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SIMULATION OF ZERO-EMISSIONS SELF-DRIVING DRAYAGE TRUCKS IN A BUSY FREIGHT CORRIDOR

THESIS

Submitted in partial satisfaction of the requirement

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by

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Abstract of the Thesis

Simulation of Zero-Emissions Self-Driving Drayage Trucks in a Busy Freight Corridor

By

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Improved traffic safety and air quality are the primary objectives of the I-710 corridor project, a freeway improvement project along the I-710 freeway in Los Angeles County between Ocean Boulevard and State Route 60 (SR-60), which covers approximately 18 miles of the I-710. For years, traffic operations have disproportionately burdened low-income and minority communities in the form of exposure to air pollutants and their associated health impacts. This thesis performs a microscopic traffic simulation to study traffic improvements associated with the addition of lanes to the I-710 and the replacement of San Pedro Bay ports diesel trucks with autonomous (self-driving), zero emission, trucks. The impact on traffic of autonomous trucks was simulated using TransModeler 5.0, which allows simulating autonomous vehicles with Cooperative Adaptive Cruise Control (CACC). CACC is a subset of the broader class of automatic vehicles speed and control systems. Emission estimates of nitrogen oxides (NO_x) and particulate matter ($PM_{2.5}$ and PM_{10}) were then quantified using the Operating Mode (OpMode) lookup tables based on EPA's MOVES model. My results show that autonomous truck operations could allow a 90% increase in demand while providing a 13% improvement in the traffic performance of port-related vehicles while reducing by 70% NO_x, $PM_{2.5}$, and PM_{10} emissions within my study area.

Chapter 1 Introduction

To measure the effects of autonomous trucks in traffic, this thesis employs a microscopic simulation approach to study four scenarios. Scenario 0 represents the baseline scenario, Scenario 1 represent 2035 traffic conditions with the addition of a general-purpose lane, and Scenario 2 uses the same demand and geometry as Scenario 1, but it replaces diesel trucks for Autonomous, zero-emission, trucks by 50% (Scenario 2A) and 100% (Scenario 2B). Scenarios 1 and 2A-B are based on Alternative 5C, and the Zero Emission/Near Zero Emission Truck Technology Deployment Program contained in the Recirculated Draft EIR of the I-710 Corridor Project.

The main contribution of this thesis is the calibration of driver-behavior parameters in TransModeler to represent autonomous truck operations. For this purpose, the headway of the Constant Time Gap Car-Following Model was calibrated to represent the spacing between a platoon of autonomous trucks. Simulation results provide second-by-second vehicle trajectories, which can be then used for estimating emissions of various air pollutants with EPA's MOVES emission model.

After some background information on the I-710 corridor project and on the state of autonomous truck technology, Chapter 3 summarizes selected papers from two facets relevant to this study: microsimulation and emission dispersion studies (particularly in the Alameda corridor), and road exposure and associated health impacts. I mainly focus on previous southern California studies measuring emission impacts of different freight alternatives and scenarios.

Chapter 4 presents the methodology I followed to perform microscopic traffic simulations and for estimating respectively the emissions of various air pollutants using TransModeler 5.0 and the OpMode lookup tables extracted from MOVES.

In Chapter 5, I discuss key results of this study in two sections: changes in traffic performance and emissions before and after the deployment of autonomous vehicles. Finally, Chapter 6 summaries my findings and identifies future research opportunities.

Chapter 2 Background

2.1 Self-driving Trucks

Autonomous vehicles (AV), and in particular zero-emissions AVs, promise to revolutionize transportation, decrease its environmental footprint, and possibly deeply affect the built environment over the next few decades. A cursory look at the news suggests that zero-emissions, self-driving trucks are on a horizon with recent announcements by truck manufacturers. For example, Tesla's Electric Semi can accelerate from 0 to 60 mph with an 80,000 pounds load (the maximum weight permitted on a US highway) in twenty seconds, and it offers a 500-mile range at maximum weight and at highway speed. An alternative is the Nikola One, which is expected to be road ready by 2019. Nikola's truck, an electric hydrogen hybrid, is expected to travel 800 to 1,200 miles while carrying a full load of 65,000 pounds without stopping at a hydrogen refueling station.

In addition to a stellar environmental record, zero-emission self-driving trucks are expected to be safer (computers do not doze off after driving for too long), to decrease the cost of hauling freight (partly by reducing manpower requirements once the technology is established), and to increase road capacity. Indeed, self-driving vehicles are expected to eliminate stop-and-go traffic by regulating the spacing and the pace of vehicles, thus eliminating "phantom traffic jams" generated by human drivers. A steady speed and a constant distance between consecutive vehicles is expected to create a safer environment where vehicles are less likely to collide, and where traffic moves more smoothly (Sterna, 2017).

In spite of their expected benefits, the public still has reservations about AVs. Indeed, a 2017 study conducted by the PEW Research Center found that 65% of Americans would feel unsafe sharing the road with an autonomous freight truck, and 83% of Americans favor requiring driverless vehicles to travel in dedicated lanes. Thus, public concerns could be eased by restricting driverless vehicles to dedicated lanes or geographically bounded locations.

2.2 Project Overview

Port operations require a large number of diesel engines to power trucks, trains, ships, and cargo-handling equipment. Diesel engines contribute to vast amounts of air pollution that impairs the health of those residing or working in proximity to ports. Further, diesel exhaust emissions contribute substantially to regional air pollution (Natural Resources Defense Council, 2004).

This study estimates air pollution and associated health effects of the fleet replacement of diesel trucks for autonomous trucks. The primary objective is to quantify the possible benefits associated with the incorporation of autonomous vehicles within the study area in the context of environmental justice.

For my thesis, I use a microsimulation approach to estimate transportation-related emissions that directly impact minority communities along 18 miles of the I-710 freeway (Figure 1). The study area was selected based on the plans for modernizing the I-710 freeway. For decades, the I-710 freeway has been the source of major controversies on issues ranging from the 1970's proposal to scale down the freeway, noise mitigation complaints from mostly minority communities in the area, and legal challenges raised by South Pasadena under the Clean Air Act. Most recently, several freeway proposals have featured the incorporation of astonishing features such as side-by-side, double-decker tunnels to separate northbound and southbound traffic, or the addition of an elevated freight corridor (Nelson, 2017).

The Recirculated Draft Environmental Impact Report (RDEIR) for the I-710 Corridor Project evaluates two alternatives, Alternative 5C (Widening and Modernization) and Alternative 7 (Zero Emission/Near Zero Emission Freight Corridor). The primary objectives of the I-710 Corridor project are the following:

- Improve traffic safety;
- Improve public health;
- Improve air quality;
- Modernize freeway design; and
- Accommodate forecasted demand.

The need for the I-710 Corridor Project arose from air quality, health, and safety concerns. The South Coast Air Basin has been designated as an extreme ozone non-attainment area and a non-attainment area for small airborne particulate matter (PM_{10} and $PM_{2.5}$). Adverse health effects including decreased lung function, aggravated asthma, increased lung and heart disease, and chronic bronchitis are some of the ailments associated with current air quality. Additionally, the population in Los Angeles, according to growth forecasts is expected to increase from 10.2 million in 2015 to 11.5 million in 2040. This regional growth will likely further increase travel demand on the I-710.

The Recirculated Draft Environmental Impact Report (RDEIR) evaluates two alternatives, Alternative 5C (Widening and Modernization) and Alternative 7 (Zero Emission/Near Zero Emission Freight Corridor).

Alternative7 is a direct response to Community Alternative 7 (CA-7) and to EPA's support for an alternative that included a Zero Emission/Near Zero Emission (ZE/NZE) freight corridor without expanding general-purpose lanes. During the 2012 Draft EIR circulation period, there was strong support for the retention of the ZE/NZE freight corridor. The Coalition for Environmental Health put forth a comprehensive proposal of Community Alternative 7. As a result, the Metro Board of Directors passed Board Motion 22.1 in October 2015, which directed Metro and Caltrans to study the implications of current design options, the feasibility to operate ZE trucks along the freight corridor, traffic control, traffic management, and operational improvements.

Alternative 5C would add one general-purpose lane in each direction. It would also include a Zero Emission/Near Zero Emission Truck Technology Deployment Program which would provide zero-emission trucks for operation on the I-710 as well as electric charging and hydrogen refueling stations (California Department of Transportation, LA County Metropolitan Transportation Authority, 2017).

In this context, this thesis will evaluate the incorporation of autonomous vehicles within the study area (shown in Figure 1). Autonomous truck performance is expected to improve traffic conditions to the point where the high cost of an elevated corridor may not be justified. As mentioned above, I analyze four scenarios; a no-build alternative (Scenario 0), the addition of one lane with increased demand to reflect 2035 port operations (Scenario 1); and the addition of a lane in each direction with year 2035 increased demand and autonomous, zero emission, drayage trucks (50% penetration: Scenario 2A; 100% penetration: Scenario 2B). I rely on microscopic vehicular simulation and then use EPA's MOVES model to estimate emissions of nitrogen dioxide (NO2), and particulate matter (PM).

