



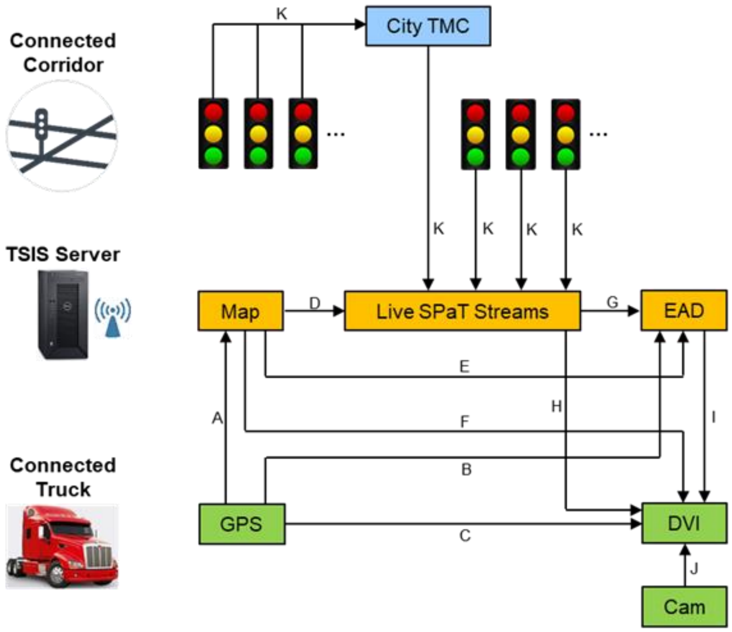
Photos showing the cabinet configuration with Econolite controller
Credit: University of California, Riverside

Figure 24: Cabinet configuration with McCain controller

Photos showing the cabinet configuration with McCain controller
Credit: University of California, Riverside

Vehicles traveling on the three corridors can receive real-time SPaT data of the connected intersections from the TSIS server through a cellular communication. Figure 25 shows the data flow of the cellular-based Eco-Drive application. The flow of SPaT data from the connected intersections to the connected truck is represented by arrows K and H in Figure 25. The TSIS server is also the host of digital map and Eco-Drive planner (i.e., the EAD block in the figure). The digital map uses the GPS data about the truck location from the tablet onboard the truck (arrow A) to identify the upcoming intersection, estimate the distance to the intersection, and determine the speed limit of the road by performing map-matching, and then return the results to the tablet to be displayed (arrow F). The Eco-Drive planner takes the vehicle speed data from the GPS (arrow B), the distance to the intersection result from the map (arrow E), and the SPaT information from the TSIS server (arrow G) to calculate the recommended speed for the connected truck, which is then sent to the tablet (arrow I). The Eco-Drive application running on the tablet then display the information received from all the sources on the DVIs.

Figure 25: Data flow of cellular-based Eco-Drive application



Component	Description
City TMC	Traffic management center
Map	Digital map of Southern California
Live SPaT Streams	Real-time SPaT from connected intersections
EAD	Eco-Approach and Departure algorithm
GPS	GPS for identifying truck position
Cam	Camera for detecting preceding vehicle
DVI	Driver-vehicle interface on tablet

ID	Data Elements	Update Frequency (Hz)
A	Latitude, longitude, & heading	1
B	Veicle speed (GPS)	1
C	Veicle speed (GPS)	10
D	Upcoming intersection & direction	1
E	Distance to intersection	1
	Roadway speed limit	1
F	Distance to intersection	1
	Roadway speed limit	1
G	Upcoming SPaT	1
H	Upcoming SPaT	1
I	Recommended driving speed	10
J	Preceding vehicle detection signal	10
K	Real-time SPaT	1

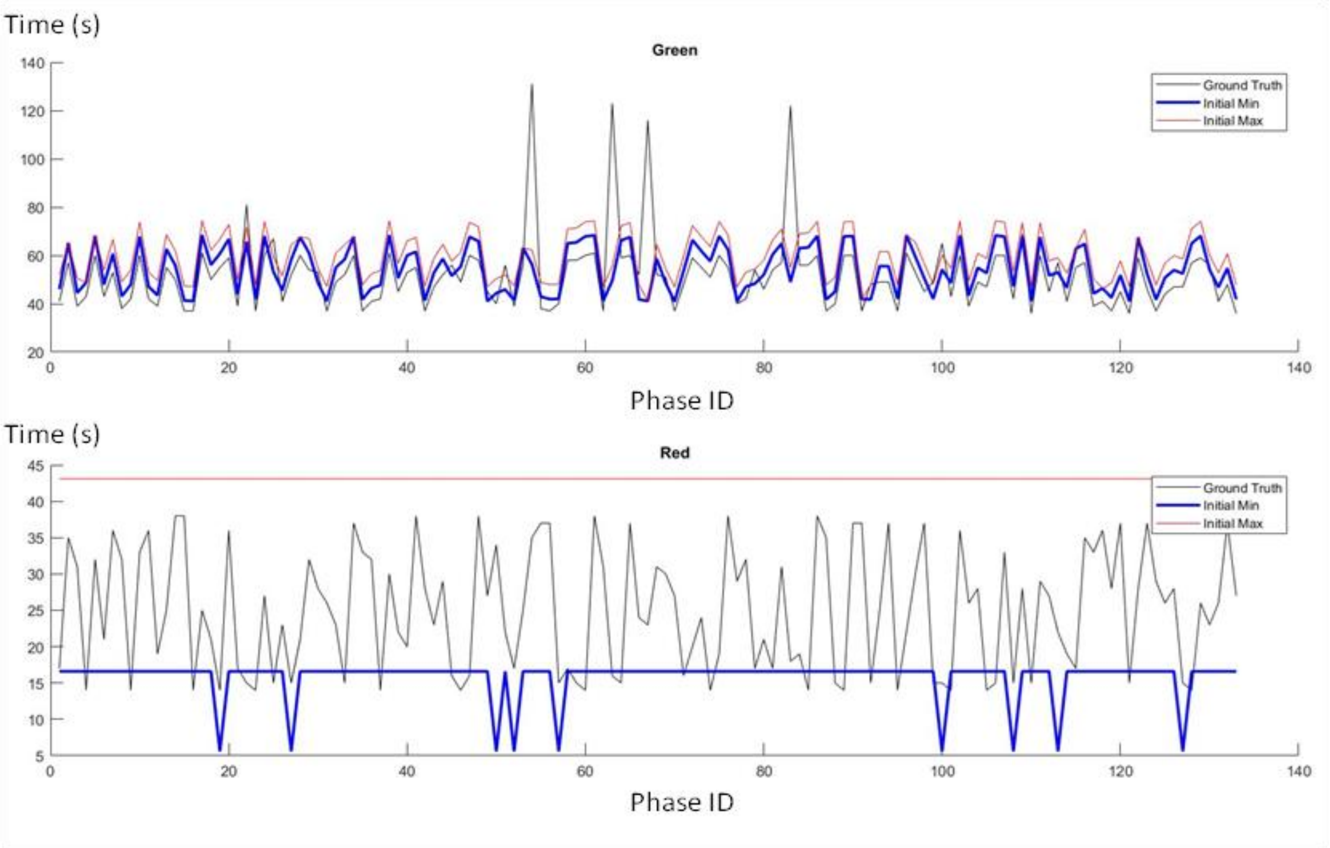
Diagram illustrating the data flow of the cellular-based Eco-Drive application
Credit: University of California, Riverside

3.5.2 SPaT Prediction

All the 15 connected intersections are configured with actuated signal control, in which the signal timing is dynamic due to the high variation in phase extension and phase skipping caused by vehicle actuation. When the connected truck is approaching a connected intersection with actuated signal control, the remaining time of the current signal phase indicated by the SPaT message will be updated dynamically due to the traffic from all directions. For any signal phase of an actuated signal system, the cycle length and phase duration are no longer a constant value. For this circumstance, the signal controller usually broadcasts minimum and maximum remaining time of the phase to provide a rough predictive range in SPaT. In Hao et al. (2019), a rule-based eco-driving algorithm has been developed based on the assumption that the min/max values in SPaT messages are reliable enough to represent the real upper and lower bound of the phase remaining time. However, the real SPaT data collected from the connected corridors show that even this assumption does not hold in many cases in the real world.

Figure 26 shows an example of SPaT for the major approach of one connected intersection. The minimum and maximum remaining time provided in the first second of the phase are compared, along with the exact phase duration. For the green phase, the exact phase duration is not well bounded by the min and max value, especially for cases when the green time is significantly extended due to minor phase skipping. For the red time, the min and max values provide a wide range for the remaining time, which also brings difficulty in phase duration prediction. These issues increase the difficulty to predict the actual remaining time in a phase using signal phase and timing (SPaT) information. It further brings a great challenge to derive an energy-efficient speed profile for vehicles to follow.

Figure 26: Sample SPaT messages from one connected intersection



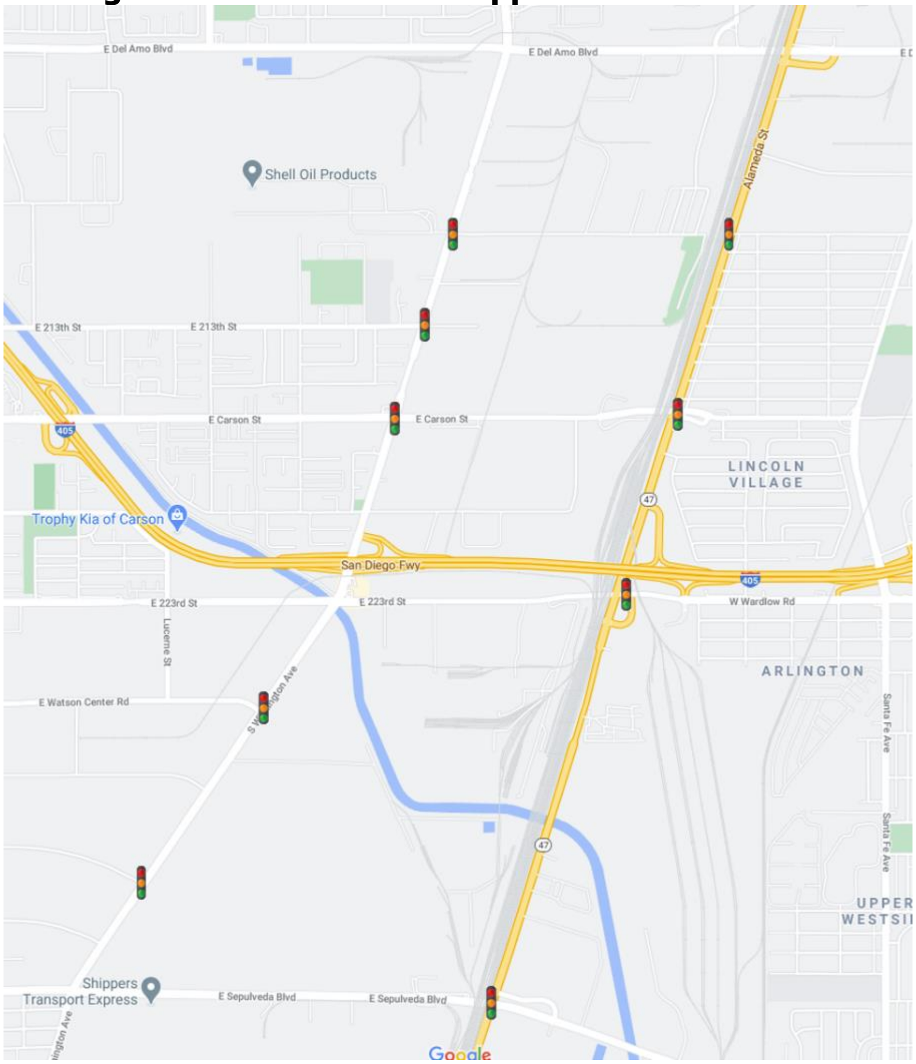
Plot showing a SPaT example of the major approach of one connected intersection
Credit: University of California, Riverside

As shown in Figure 25 the TSIS server receives continuous data streaming from each connected signal to collect and archive all SPaT data, including current signal phase, time in the current phase (t_p), minimum remaining time (t_{min}), and maximum remaining time(t_{max}). A machine learning model is then developed to predict the actual phase remaining time using both historical and real time SPaT information. In the following subsections, we will describe how we collect and preprocess the signal data, and then train the deep neural network using the preprocessed data.

3.5.3 Data collection and preprocessing

The SPaT data were collected from both Alameda and Wilmington corridors in Carson, California. As mentioned in the previous subsection, there are five connected intersections along each corridor. SPaT data from all 10 intersections were collected (Figure 27), but the data from Alameda Street at Del Amo Boulevard were not utilized in eco-driving as the truck made turns at this intersection during the test.

Figure 27: Intersections applicable to Eco-Drive



Map showing the locations of intersections that are applicable to Eco-Drive
Credit: University of California, Riverside

The SPaT information can be sent to the cloud and saved in the server in a frequency of 1 Hz. Taking Wilmington Avenue and Watson Center Road as an example, two different plans are designed for different day of week. Six subplans are used for weekday times and two subplans are used for weekend times, shown as below.

- Weekdays (Mon-Fri): Plan 1: 0:00-4:59, 5:00-8:59, 9:00-14:59, 15:00-18:59, 19:00-19:59, 20:00-23:59
- Weekends (Sat-Sun): Plan 2: 9:00-18:59, 19:00-8:59

All data are classified into a full phase based on its intersection, direction, subplan, and signal type and the actual total time of the phase is calculated using its total duration.

3.5.4 Long short-term memory (LSTM) network and structure

Given the nonlinear nature of actuated signals, the LSTM neural network is selected to be the training algorithm due to its significant ability of fitting complex dynamics with a large amount of sequential data. The input to the network will be the current signal phase, time in the phase, minimum remaining time, and maximum remaining time. The output of the network will be the total duration of the current phase. The complexity of the neural network has an impact on model accuracy. In general, the higher the complexity, the easier it is to fit the training data, but it is more likely to overfit and reduce the model's generalizability.

At time step t, the LSTM network receives the input data from the current time step, hidden and cell states from previous time step t-1, the initial state of the output, and predicts the output at the next time step t+1, which can be described as the mapping below:

$$y(t+1) = f(x(t), c(t-1), h(t-1), y_0) \tag{1}$$

where x and y are the input/output pair for each signal, c and h are the cell state and hidden state, respectively, produced by the LSTM cell to store the memory from previous time steps, y_0 is the initial state of the output, and f represents the mapping function.

For the training set collected on weekdays from July 15, 2019, to September 23, 2019, the different network structures were designed for red or green phase duration prediction, as shown in Table 20. The simpler design for the red phase is due to the less signal timing variation. The neural network consists of LSTM layers, dropout layers, nonlinear activation function, and fully connected layers (FC). A dropout layer is adopted with a dropout ratio of 0.2 after each LSTM layer to prevent over-fitting. The rectified linear unit is chosen to be the nonlinear activation function after each FC layer. During the training, the maximum epoch is set to be 100 with a preset early stop criterion to avoid over-fitting. The trainable parameters are updated using an adaptive moment estimation optimizer with an initial learning rate of 5×10^{-3}.

Table 20: Input/Output and Network Structure for Red/Green Phase Prediction

Phase	Input	Output	Structure
Red	Passing Time Min Remaining Time Max Remaining Time	Total Phase Time	LSTM(200) FC(1)
Green			LSTM(200) LSTM(100) FC(100) FC(100) FC(100) FC(1)

Source: University of California, Riverside

3.5.5 Test Result

To evaluate the performance of the proposed system, the mean absolute error (MAE) is calculated to evaluate the prediction accuracy. The MAE is defined as below:

$$MAE = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n} \tag{2}$$

where y is the ground truth value and $\hat{y}$ is the predicted value. To compare with the LSTM network, two other baseline methods, minimum and maximum prediction, are used as comparison, defined as below:

$$MAE_{min} = \frac{\sum_{i=1}^{n} \left| y_i - (t_{i_{min}} + t_{i_p}) \right|}{n} \tag{3}$$

$$MAE_{max} = \frac{\sum_{i=1}^{n} \left| y_i - (t_{i_{max}} + t_{i_p}) \right|}{n} \tag{4}$$

The preprocessed data is split into 80 percent training, 10 percent validation, and 10 percent testing. The testing result is shown in Table 21 and 22.

Table 21: Testing Result for Each Intersection South Bound

Intersection		Phase	MAE LSTM (sec)	MAE Min (sec)	MAE Max (sec)
Wilmington Ave. at …	Watson Center Rd.	Red	4.05	5.43	10.61
		Green	27.55	39.05	31.11
	Carson St.	Red	3.34	4.23	4.41
		Green	7.13	13.24	9.61
	213th St.	Red	6.14	10.17	10.02
		Green	17.99	0.80	0.80
	233rd St.	Red	4.22	5.48	5.51
		Green	47.62	54.14	54.14
	Dominguez St.	Red	5.31	7.01	20.25
		Green	18.42	26.38	24.16
Alameda St. at …	Dominguez St.	Red	60.97	92.05	65.68
		Green	44.46	49.64	51.63
	Carson St.	Red	6.45	8.72	26.53
		Green	14.97	14.18	14.25
	223rd St.	Red	0.64	13.12	13.12
		Green	3.10	26.41	26.41
	Sepulveda Blvd.	Red	3.72	7.60	17.20
		Green	31.67	39.17	49.75

Source: University of California, Riverside

Table 22: Testing Result for Each Intersection North Bound

Intersection		Phase	Error LSTM (sec)	Error Min (sec)	Error Max (sec)
Wilmington Ave. at …	Watson Center Road	Red	4.05	5.43	10.61
		Green	27.55	39.05	31.11
	Carson St.	Red	2.84	5.74	5.66
		Green	5.99	11.99	10.24
	213th St.	Red	6.14	10.17	10.02
		Green	17.99	0.80	0.80
	233rd St.	Red	2.27	3.21	3.34
		Green	65.77	69.99	69.99
	Dominguez St.	Red	4.03	4.80	23.59
		Green	14.20	38.37	44.30
Alameda St. at …	Dominguez St.	Red	63.16	66.36	92.30
		Green	42.04	48.19	46.51
	Carson St.	Red	6.41	8.84	28.06
		Green	16.15	20.55	43.10
	223rd St.	Red	3.06	7.64	14.71
		Green	6.54	0.66	0.66
	Sepulveda Blvd.	Red	2.56	7.37	8.02
		Green	11.33	10.64	10.27

Source: University of California, Riverside

As can be seen from the tables, the MAE of LSTMH network is less than the prediction direction provided by the minimum or maximum remaining time in both directions for the red phase. For the green phase, the MAE of LSTM network is smaller for over 70 percent of the intersections, showing that the proposed method is a better phase timing prediction method. The min and max values give too broad a range, which brings difficulty in phase duration prediction. The MAE for the green phase is higher, as the side-street traffic at some intersections is light and the phase assigned to those approaches may be skipped if there is no traffic. Then the green time duration of the study phase (associated with the main street) has high uncertainty due to frequent phase skipping from the side street.

3.6 Eco-Drive Application

In this section, UCR will first introduce the truck trajectory planning algorithm designed for eco-drive application. This algorithm is the basic model that is applicable to fixed-timing signals, so we further develop the on-board application and DVI that can accommodate actuated signals along with test corridors.

