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Evaluation of Benefits and Costs of Truck Connected Eco-Driving Program on Urban Freight Corridors

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Evaluation of Benefits and Costs of Truck Connected Eco-Driving Program on Urban Freight Corridors

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December 2021

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16. Abstract

This research estimates the costs and benefits of implementing connected eco-driving technology for freight trucks on signalized freight corridors as a strategy to mitigate the impacts of truck traffic. The costs associated with enabling the technology include capital investment for infrastructure upgrades such as upgrading traffic controllers and installing communication modems. The costs also include operating costs for wireless data plans and computing servers. Over a period of 20 years, the total cost for one intersection is estimated to be $18,200. The benefits of the technology include reductions in energy consumption and emissions from a connected truck traveling on connected corridors. Under cold start conditions, the technology could help reduce overall fuel consumption by 20%, and emissions of carbon dioxide, nitrogen oxides, and particulate matter by 22%, 20%, and 15%, respectively. Under hot running conditions, the technology could help reduce overall fuel consumption by 10% and emissions of carbon dioxide, nitrogen oxides, and particulate matter by 10%, 0%, and 41%, respectively. Based on these estimates, connected eco-driving technology can play an important role in addressing greenhouse gas emissions from freight trucks, as well as mitigating the air quality and health impacts associated with truck emissions in communities that are heavily impacted by truck traffic.

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Executive Summary

Executive Summary

Over the last several years, California has experienced faster growth in freight volume than freight-related infrastructure, leading to inefficiencies in terms of travel delays as well as externalities in the form of traffic congestion and air pollution. One operational strategy to improve the efficiency of freight movement while also reducing climate and environmental impacts is to provide advanced traveler information to truck drivers. Innovative technologies such as connected eco-driving at signalized intersections can provide traffic signal phase and timing information which can be used to determine a recommended driving speed for the driver to pass through signalized intersections in an efficient manner. This research estimates the costs and benefits of implementing connected eco-driving technology for freight trucks on signalized freight corridors as a strategy to mitigate the impacts of truck traffic on these corridors.

As summarized in Table 1, the costs associated with enabling the technology include capital investment for infrastructure upgrades such as upgrading traffic controllers and installing communication modems. The costs also include operating costs such as wireless data plans and computing servers. Over a period of 20 years, the total cost for one intersection is estimated to be $18,200. However, large-scale implementation could result in cost savings. For example, by implementing the technology at 100 intersections, the total cost per intersection would be reduced to $12,460 over a period of 20 years. Note that the costs estimated in this research would be incurred by public agencies who own and operate traffic signals at the connected intersections. There are also costs associated with enabling the technology on vehicles for the drivers to use, but those costs are assumed to be borne by private entities, such as vehicle manufacturers and mobile application developers.

Table 1. Summary of costs and benefits of connected eco-driving system for freight trucks

System Costs per Intersection	System Benefits per Vehicle
• $3,500 for traffic signal controller upgrade • $1,500 for communication modem • $30 per month for wireless data plan • $25 per month for computing server • $0.8 per month for storage server • Total cost up to $18,200 over 20 years	• *Cold start condition* – 20% reduction in fuel consumption, 22% for CO2 emission, 20% for NOx emission, 15% for PM emission • *Hot running condition* – 10% reduction in fuel consumption, 10% for CO2 emission, 0% for NOx emission, 41% for PM emission

The benefits of the technology are primarily the reduction in energy consumption and emissions of connected trucks traveling on connected corridors. These include a 20 percent reduction in fuel consumption under cold start conditions—such as during the first few minutes of operation after overnight parking at the home base or a long stop at a warehouse when the temperature inside the truck's emission control system drops below a certain threshold, making it less effective. The savings would be 10 percent under hot running conditions —

such as when operating on highways or after a few minutes of vehicle operation — despite a 4 percent increase in travel time. If truck drivers and fleet operators can accept the slight increase in travel time, then this level of fuel savings should be attractive as fuel cost is typically the second largest cost of trucking.

In terms of emissions, the primary benefits include reductions in carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matter (PM). On average, the connected eco-driving system could reduce CO2 emission from connected trucks by 22 percent under cold start conditions and by 10 percent under hot running conditions, and thus, could play an important role in addressing greenhouse gas emissions from freight trucks in the near term while these trucks are transitioning to zero emission vehicles over the next few decades. The reductions in NOx and PM emissions are also substantial. Under cold start conditions, the system could help reduce overall NOx and PM emissions from connected trucks by 20 and 15 percent, respectively. While the system would not increase or decrease overall NOx emissions from connected trucks under hot running conditions, it could help reduce overall PM emissions by 41 percent. Thus, connected eco-driving technology can serve as one strategy for mitigating the air quality and health impacts associated with truck emissions in communities that are heavily impacted by truck traffic.

Based on the state of the technology, connected eco-driving technology has several characteristics that are attractive. It is ready for implementation, relatively low cost, compatible with both legacy and new vehicles, extendable to other types of vehicles such as cars and buses, and easily scalable from one intersection to hundreds of intersections. In addition to the energy savings and emissions reduction benefits, the technology also has potential to provide other co-benefits, such as improving traffic safety, reducing brake and tire wear emissions, and mitigating noise pollution, as a result of smoother vehicle operation. These potential co-benefits of connected eco-driving technology have not been studied, but should be researched in the future.

Contents

Introduction

Freight transportation is an important driver of the California economy. However, over the last several years, the state has experienced faster growth in freight volume than freight-related infrastructure, leading to inefficiencies in terms of travel delays as well as externalities in the form of traffic congestion and air pollution. In 2016, the State of California released the California Sustainable Freight Action Plan to help guide the state's transition to a more efficient, more economically competitive, and less polluting freight transportation system. In 2017, the California Air Resources Board (CARB) established the Community Air Protection Program (CAPP) in response to Assembly Bill (AB) 617, with a focus on reducing human exposure to air pollution in the most impacted communities. Many communities selected for CAPP implementation cite freight-related sources such as trucks as one of the key pollution sources in their communities (California Air Resources Board, 2019).

At the same time, the state has continued it efforts to reduce truck emissions and the associated health impacts by, for example, imposing more stringent emission standards (California Air Resources Board, 2021a), mandating zero emission vehicle sales targets (California Air Resources Board, 2021b), and incentivizing purchases of clean vehicles (California Air Resources Board, 2021c). These programs will help transition the existing truck inventory to more advanced, cleaner technologies, although it will take a long time and require a sizable investment. In the near term, other efforts to reduce truck emissions and mitigate their health impacts on communities are needed. This is especially important for disadvantaged communities near freight hubs such as ports, railyards, and warehouses that bear disproportionate burdens from the negative impacts of truck traffic.

One operational strategy to improve the efficiency of freight movement while also reducing climate and environmental impacts is to provide advanced traveler information to truck drivers. In recent years, truck drivers have been able to access real-time traffic information from smart devices, and then use that information to select a travel route to avoid traffic congestion, save time, and reduce fuel consumption (Scora et al., 2015). In addition to routing, advanced traveler information can also be used to promote efficient driving among truck drivers (Boriboonsomsin, 2015). Research has shown that using real-time traffic information to provide driving speed recommendations to truck drivers can help smooth their driving, which reduces fuel consumption and emissions (Jin et al., 2016).

On freeways, average real-time traffic speed information has been used to drive various traffic management strategies such as travel time information and variable speed limits. On surface streets, traffic signal status is a critical piece of real-time advanced traveler information that can enable innovative applications such as connected eco-driving where traffic signal phase and timing (SPaT) information is used to determine a recommended driving speed for the driver to pass through signalized intersections in an efficient manner. Since traffic signals are owned and operated by public agencies, an understanding of the costs and benefits associated with providing SPaT information to drivers is needed.

Research Program

This research estimated the costs and benefits of implementing connected eco-driving technology on signalized freight corridors as a strategy to mitigate the impacts of truck traffic. The costs associated with enabling the technology include capital investment in infrastructure upgrades such as upgrading traffic controllers to export real-time SPaT data and installing communication links or devices to send the SPaT data to a server. The costs also include operating costs such as wireless data plans and server maintenance.

The benefits of technology implementation include reductions in energy consumption and emissions of freight trucks traveling on the corridors. Previous research has described the benefits of connected eco-driving technology for freight trucks, both in simulated traffic environments and in real-world settings, focused on energy consumption. As a result, there is a knowledge gap in terms of the emissions reduction potential of this technology. This research addresses this knowledge gap by conducting emissions testing of a heavy-duty diesel truck (HDDT) driving without and with the technology to evaluate emissions reductions resulting from the use of the technology.

Report Organization

The main body of this report presents a concise summary of the research findings, with additional information and technical explanations provided in appendices. The first part provides a generic description of connected eco-driving technology, describes the recent pilot implementation of a connected eco-driving system for freight trucks in Southern California, and discusses the evaluation of the system in a traffic simulation environment. The second part of the report provides an estimate of the various system costs and discusses system benefits in terms of energy savings and emissions reduction for vehicles that use the system. The final part provides conclusions drawn from this research, considerations for follow-on research, and implications for future implementation of the technology.

Connected Eco-Driving at Signalized Intersections

Recent advances in connected vehicle (CV) technology have created new opportunities to improve safety, mobility, energy efficiency, and environmental sustainability of people and freight movement through information sharing among road users and roadway infrastructure. Several CV applications have been developed, evaluated, and demonstrated over the last decade. Among these, connected eco-driving at signalized intersections has been shown to be one of the most effective CV applications for energy savings and emissions reduction. The application uses SPaT information from the upcoming traffic signal along with information about the current state of the connected vehicle and preceding traffic to determine the best course of action for the connected vehicle to pass through the intersection. As shown in Figure 1, common scenarios include: 1) cruising through the green light, 2) speeding up (while staying under the speed limit) to pass through the intersection before the signal turns red, 3) slowing down in advance so that the vehicle reaches the intersection just when the signal turns green, and 4) coasting to a stop if the red light is unavoidable.

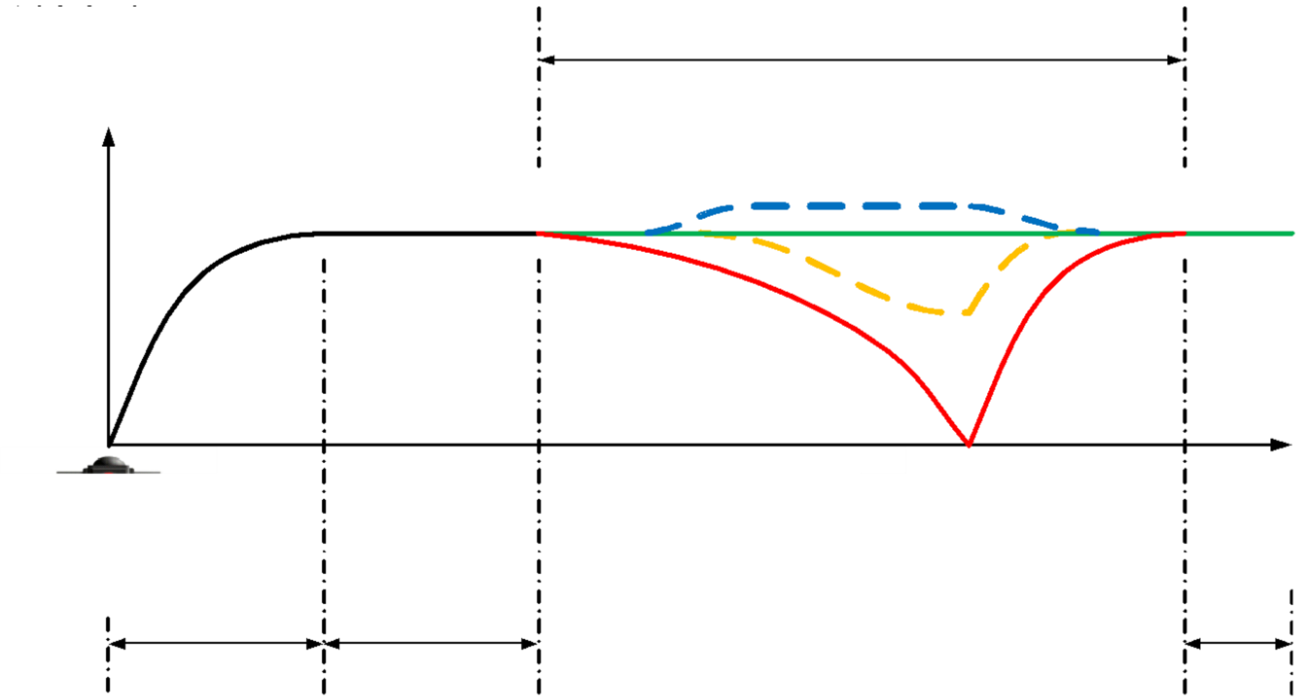


Figure 1. Scenarios for driving through an intersection with traffic signal

Once the application has determined the best course of action, it then designs and recommends to the driver a driving speed profile that would minimize vehicle energy consumption and delay. Previous studies have shown that with a well-designed speed profile, the connected vehicle would pass through the intersection in a way that reduces the frequency of stops as well as unnecessary acceleration and deceleration, resulting in significant energy savings and emissions reduction.

Most of the early research and development on connected eco-driving at signalized intersections has been focused on passenger cars (Xia et al., 2013; Altan et al., 2017; Hao et al., 2019). However, in the last several years there has been increasing interest in developing and implementing this technology on other types of vehicles. Since 2017, researchers at the University of California, Riverside (UCR), have been conducting research and development of connected eco-driving at signalized intersections technology for freight trucks. For example, they performed a numerical simulation of a connected eco-driving algorithm for HDDTs traveling through signalized intersections and found that it could provide average fuel savings of 11 percent on flat terrain, six percent on uphill grades, and 20 percent on downhill grades (Hao et al., 2021a). They also implemented the algorithm in a traffic simulator and evaluated the impact of the technology on an equipped HDDT traveling on signalized freight corridors (Hao et al., 2021b). In addition, UCR researchers, along with public agency and industry partners, implemented a connected eco-driving system on a HDDT and demonstrated its operation in real-world traffic on urban freight corridors in Carson, California (Wang et al., 2019). These efforts at UCR provide a foundation for this research and are summarized in the sections that follow.

Real-World Pilot Implementation

The Ports of Los Angeles and Long Beach are the busiest port complex in the U.S. by container volume. Together, they generate a large number of truck trips each day, the majority of which are made by HDDTs. Unlike long-haul trucks, these port trucks or drayage trucks spend a large amount of time traveling on arterial corridors with traffic signals and stand to benefit greatly from connected eco-driving technology. Thus, they are the prime candidate for the pilot implementation of this technology.

To implement the connected eco-driving technology in the real world, UCR researchers developed and implemented a series of hardware and software for both the vehicle and the traffic signals. These development and implementation efforts were made with support from the California Air Resource Board (CARB), California Energy Commission (CEC), South Coast Air Quality Management District (SCAQMD), Port of Los Angeles (POLA), Los Angeles County Metropolitan Transportation Authority (LA Metro), Los Angeles County's Department of Public Work (LADPW), City of Carson, City of Los Angeles' Department of Transportation (LADOT), Econolite, McCain, Western System, and Volvo Technology of America.

On the roadway infrastructure side, the research team worked with POLA, LA Metro, LADPW, City of Carson, and LADOT to deploy 15 connected signalized intersections near the Ports of Los Angeles and Long Beach to support a variety of connected vehicle applications. The 15 connected signalized intersections are located on three urban freight corridors, which carry high volume of truck traffic. These corridors are: 1) Alameda St., 2) S. Wilmington Ave., and 3) W. Harry Bridges Blvd., as shown in Figure 2. On each of the corridors, five signalized intersections were chosen and enabled to send real-time SPaT data to the Traffic Signal Information System (TSIS) server at UCR.

