Impacts of Accidents on the Analysis of Measures to Reduce Vehicular Emissions

THESIS

submitted in partial satisfaction of the requirement
for the degree of

MASTER OF SCIENCE

in Civil Engineering

by

Karen Sujata

Thesis Committee:
Jean-Daniel Saphores, Chair
R. Jayakrishnan
Michael McNally

2015
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>v</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>vi</td>
</tr>
<tr>
<td>Abstract of the Thesis</td>
<td>vii</td>
</tr>
<tr>
<td>Chapter 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Objective</td>
<td>4</td>
</tr>
<tr>
<td>Chapter 2 Literature Review</td>
<td>5</td>
</tr>
<tr>
<td>Chapter 3 Data and Methodology</td>
<td>11</td>
</tr>
<tr>
<td>3.1 Accident Classification</td>
<td>11</td>
</tr>
<tr>
<td>3.1.1 Data</td>
<td>11</td>
</tr>
<tr>
<td>3.1.2 Data Analysis</td>
<td>12</td>
</tr>
<tr>
<td>3.2 General Accident Characteristics</td>
<td>15</td>
</tr>
<tr>
<td>3.2.1 Frequency and Location of Accidents</td>
<td>15</td>
</tr>
<tr>
<td>3.2.2 Accident Time of Day</td>
<td>16</td>
</tr>
<tr>
<td>3.2.3 Duration of Accidents</td>
<td>17</td>
</tr>
<tr>
<td>3.3 TransModeler Simulation Parameters</td>
<td>19</td>
</tr>
<tr>
<td>3.3.1 Simulation 1: Base Case</td>
<td>19</td>
</tr>
<tr>
<td>3.3.2 Simulation 2: AM Peak Hour Incident</td>
<td>20</td>
</tr>
<tr>
<td>3.3.3 Simulation 3: PM Peak Hour Incident</td>
<td>20</td>
</tr>
<tr>
<td>3.4 Port Trucks OD Estimation and Data Collection</td>
<td>21</td>
</tr>
</tbody>
</table>
3.5 Emissions Estimation ................................................................. 22
   3.5.1 Types of Pollutants ............................................................ 23
   3.5.2 Estimation Procedure ....................................................... 24

Chapter 4       Results ........................................................................ 29
   4.1 Traffic Performance Results .................................................. 29
   4.2 Emissions Estimation Results ................................................ 31

Chapter 5       Conclusions and Future Work ..................................... 41

Appendix .......................................................... 43

References .......................................................... 45
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Study Area</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Segment Locations</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Frequency of accidents by segment</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Frequency of truck accident by time period</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>Total duration of accidents by segment and time period</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Average duration of accidents by segment and time period</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>Base network in TransModeler</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>Accident location as seen in TransModeler</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>Accident simulation in TransModeler</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>HC emissions in kg over a 24 hour period</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>CO emissions in tons over a 24 hour period</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>NO\textsubscript{X} emissions in kg over a 24 hour period</td>
<td>37</td>
</tr>
<tr>
<td>13</td>
<td>Atm. CO\textsubscript{2} emissions in tons over a 24 hour period</td>
<td>37</td>
</tr>
<tr>
<td>14</td>
<td>Energy emissions in GJ over a 24 hour period</td>
<td>38</td>
</tr>
<tr>
<td>15</td>
<td>CO\textsubscript{2} emissions in tons over a 24 hour period</td>
<td>38</td>
</tr>
<tr>
<td>16</td>
<td>PM\textsubscript{10} emissions in kg over a 24 hour period</td>
<td>39</td>
</tr>
<tr>
<td>17</td>
<td>PM\textsubscript{2.5} emissions in kg over a 24 hour period</td>
<td>39</td>
</tr>
</tbody>
</table>
List of Tables

Table 1. Vehicle Types .................................................................................................................................................. 22
Table 2. Vehicle Category by Type ................................................................................................................................ 25
Table 3. L.A. County Mapped Vehicle Class Fleet Distribution ..................................................................................... 26
Table 4. OpMode Vehicle Type ID and TransModeler Vehicle Type Mapping ............................................................... 27
Table 5. Base Network Case Simulation Traffic Performance Results ........................................................................ 30
Table 6. AM Peak Hour Incident Simulation Traffic Performance Results ................................................................ 30
Table 7. PM Peak Hour Incident Simulation Traffic Performance Results ................................................................ 30
Table 8. Base Network Emissions Results ....................................................................................................................... 31
Table 9. AM Peak Hour Incident Emission Results ...................................................................................................... 32
Table 10. PM Peak Hours Incident Emissions Results .................................................................................................... 32
Table 11. AM Peak Hour Incident Emissions Results – Corrected for VMT ................................................................. 33
Table 12. PM Peak Hour Incident Emissions Results – Corrected for VMT ................................................................. 34
Table 13. AM Peak Hour Incident Emissions Results – Percent Difference ................................................................. 35
Table 14. PM Peak Hour Incident Emissions Results – Percent Difference ................................................................. 35
Acknowledgements

First, I would like to acknowledge Professor Jean-Daniel Saphores for his guidance and support during my time as both an undergraduate and graduate student. This thesis was possible with his direction and input. I would also like to thank Professor R. Jayakrishnan and Professor Michael McNally for their valuable insight on various topics throughout the year.

Second, I would like to thank Ankoor Bhagat for sharing knowledge of his dissertation and teaching me how to best utilize and replicate his work. I would also like to thank Kevin Wang for tirelessly helping with his MatLab expertise. Their kindness was inspiring and this would not have been possible without them.

Third, I would like to extend my thanks to the University of California Transportation Center (UCTC) for funding my studies during my graduate education at UCI. UCTC gives valuable opportunities that fuel new ideas, research, and learning every year.

Lastly, I thank my friends and family for their unconditional love and support through my graduate education. Their unwavering belief in me motivated me through times of hard disk failures, computer freeze-ups and code errors. I would like to personally thank my parents for their love and support and giving me independence from a young age which allowed me to grow and learn from my own mistakes. I would also like to thank Abdon Iniguez for his support throughout my graduate studies, and most importantly, letting me run code on his computer.
Abstract of the Thesis

Impacts of Accidents on the Analysis of Measures to Reduce Vehicular Emissions

By
Karen Sujata
Master of Science in Civil Engineering
University of California, Irvine 2015
Professor Jean-Daniel Saphores, Chair

The Long Beach Freeway Corridor Improvement Project was started to address concerns regarding increasing air pollutant emissions and traffic congestion, which are partly due to increases in truck volumes and high accident rates. In addition to these efforts, a non-profit organization called PierPass was created in 2005 by the marine terminal operators at the ports of Los Angeles and Long Beach. The PierPass program aimed to alleviate congestion, security and air quality issues experienced by the ports and freeways by incentivizing freight movements during off-peak hours. This paper explores whether it is important to model accidents when analyzing the environmental benefits of policies designed to reduce air pollution from trucks with an application to PierPass. A microscopic traffic simulation model of the freeway network containing the I-710 freeway was utilized to simulate truck accidents under uniquely identified scenarios based on frequent conditions. Then, vehicular emissions for seven common air pollutants were calculated and compared to a no-accident scenario to quantify the effects of accidents on pollutant emission. Results showed that the introduction of incidents slightly increased the average vehicular speeds and slightly decreased the total amount of emissions; however, the effect of incidents may be more pronounced on a network that is not already known to be heavily congested.
Chapter 1  Introduction

1.1 Background

To address rising concerns about air pollution, several agencies with a presence in Southern California created the Long Beach Freeway Corridor Improvement Project (Metro 2014). These agencies include Caltrans, Los Angeles County Metro, Gateway Cities Council of Governments (GCCOG), Southern California Agency of Governments (SCAG), the Ports of Los Angeles and Long Beach (also known as San Pedro Bay Ports or SPBP), and the I-5 Joint Powers Authority (I-5 JPA).