As the key component of the Eco-Drive system, Eco-Drive Planner determines the truck speed trajectory for passing through the intersection in a way that minimizes unnecessary idling and speed fluctuation. The flow chart of Eco-Drive Planner is shown in Figure 28, which includes the calculations in the cases of both fixed-time and actuated signals. In the case of actuated signals, the information regarding maximum/minimum time-to-change for the current phase is also needed. It can be extracted from the SPaT message, and then dynamic speed trajectory strategies are designed to adapt to the uncertainty in signal timing. To avoid driver distraction when the subject vehicle follows other vehicles, a state machine is introduced to govern the display of the advisory driving speed based on detection information from the onboard sensors.

Figure 28: Flow chart of Eco-Drive Planner

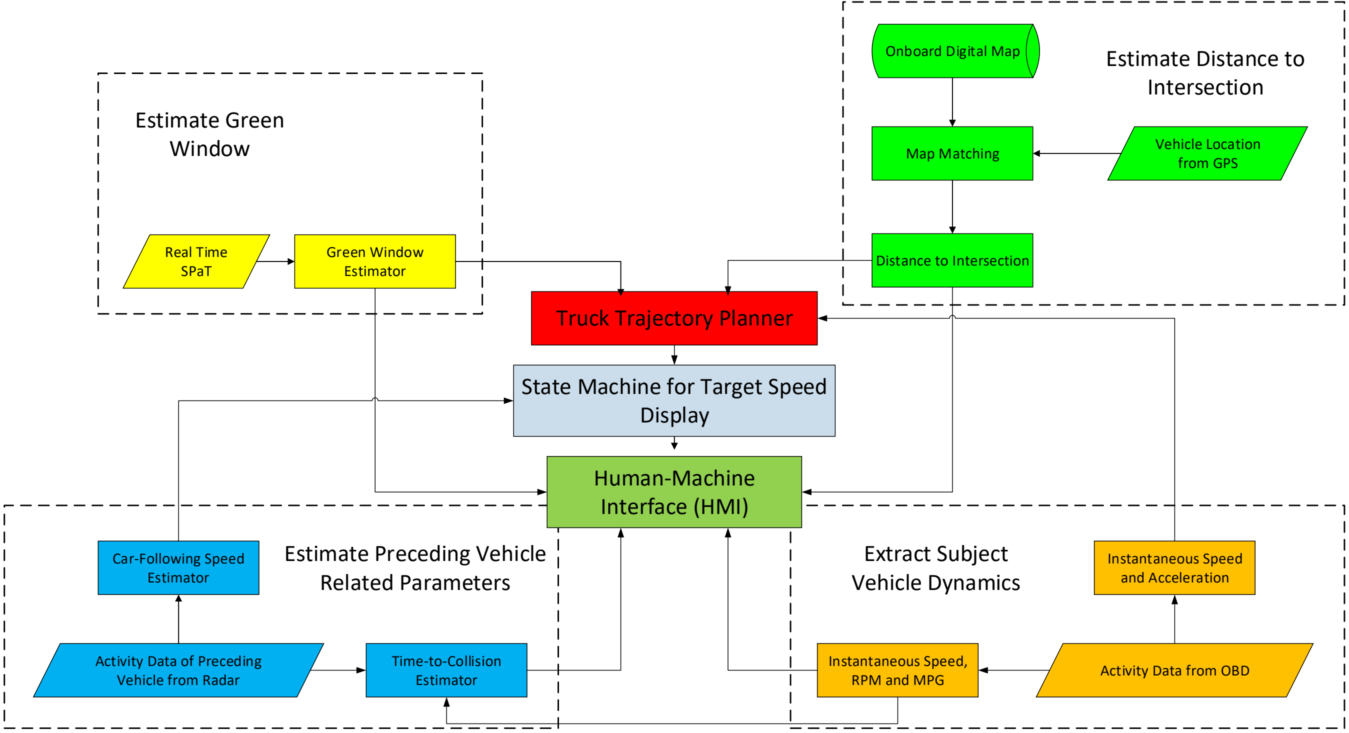


Diagram illustrating the flow chart in the Eco-Drive planner. Credit: University of California, Riverside

3.6.1 Trajectory Planning Algorithm

As the truck trajectory planner aims to find the most energy efficient strategy to pass the intersection without compromising mobility and safety, three rules are defined, list by priority:

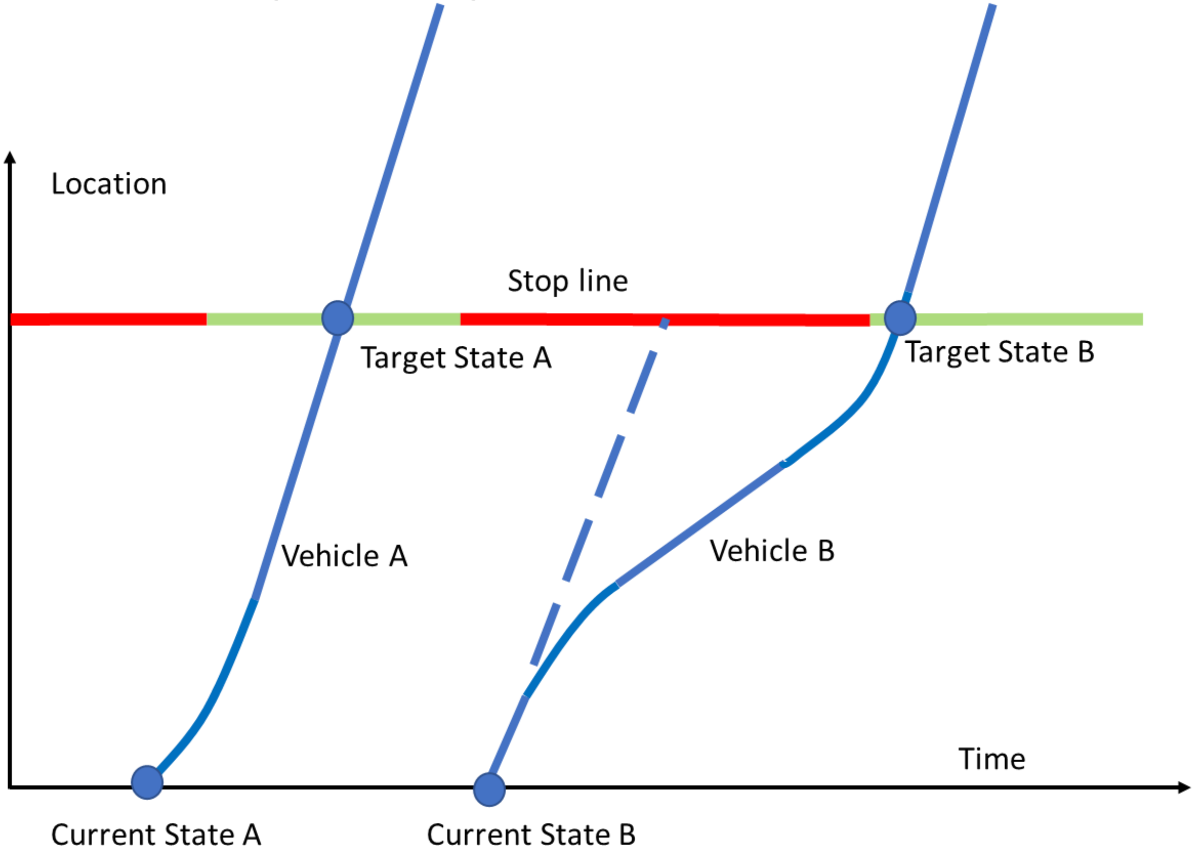
1. Safety Rule: No red violation, speed within speed limit $[0, v_l]$, acceleration in a proper range $[a_{min}, a_{max}]$;

2. Mobility Rule: Under Safety Rule, the vehicle will minimize the travel time to pass the stop line

3. Fuel-saving Rule: Under Safety Rule and Mobility Rule, the vehicle will minimize the total fuels consumed in the EAD process from the current state to the target state.

According to the Safety Rule and the Mobility Rule, the target state corresponds to the earliest time the vehicle can safely pass the stop line. As the speed limit is v_l and the max acceleration is a_{max}, assuming the vehicle first accelerates with a_{max}, then keep the speed if it reaches speed limit v_l, the time it can reach the stop line (defined as t_e) can be calculated based on kinematic equations. As t_e is the earliest time the vehicle can reach the stop line if ignoring the signal, it can be utilized to identify the target state. If t_e falls within the green time, it can be directly considered as the target time of vehicle (see Vehicle A in Figure 29). If t_e falls within the red time, the target time will be switched to the beginning the next green phase (plus a short buffer time, see Vehicle B in Figure 20).

Figure 29: Target state identification for EAD



Time-location plots showing the method to identify target state given current state of the truck. Credit: University of California, Riverside

Once Eco-Drive has determined the target state, it then designs the optimal driving speed profile that would minimize delay and fuel consumption without compromising safety. In this research, a powertrain-based energy optimization model is developed to find the optimal solution for drayage trucks. Road grade and preceding traffic information are also considered in the proposed model. The proposed model has two levels. In the lower level, UCR built a well-calibrated powertrain-based fuel consumption estimation model with speed and acceleration as the input. In the upper level, UCR formulated a shortest path problem with the combination of time, distance to intersection and speed as the state on each node, and fuel consumption rate as the cost on state transition.

3.6.2 Powertrain Model for Diesel Trucks

In the fuel consumption estimation model, UCR focused on diesel trucks with manual transmissions and assumed that the gear level is decided by the current vehicle speed v using a rule-based step function. When the vehicle is under traction mode, UCR assumes the engine speed ω is the vehicle speed multiple by the "lumped" gear ratio [Hu et al., 2017]

$$\omega = n \cdot v \tag{5}$$

where the lumped gear ratio $n = r_f r_t / r_r$ is decided by the final drive ratio r_f, the gear ratio of the transmission r_t, and the radius of wheel r_r . The unit of lumped gear ratio n is revolution per meter when the unit of engine speed is revolution per second and the unit of vehicle speed is m/s. As n is determined by the gear level, it can be formulated as a step function in term of speed.

$$n(v) = \sum_{i=1}^{G} \chi_{A_i}(v) N_i \tag{6}$$

where G is the number of gear level and N_i is the "lumped" gear ratio for gear level *i*. χ_{A_i} is an indicator function of speed interval A_i of gear level *i*, i.e.

$$\chi_{A_i}(v) = \begin{cases} 1 \;\; if \;\; v \in A_i \\ 0 \;\; if \;\; v \notin A_i \end{cases} \tag{7}$$

To simplify the model and improve the computation efficiency, equation (6) and (7) assumes a deterministic relationship between truck speed, gear level and gear ratio, as the truck speed is the only output that is deliverable to the drivers. UCR then used data to calibrate the average speed that the truck drivers shift to each gear level during the acceleration process, and the lumped gear ratio, for each gear level. More discussion on parameter calibration will be provided later in Table 13 of Powertrain Model Calibration section. Based on this assumption, the proposed model can find the optimal profile of speed, gear ratio and other associated parameters that connect the current state to the target state.

On the other hand, according to the overall longitudinal vehicle dynamics model, the acceleration rate of the vehicle depends on the traction/brake force and resistance force including grade resistance, rolling resistance and air drag, as shown in (8).

$$ma = F - (mg\sin\theta + \mu mg\cos\theta + \frac{1}{2} C_D \rho_a A v_i^2) \tag{8}$$

where *m* is the equivalent vehicle mass which is the sum of the actual mass and rotational mass (kg), *g* is gravity constant, θ is the road grade (rad), μ is the rolling resistance coefficient, C_D is the drag coefficient, $\rho_a$is the air density (kg/m^3) and *A* is the vehicle frontal area (m^2).

Equation (8) also indicates the critical acceleration rate when the vehicle is coasting (i.e. *F*=0):

$$a_{coast} = -g\sin\theta - \mu g\cos\theta - \frac{1}{2m} C_D \rho_a A v_i^2 \tag{9}$$

When the diesel truck is under coasting or braking mode, i.e. $a \leq a_{coast}$, UCR assumes the fuel consumption rate is a constant Q_i which equals to the fuel rate when idling.

When the diesel truck is under traction mode ($a > a_{coast}$), the tractive force based on engine torque τ (in Nm) is formulated as

$$F = \eta\tau \cdot \frac{r_f r_t}{r_r} = \eta\tau n \tag{10}$$

where η is the overall efficiency of powertrain. From (8) and (10), UCR derives the function of torque in term of speed and acceleration rate:

$$\tau = \frac{1}{\eta n}\left(ma + mg\sin\theta + \mu mg\cos\theta + \frac{1}{2} C_D \rho_a A v^2\right) \tag{11}$$

In this research, UCR regards $\tau \cdot n$ as a quadratic function as follows:

$$\tau \cdot n = \frac{m}{\eta}(a + g\sin\theta + \mu g\cos\theta) + \frac{1}{2\eta} C_D \rho_a A v^2 = \alpha_1(a + g\sin\theta + \mu g\cos\theta) + \alpha_2 v^2 \triangleq H(v, a, \theta) \tag{12}$$

Note that we regard the rolling resistance coefficient μ as a predefined constant, so two parameters, $\alpha_1 = \frac{m}{\eta}$ and $\alpha_2 = \frac{1}{2\eta} C_D \rho_a A v^2$, are two parameters to be calibrated in (12). UCR then uses activity data from on-road heavy-duty diesel vehicles to calibrate the parameters of the function.

The same truck activity dataset is also applied to generate the engine fuel consumption map for certain type of diesel trucks under traction mode. Based on that dataset, we fit the energy consumption rate Q as a quadratic function of torque τ and engine speed ω, as follows:

$$Q_t(\tau,\omega) = \beta_0 + \beta_1\tau + \beta_2\omega + \beta_3\tau\omega + \beta_4\tau^2 + \beta_5\omega^2 \tag{13}$$

UCR further substitutes (6) and (11) into (13) to reformulate $Q_t(\tau,\omega)$ as a function of speed, acceleration and road grade:

$$Q_t(v,a,\theta) = \beta_0 + \beta_1\frac{H(v,a,\theta)}{n(v)} + \beta_2 n(v)v + \beta_3 vH(v,a,\theta) + \beta_4\frac{H^2(v,a,\theta)}{n^2(v)} + \beta_5 n^2(v)v^2$$

$$if a > a_{coast} \tag{14}$$

3.6.3 Eco-Drive Trajectory Optimization

UCR first determined target arrival time at the intersection based on SPaT information, e.g. for Vehicle *B* in Figure 20, the target arrival time is the start of the next effective green phase; and for Vehicle *A*, the target time is the earliest time the vehicle can reach the stop line considering safety and vehicle dynamic constraint. UCR then developed a graph model to solve the trajectories planning problem with constraints on total travel time *T*, total distance *X* and destination speed v_d at the stop line. To formulate this graph model, UCR discretized the time and space into fixed time step Δt and distance grid Δx. The vehicle speed domain is therefore discretized with $\frac{\Delta x}{\Delta t}$ as the step. At each node of the proposed directed graph *G*=(*V*, *E*), UCR assigned a unique 3-D coordinate (*t*, *x*, *v*) which describes the dynamic state of the vehicle, where $t \in (0,T]$ is the time (in second), $x \in [0,X]$ is the distance to the intersection (in meter) and $v \in [0,v_l]$ is the speed (in m/s), where v_l is the speed limit In this graph. Note that v>0 if x>0, as the vehicle is only allowed to stop at the stop line. There is an edge from V_1 (t_1, x_1, v_1) to V_2 (t_2, x_2, v_2) if and only if following rules are satisfied:

1) Time at V_2 is consecutive with time at V_1: $t_2 = t_1 + \Delta t$;

2) Consistency on distance and speed: $x_2 = x_1 + v_1\Delta t$

3) Acceleration constraint: $a_{min} \le \frac{v_2-v_1}{\Delta t} \le a_{max}$, where a_{min} and a_{max} are the maximum deceleration rate and maximum acceleration rate for the study diesel truck, respectively.

UCR further defined the cost on edge $V_1 \to V_2$ as the fuel consumption during this state transition process. UCR assumed the road elevation satisfies a predefined function of distance *r*(*x*). Then the road grade θ from V_1 to V_2 can be expressed as:

$$\theta_1 = arcsin\frac{r(x_2)-r(x_1)}{x_2-x_1} = arcsin\frac{r(x_2)-r(x_1)}{v_1\Delta t} \tag{15}$$

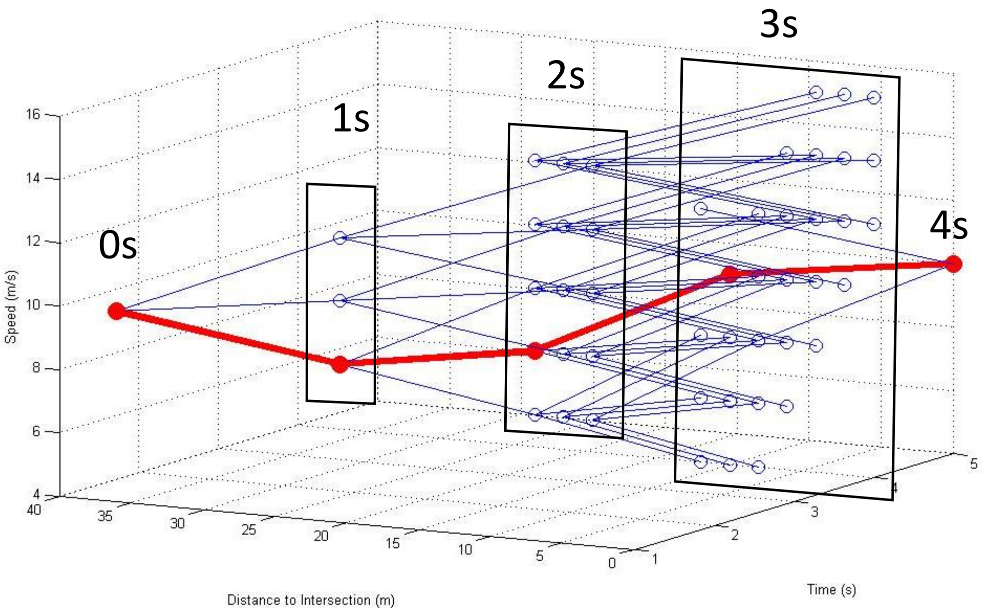
Since the average acceleration rate is $\frac{v_2-v_1}{\Delta t}$ and the average speed is v_1, the cost on edge $V_1 \to V_2$ satisfies:

$$\varepsilon_{V_1\to V_2} = \begin{cases} Q_t(v_1,\frac{v_2-v_1}{\Delta t},\theta_1) & if\ \frac{v_2-v_1}{\Delta t} > a_{coast} \\ Q_i & if\ \frac{v_2-v_1}{\Delta t} \le a_{coast} \end{cases} \tag{16}$$

At this point, the fuel consumption minimization problem is converted into a problem to find the shortest path from the source node V_s(0, *X*, v_s) to the destination node V_d (*T*, 0, v_d) in the directed graph *G*=(*V*, *E*). We apply Dijkstra's algorithm [Dijkstra, 1959] to solve this single-source shortest path problem with non-negative cost.

Figure 30 illustrates a simple EAD optimization problem as an example. The vehicle aims to traverse 36 meters in exactly 4 seconds. The initial speed is 10 meters per second (m/s) and the final speed is also 10 m/s. We further take 1 second and 2 meters as the time step and distance grid, and take 2 m/s2 and -2 m/s2 as the upper and lower bound of the acceleration rate. In Figure 21, circles represent nodes in the graph, and lines represent edges. According to the first rule for edge definition, edges are added between nodes from two consecutive time frames. The highlighted piece-wise linear curve represents the shortest path from the source node to the destination node, which corresponds to the optimal EAD speed profile with minimal fuel consumption. Note that this is a simplified example with small node and edge size to clearly show the entire network. The proposed algorithm is able to deal with more complicated problem with longer time period/distance and higher time/location resolution efficiently, as the time complexity for Dijkstra's algorithm is O(log(N)*E) [Dijkstra, 1959].