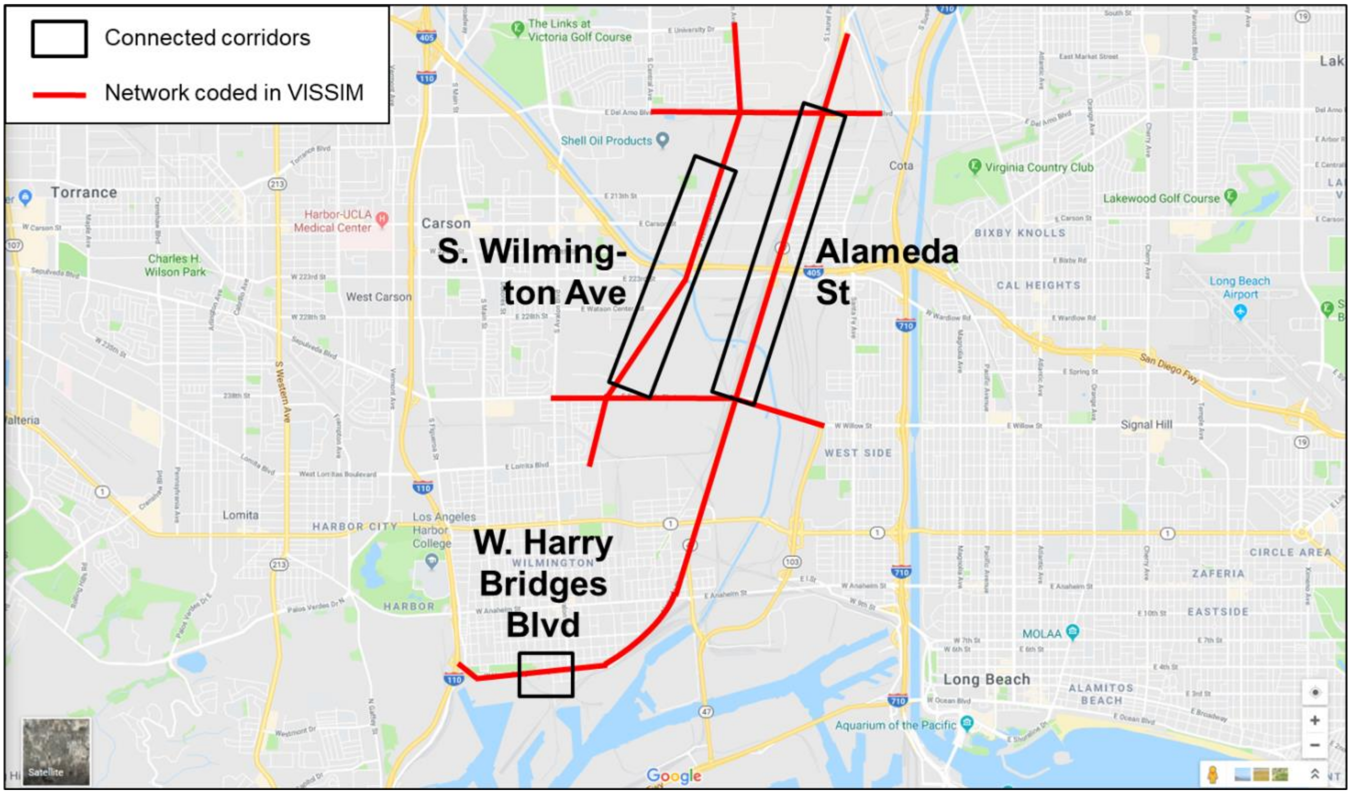


Figure 2. Connected signalized freight corridors near Ports of Los Angeles and Long Beach

The connected corridor on Alameda St. is a three-mile segment with two to three lanes per direction and speed limit of 45 mph. The connected corridor on S. Wilmington Ave. is a two-mile segment with two lanes per direction and speed limit of 35-40 mph. The connected corridor on W. Harry Bridges Blvd. is a 0.5-mile segment with two lanes per direction and speed limit of 35-40 mph. For the five connected intersections on W. Harry Bridges Blvd., real-time SPaT data are obtained from the Traffic Management Center (TMC) of LADOT. On the other hand, the connectivity of the 10 connected intersections on Alameda St. and S. Wilmington Ave. is enabled by a 4G/LTE modem where real-time SPaT data is sent to the TSIS server at UCR via cellular communication. The locations of these 10 connected signalized intersections are shown on the map in Figure 3.

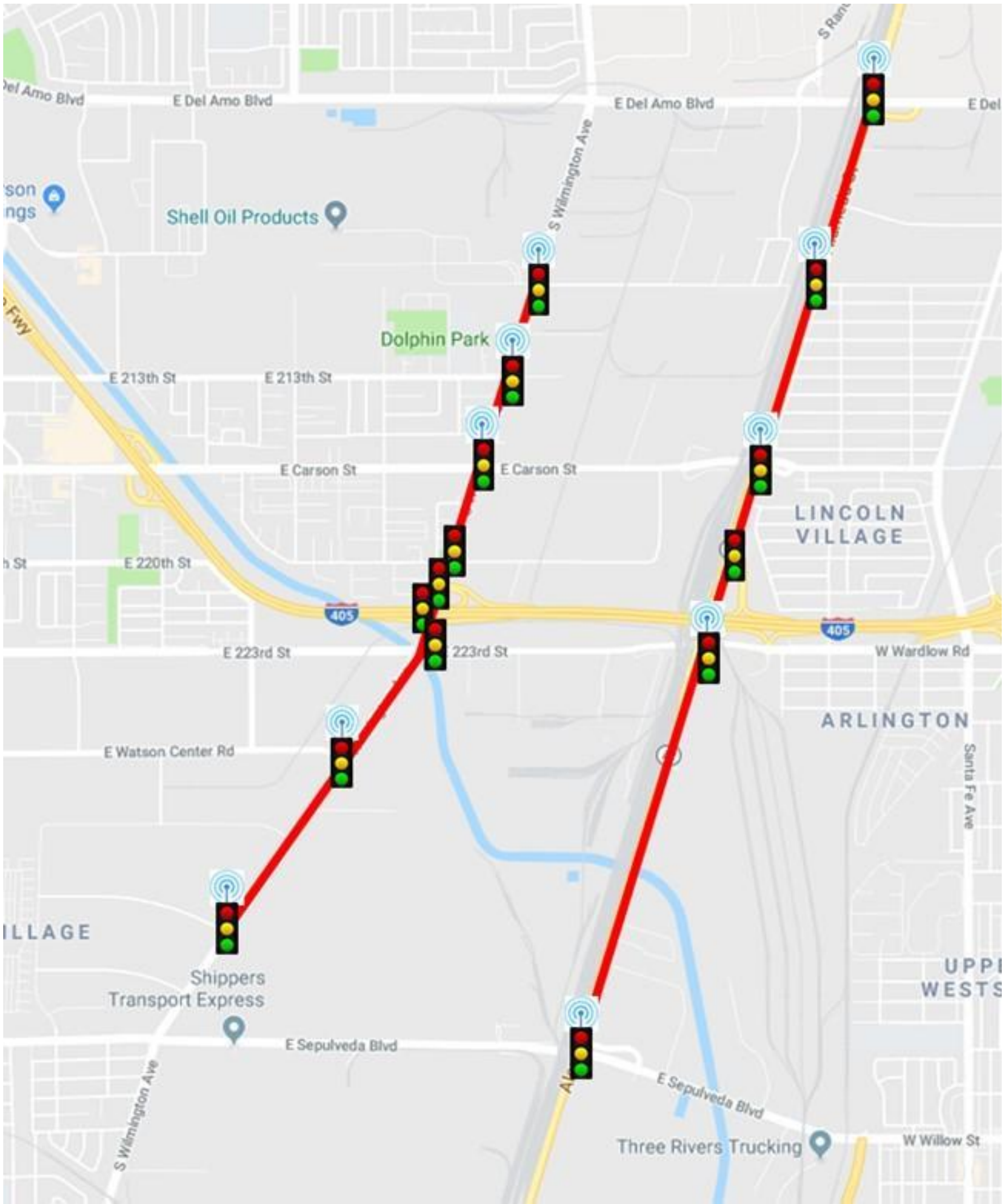
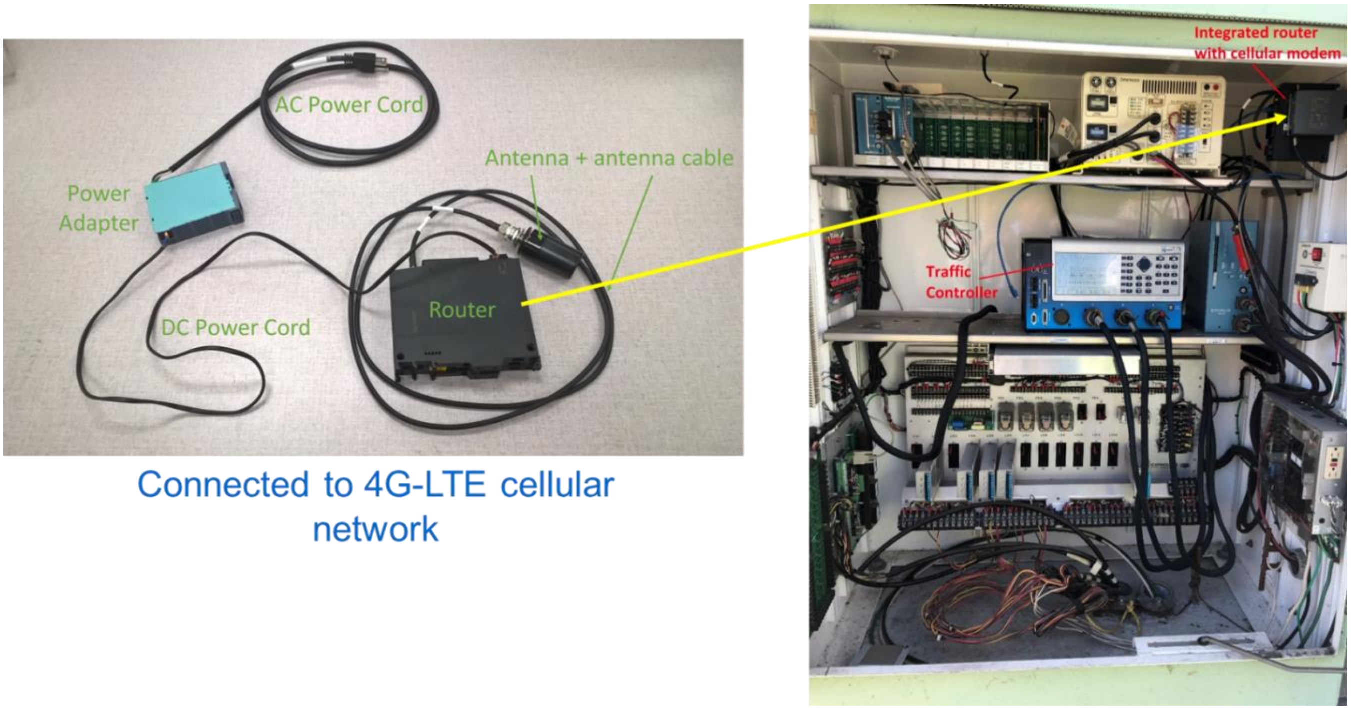


Figure 3. Locations of 10 connected signalized intersections on Alameda St. and Wilmington Ave.

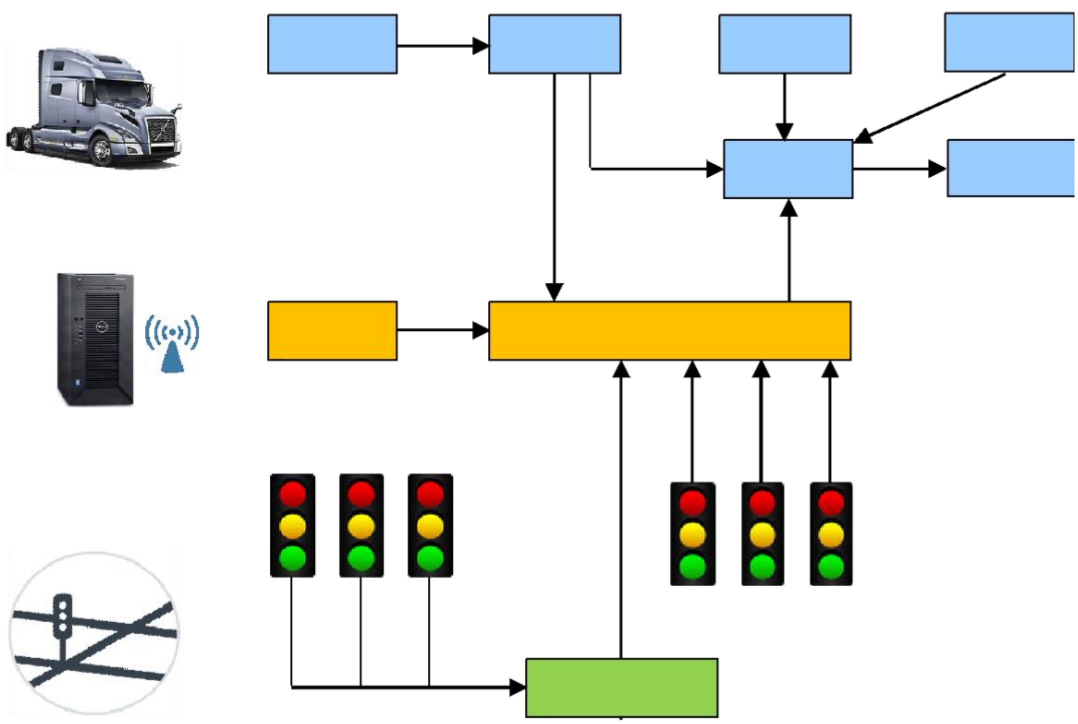
Figure 4 shows the instrumented hardware inside the traffic signal controller cabinet at one of the intersections. The router mounted in the cabinet is a rugged, industrial-graded router that can withstand temperatures of up to 160 °F. After connecting to the traffic signal controller, the cellular modem forwards SPaT messages from the traffic signal controller to the TSIS server over the 4G/LTE cellular network. The communication time varies but is usually less than two seconds. This level of latency is acceptable for connected eco-driving at signalized intersections, which is a non-safety critical application.



Connected to 4G-LTE cellular network

Figure 4. Instrumentation of traffic signal controller cabinet with wireless communication

Figure 5 presents the components and data flow of the connected eco-driving system. On the roadway infrastructure side, the system must be able to obtain real-time SPaT information from the traffic signals at connected signalized intersections. There are two general approaches for obtaining SPaT information — centralized and decentralized. The centralized approach applies to traffic signals that are already connected to a TMC, through fiber optics or other means. For those traffic signals, SPaT information can be obtained from the TMC. In the decentralized approach, SPaT information is obtained directly from individual traffic signals through wireless communication, such as dedicated short-range communication or cellular network. With both approaches, the SPaT information is sent to the TSIS server in real time.



Component	Description
GPS	For identifying truck position
Map	Digital map
Radar	For detecting preceding vehicle
ECU	For reporting engine parameters
EAD	Trajectory planning algorithm
DVI	Driver-vehicle interface on 7-in display
Map	Digital map of Southern California
Live SPaT Streams	Real-time SPaT from connected intersections
City TMC	Traffic management center

ID	Data Elements	Update Frequency (Hz)
1	Latitude, longitude, & heading	1
2	Upcoming intersection & direction	1
3	Distance to intersection	1
	Roadway speed limit	1
4	Upcoming SPaT	1
5	Preceding vehicle detection signal	10
6	Vehicle speed (ECU)	10
7	Upcoming SPaT	1
	Roadway speed limit	1
	Recommended driving speed	10
8	Real-time SPaT	1
9	Upcoming intersection & direction	1

Figure 5. Components and data flow of truck connected eco-driving system

On the vehicle side, the connected vehicle is equipped with onboard hardware that supports the connected eco-driving system, as shown in Figure 6. These include the onboard computer, GPS receiver, wireless communication modem, radar sensor, and driver display. The onboard computer is the heart of the system. It receives and processes data inputs from other system components, calculates the algorithms, and sends the resulting outputs to the driver display. The onboard computer stores a map of the connected corridors that contains the coordinates of each traffic signal and the speed limit of each roadway segment on the corridors. Using this map and GPS information about the position and direction of travel of the connected vehicle, a map matching algorithm determines if the connected vehicle is approaching one of the connected intersections. If that is the case, the system requests, and then receives, real-time SPaT information for the connected intersection from the TSIS server.