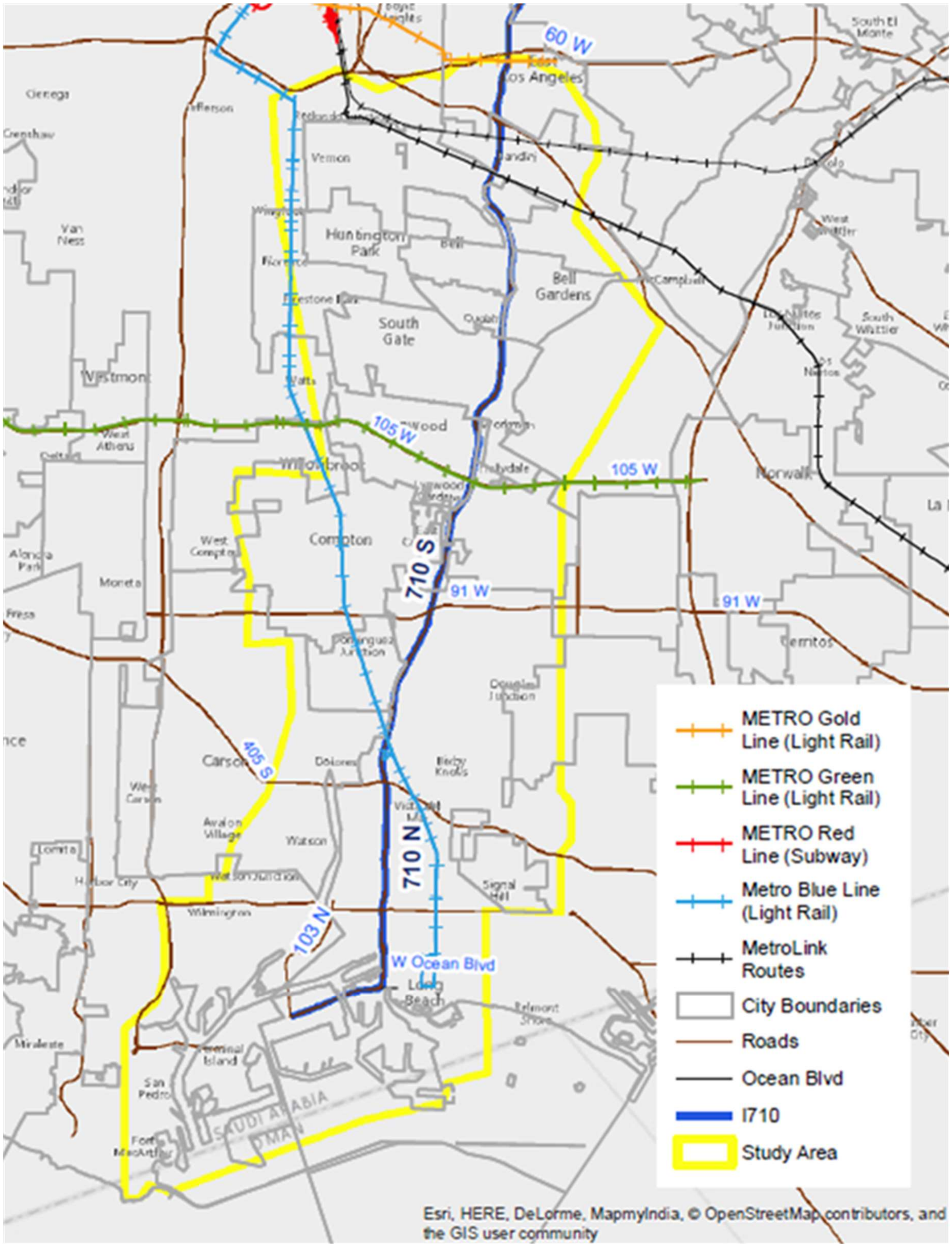

Figure 1 - Study Area

Chapter 3 Literature Review

In this section, I review selected papers published in the past ten years. I focus on two topics: 1) microsimulation and emission dispersion studies; and 2) road exposure and associated health impacts. I pay particular attention to studies concerned with the I-710 freeway and its surrounding areas.

3.1 Microsimulation & Emissions Dispersion Studies

Meeting Federal air quality standards while curbing greenhouse gas emissions are the stated air quality goals of the I-710 Corridor Project. Thus, quantifying the potential environmental externalities of the modernization of the I-710 is of particular interest in this study. This section reviews the use of microscopic simulation for quantifying air pollution.

Yang and Regan (2007) studied the impact of truck lane restrictions on urban freeways via traffic simulation with an application to the I-710 in Los Angeles County. They identified and tested two alternatives that differ in the number of restricted lanes. OD demands for the study area were estimated using TransCAD (a traffic planning model). They obtained static demand in a TRANPLAN format and the Southern California network for the year 2000 from the Southern California Association of Government (SCAG). They concluded that differences in air pollution between the alternatives considered are insignificant. Moreover, restricting the two leftmost lanes provides the most significant benefit for travel time.

Lee *et al*. (2012) analyzed the environmental impacts of the I-710 as a major freight corridor. They combined microsimulation with MOVES (to estimate emissions), Calpuff View (to disperse air pollutants) and BenMAP (to estimate selected health impacts) to quantify changes in health impacts related to the operation of heavy-duty diesel trucks in the San Pedro Bay Ports' area. The different scenarios they considered include replacing fractions of existing heavy-duty diesel trucks with cleaner trucks and to shift containers from trucks to trains in the Alameda corridor.

Cho and Hu (2013) considered air pollution emissions associated with truck operations in California. They estimated truck flows among ZIP code areas with the use of data gathered from IMPLAN (Impacts for Planning) and FAF (Freight Analysis Framework). They then used their estimated flows as input to the EMFAC air pollution emissions model. They tested three scenarios that entailed: 1) replacing older trucks with newer trucks; 2) creating a zero-emission truck-only freight corridor along the I-710; and 3) developing an intermodal inland port that would promote railways at seaports to reduce truck flows from the Ports by 50%. They reported that replacing trucks or creating a zero-emissions corridor would reduce air pollution in Los Angeles County while the development of an inland port would increase air pollution emissions in the MSA, even after accounting for reductions around the ports areas.

Bhagat (2014) focused instead on the environmental and health impacts of shifting the hours of drayage trucks operation, from peak-hours to off-peak hours under the PierPASS program, which aimed at reducing congestion and air pollution from freight operations associated with the San Pedro Bay Ports. He reported that PierPASS only had a small impact on traffic congestion but substantial changes in pollutant concentrations during the day (PM and NO_x concentrations decreased) and during the off-peak period (where the concentrations of air pollutants increased substantially).

3.2 Road Exposure and Associated Health Impacts

According to the Multiple Air Toxic Exposure study (MATES-IV, May 2015), the average South Coast Basin cancer risk from air toxics based on the average annual levels of ten monitoring sites was approximately 148 per million. The key driver for air toxics risk, which accounts for 68 % of the estimated total air toxics, was diesel exhaust, which makes the communities adjacent to the SPBP particularly vulnerable. In this section, I review selected air pollution epidemiology and near road exposure studies with a focus on California.

Gauderman *et al*. (2007) conducted a medical study of 3,677 children from 12 southern California communities to explore the connection between residential exposure to traffic and children's respiratory health. The Children's Health Study recruited two cohorts of fourth-grade children with a mean age of 10 years. Trained field technicians gathered yearly pulmonary-function data for each participant. The outcome data consisted of 22,686 pulmonary tests from 3,677 children. They then estimated a hierarchical mixed-effect model to relate the growth over an 8-year period of each lung-function measure. They concluded that children living within 500 meters of a freeway had affected lung development, which could result in substantial deficits in attained lung function in later life compared to children who live at least 1500 meters from a freeway.

Perez *et al.* (2009) conducted a health risk assessment to estimate the cases of childhood asthma attributable to air pollution generated by freight transport. The burden of asthma was determined for O_3 and nitrogen dioxide (NO_2). Perez (2009) considered two scenarios: the first one measured the burden of asthma related to the contribution from ships alone ignoring all other port activities, and the second one assessed the reduction in disease that would result from reducing NO_2 to concentrations present in cleaner Southern California Communities. They reported that heavy traffic corridors in Long Beach and Riverside are responsible for 2,290 childhood asthma cases (15% of all cases). However, they could not estimate the direct contribution of goods movement. The morbidity associated with ship emissions alone showed that the ports are an essential contributor to the health impact of air pollution in Los Angeles.

Sathaye *et al.* (2009) studied the variation of diesel exhaust concentration in two California cities resulting from the shift in freight vehicle trips during night and day. They concluded that nighttime policies tend to increase the concentration of PM emissions in some metropolitan areas. Moreover, while a shift in operating hours may create environmental benefits, air pollutant concentrations could eventually increase depending on the magnitude of the shift.

Rowangould (2013) created a US census of people who live near roadways to quantify the size and distribution of the near roadway population while accounting for the connection with the regulatory air quality monitoring network. This study considered all US states and analyzed the year 2008 average annual daily traffic volumes (AADT) data from the highway performance monitoring system (HPMS). Results showed that 19% of the US population lives in proximity to high volume roads in almost every region of the country. However, minority and low-income households are more likely to live near a high-volume road. In particular, the Los Angeles metropolitan area was found to house high proportions of low-income and minority residents in proximity to high volume roads.

Finally, Poorfakhraei (2017) studied the health outcomes of vehicle emissions exposure in the Atlanta (Georgia) metropolitan area. Health effects were modeled in three steps: dispersion modeling, exposure analysis, and health impacts analysis. $PM_{2.5}$ exposure was estimated via a log-linear model using a 2010 base scenario, and for 2020 and 2040. The impacts of $PM_{2.5}$ on health were estimated for three outcomes: chronic obstructive pulmonary disease (COPD) mortality, ischemic heart disease (coronary artery disease) mortality, and lung cancer mortality. The author reported a decline from base year levels by 2020 followed by some increases in some areas by 2040.