Figure 30: Shortest path graph of a simplified Truck EAD problem



3-D plots explaining the shortest path graph of a simplified Truck EAD problem.
Credit: University of California, Riverside

3.6.4 Powertrain Model Calibration

The proposed powertrain model is calibrated using vehicle activity data from 100 heavy-duty diesel trucks collected in California. On-board electronic control unit (ECU) data loggers were connected to the vehicle's controller area network (CAN) bus through J1939[16] port for heavy-duty vehicle and engine performance studies. An ECU data logger can record engine parameters such as gear ratio, engine torque, engine speed, fuel rate, altitude etc. at high frequency for a long period of time. Based on the ECU data from one sample diesel truck, UCR

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[16] Society of Automotive Engineers standard SAE J1939 is the vehicle bus recommended practice used for communication and diagnostics among vehicle components.

first explored the critical speed for gear shift and the average lumped gear ratio for each gear level in equation (6).

Table 23: Gear ratio and critical speed for gear shift

Gear level	Gear ratio	Critical speed (mph)	“Lumped” gear ratio (m-1)
1	3.51	0.3	255.0
2	1.90	11.2	100.6
3	1.44	20.1	71.2
4	1.00	27.2	50.2
5	0.74	37.2	37.8
6	0.64	48.9	33.4

Source: University of California, Riverside

In Table 23, the critical speed for gear level N is defined as the average speed that the truck drivers shift to Nth gear during the acceleration process. The lumped gear ratio is the average engine speed – speed ratio for each gear level based on (5).

Based on the engine torque and vehicle speed, acceleration and road grade data, UCR calibrated the parameters in (12), the engine torque equation.

$$\tau \cdot n(v) = 62118(a + g\sin\theta + \mu g\cos\theta) + 55.263v^2 \tag{18}$$

The parameters in energy consumption equation (13) are calibrated using energy rate, torque and engine speed data in the ECU dataset, as shown in Table 3.

$$\begin{aligned} Q_t(\tau,\omega) = {} & 0.486 + 4.225\,\mathrm{x}10^{-3}\tau + 5.091\,\mathrm{x}10^{-4}\omega \\ & + 1.749\,\mathrm{x}10^{-5}\tau\omega + 9.674\,\mathrm{x}10^{-4}\tau^2 + 2.396\,\mathrm{x}10^{-7}\omega^2 \end{aligned} \tag{19}$$

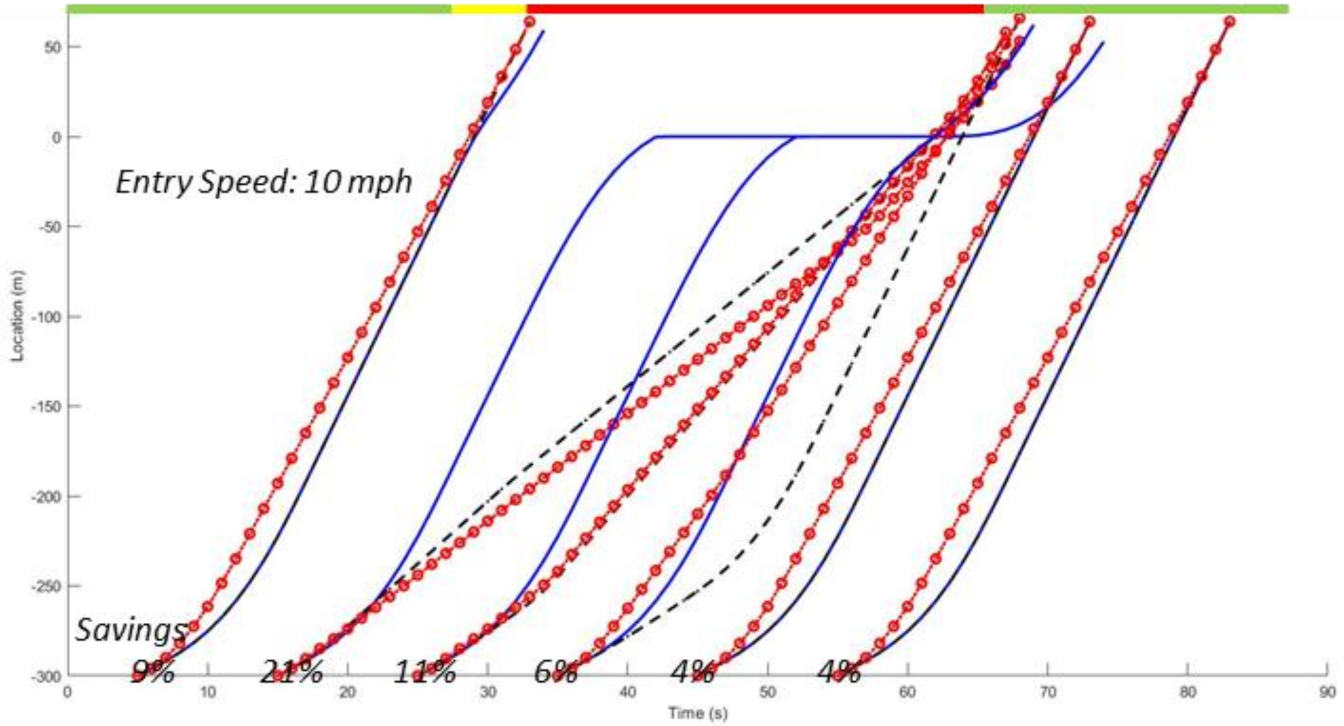
The fitted model matches well with the data as the R-Square is 0.92.

3.6.5 Numerical Experiments

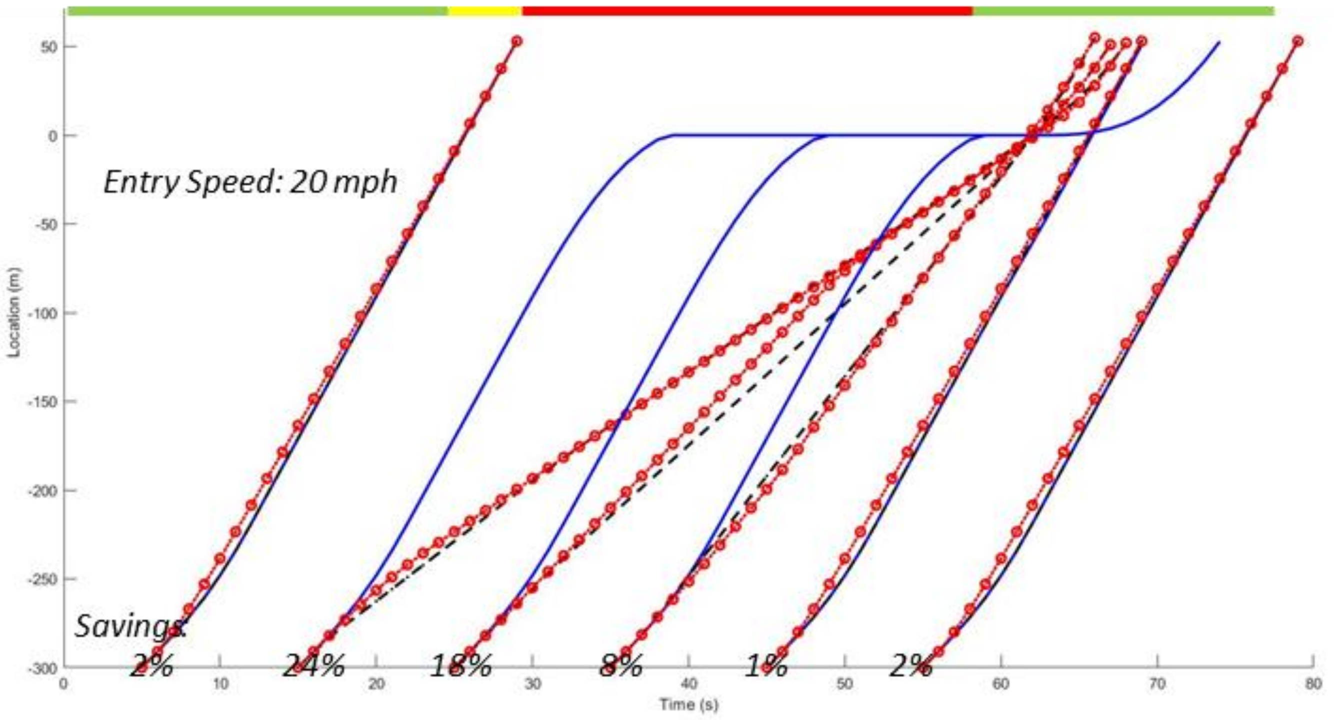
In this section, the proposed EAD algorithm is applied to simulate vehicle trajectories of a single diesel truck at a hypothetical signalized intersection with different entry times. The length of the study area is 300 meters: from 300 meters upstream of the intersection to the stop line. The speed limit is set to 40 mph. The time of the green phase is 27s, the time for yellow is 3 seconds and the time for the red phase is 30 seconds. As shown in Figure 4, six different entry times in a cycle are tested: the 5th second in Green (G5), the 15th second in Green (G15), the 25th second in Green (G25), the 5th second in Red (R5), the 15th second in Red (R15) and the 25th second in Red (R25). UCR also tested multiple initial speeds from 10 mph to 40 mph, with 10 mph as the increment.

UCR first tested the performance of the proposed method for level terrain where the road grade is assumed to be 0. In Figure 31(a)(b)(c)(d), UCR shows the numerical results for four scenarios under different entry speed. The blue solid curves represent the trajectories from an uninformed driver with time as priority. The black dashed curves represent the trajectories baseline trigonometric EAD algorithm which was widely applied in previous studies [Barth et al, 2015; Hao et al, 2019]. The red curves with circles represent the trajectories designed by the proposed diesel truck EAD algorithm. UCR also showed the signal phase using different colors in the figure. Note that in each figure UCR overlayed the trajectories of the single study truck under six different entry time.

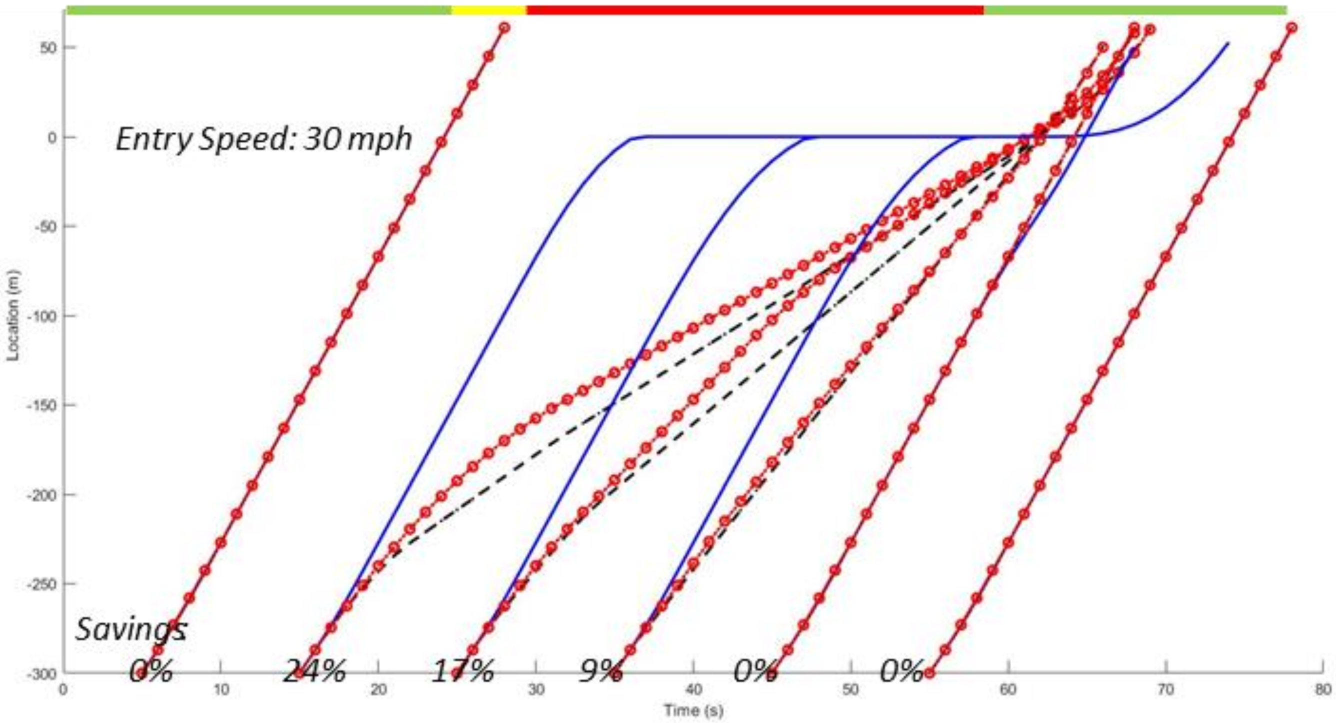
Figure 31: Trajectories comparison for EAD algorithm



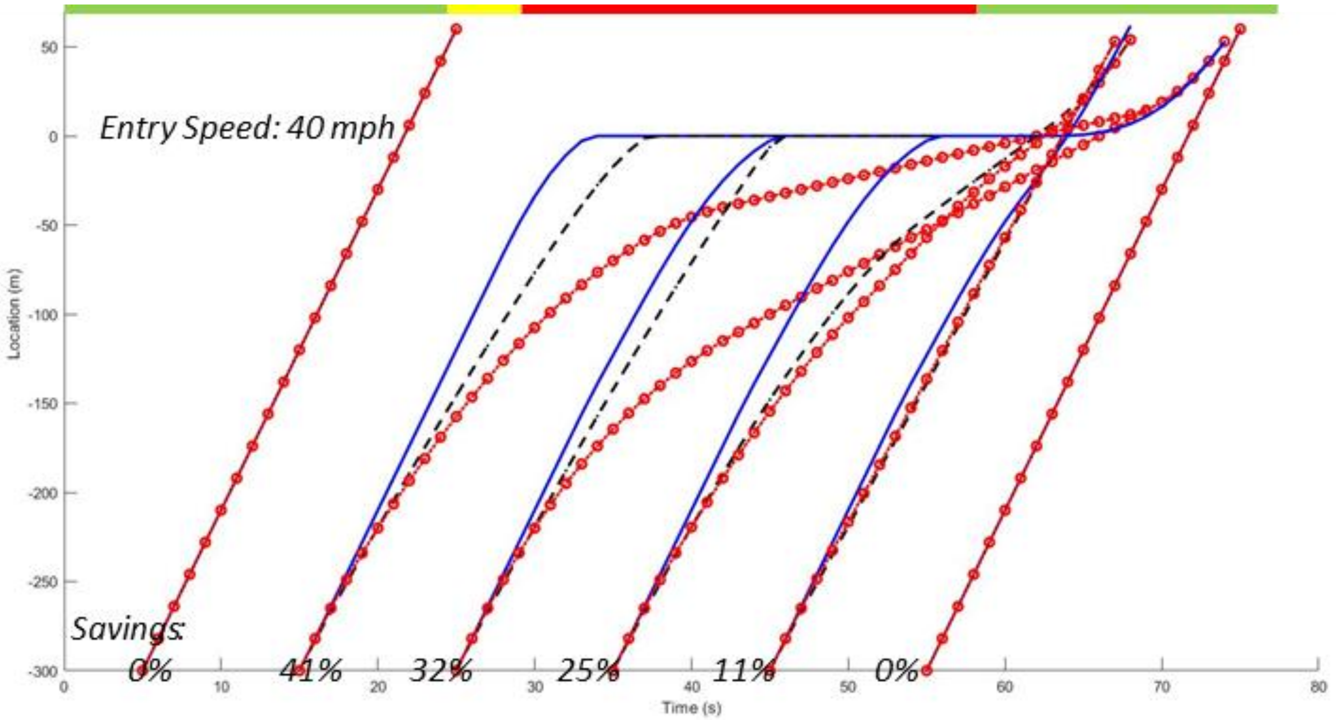
(a) Entry speed: 10 mph



(b) Entry speed: 20 mph



(c) Entry speed: 30 mph



(d) Entry speed: 40 mph

Four time-location trajectory plots comparing the proposed model and baseline models
Credit: University of California, Riverside

For entry time G5, R15 and R25 that correspond to scenarios 2 (acceleration first) and 3 (keep the speed) in Figure 31, the trajectories designed by the new algorithm are similar to those from uninformed driver or previously developed methods. For entry time G15, G25 and R5, as the vehicles have to slow down first and reach the intersection just when the signal turns green, the trajectories designed by the new method show significant difference from the traces designed by the baseline methods. In Figure 31(d), the proposed truck EAD method suggests a non-stop profile, while either uninformed driver or trigonometric EAD algorithm suggests stopping at the stop line. In Figure 31(a)(b)(c), both proposed and trigonometric methods design non-stop trajectories, but they have different strategies in developing the speed profiles for deceleration.

In Table 24, UCR shows the percentage fuel saving of the proposed truck EAD algorithm by comparing the uninformed driver with the baseline trigonometric algorithm. This table indicates that significant energy benefit comes along with scenarios 1 and 4 given entry time G15, G25 and R5. Meanwhile, higher entry speed usually corresponds to higher fuel saving. On average, the proposed EAD method saves 11.0 percent fuels from the uninformed driver and 5.9 percent from the baseline trigonometric algorithm. Note that for R15/30 mph scenario the proposed truck EAD algorithm consumes more fuels than the baseline method, as the discretization on time and space may slightly affect the optimization performance. For all other cases, the proposed method has stable energy benefit. Compared with uninformed driving scenario, the proposed algorithm also significantly reduces the travel time for diesel trucks by 7 percent due to the reduction of start-up delay at the beginning of the green phase. If UCR takes 1 second and 1 m/s as the time/speed step, the computation time is about 0.6s for a 20s trip in MATLAB on a computer with Intel i7 CPU@2.40GHz and 8G RAM. It shows that the computation efficiency is good for real time application.

