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# Geofencing as a Strategy to Lower Emissions in Disadvantaged Communities

## (CARB Agreement No. 17RD009)

## FINAL REPORT

**Prepared for:**

**California Air Resources Board**

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**December 2020**

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# Acknowledgements

The Research Team acknowledges the program support from CARB Contract Manager, Sarah Pittiglio, during the course of the project. The Research Team also thanks CARB staff and internal stakeholders for comments and feedback on the research.

This Report was submitted in fulfillment of Agreement No. 17RD009 “Geofencing as a Strategy to Lower Emissions in Disadvantaged Communities” by the University of California at Riverside under the sponsorship of the California Air Resources Board. Work was completed as of July 31, 2020.

# Table of Contents

# List of Tables

# List of Figures

# Executive Summary

The main objective of this research project was to identify and evaluate geofencing strategies in the heavy-duty truck sector that could lower pollutant emissions in disadvantaged communities (DACs) or other areas of poor air quality. For the purposes of this study, geofencing was defined as using a virtual boundary of a specific area within a broader geographic area where strategies can be triggered to reduce air pollutant emissions and adverse public health and environmental impacts. Such strategies can be triggered temporally and spatially. This Executive Summary discusses project results and the potential use of geofencing to achieve public policies established by the California Governor, Legislature and Air Resources Board related to air pollution control and improved public health.

The research consists of two major parts: 1) Literature Review, and 2) Case Study Modeling and Simulation Evaluation. Two study areas were chosen for the evaluation—East Los Angeles/Boyle Heights/West Commerce (ELABHWC) community and Wilmington/West Long Beach /Carson (WWLBC) community. Both communities are categorized as DACs by CalEnviroScreen and selected in 2018 to participate in the Community Air Protection Program under California law AB 617. In addition, the requisite data for each area was available for both travel demand modeling and air pollution/human exposure modeling. Community concerns in each area regarding local air quality have also well documented, and a number of air quality studies have verified disproportionate environmental justice impacts compared to many other communities in California.

### *Literature Review*

As noted above, one major part of the study was an extensive literature review of publications and reports pertaining to geofencing case studies and related transportation and/or air pollution modeling and impact studies. More than 100 such studies were reviewed to assess the state-of-the-science regarding various kinds of geofencing strategies, categorized into three groups—transportation network level, vehicle and driver level, and powertrain and emission control system level. Table E-1 provides a qualitative comparison of geofencing strategies reviewed in this report. The comparison was made in terms of technology readiness, ease of implementation (from political, institutional, legal, and operational perspectives), benefits (environmental, climate, and public health), and costs (for implementation and operation).

Several observations emerged from this review that were important from a policy perspective. First, the information confirmed that a wide variety of strategies fall under the umbrella of access restriction and pricing. These technical/implementation approaches include no drive zones, fees on high emission vehicles, both geographic and temporal controls, limitations on certain fuel types, required vehicle pollution controls, permits, preferred vehicle access, and others. Case studies and technical analyses clearly demonstrate that a variety of approaches have been successfully or could be successfully used around the world.

**Table E-1. Qualitative comparison of geofencing strategies reviewed in this research**

| Geofencing Strategies | Short Description | Technology Readiness | Ease of Implementation* | Benefits** | Costs*** |
|---|---|---|---|---|---|
| | ***Transportation Network Level*** | | | | |
| **Access Restriction and Pricing** | Require vehicles entering or operating in a DAC to meet certain emission requirements; otherwise, impose some fees | *High* | *Low* | *High* | *High* |
| **Designating Truck Routes** | Designate specific roadways in a DAC for trucks to use as primary travel routes | *High* | *High* | *Low* | *Low* |
| **Energy-, Emission-, or Exposure-based Routing** | Determine a travel route for a trip in a DAC that would minimize vehicle fuel consumption or emissions, or reduce human exposure to emissions from the vehicle, as compared to the shortest distance or shortest time route | *Medium* | *Medium to High* | *Medium* | *Low to Medium* |
| **Speed Management** | Manage vehicle speed when traveling in a DAC to reduce vehicle emissions through enforcement, speed governor, or speed advisory system | *High* | *High* | *Low to Medium* | *Low to Medium* |
| | ***Powertrain and Emission Control System Level*** | | | | |
| **Eco-Driving** | Encourage efficient driving inside a DAC | *High* | *High* | *Low to Medium* | *Low to Medium* |
| **Connected Eco-Driving** | Use real-time information from traffic signal inside a DAC to provide recommended driving speed for more efficient driving | *Medium* | *Medium* | *Medium* | *Low to Medium* |
| | ***Vehicle and Driver Level*** | | | | |
| **Engine Management** | Adjust engine parameter settings to reduce engine-out emissions when the vehicle operates inside a DAC | *Medium* | *Low to Medium* | *Medium to High* | *Medium* |
| **Hybrid Energy Management** | Operate hybrid or plug-in hybrid electric vehicles in the all-electric mode inside a DAC | *High* | *Medium to High* | *Medium to High* | *Low to Medium* |
| **Emission Control Management** | Adjust emission control system settings to further reduce tailpipe emissions when the vehicle operates inside a DAC | *High* | *Low to Medium* | *Medium to High* | *Medium* |

** From political, institutional, legal, and operational perspectives*
*** Environmental, climate, and public health benefits*
*** Implementation and operation costs*

Relative to the United States, including California, there has been more limited use of these approaches to date. The recent use of hybrid diesel electric buses in downtown San Francisco which run on electricity in high impact areas and diesel fuel elsewhere is one such example. High-occupancy lane access for low emission vehicles is another example that has been widely used in California. The ports of Los Angeles and Long

Beach's Clean Trucks Programs, which limit marine terminal access to lower emitting trucks and provides an air quality benefit to the people working in the ports and to the surrounding community, are yet another example. The bottom line, similar to many other pollution control approaches, is that one size does not necessarily fit all. In other words, the geofencing approach needs to be tailored to the specific characteristics of the community, need, compliance with existing laws, vehicle type and duty cycle, public health and environmental impacts, equity and economics, technology feasibility and practicability, public acceptance and politics, possible conflicts or synergistic effects with other public policies, to mention a few. The normal process of consultation with stakeholders and establishing a formal advisory group is thus recommended.

Nonetheless, the fact is that geofencing has been successfully implemented under a variety of circumstances in the past, and new opportunities will arise from ongoing changes in technology. Therefore, an action should be taken to establish a more formal role for geofencing strategies in some of California's premier efforts to reduce local and regional air pollution such as AB 617 community air quality plans, reducing air toxics exposure, achieving federal and state clean air standards, and achieving greenhouse gas reduction targets.

### *Case Study Modeling and Simulation Evaluation*

The modeling and simulation evaluation of two selected geofencing strategies was conducted to demonstrate their potential in reducing truck emissions and their impacts inside DACs. One is the emission-based pricing strategy implemented in the ELABHWC community where a $10 emission fee is collected from heavy heavy-duty trucks (HHDTs) that do not meet the 2007 emission standards (model years 2009 and older) when they enter the community, which is considered to be a low emission zone (LEZ), shown in Figure E-1. Under the modeling scopes and assumptions used in this research, the effect of the emission fee was found to be significant. It diverted 7% of the 11% pass through HHDTs of model years 2009 and older away from the LEZ.

Figure E-2 shows the changes in emissions from all HHDTs as a result of the emission fee implementation. According to the figure, the emission fee resulted in reductions in fine particles (PM2.5), oxides of nitrogen (NOx), and carbon dioxide (CO2) emissions from HHDTs inside the LEZ by 38%, 37%, and 25%, respectively. On the other hand, the emission fee resulted in emission increases in the areas outside of 5-mile radius from the center of the LEZ, but those emission increases were no more than 6%. Lastly, it was found that the emission fee had minimal impacts on the total emissions in the modeling area. The total NOx and CO2 emissions remained unchanged, while the total PM2.5 emission increased by 1%. These results demonstrate a potential for the emission-based pricing strategy to reduce truck emissions inside DACs with minimal impact on the regional emission inventory. Nonetheless, any issues of equity arising between communities should be addressed through, for instance, AB617 implementation, air quality management plans, and other policy mechanisms.

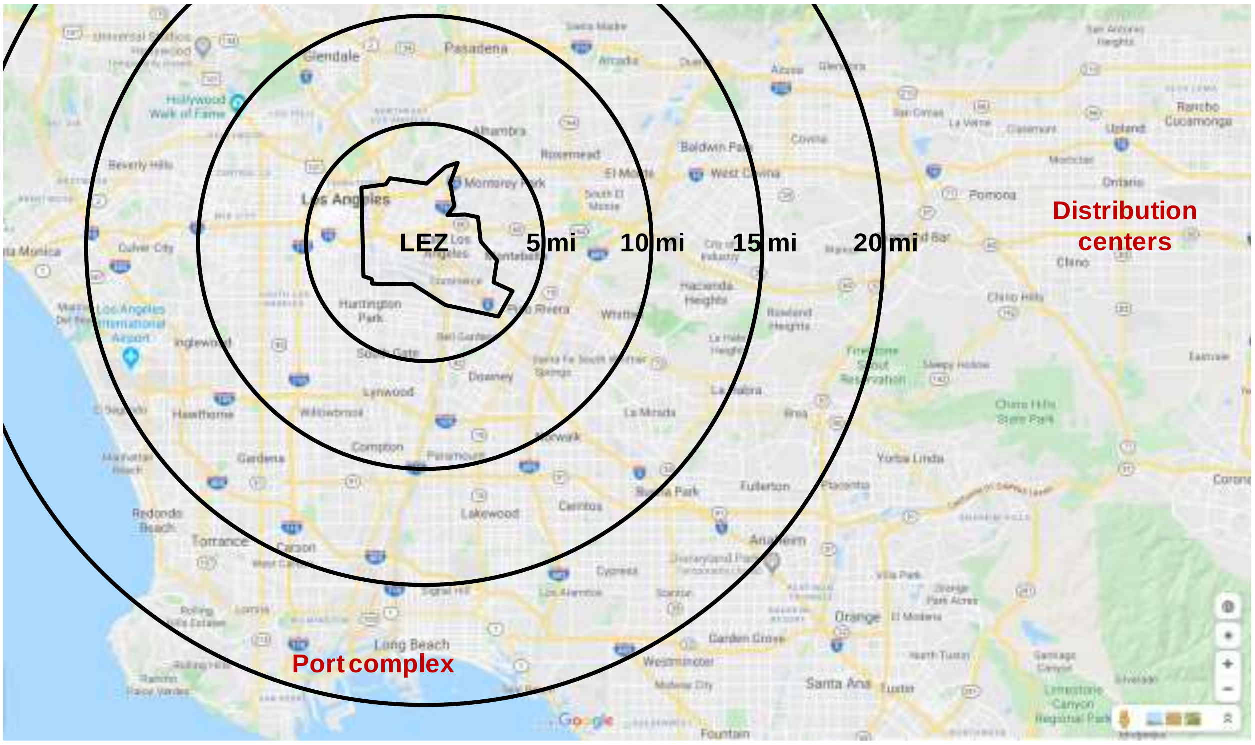



**Figure E-1. Boundary of low emission zone and impact analysis areas**

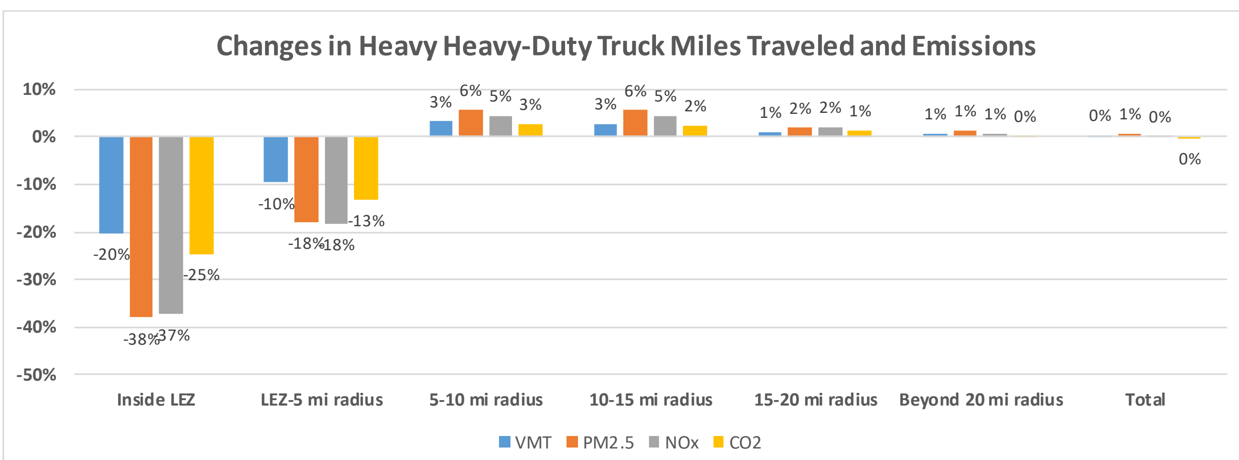



**Figure E-2. Changes in HHDT miles traveled and emissions due to emission fee implementation**

Another modeling and simulation evaluation effort was made on the exposure-based routing strategy where a HHDT is navigated through a DAC in a way that lowers the total exposure of community members to the pollutant emissions from the truck without significantly increasing travel time. This low exposure route can change dynamically depending on traffic and meteorological conditions, spatiotemporal distribution of population, and other factors. The evaluation was conducted for two case study areas—the ELABHWC community and the city of Carson, CA—and two times of day—10 A.M. and 10 P.M. on May 9, 2016. The results showed that for some trips, the route that a truck driver would normally take or the baseline route is already the low exposure route. For other trips, the low exposure route is different from the baseline route, and there are tradeoffs among the different route attributes (trip distance, trip time, tailpipe CO2 emission, and human exposure to PM2.5 and NOx emissions) between the two route options. Figure E-3 shows these tradeoffs for an example trip in Carson.

Among the trips whose low exposure route is different from the baseline route, those with a slightly longer trip time are considered to be attractive. For these trips, the truck drivers should be encouraged to take the low exposure route. Figure E-4 shows route attribute comparison for the trips where the low exposure route would take no more than 10% longer trip time. For the four scenarios evaluated in this research, approximately 13% to 23% of all the trips fall into this category.


| | 10 A.M. | | | 10 P.M. | | |
|---|---|---|---|---|---|---|
| | BR | LER | % Diff. | BR | LER | % Diff. |
| Trip Distance (miles) | 11.9 | 9.3 | -22% | 11.9 | 8.7 | -27% |
| Trip Time (minutes) | 16.4 | 17.0 | 4% | 15.9 | 17.6 | 11% |
| Inhaled Mass of PM2.5 (µg) | 0.3 | 0.1 | -73% | 3.7 | 0.9 | -77% |
| Inhaled Mass of NOx (µg) | 29.9 | 20.6 | -31% | 369.0 | 205.7 | -44% |
| Tailpipe emission of CO2 (kg) | 17.6 | 15.9 | -9% | 17.4 | 15.5 | -11% |

**Figure E-3. Comparison of baseline route and low exposure route for an example trip in Carson, CA, on May 9, 2016, at 10 A.M. (left) and 10 P.M. (right)**

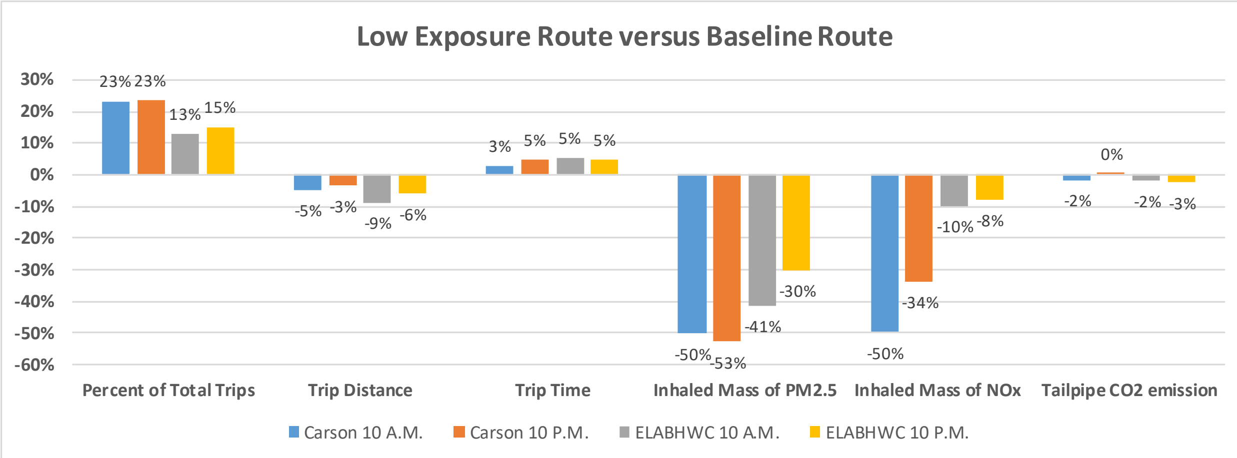



**Figure E-4. Route attribute comparison for trips with attractive low exposure route**

According to Figure E-4, for the 10 A.M. scenario in Carson, a low exposure route with up to 10% longer trip time was found in 257 out of 1,100 simulated trips (23%). On average, the low exposure route for these trips would have 3% longer trip time as compared to the baseline route, but it would reduce the amount of PM2.5 and NOx emissions from the truck that would be inhaled by community members by 50% and 50%, respectively. In addition, the low exposure route would also reduce tailpipe CO2 emission from the truck by 2% on average. Similar results were observed in the 10 P.M. scenario in Carson. On the other hand, the results for trips in ELABHWC were quite different from those for trips in Carson. These results imply that the effectiveness of the exposure-based routing strategy varies by community and time of day. It is more likely to be able to find a low exposure route for the trip in, for example, a community that has more route options for the truck, a community where sensitive facilities and dense residential neighborhoods are far away from major roadways, and a community where truck trip attractions are not located near where people live, work, and play. Nevertheless, the results presented in this report demonstrate a potential for the exposure-based routing strategy to help mitigate the impacts of truck emissions on DACs, either in conjunction with or independent of the emission-based pricing strategy.

### *Pathways toward Implementation*

California maintains a leadership role in environmental management on many fronts, including air pollution control, climate change, environmental justice/equity, and piloting of innovative technologies, policies and programs. Nonetheless, California must redouble its efforts to achieve federal and state clean air standards, reduce greenhouse gas emissions, and reduce disproportionate impacts, which occur predominantly in low income communities and communities of color. Mobile source emissions continue to be a very large source of pollutant impacts on the breathing public and a contributor to climate change. Geofencing strategies provide an array of additional opportunities to reduce pollutant emissions and population exposure to harmful air contaminants. This section of the report makes specific recommendations pertaining to research, policy development, and policy implementation to expedite the further inclusion of geofencing strategies in California's air pollution and climate change programs. While this research project is focused on heavy-duty trucks, the approaches identified could be applied to other vehicle categories. Recommendations for moving toward implementing geofencing strategies are given in Table E-2.