Chapter 4 Methodology

To quantify the environmental impacts of the deployment of self-driving vehicles in the I-710 corridor, I combined microscopic traffic simulation results with EPA's MOVES lookup tables. Emission modeling was conducted using a project level analysis based on vehicle specific power that processes speed/acceleration profiles. This chapter describes the scenarios, parameters, data, and assumptions used for traffic simulation and emission modeling.

Changes in air emissions were modeled to quantify the exposure of residents who live close to the I-710. The pollutants of interest include nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$ and PM_{10}).

4.1 Scenarios

To analyze the environmental impacts of deploying self-driving vehicles, I created four different scenarios:

Scenario 0: Current conditions (no-built alternative)

Scenario 1: One lane added in each direction (no autonomous Zero Emission /Near Zero Emission trucks).

Scenario 2A-B: One lane added in each direction (autonomous Zero Emission /Near Zero Emission trucks), with 2 sub-scenarios:

- 50% Autonomous, Zero Emission, Trucks and 50% Diesel Trucks (Scenario 2A); and
- 100% Autonomous, Zero Emission, Trucks (Scenario 2B).

4.2 Microscopic Traffic Simulation

For my baseline (Scenario 0), I relied on the network initially developed by Lee *et al.* (2009) and expanded by Bhagat (2014). Additionally, the network was altered for Scenarios 1 and 2A-B as explained above.

4.2.1 OD Estimation and Validation

My simulations rely on previously estimated OD matrices (Bhagat, 2014) based on a travel demand model derived from SCAG with a TransCAD sub-area analysis.

Seed OD demand was generated by applying the proportion method as input for a traffic simulation in order to gather detector and path data. Path-based dynamic OD estimation was applied to the traffic simulation data (Choi, 2009).

For OD validation, I collected traffic count data from Caltrans' Performance Measurement System (PeMS). Data from randomly selected detectors were compared to estimated traffic flows using the GEH statistics, which is an empirical formula that compares two sets of traffic volumes. It can be written:

$$GEH = \sqrt{\frac{[2\times(Simulated-Observed)^2]}{Simulated+Observed}} \tag{3-1}$$

I used twenty randomly selected stations for GEH and status checks. 75% of the stations chosen were healthy detectors, 73% of the healthy detectors had a GEH value under 5, which is considered a good match.

Appendix B shows traffic count data comparing TransModeler vs. PeMS 15-minute count data. Since PeMS only reports 30-seconds, 5-minute, or hourly observations, PeMS data was aggregated to 15 minutes increments from 5-minute raw data.

Further, previously generated OD matrices were adjusted using Matlab to include a new vehicle class for Zero Emission port trucks. Two scenarios (2A and 2B) were then created to analyze potential impacts on air quality of 50% (Scenario 2A) and 100% (Scenario 2B) of zero-emission, autonomous drayage trucks.

Table 1 – TransModeler Matrix Settings for Scenario 0 and Scenario 1

Matrix Name	Vehicle Type	Vehicle Class	HOV	ETC	User A	User B	Probe
3	PC1	Passenger Cars	No	No	No	No	Yes
4	PC1	Passenger Cars	2+	No	No	No	Yes
5	PU	Light Duty Truck	No	No	Yes	No	Yes
6	ST	Medium Duty Truck (non-port related)	No	No	Yes	No	Yes
7	TT	Heavy Duty Truck (non-port related)	No	No	Yes	No	Yes
8	TT	Heavy Duty Truck (port-related)	No	No	Yes	Yes	Yes

Table 2 - TransModeler Matrix Settings for Scenario 2A-B

Matrix Name	Vehicle Class	Vehicle Class	HOV	ETC	User A	User B	Probe
3	PC1	Passenger Cars	No	No	No	Yes	No
4	PC1	Passenger Cars	2+	No	No	Yes	No
5	PU	Light Duty Truck	No	No	No	Yes	Yes
6	ST	Medium Duty Truck (non-port related)	No	No	No	Yes	Yes
7	TT	Heavy Duty Truck (non-port related)	No	No	No	Yes	Yes
8	TT	Heavy Duty Truck (port-related)	No	Yes	No	Yes	Yes
9	TT	Heavy Duty Truck (autonomous port-related)	No	Yes	Yes	No	Yes

Demand files were then converted into TransModeler matrices to reflect the different vehicle types used for simulation. TransModeler' user-defined parameters (User A and User B), "Probe," and "ETC" were used to distinguish between zero-emission trucks, gas and diesel vehicles, all trucks, and port-related trucks respectively (Tables 1 and 2).

To find a realistic estimate of how drayage traffic could increase by 2035, I relied on the Recirculated Draft Environmental Report (RDEIR). This document forecasts that the San Pedro Bay ports could see an increase in annual twenty-foot equivalent units (TEUs) from 14.1 million in 2012 to 41.1 million in 2035, a ~190% increase. Assuming that 35% of this volume is moved by rail (14.1 million annual TEUs) and that the remaining 65% is moved by truck would represent a ~90% increase in drayage truck traffic on the I-710 by 2035. The demand for port-related heavy-duty trailer trucks was adjusted accordingly using Matlab, but I kept constant the demand for other classes of vehicles.

4.2.2 Network Alterations

For Scenarios 1 and 2A-B, one lane was added in each direction, and car-following parameters were modified to represent autonomous vehicles. Truck platooning was modeled using the Constant Time Gap model (Wang and Rajamani, 2004). Lane additions did not alter current freeway alignment.

4.2.3 Truck Platooning

As mentioned above, self-driving technology is expected to have a positive impact on traffic flow conditions partly by dissipating stop-and-go traffic. When an autonomous vehicle maintains a steady speed and a constant distance between the car in front, it causes the following vehicles to reduce their number of breaking events. This creates a safer environment as vehicles are less likely to collide, enabling them to move more smoothly in traffic (Sterna *et al.*, 2017).

TransModeler 5.0 includes features that allow simulating autonomous vehicles with Cooperative Adaptive Cruise Control (CACC). CACC is a subset of the broader class of automatic vehicles speed and control systems. CACC only provides longitudinal control of vehicle motions, while the driver remains responsible for the steering control and monitoring of the driving environment (Shladover, 2014).

A white paper published in 2015 by TNO, a Netherlands Organization for applied scientific research, presents truck platooning as the future of transportation. The authors studied the Cooperative Adaptive Cruise Control (CACC) technology and the benefits associated with lower fuel consumption and productivity. Societal benefits include fewer accidents, less congested roads, and lower carbon emissions.

According to this TNO report, truck platoons are defined as two trucks driving less than one second apart, while using wireless vehicle-to-vehicle communication. The time headway between two trucks is assumed to be as low as 0.3 seconds, which at 80 km/h is roughly 6.7 meters (0.3 seconds at 50 mph is ~22 ft). This is much less than the recommended safe following distance for human-driven vehicles (“the 3-second rule”). I used information form the TNO report to set key TransModeler parameters for self-driving trucks.

4.2.4 Autonomous Truck Calibration

TransModeler 5.0 implements a Constant Time Gap Car-Following Model to approximate the behavior of connected vehicles with Cooperative Adaptive Cruise Control (CACC). The constant time gap (CTG) model simply assumes that a vehicle seeks to maintain a constant, desired headway with the vehicle in front. Wang and Rajamani (2004) studied the stability of traffic flow on a highway when the vehicles operate with adaptive cruise control (ACC) system using the desired headway, or time gap, as the primary parameter of the Constant Time Gap Model. In that model:

$$A_i(t) = -\frac{1}{h}(V_i(t) - V_{i-1}(t) + \lambda\delta_i) \quad (3\text{-}2)$$

The spacing error is estimated by:

$$\delta_i(t) = D_{i,i-1}(t) + hV_i(t) + D_{i,i-1}{}^{desired} \quad (3\text{-}3)$$

where,

$A_i(t)$ = Acceleration rate of vehicle i at time t;

h = Desired following time headway (sec);

$V_i(t)$ = Speed of vehicle i at time t;

$V_{i-1}(t)$ = Speed of vehicle i-1 at time t;

δ_i = Spacing error for vehicle i requiring correction to achieve the desired headway h;

$D_{i,i-1}(t)$ = Distance between the vehicle i and front vehicle i-1 at time t;

$D_{i,i-1}(t)$ = Desired distance between vehicle i and the front of vehicle i-1 at 0 speed; and

λ = Model parameter (control gain);

To represent autonomous driving operations, I set the desired time headway *h* to 0.3 seconds (approximately 1/3 of the headway used by the Modified General Motors model used for all other vehicle classes). In this thesis, to simulate a platoon of trucks, the Constant Time Gap Model was only applied to port-related, zero emission, trucks whenever the leading vehicle was also a port, zero emission, truck.

Table 3 - Constant Time Gap Model Parameters

Class	Category	Time Headway	Lambda
TT	User A	0.3	0.4

4.3 Emission Modeling

To quantify air pollution changes associated with the deployment of autonomous trucks and associated traffic conditions, I estimated changes in emissions of particulate matter (PM) and nitrogen dioxide (NO_2). These pollutants were selected based on the United States Environmental Protection Agency's designation of criteria air pollutants. Under the Clean Air Act, the EPA is required to set National Ambient Air Quality Standards (NAAQS) for six common air pollutants known as "criteria pollutants." Particulate matter and nitrogen oxides are criteria pollutants due to their widespread threat to human health and the environment.