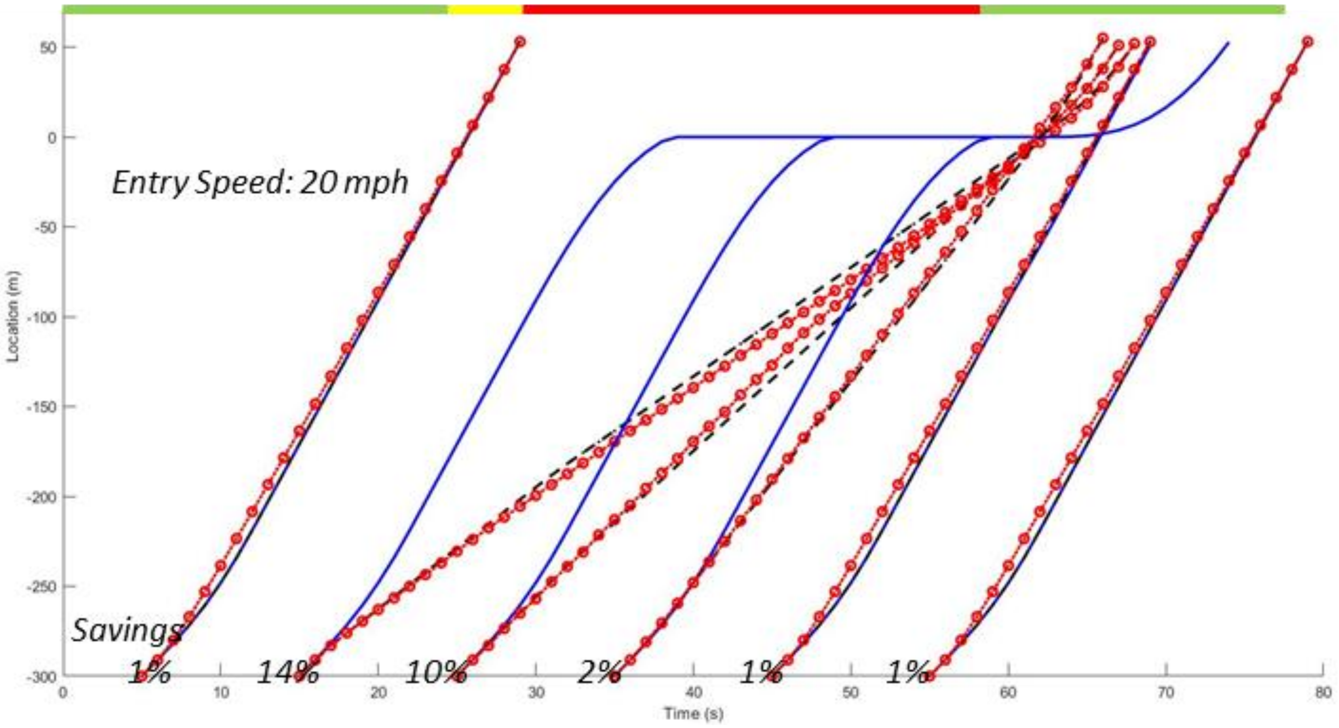
Table 24: Percentage fuel savings from the uninformed driver – comparison between proposed truck EAD algorithm and baseline trigonometric algorithm

Speed / Time	10 mph		20 mph		30 mph		40 mph	
	Proposed	Baseline	Proposed	Baseline	Proposed	Baseline	Proposed	Baseline
G5	8.9	5.5	1.6	0.0	0.1	0.0	0.0	0.0
G15	21.3	19.6	24.0	22.4	23.5	19.4	40.6	11.6
G25	10.7	9.3	17.6	16.4	16.9	11.6	31.5	-4.5
R5	6.1	0.3	7.9	7.0	9.4	5.7	25.3	11.0
R15	3.5	0.0	1.0	-0.6	-2.5	-2.7	10.9	2.1
R25	3.5	0.0	1.6	0.0	0.1	0.0	0.0	0.0
Average	9.0	5.8	9.0	7.5	7.9	5.7	15.3	2.8

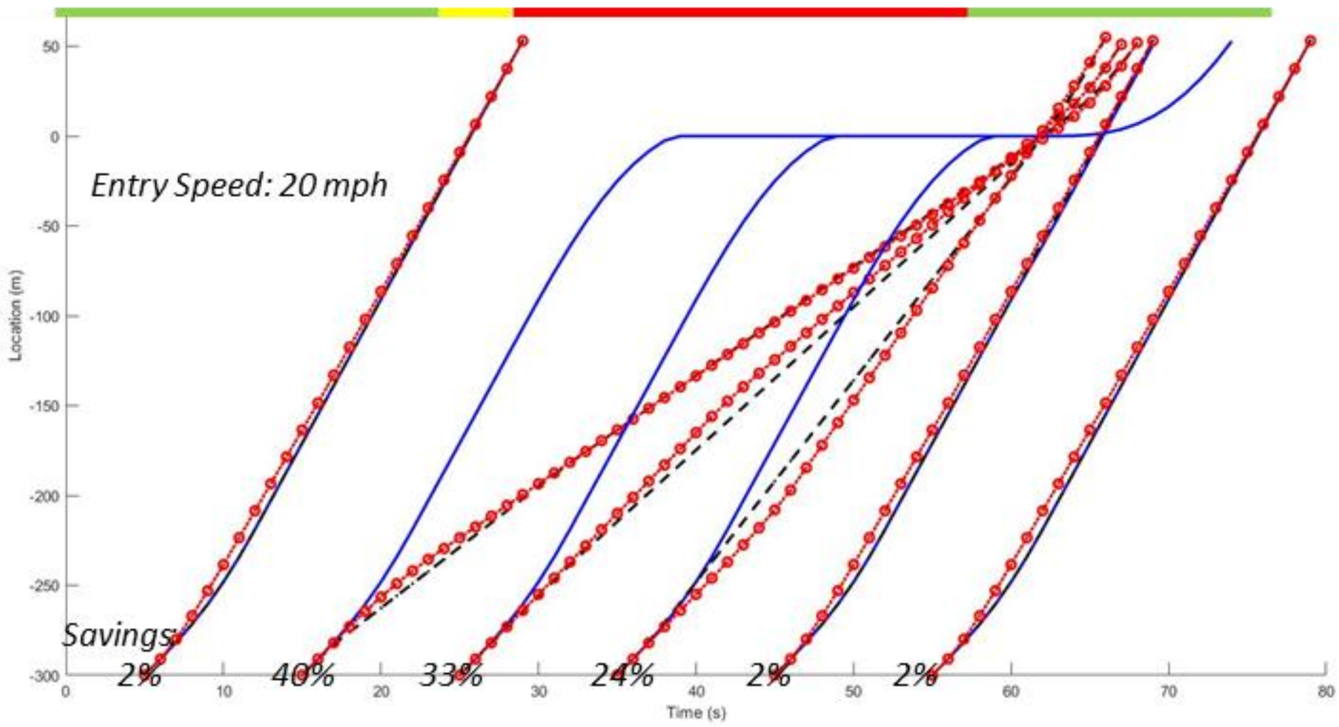
Source: University of California, Riverside

UCR further tested the impact of road grade on the performance of the proposed method. UCR assumed the experiment is conducted in both uphill and downhill roads with 5 percent as the constant road grade, and keep other configuration the same as previous experiments. In Figure 32(a), UCR assumed 20 mph as the initial speed to enter an uphill road segment, and plot the estimated trajectories of three strategies: 1) the proposed algorithm considering road grade (red curve with circles); 2) the baseline trigonometric EAD algorithm ignoring road grade (black dashed curve); and 3) uninformed driving strategy (blue solid curve). As 2) and 3) do not consider road grade factor when developing the strategy, their trajectories are exactly the same as those from Figure 31(b), but the fuel consumption should be higher for this uphill case. In Figure 32(b), UCR shows the estimated trajectories from three methods in a downhill road segment with 20mph as the entry speed as well.

Figure 32: Trajectories comparison for EAD algorithm considering road grade



(a) Uphill with 5 percent road grade. Entry speed: 20 mph



(b) Downhill with 5 percent road grade, Entry speed: 20 mph

Two time-location trajectory plots comparing the proposed model and baseline models considering road grade. Credit: University of California, Riverside

Based on the estimated trajectories, UCR can compute the fuel saving of the proposed truck EAD algorithm considering road grade in Table 25. On average, for uphill road, the proposed EAD method saves 5.6 percent fuels from the uninformed driving method, and 3.7 percent from the baseline method. UCR also compared the performance of proposed EAD model considering road grade with the proposed EAD method ignoring road grade. The improvement is only 0.2 percent. That means road grade is not a dominant factor for EAD design in rolling terrain. If road grade information is not available in the study area, the proposed method still works with similar performance. For the downhill cases, the proposed EAD method saves 18.7 percent fuels from the uninformed driving method, and 14.6 percent from the baseline method. which is higher than the saving for level terrain and uphill case. The addition energy saving by knowing road grade is 1.4 percent.

Table 25. Percentage fuel savings of the proposed truck EAD algorithm on rolling terrain

Speed Time	Uphill with 5% road grade				Downhill with 5% road grade			
	10 mph	20 mph	30 mph	40 mph	10 mph	20 mph	30 mph	40 mph
G5	4.8	1.4	0.2	0.0	16.6	2.2	0.0	0.0
G15	12.5	14.3	12.9	28.2	39.4	40.4	36.0	39.4
G25	3.8	9.5	7.6	18.9	26.3	33.1	30.6	36.4
R5	1.2	1.7	2.4	12.5	19.2	23.6	24.5	39.2
R15	2.7	0.8	-2.9	5.6	5.3	2.5	3.0	27.7
R25	2.7	1.4	0.2	0.0	5.3	2.2	0.0	0.0
Average	5.8				20.2			

Source: University of California, Riverside

Weight is another key factor to impact the fuel consumption of diesel trucks. During deliveries, the weight of the truck may vary significantly based on its status, e.g. from bobtail to fully loaded. According to equation (8), the tractive power of the truck is approximately linear to the weight if all other factors are fixed. By changing the value of ɑ1 in equation (11), UCR can further estimate the fuel consumption rate of the truck by substituting the updated value of torque into equation (13). In this paper, UCR tested two cases with doubled weight and halved weight respectively from the original truck calibrated by the raw data. The optimal trajectories that minimize the total fuel consumption based on the new powertrain models are then derived respectively. For the double-weighted case, the proposed method would save 9.4 percent fuels from the uninformed driving. For the half-weighted case, the saving is as high as 14.2 percent. Table 16 shows the comparison results from all the special case, including rolling terrain and different weight. Like the rolling terrain case, UCR also considered the case if weight information is not available during the trip. UCR then estimated the optimal trajectory by applying the standard truck EAD algorithm which uses the average wight value in the model. As shown in Table 26, knowing exact weight information can save up to 0.5 percent addition energy, but even without the weight information, the fuel saving is still significant. Therefore, in practice, UCR can apply the standard EAD algorithm assuming zero grade and average weight to design the standard optimal trajectory and then approximate the optimal solution from any common road grade and weight condition, with both high fuel efficiency and high computational efficiency.

Table 26. Fuel savings of the proposed truck EAD algorithm on multiple special cases

Method Case	Uninformed driver Fuel rate (gallon/mile)	Baseline trigonometric algorithm Saving (percent)	Proposed truck EAD algorithm Saving (percent)	“Standard” truck EAD algorithm Saving (percent)
Level, normal weight	0.196	5.9	11.0	11.0
Uphill, 5 percent road grade	0.266	2.2	5.8	5.6
Downhill, 5 percent road grade	0.131	14.6	20.2	18.7
Double weight	0.354	4.7	9.4	9.0
Half weight	0.121	8.1	14.2	13.7

Source: University of California, Riverside

3.6.6 On-Board Application for Actuated Signals

3.6.6.1 EAD algorithm for actuated signals

Unlike previous studies for fixed-timing signals, the EAD for actuated signals in real-world traffic needs to be adaptive to the dynamic uncertainty in the states of both signals and traffic. It is unrealistic to design a perfect trajectory when the vehicle is still far away from the intersection. At the beginning of a green/red phase, it is difficult to accurately predict the remaining time as there is significant uncertainty in actuations and thus extension period of the active phase. The minimum and maximum time-to-change usually have large gap in the beginning, and converge to the same value when the phase comes to the end. To adapt the uncertainty from the actuated signals, UCR designed a rule-based model that covers all possible scenarios in both green and red time.

Considering the impact of drivers’ adaptability to eco-driving, UCR introduced a buffer time (t_b) to guarantee safety even when the driver does not accurately follow the advised trajectory. The EAD algorithm is then developed based on the effective time-to-change which considers the buffer time. For the green time, the maximum/minimum effective time-to-change (denoted as g_u/g_l) is the sum of maximum/minimum remaining green time (G_{max}/G_{min}) and yellow time (Y), minus the buffer time (t_b). Similarly, UCR can derive the effective time-to-change for the for the red time (r_u/r_l). In yellow time, UCR turned off the speed recommendation display to give control to drivers for safety reason.

UCR then defined the threshold distance d_s as the minimum distance for a vehicle to make a safe stop from the current speed comfortably. It is computed based on the deceleration speed profile model. If the vehicle is close to the intersection (i.e., $d \leq d_s$), a safety-prior rule is implemented to guarantee that the vehicle never passes the intersection on red time. A conservative strategy is made based on the minimum time-to-change for the green time and maximum time-to-change for the red time, which are the boundaries of guaranteed green phase. If the vehicle is far from the intersection (i.e., $d > d_s$), more focus can be put on time and energy saving perspective.

Assume $t_{\min}$ is the minimum travel time for the vehicle to accelerate to the speed limit and reach the stop line. As shown in Figure 33, strategies are differentiated by comparing $t_{\min}$ with the effective time-to-change. The objective speed of the vehicle can be the speed limit v_m, the current speed v_c, the estimated uniform speed based on the start of green $v_u = d/r_{\max}$, or 0 if a stop is inevitable. The details of the algorithms are shown below, specified by two cases, approach in green and approach in red.

Approaching in Green

If the vehicle is close to the intersection (i.e., $d \leq d_s$), UCR used the following criteria to ensure that the vehicle never crosses the intersection on red: If the guaranteed remaining green time g_l is not long enough, i.e. $g_l < t_{\min}$, the vehicle should decelerate in order to stop at the stop line. Otherwise, the vehicle should accelerate to the speed limit to pass through the intersection.

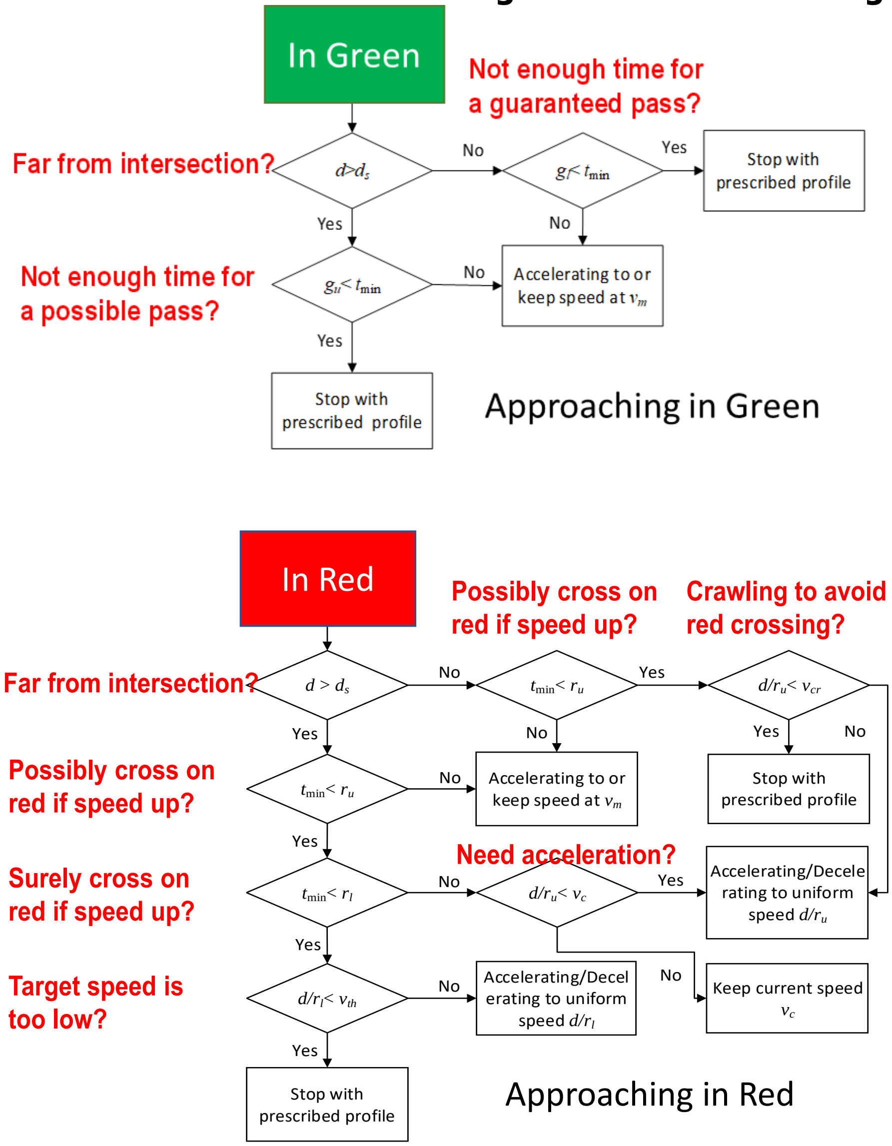
If the vehicle is far from the intersection ($d > d_s$) and it is possible to pass the stop line within the current green time, i.e., $g_u \geq t_{\min}$, the vehicle will be advised to accelerate to the speed limit and pass the intersection before the signal turns red. Otherwise, the vehicle should gradually slow down to stop at the stop line.

Approaching in Red

If the vehicle is close to the intersection, i.e., $d \leq d_s$, UCR used r_u for a conservative decision. If $r_u \leq t_{\min}$, the vehicle will be safe to reach the stop line at the speed limit. Otherwise, the driver has to keep the average speed below d/r_u to ensure that the vehicle never passes the intersection during the red phase. If d/r_u is lower than the crawling speed v_{cr} (say 5 mph), the vehicle will choose to stop at the stop line rather than keep crawling, as the energy consumption and emissions per mile are high at low speeds, and it is not comfortable to drivers or passengers when the vehicle is crawling for a long period.

If the vehicle is far from the intersection, UCR first checked if the current red phase is terminated before the vehicle arrives at the stop line with speed limit. If $r_u \leq t_{\min}$, the vehicle is free to speed up safely to meet the green phase at the stop line. If $r_u < t_{\min} \leq r_l$, the driver should accelerate to uniform speed d/r_u if the current speed v_c is below d/r_u, otherwise the vehicle should maintain its current speed. If $r_l > t_{\min}$, the target average speed of the vehicle should be d/r_l. Note that if d/r_l is lower than a threshold value v_{th} (say 20 mph), the vehicle will stop instead of keeping low speed for a long distance due to comfort concern.