**Table E-2. Recommendations for moving toward implementing geofencing strategies**

| Level | Recommendations |
|---|---|
| **Strategic** | • Initiate parallel tracks of research, policy development and adoption, and implementation.<br>• Strengthen efforts to improve modeling and evaluation methods, including development of guidelines for assessing impacts of geofencing strategies. This should include recommended data sources, calculation methods, models, and desired outputs (e.g., environmental, health, economic, equity, mobility, etc.) for formal policymaking. Development and approval of guidelines should be done through an open and participatory process.<br>• Identification of priority needs to facilitate analysis that raises research approaches to the standards required for use in policy setting by legislative bodies, regulatory agencies, and local government.<br>• Initiate a process to screen geofencing strategies for applicability to CARB's policy programs and readiness for adoption. Place appropriate measures in the California motor vehicle control strategy and CARB's various existing plans and strategies. Make appropriate recommendations for other state agency inclusion in their policies and that of local governments.<br>• Establish demonstration projects for emerging technologies or groups of technologies associated with geofencing that provide new tools for meeting California's air quality, climate change, and equity/environmental justice objectives. Prioritize such projects and locate as appropriate in DACs.<br>• Establish stakeholder engagement plans for above activities, share this research information with DACs and other stakeholders, gather feedback, and implement actions to foster success. |
| **Tactical** | • Identify a model community for pilot implementation.<br>• Conduct transportation-related air pollution audits and determine appropriate geofencing strategies for the model community.<br>• Engage with stakeholders such as community-based organizations, truck fleets and independent owner operators, local governments early in the process.<br>• Prioritize the use of incentives over regulations, and try to be revenue-neutral.<br>• Start with something simple and predictable to maximize buy-ins from stakeholders.<br>• Explore creative ways for implementation, for example:<br>  ○ State level - Through California Environmental Quality Act or State Implementation Plan<br>  ○ Regional level - Through air quality management plans<br>  ○ Local level - Through general plan elements or ordinances |

| | |
|---|---|
| | • Align the timeline with the timelines of other programs and regulations, such as Heavy-Duty Omnibus and Advanced Clean Trucks regulations. |
| **Operational** | • Designate or update truck routes in the model community by explicitly taking into account human exposure to truck emissions.<br><br>• Pilot three geofencing strategies in an integrated fashion:<br>o Emission-based pricing – Assess an emission fee on trucks of older model years upon entry to the community.<br>o Exposure-based routing – Waive the emission fee if the truck opts in and uses a low exposure route.<br>o Connected eco-driving – Equip traffic signals along truck routes and provide trucks that opt in with free access to connected eco-driving application.<br><br>• Create a Win-Win-Win situation for all stakeholders.<br>o Community – Experience reduced truck emissions and reduced exposure to these emissions inside the community.<br>o Agency – Use the collected fees to fully (or partially) pay for the implementation costs, and improve public health.<br>o Truck fleets and independent owner operators – Can claim part of the fees paid earlier as credits toward purchasing/leasing cleaner trucks that are not subject to the emission fee. |

# 1. Introduction

## 1.1. Background

Medium- and heavy-duty diesel trucks, the majority of which are used for freight movement, are significant contributors of nitrogen oxides (NOx) and particulate matter (PM) emissions in California. As a result, areas close to freight hubs such as ports, railyards, and distribution centers often experience elevated levels of diesel-related air pollution. There has been increasing awareness of this environmental justice issue, which has led to the designation of disadvantaged communities (DACs) in California per Senate Bill 535. These communities are now specifically targeted for investments aimed at improving public health, quality of life, and economic opportunity of their residents per Assembly Bill 1550. Figure 1-1 shows the map of DACs in Southern California.

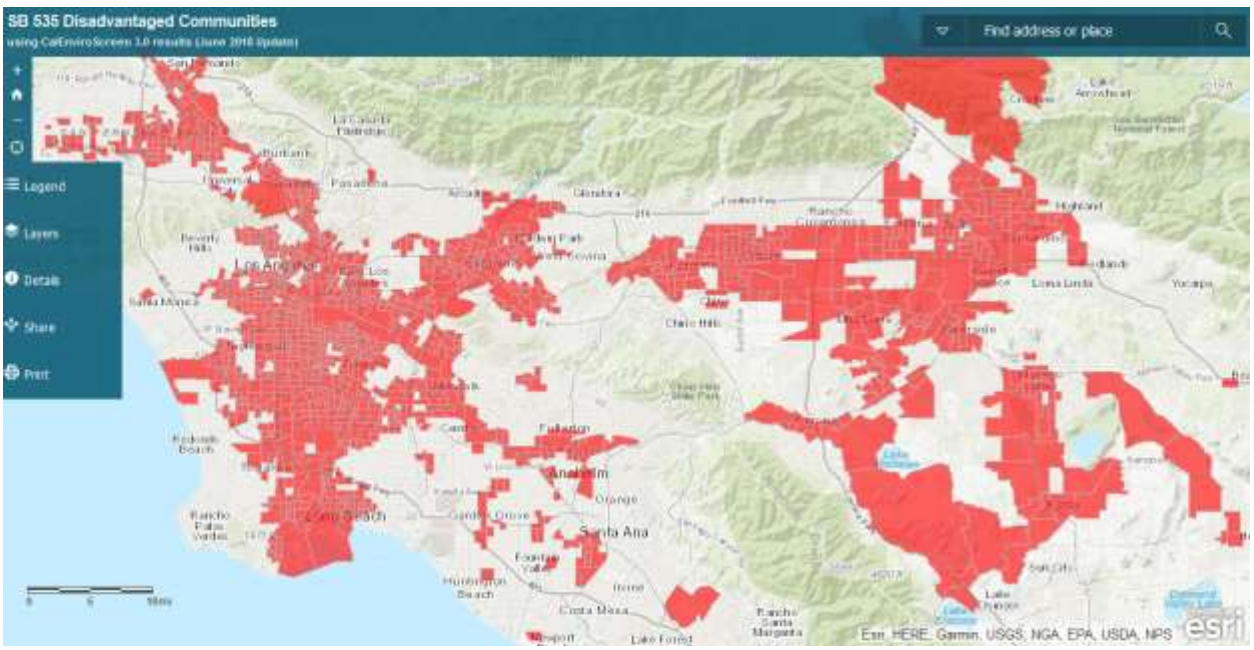



Figure 1-1. Map of disadvantaged communities in Southern California

While the levels of fine particles (PM2.5) have been decreasing in many parts of California, especially in the most impacted communities, the disparity between the levels of PM2.5 in the most and the least DACs still persists. Thus, research is needed to identify and monitor sources of PM2.5 emission in DACs, as well as to develop strategies that can reduce exposure to traffic-related PM2.5 emission in those DACs. "Geofencing" is a promising new approach for reducing such exposure. It defines a virtual boundary of a specific area within a broader geographic area. The main idea is that when a vehicle enters a pre-defined "geofenced" area, its operation will be modified in a way that lowers its emissions in the geofenced area. In a broader sense, geofencing strategies can be applied not only spatially within a geofenced area, but also temporally, i.e, during specific time periods.

Geofencing strategies can be designed to achieve different objectives. It is important to understand their differences.

1. ***Reduce tailpipe emissions*****:** This set of strategies aims to reduce tailpipe emissions from the vehicle while it is within the geofenced area. This is the most basic objective of any geofencing strategy.

2. ***Reduce pollutant concentration*****:** This set of strategies aim to reduce the level of air pollutant concentration in the geofenced area by taking into consideration how the tailpipe emissions disperse in the area. To achieve this objective, the vehicle's operation outside but upwind of the geofenced area will also need to be considered. The development and implementation of these strategies will involve the use of air dispersion modeling. The determination of the level of air pollutant concentration in the geofenced area will be based on one or more receptors located in the geofenced area.

3. ***Reduce population exposure*****:** This set of strategies aim to reduce the exposure of a target population in the geofenced area to air pollutants from the vehicle. The target population may be all residents in the area or sensitive groups such as children, the elderly, and at-risk patients. To achieve this objective, these strategies will have to take into account the locations of sensitive sites (e.g., daycare centers, schools, hospitals) and space-time activity patterns of the target population in the geofenced area, which may change throughout the day.

4. ***Reduce fuel consumption*****:** This set of strategies aim to reduce fuel use (and greenhouse gas emissions) from the vehicle while it is outside the geofenced area. This objective is geared towards benefiting the vehicle or fleet owner. It can be used in conjunction with any of the first three objectives in order to achieve a balance between economic and public health goals.

For any one of the objectives described above, geofencing strategies can be developed and applied at many levels as described below.

1. ***Transportation system level*****:** These strategies involve modifications to how the vehicle operates in the transportation network. Example strategies at this level are:

    a. *Access restriction and pricing* - Limit entry into the geofenced area or impose a fee when the vehicle is operated in the geofenced area. The fee can be per entry, per unit distance traveled, or per unit mass of emissions emitted in the geofenced area, etc.

    b. *Routing* - Recommend a specific travel route for the vehicle to get from an origin to a destination. Routing strategies can be designed to achieve any of the four objectives above to minimize the vehicle's impacts on the geofenced area. They can be designed to minimize a specific pollutant emission (e.g., PM2.5) or a combination of multiple pollutant emissions.

   c. *Speed management* - Impose a lower speed limit inside the geofenced area. It also includes the use of advanced traffic management techniques such as intelligent speed adaptation and speed harmonization with a focus on reducing vehicle emissions.

2. ***Vehicle and driver level*:** These strategies involve modifications to how the vehicle operates on a specific roadway inside the geofenced area, either through driver input or through automation. Example strategies at this level include:

   a. *Eco-driving* - Include a wide range of driving techniques for reducing fuel consumption and emissions, such as keeping constant speed, accelerating and braking mildly, etc.

   b. *Connected eco-driving* - Take advantage of connected vehicle technology to apply more advanced eco-driving techniques around signalized intersections.

3. ***Powertrain and emission control system level*:** These strategies involve modifications to how the vehicle powertrain and emission control system operate at any point in time, usually without driver input. Example strategies at this level include:

   a. *Real-time engine management* - Calibrate the engine dynamically based on location (e.g., when inside vs. outside the geofenced area) and time (e.g., during peak vs. offpeak hours) to reduce engine-out emissions.

   b. *Real-time aftertreatment management* - Tune the emission control systems (e.g., selective catalytic reduction and diesel particulate filter) dynamically based on location (e.g., while inside vs. outside the geofenced area) and time (e.g., during peak vs. offpeak hours) to reduce tailpipe emissions.

   c. *Real-time hybrid energy management* - Have hybrid electric vehicles (HEVs) and plugin-hybrid electric vehicles (PHEVs) operate in the all-electric mode while inside the geofenced area.

## 1.2. Scopes and Objective

The objective of this research is to identify and evaluate geofencing strategies in the heavy-duty sector that could lower emissions in DACs or other areas of poor air quality, for all the time or during specific time periods. The results from this research will provide important information that could be used to inform the development of geofencing technologies by the industry, as well as the development of incentive or regulatory policies by regulatory agencies, that reduce pollutant emissions in DACs.

To achieve the research objective, the research team examined the potential for geofencing strategies to reduce criteria pollutant and greenhouse gas emissions in DACs. The estimation of emission impacts was performed through modeling and simulation of selected geofencing strategies using existing emission data. The modeling and simulation of geofencing strategies was conducted for selected DACs in California that are subject to high levels of exposure to pollutant emissions from medium- and heavy-duty diesel trucks as identified through CalEnviroScreen 3.0[1], and thus, are good candidates for geofencing strategies. The estimation of emission impacts was focused on NOx and PM2.5 emissions as medium- and heavy-duty diesel trucks—the main targets of geofencing strategies in this research—are significant contributors of these emissions. NOx is also a precursor of tropospheric ozone and secondary PM, for which many areas in California are in nonattainment.

## 1.3. Report Organization

This report presents every aspect of the research activities that have been conducted during the course of the project. It is organized as follows:

- Chapter 2 describes the different geofencing strategies in more detail, and summarizes available information on criteria pollutant and greenhouse gas emission reductions associated with the geofencing strategies.

- Chapter 3 explains the modeling and simulation of selected geofencing strategies in selected case study communities, and presents the results.

- Chapter 4 discusses key findings and policy implications from the modeling and simulation results, suggests pathways toward implementation of the geofencing strategies, and recommends future research directions.

- In addition, Appendix A provides a summary of key information from the review of various geofencing strategies in the literature.

[1] https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30

# 2. Review of Geofencing Strategies

This chapter describes the different geofencing strategies mentioned in Chapter 1 in more detail, and summarizes available information on criteria pollutant and greenhouse gas emission reductions associated with the geofencing strategies. In addition, a summary of key information from the review of various geofencing strategies in the literature is given in Appendix A.

## 2.1. Transportation Network Level

### 2.1.1. Access Restriction and Pricing

A variety of access restriction and pricing schemes have been used around the world to limit excessing number of vehicles or restrict certain types of vehicles from entering a designated area to address traffic congestion, air pollution, and other issues in the area. The most common ones are congestion pricing schemes and low emission zones (LEZs). Congestion pricing schemes charge a fee or toll for a vehicle to enter a designated area such as city center. They are implemented primarily to reduce traffic congestion in the area, but they can also help address other issues such as air quality and noise. Some of the well-known congestion pricing schemes are those in London, U.K. and Stockholm, Sweden. In March 2019, New York became the first city in the U.S. to approve congestion pricing[2]. In California, there has been interest in congestion pricing as well. A recent feasibility study estimated that charging a $4 fee during rush hour to enter a zone in West Los Angeles would reduce traffic and greenhouse gas emissions by about 20% [Southern California Association of Governments, 2019]. In addition, another feasibility study of congestion pricing in Los Angeles is being conducted [Transport Topics, 2019].

On the other hand, LEZs are focused primarily on reducing air pollution in the area. Typically, vehicles with high emissions are not allowed to enter a LEZ or will have to pay a fee to enter. LEZs have been implemented around the world, but most notably in Europe where there are about 250 LEZs in different cities [McGrath 2019]. Some of the LEZs in Europe are shown on the map in Figure 2-1. These LEZs vary widely in many aspects such as geographic coverage, vehicle types restricted, required emission standards, period (time/day/month) when LEZ is in effect, entry fee and fine, enforcement, among others. The Urban Access Regulations in Europe website[3] compiles detailed information about LEZs and other access restrictions in a number of European cities. One of the largest LEZs in Europe (and the world) is the London LEZ, which has become increasingly stricter (in terms of both emission requirements and vehicle types restricted) since 2008 (Table 2-1). London turned part of its LEZ into Ultra Low Emission Zone (ULEZ) in April 2019; see Figure 2-2.

[2] https://en.wikipedia.org/wiki/Congestion_pricing_in_New_York_City
[3] https://urbanaccessregulations.eu/

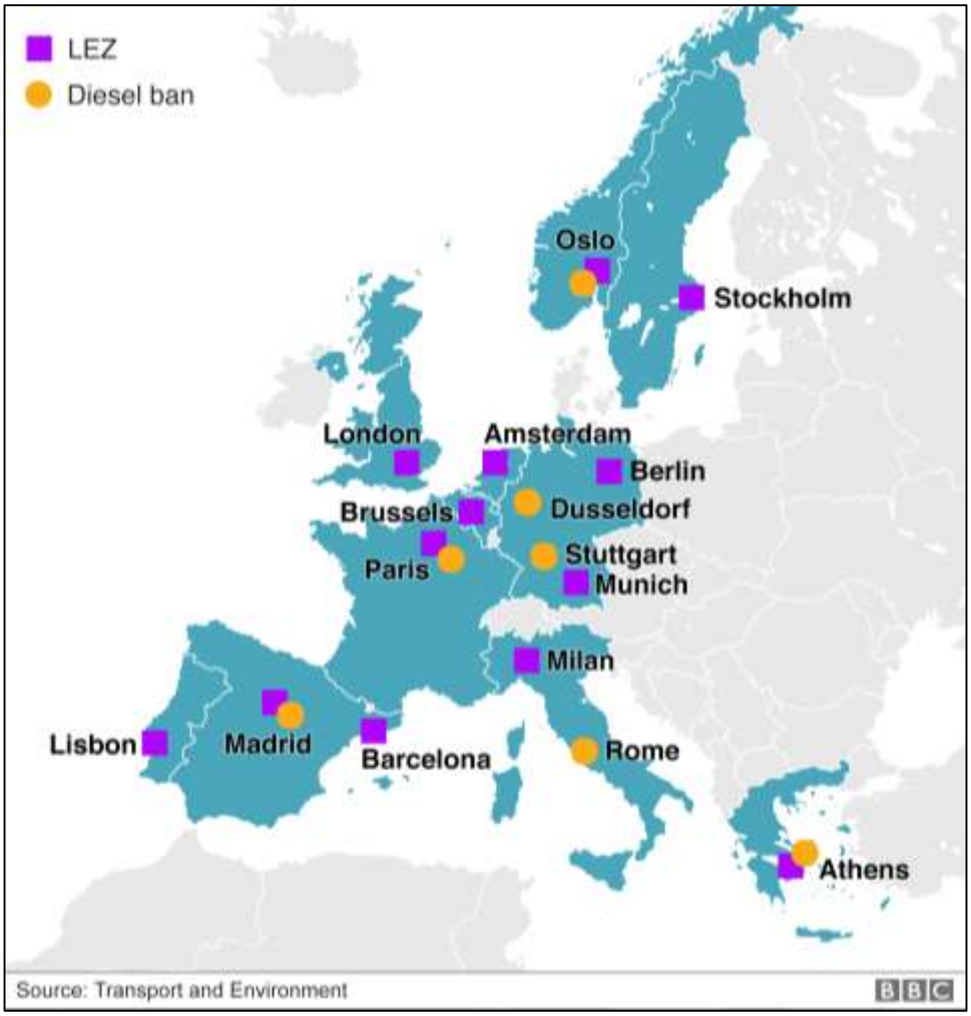



**Figure 2-1. Map of low emission zones in Europe.**

**Table 2-1. Progression of low emission zone in London, U.K.**

| Phase | Date introduced | Vehicles restricted | Gross vehicle weight (GVW) (tonnes) | Minimum emission standard[a] |
|---|---|---|---|---|
| 1 | 4 Feb 2008 | Heavy goods vehicles (HGVs) | >12 t | Euro III for PM |
| 2 | 7 July 2008 | HGVs | >3.5 t | |
| 3 | 3 Jan 2012 | Large vans | 1.205 (unladen) – 3.5 t (GWV) | Euro III |
| | | 4 × 4 light utility vehicles | | |
| | | Motorised horseboxes | | |
| | | Pickups | | |
| | | Ambulances | 2.5–3.5 t | |
| | | Motor caravans | | |
| | | Minibuses (>8 passengers) | ≤5 t | |
| 4 | 3 Jan 2012 | HGVs | >3.5 t | Euro III |
| | | Buses, coaches | >5 t | |
| 5 | Dec 2015 | Buses operated by Transport for London | | Euro IV |
| 6 | Planned for 2020 | All vehicles. This ultra-low emissions zone is currently under development, and may apply just within the 22 km$^2$ of the London Congestion Charging Zone in Central London, and for restricted hours. | All vehicles | Euro 6/VI (?) |

Euro III and Euro IV standards were mandated for all vehicles first registered after October 2001 and 2005 respectively.
[a] Or fitted with a diesel particle filter with a Reduced Pollution Certificate.

Source: [Holman et al., 2015]


Source: Transport for London

**Figure 2-2. Low emission zones in London, U.K.**

There have been many studies that evaluated the impact of LEZs, either through modeling or measurement. For example, the evaluation of the ULEZ in central London after six months showed that CO2 and NOx emissions from motor vehicles inside the zone decreased by 4% and 31%, respectively, as compared to if the ULEZ was not in place. The reduction in NOx emission also helped contribute to the drop in nitrogen dioxide (NO2) concentration by 29% as measured before and after the implementation of the ULEZ [Greater London Authority, 2019].

In the U.S. and specifically in California, the emission-based access restriction and pricing strategy has been implemented at the ports of Los Angeles and Long Beach. First began in 2008, the Clean Trucks Programs at both ports banned pre-1989 trucks followed by a progressive ban on all trucks that did not meet the 2007 emission standards for heavy-duty diesel engines by 2012. During the phase-in period from 2009 to 2011, a $35 per loaded 20-foot equivalent unit (TEU) container fee was assessed for container moves by trucks that did not meet the 2007 emission standards. The collected fees were used to administer the Clean Trucks Programs and provide incentives for the purchase of trucks meeting the 2007 emission standards. When the Clean Trucks Program was fully implemented in 2012, port truck emissions were estimated to reduce by more than 90% [Port of Los Angeles, 2020].

The Clean Trucks Programs at both ports have continued to be updated. Starting on October 1, 2018, any new trucks registered in the Port Drayage Truck Registry (for entering marine terminals to pick up and/or drop off containers) must be of model year

2014 or newer. Existing trucks that are already registered as of September 30, 2018, are allowed to continue to operate. Recently, the Clean Trucks Programs were further updated to establish a Clean Truck Fund (CTF) rate that will be charged to the beneficial cargo owners for loaded containers hauled by trucks that enter or exit the ports' marine terminals, with exemptions for zero emission trucks and trucks that meet the California Air Resources Board (CARB)'s heavy-duty low NOx standards. A CTF rate of $10 per loaded TEU is being considered, which would initially generate approximately $90 million per year. These funds will be used to administer the program and provide incentives for the purchase of low NOx and zero emission trucks to service the ports, and potentially to support charging and/or fueling infrastructure [Port of Los Angeles and Port of Long Beach, 2020].