The project is located on the 18 miles of the I-710 in Los Angeles County between Ocean Boulevard and the SR-60. The selected baseline year for the purposes of this paper is 2005. The study area used by Caltrans and Metro for this project follows the flow of goods from the SPBP complex at the southern end of the I-710 up to the BNSF & Union Pacific (UP) railroad yards in the cities of Vernon and Commerce. A figure showing the study area can be seen on the following page as Figure 1. The Long Beach Freeway Corridor Improvement Project was started to address concerns regarding increasing air pollutant emissions and traffic congestion, which are partly due to increases in truck volumes and high accident rates (Caltrans 2012).
The need to upgrade the I-710 facilities contributed to the motivation as well. Of particular concern is the impact on local residents of the high levels of diesel particulate matter (PM) emitted by freeway traffic. A study found that during 2005, the highest estimated cancer risks (1,200 out of 1 million people affected) occurred near the I-710, the Ports, and the rail yards (URS, 2012, pg. 27). In particular, two pollutants were found to have high levels: PM$_{10}$ and PM$_{2.5}$. Coarse dust particles (PM$_{10}$) are 2.5 to 10 micrometers in diameter. Sources include crushing or grinding operations and dust stirred up by vehicles on roads (AirNow 2015). Fine
particles (PM$_{2.5}$) are 2.5 micrometers in diameter or smaller, and can only be seen with an electron microscope. Fine particles are produced from all types of combustion, including motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, and some industrial processes (AirNow 2015).

Because of high levels of PM$_{10}$ and PM$_{2.5}$, this area is a non-attainment area for small micro-airborne particulate matter. Health impacts from PM exposure include reduced lung functions, asthma, and heart problems. Toxic air exposure studies by the South Coast Air Quality Management District (SCAQMD) show that diesel particulate matter (DPM) produced by diesel trucks is the highest contributor to cancer risks caused by air pollution in this study area (Caltrans, 2012, pg. 2).

Another cause for concern is the high level of traffic congestion on the I-710 where many stretches experience a level of service (LOS) of E or F throughout the day (Metro 2012). Freight trucks that serve the Ports are heavy contributors to congestion and to SCAG’s projected traffic increase on the I-710 (SCAG 2012). SCAG’s 2012 Regional Transportation Plan forecasts that container truck volume could increase from 14 million annual TEUs (twenty-foot equivalent units) in 2008 to 43 million annual TEUs in 2035. Moreover, high accident rates along the corridor can be attributed to congestion, poor freeway design, and high traffic volumes. The percentage of accidents involving trucks is higher on the I-710 than the state average (Caltrans, 2012, pg. 3). Lastly, updating and modernizing the I-710 is necessary because it was designed and constructed in the 1950s before large increases in freight traffic.

In addition to these efforts, a non-profit organization called PierPass was created in 2005 by the marine terminal operators at the ports of Los Angeles and Long Beach (PierPass 2014). The PierPass program aims to alleviate congestion, security and air quality issues experienced by
the ports and freeways by incentivizing freight movements during off-peak hours. The two ports established five new shifts per week and established a Traffic Mitigation Fee (TMF) for cargo movement during peak hours, which were defined as Monday through Friday from 3am to 6pm. Off-peak travel is incentivized as there is no TMF collected if the trucks move after 6pm. Shifting the behavior of freight truck movement could lead to lower pollutant emissions, as taking a truck out of gridlocked traffic and allowing it to travel at higher speeds by driving at night reduces air pollution (PierPass 2014). More information on the PierPass program can be found on www.pierpass.org.

1.2 Objective

In this context, the purpose of this study is to explore whether it is important to model accidents when analyzing the environmental benefits of policies designed to reduce air pollution from trucks with an application to PierPass. A microscopic traffic simulation model of the freeway network containing the I-710 freeway will be utilized to simulate truck accidents under uniquely identified scenarios based on frequent conditions. Then, pollutant emissions will be calculated and compared to a no-accident scenario to quantify the effects of accidents on pollutant emissions. This paper utilizes and complements work done by Bhagat (2014). Bhagat created a microscopic traffic simulation model of the I-710 and I-110 and the surrounding area in order to assess the effectiveness of the PierPass program. His results show that the PierPass program was in fact effective in lowering emissions. It is the objective of this paper to find whether accidents should be included in this work to further gain accurate results.
Chapter 2  Literature Review

Previously published research which rely on outputs from microscopic traffic simulation models in order to estimate emissions, and those which discuss how congestion affects emissions output will be reviewed in this chapter. Papers that also specifically studied the I-710 or the surrounding area were studied to gain a better understanding of the congestion and vehicular emissions problem in the area.

In an early study, Ahn (1998) used microscopic traffic simulation models to estimate emissions based on fuel consumption and look-up tables for different vehicle accelerations and speeds. Three pollutants were considered: hydrocarbons, carbon monoxide, and nitrogen oxide. Ahn tested the pollutants for eight light duty vehicles with data collected by the Oak Ridge National Laboratory (Ahn 1998). Ahn concluded that vehicle fuel consumption and emissions depend more on vehicular acceleration than speed. He argued that signalization techniques could help reduce fuel consumption and emissions significantly, while incident management techniques do not affect the energy and emissions rates notably. In the analysis, Ahn shows that changes in incident duration do not affect the total fuel consumption and emissions rates significantly partly because vehicles produce very small amounts of emissions during idling condition and in the case of incidents, the effect of acceleration, which is the main factor affecting fuel consumption and emissions, is relatively small.

Yang and Regan (2007) studied general truck management strategies using microsimulation traffic models created in TransCAD and Paramics on a portion of the I-710 corridor selected for its high truck volume. Their research focused on analyzing the effect on traffic conditions when restricting a variable number of lanes on the freeway to only heavy-duty
freight trucks. Three scenarios were tested based on the number of restricted lanes. They found that benefits are maximized overall when two lanes in each direction are dedicated to freight trucks.

You et al. (2009) estimated emissions of pollutants on the I-110 and I-710 freeways using microscopic simulation to analyze the potential impacts of shifting container traffic from trucks to trains as part of an emission mitigation measure for the San Pedro Bay Ports. They relied on TransModeler to perform microscopic simulations while trying to match traffic counts from the California Performance Measurement System (PeMS). TransModeler vehicle trajectories and EMFAC2007 emission factors were used to estimate emissions. This paper identifies the two greatest issues with static planning models: first, they ignore individual vehicle behavior, which leads to under-estimating pollutant emissions, and second, they do not take into account link capacity, so it assigns excessive traffic volumes to specific links in congested conditions resulting in emission over-estimates (You 2009). Microscopic simulation provides better estimates of air pollution emissions as it models accelerations/decelerations and lane changing, which are important in stop-and-go traffic. Results showed that heavy duty truck-oriented pollutants were significantly reduced by moving containers from trucks to train when possible.

In related work, Lee et al. (2009) created a microscopic simulation model of the I-710 to assess the impacts on air quality of various scenarios involving drayage trucks serving the San Pedro Bay Ports complex. Several scenarios were considered in addition to the 2005 baseline case: a second case where a fraction of existing diesel trucks were replaced with zero-emission vehicles, a third case where the volume of trucks was reduced by shifting containers to other modes such as rail, and a fourth case which implemented a truck-restricted lane. The results
showed that a fleet replacement in which existing diesel trucks are replaced with zero-emission vehicles yield the most emission reductions (Lee 2009).

In a follow-up study, Lee et al. (2010) used microscopic simulation and emissions estimation modeling with CALPUFF and BenMAP to quantify the health impacts from nitrogen oxide (NO\textsubscript{x}) and particulate matter (PM) exposure near the I-710 and the I-110 (Lee 2010). They found that the cost of these health impacts exceed $200 million per year, with heavy duty trucks contributing to most of these pollutants. One third of these emissions can be attributed to port trucks.