This section describes the data and procedure applied to estimate emissions of NO_2 and PM using the OpMode lookup table. I relied on the methodology implemented by Bhagat (2014) to estimate emission rates from the different vehicle classes simulated.

4.3.1 Pollutants

Nitrogen Dioxide (NO_2) is one of the highly reactive gases known as nitrogen oxides (NO_X). The primary source of NO_2 is the burning of fuel, so it is present in the emissions of motor vehicles. Short-term exposure to this pollutant can aggravate respiratory diseases such as asthma. Continuous exposure to elevated concentrations of NO_2 can contribute to the development of asthma and respiratory infections (U.S. Environmental Protection Agency, 2018).

Particulate Matter (PM) pollution is formed in the atmosphere by a mixture of liquid droplets and solid particles such as dust, dirt, soot, or smoke. Particulate pollution includes inhalable particles (PM_{10}; here PM_x denotes particulate matter with a diameter under x micrometers), and fine, inhalable particles ($PM_{2.5}$). Particulate matter is so small that it can go deep into the lungs, enter the bloodstream and cause serious health problems. Some of the health effects associated with exposure to such particle are premature death, nonfatal heart attacks, respiratory problems, and asthma (U.S. Environmental Protection Agency, 2018).

4.3.2 MOVES OpMode

To estimate the emissions of NO_2 and PM, microsimulation results were combined with MOVES OpMode lookup tables. Initially, lookup tables were generated by vehicle class, based on vehicle age distribution and meteorological data such as humidity and temperature. Vehicle classes include one created to represent zero-emission drayage trucks. Then, trajectory outputs generated from the TransModeler simulation were combined with OpMode lookup tables using Matlab. Emission results were aggregated by time periods. This method was implemented by Lee (2010) and Bhagat (2014).

Table 3 - Vehicle Category by Type

Vehicle type	Vehicle category	OpMode Vehicle ID
PC (private car)	11	1 and 2
LDT (light duty truck)	24	3 to 6
MDT (medium duty truck)	25	7 and 8
HDT (heavy duty truck, non-port)	26	9 to 16
HDT (heavy duty port truck)	46	17
HDT (zero-emission heavy duty truck)	86	18

Fleet distributions were extracted from the 2005 EMFAC’s vehicle class and age distribution database. These distributions were used for the mapping of vehicle categories to match MOVES' vehicle classes based on the fuel source.

Table 4 - EMFAC and MOVES Vehicle Classes

Vehicle Class	EMFAC Vehicle Type		MOVES Vehicle Type	
LDV	1	Passenger Cars	21	Passenger Cars
LDT	2	Light-Duty Trucks 1	31	Passenger Trucks
	3	Light-Duty Trucks 2	32	Light Commercial Trucks
MDT	4	Medium-Duty Trucks	51	Refuse Trucks
HDT	5	Light-Heavy-Duty Trucks 1	52	Single Unit Short-Haul Trucks
	6	Light-Heavy-Duty Trucks 2	53	Single Unit Long-Haul Trucks
	7	Medium-Heavy-Duty Trucks	61	Combination Short-Haul Trucks
	8	Heavy-Heavy-Duty Trucks	62	Combination Long haul Trucks

Table 5 - Vehicle Class Distribution for Los Angeles

Vehicle Class	EMFAC Vehicle Type		MOVES Vehicle Type		Fuel Type	Fleet Distribution
LDV	1	Passenger Cars	21	Passenger Cars	Gas	99.54%
					Diesel	0.46%
LDT	2	Light-Duty Trucks 1	31	Passenger Trucks	Gas	23.16%
					Diesel	0.72%
	3	Light-Duty Trucks 2	32	Light Commercial Trucks	Gas	75.93%
					Diesel	0.19%
MDT	4	Medium-Duty Trucks	51	Refuse Trucks	Gas	99.57%
					Diesel	0.43%
HDT	5	Light-Heavy-Duty Trucks 1	52	Single Unit Short-Haul Trucks	Gas	39.94%
					Diesel	4.84%
	6	Light-Heavy-Duty Trucks 2	53	Single Unit Long-Haul Trucks	Gas	8.61%
					Diesel	5.36%
	7	Medium-Heavy-Duty Trucks	61	Combination Short-Haul Trucks	Gas	7.11%
					Diesel	20.92%
	8	Heavy-Heavy-Duty Trucks	62	Combination Long haul Trucks	Gas	1.55%
					Diesel	11.67%

Table 5 shows vehicle fleet distributions based on the fuel source and Table 6 shows the vehicle age distributions for mapped vehicle classes within the study area. The fuel source for each vehicle class is gasoline and diesel.

MOVES allows a vehicle fleet of up to 31 years (0 to 30 years). Under this distribution, vehicles 31 years and older were grouped together (U.S. EPA, 2010b).

Table 6 - EMFAC Age Distribution

Model Year	21-LDV	31-LDT	32-LDT	51-MDT	52-HDT	53-HDT	61-HDT	62-HDT
2005	9.60%	6.50%	10.00%	8.80%	8.30%	6.80%	6.90%	4.00%
2004	7.20%	5.80%	9.20%	11.00%	8.50%	7.80%	6.90%	3.10%
2003	7.10%	6.40%	8.30%	9.60%	7.90%	6.00%	5.90%	3.30%
2002	6.50%	6.90%	8.10%	8.30%	4.90%	4.80%	5.10%	2.80%
2001	6.30%	11.60%	6.30%	7.80%	2.80%	3.00%	6.60%	4.70%
2000	6.40%	10.30%	7.00%	5.90%	2.70%	8.30%	7.90%	5.90%
1999	5.30%	8.80%	6.20%	5.50%	2.30%	8.60%	7.10%	5.80%
1998	4.90%	5.10%	5.50%	5.80%	3.60%	3.70%	4.60%	5.10%
1997	4.70%	3.80%	4.70%	6.40%	4.90%	4.80%	4.40%	4.90%
1996	4.10%	3.60%	4.10%	3.80%	3.90%	4.30%	3.60%	5.40%
1995	4.60%	3.30%	4.40%	4.60%	4.90%	5.10%	4.80%	6.30%
1994	3.90%	2.80%	3.80%	3.50%	3.40%	4.40%	2.80%	5.00%
1993	3.60%	2.50%	3.50%	2.50%	3.00%	3.10%	2.50%	4.00%
1992	3.20%	1.80%	2.70%	1.90%	2.70%	2.60%	2.20%	3.00%
1991	3.50%	2.00%	2.80%	1.60%	3.00%	2.60%	2.90%	3.30%
1990	3.30%	1.60%	2.10%	1.50%	4.00%	3.90%	3.60%	4.20%
1989	3.00%	1.60%	2.20%	1.60%	4.90%	3.70%	2.70%	4.40%
1988	2.30%	1.40%	1.70%	1.50%	3.30%	2.60%	2.40%	3.40%
1987	2.00%	1.40%	1.50%	1.30%	2.70%	1.90%	2.10%	3.00%
1986	1.50%	1.30%	1.40%	1.20%	3.20%	2.30%	1.60%	2.50%
1985	1.20%	1.10%	0.90%	0.90%	2.90%	1.70%	1.80%	2.30%
1984	0.90%	0.90%	0.70%	0.70%	2.00%	1.10%	1.20%	1.90%
1983	0.50%	0.50%	0.30%	0.40%	1.10%	0.60%	0.50%	0.80%
1982	0.40%	0.50%	0.30%	0.40%	1.10%	0.80%	0.60%	0.90%
1981	0.30%	0.40%	0.20%	0.30%	1.30%	0.50%	0.80%	1.10%
1980	0.20%	0.30%	0.20%	0.30%	1.10%	0.50%	0.60%	0.90%
1979	0.30%	0.30%	0.20%	0.70%	1.40%	0.80%	0.90%	1.00%
1978	0.20%	0.30%	0.20%	0.50%	1.10%	0.50%	0.60%	0.70%
1977	0.20%	0.20%	0.10%	0.60%	0.90%	0.50%	0.40%	0.50%
1976	0.10%	0.20%	0.10%	0.40%	0.60%	0.20%	0.40%	0.40%
1975	2.80%	6.70%	1.30%	0.80%	1.50%	2.50%	5.30%	5.30%

Temperature and humidity data are required for emission modeling using mode lookup tables. For this study, meteorological data purchased for Bhagat (20014) from WeatherSpark were used. The location of the data is Long Beach Airport (Station ID 30723).

OpMode lookup tables were generated based on vehicle age distribution, temperature, and humidity as implemented by Claggett (2011) for emission estimates.

Second-by-second TransModeler trajectories were split by time period, fuel source, by vehicle type ID, and by link type. Through the application of Second-by Second trajectories, we can capture congestion effects such as acceleration, braking, and idling (Tasnim, 2014).