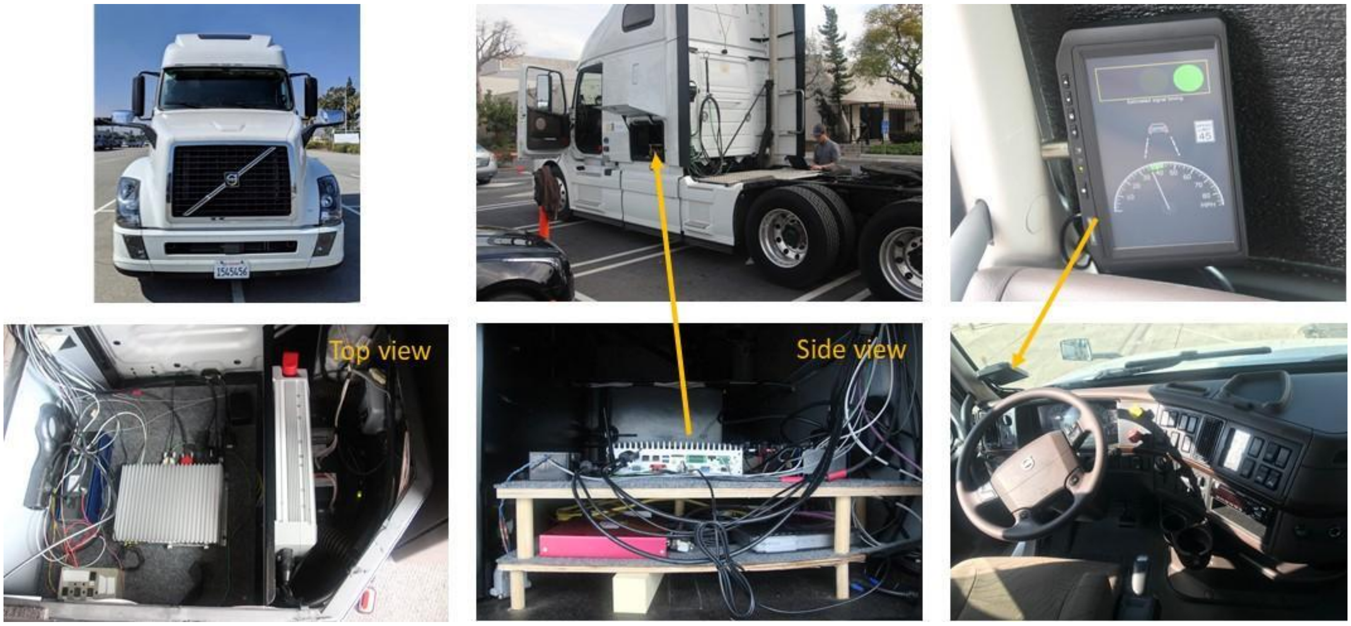


Figure 6. Instrumentation of Class 8 truck with onboard hardware for connected eco-driving

The map matching algorithm also identifies the speed limit of the roadway segment, calculates the distance from the connected vehicle to the upcoming connected intersections, and passes this information on to the vehicle trajectory planning algorithm. Using this information, along with the real-time SPaT information for the connected intersection from the TSIS server, the current speed of the connected vehicle from the engine control unit (ECU), and the distance between the connected vehicle and the preceding vehicle (if any) from the radar sensor, the vehicle trajectory planning algorithm calculates the recommended driving speed for the connected vehicle. The recommended speed, together with the SPaT and roadway speed limit information, is then sent to the driver display to be shown on the driver-vehicle interface (DVI). A video demonstrating the DVI while the connected eco-driving system is in operation can be viewed at https://www.youtube.com/watch?v=1CR4vMh8ufE.

System Evaluation using Traffic Simulation

A systematic evaluation of the connected eco-driving system for freight trucks in real-world traffic can be difficult as it is not possible to control for all the influencing factors (e.g., SPaT, traffic congestion, presence and movement of surrounding vehicles, etc.) during experiments conducted with and without using the system. On the other hand, a mathematical simulation as conducted in Hao et al. (2021a) lacks a realistic representation of interactions between the connected vehicle and other vehicles in traffic. A traffic simulation, which simulates multiple vehicles in traffic at the same time, offers a good compromise since it can create identical traffic conditions for the vehicle to experience with and without the use of the system and represent the behavior of surrounding vehicles better than with a purely mathematical simulation. Along with the real-world implementation of the connected eco-driving system on a HDDT described in the previous section, UCR researchers also tested the system in a traffic simulation environment for a robust evaluation of the system benefits.

The simulation network covers the roadways indicated by the red lines in Figure 2. It was calibrated to match real-world conditions using traffic counts and signal timing plans from local agencies. The connected eco-driving system was introduced into the traffic simulator through an application programming interface (API). As shown in Figure 7, the connected eco-driving system consists of online and offline components. The offline components are prepared prior to running the simulation whereas the online components are executed in real time during simulation runs.

At each time step during a simulation run, the system first gathers various data inputs, including SPaT for the upcoming traffic signal, distance from the preceding vehicle, speed of the connected vehicle, as well as speed limit and vertical grade of the roadway. If not all data inputs are available or if there is another vehicle in close proximity in front of the connected vehicle, then the system will be turned off and wait until the next time step. Otherwise, it will proceed to calculate the vehicle’s trajectory and optimum speed profile to enable the vehicle to pass through the upcoming connected intersection in the most energy-efficient manner without compromising safety and mobility. To address the unique vehicle dynamic and powertrain characteristics of HDDTs in the algorithm, the algorithm is trained using calibrated acceleration and deceleration profiles and power-based cost tables that are specific for HDDTs. These data inputs are fed into the graph-based trajectory planning algorithm first to generate a pool of vehicle trajectories for all combinations of the starting and ending states of the connected vehicle. Then, a machine learning-based trajectory planning algorithm is used to determine an optimal vehicle trajectory from the pool of trajectories in real time. Detailed description of the connected eco-driving system logics and algorithms is provided in Appendix A.

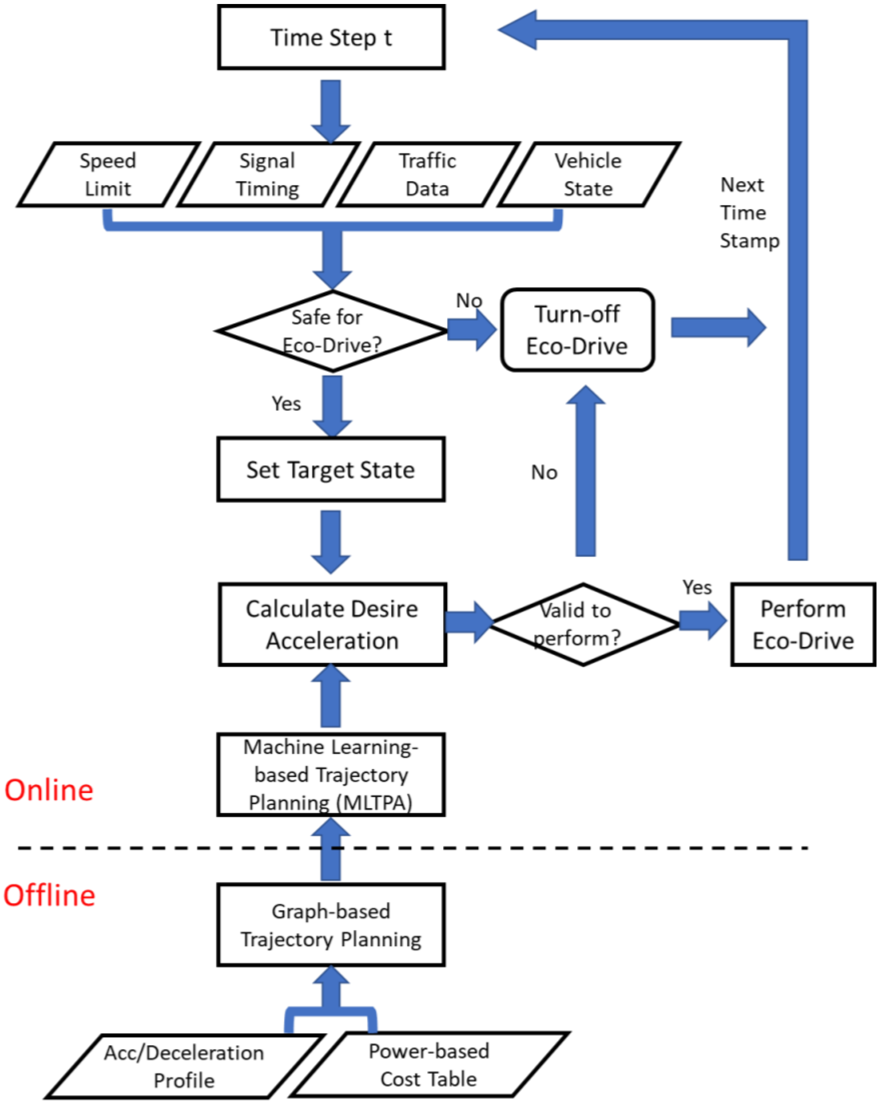


Figure 7. Flow chart of truck connected eco-driving system as implemented in traffic simulator

The evaluation of the system benefits focused on the connected corridors on Alameda St. and Wilmington Ave. Simulation runs were made separately for the northbound and the southbound directions of each connected corridor. That means there are four separate segments on which the connected eco-driving system was evaluated: 1) Alameda St. northbound, 2) Alameda St. southbound, 3) Wilmington Ave. northbound, and 4) Wilmington Ave. southbound. For each segment, a pair of simulation runs was made, one with a baseline vehicle not using the connected eco-driving system and the other with a connected vehicle. Data regarding vehicle speed, acceleration/deceleration, travel time, and energy consumption were recorded for use in the comparative evaluation. A total of 350 pairs of simulation runs were made with different seed numbers from 1 to 350 in order for the vehicles to experience a variety of traffic conditions. Details of the simulation setup and results are provided in Appendix B.

System Costs and Benefits

This chapter describes the costs for enabling the connected eco-driving system and summarizes the system benefits in terms of reduction in energy consumption and emissions of freight trucks traveling on connected corridors.

Implementation Costs

As shown in the system diagram in Figure 5, the connected eco-driving system consists of a connected vehicle, a server, and connected intersections. The analysis focused on the costs to the public agencies who own and operate traffic signals, which include the costs associated with connected intersections and the server. On the other hand, the costs associated with connected vehicles are expected to be borne by private entities, such as vehicle manufacturers and mobile application developers, who would invest in system hardware and software to be marketed to consumers.

The following cost items apply to a public agency interested in enabling the connected eco-driving system at signalized intersections in its jurisdiction:

- *Traffic signal controller upgrade* — Depending on the capability of the existing traffic signal controller, an upgrade may be necessary to enable the export of real-time SPaT information.
- *Data communication* — This cost item varies depending on the existing infrastructure of the agency. If the agency already has a TMC that receives real-time SPaT information from traffic signals in its jurisdiction, then this cost item would not apply except for the typical maintenance costs for the TMC. If a TMC does not exist, then the agency could choose to create a TMC and establish a data communication line (e.g., through fiber optics) to send real-time SPaT information to the TMC. Alternatively, the agency could choose to install a wireless communication modem in the traffic controller cabinet to send real-time SPaT information to the server. With this approach, the cost will include a one-time cost of the communication modem and a monthly or annual cost of a wireless data plan.
- *Server* — The server for receiving, and optionally storing, SPaT information can be a dedicated or cloud server, depending on the agency's preference.

Table 2 summarizes the estimated costs of the basic items for enabling the connected eco-driving system at one signalized intersection. The actual costs could be different depending on a number of factors, for example, vendor, equipment model, special pricing, volume discount, etc. However, the estimated costs given here can serve as a starting point. Note that the labor costs for upgrading the traffic signal controller, installing and configuring a communication modem, setting up a server, and maintaining these components are not provided in Table 2. It is assumed that these tasks would be performed by the agency's existing personnel, and thus, there would be no additional out-of-pocket cost to the agency.

Table 2. Estimated costs of connected eco-driving system components for one intersection

Cost Item	Estimated Cost	Comment
Traffic signal controller upgrade	$3,500	Does not apply if existing controller can already export real-time SPaT information
Communication modem	$1,500	Does not apply if SPaT information is already sent to existing TMC
Wireless data plan	$30 per month	For unlimited data; does not apply if SPaT information is already sent to existing TMC
Server – computing	$25 per month	For cloud computing; used to receive and forward SPaT information to third party
Server – storage	$0.80 per month	For cloud storage; does not apply if not storing historical SPaT information

Based on the estimated costs in Table 2, the cost for enabling the connected eco-driving system at one intersection includes up to $5,000 in capital investment plus up to $25 per month of operating expenses, assuming that historical SPaT information will not be stored. Over a period of 20 years, the total cost would add up to $18,200 or $910 per year. Note that there is potential for significant cost savings from large-scale deployment of the system. For example, the cost for the cloud computing would increase to only $110 per month for 100 intersections, or just $1.10 per month per intersection. This would result in a total cost of $12,460 per intersection or $623 per intersection per year over a period of 20 years.

Energy Savings Benefit

One of the intended benefits of the connected eco-driving system is energy savings. In fact, the trajectory planning algorithms used by the system aim to minimize the tractive power required of the engine for the vehicle to pass through the intersection, which is directly correlated with the energy use by the engine. In the evaluation of the connected eco-driving system for freight trucks in a traffic simulation, the energy consumed by the connected vehicle as calculated by summing up the tractive power required over the course of several connected corridors is used to estimate the energy savings benefit of the system. Table 3 provides the average values of energy use and travel time for the baseline vehicle and the connected vehicle on four different segments (detailed results are provided in Appendix B). As shown in this table, the connected vehicle that uses the connected eco-driving system would consume 6 to 18 percent less energy than the baseline vehicle, depending on the road segment. When combining the energy use across all four road segments, the average energy savings from using the system is 10 percent. Note that the system could lead to longer travel times on some of the road segments. For the four segments combined, the travel time of the connected vehicle is four percent longer on average.

Table 3. Energy use and travel time results from traffic simulation

Metric	Alameda Northbound	Alameda Southbound	Wilmington Northbound	Wilmington Southbound	Combined
Baseline Vehicle					
Energy use (kWh/mi)	1.20	1.35	1.55	1.46	1.37
Travel time (s/mi)	117.5	179.1	190.5	250.7	179.3
Connected Vehicle					
Energy use (kWh/mi)	1.12	1.25	1.27	1.29	1.23
Travel time (s/mi)	116.9	181.2	213.7	260.4	186.5
Difference					
Energy use (kWh/mi)	-6%	-7%	-18%	-12%	-10%
Travel time (s/mi)	-1%	1%	12%	4%	4%

Emissions Reduction Benefit

Another intended benefit of the connected eco-driving system is the reduction in tailpipe emissions when the connected vehicle travels on the connected corridors. The emissions reduction benefit of the connected eco-driving system was estimated based on real-world emissions testing of a HDDT on the heavy-duty chassis dynamometer at UCR, as described in Appendix C. Five pairs of second-by-second speed profiles — one for the baseline vehicle and the other for the connected vehicle — from the traffic simulation runs were used as test cycles for emissions testing. The test vehicle was a 2015 model year class 8 truck with 13-liter diesel engine and rated power of 455 HP, shown in Figure 6. One of the test cycles was tested under cold start conditions — when the engine had been shut off long enough for the temperature inside the emission control system to drop below a certain threshold, which makes it less effective. This threshold varies by specific emission control systems, but it tends to be at least 200 °C (Boriboonsomsin et al., 2018). The other four cycles were tested under hot running conditions. Table 4 presents the fuel consumption and emission test results.