Thomas (2011) developed a stochastic model to estimate the average excess emissions of carbon monoxide (CO), volatile organic compounds (VOC), oxides of nitrogen (NO\textsubscript{x}), and particulate matter (PM\textsubscript{2.5}) and the traffic delay due to incidents. He modeled incident characteristics such as incident clearance time, degree of capacity reduction, and the demand-to-capacity ratio as random variables to derive the statistical characteristics of excess emissions and of traffic delays. Average incident clearance time for this study was found to be 26 min. The average degree of capacity reduction and demand-to-capacity ratio were assumed to be 63% and 71%, respectively. Results show that under these conditions, incidents resulted in a 138% increase in CO emissions, a 500% increase in VOC emissions, a 26% increase in NO\textsubscript{x} emissions, and a 43% increase in PM\textsubscript{2.5} emissions compared with normal traffic emissions. A sensitivity analysis of incident management strategies revealed that air pollutant emissions and traffic delay could be reduced by as much as 30% by detouring as little as 5% of the incoming traffic. These findings differ vastly from those of (1998).

Cho and Hu (2013) used truck flow estimates to develop a network model for simulations combined with the EMFAC air pollution emissions model to study the San Pedro Bay in
California. (Cho 2013). Data concerning complete trade flows in a ZIP code area and O-D and mode information were gathered from IMPLAN (Impacts for Planning) and FAF (Freight Analysis Framework) for the MSAs (Metropolitan Study Area). Three scenarios were tested with various differences, including replacing old trucks with newer trucks, improving the network by adding zero-emission truck only lanes on the I-710, in which 50% of existing truck flows were redirected to these lanes, and implementing an intermodal port that would promote railways at seaports to reduce truck flows from the Ports by 50%. Results show that vehicle replacement strategies help reduce overall air pollution emissions in larger areas, and can decrease emissions by 0.01 tons/day to 0.46 tons/day. However, reducing air pollution in a specific location can increase emissions in zones outside of that location. Since the analysis was conducted without the inclusion of passenger car data, the model may not evaluate the congestion effects properly.

Kabit (2013) developed a VISSIM microsimulation model of the Logan Motorway network in Brisbane, Australia and utilized it to quantify impacts of a major incident in terms of associated costs. The modelled results reveal that a 65% capacity reduction results in 36% more incident-induced delay when compared with the application of a 50% capacity reduction assumption for a two-hour incident clearance duration that blocked one lane of a two-lane motorway. It was also found that an incident that caused a full blockage incurred 40 times more associated impact costs when compared with a major incident that blocked only one lane. A 23% cost saving can be achieved by clearing one lane of a fully blocked two-hour major traffic incident after 90 minutes, while a 37% cost saving can be achieved by clearing all blockages after 90 minutes (Kabit 2013).

Chung et al. (2013) assessed the CO₂ emissions impacts of freeway accidents, applied to an existing model to delineate in space and time congested regions resulting from freeway
accidents. They used a methodology developed by Chung and Recker (2012) to separate non-recurrent from recurrent delays present on the road at the time and place of a reported accident, in order to estimate the contributions to non-recurrent delays of a specific accident. To estimate emissions at different speeds, a model developed by Barth and Boriboonsomsin (2008) was used. The methodology was applied to two datasets: one obtained from the Traffic Accident Surveillance and Analysis System (TSAS) and another obtained from the vehicle detection system (VDS) for the same set of freeways in Orange County, California. The freeways studied included Interstate freeway 5 (I-5), Interstate freeway 405 (I-405), State Route 55 (SR-55), State Route 57 (SR-57), and State Route 91 (SR-91). Using a spatio-temporal analysis to estimate emissions resulting from traffic incidents (Chung 2013), they found that five key factors are significant in contributing to emissions due to accidents: five-minute occupancy, AADT, ruck AADT, accidents with three or more vehicles involved, and accidents during night time period.

Bhagat (2014) studied the impact of shifting of port-related drayage trucks from peak hours to off-peak hours as part of the PierPASS program adopted by the ports of Los Angeles and Long Beach. Microscopic traffic simulation was utilized along with emissions estimation through the use of the OpMode lookup table approach. Dynamic OD estimation was used in the traffic simulation with data gathered from the PeMS database and Caltrans’ AADT data (Bhagat 2014). Bhagat studied the effect on congestion, pollution, and pollution-related health impacts from the PierPASS program. He found that PierPASS had little impact on traffic congestion and on overall emissions of pollutants. However, PierPASS had a significant impact on the distribution of the emissions between day and night. During night-time, total port truck emissions increased by 71%. A health impact analysis done by Bhagat shows the annual social costs of PierPASS to be $438 million.
Avetisyan (2014) quantified the effects of newer and more efficient vehicle technologies, traffic volume changes, and work zones on emissions production from on-road traffic. Both microscopic traffic simulations and emissions estimation tools were used together to calculate the effects from the parameters of the vehicles. He studied the I-270-MD-355 corridor in Montgomery County, Maryland, including its connecting arterials. Results show that vehicle composition greatly impacts the amount of emissions, with older cars producing more emissions than new ones. It was also found that the emissions estimates associated with the blocking of a lane due to an incident were found in general to decrease with lane closure duration. The author described this “counterintuitive” result to be a consequence of increased speeds after an accident due to rubbernecking, where drivers slow down to look at an accident, then speed up once it has passed. The simulations conducted showed average speed of vehicles to be 34 to 35 miles per hour for a case with a 60 minute incident duration, and an average speed of vehicles at 25 miles per hour in a zero minute closure case. This disparity in average speed of vehicles led to decreased emissions with increasing incident duration. The emissions rate per vehicle, however, was found to generally increase with longer incident or work-zone durations.

This cursory review of the literature shows that there is no agreement in the literature about the impact of incidents on the emissions of various air pollutants. Some papers claim that incidents increase emissions due to reduced speeds and increased opportunities for acceleration, while others claim that incidents could reduce emissions due to increased speeds after incident zones. The purpose of this these is to contribute to this emerging literature by using state-of-the-art vehicle simulation and emission estimation on a large network.
Chapter 3  Data and Methodology

In order to simulate truck accidents on I-710, accident data was obtained and classified based on four criteria: location, time of day, duration, and number of lanes blocked. To address location and time of day, the full length of the I-710 was divided into four segments based on lane configuration changes and analyzed with data obtained from the Statewide Integrated Traffic Records System (SWITRS). To determine duration and number of lanes blocked, an interview with a CHP officer was conducted to gain real-life insight. The information obtained was combined with data obtained from the California Performance Measurement System (PeMS). General accident characteristics were found from the data analysis and they were used to set incident parameters for TransModeler. After the accidents were simulated, post-processing of the outputs was conducted to estimate emissions for each scenario considered.

3.1 Accident Classification

Based on the literature reviewed in the previous section by Ahn (1998), Thomas (2011) and Avetisyan (2014), four sets of parameters were chosen in order to simulate accidents that were most likely to replicate the congestion created by real-life truck accidents: location, time of day, duration, and number of lanes blocked.

3.1.1 Data

Collision records from the Statewide Integrated Traffic Records System (SWITRS) for the 2005 baseline year were analyzed in order to determine how accidents should be simulated along the I-710 freeway. The California Highway Patrol (CHP) collects and maintains the SWITRS dataset
that provides detailed information about each recorded accident, including its location (California postmile), date, time of day, accident type, weather conditions, collision severity, light conditions, lane number, type of vehicle involved, and movement preceding collision. Data used for this study were filtered for truck-involved collisions only. A total of 567 accidents involving large trucks were recorded during 2005. The incidents obtained from the Statewide Integrated Traffic Records System (SWITRS; see http://iswitsr.chp.ca.gov/) were matched with information from the Caltrans Performance Measurement System (PeMS). PeMS is an archived data user service that provides over ten years of California traffic data for historical analysis purposes. Some collision information for individual unique collisions failed to match between the SWITRS and PeMS databases so they were discarded.

3.1.2 Data Analysis

Raw data obtained from the SWIRTS, which was in ASCII fixed record length, were processed in Microsoft Excel. The information of each incident was split into three files: collision, party, and victim. All three files were combined and matched using their collision identification numbers; data for which the collision identifications failed to match were discarded.