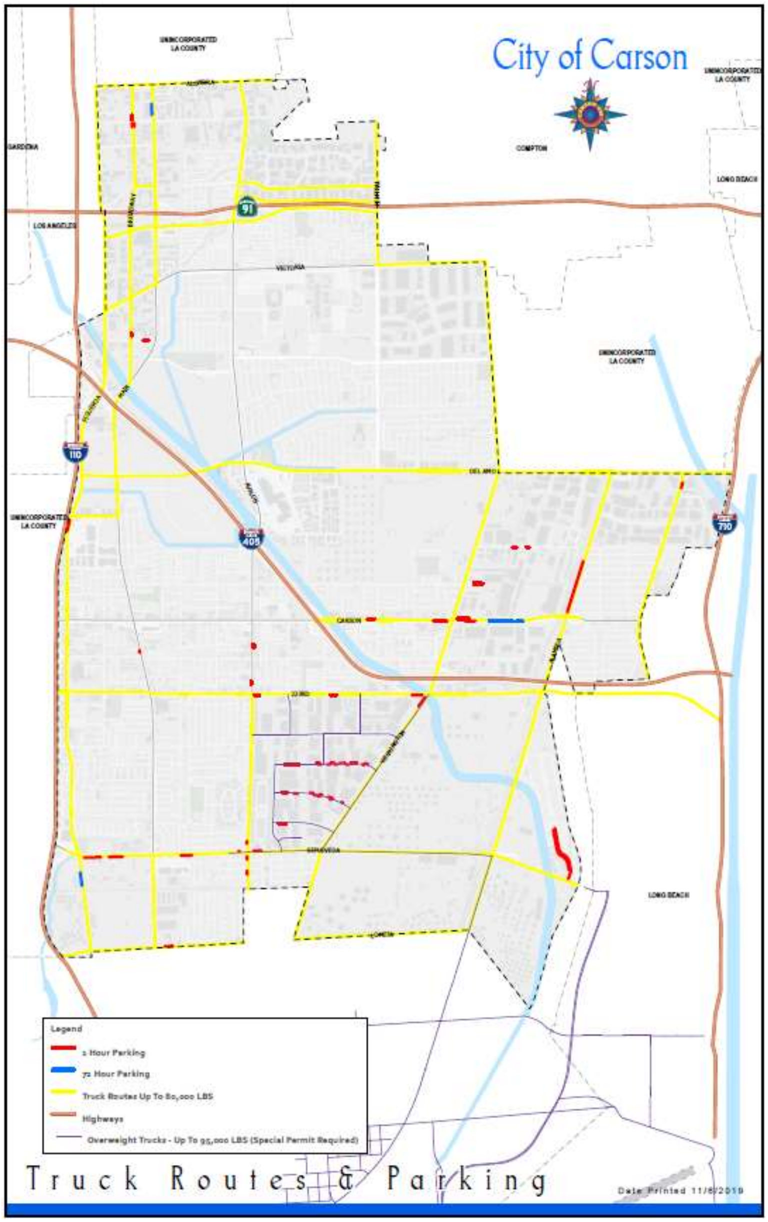
### 2.1.2. Routing

#### *Truck Routes*

Routing is a major strategy for managing truck traffic in communities. Many cities have designated truck routes for carrying commercial vehicles between the highways and commercial zones in the city. As an example, Figure 2-3 shows the map of truck routes in City of Carson, CA. The designation of truck routes typically takes into account road type, available right-of-way, traffic volume, clearance, safety, among others. Cities also often avoid routing trucks through residential zones due to concerns regarding traffic safety as well as air and noise pollution. Nevertheless, as land use, population, and truck traffic pattern in the area evolve, these concerns may re-emerge and truck routes may need to be updated to mitigate the impacts of truck traffic. For example, a re-routing of truck traffic in the Barrio Logan community in San Diego, CA, was estimated to reduce vehicle miles traveled (VMT) of heavy-duty diesel trucks along the previously affected corridor by 87% and PM emissions by 99% [Karner et al., 2009].

#### *Energy-Based Routing*

From the truck driver perspective, routing involves determining a specific travel route to take from an origin (e.g., the current location) to a destination (e.g., delivery location). Over the past several years, there has been proliferation of navigation systems in multiple platforms to assist truck drivers with that task. Some navigation systems can take truck-specific restrictions such as truck routes and clearance into consideration. These navigation systems primarily find the shortest distance or shortest time route between an origin and a destination. It is commonly assumed that taking either of these routes will also result in minimum fuel consumption and emissions from the vehicle. However, there are several cases where this may not be true. A shortest distance route may include roadway sections with steep road grades, requiring more energy for the vehicle to climb the hills while producing more emissions in the process. The route may also have the vehicle travel through heavily congested roadways, resulting in longer travel time and more fuel consumption and emissions. A shortest time route may have the vehicle travel longer distance, albeit on less congested roadways. Traveling at high speeds for longer distance will result in higher fuel consumption (and emissions) compared to a more direct route at lower speeds. This is especially true for heavy-duty trucks whose power-to-weight ratio is low.




Source: City of Carson

**Figure 2-3. Truck routes in City of Carson, CA**

Over the last decade, there has been much research and development on new routing techniques for navigation systems. Instead of finding the shortest distance or shortest time route for the trip, these new routing techniques are aimed at finding the route that would minimize vehicle energy consumption and/or emissions. These so-called "eco-routing" techniques were focused initially on energy consumption and mostly on light-duty passenger vehicles [Boriboonsomsin et al., 2012; Boriboonsomsin et al., 2014]. Figure 2-4 shows an example eco-routing application that displays multiple route options—shortest distance (blue), shortest time (purple), and least fuel consumption (green)—for a trip from Los Angeles Airport to Downton Los Angeles.


Source: [Boriboonsomsin et al., 2012]

**Figure 2-4. Eco-routing application**

Eco-routing techniques have also been applied to other types of vehicle including heavy-duty trucks. For instance, Scora et al. [2015] developed an eco-routing application for heavy-duty diesel trucks and evaluated the least fuel consumption route against the shortest time route for more than 500,000 simulated trips in the Greater Los Angeles Metropolitan Area. It was found that, as compared to the shortest time, the least fuel consumption route would require 4% to 33% less fuel, but would increase travel time by 6% to 53%. By converting fuel and travel time into monetary values, it was found that the least fuel consumption route would result in net dollar savings for about 50% of the simulated trips. Based on this finding, it was suggested that eco-routing could be beneficial to truck drivers and fleet operators. They can choose to use the fuel-optimized route for those trips where the fuel savings justify the extra travel time.

### *Emission-Based Routing*

Eco-routing techniques are also aimed at finding the route that would minimize vehicle emissions. Note that the least fuel consumption route is also the least CO2 emission route. However, this may not be true for other pollutant emissions. The reason is that different emissions have different relationships with travel speed, such as those shown in Figure 2-5, which are obtained from CARB's EMFAC2017 model. Based on these emission curves, the least CO2 emission route would prefer roads with prevailing speeds around 50 mph whereas the least PM2.5 emission route would prioritize roads with prevailing speeds around 25 mph.

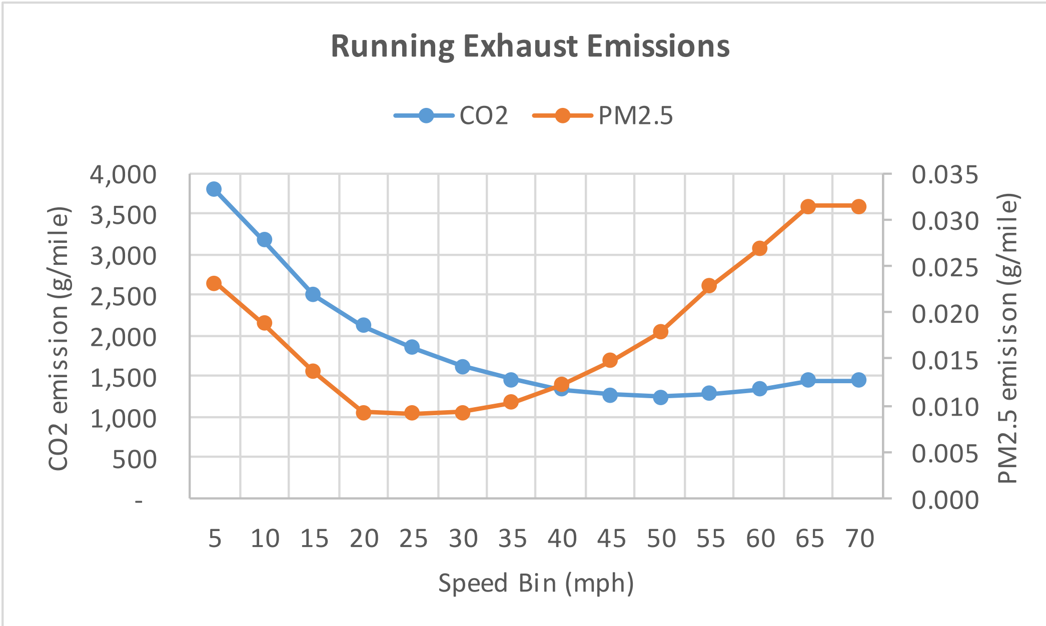



**Figure 2-5. Running exhaust emissions of model years 2010-2017 heavy-duty diesel trucks**

Compared to energy- or fuel-based routing, less attention has been given to emission-based routing, especially for pollutant emissions. This may be because while fuel cost accounts for about 20-25% of total operating cost of commercial trucking [Hooper and Murray, 2018], there is currently no incentive for truck drivers and fleet operators to reduce pollutant emission through routing. Nevertheless, a recent study by Scora et al. [2019] investigated the effect of route choice on NOx emission of heavy-duty diesel trucks through real-world experiments. In each experiment, two identical model year 2014 heavy-duty diesel trucks left the same origin at the same time but took different routes to the same destination (see Figure 2-6). A total of four experiments were conducted and their results are shown in Table 2-2.

Source: [Scora et al., 2019]

**Figure 2-6. Two identical trucks taking two different routes from Ontario, CA to Vernon, CA**

**Table 2-2. Comparison of two alternative routes taken by heavy-duty diesel trucks for the same trips**

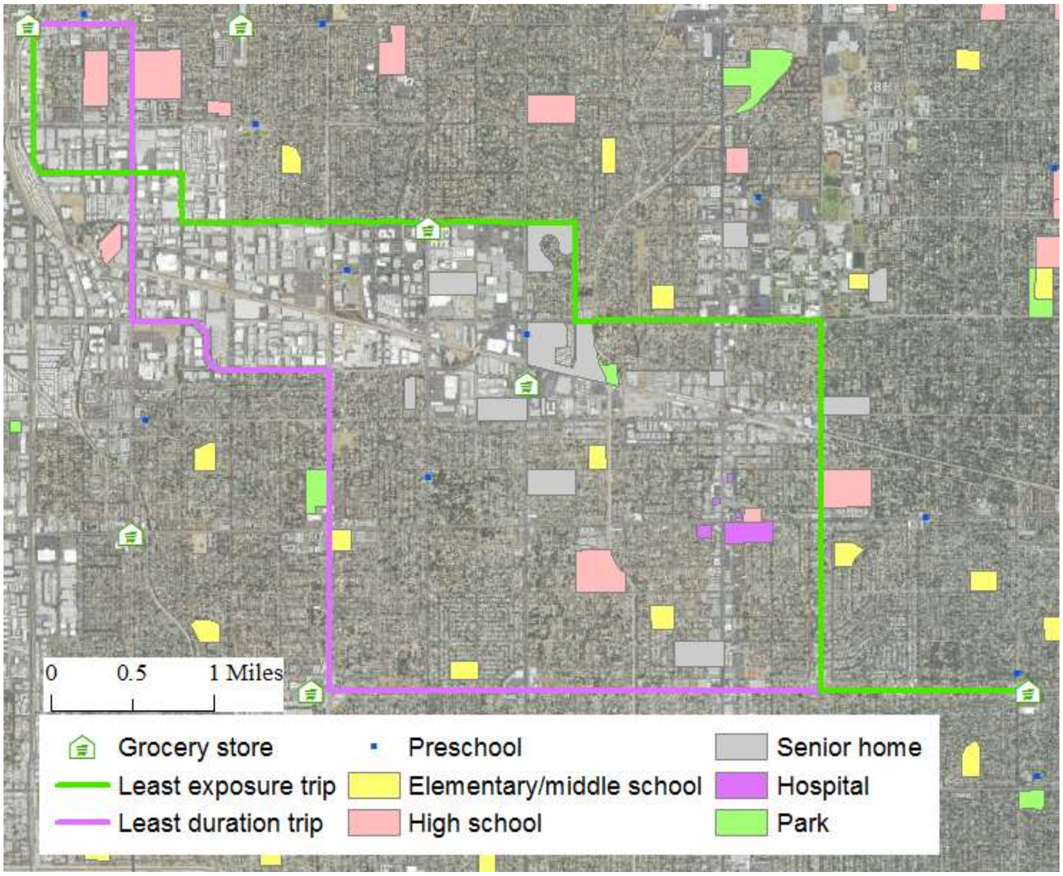
| Trip | Route | Location | Duration (min) | Distance (miles) | Average Trip Speed (mph) | Fuel (Liters) | Measured NOx (g) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | Riverside to | 24.32 | 21.53 | 53.12 | 8.2 | 15.53 |
| | 2 | Ontario | 19.03 | 14.12 | 44.52 | 5.57 | 18.85 |
| | | ***Route Difference (%)*** | ***21.75*** | ***34.42*** | ***16.19*** | ***32.07*** | ***-21.41*** |
| 2 | 1 | Ontario to | 48.63 | 43.4 | 53.55 | 15.22 | 27.19 |
| | 2 | Vernon | 50.22 | 42.63 | 50.93 | 13.01 | 31.91 |
| | | ***Route Difference (%)*** | ***-3.27*** | ***1.77*** | ***4.88*** | ***14.52*** | ***-17.37*** |
| 3 | 1 | Vernon to San | 45.75 | 24.98 | 32.76 | 10.29 | 37.92 |
| | 2 | Pedro | 47.77 | 30.43 | 38.22 | 11.34 | 26.5 |
| | | ***Route Difference (%)*** | ***-4.42*** | ***-21.82*** | ***-16.67*** | ***-10.20*** | ***30.11*** |
| 4 | 1 | San Pedro to | 48.23 | 28.44 | 35.38 | 12.01 | 20.18 |
| | 2 | Corona | 60.68 | 25.66 | 25.37 | 11.13 | 38.53 |
| | | ***Route Difference (%)*** | ***-25.81*** | ***9.77*** | ***28.29*** | ***7.33*** | ***-90.98*** |

Source: [Scora et al., 2019]

The experiment results in Table 2-2 confirm that the choice of travel route can have significant impacts on NOx emission of heavy-duty diesel trucks. The route with less NOx emission was not necessarily the shorter or faster route. In fact, the route with less NOx emission took longer distance, had higher average speed, and consumed more fuel (and thus, produced more CO2 emission) in all the experiments. This may be explained by the fact that the performance of selective catalytic reduction (SCR) in controlling NOx emission depends on having high enough exhaust gas temperatures, which usually occur when the truck travels at high speeds, incurring high engine load and consuming more fuel [Misra et al., 2013].

### *Exposure-Based Routing*

In recent years, due to the concerns with near-road exposure to pollutant emissions from heavy-duty diesel trucks, there has been research that expands the emission-based routing technique to account for how the emissions disperse from the road into nearby communities and be exposed by community members. This exposure-based routing technique is aimed at finding the route that would minimize or lower the total exposure of community members to the emissions from the truck for any given trip. Luo et al. [2018] developed an exposure-based routing algorithm that accounted for not only how much emission would be generated by a heavy-duty diesel truck when it travels on the different roads in the community, but also the meteorological conditions that affect emission dispersion (e.g., wind speed and direction), number of population in different parts of the community, and locations of sensitive facilities (e.g., daycares, schools, senior facilities), among others (see Figure 2-7). The researchers applied the algorithm to 400 simulated truck trips in the Reseda-Northridge area in Southern California, and found that for 60% of those 400 trips the low exposure route would reduce the cumulative community exposure to PM2.5 emission by more than 10%, as compared to the shortest time route, without increasing travel time by more than 10%.




Source: [Lou et al., 2018]

**Figure 2-7. Least exposure and least duration routes for the same truck trip**

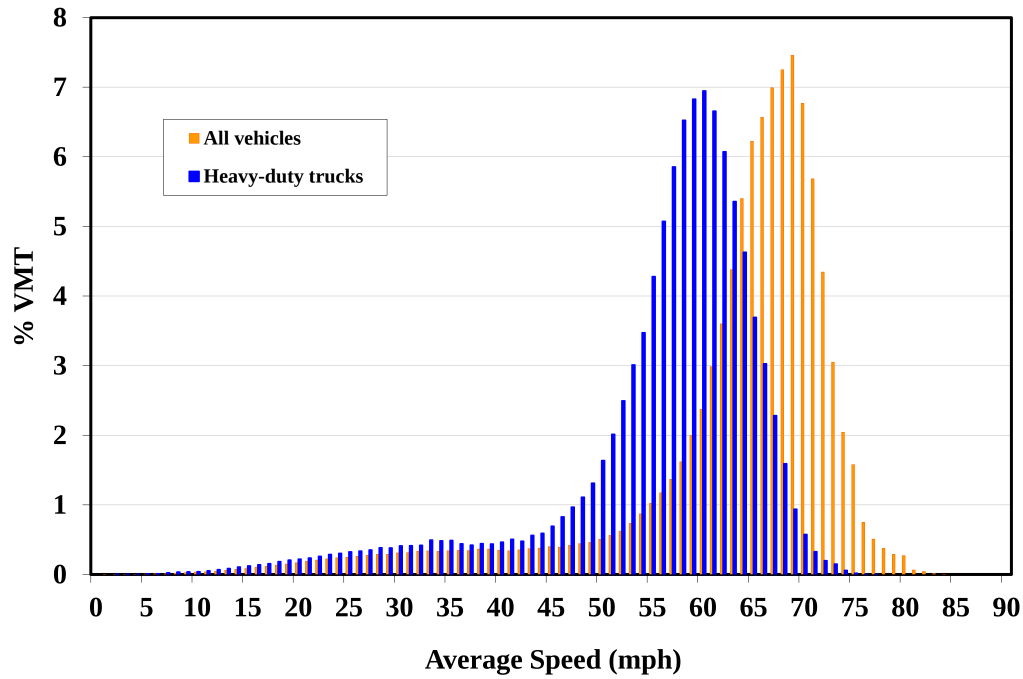
### 2.1.3. Speed Management

Traffic speed management is mostly concerned with traffic safety. However, it has also been used as a strategy for reducing fuel consumption and emissions from motor vehicles as well. For instance, the 1974 National Maximum Speed Limit[4] law imposed a 55 mph maximum speed limit nationwide in response to oil price spikes and supply disruptions during the 1973 oil crisis. It was estimated that the law reduced fuel consumption by 0.2 to 1.0% [Bloomquist, 1984].

In California, heavy-duty trucks are already subject to a maximum speed limit of 55 mph when traveling on highways. However, it was estimated that about two-third of truck VMT on Southern California highways were at speeds greater than 55 mph, with the peak at around 60 mph, as shown in Figure 2-8 [Boriboonsomsin et al., 2011]. Therefore, there is potential to achieve emission reductions on highways in geofenced areas through

[4] https://en.wikipedia.org/wiki/National_Maximum_Speed_Law

speed management techniques. For instance, speed enforcement efforts can be increased on highway sections that pass through DACs. Based on the emission curves in Figure 2-5, if the travel speed of heavy-duty diesel trucks can be reduced from 60 mph to 55 mph, to be in compliance with the speed limit, then the emissions per mile would decrease by 4% and 15% for CO2 and PM2.5, respectively. For NOx, it would be 7%.




Source: [Boriboonsomsin et al., 2011]

**Figure 2-8. VMT vs. speed distribution on Southern California freeways**

The speed management strategy can also be applied to surface streets including urban freight corridors in many cities. However, there may be tradeoffs among the different emission goals. Using the emission curves in Figure 2-5 as an example, if the travel speed of heavy-duty diesel trucks can be reduced from 45 mph to 40 mph, then the PM2.5 emission per mile would decrease by 18% but the CO2 and NOx emissions per mile would increase by 6% and 13%, respectively.