Table 7 - OpMode Vehicle Type ID and TransModeler Vehicle Type Mapping

MOVES Vehicle Type		Fuel Type	OpMode Look-up Table Vehicle Type	TransModeler Vehicle Type
21	Passenger Cars	Gas	1	LDV
		Diesel	2	
31	Passenger Trucks	Gas	3	LDT
		Diesel	4	
32	Light Commercial Trucks	Gas	5	
		Diesel	6	
51	Refuse Trucks	Gas	7	MDT
		Diesel	8	
52	Single Unit Short-Haul Trucks	Gas	9	HDT (non-port related)
			10	
53	Single Unit Long-Haul Trucks	Gas	11	
		Diesel	12	
61	Combination Short-Haul Trucks	Gas	13	
		Diesel	14	
62	Combination Long haul Trucks	Gas	15	
		Diesel	16	
62	Combination Long haul Trucks	Diesel	17	HDT (port-related)
62	Combination Long haul Trucks	Diesel	18	HDT (ZE port-related)

Trajectory outputs generated by the microsimulation were split by vehicle class and time period for all vehicles simulated. First, emission outputs were aggregated by vehicle classes and then by time of day. Lastly, emission outputs were aggregated over 24 hours for each one of the vehicle types (LDV, LDT, MDT, HDT, and Ports).

Chapter 5 Results

This chapter presents changes in traffic performance and emissions before and after the deployment of autonomous vehicles to replace existing port-related drayage trucks in operation within the I-710 corridor. Results from the different scenario are then discussed and compared.

5.1 Traffic Performance

In order to evaluate traffic performance improvements, I collected summary statistics by vehicle class for each of the scenarios simulated, including the total number of vehicles in the network, vehicle miles traveled (VMT), vehicle hours traveled (VHT), and average speed (mph). Table 8 present these summary statistics for the baseline scenario, which corresponds to the no built alternative and to traffic conditions prior to a demand increase and the deployment of autonomous trucks.

Table 8 - Traffic Performance Measures for Scenario 0

Vehicle Class	Vehicle Count	VMT	VHT	Speed
LDV	3,536,626	18,913,590	563,754	34
LDT	50,675	321,814	7,241	44
MDT	42,296	231,079	6,000	39
HDT	51,153	318,420	8,167	39
PORT HDT	56,905	611,636	11,968	51

Table 9 shows summary statistics for each vehicle class after the freeway widening (one lane in each direction), and after the 90% increase in port-related trucks demand to represent 2035 traffic conditions (Scenario 1).

Table 9 - Traffic Performance Measures for Scenario 1

Vehicle Class	Vehicle Count	VMT	VHT	Speed
LDV	3,496,537	18,762,776	572,623	33
LDT	50,262	319,426	8,517	38
MDT	41,711	229,371	6,555	35
HDT	50,859	317,770	8,935	36
PORT HDT	108,000	1,160,237	29,821	39

Before the demand increase for port-related trucks on the network, the total number of trucks represented 5% of all vehicles, approximately 30% of all trucks were port-related drayage trucks, the average speed for port-related drayage trucks was 51 mph, and the average speed for all vehicles in the network was 34 mph. After the increase in demand, the percentage of port-related drayage trucks increased to 7% of all vehicles and 45% of all trucks. In addition, the average speed of port-related drayage trucks decreased to 39 mph, and the average speed for all vehicles in the network decreased to 33 mph.

Table 10 - Traffic Performance Measures for Scenario 2A

Vehicle Class	Vehicle Count	VMT	VHT	Speed
LDV	3,493,670	18,782,836	556,614	34
LDT	50,251	320,391	8,380	38
MDT	41,730	228,345	6,397	36
HDT	50,767	318,193	8,576	37
PORT HDT	53,296	573,575	13,610	42
AUTONOMOUS PORT HDT	53,421	574,979	13,609	42

After replacing the fleet of port-related trucks with autonomous trucks, there was a less than 1.5% variation in the total number of trips. However, the average speed for port-related trucks increased to 44 mph, a 13% improvement. Moreover, the average speed for the network increased to 34 mph. Table 10 and 11 show trip statistics by vehicle class after fleet replacement. The vehicle replacement proportions used for simulation are 50% and 100%.

Table 11 - Traffic Performance Measures for Scenario 2B

Vehicle Class	Vehicle Count	VMT	VHT	Speed
LDV	3,496,701	18,784,016	553,786	34
LDT	50,372	321,308	8,311	39
MDT	41,751	228,667	6,411	36
HDT	50,960	316,729	8,591	37
PORT HDT	0	0	0	-
AUTONOMOUS PORT HDT	107,978	1,158,070	26,463	44

After fleet replacement, the average speed of port-related trucks increased from 33 to 34 mph. However, while the increase in average speed of the network after 100% replacement is marginal, the speed of the network before the increase of port-related drayage truck demand was 34 mph. Table 12 shows a comparison of average speeds for all scenarios.

Table 12 - Vehicle Count, VMT, and Average Speed

Scenario	Autonomous Truck Count	Average Speed Port Trucks (mph)	Δ Average Speed Port Trucks (mph)	Average Speed All Veh (mph)	Δ Average Speed All Veh (mph)
0%	0	39	0	33	-
50%	53,421	42	3	33	0
100%	107,978	44	5	34	1

5.2 Emission Modeling Results

To quantifying air pollution changes associated with the deployment of autonomous trucks, I estimated emission changes of NO_X, $PM_{2.5}$, and PM_{10} within the study area. This section summarizes and compares changes in emissions associated with Scenarios 1, 2A-B compared to the baseline (Scenario 0). My primary focus here is on port-related emissions.

Table 13 presents emission estimates before the deployment of autonomous trucks, and before the increase in port-related truck traffic that represents 2035 traffic conditions. The emission estimates for Scenario 0 show that port-related heavy-duty trucks contribute approximately 50% of nitrogen oxide, $PM_{2.5}$, and PM_{10} emissions even though they account for less than 2% of all vehicles in the network.

Table 13 – Baseline Emission Results (Scenario 0)

Vehicle Category	**NO_X (kg)**	**PM_{10} (kg)**	**$PM_{2.5}$ (kg)**
LDV Arterial	2,688.1	221.7	204.1
LDV Freeway	13,869.8	410.9	378.3
LDV Total	16,558.0	632.6	582.5
LDT Arterial	55.0	2.7	2.4
LDT Freeway	411.2	8.9	8.2
LDT Total	466.2	11.6	10.7
MDT Arterial	17.4	0.4	0.4
MDT Freeway	82.1	1.1	1.1
MDT Total	99.5	1.5	1.5
HDT Arterial	604.1	37.8	36.6
HDT Freeway	3,815.2	147.0	142.3
HDT Total	4,419.3	184.7	178.9
Ports Arterial	1,810.4	126.7	122.9
Ports Freeway	20,423.7	762.5	739.6
Ports Total	22,234.1	889.2	862.6
All	***43,777.0***	***1,719.6***	***1,636.1***

Table 14 shows emission estimates before the deployment of autonomous trucks, and after the 90% increase in port-related truck demand (Scenario 1). This scenario was examined to study traffic performance and emission changes associated with the deployment of autonomous trucks. Furthermore, Scenarios 1 and 2A-B feature the addition of a general-purpose lane in each direction. As expected, under Scenario 1 we see a decrease in traffic performance and a large (90%) increase in nitrogen oxide, $PM_{2.5}$, and PM_{10} emissions. Port-related trucks in Scenario 1 contribute 70% of all tailpipe emissions of these pollutants within the study area. Compared to the estimates before the increase in demand, this represents a 20% increase in port-related emission.

Table 14 - Scenario 1 Air Pollutant Emissions Results

Vehicle Category	**NO_X (kg)**	**PM_{10} (kg)**	**$PM_{2.5}$ (kg)**
LDV Arterial	2,689.3	221.6	204.1
LDV Freeway	13,789.2	410.7	378.2
LDV Total	16,478.5	632.4	582.3
LDT Arterial	55.1	2.6	2.4
LDT Freeway	409.0	8.9	8.2
LDT Total	464.1	11.5	10.6
MDT Arterial	17.6	0.4	0.4
MDT Freeway	79.0	1.0	1.0
MDT Total	96.6	1.4	1.4
HDT Arterial	599.3	37.4	36.3
HDT Freeway	3,804.0	146.9	142.2
HDT Total	4,403.3	184.3	178.5
Ports Arterial	3,471.2	242.9	235.7
Ports Freeway	39,724.3	1,530.7	1,484.8
Ports Total	43,195.5	1,773.7	1,720.5
Total	***64,638.1***	***2,603.3***	***2,493.3***

Table 15 shows emission estimates after replacing all port-related drayage trucks for autonomous zero-emission trucks (Scenario 2B), and after the increase in port-related truck demand. As expected, by eliminating port-related emissions, we observe a ~70% reduction in nitrogen oxide, $PM_{2.5}$, and PM_{10} emissions. In addition, this scenario resulted in a 50% decrease in overall nitrogen oxide, $PM_{2.5}$, and PM_{10} emissions compared to the baseline (Scenario 0). However, while electric vehicles have zero tailpipe emissions, their operation may still result in additional power plant emissions (U.S. Department of Energy, 2017).

A small increase in nitrogen oxide, $PM_{2.5}$, and PM_{10} can be observed for vehicle classes light-duty vehicles (LDV) and light/medium duty trucks (LDT and MDT) as a result of the improvement in traffic conditions caused by trucks traveling in platoons. Given the average speed increase, more vehicles were able to reach their destination in the simulation. Thus, VMT for vehicle classes LDV, LDT, and MDT also increased.