The full length of the I-710 freeway was surveyed and categorized into four sections, taking into account changes in lane configuration that could affect incidents. The four sections are bounded by the following off-ramps: West Shoreline Drive to Long Beach Boulevard, Long Beach Boulevard to Firestone Boulevard, Firestone Boulevard to Pomona Highway, and Pomona Highway to the end of I-710. Each section is roughly 5 miles in length. Each segment can be seen mapped at their corresponding locations in their corresponding locations in Figure 2. To figure out which section accidents occurred most frequently in, the data were sorted by recorded postmiles.
Accident Duration

The duration of accidents was obtained from information in the PeMS database and complemented with a phone interview with a CHP officer. (The personal communication took place on July 6, 2015 with Officer Robinson at 2pm.) Each accident from PeMS was matched with its SWITRS counterpart based on date, time, and location. Only accidents matched in both
PeMS and SWITRS were used for this analysis. PeMS data contain call information recorded by the 911 dispatcher, as well as time stamps of when CHP arrived on-scene. These time stamps allowed for the determination of the time it took CHP to arrive on-scene after receiving a 911 call; this is denoted as the arrival time. The duration of the accident also comprises the time it took CHP to clear the lanes and to restore traffic. This information was obtained through phone interviews with Officer Robinson. He indicated that the time it takes to clear an accident depends on its severity: minor accidents with no injuries can be cleared in 3 minutes, accidents with mild injuries and paramedics can take 30 minutes, while accidents involving severe injuries or deaths can take up to an hour to clear. SWITRS data contains information about the severity of each accident on a 0-4 scale: 0 denotes property damage only, 4 denotes injury (with complaints of pain), 3 denotes injury (other visible), 2 denotes injury (severe) and 1 denotes fatal. Severities of 0 were assigned a clearance time of 3 minutes, 3 and 4 were assigned a clearance time of 30 minutes, and 1 and 2 were assigned a clearance time of 60 minutes. The arrival time and clearance time was added for the total duration of time the accident affected traffic.

**Number of Lanes Blocked**

The number of lanes blocked was estimated from the information provided in the collision records and based upon the accident hot spots identified. Each accident recorded in the PeMS database contains dispatcher information, which can include information about the number of lanes and which lanes were blocked. Most accidents only involved one lane on the right side of the road usually in lane number 4 or 5, presumably because trucks generally travel at slower speeds than passenger cars. On rare occasions, two or more lanes were blocked.
3.2 General Accident Characteristics

Accidents were classified based on their characteristics. Different characteristics resulted in different durations during which they may contribute to congestion.

3.2.1 Frequency and Location

The percent of accidents involving trucks as a factor of all total accidents for the year 2005 was approximately 27%. An analysis of the data showed that an average of 1.55 truck accidents occur on I-710 each day. Accidents occurred most often in the area between postmiles 18 and 24, which is Segment 3 in this study. The corresponding geographic locations were found by matching up the postmiles with those listed in Caltrans Traffic Counts. Segment 1 includes postmiles 6 to 12, which corresponds to the area between exits West Shoreline Drive and Long Beach Boulevard. Segment 2 includes postmiles 12 to 18, which approximately corresponds to the segment between the exits of Long Beach Boulevard and Firestone Boulevard. Segment 3 is defined by postmiles 18 to 24, which corresponds to the area between exits of Firestone Boulevard and Pomona Highway. Finally, segment 4 includes postmiles 24 to 30, which corresponds to the area between the exit of Pomona Highway and the end of the I-710 freeway. The frequency of accidents by segments can be seen in Figure 3 below. Segments were determined based on lane configuration changes that could affect incidents.
3.2.2 Time of Day

The time of day an accident occurs is likely to greatly impact its duration, the number of lanes closed and the congestion it causes. Hours of the day were split into 4 blocks to describe general traffic conditions: 3AM – 9AM for morning traffic, 9AM – 3PM for mid-day traffic, 3PM – 9PM for afternoon traffic, and 9PM – 3PM for late night traffic. The frequency of truck accidents by time block can be seen in Figure 4. The greatest number of accidents happened between 9AM – 3PM, or mid-day traffic, followed by the time block between 3PM – 9PM, or afternoon traffic. This could be rationalized through the idea that truck drivers are driving mostly during mid-day, after the morning work rush traffic and before the afternoon rush traffic. The accidents occurring during the afternoon traffic can be attributed to slow moving traffic and merging lanes in Segment 3.

Figure 3. Frequency of accidents by segment
Figure 4. Frequency of truck accident by time period

3.2.3 Duration

The sum of all truck accidents durations based on segments was largest on Segment 3, with accidents involving trucks blocking traffic a total of 7,787 minutes in 2005. The second greatest duration was in Segment 2, with 6920 minutes blocked. Within the segments, most of the durations occurred between the hours of 9AM to 3PM, followed by 3PM to 9PM as shown on Figure 5. When divided by the total number of accidents to find the average duration of accidents involving trucks, it was found that Segment 1 contained the longest accidents overall, which can be seen in Figure 6. This shows that while most accidents occurred in Segment 3, when accidents did happen in Segment 1, they tended to last longer than those in all other segments.
Figure 5. Total duration of accidents by segment and time period

Figure 6. Average duration of accidents by segment and time period
3.3 TransModeler Simulation Parameters

The information found in the previous sections was used to create three simulation scenarios to replicate common truck accident conditions. Segment 3 was chosen for the accident location simulations, as most accidents during afternoon rush hour occurred in this segment. For better comparison, two accidents were simulated in the same location for morning rush hour and afternoon rush hour. To simulate the worst case scenario, a duration of 150 minutes was chosen for both accidents to mimic a serious accident.

3.3.1 Simulation 1: Base Case

The first simulation scenario ran the initial network developed by Bhagat (2014) with no modifications and was set as the base case. The simulation network as seen in TransModeler can be seen below in Figure 7. The long vertical stretch on the right side of the image is the I-710.

![Figure 7. Base network in TransModeler](image-url)
3.3.2 Simulation 2: AM Peak

The second scenario used postmile Segment 3 and a time of 7:00AM – 9:30PM as the time of day. Lane 4 was blocked for 150 ft. in TransModeler for a duration of 150 minutes. The accident was simulated between the Florence Avenue and South Atlantic Boulevard off ramps. The accident location as seen in TransModeler are shown in Figure 8.

![Figure 8. Accident location as seen in TransModeler](image)

3.3.3 Simulation 3: PM Peak

The third scenario used postmile Segment 3 and during the 4:00PM-6:30PM time block. Lane 4 was blocked in TransModeler for a duration of 150 minutes. The accident was simulated between the Florence Avenue and South Atlantic Boulevard off ramps at the same location as the AM peak simulation to ensure consistent results. Figure 9 shows the accident simulation in
TransModeler. The 4 brown areas represent the length of the incident. The three dark brown lanes were not constrained in their speed, while the speed in the light brown lane was set to 0 miles per hour to simulate a full 150 ft. lane closure.

![Figure 9. Accident simulation in TransModeler](image)

### 3.4 Simulation Methodology

Simulation methodology primary followed that used by Bhagat (2014) and Tasnim (2014). A travel demand model derived from SCAG data with a TransCAD sub-area analysis was combined with previously estimated OD matrices (Lee et al., 2012; Bhagat, 2014). Seed OD demands were created by applying the proportion method as inputs 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 et al., 2009).
AADT data were collected from Caltrans, and freeway traffic count data were collected from PeMS. Data from 354 mainline freeway, ramp, and arterial detectors were used for the simulations. Simulations were conducted using TransModeler 4.0. Count data were compared to the path-based dynamic OD estimation to see if the GEH statistics converged (Bhagat 2014). If convergence was achieved, the path-based OD estimation was used. Otherwise, the updated OD matrices were put back into the traffic simulator and the process was repeated until convergence was achieved (Bhagat 2014).