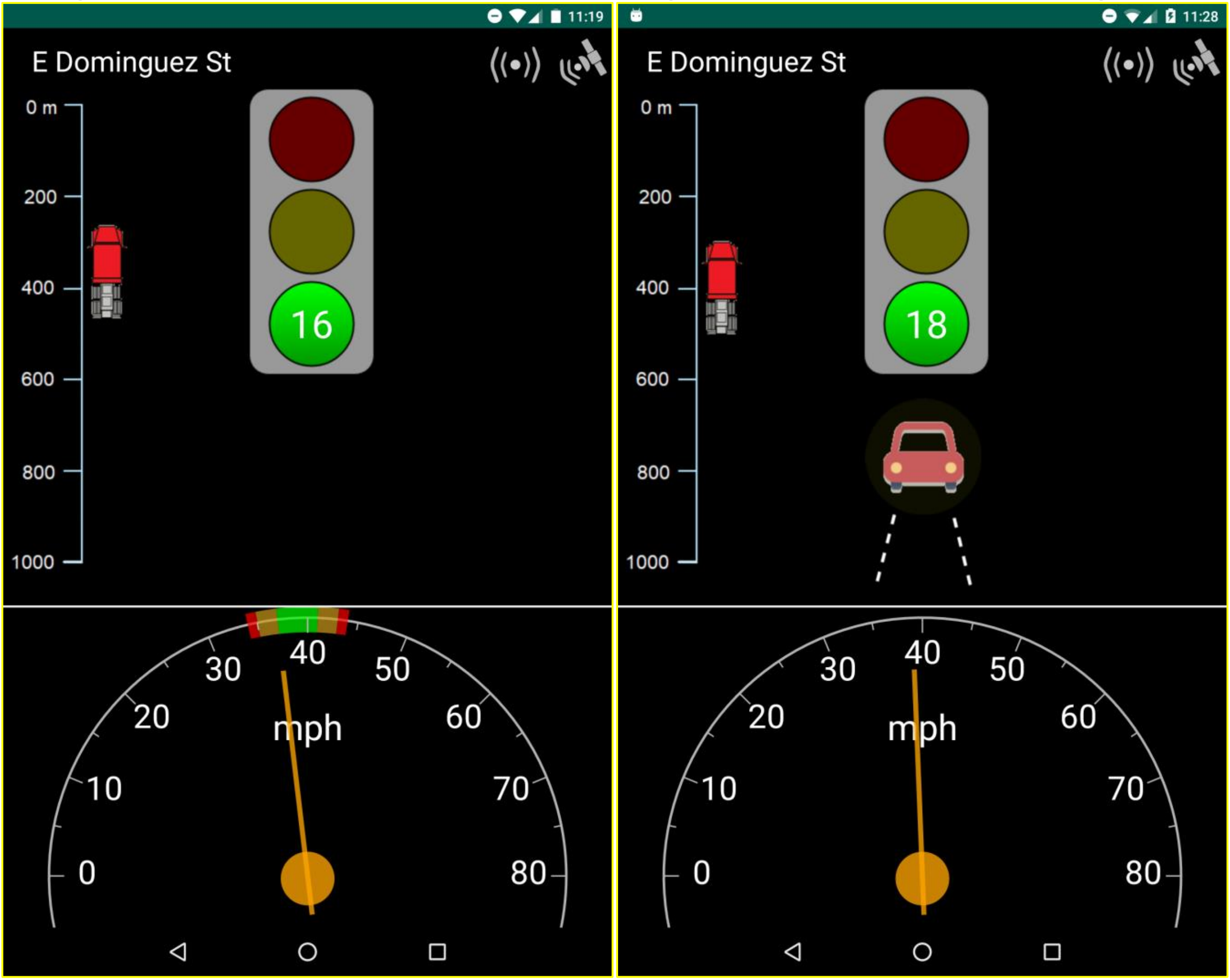
Figure 33: Flowchart of the EAD algorithm for actuated signals



Two flowcharts of the EAD algorithm for actuated signals, considering both green and red time when approaching. Credit: University of California, Riverside

After Eco-Drive determines an appropriate scenario, it provides recommendation in terms of advisory driving speed to the driver through the DVI; see Figure 34(a). The advisory driving speed can be deactivated when the system detects a preceding vehicle; see Figure 34(b).

Figure 34: Eco-Drive display when driving with and without preceding vehicle



(a) without preceding vehicle (b) with preceding vehicle

Screenshot of Eco-Drive display when driving with and without preceding vehicle
Credit: University of California, Riverside

3.6.6.2 DVI Design

As shown in Figure 25, the following information were displayed on the DVI of Eco-Drive:

1. The vehicle's current speed (i.e., speedometer)
2. An "advisory" speed as calculated from the speed planning algorithm
3. The SPaT countdown information for the current signal phase
4. Signal strength indicators for 4G-ITE and GPS, respectively
5. Vehicle detection indicator (i.e., indicating if a vehicle was within the camera range)
6. Distance to the intersection (in meter)
7. Vehicle and intersection location indicators

Figure 34(a) shows the case when there was no preceding vehicle nearby in the same lane. The target speed estimated from the trajectory planning algorithm was then displayed at the speedometer. The right part of Figure 34(b) shows the case when the sensor detected a preceding vehicle in front. The display of advisory driving speed was then turned off to avoid any distraction. Instead, the DVI displayed a vehicle icon at the center of the screen.

3.7 Eco-Drive Evaluation

3.7.1 Background

In the original Eco-Drive data collection and analysis plan, UCR planned to install Eco-Drive on 20 trucks of the participating fleet and collect data from the trucks throughout the deployment period. Using the historical data collected from the trucks of this fleet, UCR identified 20 trucks that frequently traveled on the connected corridors that were set up earlier in the project. Then, UCR proceeded to install the Eco-Drive system on these trucks. The system includes an Android tablet running the Eco-Drive application and a camera sensor for detecting preceding vehicles (see Figure 35).

Figure 35: Eco-Drive System installed on a truck of the participating fleet

Photo showing the Eco-Drive System installed on a truck of the participating fleet
Credit: University of California, Riverside

In addition to the Eco-Drive system, UCR also installed a combined GPS and ECU data logger on each truck (see Figure 36) to collect its real-world vehicle and engine operation data at the frequency of 1 Hz. The data collected by this data logger include GPS parameters such as timestamp, vehicle speed, latitude, and longitude as well as ECU parameters as engine speed and fuel consumption. Both sets of parameters are time aligned, which allows for analyzing truck fuel consumption at different locations and times.

Figure 36: J1939 Mini Logger^{TM} used for data collection

Photos showing the J1939 Mini LoggerTM used for data collection and ECU port on a truck
Credit: University of California, Riverside

However, the deployment could not begin due to liability concerns from the parties involved. As a result, UCR proposed an alternative data collection plan where UCR would lease a truck and hire a truck driver to collect driving data on the connected corridors without and with the use of Eco-Drive. After this alternative plan was agreed upon by POLA and approved by CEC, UCR proceeded according to the plan and completed the evaluation work. This chapter describes the details about the data collection and analysis as well as discusses the results from the performance evaluation of Eco-Drive.

3.7.2 Data Collection and Analysis

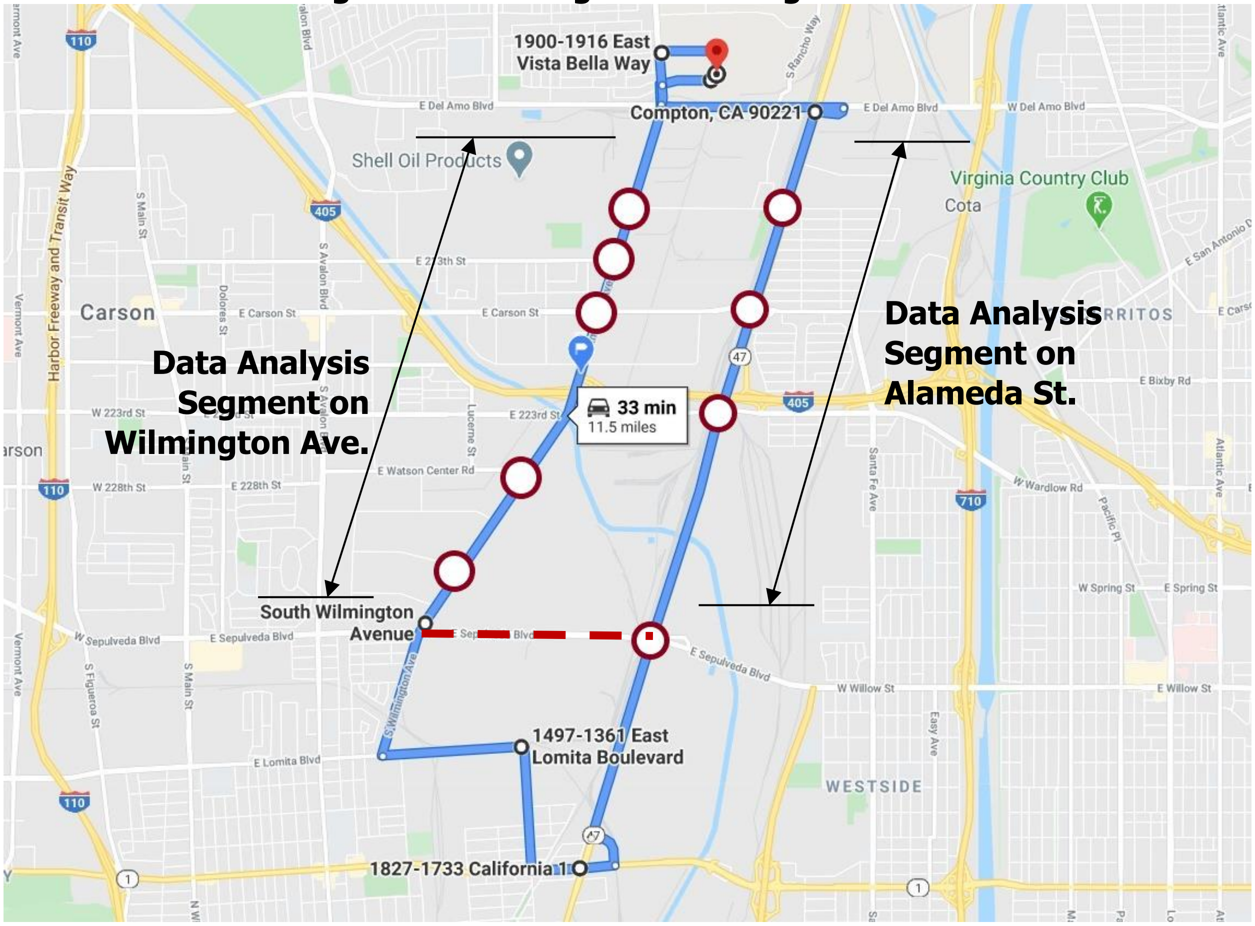
3.7.2.1 Data Collection

UCR used the Volvo truck that was used for the Eco-Drive demonstration event in March 2019 (see Figure 37). It is a class 8 truck with 13 liters diesel engine and rated power of 455 HP. UCR hired a professional truck driver to drive this truck on a designated driving route. The driving route was a loop that included four connected intersections on Alameda Street and five connected intersections on Wilmington Avenue, as marked by white circles shown in Figure 38. It was designed to maximize the driving time on the portion of the two corridors with connected intersections. The driver was instructed to drive the route in both clockwise and counterclockwise directions so that data were collected on both directions of each corridor. The data without the use of Eco-Drive (i.e., baseline data) were collected in July 2020, and the data with the use of Eco-Drive were collected in August and September, 2020. Durign the data collection in September, the condition of the road on E. Lomita Boulevard that connects the two connected corridors on the south side of the loop became deteriorated. Thus, UCR modified the driving route by using E. Sepulveda Boulevard instead (i.e., brown dashed line in Figure 29) to connect between the two corridors on the south side. As a result, the data analysis was conducted on the 2.5-mile segments on both corridors, as shown in Figure 29.

Figure 37: Truck used for data collection

Photo of the truck used for data collection. Credit: University of California, Riverside

Figure 38: Driving route during data collection



Map of the driving route during data collection that includes nine connected intersections
Credit: University of California, Riverside

3.7.2.2 Data Processing

The analysis of both baseline and Eco-Drive datasets was conducted following the steps described below.

Data Reduction

During the data collection, the data logger collected data continuously throughout the driving period. However, the analysis was focused only on the 2.5-mile segments shown in Figure 38. Note that these analysis segments exclude the portion of driving that involves making a turn at each of the four corners of the driving loop. This is to remove the influence of those turning movements on the driving performance metrics. Thus, the first step in the data processing was to reduce the data to only the portion when the truck was on the analysis segments. This was accomplished by a spatial analysis technique called *geofencing* where virtual boundaries of the analysis segments (i.e., geofences) were created on the map, and the data points inside these boundaries were identified based on their latitude and longitude information.

Road Identification

After that, the selected data points were processed through another spatial analysis technique called *map matching*. Using latitude, longitude, and heading information, each data point was assigned to a road link inside the geofences based on its proximity (a data point usually belongs to the closest road link), orientation (a data point heads into the same direction as the road link), and history (a data point is more likely to be on the same road link as the few previous data points than not). The map matching results allowed us to identify data associated with each of the four analysis segments below:

1. Alameda Street northbound
2. Alameda Street southbound
3. Wilmington Avenue northbound
4. Wilmington Avenue southbound

Performance Metrics Calculation

Using the data that were processed through the steps described above, UCR separated the data on each analysis segment into multiple observations where each observation represented a driving from the start of the analysis segment to the end of the analysis segment. For each data observation, UCR then calculated the performance metrics for the truck as listed below:

1. Travel distance (miles)
2. Travel time (seconds)
3. Average travel speed (miles per hour)
4. Travel delay (seconds)
5. Number of stops
6. Mean of acceleration (mph/s)
7. Variance of acceleration (mph^2/s^2)
8. Mean of deceleration (mph/s)
9. Variance of deceleration (mph^2/s^2)
10. Fuel consumption (liters)

Because the use of GPS data to derive these metrics could result in minor discrepancies in travel distance of each data observation, UCR normalized the travel time, travel delay, number of stops, and fuel consumption by the travel distance of each data observation. This resulted in the performance metrics below, which were used in the analysis instead of their original metrics:

1. Travel time per mile (seconds/mi)
2. Travel delay per mile (seconds/mi)
3. Number of stops per mile
4. Fuel consumption per mile (liters/mi)

3.7.2.3 Data Analysis

The processed data were in the form of a data table with a number of records where each record contained the calculated performance metrics for each data observation. This master data table was divided into four data tables, one for each of the four analysis segments. Then, each data table was further divided into two tables, one for the baseline case and the other for the Eco-Drive case. Therefore, there were a total of eight data tables. For each of these data tables, the data analysis was performed as follows:

Data Filtering

Data filtering was performed to remove data records with incomplete or erroneous driving data. This could occur due to unexpected interruptions during the driving, poor GPS signal resulting in erroneous data, etc. This was determined based on the travel distance where data records with the travel distance outside the range of 2.5 ± 0.3 miles were removed.

Outlier Detection

Because the driving data were collected in real-world traffic conditions which could vary greatly, there could be circumstances that caused some data observations to be drastically different from the rest. For example, an incident or a construction on the road could increase the travel time, travel delay, number of stops, and fuel consumption of a data observation considerably, making that data observation an outlier. Therefore, outliers were removed to minimize their impact on the performance metrics. Out of the 10 performance metrics that were calculated, travel time per mile, travel delay per mile, number of stops per mile, and fuel consumption per mile were the primary focus as the promise of Eco-Drive was that it could help reduce fuel consumption along signalized corridors without significantly impacting travel time by reducing number of stops and associated travel delays at connected intersections. Therefore, the data records whose values of these four metrics were considered outliers were removed. A value was considered to be an outlier if it was outside the range of mean ± 3 times the standard deviation.

Statistical Analysis

After the data filtering and outlier detection steps, the remaining data records were used to calculate various description statistics (e.g., mean and standard deviation) of each performance metric in each of the eight data tables. Then, the difference in the mean values between the baseline and the Eco-Drive cases were calculated, and the t-test was conducted to determine if the difference was statistically significant at 5 percent significance level.

3.7.3 Results

Table 27 provides descriptive statistics of the 10 performance metrics for both the baseline and the Eco-Drive cases.

Table 27: Descriptive statistics of performance metrics

	Baseline					**Eco-Drive**				
	Count	**Max**	**Min**	**Mean**	**S.D.**	**Count**	**Max**	**Min**	**Mean**	**S.D.**
Alameda St. Northbound										
Travel distance (mi)	41	2.4	2.3	2.4	0.0	76	2.4	2.3	2.4	0.0
Travel time (s/mi)	41	117.8	79.6	98.4	10.2	76	133.3	81.4	104.9	11.3
Fuel consumed (liters/mi)	41	0.47	0.25	0.33	0.05	76	0.40	0.24	0.31	0.04
Travel delay (s/mi)	41	19.2	0.0	5.0	6.0	76	19.7	0.0	5.7	5.3
No. of stops per mile	41	0.85	0.00	0.36	0.36	76	1.26	0.00	0.39	0.30
Average speed (mph)	41	45.2	30.6	37.0	3.8	76	44.2	27.0	34.7	3.8
Mean of accel (mph/s)	41	1.6	0.2	0.8	0.3	76	1.4	0.2	0.7	0.3
Variance of accel (mph^2/s^2)	41	2.4	0.1	0.8	0.5	76	1.8	0.0	0.8	0.5
Mean of decel (mph/s)	41	-0.3	-1.8	-1.0	0.3	76	-0.2	-1.5	-0.8	0.3
Variance of decel (mph^2/s^2)	41	2.6	0.0	1.4	0.7	76	3.2	0.0	1.2	0.7
Alameda St. Southbound										
Travel distance (mi)	56	2.4	2.3	2.4	0.0	73	2.4	2.3	2.4	0.0
Travel time (s/mi)	56	118.6	72.6	93.3	10.6	73	125.2	77.4	97.2	10.8
Fuel consumed (liters/mi)	56	0.42	0.23	0.32	0.04	73	0.40	0.22	0.30	0.04
Travel delay (s/mi)	56	14.8	0.0	3.6	3.8	73	15.2	0.0	4.2	5.0
No. of stops per mile	56	0.85	0.00	0.34	0.33	73	1.27	0.00	0.30	0.33
Average speed (mph)	56	49.6	30.4	39.1	4.5	73	46.5	28.8	37.5	4.0
Mean of accel (mph/s)	56	1.2	0.2	0.7	0.2	73	1.2	0.2	0.7	0.2
Variance of accel (mph^2/s^2)	56	1.7	0.0	0.8	0.5	73	1.9	0.0	0.7	0.5
Mean of decel (mph/s)	56	-0.2	-1.6	-0.9	0.4	73	-0.2	-1.4	-0.8	0.3
Variance of decel (mph^2/s^2)	56	2.5	0.0	1.2	0.6	73	3.9	0.0	1.0	0.7
Wilmington Ave. Northbound										
Travel distance (mi)	45	2.6	2.6	2.6	0.0	63	2.6	2.6	2.6	0.0
Travel time (s/mi)	45	204.7	99.0	148.3	25.0	63	187.7	103.2	137.9	18.9
Fuel consumed (liters/mi)	45	0.48	0.26	0.38	0.05	63	0.44	0.25	0.33	0.04

Travel delay (s/mi)	45	84.2	0.0	35.3	20.4	63	59.6	1.5	25.0	16.1
No. of stops per mile	45	2.31	0.00	1.25	0.57	63	1.91	0.38	0.89	0.36
Average speed (mph)	45	36.4	17.6	25.0	4.5	63	34.9	19.2	26.6	3.6
Mean of accel (mph/s)	45	1.5	0.5	1.1	0.2	63	1.4	0.5	0.9	0.2
Variance of accel (mph^2/s^2)	45	2.4	0.1	1.3	0.4	63	2.1	0.4	1.2	0.4
Mean of decel (mph/s)	45	-0.5	-1.9	-1.3	0.3	63	-0.5	-1.7	-1.0	0.2
Variance of decel (mph^2/s^2)	45	3.1	0.5	1.7	0.5	63	2.1	0.4	1.3	0.4
Wilmington Ave. Southbound										
Travel distance (mi)	34	2.6	2.5	2.6	0.0	60	2.6	2.5	2.6	0.0
Travel time (s/mi)	34	196.1	112.2	146.6	23.7	60	165.3	99.1	130.2	15.3
Fuel consumed (liters/mi)	34	0.49	0.28	0.40	0.05	60	0.40	0.26	0.34	0.03
Travel delay (s/mi)	34	58.3	1.2	29.5	16.8	60	38.4	0.0	15.1	9.8
No. of stops per mile	34	2.69	0.38	1.28	0.59	60	1.92	0.00	0.87	0.44
Average speed (mph)	34	32.1	18.4	25.1	4.1	60	36.3	21.8	28.0	3.3
Mean of accel (mph/s)	34	1.6	0.6	1.1	0.2	60	1.3	0.5	0.9	0.2
Variance of accel (mph^2/s^2)	34	2.3	0.5	1.3	0.4	60	1.6	0.4	1.0	0.3
Mean of decel (mph/s)	34	-0.6	-2.1	-1.3	0.3	60	-0.4	-1.4	-1.0	0.2
Variance of decel (mph^2/s^2)	34	4.1	0.7	2.0	0.7	60	2.5	0.2	1.3	0.4

Source: University of California, Riverside

As mentioned earlier, travel time per mile, travel delay per mile, number of stops per mile, and fuel consumption per mile are the primary focus of Eco-Drive performance evaluation. This is because the promise of Eco-Drive is that it can help reduce fuel consumption along signalized corridors without significantly impacting travel time by reducing number of stops and associated travel delays at connected intersections. In addition, Eco-Drive can help smooth the driving speed profile through reductions in the frequency and magnitude of acceleration and deceleration events, which will translate to lower mean acceleration and mean deceleration values. Table 28 shows the differences in mean values of these key performance metrics between the baseline case and the Eco-Drive case, along with the indicator of their statistical significance. The results for each analysis segment are discussed below.