Table 15 – Emission Results under Scenario 2B (100% Autonomous Trucks)

Vehicle Category	**NO_X (kg)**	**PM_{10} (kg)**	**$PM_{2.5}$ (kg)**
LDV Arterial	2,718.5	224.9	207.1
LDV Freeway	14,502.1	440.1	405.3
LDV Total	17,220.6	665.0	612.4
LDT Arterial	56.0	2.7	2.5
LDT Freeway	424.2	9.1	8.3
LDT Total	480.2	11.8	10.8
MDT Arterial	18.3	0.4	0.4
MDT Freeway	83.0	1.1	1.0
MDT Total	101.3	1.5	1.4
HDT Arterial	600.4	37.5	36.3
HDT Freeway	3,939.5	151.4	146.5
HDT Total	4,539.8	188.8	182.9
Ports Arterial			
Ports Freeway			
Ports Total	-	-	-
Total	***22,341.9***	***867.1***	***807.5***

To compare emissions before and after the deployment of autonomous trucks, Table 16 show emission changes for Scenario 2B compared to the baseline scenario. The most significant difference among non-port-related truck vehicle classes was in particulate matter emissions for vehicle class MDT on arterials and freeways (16%).

Table 16 - Changes in Emissions (100% Autonomous Trucks)

Vehicle Category	NOX (%Δ)	PM_{10} (%Δ)	$PM_{2.5}$ (%Δ)
LDV Arterial	1.13	1.46	1.46
LDV Freeway	4.56	7.12	7.12
LDV Total	4.00	5.13	5.13
LDT Arterial	1.79	1.68	1.69
LDT Freeway	3.16	1.46	1.46
LDT Total	3.00	1.52	1.51
MDT Arterial	4.65	16.37	16.70
MDT Freeway	1.16	-8.48	-8.60
MDT Total	1.77	-2.32	-2.35
HDT Arterial	-0.61	-0.80	-0.80
HDT Freeway	3.26	3.00	3.02
HDT Total	2.73	2.22	2.24
Ports Arterial	-100.00	-100.00	-100.00
Ports Freeway	-100.00	-100.00	-100.00
Ports Total	-100.00	-100.00	-100.00
All	**-48.96**	**-49.58**	**-50.64**

Figures 2 to 7 show the distribution of air pollution before and after the deployment of autonomous trucks. Since most of the traffic is observed on freeways, the concentrations of NO_2 were approximately ten times greater on freeways than arterials, while the concentrations of PM were roughly five times greater. I thus analyzed freeways and arterials separately.

As observed from Figure 3, 5, and 7, the reductions in NO_2, $PM_{2.5}$, and PM_{10} is substantial between 6:00 AM and 3:00 PM on both arterial and freeways, with a larger impact on freeways. Figure 3 shows that the concentration of nitrogen oxide per 15-minute period is almost stable at 200 kg. Similarly, by replacing the fleet of port-related vehicles for autonomous vehicles the concentration on freeways of $PM_{2.5}$, and PM_{10} per 15-minute period is consistently less than 10 kg throughout the 24-hour period (Figures 5 and 7).