Dynamic OD demands were used because traffic patterns can better be portrayed this way, especially during peak periods throughout the day when congestion is present (Tasnim 2014). Five minute count data were aggregated into 15 minute count data for a simulation lasting 24 hours, which therefore gave 96 demand files for all vehicle types. The four main vehicle classes can be seen in Table 1 below. The variations column lists the variations within these vehicle types, if any.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Vehicles included</th>
<th>Variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV = light duty vehicle</td>
<td>PC = Passenger cars</td>
<td><em>PC</em> for general purpose lanes and <em>PC</em> for HOV lanes</td>
</tr>
<tr>
<td>LDT = light duty truck</td>
<td>PU = pickup trucks, vans, and SUVs</td>
<td></td>
</tr>
<tr>
<td>MDT = medium duty truck</td>
<td>ST = single-unit truck</td>
<td></td>
</tr>
<tr>
<td>HDT = heavy duty truck</td>
<td>TT = tractor trailer</td>
<td><em>TT</em> for general purpose lanes, <em>TT</em> for port-related trips, <em>TT</em> for port trips via freight corridor</td>
</tr>
</tbody>
</table>

### 3.5 Emissions Estimation

To understand the exposure of people living near the I-710 to toxic pollutants generated by local traffic, emissions of various air pollutants were estimated to quantify overall air emissions changes from simulating various degrees of traffic accidents on the freeway.
3.5.1 Types of Pollutants

A total of 7 pollutants were considered in the emissions estimation: hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO\(_x\)), atmospheric carbon dioxide (Atm. CO\(_2\)), carbon dioxide equivalent (CO\(_2\) Eq.), and particulate matter (PM\(_{10}\) and PM\(_{2.5}\)). Changes in energy consumption were also considered, but is not a direct pollutant.

Hydrocarbons (HC) emissions are caused by fuel molecules which only partially burn or do not burn in the engine. These hydrocarbons can react with nitrogen oxides and sunlight to form ozone, a major component of smog. Serious respiratory issues, lung damage, and eye irritation result from exposure to ozone. Some exhaust hydrocarbons are toxic and may cause cancer (U.S. E.P.A. 1994).

Carbon Monoxide (CO) is an odorless and colorless gas that results from incomplete mobile engine combustion processes, as with hydrocarbons. It forms when the carbon in the fuel is oxidized only partially, rather than fully oxidized to carbon dioxide. Carbon monoxide can cause a reduction in the flow of oxygen to the blood and to vital organs such as the brain and the heart. Continuous exposure to large levels of CO is dangerous, especially to those with a heart disease (U.S. E.P.A.1994).

Nitrogen Oxide (NO\(_x\)) emissions are caused when nitrogen and oxygen atoms in the air react under high pressure and temperature conditions in an engine. Exposure to NO\(_x\) can cause airway inflammation and worsening asthma symptoms. Nitrogen oxide also contributes to the formation of acid rain (U.S. E.P.A. 1994).

Carbon Dioxide (Atm. CO\(_2\) and CO\(_2\) Eq.) emissions enter the atmosphere through the complete burning of fossil fuels. While no direct negative health effects have been linked to
carbon dioxide, CO₂ is one of the many greenhouse gases that contributes to global climate change. Carbon dioxide is removed from the atmosphere when it is absorbed by plants (U.S. E.P.A.2015).

Particulate Matter (PM₁₀ and PM₂.₅) emissions are made up of a complex mixture of small particles such as dust, soils, metals, liquid chemical droplets, and sulfate and nitrate acids. Coarse dust particles (PM₁₀) are 2.5 to 10 micrometers in diameter. Sources include crushing or grinding operations and dust stirred up by vehicles on roads. Fine particles (PM₂.₅) are 2.5 micrometers in diameter or smaller, and can only be seen with an electron microscope. Fine particles are produced from all types of combustion, including motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, and some industrial processes. Because some particles can be less than or equal to 10 micrometers in diameter, the particles can get into the lungs and cause serious health problems. Numerous scientific studies have connected particle pollution exposure to a variety of health issues, such as asthma attacks, heart attacks, reduced lung function, and premature death in people with heart or lung disease (AirNow 2015).

3.5.2 Estimation Procedure

The estimation procedure used primarily follows that of Bhagat (2014) and Tasnim (2014). Since estimating emissions using EPA’s MOVES software would be very time consuming in this large network, the OpMode lookup table approach proposed by Claggett (2011) and implemented by Lee (2010) and Bhagat (2014) was used. Operating mode (OpMode) lookup tables were generated by vehicle class and pollutant based on inputs such as vehicle age and meteorological data such as temperature and humidity. A detailed overview of the procedure developed by Bhagat can be found in Bhagat (2014).
A vehicle type and vehicle category was assigned to each TransModeler vehicle type. These values were subsequently assigned to the OpMode vehicle ID. Table 2 shows this below.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Vehicle Category</th>
<th>OpMode Vehicle ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car (PC)</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Light Duty Truck (LDT)</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Medium Duty Truck (MDT)</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>High Duty Truck (HDT) (non-port)</td>
<td>26</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>High Duty Truck (HDT) (port)</td>
<td>46</td>
<td>17</td>
</tr>
</tbody>
</table>

The vehicle categories were mapped to a new vehicle class through uniform fleet distributions in Los Angeles County. EMFAC’s vehicle class and age distributions from 2005 were used for the distributions. The distributions were then mapped to be recognized as MOVES vehicles. Each mapped vehicle has two different fuel types, gasoline and fuel (Bhagat 2014).
Table 3. L.A. County Mapped Vehicle Class Fleet Distribution

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

TransModeler simulations were configured to output second-by-second vehicle trajectories. Second-by-second trajectories is advantageous in that that congestion effects from acceleration, braking, and idling can better be modeled (Bhagat 2014). Since the original output file was much too large for computing programs to handle on its own, the data was split by time (15 minute intervals) and operating mode (OpMode) vehicle type ID. Vehicle categories from the Monte Carlo simulation were used for the trajectory split. OpMode lookup tables for different vehicle classes and pollutants were created based on vehicle age distribution, temperature, and humidity. Claggett (2011) suggested this method to efficiently estimate vehicular emissions.
Table 4. OpMode Vehicle Type ID and TransModeler Vehicle Type Mapping

<table>
<thead>
<tr>
<th>Vehicle Type in MOVES</th>
<th>Fuel Type</th>
<th>OpMode Look-up Table Vehicle Type ID</th>
<th>TransModeler Vehicle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 Passenger Cars</td>
<td>Gas</td>
<td>1</td>
<td>LDV</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>31 Passenger Trucks</td>
<td>Gas</td>
<td>3</td>
<td>LDT</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>32 Light Commercial Trucks</td>
<td>Gas</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>51 Refuse Trucks</td>
<td>Gas</td>
<td>7</td>
<td>MDT</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>52 Single Unit Short haul Trucks</td>
<td>Gas</td>
<td>9</td>
<td>HDT (Non-Port related)</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>53 Single Unit Long-haul Trucks</td>
<td>Gas</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>61 Combination Short-haul Trucks</td>
<td>Gas</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>62 Combination Long-haul Trucks</td>
<td>Gas</td>
<td>15*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

A Matlab program written by Bhagat and modified by Saphores and Wang was used to process the trajectory split output. OpMode lookup tables were used to estimate the emissions produced. First, the data was separated by vehicle classes 1 through 17 corresponding to the OpMode vehicle ID. The data was then separated once again by time of day in 15 minute intervals (96 sections in 24 hours). The emissions produced by these separated categories were then estimated to produce a total of 17*96 emission results. To aggregate this information, another Matlab program was used to sort the emissions into five vehicle types of Light Duty Vehicles (LDV), Light Duty Trucks (LDT), Medium Duty Trucks (MDT), High Duty Truck
(HDT)(non-port), and High Duty Trucks (HDT)(ports). The total amount of emissions sorted by each 15 minute segment was also calculated as well.
Chapter 4  Results

For each simulation case, traffic performance results and estimated emissions are especially of interest. Traffic performance results show network performance measures such as vehicle counts, vehicle miles travelled, vehicle hours travelled, and average speed. The emissions estimation shows 7 common air pollutants: hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO\textsubscript{x}), atmospheric carbon dioxide (Atm. CO\textsubscript{2}), carbon dioxide equivalent (CO\textsubscript{2} Eq.), and particulate matter (PM\textsubscript{10} and PM\textsubscript{2.5}). Energy consumption was also calculated for each case.