Table 28: Average differences between baseline and Eco-Drive

	Alameda St. NB	**Alameda St. SB**	**Wilmington Ave. NB**	**Wilmington Ave. SB**
Travel time (s/mi)	6.5 percent*	4.1 percent*	-7.1 percent*	-11.2 percent*
Travel delay (s/mi)	13.3 percent	19.4 percent	-29.2 percent*	-48.7 percent*
No. of stops per mile	7.6 percent	-11.3 percent	-28.8 percent*	-32.0 percent*

Fuel consumed (liters/mi)	-6.1 percent*	-6.2 percent*	-12.0 percent*	-15.0 percent*
Mean of accel (mph/s)	-8.2 percent	-11.8 percent*	-15.5 percent*	-18.8 percent*
Mean of decel (mph/s)	-18.1 percent*	-16.3 percent*	-23.4 percent*	-23.6 percent*

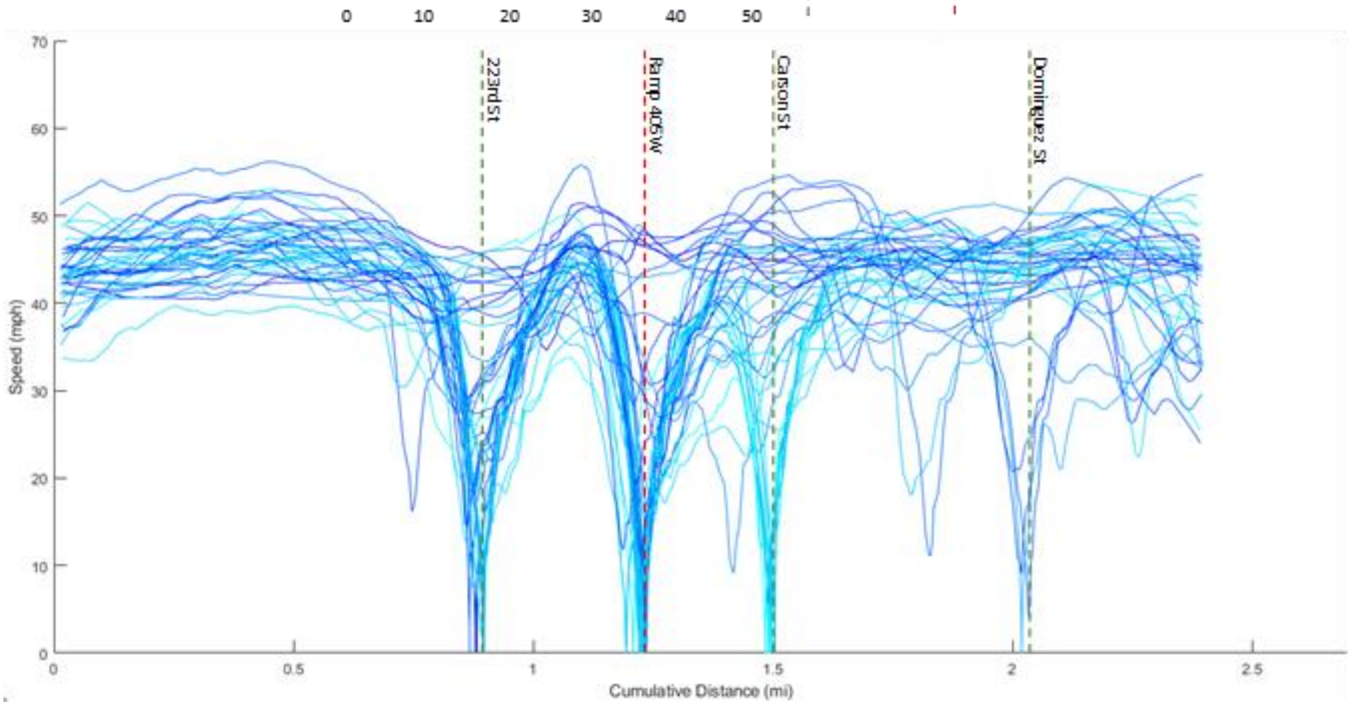
***Statistically significant at 5 percent significance level**

Source: University of California, Riverside

Alameda Street Northbound

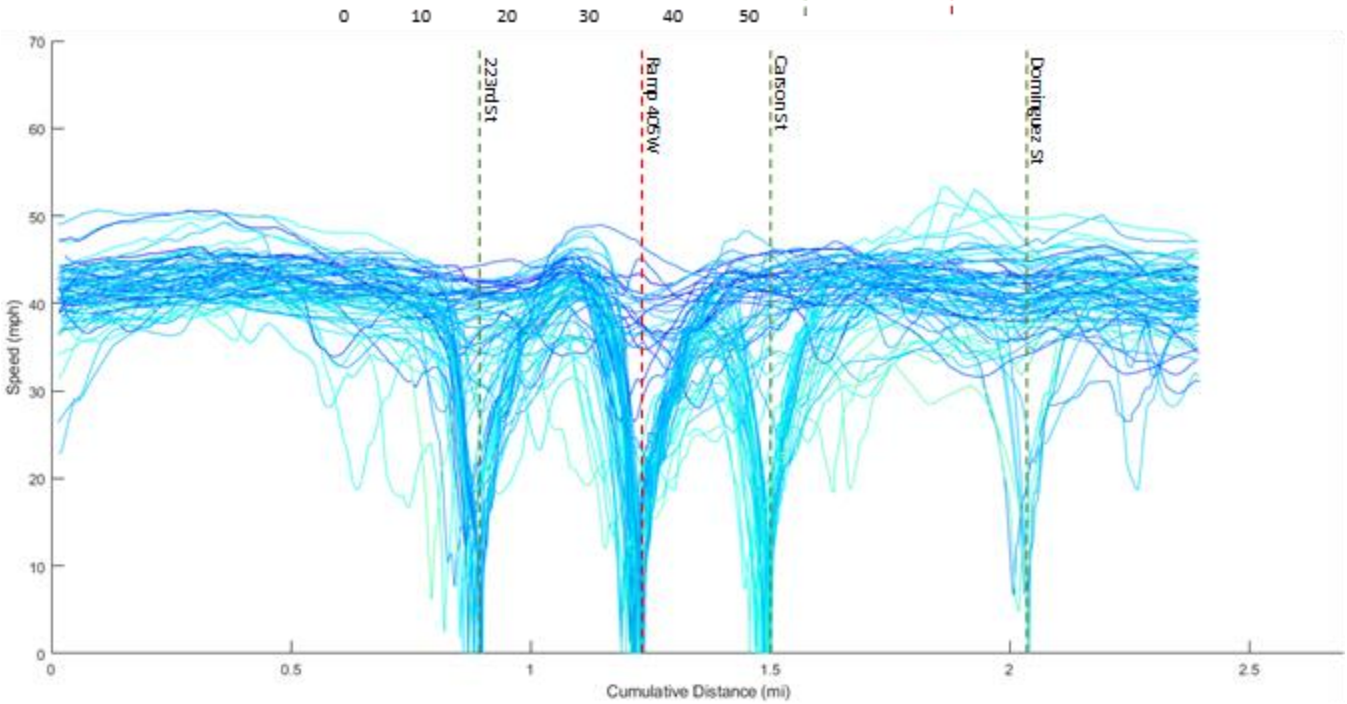
The results show that, on average, fuel consumption in the Eco-Drive case was 6.1 percent less than in the baseline case, and the difference was statistically significant at 5 percent significance level. However, travel time, travel delay, and number of stops in the Eco-Drive case were 6.5 percent, 13.3 percent, and 7.6 percent more than in the baseline case, respectively, although it should be noted that only the travel time difference was statistically significant. The lower fuel consumption in the Eco-Drive case is as expected, but the higher travel time is not. To understand the reasons behind these results, UCR plotted the speed profiles of the truck along Alameda Street northbound for the baseline case and the Eco-Drive case as shown in Figure 39 and Figure 40, respectively. Note that there are 41 speed profiles in the baseline case and 76 speed profiles in the Eco-Drive case. It can be seen that the free-flow speeds of the truck in the baseline case in Figure 39 were generally higher than those in the Eco-Drive case in Figure 40. This explains why the travel time in the baseline case was less than in the Eco-Drive case. Note that the speed limit on this analysis segment is 45 mph. It is obvious that the truck was exceeding the speed limit more often in the baseline case. This implies that Eco-Drive might help the driver better comply with the speed limit as Eco-Drive never suggested a driving speed higher than the speed limit. Also, the speed limit information was shown on the Eco-Drive screen all the time, reminding the driver of the speed limit of the road that the driver was driving on. In addition, the better compliance with speed limit also helped reduce speed fluctuations around the cruising speed. As reported in Table 18, driving with Eco-Drive resulted in 8.2 percent lower mean acceleration and 18.1 percent lower mean deceleration than driving without it, where the lower mean deceleration was statistically significant. These effects likely contributed to less fuel consumption in the Eco-Drive case as smooth driving with few acceleration and deceleration events is known to result in higher fuel efficiency.

Figure 39: Speed profiles of the truck along Alameda St NB without Eco-Drive



Plot showing speed profiles of the truck along Alameda St northbound without Eco-Drive
Credit: University of California, Riverside

Figure 40: Speed profiles of the truck along Alameda St NB with Eco-Drive



Plot showing speed profiles of the truck along Alameda St northbound with Eco-Drive
Credit: University of California, Riverside

Alameda Street Southbound

The results in Table 18 shows 11.3 percent fewer number of stops and 6.2 percent less fuel consumption in the Eco-Drive case as compared to the baseline case, where the fuel consumption difference was statistically significant. On the other hand, travel time and travel delay in the Eco-Drive case were 4.1 percent and 19.4 percent more than in the baseline case, respectively, where the travel time difference was statistically significant. These results are similar to the results for Alameda Street northbound. Figure 41 and Figure 42 show the speed profiles of the truck along Alameda Street southbound for the baseline case and the Eco-Drive case, respectively. By comparing these two figures, it can be seen that the free-flow speeds of the truck in the baseline case were generally higher than those in the Eco-Drive case, which explains why the travel time in the baseline case was less than in the Eco-Drive case. As in the case of Alameda St northbound, Eco-Drive seemed to help the driver better comply with the speed limit, which is 45 mph on this analysis segment. In addition, the better compliance with speed limit also helped reduce speed fluctuations around the cruising speed. As reported in Table 18, driving with Eco-Drive resulted in 11.8 percent lower mean acceleration and 16.3 percent lower mean deceleration than driving without it, both of which were statistically significant. These effects likely contributed to less fuel consumption in the Eco-Drive case.

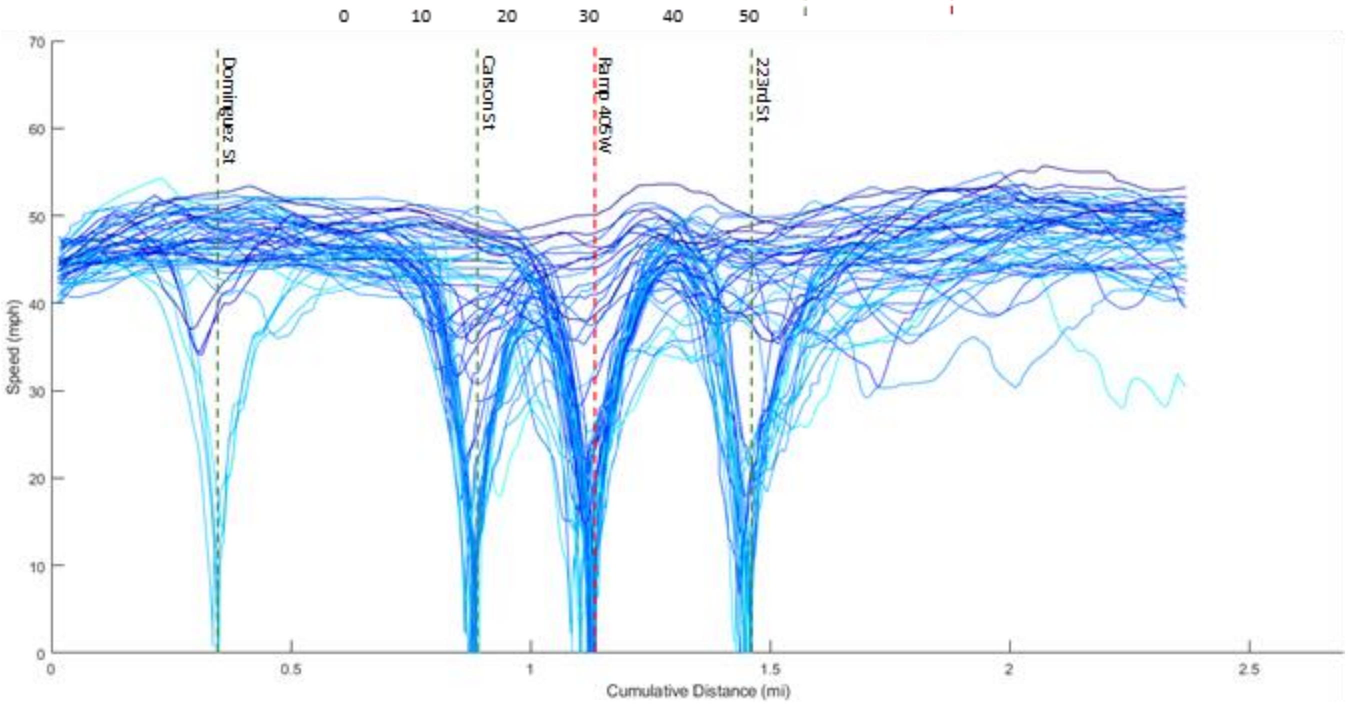
Wilmington Avenue Northbound

The results in Table 18 show that fuel consumption in the Eco-Drive case was 12.0 percent less than in the baseline case, which was statistically significant. In addition, travel time and travel delay in the Eco-Drive case were 7.1 percent and 29.2 percent less than in the baseline case, respectively, which were statistically significant as well. These fuel and travel time savings can be attributable to the 28.8 percent reduction in number of stops, 15.5 percent lower mean acceleration, and 23.4 percent lower mean deceleration in the Eco-Drive case, all of which were statistically significant. These effects can be seen by comparing the truck speed profiles in the baseline case in Figure 43 with those in the Eco-Drive case in Figure 44, especially over the three consecutive connected intersections with Carson St, 213th Street, and Dominguez Street Taking the intersection with 213th Street as an example, the truck came to a full stop once out of 63 times that it passed that intersection with Eco-Drive, which is a smaller fraction than one out of 45 times that it passed that intersection without Eco-Drive. In addition, at the intersection with Dominguez Street, it is evident that the fraction of passes without stopping at the intersection in the Eco-Drive case was higher than in the baseline case.

Wilmington Avenue Southbound

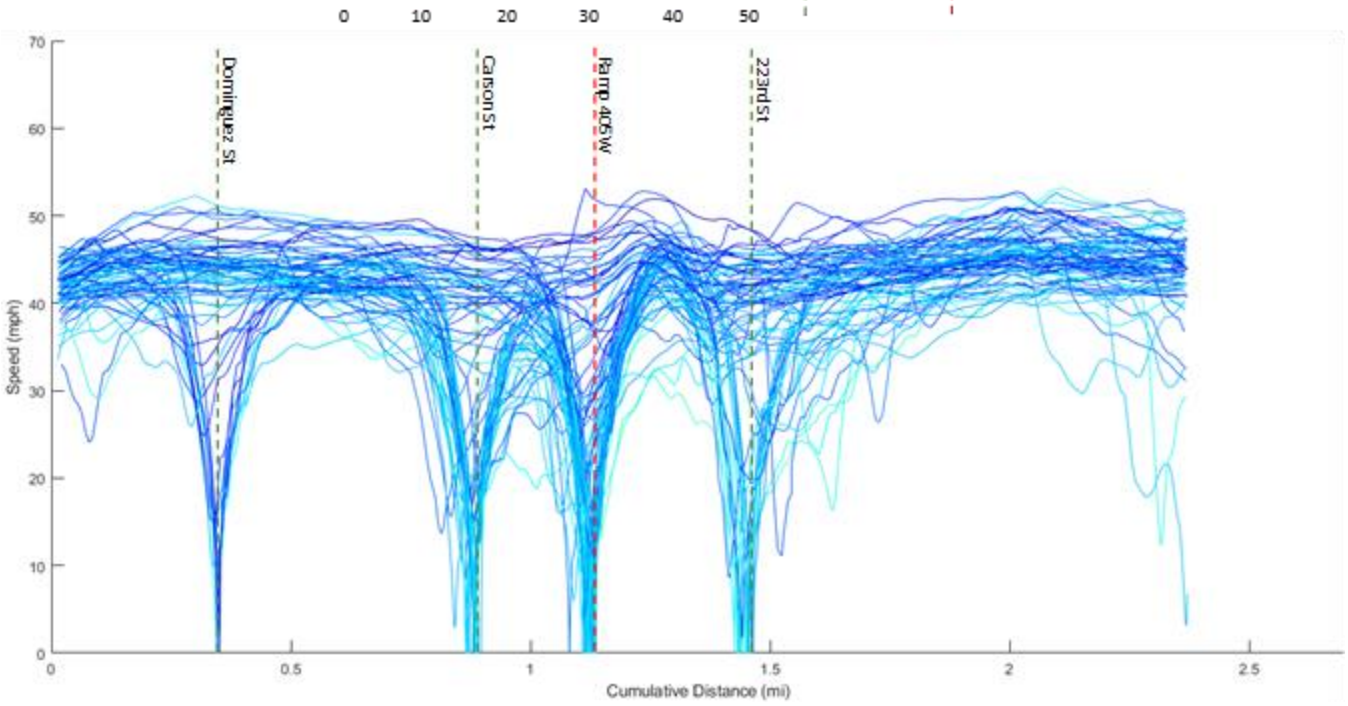
Similar to Wilmington Avenue northbound, the results for Wilmington Avenue southbound show that fuel consumption, travel time, and travel delay in the Eco-Drive case were 15.0 percent, 11.2 percent, and 48.7 percent less than in the baseline case, respectively, all of which were statistically significant. These fuel and travel time savings can be attributable to the 32.0 percent reduction in number of stops per mile, the 18.8 percent lower mean acceleration, and the 23.6 percent lower mean deceleration in the Eco-Drive case, all of which were statistically significant as well. These effects can be seen by comparing the truck speed profiles in the baseline case in Figure 45 with those in the Eco-Drive case in Figure 46, especially over the connected intersections with 213th Street and Dominguez Street. It is evident that the fraction of passes without stopping at those intersections in the Eco-Drive case was higher than in the baseline case.