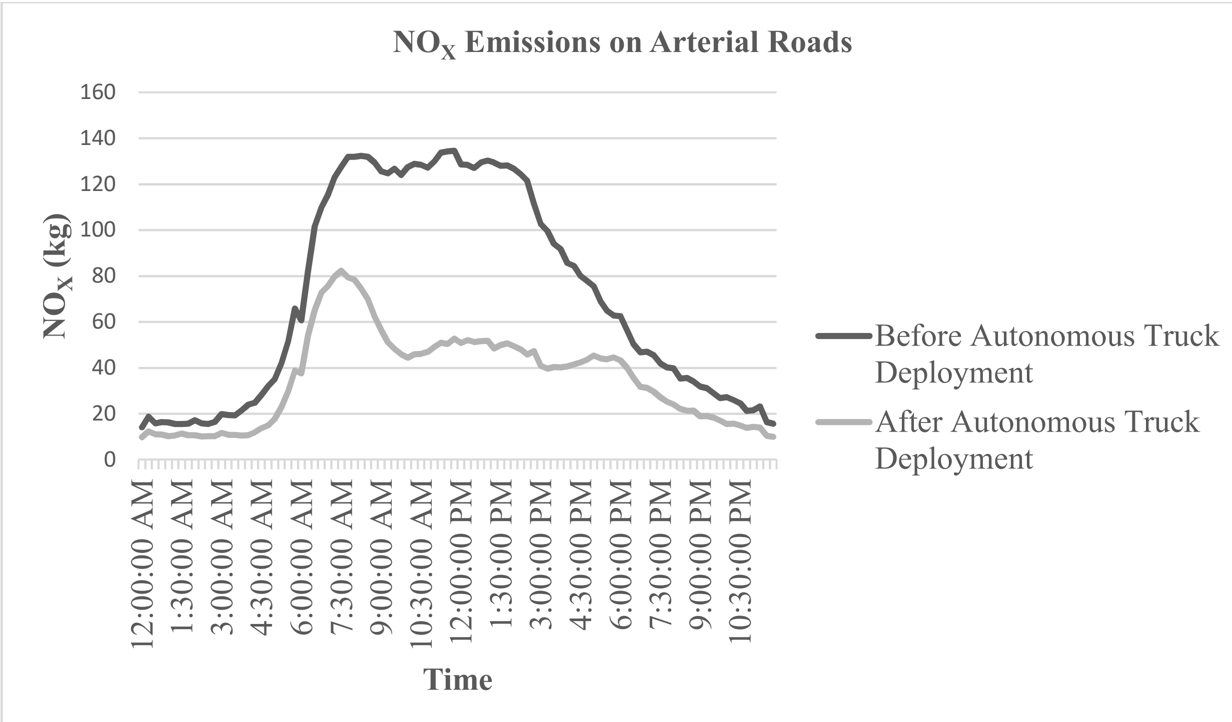

Figure 2 - Comparison of NOx Emissions on Arterials

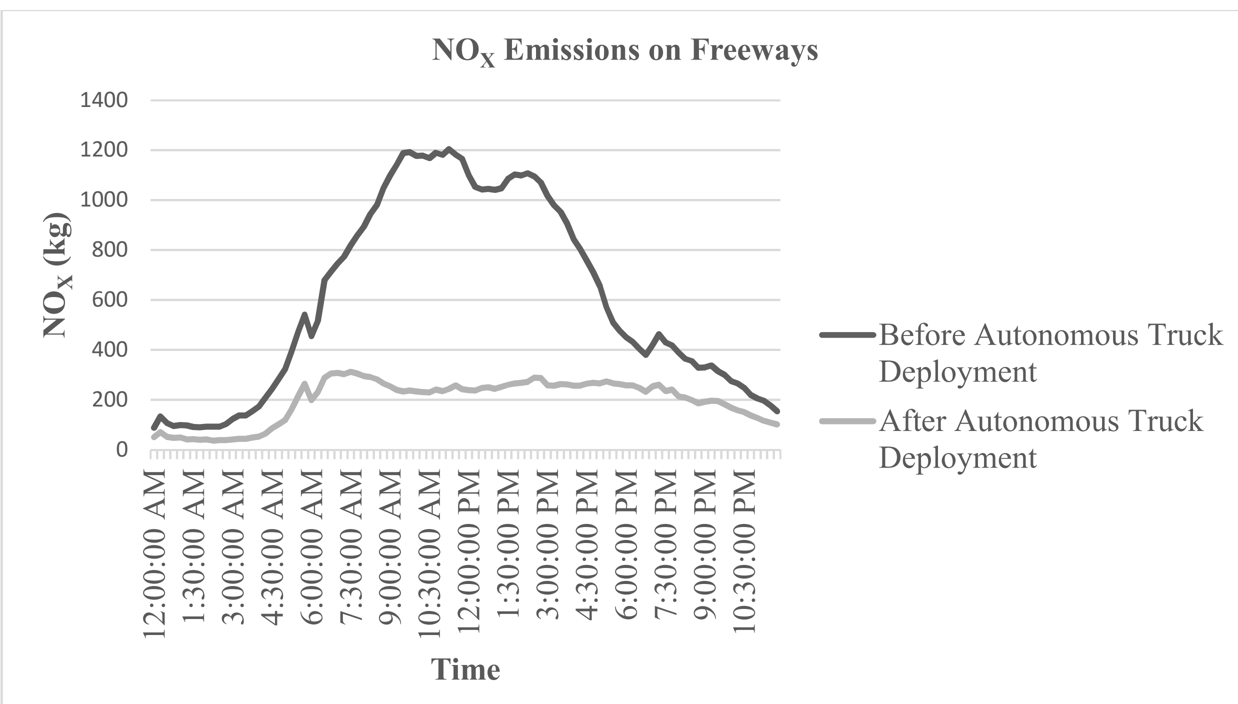

Figure 3 - Comparison of NOx Emissions on Freeways

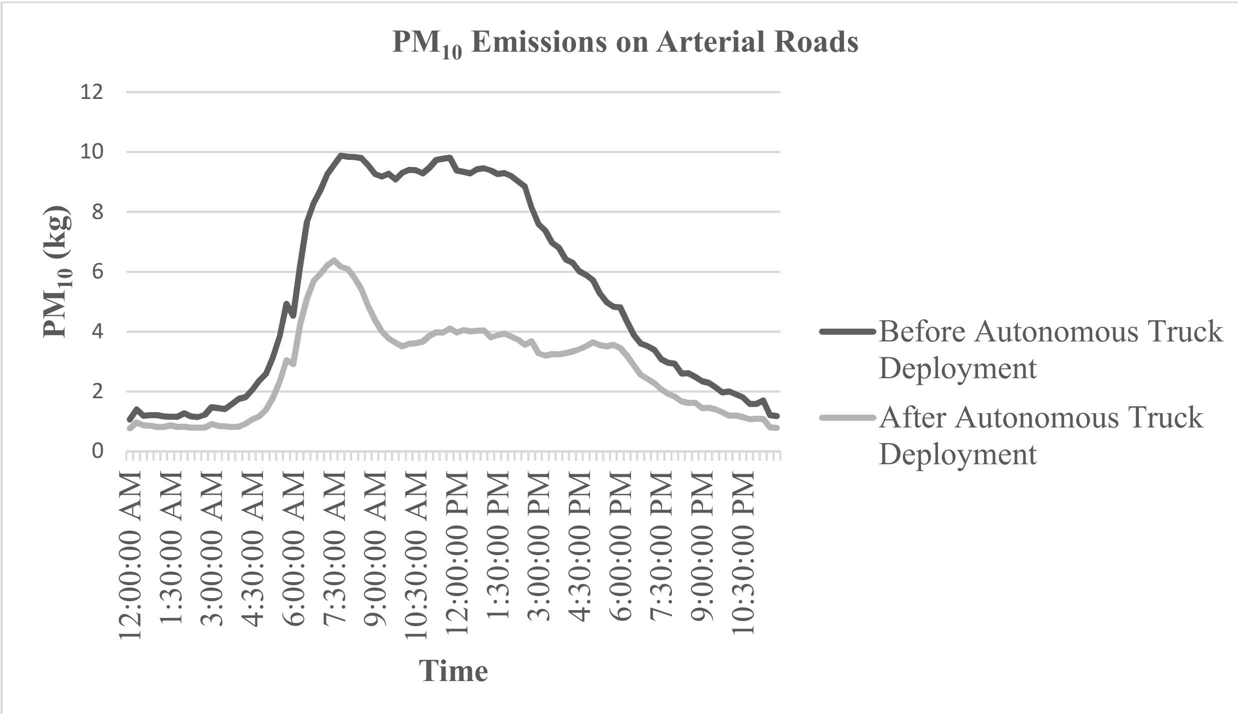

Figure 4 - Comparison of PM10 Emissions on Arterials

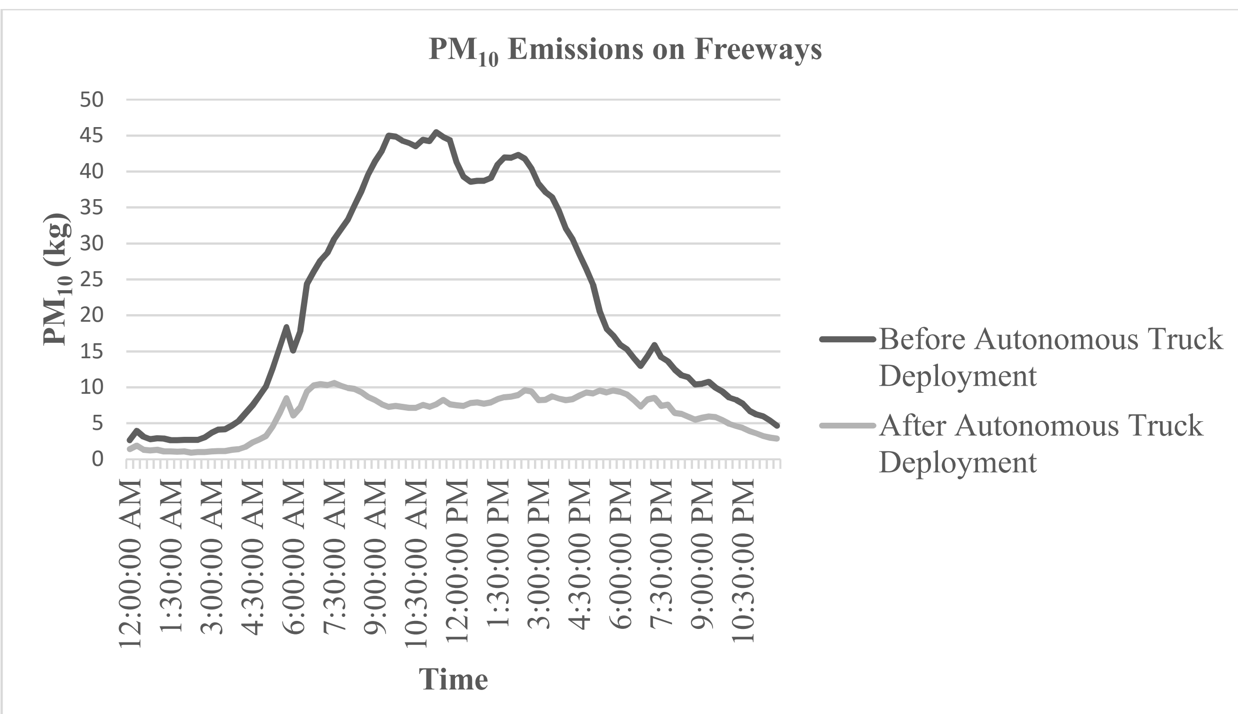

Figure 5 - Comparison of PM10 Emissions on Freeways

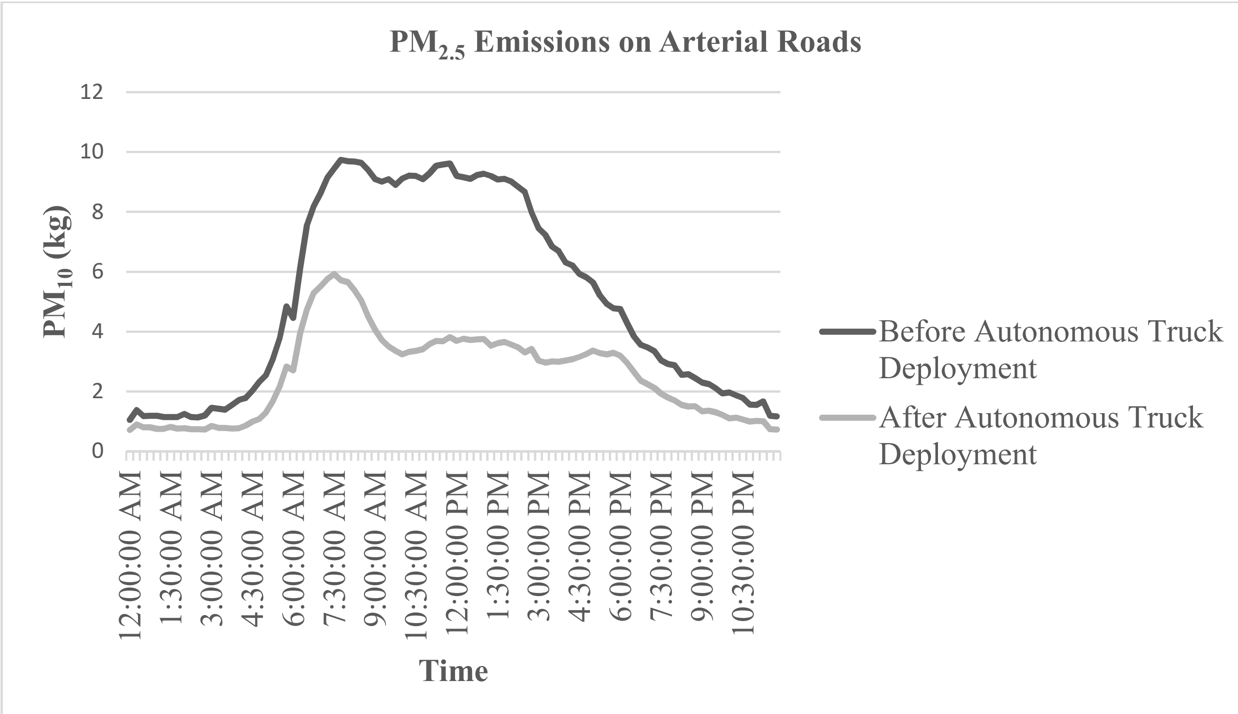

Figure 6 - Comparison of PM2.5 Emissions on Arterials

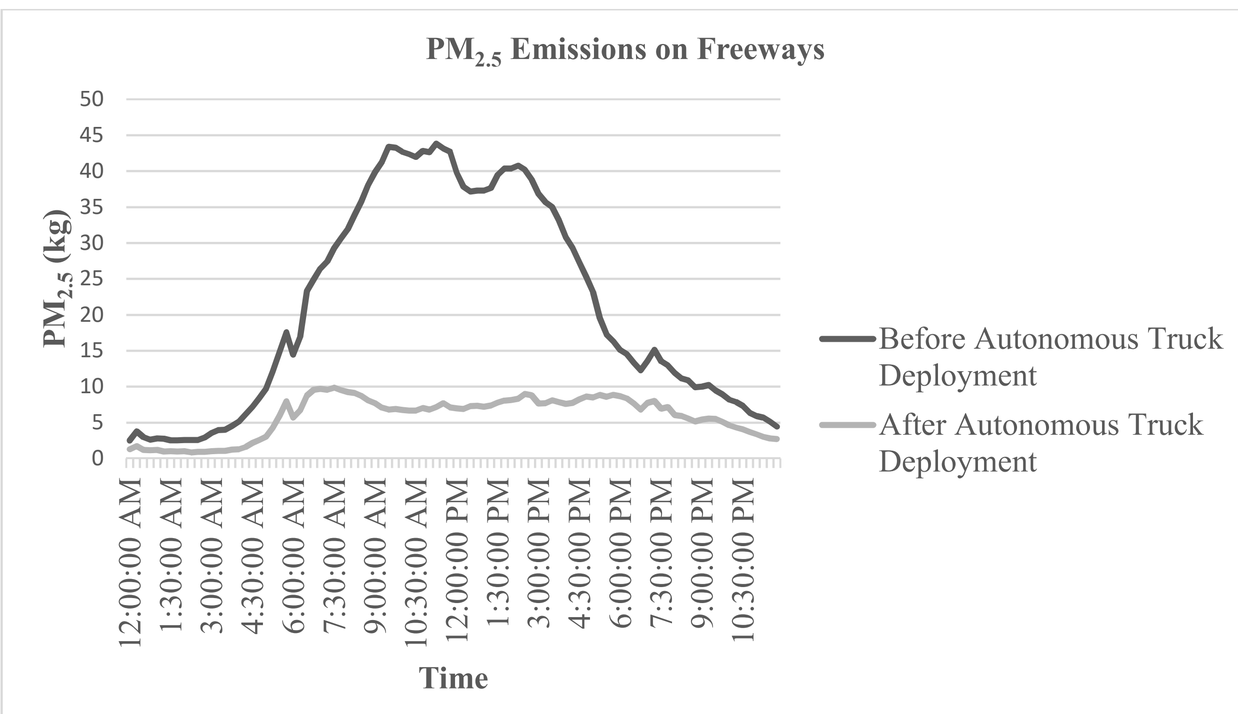

Figure 7 - Comparison of PM2.5 Emissions on Freeways

Chapter 6 Conclusions

The purpose of this thesis was to quantify air pollution changes associated with the deployment of autonomous, zero-emission, trucks to replace port-related drayage trucks currently operating within the study area. Four scenarios were analyzed as an abstraction of alternatives 5C of the Recirculated Draft EIR of the I-710 Corridor Project. Further, this study aimed at quantifying the possible air quality benefits to communities identified in this study as burdened, which comprise mostly low-income and minority groups.

In addition to a baseline, three scenarios were simulated to analyze the impact of replacing 50% and 100% of port heavy-duty diesel trucks with autonomous, zero-emission, trucks over 24 hours for a representative day in 2005 without traffic accidents. During that 24-hour period, approximately 3.75 million vehicles were simulated. To analyze 2035 conditions, the number of port trucks was increased by 90% in Scenarios 2A-B, which represents approximately 55,000 vehicles.

Results show that after fleet replacement the average speed for port-related trucks increased from 39 mph to 44 mph, which represents a 13% increase in traffic performance. This increase may be attributed to smoother traffic conditions since autonomous trucks travel in platoons at a smaller and almost constant headway.

Further, I relied on Operating Mode lookup tables based on MOVES to estimate nitrogen oxide, $PM_{2.5}$, and PM_{10} emissions. My results show a 70% reduction in nitrogen oxide, $PM_{2.5}$, and PM_{10} emissions within the study area.

Environmental Justice issues have been increasingly part of the planning process in the US since the 1970's, usually referred to as environmental racism by activist groups. For decades, community and environmental activists have claimed a correlation between the residence of poor minorities and toxic waste or emissions. The root of environmental justice issues dates back to the 1970's with the transportation and illegal disposal of toxic waste (Sen, 2008).

Living near major roadways is a primary concern, as communities near roadways tend to be disproportionately burdened by everyday transportation activities. Proximity-based studies suggest that nonwhite children in California are three to four times more likely than white children to live in areas with high traffic density (Gunier, 2003). To capture the environmental justice impacts of the changes implemented in this study, future work may extend this analysis to include emission dispersion modeling and health benefits analysis using the framework developed by Lee *et al*. (2012) and Bhagat (2014).

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Appendix A: PeMS Validation

Table 17 - PeMS Validation Results