4.1 Traffic Performance Results

Traffic performance data were collected along with vehicle trajectories for each simulation scenario. These traffic performance data were vehicle counts of each vehicle class, vehicle miles travelled in miles (VMT), vehicle hours travelled in hours (VHT), and average speed in miles per hour. Average speed for each vehicle class was found by dividing the respective VMT by VHT. The traffic performance results for the base network case can be seen in Table 5. The traffic performance results for the AM peak hour incident can be seen in Table 6, and the PM peak hour incident traffic performance results can be seen in Table 7.
Table 5. Base Case Simulation Traffic Performance Results

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vehicle Count</th>
<th>VMT (mi)</th>
<th>VHT (hr.)</th>
<th>Average Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>3,437,650</td>
<td>21,675,886</td>
<td>738,888</td>
<td>29.33</td>
</tr>
<tr>
<td>LDT</td>
<td>49,603</td>
<td>360,303</td>
<td>11,726</td>
<td>30.72</td>
</tr>
<tr>
<td>MDT</td>
<td>38,123</td>
<td>254,582</td>
<td>8,088</td>
<td>31.47</td>
</tr>
<tr>
<td>HDT</td>
<td>45,562</td>
<td>334,103</td>
<td>10,898</td>
<td>30.65</td>
</tr>
<tr>
<td>Port HDT</td>
<td>55,844</td>
<td>379,770</td>
<td>21,592</td>
<td>17.58</td>
</tr>
<tr>
<td>All vehicles</td>
<td>3,626,782</td>
<td>23,004,626</td>
<td>791,192</td>
<td>29.07</td>
</tr>
</tbody>
</table>

Table 6. AM Peak Hour Incident Simulation Traffic Performance Results

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vehicle Count</th>
<th>VMT (mi)</th>
<th>VHT (hr.)</th>
<th>Average Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>3,489,818</td>
<td>22,017,891</td>
<td>745,470</td>
<td>29.53</td>
</tr>
<tr>
<td>LDT</td>
<td>49,868</td>
<td>361,976</td>
<td>11,778</td>
<td>30.73</td>
</tr>
<tr>
<td>MDT</td>
<td>38,740</td>
<td>258,738</td>
<td>8,277</td>
<td>31.25</td>
</tr>
<tr>
<td>HDT</td>
<td>46,787</td>
<td>342,758</td>
<td>11,349</td>
<td>30.20</td>
</tr>
<tr>
<td>Port HDT</td>
<td>55,926</td>
<td>380,304</td>
<td>21,427</td>
<td>17.71</td>
</tr>
<tr>
<td>All vehicles</td>
<td>3,681,139</td>
<td>23,361,667</td>
<td>798,301</td>
<td>29.26</td>
</tr>
</tbody>
</table>

Table 7. PM Peak Hour Incident Simulation Traffic Performance Results

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vehicle Count</th>
<th>VMT (mi)</th>
<th>VHT (hr.)</th>
<th>Average Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>3,492,497</td>
<td>22,018,544</td>
<td>743,339</td>
<td>29.62</td>
</tr>
<tr>
<td>LDT</td>
<td>50,162</td>
<td>361,792</td>
<td>11,756</td>
<td>30.75</td>
</tr>
<tr>
<td>MDT</td>
<td>38,810</td>
<td>263,274</td>
<td>8,468</td>
<td>31.09</td>
</tr>
<tr>
<td>HDT</td>
<td>47,855</td>
<td>346,205</td>
<td>11,482</td>
<td>30.15</td>
</tr>
<tr>
<td>Port HDT</td>
<td>56,221</td>
<td>382,620</td>
<td>21,447</td>
<td>17.84</td>
</tr>
<tr>
<td>All vehicles</td>
<td>3,689,227</td>
<td>23,372,435</td>
<td>796,492</td>
<td>29.34</td>
</tr>
</tbody>
</table>

During each of the 24 hour simulations, each case involved approximately 3.5 million light duty vehicles, 0.05 million light duty trucks, 0.038 million medium duty trucks, 0.047
million heavy duty trucks, and 0.056 million heavy duty port trucks, for a total of approximately 3.7 million vehicles. Out of approximately 3.7 million vehicles, 5.2% were trucks, approximately 29.1% of which were port trucks. These numbers are very similar to the ones that Bhagat (2014) found. Minor discrepancies may result from slight random variations in different TransModeler simulations.

As observed, the traffic performance data shows counterintuitive results. It shows the overall speed increasing slightly in each vehicle class in the simulations with traffic incidents. This may be the result of cars speeding up after an incident in order to make up for lost time, as proposed by Avetisyan (2014).

4.2 Emissions Results

Preliminary emissions results for each simulation case can be seen in Tables 8-10. Energy consumption is included in the table, although it is not a direct pollutant.

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO₂ (Tons)</th>
<th>Energy (GJ)</th>
<th>CO₂ Eq. (Tons)</th>
<th>PM₁₀ (kg)</th>
<th>PM₂.₅ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>4160.1</td>
<td>137.8</td>
<td>16500.3</td>
<td>7165.1</td>
<td>90401.1</td>
<td>7198.2</td>
<td>720.1</td>
<td>663.1</td>
</tr>
<tr>
<td>LDT</td>
<td>90.1</td>
<td>3.4</td>
<td>463.4</td>
<td>158.5</td>
<td>1998.8</td>
<td>159.8</td>
<td>11.5</td>
<td>10.7</td>
</tr>
<tr>
<td>MDT</td>
<td>15.3</td>
<td>0.8</td>
<td>93.1</td>
<td>20.7</td>
<td>261.2</td>
<td>20.7</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>160.7</td>
<td>3.3</td>
<td>3995.7</td>
<td>353.9</td>
<td>4388.5</td>
<td>353.9</td>
<td>171.9</td>
<td>166.5</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>524.0</td>
<td>4.06</td>
<td>23400.0</td>
<td>1752.7</td>
<td>21700.0</td>
<td>1752.7</td>
<td>994.0</td>
<td>964.0</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>4950.0</td>
<td>149.4</td>
<td>44452.5</td>
<td>9450.4</td>
<td>118749.6</td>
<td>9485.3</td>
<td>1898.9</td>
<td>1805.5</td>
</tr>
</tbody>
</table>

The base network emissions are very close to those estimated by Bhagat (2014). It can be noted that heavy duty trucks produce the most emissions out of all trucks, and port trucks make up a large fraction of it (over 80% in most cases). LDV or passenger cars produced the most HC.
CO, CO₂ and substantial amounts of NOₓ. This is not surprising because the number of passenger cars on the freeways is much larger than the number of trucks - 3.5 million LDV’s were simulated over 24 hours, as opposed to roughly 200,000 trucks in the same period.

**Table 9. AM Peak Hour Incident Emission Results**

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO₂ (Tons)</th>
<th>Energy (GJ)</th>
<th>CO₂ Eq. (Tons)</th>
<th>PM₁₀ (kg)</th>
<th>PM₂⁻⁵ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>4100.0</td>
<td>135.6</td>
<td>16200.3</td>
<td>7021.8</td>
<td>88601.1</td>
<td>7054.8</td>
<td>713.1</td>
<td>656.1</td>
</tr>
<tr>
<td>LDT</td>
<td>90.2</td>
<td>3.4</td>
<td>461.4</td>
<td>158.4</td>
<td>1996.8</td>
<td>159.7</td>
<td>11.5</td>
<td>10.62</td>
</tr>
<tr>
<td>MDT</td>
<td>15.1</td>
<td>0.8</td>
<td>90.9</td>
<td>20.3</td>
<td>256.2</td>
<td>20.3</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>156.0</td>
<td>3.2</td>
<td>3838.7</td>
<td>341.0</td>
<td>4228.2</td>
<td>341.4</td>
<td>166.4</td>
<td>161.1</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>532.0</td>
<td>4.14</td>
<td>23700.0</td>
<td>1785.7</td>
<td>22000.0</td>
<td>1785.7</td>
<td>1020.0</td>
<td>988.0</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>4893.2</td>
<td>147.2</td>
<td>44291.3</td>
<td>9327.3</td>
<td>117082.3</td>
<td>9362.1</td>
<td>1912.3</td>
<td>1817.1</td>
</tr>
</tbody>
</table>