Figure 41: Speed profiles of the truck along Alameda St. SB without Eco-Drive



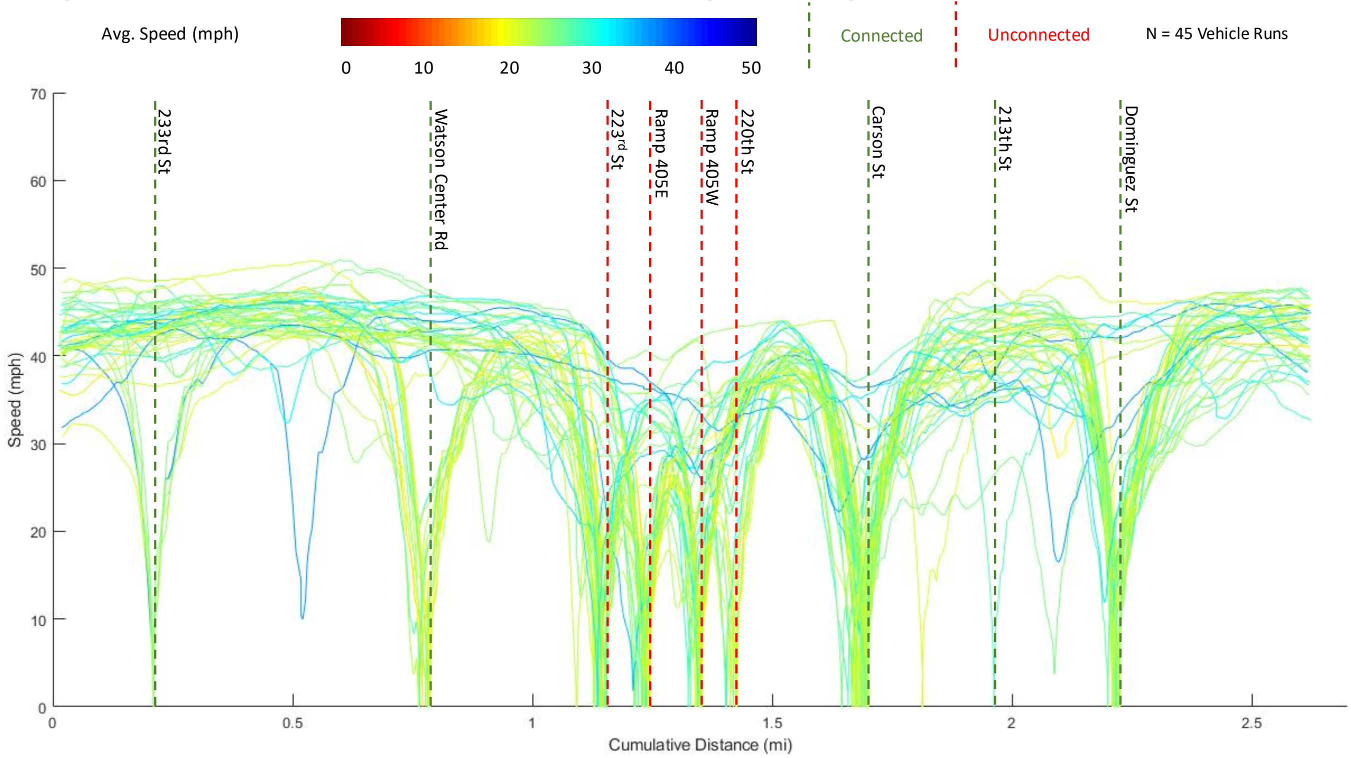
Plot showing speed profiles of the truck along Alameda St. southbound without Eco-Drive
Credit: University of California, Riverside

Figure 42: Speed profiles of the truck along Alameda St. SB with Eco-Drive



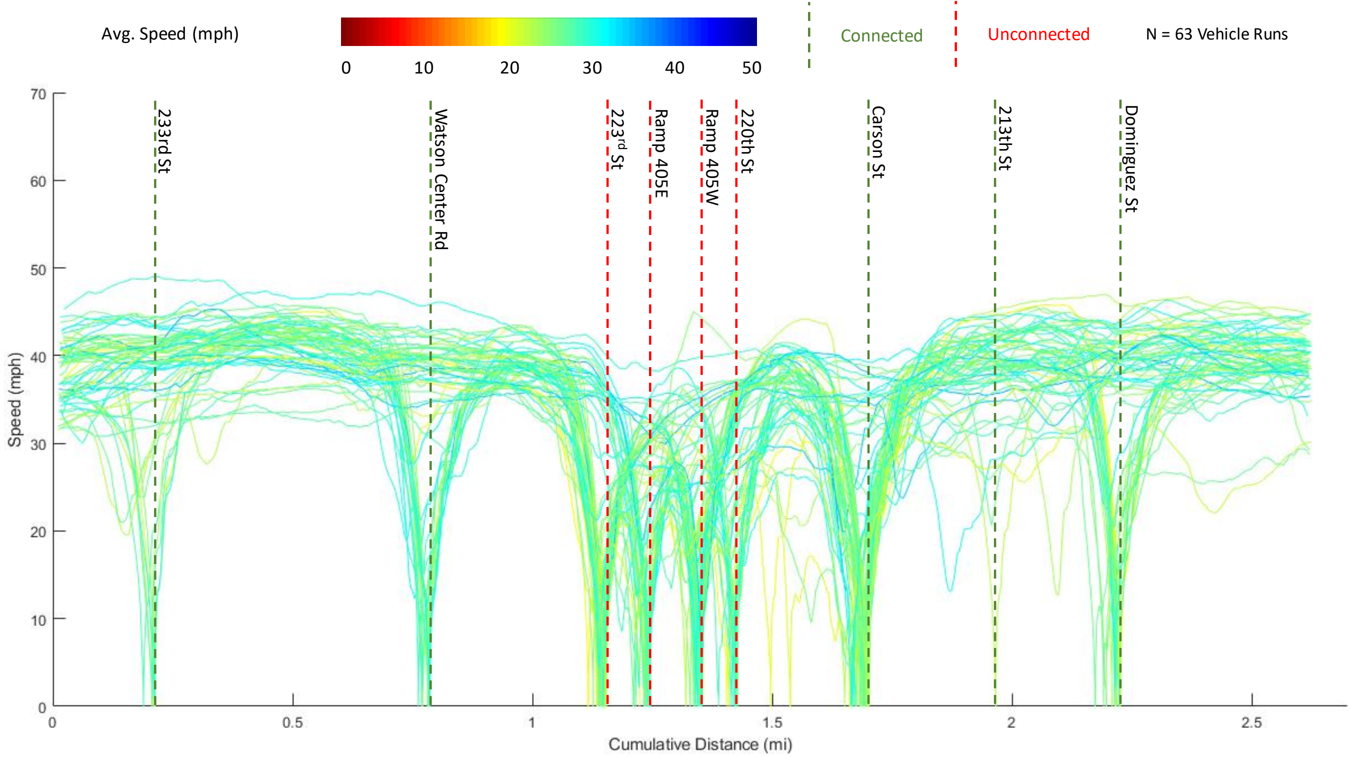
Plot showing speed profiles of the truck along Alameda St southbound with Eco-Drive
Credit: University of California, Riverside

Figure 43: Speed profiles of the truck along Wilmington St. NB without Eco-Drive



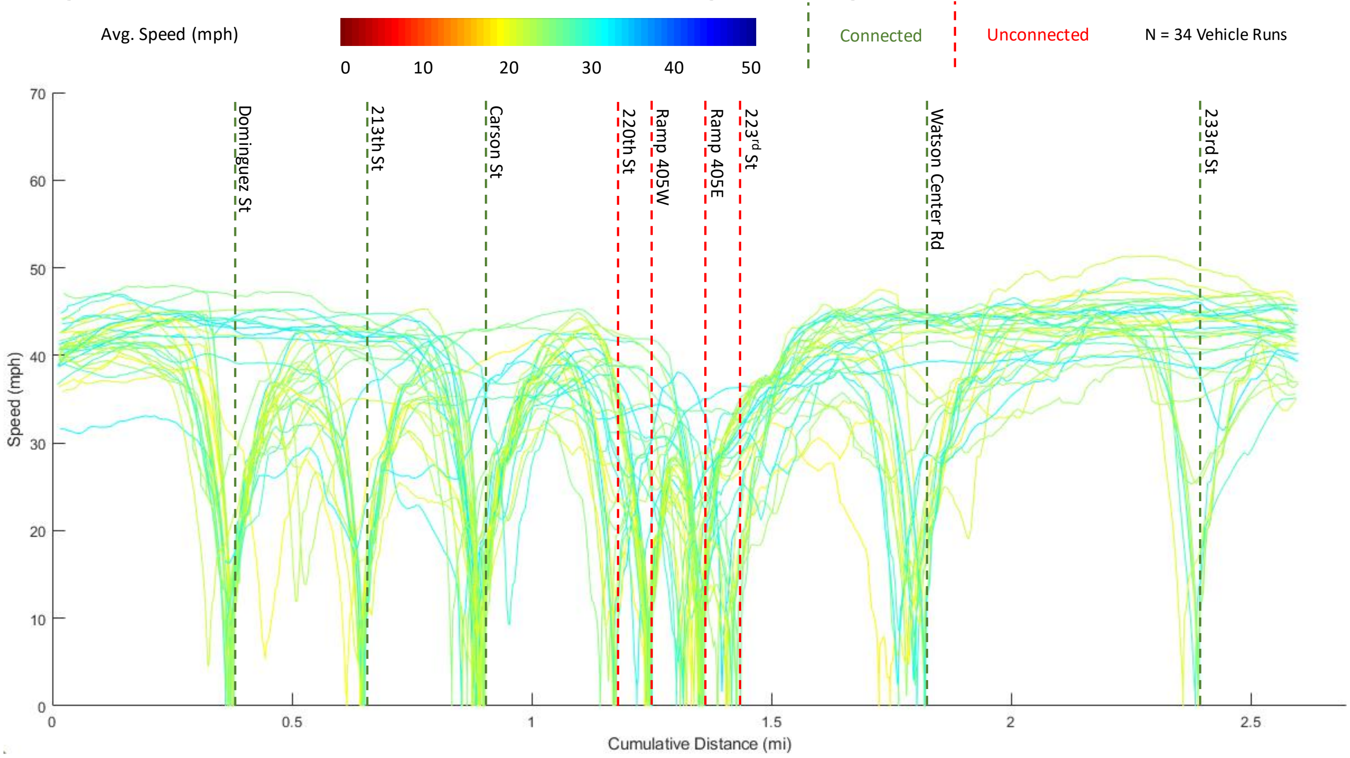
Plot showing speed profiles of the truck along Wilmington St. northbound without Eco-Drive
Credit: University of California, Riverside

Figure 44: Speed profiles of the truck along Wilmington St. NB with Eco-Drive



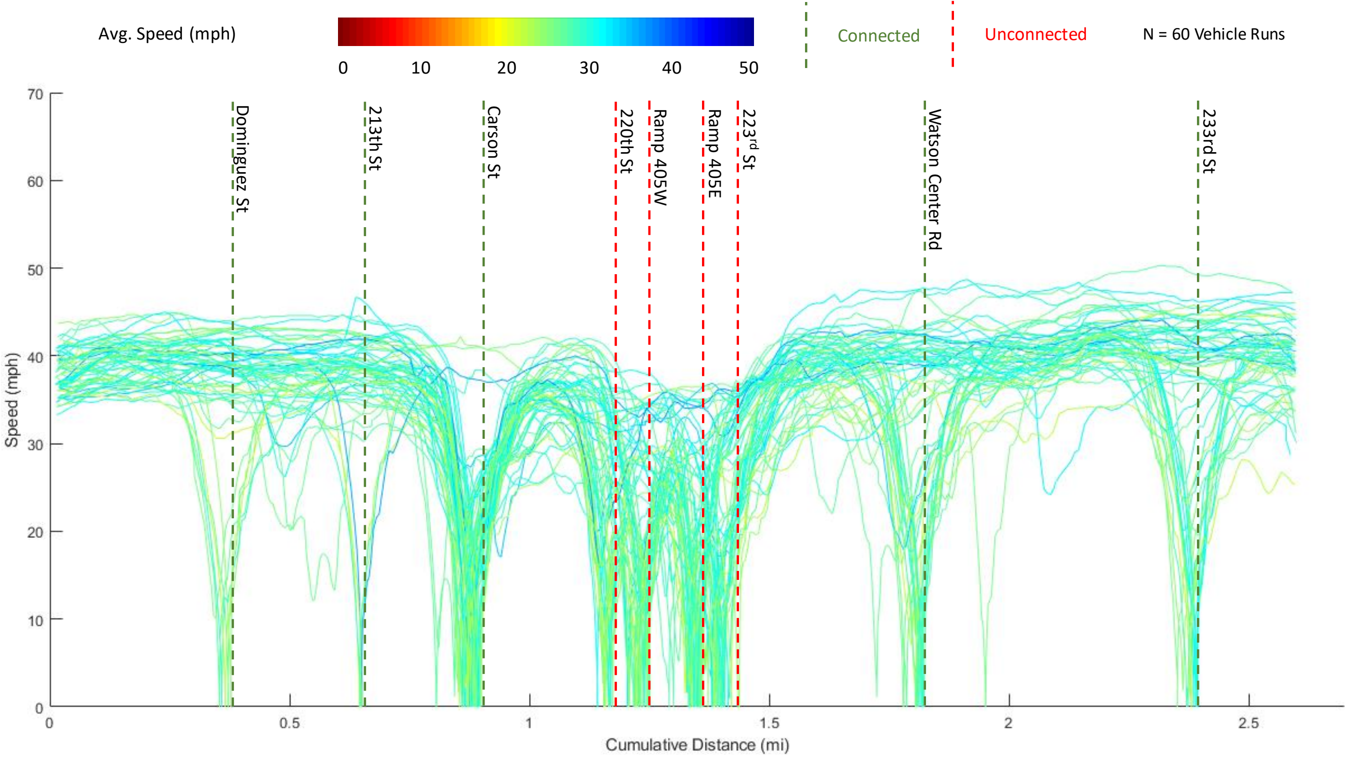
Plot showing speed profiles of the truck along Wilmington St. northbound with Eco-Drive
Credit: University of California, Riverside

Figure 45: Speed profiles of the truck along Wilmington St. SB without Eco-Drive



Plot showing speed profiles of the truck along Wilmington St. southbound without Eco-Drive
Credit: University of California, Riverside

Figure 46: Speed profiles of the truck along Wilmington St. SB with Eco-Drive



Plot showing speed profiles of the truck along Wilmington St. southbound with Eco-Drive
Credit: University of California, Riverside

3.7.4 Discussion

The results from the Eco-Drive performance evaluation show that driving with Eco-Drive resulted in less fuel consumption than driving without it by 6 percent to 15 percent, but the underlying reasons for which the fuel savings were achieved varied by analysis segment.

On both northbound and southbound of Alameda Street, Eco-Drive helped the driver better comply with the speed limit, which is 45 mph on both analysis segments. It can be observed from the truck speed profiles that the truck was exceeding the speed limit less often in the Eco-Drive case than in the baseline case. In addition, the better compliance with speed limit also helped reduce speed fluctuations around the cruising speed, resulting in lower mean acceleration and mean deceleration values. Smooth driving with few acceleration and deceleration events is known to result in higher fuel efficiency. On the other hand, the better compliance with speed limit while driving with Eco-Drive caused the travel time to be longer than driving without it. This should not be viewed negatively as it was due to the baseline driving exceeding the speed limit more frequently. In fact, the better compliance with speed limit can be viewed as another benefit of Eco-Drive as it could help improve safety for the driver and the surrounding traffic.

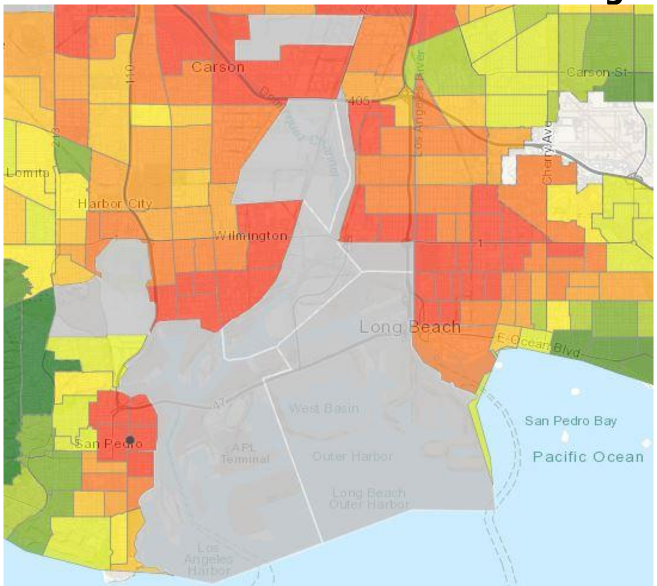
On both northbound and southbound of Wilmington Avenue, Eco-Drive helped cut down number of stops at connected intersections considerably, which resulted in lower mean acceleration and mean deceleration values. These effects contributed to not only fuel savings but also travel time savings when driving with Eco-Drive on these analysis segments. Note that the fuel savings observed on Wilmington Avenue northbound and Wilmington Avenue southbound (12 percent and 15 percent, respectively) are much higher than those on Alameda Street northbound and Alameda Street southbound (6 percent for both). This may be because the driver was able to use Eco-Drive at five intersections on Wilmington Avenue northbound and Wilmington Avenue southbound while he could do so at only three intersections on Alameda Steet northbound and Alameda Street southbound.

It should be noted that during the data collection the truck was not pulling any load (i.e., bobtailing). It is expected that Eco-Drive would provide a higher level of fuel savings than observed in this evaluation if the truck pulls a load, especially a heavy one. This is because the effects of acceleration and deceleration events on fuel consumption would be more pronounced when pulling a heavy load. Thus, avoiding those events would result in more fuel savings.

CHAPTER 4: Findings and Recommendations

Overall, the project had a positive health impact by helping to reduce harmful diesel emissions at the Port and the surrounding local community. The demonstration units performed identical duties to diesel equipment already routinely utilized at the Everport terminal, resulting in a net emissions reduction at the Port, which benefits adjacent neighboring communities. The successful integration of the Eco-FRATIS suite also resulted in an innovative solution achieved via the synergistic combination of proven technologies embodied in the FRATIS and Eco-Drive platforms. These platforms were enhanced, integrated, and deployed for the common purpose of improving freight operations in and around POLA. Further, the emission reduction benefits of this project have a direct positive impact on the Everport terminal employees and adjacent neighbors. According to CalEnviroScreen3.0, the communities closest to the Port have the highest (i.e., worst) cumulative impacts, or exposure, from all pollution sources in the geographic area. Using this tool, geographic areas are "scored" using a combination of pollution indicators such as ozone and PM2.5 concentrations, traffic density, drinking water quality, etc. and sensitivity or vulnerability of a population to the effects of the local pollution. High scoring communities are indicated by color shading from red (worst) to green (best); the worst communities are designated as the most adversely impacted disadvantaged communities. Figure 47 depicts the Ports of Los Angeles Long Beach and the surrounding communities. Port property is shown in gray, since there is no population residing on the port property.