Table 4. Fuel consumption and emission results from chassis dynamometer testing

Metric	Cold Start	Hot Running -Cycle A	Hot Running - Cycle B	Hot Running - Cycle C	Hot Running - Cycle D	Hot Running -Combined
Baseline Vehicle						
Fuel (g/mi)	1,517	870	926	1,007	946	937
CO2 (g/mi)	4,723	2,746	2,906	3,175	2,986	2,952
CO (g/mi)	4.69	0	0.47	0.17	0.31	0.20
HC (g/mi)	0.11	0.04	0.03	0.04	0.05	0.04
NOx (g/mi)	4.55	3.17	3.12	3.64	3.56	3.37
PM (□g/mi)	5.16	1.52	1.35	1.21	0.75	1.21
Connected Vehicle						
Fuel (g/mi)	1,209	812	833	872	856	843
CO2 (g/mi)	3,699	2,582	2,650	2,740	2,714	2,671
CO (g/mi)	4.95	0.25	0.06	0	0.16	0.04
HC (g/mi)	0.08	0.04	0	0.04	0	0.01
NOx (g/mi)	3.63	2.87	3.40	3.93	3.27	3.37
PM (□g/mi)	4.40	0.64	0.81	0.64	0.76	0.71
Difference						
Fuel (g/mi)	-20%	-7%	-10%	-13%	-10%	-10%
CO2 (g/mi)	-22%	-6%	-9%	-14%	-9%	-10%
CO (g/mi)	6%	-244%	-87%	-271%	-48%	-78%
HC (g/mi)	-26%	-5%	-192%	12%	-163%	-85%
NOx (g/mi)	-20%	-10%	9%	8%	-8%	0%
PM (□g/mi)	-15%	-58%	-40%	-47%	2%	-41%

As shown in Table 4, the connected eco-driving system would help reduce fuel consumption by 20 percent as well as emissions of carbon dioxide (CO2) by 22 percent, hydrocarbons (HC) by 26 percent, nitrogen oxides (NOx) by 20 percent, and particulate matter (PM) by 15 percent, under cold start conditions. The system; however, would increase carbon monoxide (CO) emissions by six percent. Under hot running conditions, the connected eco-driving system would help reduce fuel consumption and most emissions, depending on the pollutant and test cycle. When considering all hot running test cycles together, the system would help reduce fuel consumption by 10 percent, CO2 by 10 percent, CO by 78 percent, HC by 85 percent, and PM by 41 percent. The system would not impact overall NOx emissions.

It is notable that the overall fuel consumption reduction (10%) from the use of the connected eco-driving system based on the chassis dynamometer testing is in line with the estimated reduction in energy use based on the traffic simulation (which is also 10%). This level of fuel consumption reduction can have a sizeable impact on the total operating cost as fuel is typically the second largest cost of trucking behind labor cost (Hooper and Murray, 2018). Therefore, the system would be very beneficial for truck drivers and fleet operators from a cost savings perspective. In addition, the system would also help reduce greenhouse gas emissions from HDDTs, since fuel consumption is directly related to CO2 emissions (Collier et al., 2019). HDDTs used in a variety of businesses, such as drayage and regional distribution, spend a large fraction of their operating time on surface streets with signalized intersections (Scora et al., 2019), and thus would be able to significantly reduce their fuel consumption and CO2 emissions by using the connected eco-driving system.

HDDTs are a major contributor to NOx and PM emissions. Thus, it is encouraging to find that the connected eco-driving system could help reduce NOx emission by 20 percent and PM emission by 15 percent under cold start conditions, while it would also help reduce PM emissions by 41 percent under hot running conditions. Reducing these emissions will be especially important for communities near freight hubs such as ports, railyards, and warehouses that attract a large amount of truck traffic, since it could lower community members' exposure to these harmful pollutants and their associated health impacts (Robinson et al., 2018; Wilson et al., 2018), especially for sensitive population groups such as children, seniors, and people with underlying medical conditions.

Conclusions

This research estimated the costs and benefits of implementing connected eco-driving technology as a strategy to mitigate the impacts of truck traffic on signalized freight corridors. The costs associated with enabling the technology include capital investment in infrastructure such as upgrading traffic controllers and installing communication modems. The costs also include operating expenses such as purchasing wireless data plans and server storage. Over a period of 20 years, the total cost for one intersection is estimated to be $18,200. However, by implementing the technology at 100 intersections, the total cost per intersection would be $12,460 over a period of 20 years.

A large portion of the total cost is the initial capital investment in upgrading infrastructure, which is around $5,000 per intersection. After the initial investment, the annual operating cost of the technology is less than $700 per intersection. For agencies with an existing TMC, the annual operating cost can be greatly reduced or eliminated. Note that the costs estimated in this research fall on public agencies who own and operate traffic signals at the connected intersections. There are also costs associated with installing the technology on the vehicles themselves, but those costs are assumed to be borne by private entities, such as vehicle manufacturers and mobile application developers.

The main benefits of this technology are reductions in energy consumption and emissions including a 20 percent reduction in fuel consumption under cold start conditions and a 10 percent reduction under hot running conditions despite a four percent increase in travel time. If truck drivers and fleet operators can accept the slight increase in travel time, then this level of fuel savings should be attractive as fuel cost is typically the second largest cost of trucking.

In terms of emissions reduction benefits, the connected eco-driving system could reduce CO2 emissions by 22 percent under cold start conditions and by 10 percent under hot running conditions, and thus could play an important role in addressing greenhouse gas emissions from freight trucks in the near term while these trucks are transitioning to zero emission vehicles in the next few decades. The reductions in NOx and PM emissions are also substantial. Under cold start conditions, the system could help reduce overall NOx and PM emissions by 20 percent and 15 percent, respectively. While the system would not increase or decrease overall NOx emission under hot running conditions, it could help reduce the overall PM emission by 41 percent. Thus, the connected eco-driving technology can serve as one of the strategies for mitigating the air quality and health impacts associated with truck emissions in communities that are heavily impacted by truck traffic.

The energy and emission reduction benefits presented in this report are for one connected truck traveling on the corridors. However, the figures can be used to estimate the overall amount of fuel savings and emissions reductions based on truck count data and an assumption regarding the percentage of the truck fleet that could be equipped with the technology. While this research is focused on the benefits of the connected eco-driving technology for freight trucks, the technology can also be used by other vehicle types such as passenger cars traveling on connected corridors. Therefore, even more fuel savings and emissions reduction could be achieved by making this technology available to all road users.

It should be noted that the energy and emission reduction benefits reported herein are based on the roadway characteristics and traffic conditions on the corridors used in the traffic simulation, as well as the specific HDDT used in the emissions testing. And as seen in the corridor-specific results, the level of benefits varies by corridor. To estimate the benefits of implementing the technology on another corridor, a simulation-based evaluation for that specific corridor would need to be conducted. Nevertheless, the evaluation results presented in this report can be used to inform a possible range of energy and emission reduction benefits that can be achieved with the use of the technology.

Based on the current state of the technology, connected eco-driving has several attractive characteristics. It is ready for implementation, relatively low cost, compatible with both legacy and new vehicles, extendable to other types of vehicles such as cars and buses, and easily scalable from one intersection to hundreds of intersections. In addition to the energy savings and emissions reduction benefits, the technology also has potential to provide other co-benefits such as improving traffic safety, reducing brake and tire wear emissions, and mitigating noise pollution. For example, eco-driving in general has been associated with safe driving, and thus, connected eco-driving technology could improve traffic safety where it is implemented. And since the technology helps to make driving smoother by reducing the frequency of acceleration and braking, it could reduce brake and tire wear emissions, which are becoming increasingly important as tailpipe emissions continue to decrease. Lastly, smoother driving could also lower noise levels in vehicles that use the technology. These potential co-benefits of connected eco-driving technology have not been studied, but should be in the future.

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Appendix A: Connected Eco-Driving System Logics and Algorithms

Trajectory Planning for Trucks

To design the most energy-efficient trajectory for the connected truck to pass through an upcoming intersection while guaranteeing safety and mobility, we define five rules as follows:

1. *Driving Rule*: The host vehicle can only cross the stop line during the green or yellow time. The vehicle speed must stay within the road speed limit $[0, v_l]$.
2. *Gap Keeping Rule*: The host vehicle must keep a safe time gap from the preceding vehicle when passing through the intersection.
3. *Acceleration/Deceleration Rule*: The acceleration and deceleration rates of the host vehicle at a certain speed always stay in a range $[a_{min}(v), a_{max}(v)]$ capped by the dynamic performance of the vehicle and the driving style of the driver.
4. *Mobility Rule*: Under Rules 1-3, the host vehicle aims to minimize the travel time to reach a target location (usually the stop line) with a reasonable speed.
5. *Energy-Saving Rule*: Under Rules 1-4, the host vehicle aims to minimize the total amount of energy consumed in the eco-driving process from the current state to the target state.

Considering Rules 1-4, the host vehicle will attempt to safely pass the stop line at the earliest possible time. Then, the target state in Rule 5 is defined as the expected time, location (i.e., the stop line), and speed at which the vehicle fulfills this goal. Assuming that the vehicle first accelerates with $a_{max}(v)$, and then keeps the speed once it reaches the speed limit v_l, the earliest possible 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 traffic signal, it can be used to identify the target state. If t_e falls within the green phase, it can be directly considered as the target time of the vehicle. The target speed is then the maximum speed the vehicle can reach at that time. If t_e falls within the red or yellow phase, the target time will be switched to the beginning of the next green phase, plus a buffer time for the preceding vehicle queue to clear. In a later section, we provide more details on the estimation of the buffer time. The target speed is set to be a predefined value v_t.

Given the current state and the target state, we develop a graph-based algorithm to solve the trajectory planning problem with constraints on total travel time T, total travel distance X, and target speed v_t at the stop line [11]. To formulate this graph problem, we discretize 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, we assign a unique 3-D coordinate (t, x, v) to describe the dynamic state of the vehicle, where $t \in (0, T]$ is time (in second), $x \in [0, X]$ is distance to the intersection (in meter), and $v \in [0, v_l]$

is vehicle speed (in m/s). 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 the following rules are satisfied:

1. Time at V_2 is consecutive with time at V_1: $t_2 = t_1 + \Delta t$;
2. Consistency in the distance and speed relationship: $x_2 = x_1 + v_1 \Delta t$;
3. Speed constraints: $v_2 = v_1 + a\Delta t$ and $0 \leq v_2 \leq v_l$;
4. Acceleration/deceleration constraint: $a_{min}(v_1) \leq a \leq a_{max}(v_1)$, where $a_{min}(v_1)$ and $a_{max}(v_1)$ are the maximum deceleration and maximum acceleration rates at speed v_1 for the host truck, respectively. The acceleration/deceleration ranges are calibrated using real-world truck data.

We further define the cost on edge $V_1 \rightarrow V_2$ as the tractive power during this state transition process. At this point, the trajectory planning problem for energy minimization 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_t) in the directed graph. We apply the Dijkstra's algorithm [19] to solve this single-source shortest path problem with non-negative cost.

Power-based Cost Function

The cost of the edges in the Graph-Based Trajectory Planning Algorithm (GBTPA) is defined as the tractive power of the truck at a certain speed and acceleration rate. Assume that road grade is zero, the coasting acceleration rate is a function of speed as follows:

$$a_{coast} = -\mu g - \frac{1}{2m} C_D \rho_a A v_i^2$$

When the truck is in a coasting or braking mode, i.e. $a \leq a_{coast}$, we assume that the tractive power is 0. When the truck is in a traction mode ($a > a_{coast}$), the tractive power is calculated as:

$$P = Fv = \left(ma + \mu mg + \frac{1}{2} C_D \rho_a A v_i^2 \right) v$$

We calibrate the function using real-world data collected from trucks, so the tractive power can be a reasonable indicator of the fuel consumption rate of the truck. Figure 8 shows the contour map of tractive power as a function of the instant speed and acceleration rate.

Connected Eco-Driving with Preceding Queues

In the algorithm design, it is a challenge to develop an energy-efficient vehicle trajectory in traffic, considering the existence of preceding vehicle queues. If there is no queue in front, the target time can be set as the beginning of the next green phase. If there is a queue, however, the host vehicle has to keep a safe time gap from the preceding vehicle by adding a buffer time for the queue. As shown in Fig. 3(a), the buffer time consists of 4 parts:

1. *Shockwave time*: The elapsed time for the queue discharging shockwave to propagate to the preceding vehicle, i.e., the additional green time the preceding vehicle needs to wait before it can start moving.
2. *Acceleration time*: The time needed for the preceding vehicle to reach the stop line in its acceleration process. It can be formulated as $\sqrt{\frac{2L}{a_p}}$, where L is the queue length, i.e., the distance between the stop line and the stop location of the preceding vehicle, and a_p is the average acceleration rate of the preceding vehicle.

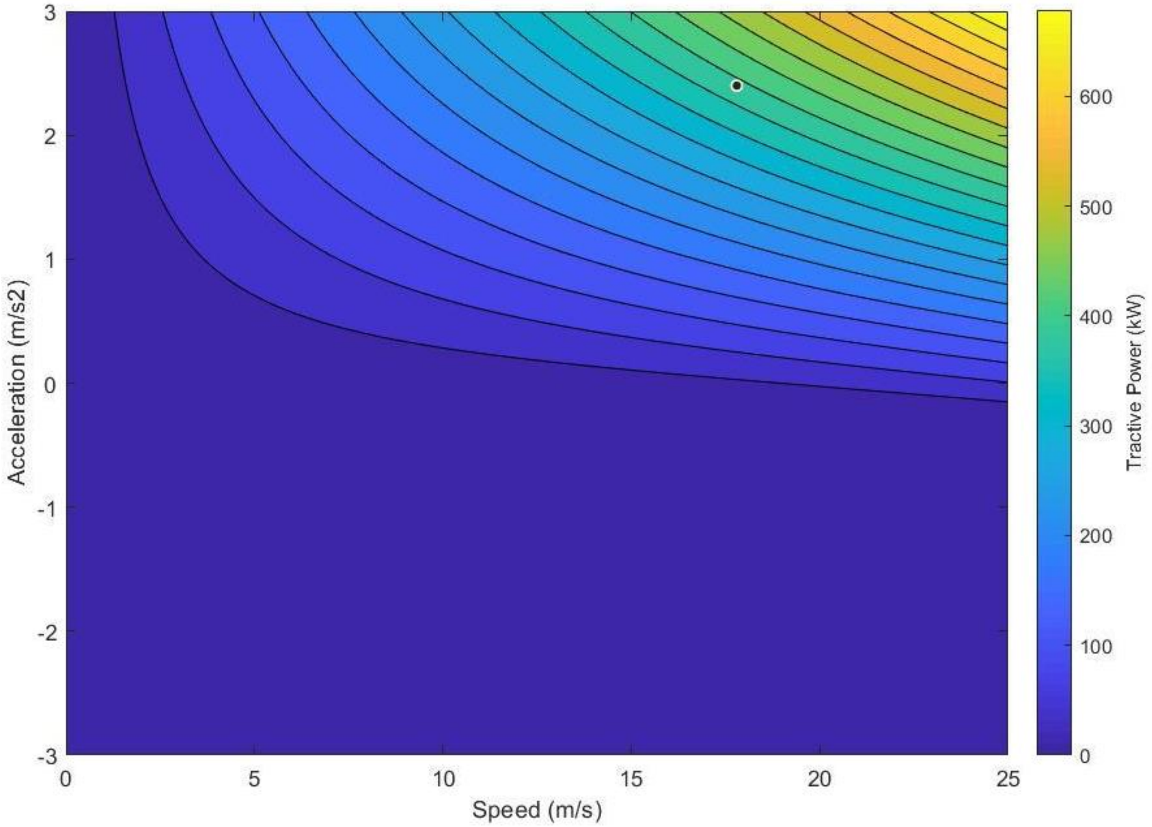

Figure 8. Contour map of tractive power vs. instant speed and acceleration rate

3. *Time compensation for speed difference*: As the connected eco-driving system usually plans a non-stop trajectory, the speed of the connected vehicle at the stop line would be higher than the typical speed when the preceding vehicle passes the stop line. This time compensation is added to the buffer time to avoid potential conflict when the host vehicle gets closer to the preceding vehicle after passing the stop line. It can be formulated as $\frac{v_t}{a_p} - \frac{1}{v_t}\left(\frac{v_t^2}{2a_p} - L\right) - \sqrt{\frac{2L}{a_p}}$, where v_t is the target speed.
4. *Safe headway*: The time headway the connected vehicle needs to keep to safely follow the preceding vehicle in the traffic.