**Table 10. PM Peak Hours Incident Emissions Results**

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO₂ (Tons)</th>
<th>Energy (GJ)</th>
<th>CO₂ Eq. (Tons)</th>
<th>PM₁₀ (kg)</th>
<th>PM₂⁻⁵ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>4110.0</td>
<td>135.6</td>
<td>16200.3</td>
<td>7032.8</td>
<td>88701.1</td>
<td>7065.9</td>
<td>713.1</td>
<td>657.1</td>
</tr>
<tr>
<td>LDT</td>
<td>89.6</td>
<td>3.4</td>
<td>459.4</td>
<td>157.0</td>
<td>1938.8</td>
<td>158.4</td>
<td>11.5</td>
<td>10.6</td>
</tr>
<tr>
<td>MDT</td>
<td>15.1</td>
<td>0.8</td>
<td>91.4</td>
<td>20.4</td>
<td>256.9</td>
<td>20.4</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>155.1</td>
<td>3.2</td>
<td>3844.2</td>
<td>340.6</td>
<td>4228.2</td>
<td>341.0</td>
<td>166.7</td>
<td>161.5</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>526.0</td>
<td>4.1</td>
<td>23400.0</td>
<td>1763.7</td>
<td>21800.0</td>
<td>1763.7</td>
<td>1000.0</td>
<td>970.0</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>4895.8</td>
<td>147.1</td>
<td>43995.3</td>
<td>9314.5</td>
<td>116970.0</td>
<td>9349.4</td>
<td>1892.6</td>
<td>1800.4</td>
</tr>
</tbody>
</table>

From these results, it can be seen that the overall total emissions of each vehicle class has decreased between the two incident cases, except for the port heavy duty trucks.

However, to compare emissions between the base case and the incident simulation cases accurately, the results for each vehicle class and time period must be multiplied by a correction.
factor based on VMT for both scenarios. Let *Corrected Emissions* be the corrected incident emission of pollutant; let Initial Emissions Output be the raw emissions data obtained; let *Base VMT* be the base case VMT; and let *Simulation VMT* be incident simulation VMT. Then:

\[
\text{Corrected Emissions} = \frac{\text{*Base VMT*}}{\text{Simulation VMT}} \cdot \text{Initial Emissions Output}
\]

This correction was done for all vehicle classes of LDV, LDT, MDT, HDT, and Port Trucks for each time period of 1 through 96 and also for each considered pollutant. The emissions results were corrected for VMT in the original output units, then changed back into units of kg, tons, and GJ. The corrected AM and PM peak hour incident emission results are presented in Tables 11 and 12.

**Table 11. AM Peak Hour Incident Emissions Results – Corrected for VMT**

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO₂ (Tons)</th>
<th>Energy (GJ)</th>
<th>CO₂ Eq. (Tons)</th>
<th>PM₁₀ (kg)</th>
<th>PM₂.₅ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>4038.5</td>
<td>133.6</td>
<td>15957.3</td>
<td>6916.5</td>
<td>87272.1</td>
<td>6949.1</td>
<td>702.4</td>
<td>646.2</td>
</tr>
<tr>
<td>LDT</td>
<td>88.8</td>
<td>3.4</td>
<td>454.5</td>
<td>156.0</td>
<td>1966.9</td>
<td>157.3</td>
<td>11.4</td>
<td>10.5</td>
</tr>
<tr>
<td>MDT</td>
<td>14.9</td>
<td>0.8</td>
<td>89.6</td>
<td>20.0</td>
<td>252.4</td>
<td>20.0</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>153.6</td>
<td>3.2</td>
<td>3781.1</td>
<td>335.9</td>
<td>4164.7</td>
<td>336.3</td>
<td>163.9</td>
<td>158.7</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>524.0</td>
<td>4.1</td>
<td>23344.5</td>
<td>1759.0</td>
<td>21670.0</td>
<td>1759.0</td>
<td>1004.7</td>
<td>973.2</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>4819.8</td>
<td>145.0</td>
<td>43627.0</td>
<td>9187.4</td>
<td>115326.1</td>
<td>9221.7</td>
<td>1883.6</td>
<td>1789.8</td>
</tr>
</tbody>
</table>
Table 12. PM Peak Hour Incident Emissions Results – Corrected for VMT

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO2 (Tons)</th>
<th>Energy (GJ)</th>
<th>CO2 Eq. (Tons)</th>
<th>PM10 (kg)</th>
<th>PM2.5 (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>4044.3</td>
<td>133.4</td>
<td>15941.1</td>
<td>6920.3</td>
<td>87281.9</td>
<td>6952.8</td>
<td>701.7</td>
<td>646.6</td>
</tr>
<tr>
<td>LDT</td>
<td>88.2</td>
<td>3.3</td>
<td>452.1</td>
<td>154.5</td>
<td>1952.1</td>
<td>155.8</td>
<td>11.3</td>
<td>10.4</td>
</tr>
<tr>
<td>MDT</td>
<td>14.8</td>
<td>0.8</td>
<td>89.9</td>
<td>20.1</td>
<td>252.8</td>
<td>20.1</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>152.6</td>
<td>3.2</td>
<td>3782.7</td>
<td>335.1</td>
<td>4160.5</td>
<td>335.5</td>
<td>164.1</td>
<td>158.9</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>517.6</td>
<td>4.0</td>
<td>23025.6</td>
<td>1735.5</td>
<td>21451.2</td>
<td>1735.5</td>
<td>984.0</td>
<td>954.5</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>4817.5</td>
<td>144.8</td>
<td>43291.4</td>
<td>9165.5</td>
<td>115098.5</td>
<td>9199.8</td>
<td>1862.4</td>
<td>1771.6</td>
</tr>
</tbody>
</table>

The percentage differences from the base case emissions (%Δ = (After – Before)/Before)) in emissions for both scenarios were also calculated. Overall, emissions of HC, CO, NOx, atm. CO2, CO2 eq., PM10, PM2.5, and energy consumption decreased in every vehicle category, although not by a large amount.

This is counterintuitive, as it is logical to think that emissions should increase in a high-traffic environment. However, Ahn (1998) explained with his research that changes in incident duration do not affect the total fuel consumption and emissions rates significantly partly because vehicles produce very small amounts of emissions during idling condition and in the case of incidents, the effect of acceleration, which is the main factor affecting fuel consumption and emissions, is relatively small. Avetisyan (2014) also found incidents to decrease emissions as the incident duration was increased. These texts offer some insight as to why emissions decreased with the addition of incidents to the network.
Table 13. AM Peak Hour Incident Emissions Results – Percent Difference from Base Case

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO₂ (Tons)</th>
<th>Energy (GJ)</th>
<th>CO₂ Eq. (Tons)</th>
<th>PM₁₀ (kg)</th>
<th>PM₂.₅ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>-2.92%</td>
<td>-3.08%</td>
<td>-3.29%</td>
<td>-3.47%</td>
<td>-3.46%</td>
<td>-3.46%</td>
<td>-2.46%</td>
<td>-2.54%</td>
</tr>
<tr>
<td>LDT</td>
<td>-1.41%</td>
<td>-1.53%</td>
<td>-1.92%</td>
<td>-1.57%</td>
<td>-1.60%</td>
<td>-1.57%</td>
<td>-1.81%</td>
<td>-1.81%</td>
</tr>
<tr>
<td>MDT</td>
<td>-2.66%</td>
<td>-3.18%</td>
<td>-3.83%</td>
<td>-3.44%</td>
<td>-3.39%</td>
<td>-3.44%</td>
<td>-5.71%</td>
<td>-5.73%</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>-4.40%</td>
<td>-3.64%</td>
<td>-5.37%</td>
<td>-4.96%</td>
<td>-5.10%</td>
<td>-4.98%</td>
<td>-4.65%</td>
<td>-4.65%</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>0.00%</td>
<td>0.37%</td>
<td>-0.24%</td>
<td>0.36%</td>
<td>-0.14%</td>
<td>0.36%</td>
<td>1.08%</td>
<td>0.95%</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>-2.63%</td>
<td>-2.96%</td>
<td>-1.86%</td>
<td>-2.78%</td>
<td>-2.88%</td>
<td>-2.78%</td>
<td>-0.80%</td>
<td>-0.87%</td>
</tr>
</tbody>
</table>