A common way to reduce excessive travel speed is direct enforcement by police, radar, camera, aircraft, etc. These various forms of speed enforcement can be applied or enhanced in the geofenced area to achieve emission reduction benefits as well as traffic safety co-benefits. In addition to the direct enforcement, there are other speed management techniques such as active accelerator pedal [Várhelyi et al., 2004], intelligent speed adaptation where top speeds are capped based on specific traffic conditions [Servin et al., 2006], variable speed limit [Grumert et al., 2018], and freeway speed harmonization [Ma et al., 2016].

## 2.2. Vehicle and Driver Level

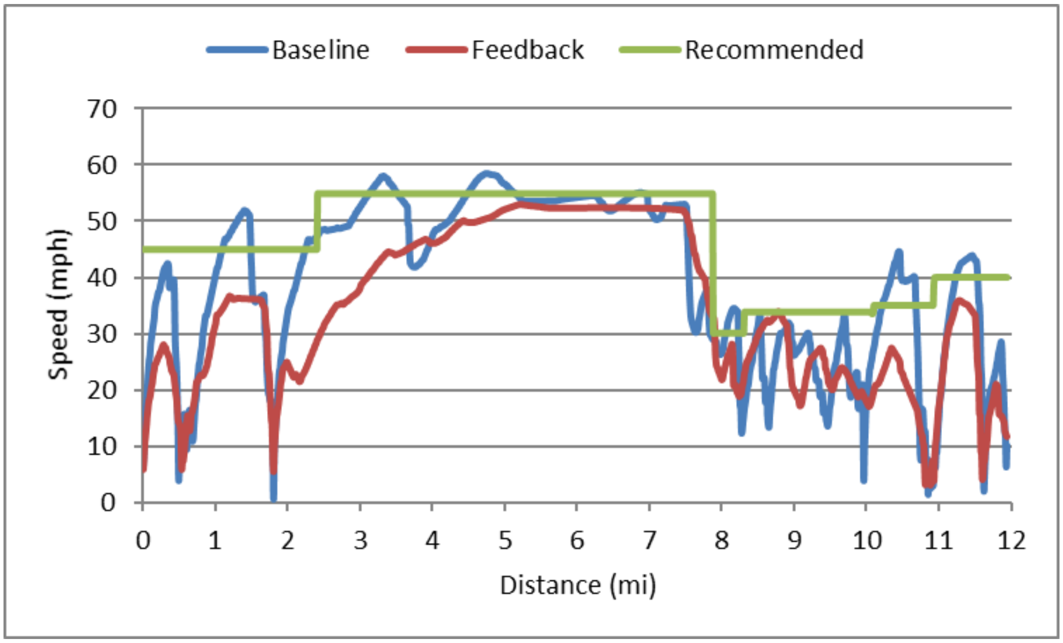
### 2.2.1. Eco-Driving

Strategies at the vehicle and driver level involve modifications of how the vehicle is operated on roadways, either through driver input or through automation. These strategies are centered on the concept of eco-driving, which is the practice of driving in such a way as to minimize fuel consumption and emissions. This includes a variety of driving techniques such as maintaining constant speed or using cruise control, accelerating and braking mildly, and avoiding unnecessary idling. Over the past two decades, there have been many efforts to develop, evaluate, and implement eco-driving programs for heavy-duty trucks. These efforts were focused primarily on reducing fuel consumption (and as a result, CO2 emissions). A review of truck eco-driving studies found that eco-driving could reduce fuel consumption and CO2 emission from heavy-duty trucks in the range of 5% to 15% [Boriboonsomsin, 2015].

To date, few studies have evaluated the pollutant emissions reduction co-benefit of truck eco-driving techniques. A truck driving simulator study by Jin et al. [2016b] showed that they could on average reduce fuel consumption (and CO2 emission), NOx emission, and PM2.5 emission by 4%, 3%, and 8%, respectively. A follow-up study by Boriboonsomsin et al. [2016] evaluated the energy and emissions reduction benefits of an advanced eco-driving feedback system that provides real-time speed advice based on the traffic condition ahead to the truck driver. This is illustrated as the green "Recommended" speed profile in Figure 2-9. According to this figure, the speed of the baseline driving exceeded the recommended speed several times. On the other hand, the speed for the driving with eco-driving feedback never exceeded the recommended speed, implying that the real-time speed advice was able to guide the driver to keep the driving speed at or below an appropriate level throughout the driving course. The real-time speed advice helped the driver maintain both an appropriate driving speed, as well as holding that speed constant. An example is the portion from the 5th to the 7.5th mile where the speed profile for the driving with feedback is smoother with less fluctuation than the one for the baseline driving. In addition to the real-time speed advice, this advanced eco-driving feedback system also provides real-time feedback on acceleration and braking. It was found that the advanced eco-driving feedback system could on average reduce fuel consumption (and CO2 emission), NOx emission, and PM2.5 emission by 11%, 8%, and 8%, respectively, with negligible impact on travel time.

### 2.2.2. Connected Eco-Driving

The advanced eco-driving feedback system discussed in the previous section relies on real-time traffic information such as traffic speed and incidents, which are more readily available on highways. Although some real-time traffic information on surface streets are available, it is less accurate due to the presence of traffic perturbations from traffic control devices (e.g., traffic signals, stop signs), turning movements (e.g., at intersections, on to parking lots), and other modes of transportation (e.g., transit buses, bicyclists). However, the emergence of connected vehicle (CV) technology has paved a way for sourcing real-time traffic information from both vehicles and roadway infrastructure (e.g., traffic signals) anywhere. In addition, the technology enables wireless communications among vehicles as well as between vehicles and infrastructure, which have prompted a variety of advanced CV applications to be developed and demonstrated over the last decade.

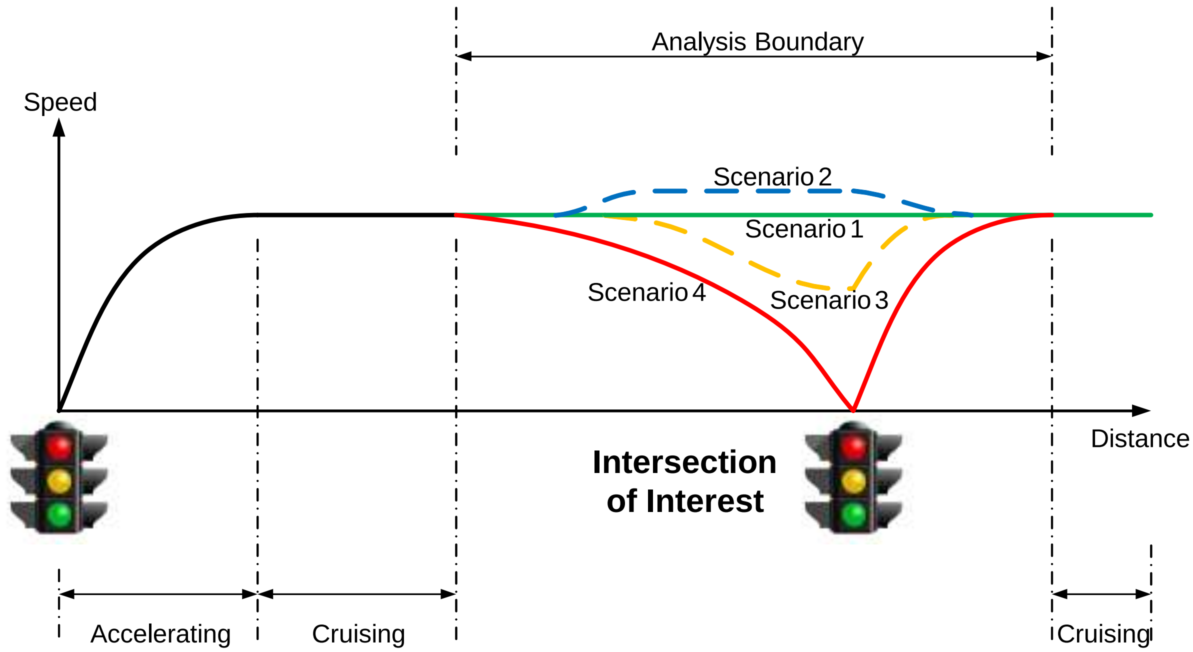



Source: [Boriboonsomsin et al., 2016]

**Figure 2-9. Example speed profiles from truck driving simulator experiment**

One of the promising CV applications for reducing energy consumption and emission from vehicles traveling on surface streets is eco-approach and departure (EAD). It uses signal phase and timing (or SPaT) information from the upcoming traffic signal along with the information about the position and states of the vehicle and surrounding traffic to determine the best course of action. Possible scenarios are shown in Figure 2-10 and include: 1) cruising through the green light; 2) speeding up (while staying under the speed limit) to pass through the intersection before the signal turn red; 3) slowing down in advance so that the vehicle reaches the intersection just when the signal turns green; and 4) coasting to a stop if the red light is unavoidable. Once the application has determined the best course of action, it then designs a driving speed profile that would minimize fuel consumption, emissions, and/or delay, and provides the recommended driving speed to the driver.

Most of the initial research and development of EAD were focused on light-duty vehicles. Results, from both simulation and real-world experiments, have shown the significant fuel savings potential of this application. Table 2-3 summarizes fuel savings from the real-world experiments of EAD on light-duty vehicles. In terms of emissions, few studies estimated the pollutant emission reduction benefits of EAD. In Hao et al. [2019], it was estimated for the experiment in Pala Alto, CA, that EAD would not only reduce fuel consumption by 6%, but it would also reduce CO, HC, and NOx by 32%, 30%, and 24%, respectively.




Source: [Hao et al., 2018]

**Figure 2-10. Connected eco-driving with infrastructure-to-vehicle communication**

**Table 2-3. Fuel savings from real-world experiments of EAD on light-duty vehicles**

| Traffic Signal Type | Location | Speed Control | Communication Type | Fuel Savings | Reference |
|---|---|---|---|---|---|
| Fixed time control | Richmond, CA | Human driver | 4G/LTE | 14% | [Xia et al., 2012] |
| | Riverside, CA | Human driver | DSRC | 11%-28% | [Barth et al., 2012] |
| | McLean, VA | Human driver | DSRC | 2.5%-18% | [Barth et al., 2012] |
| | McLean, VA | Automation | DSRC | 10-20% | [Altan et al., 2017] |
| Actuated control | Riverside, CA | Human driver | DSRC | 5-25% | [Hao et al., 2015] |
| | Palo Alto, CA | Human driver | DSRC | 6% | [Hao et al., 2019] |

Note: DSRC = Dedicated short-range communication

Recently, EAD has been applied to other types of vehicles including heavy-duty diesel trucks [Hao et al., 2018]. A recent study conducted a limited number of field experiments of EAD on a heavy-duty diesel truck traveling in real-world traffic, and found that the fuel savings ranged from 4% to 9% [Wang et al., 2019]. To date, there has not been a study to evaluate the pollutant emission reduction benefits of EAD on heavy-duty diesel trucks.

## 2.3. Powertrain and Emission Control System Level

### 2.3.1. Engine Management

Heavy-duty diesel trucks are used in a variety of applications to perform various types of work, which require different performance characteristics [Boriboonsomsin et al., 2017]. Typically, the diesel engines in these trucks are calibrated to meet the performance requirements of specific applications. The calibration process involves optimizing engine parameters such as fuel injection timing, fuel injection pressure, etc., which then results in a set of software maps that is stored in the engine control unit (ECU). The engine calibration is usually performed by the engine manufacturer prior to the vehicle being placed in service.

When performing diesel engine calibration, engine manufacturers often need to consider the tradeoffs between achieving performance requirements, improving fuel efficiency, and meeting emission standards. One example is the tradeoff between NOx emission and fuel consumption (or CO2 emission) as a function of fuel injection timing. Multiple fuel injection timing settings can be pre-programed into the ECU that can be used in different situations depending on the engine operating conditions. With the availability of GPS and wireless communication technologies, it is also possible to switch between different fuel injection timing settings based on the location of the vehicle. This concept was demonstrated by Barth et al. [2003] where they modeled emissions from a heavy-duty diesel truck making a round trip between Riverside, CA, which is inside the South Coast Air Basin (SCAB) and Coachella, CA, which is outside the SCAB to the east. Approximately half of the one-way trip is inside the South Coast Air Basin while the other half is outside. The modeling results showed that by using the location-based control of the fuel injection timing, the amount of NOx emission inside the SCAB (considered the geofenced area) could be reduced by 22% as compared to the standard control.

Over the last several years, there have been many advances in diesel engine calibration and control, which have significantly improved the performance and fuel efficiency while meeting more and more stringent emission standards. Recent studies have suggested the possibility of dynamically calibrating diesel engines while they are in operation [Tan et al., 2017] and optimizing diesel engine calibration to simultaneously reduce NOx emission and fuel consumption [Millo et al., 2018]. Figure 2-11 NOx and CO2 certification test data for heavy-duty diesel engines certified from 2002 through 2019. It can be seen that there is a tradeoff between NOx emission and CO2 emission for engines that do not meet the 2010 NOx standard. On the other hand, with the advances in diesel engine technologies in recent years, it is possible for engines meeting the 2010 NOx standard to reduce both NOx and CO2 simultaneously. Nevertheless, the ranges of NOx and CO2 emissions from these newer engines are fairly large, and there may be opportunities to dynamically calibrated the engines of heavy-duty diesel trucks to further reduce NOx emission in geofenced areas.

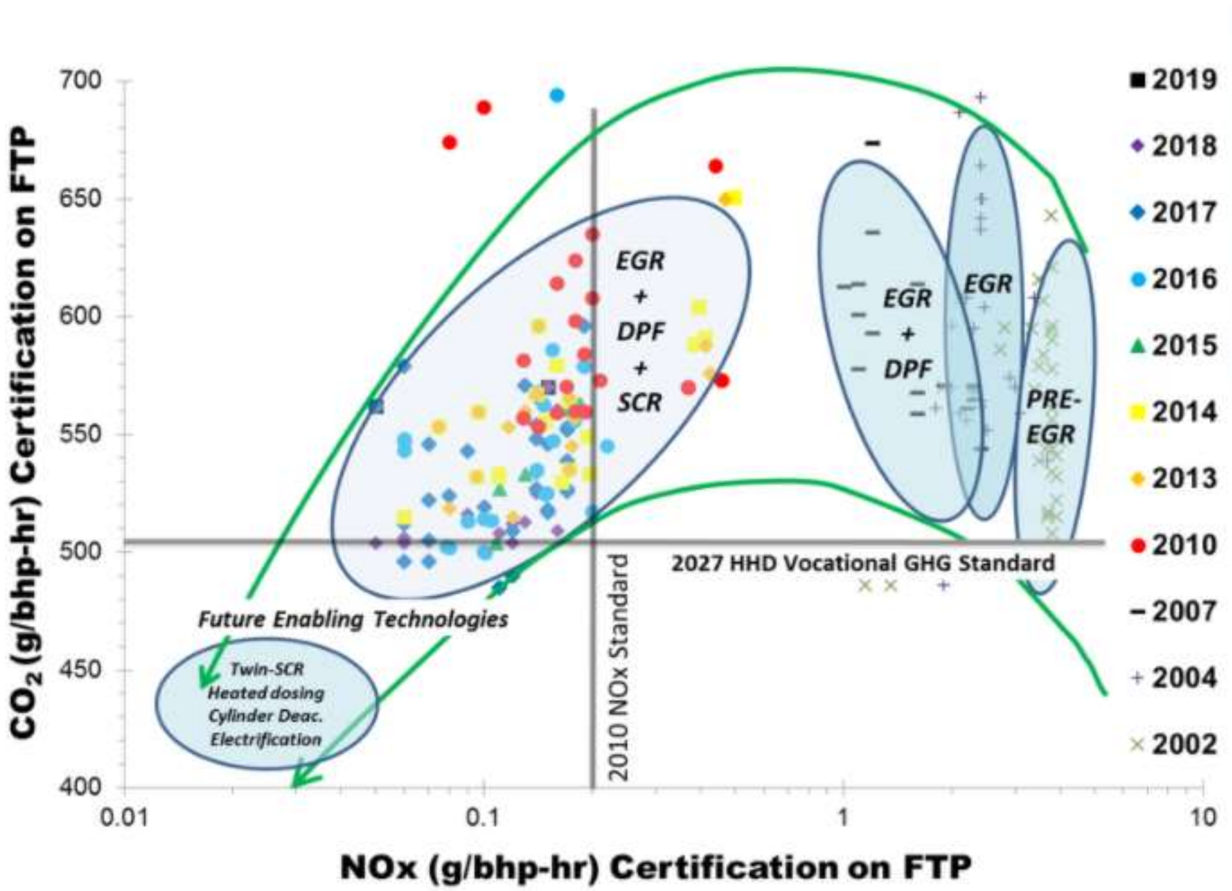



**Figure 2-11. NOx and CO2 certification test data for heavy-duty diesel engines certified from 2002 through 2019 [Manufacturers of Emission Controls Association, 2019)**

### 2.3.2. Hybrid Energy Management

Hybrid electric vehicles and plug-in hybrid electric vehicles are advanced technology vehicles powered by an internal combustion engine together with an electric motor that uses energy stored in a battery. One of the important considerations in HEV and PHEV development is the design of the energy management strategy, which determines how energy in a hybrid powertrain should be produced and utilized as a function of various vehicle operating parameters (e.g., power demand, battery state-of-charge, etc.). It is desired that the energy management strategy optimizes the hybrid operation in terms of overall vehicle performance, fuel efficiency, emissions, driver comfort, and secondary issues such as noise. When coupled with GPS and wireless communication technologies, it is possible for the energy management strategy to manage the hybrid powertrain based on the location of the vehicle.

Such geofencing strategy for HEVs and PHEVs is being tested or introduced by many vehicle manufacturers and fleets, especially in Europe, as a way to comply with the emission requirements in LEZs. For example:

- Fiat Chrysler is piloting a project in Turin to allow its plug-in hybrid cars to automatically switch to electric-only mode when entering congested city centers [Berman, 2020].

- Ford is testing the geofencing strategy in its plug-in hybrid electric vans in London, U.K., Valencia, Spain, and Cologne, Germany [Green Car Congress, 2019].

- BMW announced that the geofencing feature will be standard in BMW PHEVs starting in 2020 [Krok, 2019].

- UPS introduced 15 new delivery trucks that included the geofencing feature to its U.K. fleet in 2019 [Etherington, 2019].

In the U.S., the hybrid energy management strategy with geofencing was recently tested in Mack's Class 8 plug-in hybrid electric trucks, showing 25% to 30% fuel savings [O'Dell, 2018]. The strategy has also been implemented in transit buses. The San Francisco Municipal Transportation Agency (SFMTA) now operates 68 hybrid diesel-electric buses that automatically switch to the electric-only mode as they enter "Green Zones" throughout the city of San Francisco (see Figure 2-12). These geofenced zones include neighborhoods with high percentages of households with low incomes and people of color, and areas with poor air quality [Barnett, 2019].

### 2.3.3. Emission Control Management

The primary emission control systems in recent heavy-duty diesel trucks include diesel particulate filter (DPF) for meeting the 2007 PM2.5 emission standard, and SCR for meeting the 2010 NOx emission standard. In SCR, NOx is converted into nitrogen and water by the reaction with ammonia over a special catalyst. Typically, the exhaust gas temperature at SCR inlet needs to be at least 200 °C for a significant level of NOx conversion to occur [Cavataio et al., 2007]. However, real-world activities of some heavy-duty diesel trucks can cause this SCR temperature requirement to be unmet, such as during cold start at the beginning of a trip, low speed driving, and long idling [Boriboonsomsin et al., 2018]. These activities mostly occur on surface streets, which have speed limits lower than those on highways, and at or near freight facilities (e.g., seaports, railyards, distribution centers). Thus, higher-than-expected NOx emissions from these trucks may be released close to where people live, work, and play.

One way to address this issue is to ensure that SCR systems can work effectively under a variety of real-world operating conditions. Researchers have been developing thermal management strategies for SCR systems to provide a way to quickly activate the catalytic reactions on SCR without negatively affecting fuel consumption, e.g., [Cavina et al., 2013]. These strategies should be applied all the time to ensure that the in-use NOx emission stays below the NOx limit in the 2010 standards. But the thermal management strategies can also be tuned dynamically. For example, in geofenced areas the strategies can be tuned so that the catalytic reactions are activated as soon as possible even at the expense of fuel consumption. Thermal management strategies can also be applied to hybrid vehicles to ensure that the SCR system will be effective after the engine has been turned off for a long period during the electric-only operation inside geofenced areas [Holmer et al., 2020].