PeMS ID	3/9/2005		TM	PeMS		TM	PeMS		TM	PeMS		TM	PeMS		TM	PeMS		TM	PeMS		TM	PeMS		TM	PeMS	
STATUS	PeMS ID	TM ID	7:00:00 AM	7:00:00 AM	GEH	7:15:00 AM	7:15:00 AM	GEH	7:30:00 AM	7:30:00 AM	GEH	7:45:00 AM	7:45:00 AM	GEH	8:00:00 AM	8:00:00 AM	GEH	8:15:00 AM	8:15:00 AM	GEH	8:30:00 AM	8:30:00 AM	GEH	8:45:00 AM	8:45:00 AM	GEH
HEALTHY	717962	266	1363	1326	1.01	1281	1381	2.74	1360	1466	2.82	1439	1607	4.30	1371	1453	2.18	1236	1410	4.78	1334	1335	0.03	1232	1110	3.57
HEALTHY	717966	5	1335	1572	6.22	1296	1691	10.22	1374	1628	6.56	1405	1568	4.23	1383	1397	0.38	1219	1430	5.80	1317	1346	0.79	1240	1350	3.06
HEALTHY	718488	272	1754	2070	7.23	1736	2086	8.01	1737	2032	6.80	1738	1875	3.22	1701	1870	4.00	1586	1610	0.60	1557	1740	4.51	1443	1674	5.85
HEALTHY	717977	267	1242	1242	0.00	1247	1103	4.20	1201	1037	4.90	1155	990	5.04	1181	952	7.01	1080	933	4.63	1055	999	1.75	1037	1034	0.09
HEALTHY	718151	22	1535	1477	1.49	1543	1390	4.00	1430	1308	3.30	1417	1257	4.38	1442	1262	4.90	1279	1119	4.62	1343	1257	2.39	1303	1260	1.20
HEALTHY	717992	30	1587	1555	0.81	1571	1388	4.76	1481	1344	3.65	1468	1331	3.66	1431	1261	4.63	1337	1292	1.24	1352	1329	0.63	1305	1118	5.37
HEALTHY	718010	234	1684	1528	3.89	1833	1635	4.75	1783	1518	6.52	1585	1510	1.91	1597	1423	4.48	1558	1443	2.97	1583	1443	3.60	1568	1504	1.63
HEALTHY	717963	160	1533	2068	12.61	1484	2004	12.45	1499	2000	11.98	1541	2068	12.41	1231	2004	19.22	1248	2068	20.14	1240	2068	20.36	1216	2020	19.99
HEALTHY	761851	790	2021	2846	16.72	1913	2835	18.92	1960	2784	16.92	1955	2552	12.58	1792	2918	23.20	1816	2546	15.63	1596	2517	20.31	1608	2456	18.81
HEALTHY	717978	106	1315	1312	0.08	1351	1503	4.02	1336	1535	5.25	1337	1312	0.69	1293	1345	1.43	1248	1155	2.68	1153	1081	2.15	1123	1105	0.54
HEALTHY	716857	100	1969	2018	1.10	2041	2212	3.71	2128	2276	3.15	2074	1996	1.73	1975	2013	0.85	1940	1798	3.28	1754	1804	1.19	1756	1684	1.74
HEALTHY	717980	93	1710	1568	3.51	1834	1879	1.04	1894	1827	1.55	1862	1638	5.35	1735	1738	0.07	1748	1567	4.45	1590	1570	0.50	1586	1459	3.25
HEALTHY	717989	791	1640	1583	1.42	1701	1647	1.32	1743	1679	1.55	1604	1647	1.07	1562	1574	0.30	1533	1436	2.52	1388	1423	0.93	1429	1284	3.94
HEALTHY	718008	57	1548	1494	1.38	1536	1524	0.31	1556	1427	3.34	1403	1353	1.35	1423	1243	4.93	1345	1261	2.33	1259	1197	1.77	1255	1120	3.92
HEALTHY	718012	50	1830	1819	0.26	1786	1796	0.24	1857	1888	0.72	1812	1723	2.12	1750	1600	3.67	1660	1636	0.59	1505	1501	0.10	1524	1448	1.97
Average GEH values for healthy sensors					3.61			5.04			4.94			4.00			5.08			4.77			3.81			4.68
UNHEALTHY	717968	10	1323	934	11.58	1207	1017	5.70	1324	1010	9.19	1357	932	12.56	1300	836	14.20	1128	891	7.46	1232	805	13.38	1210	848	11.28
UNHEALTHY	717770	180	1450	1209	6.61	1439	1223	5.92	1430	1212	6.00	1358	1143	6.08	1366	1145	6.24	1305	1023	8.27	1214	1046	5.00	1165	1044	3.64
UNHEALTHY	718102	188	1179	1112	1.98	1151	1166	0.44	1156	1157	0.03	1067	1119	1.57	1082	1095	0.39	1028	1096	2.09	969	1065	3.01	957	1047	2.84
UNHEALTHY	717986	792	1877	1082	20.67	2068	1199	21.50	2078	1165	22.67	1902	1157	19.05	1889	1130	19.54	1875	1010	22.77	1693	1018	18.33	1723	951	21.11
UNHEALTHY	717960	166	1523	1625	2.57	1577	1578	0.03	1483	1575	2.35	1276	1625	9.16	1207	1578	9.94	1249	1625	9.92	1204	1625	11.19	1341	1578	6.20
Average GEH values for unhealthy sensors					8.68			6.72			8.05			9.69			10.06			10.10			10.18			9.02