Table 14. PM Peak Hour Incident Emissions Results – Percent Difference from Base Case

<table>
<thead>
<tr>
<th>Vehicle Class &amp; Road Type</th>
<th>HC (kg)</th>
<th>CO (Tons)</th>
<th>NOx (kg)</th>
<th>Atm. CO₂ (Tons)</th>
<th>Energy (GJ)</th>
<th>CO₂ Eq. (Tons)</th>
<th>PM₁₀ (kg)</th>
<th>PM₂.₅ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>-2.78%</td>
<td>-3.19%</td>
<td>-3.39%</td>
<td>-3.42%</td>
<td>-3.45%</td>
<td>-3.41%</td>
<td>-2.55%</td>
<td>-2.48%</td>
</tr>
<tr>
<td>LDT</td>
<td>-2.07%</td>
<td>-3.25%</td>
<td>-2.44%</td>
<td>-2.51%</td>
<td>-2.34%</td>
<td>-2.50%</td>
<td>-2.34%</td>
<td>-2.40%</td>
</tr>
<tr>
<td>MDT</td>
<td>-3.13%</td>
<td>-5.57%</td>
<td>-3.45%</td>
<td>-3.11%</td>
<td>-3.22%</td>
<td>-3.11%</td>
<td>-4.95%</td>
<td>-0.46%</td>
</tr>
<tr>
<td>HDT (Non-Port)</td>
<td>-5.04%</td>
<td>-3.52%</td>
<td>-5.33%</td>
<td>-5.19%</td>
<td>-5.20%</td>
<td>-5.21%</td>
<td>-4.53%</td>
<td>-4.54%</td>
</tr>
<tr>
<td>HDT (Port)</td>
<td>-1.22%</td>
<td>-1.66%</td>
<td>-1.60%</td>
<td>-0.98%</td>
<td>-1.15%</td>
<td>-0.98%</td>
<td>-1.01%</td>
<td>-0.99%</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>-2.68%</td>
<td>-3.10%</td>
<td>-2.61%</td>
<td>-3.02%</td>
<td>-3.07%</td>
<td>-3.01%</td>
<td>-1.92%</td>
<td>-1.88%</td>
</tr>
</tbody>
</table>

To gain a better understanding of the temporal variation of pollutants throughout the day, eight graphs (one for each pollutant/energy) were created to compare the amount of pollutants emitted based on simulation scenario; they are shown on Figures 10 through 17. The base case is indicated by the blue line, the AM peak incident scenario is indicated by the orange line, and the PM peak incident scenario is denoted by the green line.
Figure 10. HC emissions in kg over a 24 hour period

Figure 11. CO emissions in tons over a 24 hour period
Figure 12. NO\textsubscript{X} emissions in kg over a 24 hour period

Figure 13. Atm. CO\textsubscript{2} emissions in tons over a 24 hour period
Figure 14. Energy emissions in GJ over a 24 hour period

Figure 15. CO₂ emissions in tons over a 24 hour period
The emissions graphs show a trend of increasing emissions in the hours following the incident in AM peak (as seen in the red line) and decreasing emissions in the PM peak (as seen in the green line). However, overall emissions over 24 hours decreased slightly as compared to
the base case in both scenarios. Accidents were simulated in the same direction for the northbound I-710. Therefore, these results may depend on existing traffic congestion patterns on the northbound traffic and show that incidents tend to have a greater effect to slow down traffic in the morning rush, rather than the afternoon rush. The increased traffic congestion as a result of the incident in the morning results in significantly slower traffic and increased emissions following the introduction of the incident. In the PM peak, when the freeway is already heavily congested, the introduction of an incident can create a bottleneck in which faster speeds than a non-incident scenario be obtained. This slight increase in average vehicle speed may explain the drop in emission estimations.
Chapter 5  Conclusions and Future Work

The purpose of this thesis was to explore and quantify the changes in air pollutant emissions following the introduction of a major truck accident on the northbound I-710 freeway in Los Angeles. A cursory review of the literature showed that there is no agreement in the literature about the impact of incidents on the emissions of various air pollutants. Some papers claim that incidents increase emissions due to reduced speeds and increased opportunities for acceleration, while others claim that incidents could reduce emissions due to increased speeds after incident zones.

To decide where to simulate accidents using vehicular microsimulation, accident data were obtained and classified based on four criteria: location, time of day, duration, and number of lanes blocked. Three simulations were conducted using the procedure outlined by Bhagat (2014). The first simulation was conducted with the original network created by Bhagat as the base case. The second simulated a major truck accident between the Florence Avenue and South Atlantic Boulevard off ramps that blocked the rightmost lane for 150ft during the AM peak hours of 7:00AM – 9:30AM. In order to best observe changes between the cases, the third simulated the same accident in the same location, but for the afternoon peak hours of 4:00PM – 6:30PM.

For each case, traffic performance results and emissions estimation were found. Traffic performance results show network performance measures such as vehicle counts, vehicle miles travelled, vehicle hours travelled, and average speed. The emissions estimation shows 7 common air pollutants: hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO\textsubscript{x}), atmospheric carbon dioxide (Atm. CO\textsubscript{2}), carbon dioxide equivalent (CO\textsubscript{2} Eq.), and particulate matter (PM\textsubscript{10} and PM\textsubscript{2.5}).
A review of the traffic performance results showed a slight increase in the average speed of vehicles in each vehicle class in the simulations with traffic incidents. This may be the result of cars speeding up after an incident in order to make up for lost time. The emissions estimations show a trend of increasing emissions in the hours following the incident in AM peak and decreasing emissions in the PM peak. All major calculated pollutants decreased with the introduction of an accident in the PM peak, as compared to a base case of no accident. This may be a result of major incidents having a greater effect of increasing emissions in the morning rather than when it occurs in the afternoon. Vehicular emissions decreased in both the AM peak incident and PM peak incident cases in all categories of pollutants except for a select few in the AM peak incident case of PM$_{10}$. Overall, the introduction of a single accident on an otherwise incident free network decreased the total amount of vehicular emissions in a microsimulation model. It can therefore be concluded that in this particular case, there is little to no identifiable increase in adverse health risk associated with major incidents during the peak traffic hours on the northbound I-710.

Future work could further explore the effects of incidents by simulating accidents under a variety of different scenarios and locations in order to affirm the conclusions that incidents decrease vehicular emissions. It could also be interesting to see traffic incidents conducted on a network that is not already known to be highly congested: the effects of the incident may be less pronounced when the network is already at a congested state.
Appendix

Accident Simulation

Accident simulation was conducted using the incident/work zone function native in TransModeler 4.0. Once an incident location is chosen, a distance can be measured on the desired path and will be depicted as a brown road block in all lanes. This creates the incident. Once the incident is created, the incident info button in the Incident/Workzone Manager Toolbox (seen below in Figure 18) can be used to select the incident and bring up the Segment Properties Toolbox (seen in Figure 19). In this toolbox, the segment location and duration can be edited.

Figure 18. Incident/Work Zone Manager Tool Box
Start position locations and numbers of lanes blocked can be edited through the Impact Across Lanes box. In this example, an accident which blocked one lane are simulated through the maximum speed cars could travel in that lane. While cars in lanes 1-3 can travel at a maximum speed of 65 miles per hour, cars in lane 4 can travel at a maximum of 0 miles per hour, which effectively stops the lane from being in use during the simulated accident time. The blocked lane causes the cars to gradually congest in that lane, and the effects can be seen in the travel speeds of the other lanes as well as the cars start to merge into the through lanes.
References


AirNow (2015) “Particle Pollution (PM)” Air Quality Basics. Source:
http://www.airnow.gov/index.cfm?action=aqibasics.particle


Caltrans (2005) “California Performance Measurement System (PeMS)” Source:
http://pems.dot.ca.gov/


“Environmental Impacts of a Major Freight Corridor – A Study of I-710 in California” Transportation Research Record: Journal of the Transportation Research Board (2123), pp. 119-128.


PierPass (2014) “Off-Peak Information” About PierPass. Source:
http://www.pierpass.org/offpeak-information/