Source: San Francisco Municipal Transportation Agency

**Figure 2-12. Map of SFMTA's Green Zones as of 2019**

# 3. Modeling and Simulation Evaluation

This chapter explains the modeling evaluation of selected geofencing strategies. The identification of geofencing strategies to be modeled and the areas to be used as case studies are described. For each geofencing strategy, the modeling methods and results are presented in detail.

## 3.1. Case Studies

The selection of case studies was made in consultation with CARB staff. In terms of geofencing strategies to be evaluated, it was suggested that the research team focused on three strategies including: 1) emission-based restriction and pricing, 2) exposure-based routing, and 3) connected eco-driving. The selection of study areas was based on the degree to which the areas were disproportionately affected by traffic emissions, especially those from heavy-duty diesel trucks. Another consideration was the availability of data to support the modeling needs.

During the project period, CARB established the Community Air Protection Program (CAPP) in response to Assembly Bill (AB) 617, with a focus on reducing population exposure to air pollution in communities most impacted by it. Ten communities were selected in the first year of the program, which are listed in Table 3-1. Six of the 10 communities cited freight-related sources such as trucks as one of the key pollution source types in their communities (red boxes in Table 3-1). Three of them—East Los Angeles/Boyle Height/West Commerce, Wilmington/West Long Beach/Carson, and San Bernardino/Muscoy—planned to have both air monitoring and emissions reduction programs. In addition, the research team had collected some truck activity data in the first two communities from a previous research effort [Boriboonsomsin et al., 2017]. Thus, the research team focused on these two communities in this project.

**Table 3-1. 2018 CAPP communities**

| Community | Air Monitoring | Emissions Reduction Program | Key Pollution Source Types | | |
|---|---|---|---|---|---|
| Richmond | X* | | Urban | Refineries | Freight |
| West Oakland | | X | Port | Freight | |
| Calexico, El Centro, Heber | X | X | Border | Rural | |
| South Sacramento/Florin | X* | | Urban | Residential | Freeways |
| Portside Environmental Justice Neighborhoods (Barrio Logan, West National City, Logan Heights, Sherman Heights) | X* | | Port | Small Industry | |
| Shafter | X | X | Rural | Oil and Gas | |
| South Central Fresno | X | X | Urban | Residential | Industry |
| East Los Angeles Neighborhoods, Boyle Heights | X | X | Urban | Rail | Small Industry |
| Muscoy, San Bernardino | X | X | Trucks | Warehouses | Rail |
| Wilmington, West Long Beach, Carson | X | X | Trucks | Ports | Refineries |

*Air monitoring in these communities will focus on getting new information to support action including the development of future clean air plans, or plan elements.

## 3.2. Emission-Based Pricing

The emission-based pricing strategy was evaluated for the East Los Angeles/Boyle Height/West Commerce (ELABHWC) community. This community is located near inner Los Angeles where the feasibility study of congestion pricing is being conducted [Transport Topics, 2019]. In addition, truck flow patterns around the community are unique and interesting. Figure 3-1 shows truck flows around the ELABHWC community, which is bounded by the black line. There are three major truck flows that go in to, out of, and through the community. The first is the truck traffic on Interstate 710 (I-710), shown as red line, between the San Pedro port complex and the ELABHWC community. This is a major freight corridor with a significant amount of truck traffic that carries freight containers from the port complex to the railyards inside the community, and vice versa. Since the origin or destination of these truck trips are inside the boundary of the community, the trucks cannot be diverted away.


**Figure 3-1. Truck flows around ELABHWC**

The second major truck flow around the ELABHWC community is the truck traffic on Interstate 5 (I-5), shown as a blue line in Figure 3-1, which goes through the community. I-5 is a major freight corridor that connects Northern California, the Central Valley, and Southern California. Many of the trucks on the section of I-5 that goes through the ELABHWC community do not have stops to make inside the community; they are mostly pass-through traffic. Diverting some of these trucks away from passing directly through the community could help reduce the impact of emissions from these trucks on the community. However, based on the topology of the freeway network in the area, there is no comparable alternative route in both northbound and southbound directions for the truck to take. The shortest detour route on the freeway network for the northbound truck traffic is to take Interstate 605 (I-605) North, followed by Interstate 210 (I-210) West, before joining I-5 North again. The shortest detour route on the freeway network for the southbound truck traffic is to take Interstate 110 (I-110) South, followed by Interstate 105 (I-105) East, I-605 South, and State Route 91 (SR-91) East before getting back onto I-5 South. As can be seen in the map, both alternative routes will still incur a large amount of extra distance and, most likely, extra travel time, depending on traffic conditions on the different freeways.

The third major truck flow around the ELABHWC community is the truck traffic that travels from the San Pedro port complex on I-710 North and then heads East towards warehouses and distribution centers in the Inland Empire. One possible route for these trucks is to take I-710 North, and then get onto State Route 60 (SR-60) East, essentially passing through the ELABHWC community, as shown by the green solid line in Figure 3-1. Another possible route is to take I-710 North from the port complex, and then take either SR-91 East or I-105 East to connect to I-605 North before getting onto SR-60 East, as shown by the green dashed line. Unlike the case with the I-5 pass-through truck traffic, the alternative route for diverting pass-through truck traffic away from the ELABHWC community in this case is more comparable in terms of distance and possibly, depending on traffic conditions, travel time.

### 3.2.1. Methods and Assumptions

The modeling of the emission pricing strategy was done in the Southern California Association of Governments (SCAG)'s regional travel demand model (TDM). It covers transportation network in six counties in Southern California including Los Angeles county in which the ELABHWC community is located. The SCAG's regional TDM includes a heavy-duty truck model that is used to support project and policy planning related to goods movement in the region, such as port access improvements, freight-related land use strategies, as well as air quality and economic impact analyses. The model forecasts truck trips for three heavy-duty truck weight classes: light-heavy (8,500 to 14,000 pounds of gross vehicle weight rating (GVWR)), medium-heavy (14,001 to 33,000 pounds of GVWR), and heavy-heavy (more than 33,000 pounds of GVWR). It captures heavy-duty truck trips that have both origins and destinations within the region as well as external trips that come into, go out of, and pass through the region. In addition, the model includes a sub-model to capture heavy-duty truck trips associated with the San Pedro ports. The modeling of the emission pricing strategy was based on the following scope and assumptions.

- ***Modeling area*****:** The modeling area is a subset of the SCAG regional TDM network for calendar year 2016, as shown in Figure 3-2. It is centered around the ELABHWC community and includes key freeways that allow trucks to make a detour to avoid the community. This choice to conduct the modeling on a sub-area network was made in order to reduce the amount of time required to complete a model run. For the chosen sub-area network, each model run took around 18-20 hours on a typical desktop computer.

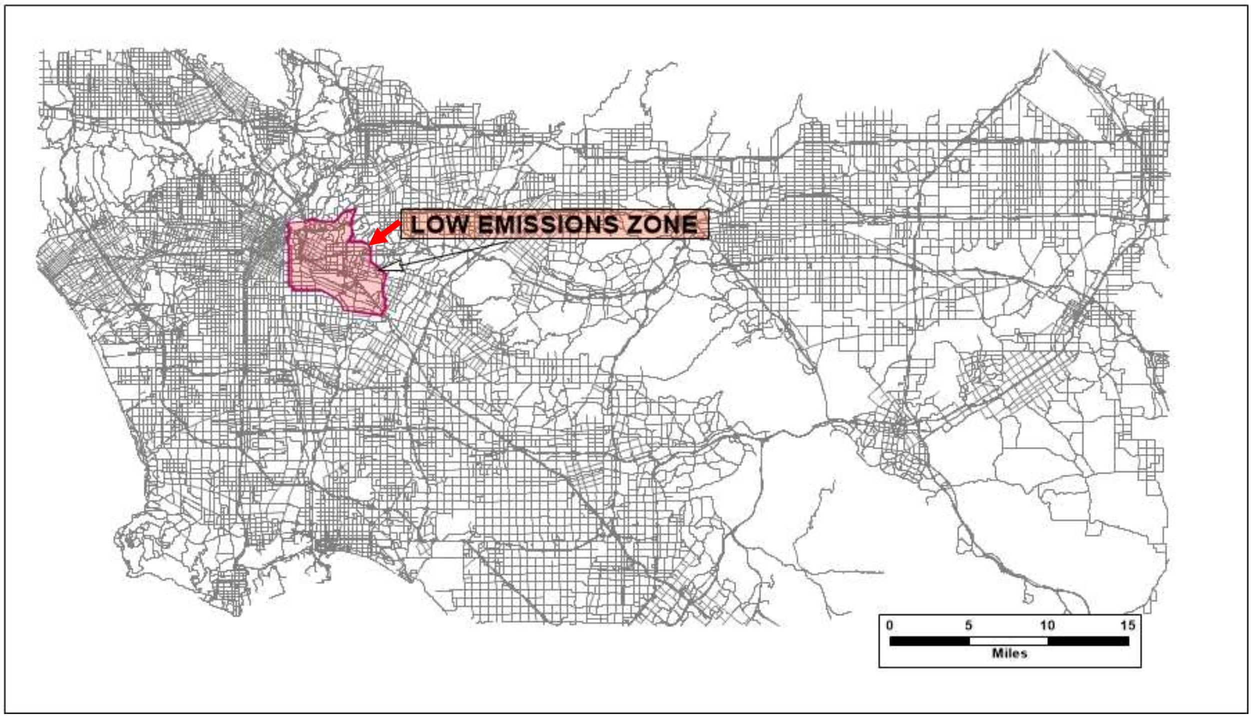



Figure 3-2. Boundary of the LEZ inside the modeling area

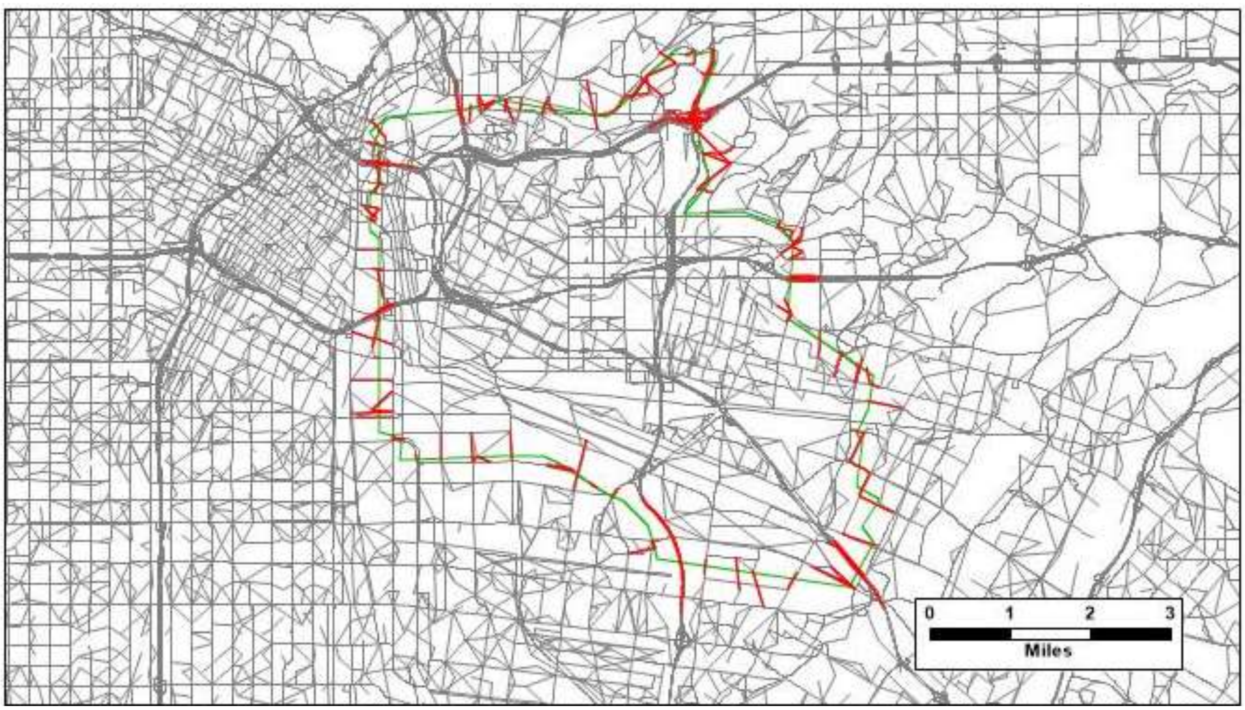



Figure 3-3. Entry links (shown as red) to the LEZ (shown in green) with emission-based entry fees

- ***Low emission zone*:** The boundary of the ELABHWC community was used as the boundary of the LEZ, as shown in Figure 3-2. The LEZ was implemented by identifying roadway links that cross the boundary of the LEZ, as shown in Figure 3-3, and then adding an emission fee to only the entry links. This means that vehicles not meeting the LEZ requirements will have to pay the emission fee when entering the LEZ, but not when exiting the LEZ.

- ***Travel demand*:** Travel demand in the SCAG regional TDM is expressed in the form of origin-destination (O-D) trip tables. Trip tables for the morning peak period (6 a.m. – 9 a.m.) in calendar year 2016 were used. There are eight trip tables, one for each of the following vehicle/occupancy classes:
  - Drive alone passenger cars and trucks
  - Passenger cars with 2 occupants using HOV facilities
  - Passenger cars with 3+ occupants using HOV facilities
  - Passenger cars with 2 occupants not using HOV facilities
  - Passenger cars with 3+ occupants not using HOV facilities
  - Light heavy-duty trucks
  - Medium heavy-duty trucks
  - Heavy heavy-duty trucks

- ***Travel costs*:** A key assumption in modeling route choice decision of drivers is that they would choose a route with the smallest total travel cost. The total travel cost is primarily a function of travel time, but it can also make up of multiple cost components (such as travel time, fuel, and toll) converted into monetary equivalence. In this study, the total travel cost includes travel time and the emission fee, which is only applied to certain heavy heavy-duty trucks (HHDTs). To convert travel time of these trucks to monetary value, it was assumed that the value of truck travel time was $60 per hour. This value was based on the average marginal costs per hour for commercial trucking in the U.S. as reported in [Hooper and Murray, 2018].

### *Emission Fee Structure*

A simple emission fee structure was assumed in this modeling study:

- The fee is applied to only HHDTs not meeting the required emission standards. These are Class 8 commercial trucks with GVWR of more than 33,000 pounds. These trucks correspond to the T7 category in CARB's EMFAC2007 emission model (see Table 3-2).

- The fee is applied only when entering the LEZ. No fee is applied when exiting the LEZ. This means that a pass-through truck will only pay the emission fee once.

- The amount of the fee is fixed and the same for each entry (i.e., no discount for multiple entries).

**Table 3-2. Mapping between different vehicle classification schemes**

| SCAG TDM Trip Table | Commercial Vehicle Classification | EMFAC2007 Category |
|---|---|---|
| Passenger cars | Class 1: 0 to 6,000 pounds | P, Passenger cars; T1, Light-duty trucks; T2, Light-duty trucks |
| | Class 2a: 6,001 to 8,500 pounds | T3, Medium-duty vehicles |
| Light-heavy duty trucks | Class 2a: 8,501 to 10,000 pounds | T4, Light-heavy duty trucks |
| | Class 3: 10,001 to 14,000 pounds | T5, Light-heavy duty trucks |
| Medium-heavy duty trucks | Class 4: 14,001 to 16,000 pounds | T6, Medium-heavy duty trucks |
| | Class 5: 16,001 to 19,500 pounds | |
| | Class 6: 19,501 to 26,000 pounds | |
| | Class 7: 26,001 to 33,000 pounds | |
| Heavy-heavy duty trucks | Class 8: 33,000+ pounds | T7, Heavy-heavy duty trucks |

One way for determining whether a HHDT will need to pay the emission fee for entering the LEZ is to base it on the emission standards that the HHDT is in compliance with. In California, CARB adopted the U.S. Environmental Protection Agency (EPA)'s 2007 and later heavy-duty engine emission standards that included very stringent limits for PM and NOx. The PM emission standard took full effect in 2007. The NOx standard was phased-in for diesel engines between 2007 and 2010. The phase-in was defined on a percent-of-sales basis—50% from 2007 to 2009 and 100% in 2010. In this study, it was assumed that all HHDTs were diesel trucks. The emission fee for entering the LEZ was waived for HHDTs of model years 2010 and newer as they met both the PM and NOx emission standards.

Figure 3-4 shows plots of the fraction of HHDTs by model year grouped according to the emission standards. The plot on the left is for HHDTs registered in the five zip codes that make up the ELABHWC community (i.e., 90022, 90023, 90033, 90040, and 90063). The plot on the right is for HHDTs registered in the Los Angeles sub-area of the South Coast air basin. The plots show that the fraction of HHDTs that would be subject to the emission fee in both areas was similar—44% for the ELABHWC community and 46% for the Los Angeles sub-area. In this modeling study, the average value between the two (i.e., 45%) was used. This means that the HHDT trip table in the TDM was split into two sub-tables, one for HHDTs of model years 2009 and older (45% of the total) and the other for HHDTs of model years 2010 and newer (55% of the total HHDT trips).

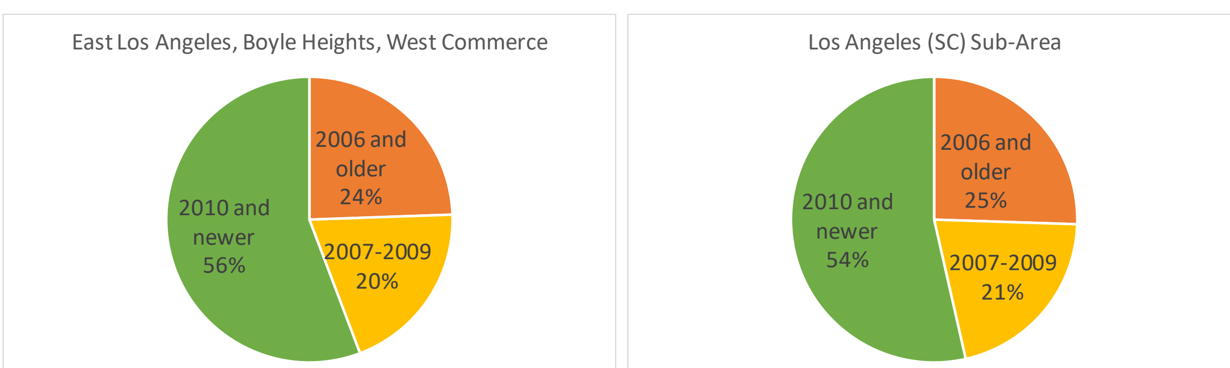



**Figure 3-4. Fraction of HHDTs by model year grouped according to emission standards**

### Modeling Approach

The modeling area is a subset of the SCAG regional TDM network for calendar year 2016. The full network consists of 4,109 traffic analysis zones (TAZs) whereas the selected sub-area network covered 3,288 TAZs (3,076 internal zones and 212 external zones). The calibrated O-D trip tables were truncated for the sub-area network using the "Multi-Modal Multi-Class Subarea Analysis" utility in TransCAD software. For each trip table, the utility ran traffic assignment process iteratively until it converged on a truncated table.

Once the sub-area O-D trip tables had been derived, the emission fee was implemented on the entry links to the LEZs, and the traffic assignment routine was executed for scenarios without and with the emission fee. Parameters for the traffic assignment routine are listed below:

- *Assignment method* – Bi-conjugate Frank-Wolfe multi-modal and multi-class assignment
- *Delay function* – Bureau of Public Roads (BPR)
- *Number of iterations* – 100
- *Relative gap* – 0.005
- *N Conjugate* – 2
- *Preload* – Preassigned transit volume added as preload to the network

The BPR function follows Equation 3-1 to calculate congested travel time on link *i*.

$$CongestedTime_i = FreeFlowTime_i \times (1 + \alpha \times (Volume_i / Capacity_i)^{\beta} \qquad (3\text{-}1)$$

The $\alpha$ and $\beta$ parameters were previously calibrated for each link considered in the sub-area network. Additionally, the values of link capacity were calibrated following the Highway Capacity Manual.