The buffer time, as the sum of the four terms above, can be formulated based on kinematic equations as follows:

$$\tau = \frac{L}{v_{sw}} + \frac{v_t}{a_p} - \left(\frac{v_t}{2a_p} - \frac{L}{v_t}\right) + \tau_h = \left(\frac{1}{v_{sw}} + \frac{1}{v_t}\right) L + \frac{v_t}{2a_p} + \tau_h (3)$$

where v_{sw} is the shockwave speed and τ_h is the safe headway. According to Equation (3), the buffer time is linear to the preceding queue length, but the parameters in the equation are related to the test site and vehicle composition, e.g. truck ratio.

Figure 9 and Figure 10 show two examples of how the buffer time is calculated in two typical situations. In the example shown in Figure 9, we create a scenario where a connected vehicle is approaching an intersection with a queue with all passenger cars. As the average acceleration rate of the last vehicle in the queue is relatively high (say 1 m/s^2), the buffer time can be relatively short. If there is only one vehicle in the queue (i.e., the queue length, defined as the front bumper location of the last vehicle in the queue, is 0 in this case), the buffer time is calculated as 10s. If the queue length is 160m, the buffer time is 58s. Note that when the queue length is long (over 50m in this case), the last vehicle in the queue may reach the target speed before passing the stop line, then the time for that vehicle to reach the stop line is the total time in the acceleration process and the speed maintaining process, i.e. $\frac{v_t}{a_p} + \left(\frac{L}{v_t} - \frac{v_t}{2a_p}\right)$, while the compensation for speed difference is no longer needed. Thus, the buffer time equation (3) still holds in this case.

In Figure 11, we create another example assuming there is at least one heavy-duty truck in the queue. Then the average acceleration rate of the last vehicle in the queue is low (e.g., 0.3 m/s$^{2)}$ as it is either a truck or impacted by a preceding truck in the queue. According to Equation (3), the buffer time is 22s when the queue length is 0, and 70s when the queue length is 160m. The time compensation for the speed difference is high when the queue length is short, e.g., about 17s when the queue length is 0. This figure shows that for any connected eco-driving systems, the preceding truck in the queue is a great challenge. Due to the slow acceleration from a stop, a single preceding truck may add 12s additional delay to the connected eco-driving process if it is not possible to change to a faster lane on the side. Another issue associated with this problem is the time uncertainty. If the host vehicle does not have advanced sensors to recognize the types of preceding vehicles in the queue, it cannot provide a precise buffer time estimate for the connected eco-driving system to design the optimal trajectory. To increase reliability in the buffer time estimation, it is necessary to know the typical truck ratio for the study intersection, and to calibrate v_{sw} and a_p using onsite data.

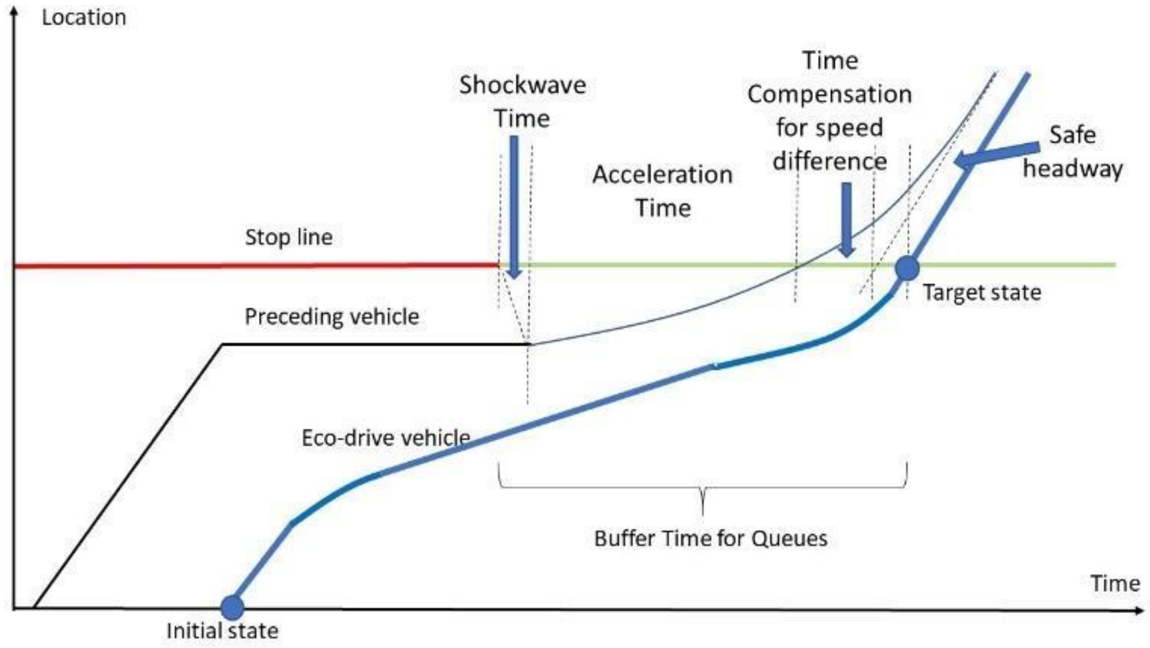

Figure 9. Definition of the buffer time

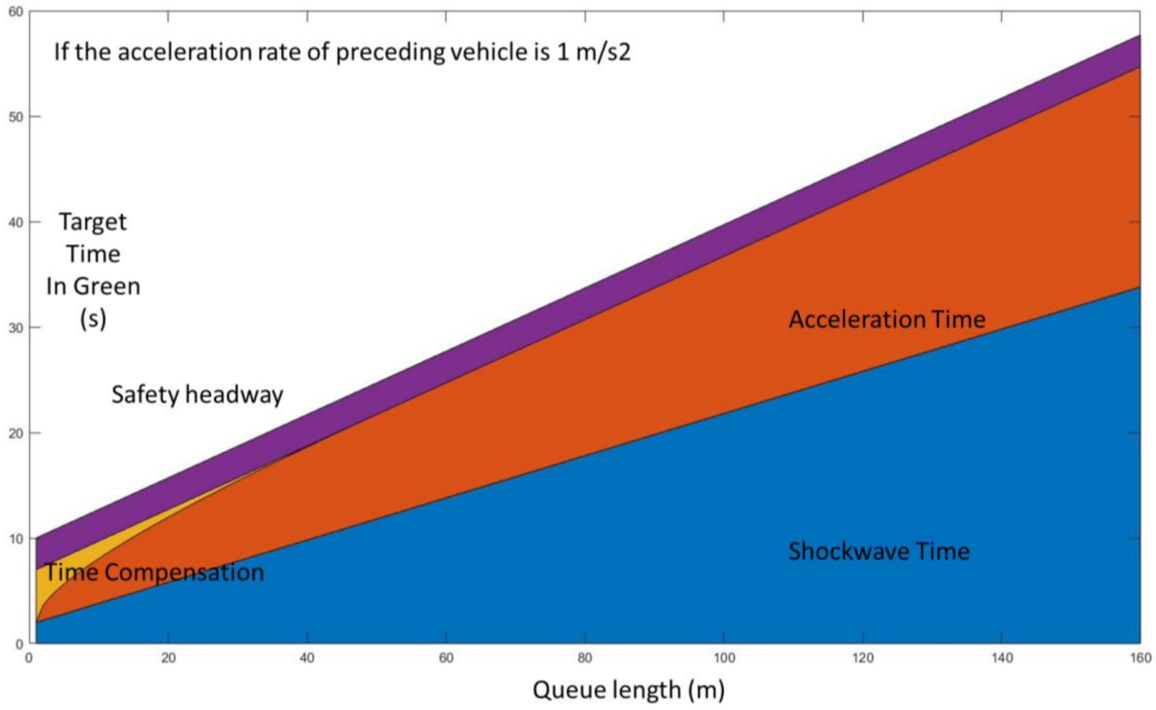

Figure 10. Example of buffer time for the queue with all passenger cars

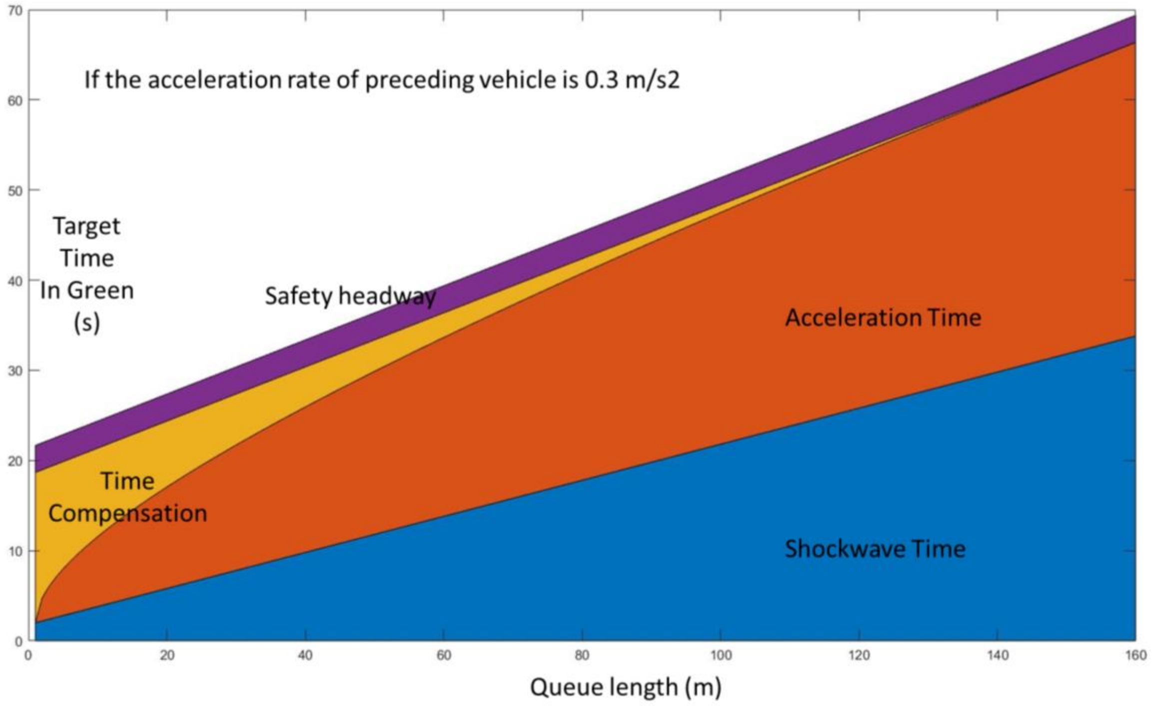

Figure 11. Example of buffer time for the queue with trucks

Machine Learning-based Trajectory Planning

The trajectory planning algorithm described above improves the computation efficiency over conventional optimization techniques by introducing a dynamic programming framework. However, we can further reduce the computation time using an innovative algorithm, named Machine Learning-based Trajectory Planning Algorithm (MLTPA) (Esaid et al., 2021). In contrast to the end-to-end model, MLTPA uses training data generated by the GBTPA on a range of representative unique inputs. Using the GBTPA-generated data, MLTPA is trained to predict the next target state for the host vehicle. We compare the prediction accuracy of five types of machine learning techniques, including linear regression, k-nearest-neighbors, decision tree, random forest, and multi-layer perceptron neural network. The random forest method has the best performance in terms of root mean square error. After being trained offline, MLTPA is then applied in the online process of connected eco-driving to yield both computation efficiency for the system and energy efficiency for the host vehicle.

Appendix B: Connected Eco-Driving System Simulation Setup and Results

Simulation Setup

To evaluate the effectiveness of the connected eco-driving system, we implemented the system API into a Vissim traffic simulator (PTV Group, 2021), and tested it in a calibrated simulation network with two signalized corridors in Carson, California, that are depicted in Figure 3. The connected corridor on Alameda St. is a three-mile segment with two-three lanes per direction and speed limit of 45 mph. There are six signalized intersections in the segment and five of them are connected. The connected corridor on S. Wilmington Ave. is a two-mile segment with two lanes per direction and speed limit of 35-40 mph. There are nine signalized intersections in the selected segment, with five of them being connected. The connected eco-driving system can receive SPaT and perform vehicle trajectory planning only when approaching the connected intersections. The simulation network is calibrated using signal timing data and traffic data provided by the local agencies.

When activated, the connected eco-driving system API replaces the inherent driving behavior model in Vissim with a user-defined behavior model embedded in the vehicle dynamics control module written in C++. During a simulation run, the API calls the External Driver Model DLL code for the host truck in each simulation time step, obtains the current vehicle state, determines its next optimal speed, and then passes this updated vehicle state back to Vissim. The MLTPA is applied to perform real-time vehicle trajectory optimization during this process. In Vissim, profiles of desired acceleration vs. speed, along with information about the vehicle's surrounding environment are used to determine each vehicle's acceleration at every time step. The same applies for deceleration. Every vehicle type in Vissim (e.g., light-duty vehicle, bus, truck) has desired acceleration and deceleration profiles, especially trucks which have diverse size, weight, and power. Using real world data, we calibrated those parameters before running the simulation to address their significant impact on truck mobility, energy, and emissions.

Simulation Results

The simulation of a HDDT without and with the connected eco-driving system was conducted in each direction of the two signalized corridors in the calibrated simulation network. For each direction in each corridor, 350 simulation runs were made using different seed numbers in order for the truck to encounter a variety of traffic situations with respect to, for instance, location and speed of the truck when entering the network, driving behaviors of other vehicles during the simulation, downstream traffic congestion, time point in the cycle of the first traffic signal, etc. The same set of seed numbers was used for the cases without the connected eco-driving system (baseline) and with the connected eco-driving system.

Since the premise of the system is that the connected vehicle would save energy without significantly sacrificing travel time by reducing unnecessary acceleration/deceleration when approaching and departing signalized intersections, we used the simulated trajectories of the truck to calculate the average values of travel time, stop delay, number of stops, cumulative acceleration, cumulative deceleration, and energy consumption across the 350 simulation runs for both the baseline and the connected eco-driving cases. Then, we calculated the difference between those average values, along with its statistical significance, as given in Table 5. Note that a stop is defined as the vehicle speed being zero for more than three seconds, and the stop delay is defined as the total amount of time during all stops. The values of all the metrics were normalized by distance as the variation in the starting and ending locations of the simulated truck on the corridors caused the travel distance in each simulation run to be slightly different. The evaluation results for each study segment are discussed below.

Table 5. Differences in travel metrics with and without connected eco-driving system

Metric	Alameda Northbound	Alameda Southbound	Wilmington Northbound	Wilmington Southbound
Travel time (s/mi)	-0.6%	1.2%	12.2%*	3.9%*
Stop delay (s/mi)	-26.5%*	-13.5%*	0.5%	-4.4%*
No. of stops per mile	-24.5%*	-3.0%	-2.2%	-2.7%
Energy consumption (kWh/mi)	-6.1%*	-7.3%*	-18.0%*	-11.6%*
Cumulative acc (mph)	-11.1%*	-3.1%*	-14.3%*	-3.4%*
Cumulative dec (mph)	-11.1%*	-2.1%*	-13.9%*	-2.9%*

**Statistically significant at 5% significance level*

Alameda St. Northbound

As shown in Table 5, the energy consumption of the truck in the connected eco-driving case is 6.1 percent less than in the baseline case, with statistical significance at the 5% significance level. The stop delay is 26.5 percent less and the number of stops is 24.5 percent fewer. In addition, both cumulative acceleration and cumulative deceleration are 11.1 percent less. These results are as expected since the connected eco-driving system helps the truck avoid unnecessary stops, acceleration, and deceleration around the connected intersections on the segment. The connected truck also has 0.6 percent less travel time as compared with the baseline truck although it is not statistically significant. To visually illustrate how the connected truck saves energy while maintaining a similar travel time, we plot the speed profiles of the truck in the baseline and connected eco-driving cases in Figure 12 and Figure 13, respectively. In Figure 12, the baseline truck makes harder brakes to stop before the red light at the connected intersections (located at the green dashed lines). On the other hand, the connected truck starts to adjust its speed far ahead of the connected intersections, and often is able to avoid coming to a full stop at those intersections, resulting in smoother speed profiles, as shown in Figure 13.