Figure 47: CalEnviroScreen 3.0 Results for Port of Los Angeles Geographic Area



Source: CalEnviroScreen3.0, California Office of Environmental Health Hazard Assessment

4.1 Advanced Yard Tractor Deployment Project

The project team considers the Capacity low-NOx, RNG yard tractor demonstration a success. An important project outcome is that Everport took over title of the demonstration equipment and continues to operate the 20 low-NOx RNG units in regular revenue service. The demonstration units worked side-by-side with conventional diesel-fueled models, completing the demanding duty cycle requirements of a port terminal operation. As discussed in Section 2.5.4, the following direct benefits accrued from the demonstration of the RNG yard tractors for 17,681 hours and the demonstration of the battery-electric yard tractors for 336 hours are estimated for this project:

- Reduction in diesel fuel consumption of 89,254 diesel gallons
- Reduction of 149 tons of CO2e
- Reduction of 0.0418 tons, or 83.6 pounds of DPM
- Reduction of 0.0377 tons, or 75.4 pounds of $PM_{2.5}$
- Reduction of 1.824 tons of NOx
- Reduction of 0.0112 tons, or 22.4 pounds of SO_2
- Improvement in carbon intensity from 92.92 gCO_{2e}/MJ for diesel to 48.96 gCO_{2e}/MJ for Clean Energy's RNG and 75.93 gCO_{2e}/MJ for Los Angeles Department of Water and Power's grid electricity.

In addition to the above direct benefits, Everport gained valuable experience from its participation in this demonstration, including:

- Gearmen and operators that worked with the RNG and battery-electric yard tractors in regular port terminal operation, gaining critical experience in both the operation and maintenance of the RNG and all-electric CHE as well as the EVSE infrastructure to support the equipment.
- Everport now has experience with alternative fuel technology from two OEMs and is better prepared for the next phase of its transition to a cleaner CHE fleet.
- The understanding that as the zero-emission fleet grows, Everport's staff and union labor will need to monitor the charge on battery-electric units to ensure uninterrupted operations.
- Mechanics will need additional training to overcome temporary breakdowns/failures when the units are no longer supported by the demonstration equipment OEMs.

Significantly, infrastructure had the highest impact on operations for the RNG units. RNG fueling time was significantly longer than typical diesel fueling done with a mobile wet hose, as discussed in Chapter 2. Due to the fueling constraints the units operated on a rotating duty cycle, with half operating on the day shift, while the other half were being fueled, and then switching the process for the night shift. This challenging situation decreased the anticipated hours of operation by half per yard tractor for the demonstration period. With Everport's decision to continue utilizing the LNG equipment beyond the demonstration period, discussions are in process with Clean Energy regarding a truly mobile wet fueler, which is expected to curtail the fueling time constraints.

BEV equipment and the fundamental differences from liquid fuels in delivery, storage and refueling will require an iterative infrastructure development process. This is true due to the scale of both expense and total energy required. The cost of infrastructure continues to be another hurdle in need of incentive assistance. As recognized on this project and others, infrastructure development costs often exceed initial estimates.

Additionally, there are costs associated with advanced vehicle maintenance. In order to continue utilizing the RNG yard tractors, Everport will need to modify the on-site maintenance facility to accommodate the equipment based on specific codes and standards governing facilities that service and store natural gas vehicles. The assessment package to upgrade the existing maintenance facility includes modifications such as mechanical ventilation, gas detection system, distinct temperature control, electrical code height specifications, and safety signage. The cost estimate is $454,410; however, this estimate is based on 2019 construction cost rates.

4.1.1 Lessons Learned

For the advanced yard tractor project, a number of important lessons learned were logged as a result of this demonstration. For both the RNG and battery-electric technologies, it is important not to underestimate the time needed to secure permit approvals and electrical component certifications (i.e., UL Certification) – this severely affected the project schedule. Additional lessons learned include:

- Field certification of infrastructure is a time-consuming process. If possible, factory certify eligible components.
- There were also significant costs incurred for site modifications such as berms, barriers and signage to satisfy permitting requirements that were not considered in the original scope; future projects should plan for permitting requirements that will add unexpected project costs.
- Equipment utilizing proprietary charging does not provide flexibility over time. The movement towards standardized charging is essential to equipment integration for continued operational use.
- OEMs familiar with producing equipment utilized in terminal operations are generally better prepared to produce advanced technology equipment for terminal operations.
- Appropriately integrated data collection tools provide more reliable robust data than gearmen tasked with manually reporting data, which is outside of their normal duties.

4.1.2 Conclusions and Recommendations

During the initial stages of the project, the team considered the most challenging aspect to be third-party certification of the various electrical components and systems associated with the temporary RNG fueling system and the BYD chargers. The challenging certification process resulted in significant and unexpected equipment demonstration delays.

The Capacity RNG yard tractors were successfully integrated into Everport’s fleet and are currently accruing operating hours in regular terminal service. Compared to the expectation that the units would accrue operational hours at the level of their diesel counterparts (1,816 hours/year), the demonstration units fell short. The BYD battery-electric units were unable to withstand the rigorous operational and safety requirements of the terminal, struggling to meet the cumulative 336 hours of recorded demonstration. Reasons for this include:

- Challenges with the project infrastructure for both fuel types, primarily focused on permit approvals.
- Challenges with the RNG fueling Harpoon, due to permitting constraints and lengthy fueling time.
- Challenges with functionality and operating consistency of the EVSE.
- BYD units needed retrofits and modifications to meet terminal safety requirements.

- The demanding terminal environment necessitates equipment manufactured with robust materials; the BYD First-Generation units were unable to withstand the severe activity.
- COVID-19 pandemic restrictions and operating protocols.
- Infrastructure remains the consideration with the highest impact on operations.
    - Expense and total energy required.
    - Charging flexibility, cost effectiveness, and ESS (energy storage solutions).
    - Logistics, labor considerations, maintenance, and installation permanence.

Overall, the Capacity RNG yard tractor demonstration was considered to be a meaningful success, providing Everport with real-world operating experience that shows advanced technology CHE is compatible with a rigorous port operating environment. The team looks forward to demonstrations involving Second-Generation BYD yard tractors, with evolution of design based on lessons learned from the First-Generation.

4.2 ECO-FRATIS Conclusions

The FRATIS portion of the project yielded an innovative solution achieved via the synergistic combination of proven technologies embodied in the FRATIS and Eco-Drive platforms. These platforms were enhanced, integrated, and deployed for the common purpose of improving freight operations in and around POLA. The project included many enhancements to the FRATIS system, key among them being:

1. Integrating with the GeoStamp database system for obtaining wait-time and turn times at marine terminals.
2. Development to automatically expend files from the directory via the FTP client.
3. Development to automatically detect order changes in the directory.
4. Development of a Mobile Application Notification system.
5. Enhancement of the algorithm to consider priority orders.
6. Enhancement of the algorithm to match equipment size between jobs when creating routes.

Based on the analysis presented when evaluating 243 days of operational data generated by the participating drayage company and the FRATIS tool, there were shown to be an 11.6 percent reduction in daily miles traveled by drivers and an increase of 11.5 percent in productivity when utilizing the FRATIS tool for planning.

Additionally, the use of optimization technology demonstrated a potential reduction on GHG emissions of up to 11.6 percent and a potential reduction of over 4.51 metric-tons of non-GHG emissions. In addition, the analysis showed a decrease of up to 418.5 gallons of fuel used per year per vehicle.

The Eco-Drive system used SPaT information from the upcoming traffic signal, that was enabled by Connected Vehicle technology, along with the information about the equipped truck and preceding traffic to determine the optimal speed profiles for the driver to follow. The key innovations of this component of the project include:

1. Deployment of 15 connected signalized intersections nearby POLA with 4G/LTE cellular communication.
2. Development of TSIS server to collect and archive real-time SPaT messages.

3. Development of deep learning based SPaT prediction algorithms for actuated signals.
4. Development of trajectory planning algorithms for conventional diesel trucks that are applicable to actuated signals.
5. Innovative design of the DVIs of an Eco-Drive application on Android platform.
6. Experiment and performance evaluation of Eco-Drive with an equipped truck in real-world traffic.

The successful deployment of the connected signalized intersections was a result of the collaboration among a number of public agencies and private entities. It exemplified the public-private partnerships needed to enable travel and energy efficiency improvements as well as GHG and criteria pollutant emission reductions through Connected Vehicle technology. Using these connected signalized intersections, the Eco-Drive system was demonstrated as part of a demo event in Carson, California, on March 6, 2019, to more than 100 attendees that included stakeholders from both the public and the private sectors.

The results from the real-world Eco-Drive performance evaluation on two connected corridors near POLA showed that driving with Eco-Drive resulted in less fuel consumption and GHG emissions than driving without it by 6 percent to 15 percent. On one of the connected corridors, driving with Eco-Drive also resulted in 29 percent to 32 percent fewer number of stops at signalized intersections, which helped reduce the overall travel time by 7 percent to 11 percent. As an unexpected co-benefit, it was found that Eco-Drive also helped the truck driver better comply with the speed limit of the road, which could improve safety for the truck and the surrounding traffic. As a portable system with only a tablet and an optional camera-based range sensor onboard, Eco-Drive can be easily adapted for use in other vehicle platforms such as passenger cars and transit buses.

4.3 Closing

The in-service demonstration of both the advanced yard tractor and ITS projects provided real-world operating experience with low- and zero-emission technology in yard tractors and advanced freight information system applications for drayage trucks. The objective of this project was to successfully demonstrate and enhance market acceptance of these advanced yard tractor technologies, as well as advanced freight information system applications for drayage trucks. The demonstration resulted in petroleum fuel reduction and significant GHG and criteria pollutant emissions reductions. Although the project experienced challenges, the team views these challenges as opportunities for investigation and development of advanced technology applications, providing positive advancement towards achieving emissions reduction goals.

GLOSSARY

ALTERNATING CURRENT (AC)—Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

APPLICATION PROTOCOL INTERFACE (API)—An application programming interface, or API, enables companies to open up their applications' data and functionality to external third-party developers, business partners, and internal departments within their companies. This allows services and products to communicate with each other and leverage each other's data and functionality through a documented interface.[17]

BATTERY ELECTRIC VEHICLE (BEV)—Also known as an "All-electric" vehicle (AEV), BEVs utilize energy that is stored in rechargeable battery packs. BEVs sustain their power through the batteries and therefore must be plugged into an external electricity source in order to recharge.

CALIFORNIA COMMUNITIES ENVIRONMENTAL HEALTH SCREENING TOOL (CalEnviroScreen)—A mapping tool that helps identify California communities that are most affected by many sources of pollution, and where people are often especially vulnerable to pollution's effects.[18]

CALIFORNIA DEPARTMENT OF TRANSPORTATION (CALTRANS)—Is responsible for the design, construction, maintenance, and operation of the California State Highway System, as well as that portion of the Interstate Highway System within the state's boundaries.

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs.
2. Licensing power plants sufficient to meet those needs.
3. Promoting energy conservation and efficiency measures.
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels.
5. Planning for and directing state response to energy emergencies.

CARBON DIOXIDE (CO2)—A colorless, odorless, non-poisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities.

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[17] IBM website (https://www.ibm.com/cloud/learn/api)

[18] California Office of Environmental Health Hazard Assessment website (https://oehha.ca.gov/calenviroscreen/about-calenviroscreen)

CARBON MONOXIDE (CO)—A colorless, odorless, highly poisonous gas made up of carbon and oxygen molecules formed by the incomplete combustion of carbon or carbonaceous material, including gasoline. It is a major air pollutant on the basis of weight.

COMMA-SEPARATED VALUE (CSV)—A text file format that uses commas to separate values.[19]

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

CONTROLLER AREA NETWORK (CAN)—A controller area network is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other.[20]

DIRECT CURRENT (DC)—A charge of electricity that flows in one direction and is the type of power that comes from a battery.

ECO APPROACH AND DEPARTURE (EAD)—An intelligent transportation system application that uses traffic light signal phase and timing to determine the best speed to reach the next traffic signal on a green light or to come to a stop in the most eco-friendly manner.[21]

ELECTRIC VEHICLE CHARGING STATION (EVSE)—Infrastructure designed to supply power to EVs. EVSE can charge a wide variety of EVs including BEVs and PHEVs.

ELECTRONIC CONTROL UNIT (ECU)—A system in automotive electronics that controls one or more of the electrical systems or subsystems in a car or other motor vehicle.[22]

FILE TRANSFER PROTOCOL (FTP)—File Transfer Protocol (FTP) is a standard Internet protocol for transmitting files between computers on the Internet over TCP/IP connections. FTP is a client-server protocol where a client will ask for a file, and a local or remote server will provide it.[23]

FREIGHT ADVANCED TRAVELER INFORMATION SYSTEM (FRATIS)—Freight Advanced Traveler Information System is a bundle of applications that provides freight-specific dynamic travel planning and performance information and optimizes drayage operations so that load movements are coordinated between freight facilities to reduce empty-load trips.[24]

GREENHOUSE GAS (GHG)—Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs) , ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs). (EPA)

GROSS VEHICLE WEIGHT (GVW)—The maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and cargo but excluding that of any trailers.

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[19] Comma-separated Values Wikipedia website (https://en.wikipedia.org/wiki/Comma-separated_values)

[20] Controller Area Network Wikipedia website (https://en.wikipedia.org/wiki/CAN_bus)

[21] United States Department of Transportation Intelligent Transportation Systems Joint Program Office website (https://www.fhwa.dot.gov/publications/research/operations/15011/15011.pdf)

[22] Electronic Control Unit Wikipedia website (https://en.wikipedia.org/wiki/Electronic_control_unit)

[23] TechTarget website (https://searchnetworking.techtarget.com/definition/File-Transfer-Protocol-FTP)

[24] United States Department of Transportation Intelligent Transportation Systems Joint Program Office website (https://www.its.dot.gov/research_archives/dma/bundle/fratis_plan.htm)

INTELLIGENT TRANSPORTATION SYSTEMS (ITS)—Technical innovations that apply communications and information processing to improve the efficiency and safety of ground transportation systems.[25]

KILOWATT (kW)—One thousand (1,000) watts. A unit of measurement of the amount of electricity needed to operate given equipment. On a hot summer afternoon, a typical home, with central air conditioning and other equipment in use, might have a demand of four kW for each hour.

KILOWATT-HOUR (kWh)—The most commonly-used unit of measure telling the amount of electricity consumed over time. It means one kilowatt of electricity supplied for one hour. In 1989, a typical California household consumes 534 kWh in an average month.

LIQUEFIED NATURAL GAS (LNG)—Natural gas that has been cooled to -259 degrees Fahrenheit (-161 degrees Celsius) and at which point it is condensed into a liquid which is colorless, odorless, non-corrosive and non-toxic. Characterized as a cryogenic liquid.

LONG SHORT-TERM MEMORY (LSTM)—A type of computer neural network that is capable of learning order dependence in sequence prediction.[26]

LOS ANGELES DEPARTMENT OF TRANSPORTATION (LADOT)—A municipal agency that oversees transportation planning, design, construction, maintenance and operations within the City of Los Angeles.

LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY (LA Metro)—The transportation planning agency that plans, coordinates funding, and operates most of the public transportation system in Los Angeles County.[27]

MEAN ABSOLUTE ERROR (MAE)—The average variance between the significant values in the dataset and the projected values in the same dataset.[28]

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (NHTSA)—The National Highway Traffic Safety Administration is an agency of the U.S. federal government, part of the Department of Transportation. It is responsible for keeping people safe on America's roadways.[29]

NITROGEN OXIDE (NOX)—A general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide (NO2) and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition. NO2 is a criteria air pollutant and may result in numerous adverse health effects.

PARTICULATE MATTER (PM)—Unburned fuel particles that form smoke or soot and stick to lung tissue when inhaled. A chief component of exhaust emissions from heavy-duty diesel engines.

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[25] California Department of Transportation website (https://dot.ca.gov/programs/local-assistance/fed-and-state-programs/its-program)

[26] Machine Learning Mastery website (https://machinelearningmastery.com/gentle-introduction-long-short-term-memory-networks-experts/)

[27] Los Angeles County Metropolitan Transportation Authority website (https://www.metro.net/about/)

[28] ScienceDirect website (https://www.sciencedirect.com/topics/engineering/mean-absolute-error)

[29] National Highway Traffic Safety Administration website (https://www.nhtsa.gov/about-nhtsa)

PORT OF LOS ANGELES (POLA)—The Port of Los Angeles is the nation's premier gateway for international commerce and the busiest seaport in the Western Hemisphere. Located in San Pedro Bay, 25 miles south of downtown Los Angeles, the Port encompasses 7,500 acres of land and water along 43 miles of waterfront.[30]

PORT OF LONG BEACH (POLB)—The Port of Long Beach is the premier U.S. gateway for trans-Pacific trade and a trailblazer in innovative goods movement, safety, environmental stewardship and sustainability. It is the second-busiest container seaport in the United States.[31]

RENEWABLE NATURAL GAS (RNG)—A pipeline quality gas that is fully interchangeable with conventional natural gas and thus can be used in natural gas vehicles. Like conventional natural gas, RNG can be used as a transportation fuel in the form of compressed natural gas (CNG) or liquefied natural gas (LNG).[32]

SIGNAL PHASE AND TIMING (SPaT)—A traffic signal cycle that is the total time to complete one sequence of signalization for all movements at an intersection.[33]

SOFTWARE AS A SERVICE (SAAS)—Is a cloud-based service where instead of downloading software your desktop PC or business network to run and update, you instead access an application via an internet browser.[34]

TRAFFIC SIGNAL INFORMATION SYSTEM (TSIS)—Also known as Multi-Modal Intelligent Traffic Signal System, a TSIS is a traffic control management system that provides the ability to monitor signal operations and can change signal control plans by time of day or in a traffic responsive manner.[35]

TRANSPORTATION MANAGEMENT SYSTEM (TMS)—A software system that helps companies manage logistics associated with the movement of physical of goods.[36]

TWENTY-FOOT EQUIVALENT UNITS (TEU)—A general unit of cargo capacity, often used for container ships and container ports. It represents a container that is 20 feet long, eight feet wide, and eight feet tall.[37]

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (USEPA)—A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting and enforcement activities.

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[30] Port of Los Angeles website (https://www.portoflosangeles.org/about)

[31] Port of Long Beach website (https://www.polb.com/port-info)

[32] United States Department of Energy Alternative Fuels Data Center website (https://afdc.energy.gov/fuels)

[33] Federal Highway Administration Office of Operations website (https://ops.fhwa.dot.gov/publications/fhwahop08024/chapter4.htm)

[34] TechRadar website (https://www.techradar.com/news/what-is-saas)

[35] United States Department of Transportation Intelligent Transportation Systems Joint Program Office website (https://www.its.dot.gov/research_archives/dma/bundle/mmitss_plan.htm#:~:text=Modern%20traffic%20control%20management%20systems,on%20traditional%20vehicle%20detector%20data.)

[36] SAP website (https://www.sap.com/products/scm/transportation-logistics/what-is-a-tms.html#:~:text=A%20transportation%20management%20system%20is,a%20combination%20of%20transportation%20modes.)

[37] Twenty Foot Equivalent Unit Wikipedia website (https://en.wikipedia.org/wiki/Twenty-foot_equivalent_unit)

UNIVERSITY OF CALIFORNIA, RIVERSIDE (UCR)—A public research university located in Riverside, California. It is one of the 10 campuses in the University of California (UC) system.

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