### Modeled Scenarios

Two scenarios were modeled to evaluate the impact of emission fee on heavy-duty diesel truck traffic and their emissions inside the LEZ. The two scenarios are as follows:

- *BASE* – The baseline network with no emission fee
- *$10 FEE* – An emission fee of $10 implemented on the entry links to the LEZ. Note that this emission fee is only applied to HHDTs of model years 2009 and older.

The selection of the level of emission fee was based on the container fee of $10 per loaded TEU being considered by the Ports of Los Angeles and Long Beach as part of their updated Clean Trucks Programs [Port of Los Angeles and Port of Long Beach, 2020].

### Emission Calculation

The calculation of emissions was focused on PM2.5, NOx, and CO2 emissions from HHDTs. There were calculated using Equation 3-2 below.

$$E_{i,j} = V_{i,k} \times L_i \times EF \tag{3-2}$$

where $E_{i,j}$ is mass emission of pollutant $j$ on link $i$; $V_{i,k}$ is HHDT volume on link $i$ with link speed $k$; $L_i$ is length of link $i$; and $EF_{j,k}$ is emission factor of pollutant $j$ at speed $k$.

The emission factors for heavy-duty diesel trucks were obtained from CARB's EMFAC2017 emission model for the following model run specifications:

- *Source* – EMFAC2017 (v1.0.2) Emission Rates
- *Region Type* – Sub-Area
- *Region* – Los Angeles (SC)
- *Calendar Year* – 2016
- *Season* – Annual
- *Vehicle Classification* – EMFAC2007 Categories
- *Model Year* – All (1972-2017)

The obtained emission factors were weighted by VMT into two groups: 1) model years 2009 and older, and 2) model years 2010 and newer. For PM2.5, the emissions from break wear (0.02646 grams per mile for all speeds and all model years) and tire wear (0.009 grams per mile for all speeds and all model years) were also added to the running exhaust emission to result in total PM2.5 emission. Figure 3-5 through Figure 3-7 show the emission curves of PM2.5, NOx, and CO2 as a function of speed that were used for the emission calculation in this modeling study. These emission curves clearly show that the PM2.5 and NOx emissions for heavy-duty diesel trucks of model years 2010 and newer are much lower than those of the older trucks as they comply with the 2007 emission standards. For CO2, the emission curve for heavy-duty diesel trucks of model years 2010 and newer are only slightly lower than those of the older trucks.

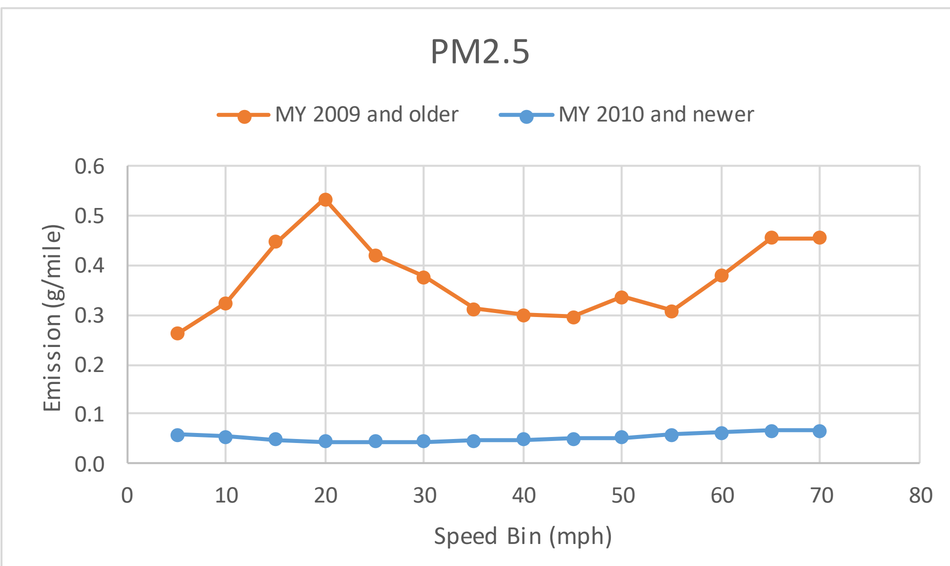



**Figure 3-5. PM2.5 emission factors for heavy-duty diesel trucks obtained from EMFAC2017**

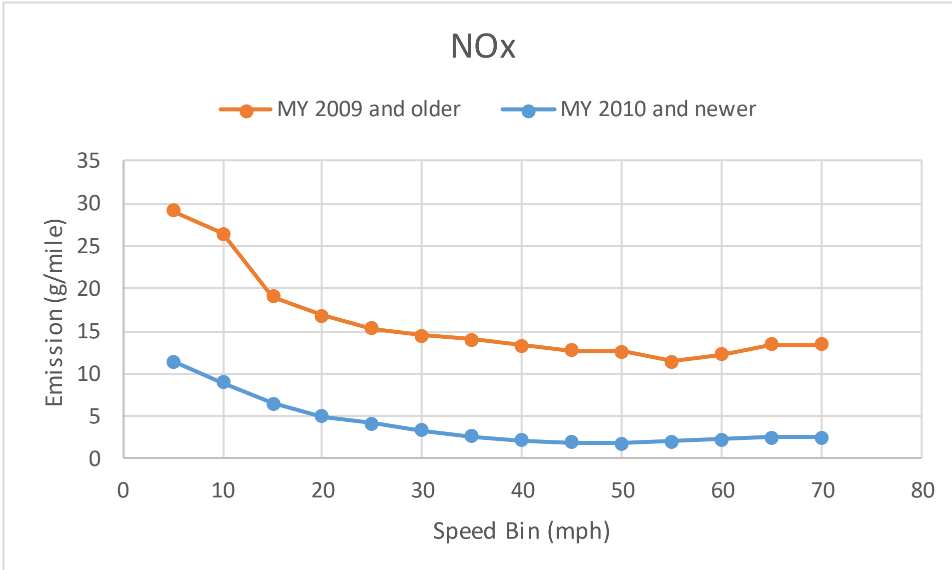



**Figure 3-6. NOx emission factors for heavy-duty diesel trucks obtained from EMFAC2017**

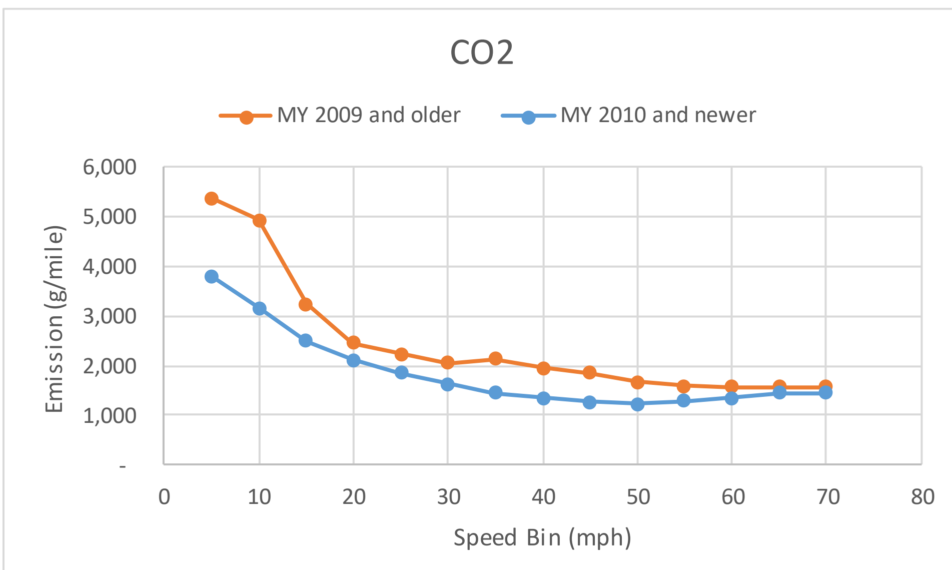



**Figure 3-7. CO2 emission factors for heavy-duty diesel trucks obtained from EMFAC2017**

### 3.2.2. Results and Discussion

Table 3-3 presents the number and percent of HHDTs making different trip types relative to the LEZ. The different trip types are described below.

- *Pass Through* – Trips that pass through the LEZ
- *Out-In* – Trips that start outside the LEZ and end inside the LEZ
- *In-Out* – Trips that start inside the LEZ and end outside the LEZ
- *Others* – Trips that do not cross the LEZ at all

Note that since the LEZ is relatively small (about 3 miles of radius), there is no internal HHDT trip that both starts and ends inside the LEZ.

**Table 3-3. Number and percent of HHDTs making different trip types**

| Trip Type | Number of HHDTs | | | | Percent of Total HHDTs | | | |
|---|---|---|---|---|---|---|---|---|
| | 2009 and older MY | | 2010 and newer MY | | 2009 and older MY | | 2010 and newer MY | |
| | BASE | $10 FEE | BASE | $10 FEE | BASE | $10 FEE | BASE | $10 FEE |
| **Pass Through** | 3,088 | 1,245 | 3,774 | 3,862 | 11% | 4% | 11% | 11% |
| **Out-in** | 956 | 956 | 1,168 | 1,168 | 3% | 3% | 3% | 3% |
| **In-out** | 988 | 988 | 1,208 | 1,208 | 4% | 4% | 4% | 4% |
| **Others** | 23,114 | 24,957 | 28,250 | 28,163 | 82% | 89% | 82% | 82% |
| ***Total*** | *28,146* | *28,146* | *34,401* | *34,401* | *100%* | *100%* | *100%* | *100%* |

According to Table 3-3, the following observations can be made:

- The distributions of HHDTs by trip type are the same for both model year groups. This is because the HHDT trip table was split into two sub-tables by applying the same ratio of older to newer trucks (45 to 55) across all the O-D pairs.

- For the 2010 and newer model year group, the distributions are the same for both the BASE and the $10 FEE scenarios. This is because these trucks were not subject to the emission fee, and thus, their total travel cost was not affected.

- For the 2009 and older model year group, the fraction of HHDTs making in-out trips (4%) are the same for both scenarios. This is because these trucks were not subject to the emission fee, and thus, their total travel cost was not affected. The fraction of HHDTs making out-in trips (3%) are also the same for both scenarios. While these trucks were subject to the emission fee, they had no choice but to pay the fee as their destinations were inside the LEZ.

- On the other hand, the fraction of 2009 and older model year HHDTs making pass through trips changed significantly. It was 11% for the BASE scenario, but dropped to 4% for the $10 FEE scenario. That means 7% of the total HHDTs of model years 2009 and older were diverted away from the LEZ with the implementation of the emission fee.

Figure 3-8 and Figure 3-9 show the modeled volumes and speeds of 2009 or older model year HHDTs in the BASE and $10 FEE scenarios, respectively. By comparing the thickness of the lines representing the freeway sections marked in Figure 3-8 with the corresponding lines in Figure 3-9, it can be seen that these trucks were diverted from I-5 and I-710 that lead up to the LEZ to other freeways such as I-605 and I-110.


**Figure 3-8. Volume (repsented by line thickness) and corresponding speed (represented by line color) for 2009 or older model year HHDTs in the baseline scenario**

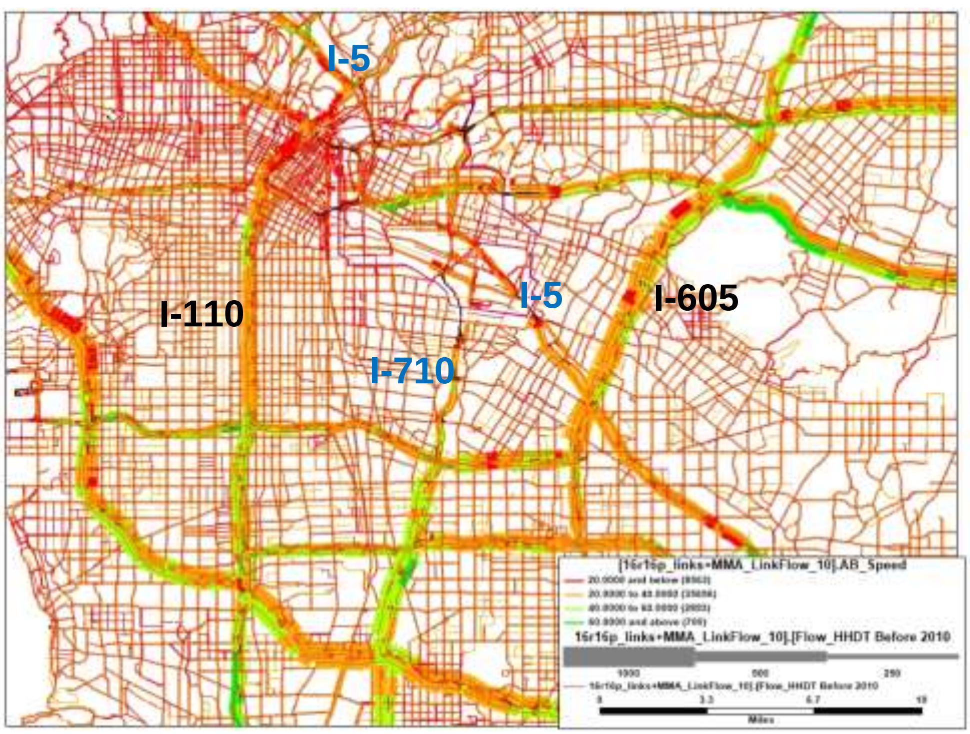



**Figure 3-9. Volume (repsented by line thickness) and corresponding speed (represented by line color) for 2009 or older model year HHDTs in the $10 fee scenario**

The impacts of the emission fee on HHDT trip patterns and emissions were analyzed for multiple zones in order to examine the shifting of some HHDT traffic and emissions from inside the LEZ to the surrounding areas. The analysis zones are shown in Figure 3-10 and include:

- *Inside LEZ* – The area inside the boundary of the LEZ
- *LEZ-5 mi radius* – The area immediately outside the LEZ but within 5-mile radius from the centroid of the LEZ
- *5-10 mi radius* – The area between 5-mile radius and 10-mile radius from the centroid of the LEZ
- *10-15 mi radius* – The area between 10-mile radius and 15-mile radius from the centroid of the LEZ
- *15-20 mi radius* – The area between 15-mile radius and 20-mile radius from the centroid of the LEZ
- *Beyond 20 mi radius* – The area outside 20-mile radius from the centroid of the LEZ

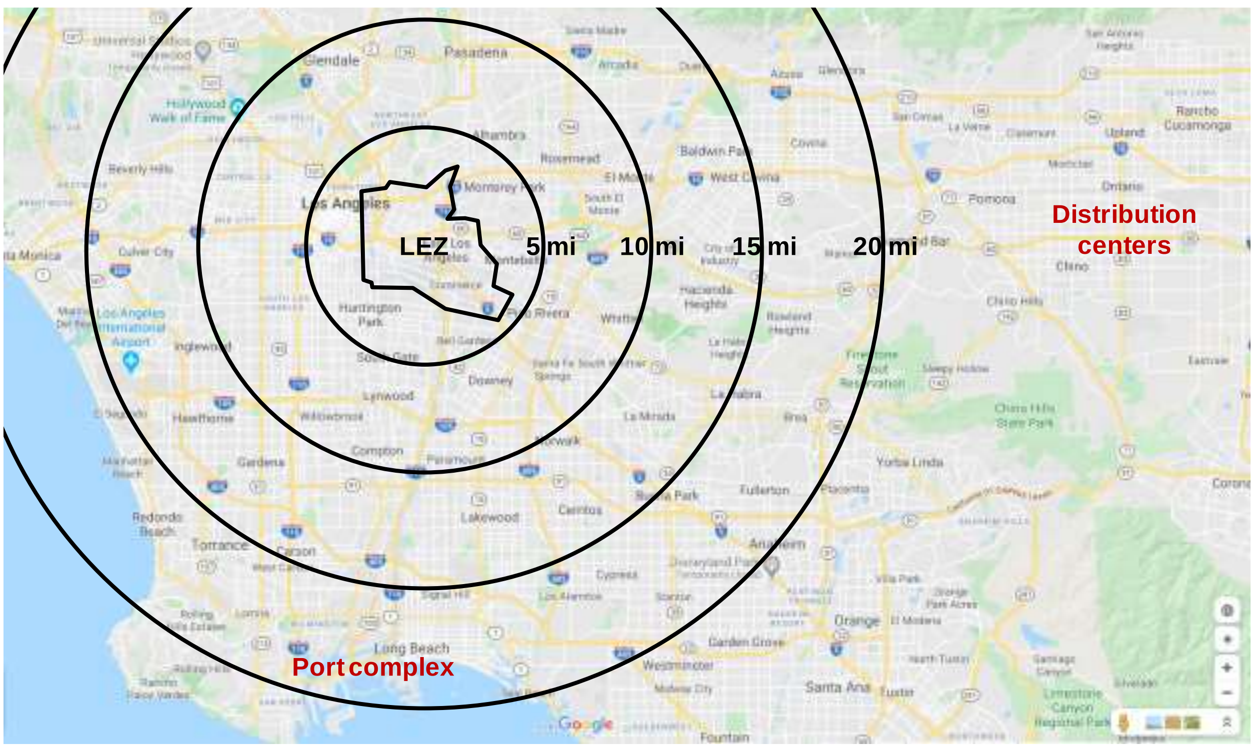



**Figure 3-10. Analysis zones for HHDT trip and emission impact analysis**

Table 3-4 presents the VMT, vehicle hours traveled (VHT), and emissions from HHDTs in the two scenarios. Then, Table 3-5 presents the absolute and percent changes in these metrics for the $10 FEE scenario as compared to the BASE scenario. The following observations can be made:

**Table 3-4. VMT, VHT, and emissions from HHDTs in different analysis zones and pricing scenarios**

| | | 2009 and older MY | | 2010 and newer MY | | All HHDTs | |
|---|---|---|---|---|---|---|---|
| | | BASE | $10 | BASE | $10 | BASE | $10 |
| VMTs of HHDTs (miles) | Inside LEZ | 23,865 | 12,456 | 29,168 | 29,850 | 53,033 | 42,306 |
| | LEZ-5 mi radius | 19,594 | 15,173 | 23,948 | 24,172 | 43,542 | 39,346 |
| | 5-10 mi radius | 83,608 | 89,249 | 102,188 | 102,640 | 185,796 | 191,889 |
| | 10-15 mi radius | 124,319 | 132,863 | 151,946 | 151,259 | 276,265 | 284,122 |
| | 15-20 mi radius | 98,754 | 101,493 | 120,699 | 120,286 | 219,453 | 221,779 |
| | Beyond 20 mi radius | 353,747 | 360,198 | 432,358 | 431,759 | 786,105 | 791,957 |
| | Total | 703,887 | 711,433 | 860,306 | 859,967 | 1,564,194 | 1,571,399 |
| VHTs of HHDTs (hours) | Inside LEZ | 920 | 457 | 1,097 | 1,112 | 2,017 | 1,569 |
| | LEZ-5 mi radius | 904 | 639 | 1,050 | 1,050 | 1,955 | 1,689 |
| | 5-10 mi radius | 3,436 | 3,526 | 3,982 | 3,964 | 7,417 | 7,490 |
| | 10-15 mi radius | 4,621 | 4,788 | 5,384 | 5,327 | 10,005 | 10,116 |
| | 15-20 mi radius | 3,817 | 3,895 | 4,395 | 4,338 | 8,212 | 8,234 |
| | Beyond 20 mi radius | 12,285 | 12,250 | 14,198 | 14,040 | 26,482 | 26,290 |
| | Total | 25,983 | 25,556 | 30,106 | 29,831 | 56,089 | 55,387 |
| PM2.5 emissions from HHDTs (metric tons) | Inside LEZ | 9.0 | 5.0 | 1.4 | 1.5 | 10.5 | 6.5 |
| | LEZ-5 mi radius | 7.7 | 6.1 | 1.2 | 1.2 | 8.9 | 7.3 |
| | 5-10 mi radius | 30.2 | 32.1 | 5.0 | 5.0 | 35.2 | 37.2 |
| | 10-15 mi radius | 44.2 | 47.1 | 7.6 | 7.6 | 51.8 | 54.7 |
| | 15-20 mi radius | 35.5 | 36.3 | 6.2 | 6.2 | 41.7 | 42.5 |
| | Beyond 20 mi radius | 130.7 | 132.7 | 23.7 | 23.8 | 154.4 | 156.5 |
| | Total | 257.4 | 259.5 | 45.1 | 45.3 | 302.5 | 304.7 |
| NOx emissions from HHDTs (metric tons) | Inside LEZ | 347 | 181 | 95 | 96 | 441 | 277 |
| | LEZ-5 mi radius | 295 | 226 | 86 | 86 | 381 | 312 |
| | 5-10 mi radius | 1,204 | 1,274 | 314 | 313 | 1,519 | 1,587 |
| | 10-15 mi radius | 1,752 | 1,857 | 440 | 434 | 2,192 | 2,291 |
| | 15-20 mi radius | 1,396 | 1,434 | 352 | 350 | 1,748 | 1,784 |
| | Beyond 20 mi radius | 4,884 | 4,941 | 1,198 | 1,187 | 6,083 | 6,129 |
| | Total | 9,878 | 9,913 | 2,486 | 2,467 | 12,364 | 12,380 |
| CO2 emissions from HHDTs (metric tons) | Inside LEZ | 50,634 | 25,526 | 47,720 | 48,639 | 98,354 | 74,165 |
| | LEZ-5 mi radius | 43,863 | 32,490 | 41,469 | 41,560 | 85,331 | 74,050 |
| | 5-10 mi radius | 177,590 | 186,881 | 162,246 | 162,198 | 339,836 | 349,079 |
| | 10-15 mi radius | 255,686 | 269,477 | 233,715 | 231,564 | 489,401 | 501,041 |
| | 15-20 mi radius | 202,415 | 208,480 | 186,316 | 185,464 | 388,731 | 393,944 |
| | Beyond 20 mi radius | 686,646 | 692,742 | 650,537 | 647,141 | 1,337,183 | 1,339,883 |
| | Total | 1,416,834 | 1,415,597 | 1,322,002 | 1,316,565 | 2,738,836 | 2,732,162 |

- The diversion of pass through truck traffic due to the emission fee reduced VMT of 2009 and older model year HHDTs inside the LEZ by 48%, which consequently reduced PM2.5, NOx, and $CO_2$ emissions from these trucks by 44%, 48%, and 50%, respectively.