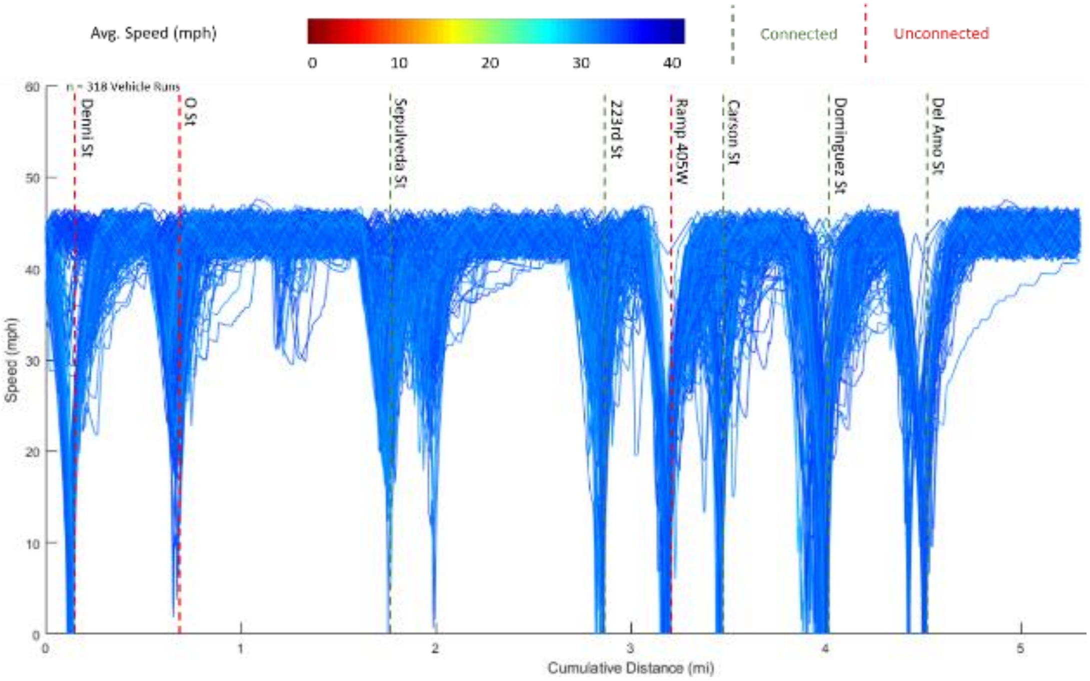

Figure 12. Speed profiles of the baseline truck along Alameda St. Northbound

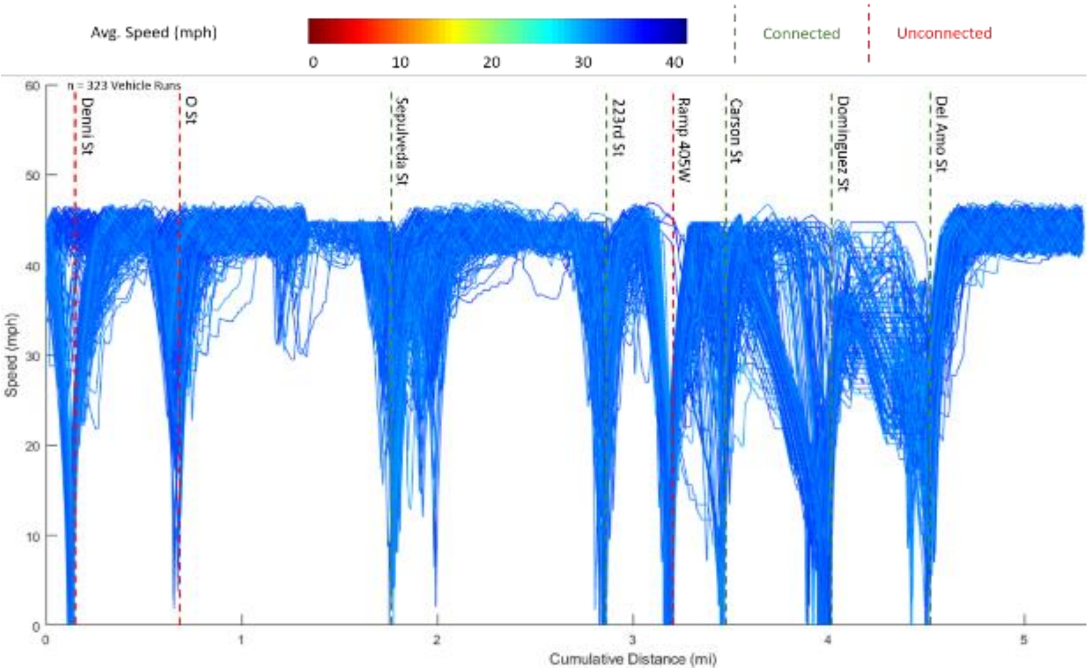

Figure 13. Speed profiles of the connected truck along Alameda St. Northbound

Alameda St. Southbound

This direction of traffic is more congested than in the northbound direction, with vehicles often experiencing long queues at the intersections with 223rd St., Sepulveda St., and O St. This results in lower average speeds as indicated by the color of the speed profiles in Figure 14 and Figure 15, which limit the connected eco-driving system's ability to help the truck avoid coming to a stop at these intersections. Nevertheless, the energy consumption of the connected truck is still 7.3 percent less than that of the baseline truck, which is statistically significant at the 5% significance level. The stop delay is 13.5 percent less and the number of stops is 3.0 percent fewer. Similarly, the cumulative acceleration and cumulative deceleration are 3.1 percent and 2.1 percent less, respectively. The travel time of the connected truck is 1.2 percent longer than that of the baseline truck, but it is not statistically significant.

Wilmington Ave. Northbound

The speed profiles of the truck on this segment are shown in Figure 16 and Figure 17. The smoother speed profiles of the connected truck result in 14.3 percent and 13.9 percent less cumulative acceleration and cumulative deceleration, respectively, than for the baseline truck. As a result, the energy consumption of the connected truck is 18.0 percent less. Different from both directions of Alameda St., the stop delay on Wilmington Ave. northbound is 0.5 percent more while the number of stops is 2.2 percent fewer, although neither of them is statistically significant. This is because the stop delay and number of stops on this segment are heavily influenced by the congestion around the four unconnected intersections (223rd St., Ramp 405E, Ramp 405W, and 220th St.) in the middle of the segment, which causes the truck to stop at the red light at one or more of those intersections.

It is also noteworthy that the travel time of the connected truck is 12.2 percent longer than that of the baseline truck. This is unexpected and in contrary to the results seen on Alameda St. However, upon closer examination, the longer travel time for the connected truck can be explained by the fact that the spacing between consecutive intersections on Wilmington Ave. is generally shorter than that on Alameda St. Therefore, sometimes the connected truck is yet to reach the cruising speed after passing one intersection before it starts to adjust speed in preparation for the next intersection, such as at the intersections with Carson St. and 213th St. Despite having a 12 percent longer travel time, the connected eco-driving system helps the truck gain an energy savings of 18 percent on this segment.

Wilmington Ave. Southbound

The speed profiles of the truck on this segment are shown in Figure 18 and Figure 19. Similar to Alameda St., the southbound traffic on Wilmington Ave. is more congested than in the northbound direction. On this segment, the connected truck consumes 11.6 percent less energy than the baseline truck but has a 3.9 percent longer travel time. The longer travel time for the connected truck is due to the same phenomenon as in the case of Wilmington Ave. northbound, which can be observed at the intersection with Watson Center Rd. in Figure 19. Overall, the stop delay is 4.4 percent less and the number of stops is 2.7 percent fewer, although only the former is statistically significant. Similarly, the cumulative acceleration and cumulative deceleration for the connected truck are 3.4 percent and 2.9 percent less than those for the baseline truck, respectively.

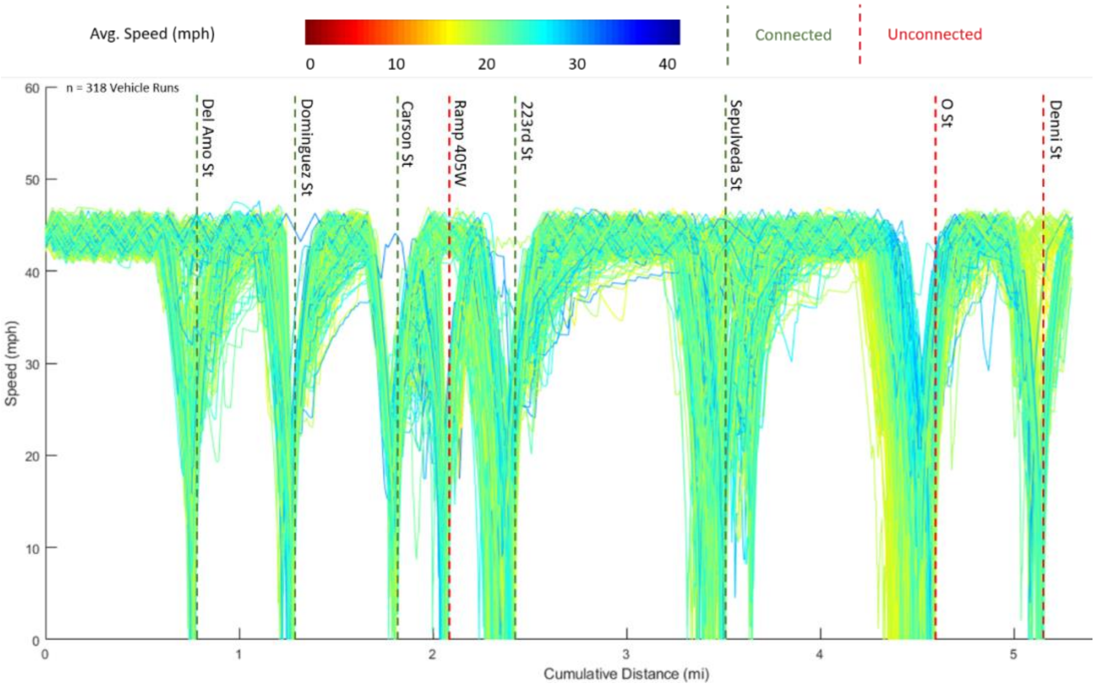

Figure 14. Speed profiles of the baseline truck along Alameda St. Southbound

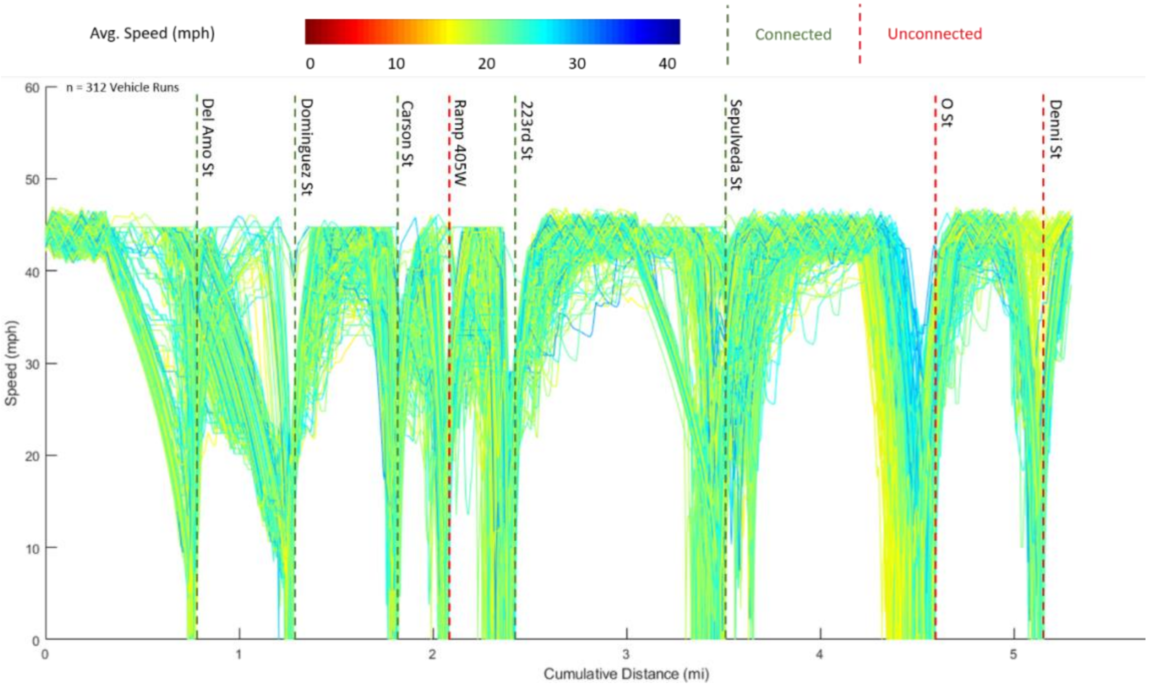

Figure 15. Speed profiles of the connected truck along Alameda St. Southbound

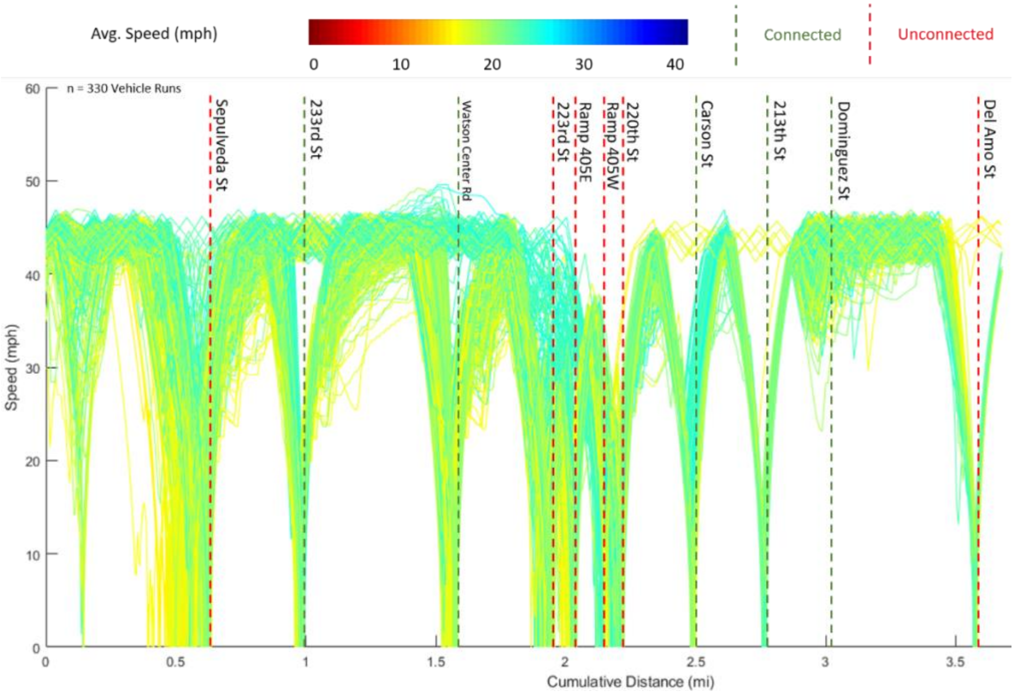

Figure 16. Speed profiles of the baseline truck along Wilmington Ave. Northbound

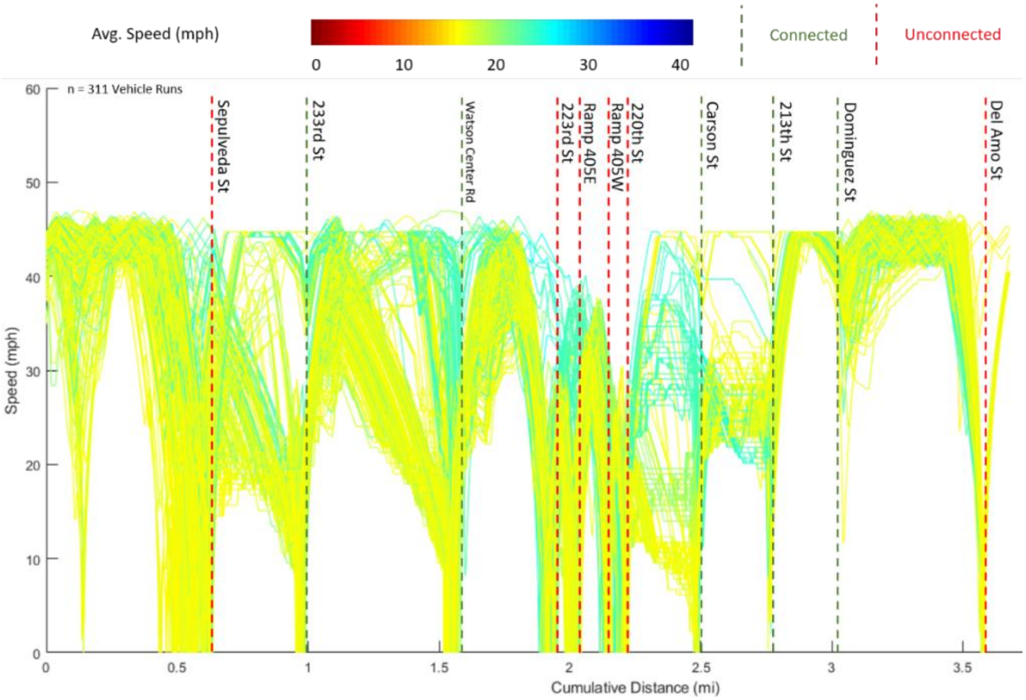

Figure 17. Speed profiles of the connected truck along Wilmington Ave. Northbound