- In addition, the diversion of pass through truck traffic due to the emission fee also reduced VMT of 2009 and older model year HHDTs in the area immediately outside the LEZ but within 5-mile radius from the centroid of the LEZ by 23%. This resulted in reductions of PM2.5, NOx, and CO2 emissions from these trucks in that area by 21%, 24%, and 26%, respectively.

- On the other hand, the diversion of old truck traffic caused the VMT and emissions from these trucks outside of the 5-mile radius from the centroid of the LEZ to increase. For the areas between 5-mile and 15-mile radius from the centroid of the LEZ, the VMT increased by 7%, and the PM2.5, NOx, and CO2 emissions increased by 7%, 6%, and 5%, respectively.

**Table 3-5. Changes in VMT, VHT, and emissions from HHDTs as compared to the baseline scenario**

| | | Changes from Baseline | | | Percent Changes from Baseline | | |
|---|---|---|---|---|---|---|---|
| | | 2009 and older MY | 2010 and newer MY | All HHDTs | 2009 and older MY | 2010 and newer MY | All HHDTs |
| VMTs of HHDTs (miles) | Inside LEZ | -11,409 | 682 | -10,727 | -48% | 2% | -20% |
| | LEZ-5 mi radius | -4,421 | 224 | -4,196 | -23% | 1% | -10% |
| | 5-10 mi radius | 5,641 | 452 | 6,093 | 7% | 0% | 3% |
| | 10-15 mi radius | 8,544 | -687 | 7,857 | 7% | 0% | 3% |
| | 15-20 mi radius | 2,740 | -413 | 2,326 | 3% | 0% | 1% |
| | Beyond 20 mi radius | 6,451 | -598 | 5,852 | 2% | 0% | 1% |
| | Total | 7,546 | -340 | 7,206 | 1% | 0% | 0% |
| VHTs of HHDTs (hours) | Inside LEZ | -463 | 15 | -448 | -50% | 1% | -22% |
| | LEZ-5 mi radius | -265 | 0 | -266 | -29% | 0% | -14% |
| | 5-10 mi radius | 91 | -18 | 73 | 3% | 0% | 1% |
| | 10-15 mi radius | 168 | -57 | 111 | 4% | -1% | 1% |
| | 15-20 mi radius | 78 | -57 | 21 | 2% | -1% | 0% |
| | Beyond 20 mi radius | -35 | -158 | -193 | 0% | -1% | -1% |
| | Total | -427 | -274 | -702 | -2% | -1% | -1% |
| PM2.5 emissions from HHDTs (metric tons) | Inside LEZ | -4.0 | 0.0 | -4.0 | -44% | 2% | -38% |
| | LEZ-5 mi radius | -1.6 | 0.0 | -1.6 | -21% | 1% | -18% |
| | 5-10 mi radius | 2.0 | 0.0 | 2.0 | 7% | 1% | 6% |
| | 10-15 mi radius | 2.9 | 0.0 | 2.9 | 7% | 0% | 6% |
| | 15-20 mi radius | 0.8 | 0.0 | 0.8 | 2% | 0% | 2% |
| | Beyond 20 mi radius | 2.0 | 0.1 | 2.1 | 2% | 0% | 1% |
| | Total | 2.1 | 0.1 | 2.2 | 1% | 0% | 1% |
| NOx emissions from HHDTs (metric tons) | Inside LEZ | -166 | 1 | -165 | -48% | 2% | -37% |
| | LEZ-5 mi radius | -69 | 0 | -70 | -24% | 0% | -18% |
| | 5-10 mi radius | 70 | -1 | 69 | 6% | 0% | 5% |
| | 10-15 mi radius | 105 | -6 | 99 | 6% | -1% | 5% |
| | 15-20 mi radius | 39 | -2 | 37 | 3% | -1% | 2% |
| | Beyond 20 mi radius | 57 | -11 | 46 | 1% | -1% | 1% |
| | Total | 35 | -19 | 16 | 0% | -1% | 0% |
| CO2 emissions from HHDTs (metric tons) | Inside LEZ | -25,108 | 919 | -24,189 | -50% | 2% | -25% |
| | LEZ-5 mi radius | -11,373 | 91 | -11,282 | -26% | 0% | -13% |
| | 5-10 mi radius | 9,290 | -48 | 9,243 | 5% | 0% | 3% |
| | 10-15 mi radius | 13,792 | -2,151 | 11,641 | 5% | -1% | 2% |
| | 15-20 mi radius | 6,065 | -852 | 5,213 | 3% | 0% | 1% |
| | Beyond 20 mi radius | 6,097 | -3,396 | 2,701 | 1% | -1% | 0% |
| | Total | -1,237 | -5,437 | -6,674 | 0% | 0% | 0% |

- The areas beyond 15-mile radius from the centroid of the LEZ also experienced increases in VMT and emissions from 2009 and older model year HHDTs by a few percents.

- Due to the less traffic congestion inside the LEZ, which made it more attractive to 2010 and newer model year HHDTs, the VMT as well as PM2.5, NOx, and CO2 emissions from these trucks inside the LEZ all increased by 2%. The changes in these metrics for these trucks outside the LEZ were all minimal (1% or less).

- When considering all the HHDTs together, the emission fee helped reduce the VMT as well as PM2.5, NOx, and CO2 emissions from these trucks inside the LEZ by 20%, 38%, 37%, and 25%, respectively

- The emission fee had minimal impacts on the total emissions in the modeling area shown in Figure 3-2. The total NOx and CO2 emissions remained unchanged, while the total PM2.5 emission increased by 1%.

## 3.3. Exposure-Based Routing

The exposure-based routing strategy was applied to two areas in Southern California. The first one is the city of Carson, CA. It is part of the Wilmington/West Long Beach /Carson community, which is also an AB 617 community designated in 2018. The city is situated about 5 miles north of the San Pedro port complex, and bounded by I-110 on the west and I-170 on the east, both of which connect to the port complex. There are many freight facilities such as logistics centers in the city, which attract a large number of truck trips. In addition, the city has a truck route network that offers alternative routes for trucks to take to the different parts of the city (see Figure 2-3).

The second case study area for this strategy is the ELABHWC community, which was also used as the case study area for the emission-based pricing strategy. The objective was to assess the possibility of using both strategies in conjunction with each other. As discussed earlier, there were some truck trips that could not be diverted away from the community through pricing mechanism as they have either an origin or a destination inside the community. For these truck trips, it may be possible to use the routing strategy to route the truck in a way that minimizes or lowers its impact on the community members.

### 3.3.1. Methods and Assumptions

Figure 3-11 presents the methodological framework of exposure-based routing. It involves a modeling chain that starts from vehicle emission modeling to air dispersion modeling, human exposure assessment, and finally vehicle route calculation where the output from one step is used as an input for the next step. In addition, each step also requires other inputs. The inputs and assumptions associated with each modeling step are described below.

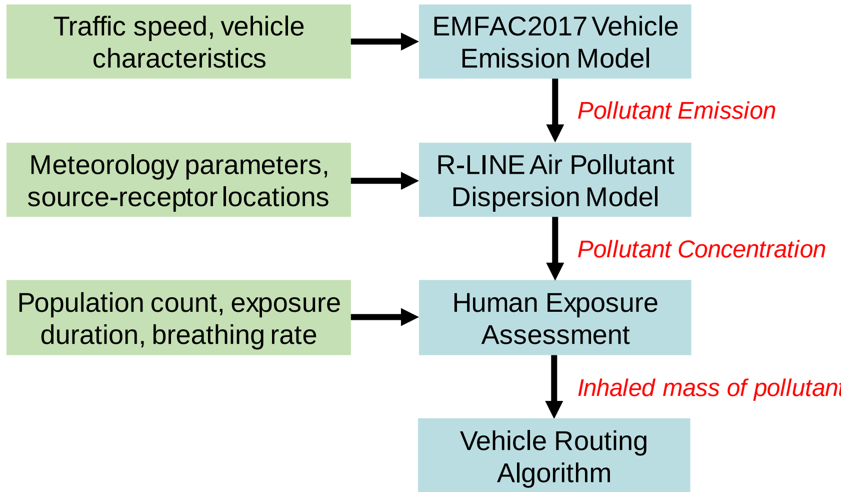



**Figure 3-11. Methodological framework of exposure-based routing**

### *Vehicle Emission Modeling*

The modeling of vehicle emissions was performed in the same way as that described in Secton 3.2.1. However, the calculation was done for only one heavy-duty diesel truck of model year 2012, but for all the roadway links in the modeling area. It was assumed that this truck would be traveling at the speed equal to the historical traffic speed on each roadway link. The data regarding historical traffic speed on roadway links was obtained from a commercial digital roadway map that features historical speed data at 5-minute intervals. Emission factors of the truck were obtained from CARB's EMFAC2017 model, which is a regulatory model for estimating on-road mobile source emissions in California. Only running exhaust PM2.5 and NOx emissions were calculated.

### *Air Dispersion Modeling*

An atmospheric dispersion model was needed to estimate the concentration of air pollutants emitted from vehicular sources at specific receptor locations. In this study, R-LINE, a research grade dispersion model for near-roadway assessment was used [Snyder and Heist, 2013]. Micrometeorology data inputs for R-LINE such as temperature, wind speed, wind direction, surface friction velocity, and Monin-Obukhov length were obtained from a South Coast Air Quality Management District website [South Coast Air Quality Management District, 2019]. The data for Monday May 9, 2016, were used. Source height was assumed to be 2.5 meters (~8.2 ft), which represents a typical height of exhaust stacks of heavy-duty diesel trucks. Receptor height was assumed to be 1 meter (~3.3 ft), which represents an average height of 5 years old children.

### *Human Exposure Assessment*

In this research, pollutant exposure is referred to the amount of pollutant inhaled by a group of subjects. Therefore, *inhaled mass (IM)* was used to represent the pollutant exposure, which was calculated as:

$$IM = C \cdot Pop \cdot t \cdot BR \quad (3\text{-}3)$$

where $C$ is pollutant concentration (µg/m$^3$) in a given microenvironment; $Pop$ is number of subjects in the microenvironment; $t$ is truck travel time on the road link (hour); and $BR$ is breathing rate (m$^3$/hour/capita) of the subjects exposed to the pollutant.

Breathing rates of population in different age groups were based on the U.S. EPA's Exposure Factors Handbook [U.S. Environmental Protection Agency, 2011]. In addition, the California Office of Environmental Health Hazard Assessment's Technical Support Document of Exposure Assessment and Stochastic Analysis included detailed breathing rate scenarios [California Office of Environmental Health Hazard Assessment, 2012]. It is desirable to reduce population exposure to traffic-related air pollutants because tailpipe emissions, such as PM2.5 and NOx, are associated with health risks in young children, older adults, patients, and even healthy adults [Brunekreef et al., 1997; Gong Jr. et al., 2004; Weichenthal et al., 2012]. Thus, in this research a population-wide average breathing rate of 17 m$^3$/day was assumed.

### *Vehicle Route Calculation*

Vehicle routing problem (VRP) is traditionally aimed at finding a travel route between a pair of O-D points that has the shortest distance or shortest travel time. However, in this research, the vehicle routing objective is to minimize inhaled mass of pollutant while limiting the increase in travel distance within a reasonable range for the trip. This is a multi-objective VRP studied by many researchers (e.g., [Grodzevich and Romanko, 2006]). Several methods for solving multi-objective VRP were summarized in [Demir et al., 2014]. In this research, a weighting method was used to transform the multi-objective VRP into a single-objective VRP as in:

$$weighted\_cost_k = \sum_{f=1}^{F}(w_f \times cost_{f,k}) \tag{3-4}$$

where $weighted\_cost_k$ is the combined cost for link $k$; $w_f$ is the weight factor for $cost_{f,k}$, which can be distance, duration, monetary cost, inhaled mass of pollutant, etc. There are a total of $F$ single costs and weigh factors, and $\sum_{f=1}^{F} w_f = 1$.

In the multi-objective VRP in this research, assume $d_k$ is the travel distance of the truck on link $k$ (i.e., length of link $k$), and $IM_k$ is the total mass of pollutant inhaled by a group of subjects after the truck traverses link $k$. Since the two costs have different units and numerical ranges, a normalization was applied as:

$$IM_k = IM_{orig}/IM_{max} \tag{3-5}$$

$$d_k = d_{orig}/d_{max} \tag{3-6}$$

where $IM_{orig}$ and $d_{orig}$ are the original inhaled mass and link length; $IM_{max}$ and $d_{max}$ are the maximum value of inhaled mass and link length in the entire network. The values of link length were indexed to differentiate links on truck routes from the other links. Together, the links on truck routes form a separate truck route network. The vehicle route calculation was then broken down into three steps: 1) find a sub-route in the base network from the trip origin to the nearest point (Point A) in the truck route network, 2) find a sub-route in the truck route network from Point A to Point B, which is a point in the truck route network that is closest to the trip destination, and 3) find a sub-route in the base network from Point B to the trip destination. Finally, the routing algorithm determined a route with the least total cost for the trip where:

$$total\ cost = \sum_{i \in L} cost_i \tag{3-7}$$

and $L$ is the set of links in the least-cost path computed by the routing algorithm. The total cost value is sensitive to $w_f$. When $w_f$ for travel distance is 1, the routing algorithm simply finds the shortest distance route. When $w_f$ for inhaled mass of pollutant is 1, the algorithm simply finds the least pollutant exposure route. Based on a sensitivity analysis of $w_f$ conducted in this study, the values of $w_f$ for travel distance, PM2.5 *IM*, and NOx *IM* were set to 0.5, 0.25, and 0.25, respectively. The calculated route is thus referred to as a low pollutant exposure route or low exposure route.

### 3.3.2. Results for Carson

Twenty-two entry/exit points along the boundary of the city of Carson, CA, and 25 truck trip attractions (e.g., large retail stores, logistic centers, and warehouses) inside the city, shown in Figure 3-12, were selected and used as the origins and destinations of simulated truck trips. Thus, a total of 22 x 25 x 2 = 1,100 trips were simulated. Facilities primarily used by individuals that are most susceptible to the effects of air pollution are termed sensitive facilities or receptors, and include daycares, schools (elementary to high schools), assisted living homes, and public parks. Population data were extracted from 2010 Census and 2017 American Community Survey. Population at sensitive facilities and census blocks were projected assuming 20% of census block-level population stay home at 10 A.M. while they all stay home at 10 P.M.

To better understand how the R-LINE model parameters impact the output concentration values, a sensitivity of road width and freeway sound barrier options in R-LINE was tested. The results showed that for the current modeling scenario, the road width and sound barrier options only have minor effects on the modeled concentration results. On the other hand, the most impactful factors are meteorological conditions, population distribution, and traffic speeds.

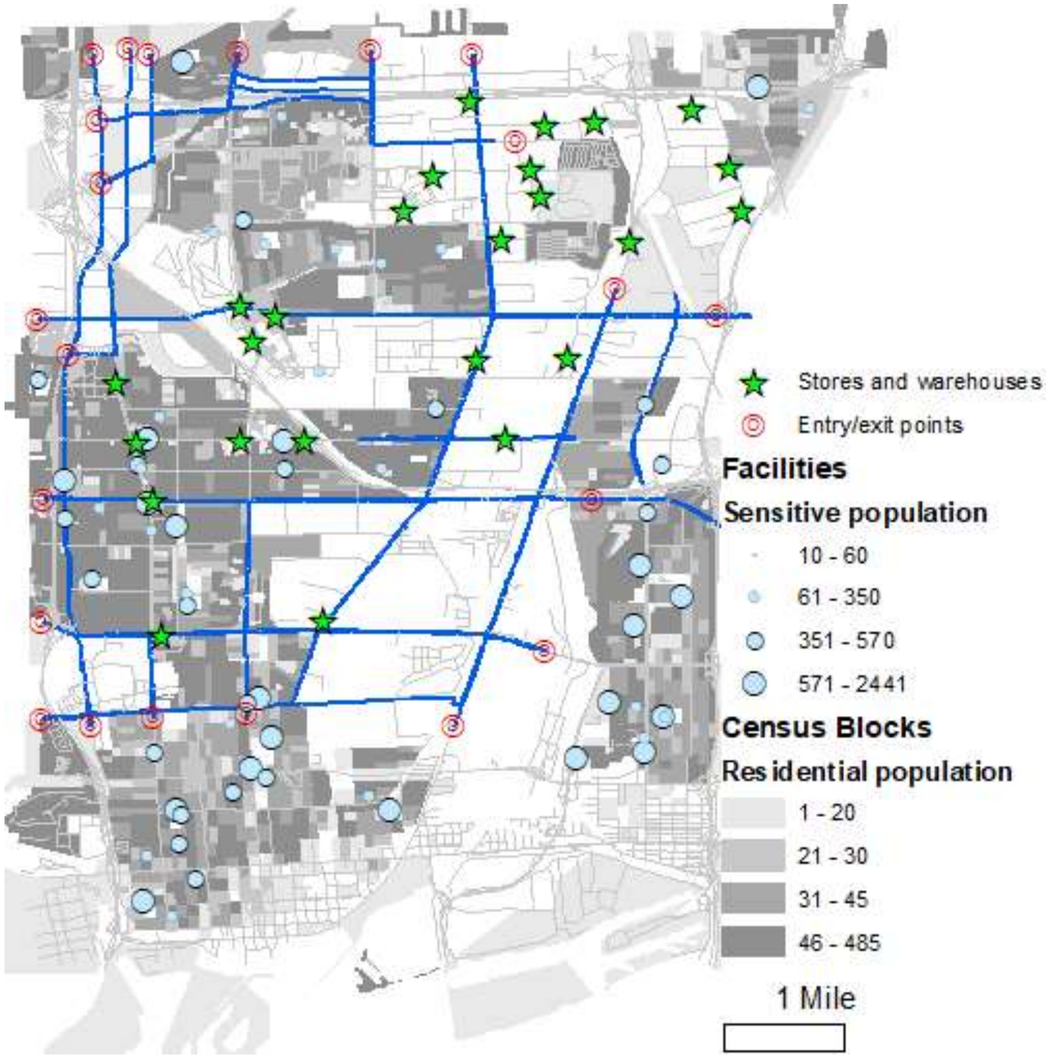



**Figure 3-12. Map of population, sensitive facilities, and truck trip attractions in Carson**

Figure 3-13 and Figure 3-14 show the colored map of modeled PM2.5 *IM* values at sensitive facilities and census blocks based on the meteorological conditions at 10 A.M. on May 9, 2016, respectively. For instance, a PM2.5 *IM* value of 1,000 µg/link means that there would be 1,000 µg of PM2.5 inhaled by the nearby population after the truck has traversed this roadway link in the given scenario. As air pollutants from one roadway link can reach multiple facilities/blocks within 1,500 meters, the *IM* values of roadway links are generally higher for those with large sensitive facilities and densely populated census blocks within proximity. Both figures also show the wind direction, and it can be observed that roadway links upwind of large sensitive facilities and densely populated census blocks generally have higher *IM* values than those downwind. Figure 3-15 shows the aggregated PM2.5 *IM* values from both sensitive facilities and census blocks. Figure 3-16 through Figure 3-18 show the same information as the previous three figures, but for the scenario of 10 P.M. They give a visual comparison of how the meteorological conditions and population distribution can affect the *IM* values.