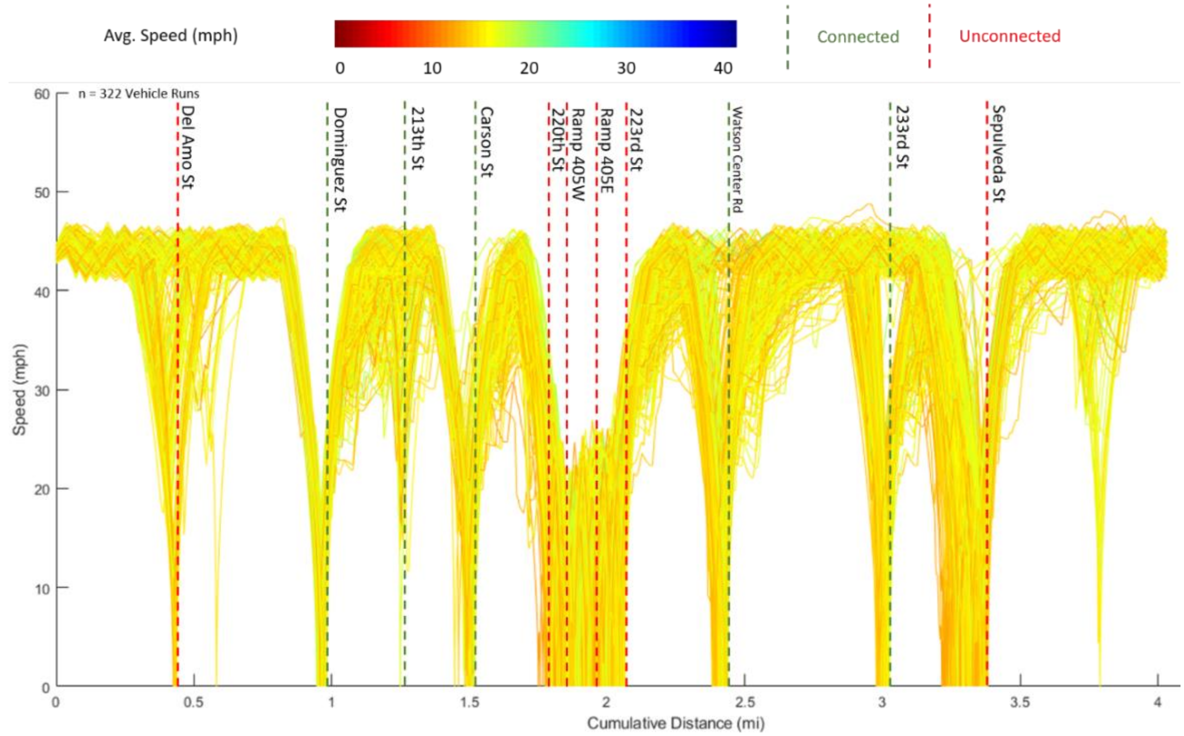

Figure 18. Speed profiles of the baseline truck along Wilmington Ave. Southbound

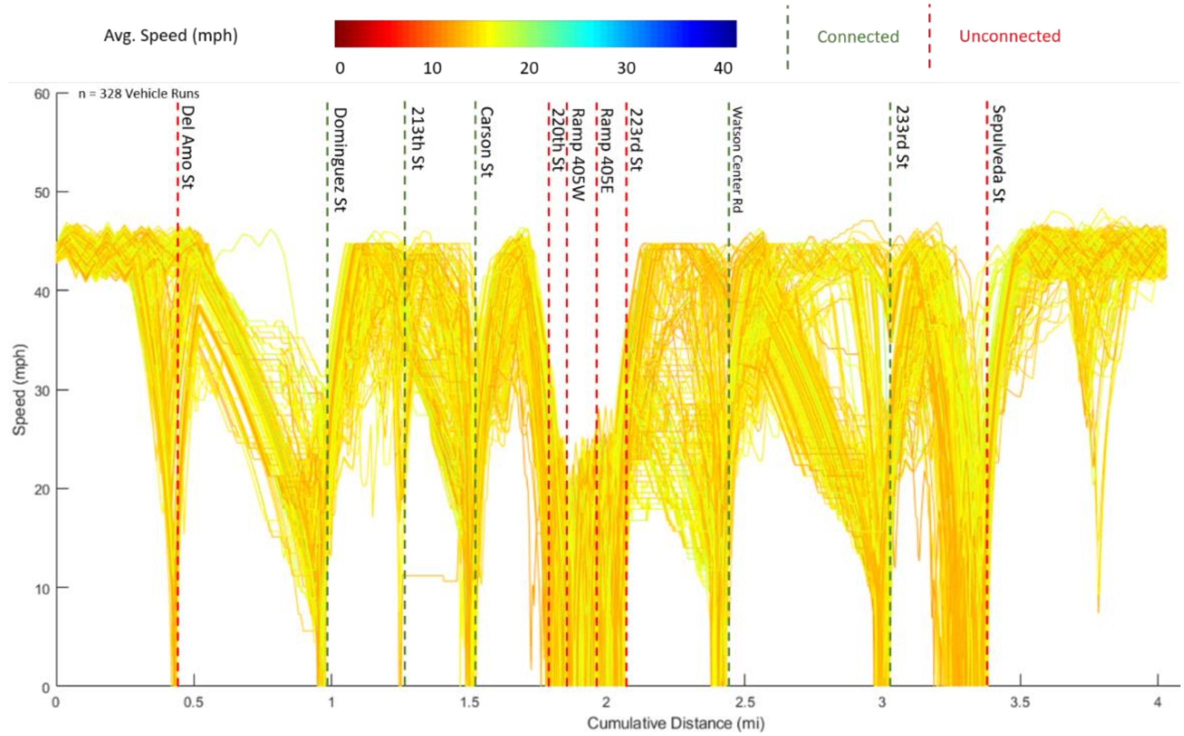

Figure 19. Speed profiles of the connected truck along Wilmington Ave. Southbound

Appendix C: Emissions Testing

Test Facilities

UCR's Heavy-Duty Chassis Dynamometer (HDCD) test facility is designed to test a variety of heavy-duty vehicles over a range of different driving cycles and conditions. UCR's chassis dynamometer is a 48" electric AC type design that can simulate inertia loads from 10,000 lbs. to 80,000 lbs., which covers a broad range of in-use medium and heavy-duty vehicles. The dynamometer includes dual, direct connected, 300 horsepower (hp) motors attached to each roll set. The dynamometer applies appropriate loads to a vehicle to simulate factors such as the friction of the roadway and wind resistance, as would be experienced under typical driving conditions. The dual roller systems allow for high levels of tire contact to support the necessary test loads for Class 8 vehicles. The dyno has the capability to absorb accelerations and decelerations up to 6 miles per hour (mph) per second, and handle wheel loads up to 600 horsepower at 70 mph. This facility is also specially geared to handle slow speed vehicles, such as yard trucks where 200 hp at 15 mph is common. Figure 20 shows the installation of a Class 8 truck on UCR's HDCD test facility for emissions testing.

Figure 20. UCR's Heavy-Duty Chassis Dynamometer test facility

The Mobile Emissions Laboratory (MEL) is used in conjunction with the HDCD test facility for certification type emissions measurements. MEL measures criteria pollutants, PM, and toxics with a constant volume sampling (CVS) system in accordance with 40 CFR Part 1065. This unique mobile emissions laboratory is designed and operated to meet those stringent specifications within a 53-foot tractor trailer. MEL is a full emissions laboratory and a schematic of the major subsystems for MEL is shown in Figure 21. When used in conjunction with the chassis dynamometer, MEL is only connected to the test vehicle by an exhaust conduit. The vehicle exhaust is routed to the inlet of the CVS system using a combination of rigid and flexible exhaust tubing. At the entrance to the CVS, an exhaust flow meter is installed to provide exhaust flow rate measurements for the raw exhaust. Care is taken to minimize flexible exhaust length in order to mitigate condensation and thermophoretic losses.

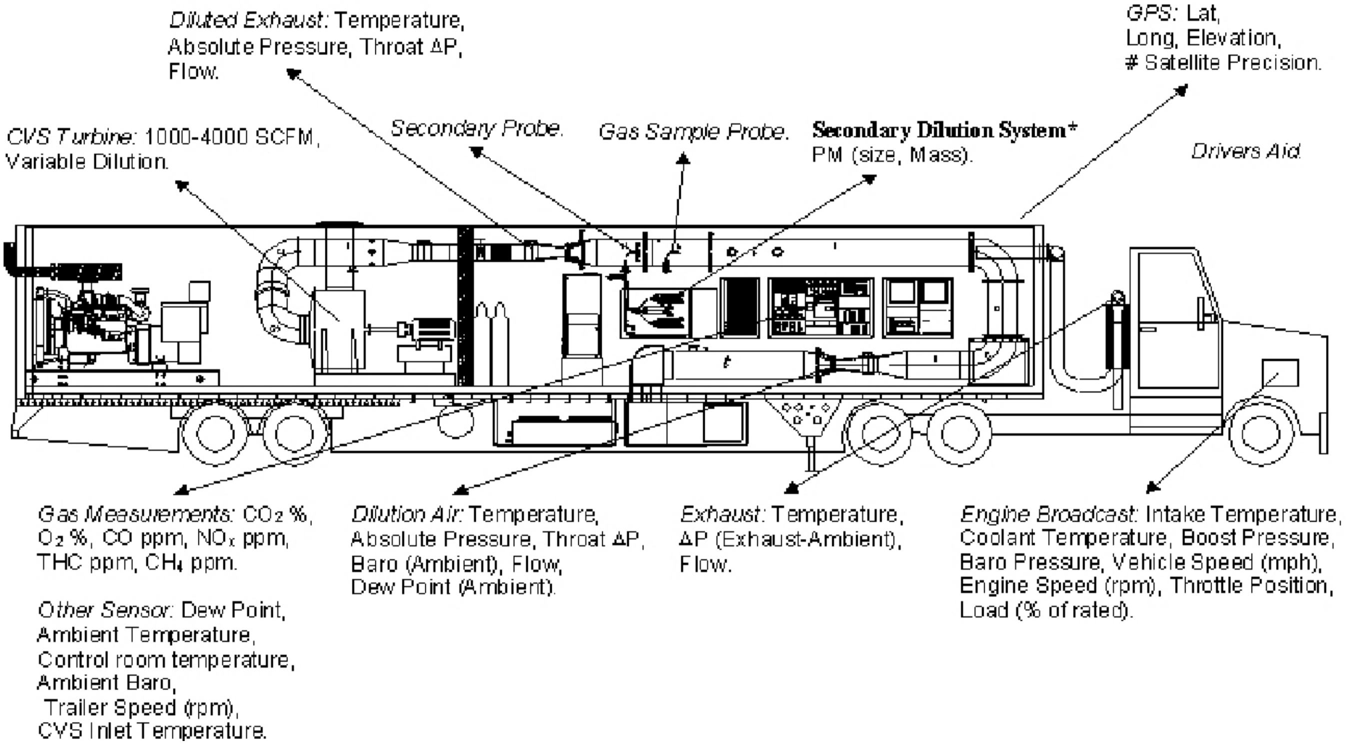

Figure 21. Major subsystems within UCR's Mobile Emission Lab

The emissions measurements include PM mass, NOx, total hydrocarbons (THC), methane (CH4), nonmethane hydrocarbon (NMHC), nitrogen dioxide (NO2), nitrogen monoxide (NO), nitrous oxide (N2O), CO, and CO2. Continuous gaseous analyzers that conform to 40 CFR Part 1065 are used for the regulated gas-phase measurements. CO and CO2 emissions are measured with a 602P nondispersive infrared analyzer from California Analytical Instruments (CAI). THC and CH4 emissions are measured with a 600HFID flame ionization detector from CAI, from which NMHC emissions are calculated. NOx emissions are measured with a 600HPLC chemiluminescence analyzer from CAI. Fuel consumption is obtained using the carbon balance method based on the THC, CO, and CO2 emissions. Calibration procedures with calibration gases following the

U.S. Environmental Protection Agency protocol are run before and after testing to ensure that the instruments are accurate during the testing.

UCR's MEL is set up to measure fine particulate matter (PM2.5) at very low levels with a system that meets all the requirements of 40 CFR Part 1065. The PM sampling system includes an appropriately designed separator stage and dilution air at 25 °C. The diluted sample flows to a specified filter cassette holder with a flow rate of 58 standard liters per minute for a face velocity of 100 centimeters per second and residence time of 2 seconds. The MEL's PM2.5 measurements were previously verified in a cross-laboratory comparison with Southwest Research Institute, where the values of PM mass measured in exhaust filtered with diesel particulate filters were within five percent of each other. The mass concentrations of PM2.5 are determined by analysis of particulates collected on 47 mm diameter 2 µm pore Teflon filters (Whatman brand). The filters are weighed to determine the net weight gains between pre- and post-testing using a UMX2 ultra precision microbalance with buoyancy correction following 40 CFR Part 1065 weighing procedure guidelines. Sampling for PM is done cumulatively over the entire duration of the cycles due to the low mass levels expected.

Test Cycles

Five pairs of second-by-second speed profiles — one for the baseline vehicle and the other for the connected vehicle — from the traffic simulation runs are used as test cycles for the emissions testing. An attempt was made to select a set of second-by-second speed profiles whose differences in energy consumption and travel time between the connected truck and the baseline truck were closest to those of the respective population means. This was to ensure that the selected speed profiles were representative of the average speed profiles resulting from the 350 simulation runs. The speed profiles selection was done in the following manner. First, for each of the four road segments (Alameda St. northbound, Alameda St. southbound, Wilmington Ave. northbound, and Wilmington Ave. southbound), the differences in energy consumption and travel time between the connected truck and the baseline truck were calculated for each of the 350 simulation runs. Then, the population means of these differences were calculated. After that, the two-dimensional Euclidean distance between each of the 350 individual values and the population means was calculated and sorted in an ascending order. Finally, the top five simulation runs with the shortest Euclidean distance were selected. In each of these simulation runs, there were two speed profiles — one for the baseline truck and the other for the connected truck.

The speed profiles from the top simulation run were used for emissions testing under a cold start condition. Since the cold start condition only lasts a few minutes, only the speed profiles from one of the four road segments was needed. The speed profiles from Wilmington Ave. southbound were chosen as it is the most congested among the four road segments. The speed profiles of the other selected simulation runs were used to create test cycles for emissions testing under a hot running condition. For these test cycles, the speed profiles from the four road segments were tied together to result in long test cycles that represent driving conditions on all four road segments. All test cycles for both the baseline truck and the connected truck are presented in Figure 22 through Figure 26.

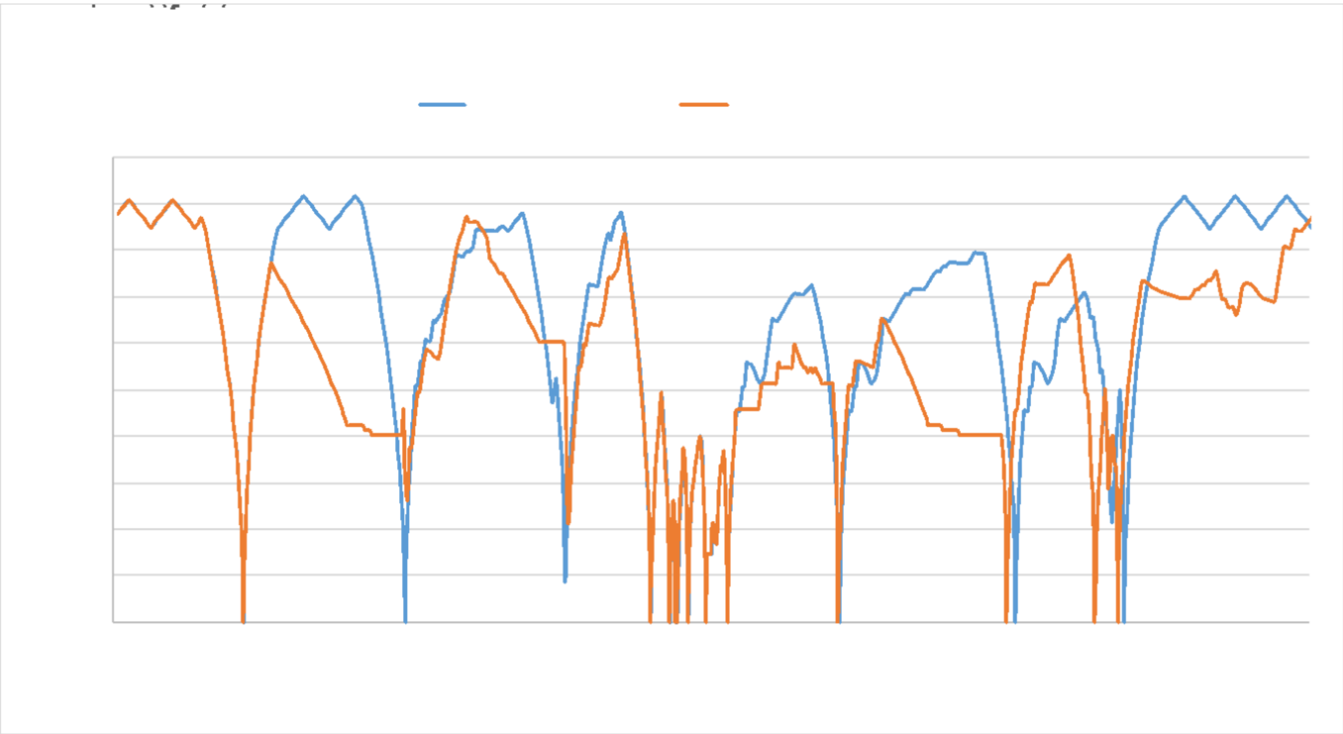

Figure 22. Cold start cycle

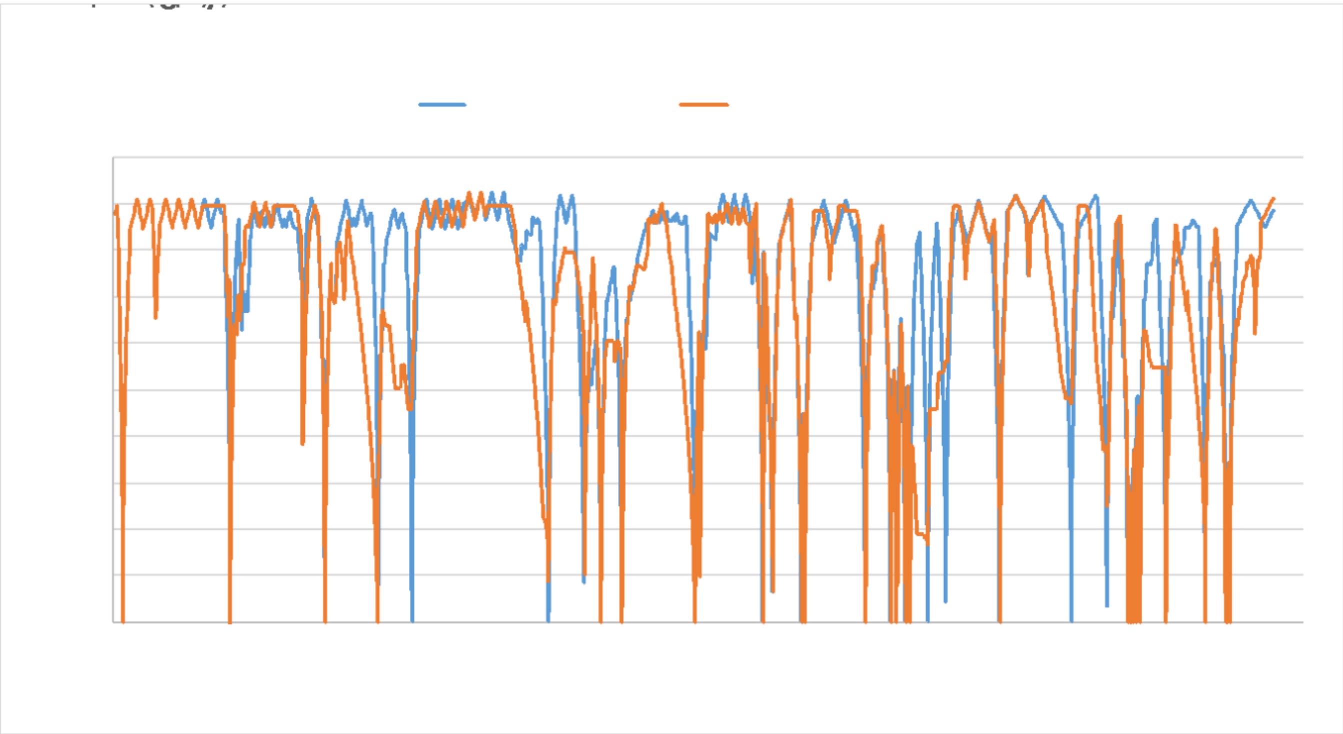

Figure 23. Hot running cycle A

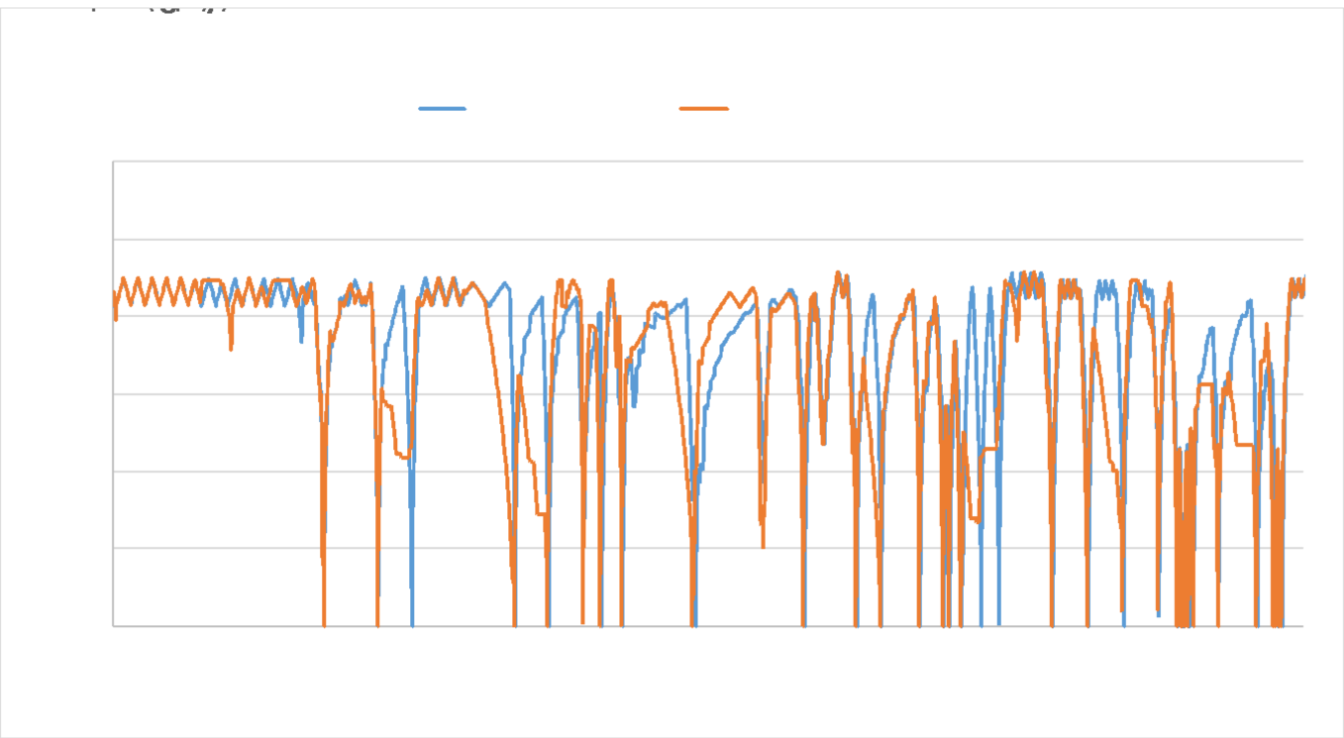

Figure 24. Hot running cycle B

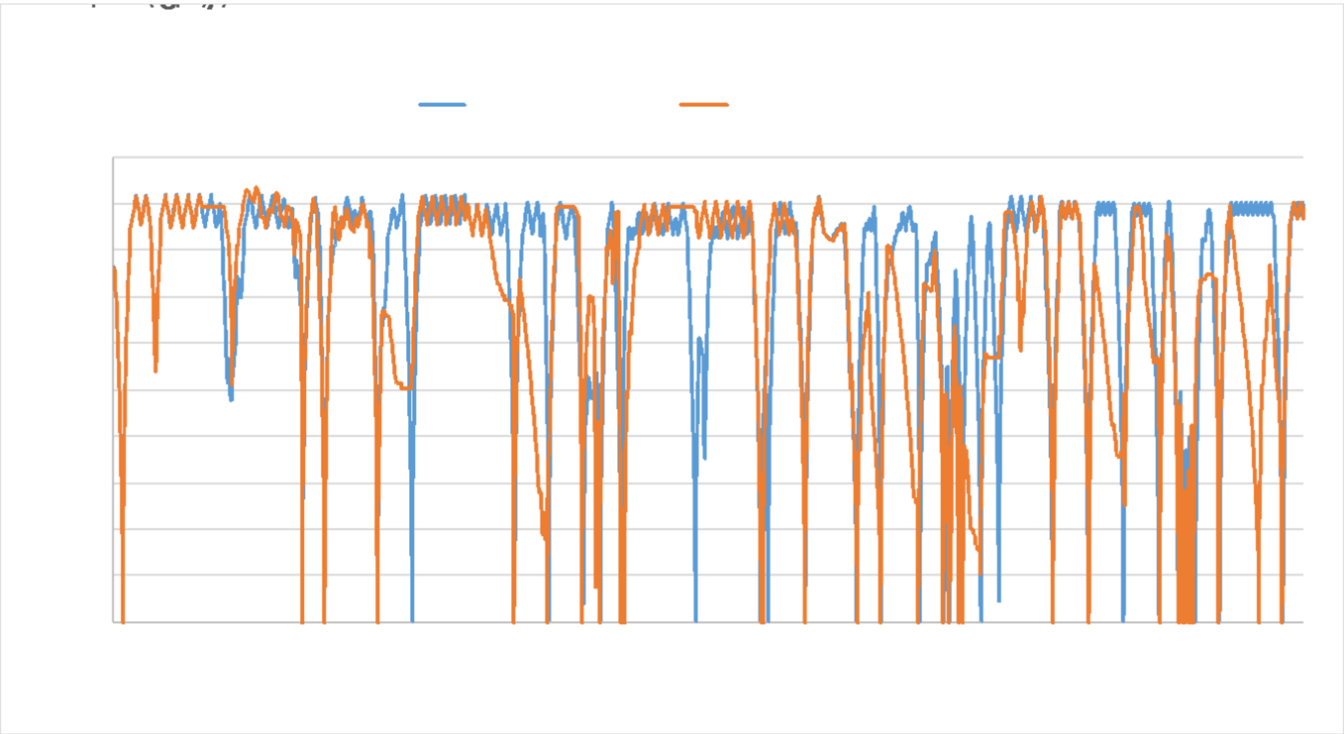

Figure 25. Hot running cycle C

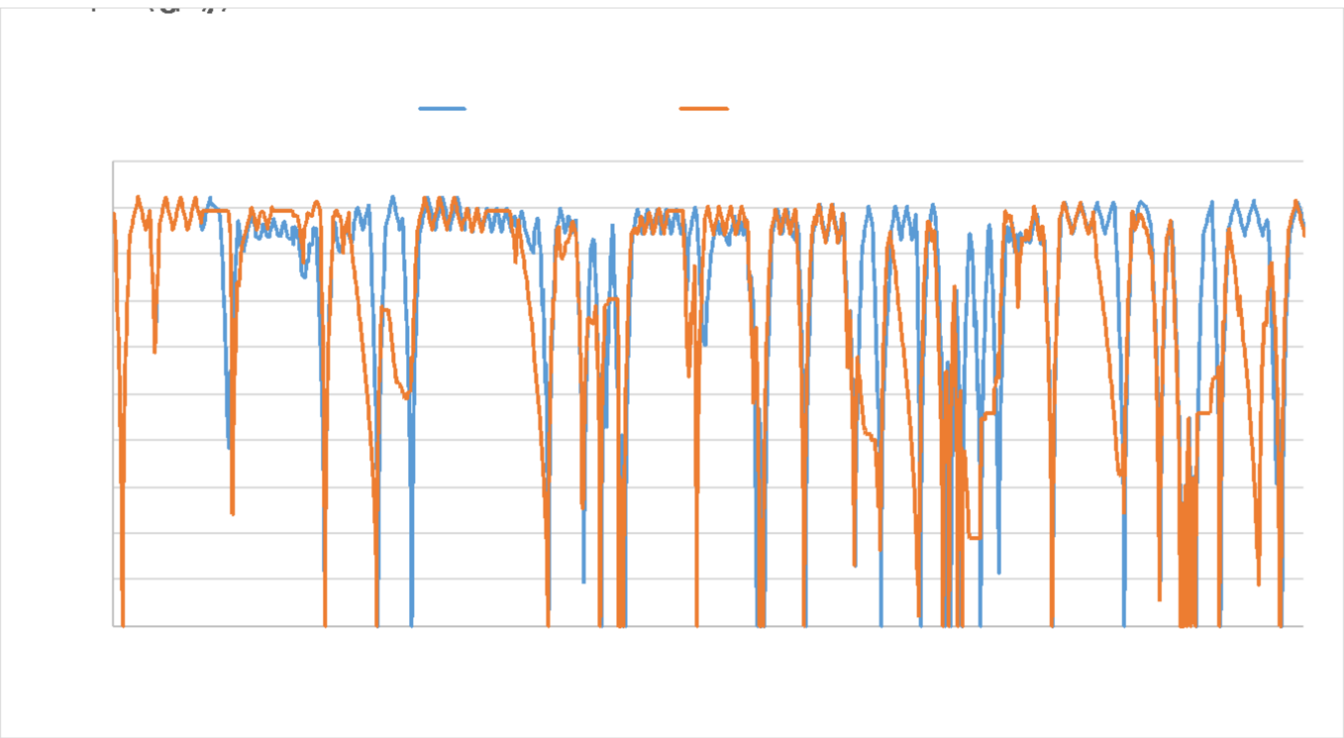

Figure 26. Hot running cycle D

The cold start test cycle was the first cycle to be tested on each test day after the test vehicle had been parked overnight. All the hot running test cycles were preceded by a warmup period where the test vehicle was run at a constant speed of 45 mph for 10 minutes in order to bring the temperature inside the emission control system above the level required for it to be effective.