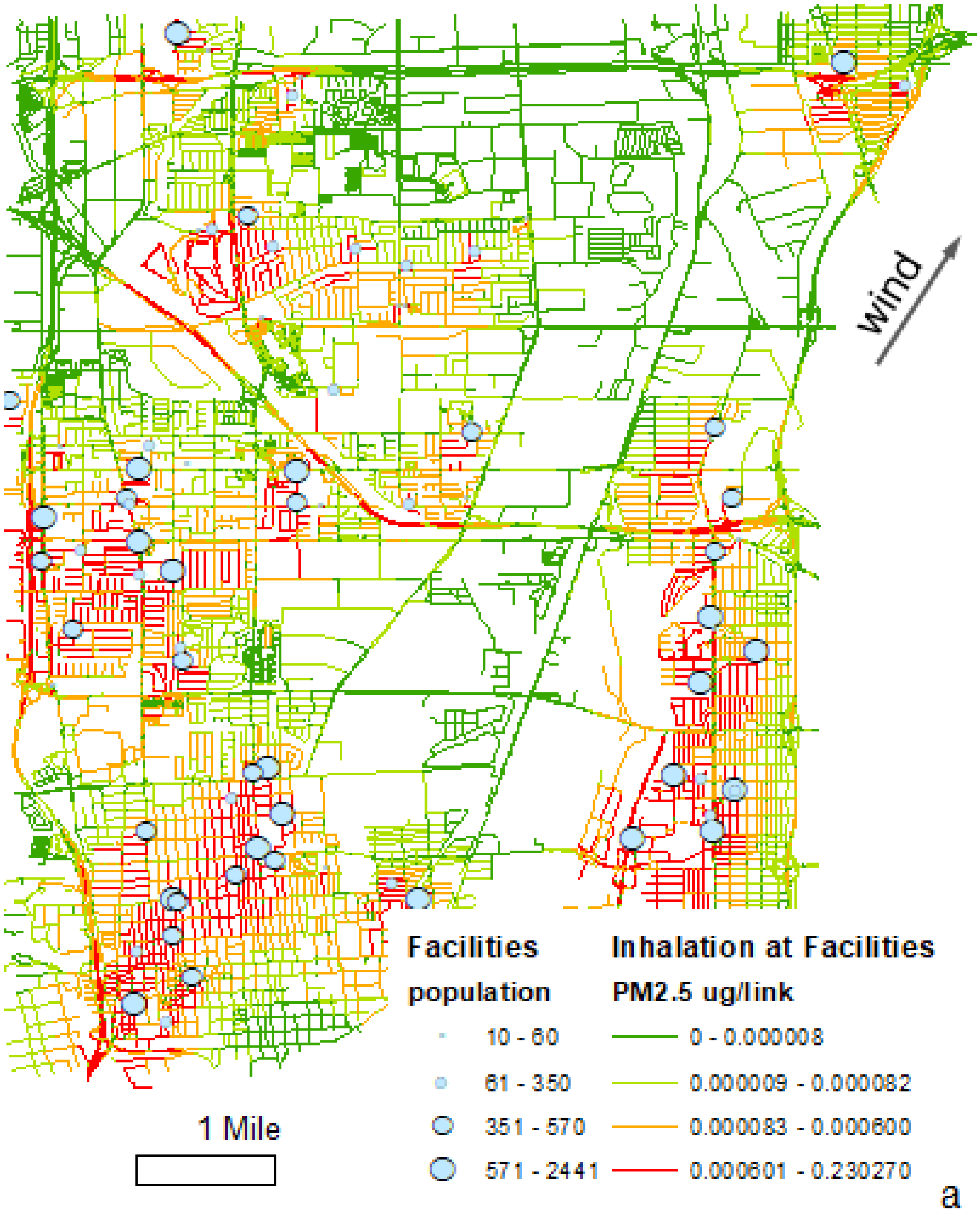



**Figure 3-13. Inhaled mass of PM2.5 ($\mu g/link$) at sensitive facilities at 10 A.M. on May 9, 2016 in Carson**

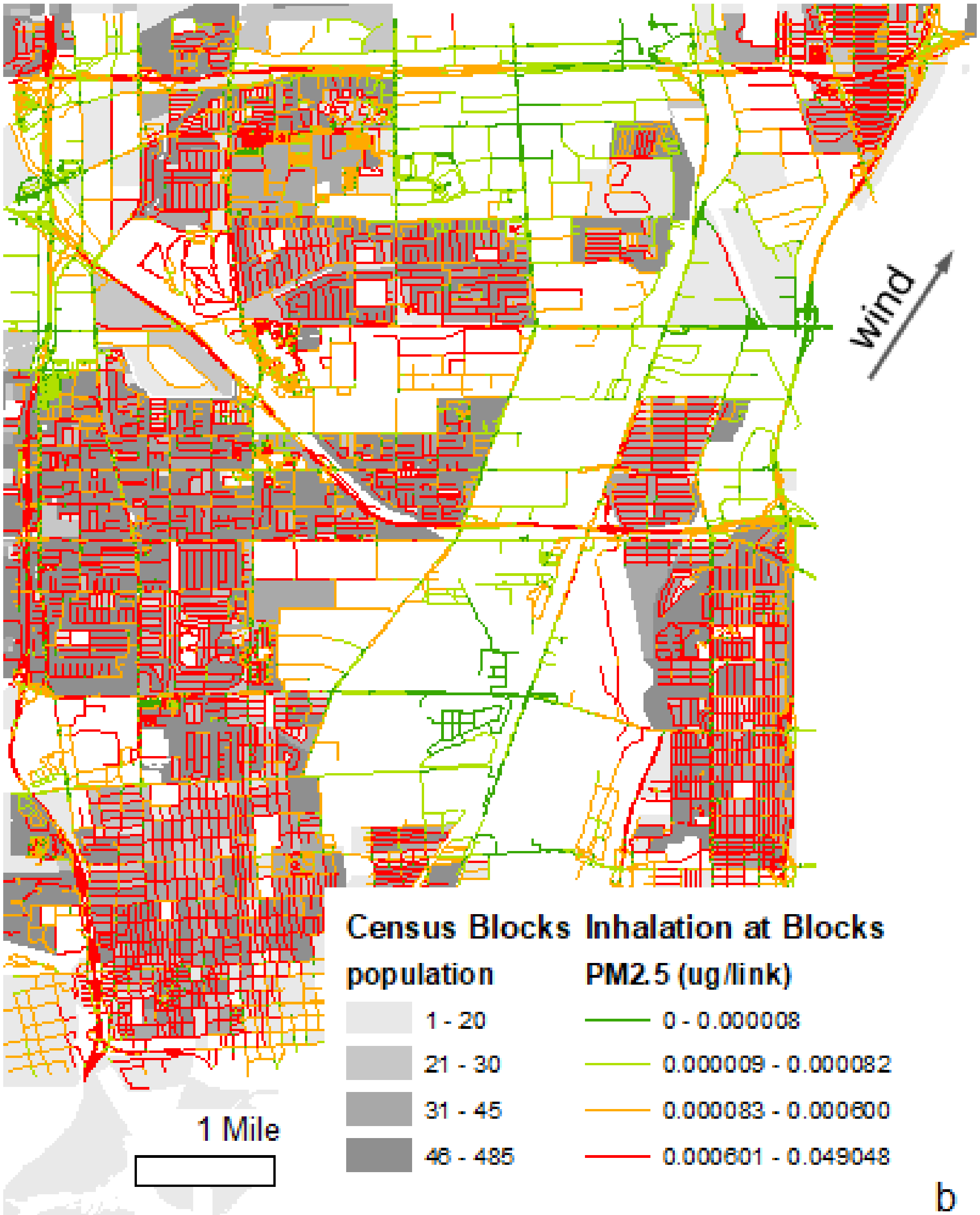



**Figure 3-14. Inhaled mass of PM2.5 ($\mu g/link$) at census blocks at 10 A.M. on May 9, 2016 in Carson**

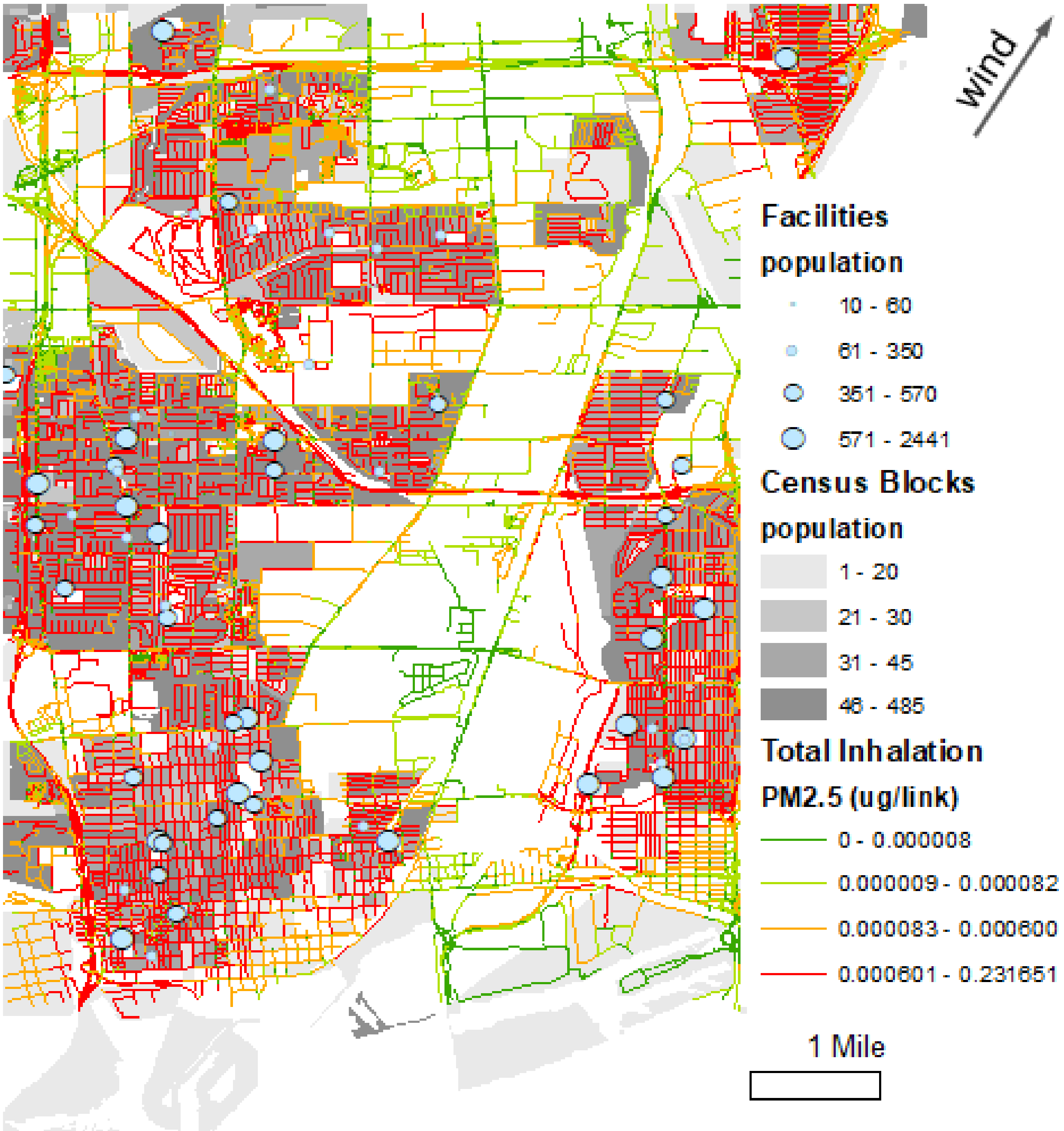



**Figure 3-15. Total inhaled mass of PM2.5 (*μg/link*) at 10 A.M. on May 9, 2016 in Carson**

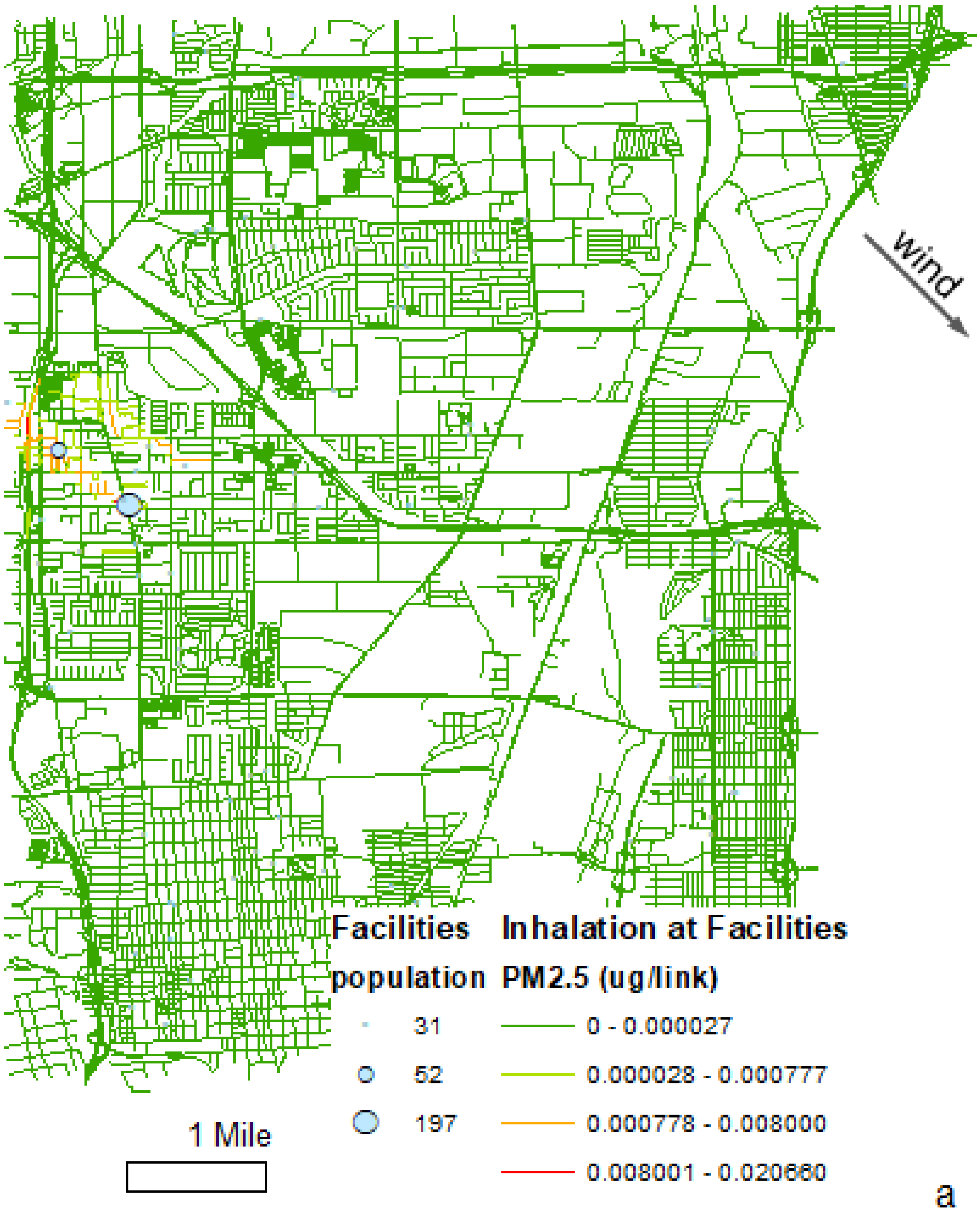



**Figure 3-16. Inhaled mass of PM2.5 ($\mu g/link$) at sensitive facilities at 10 P.M. on May 9, 2016 in Carson**

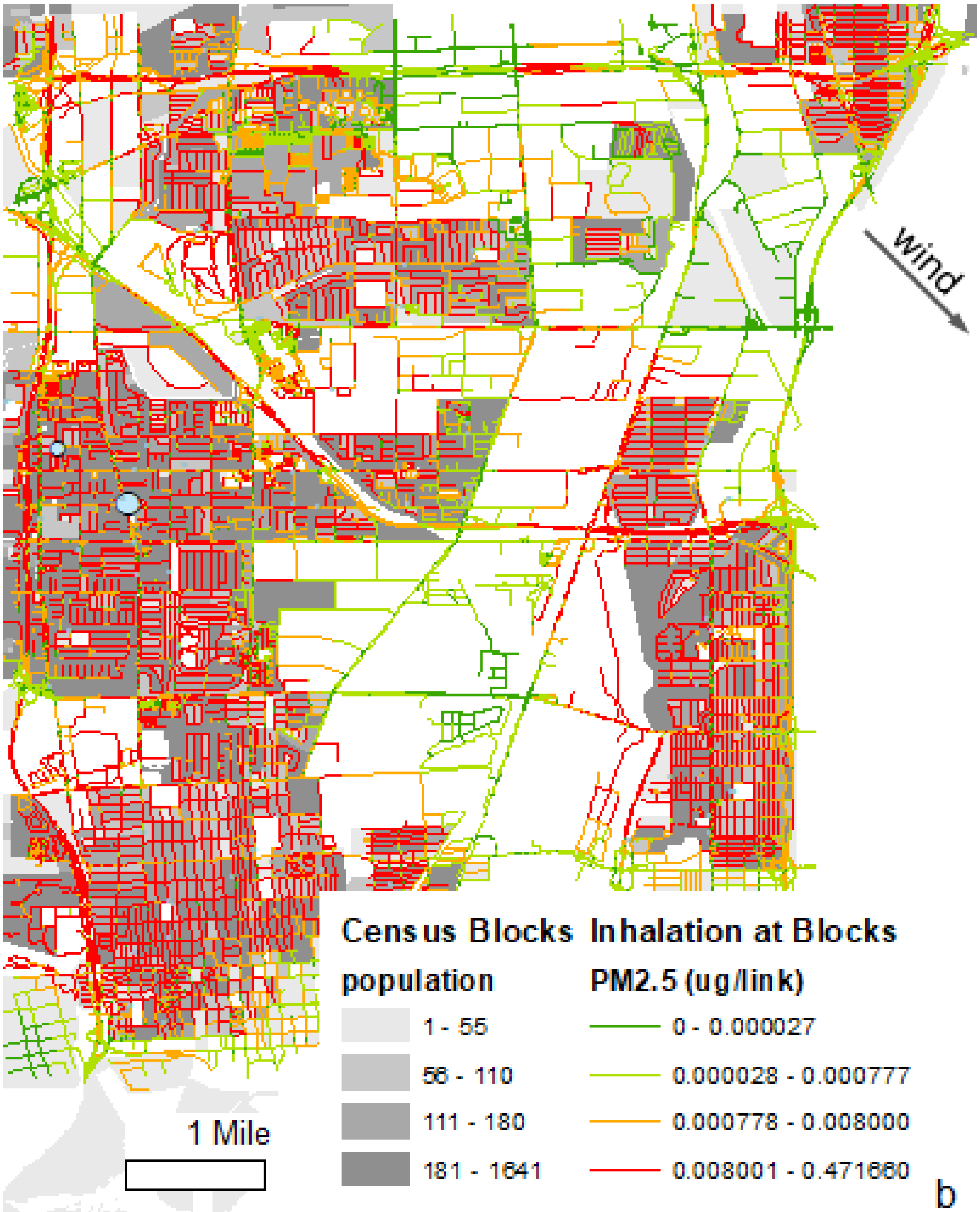



**Figure 3-17. Inhaled mass of PM2.5 (*μg/link*) at census blocks at 10 P.M. on May 9, 2016 in Carson**

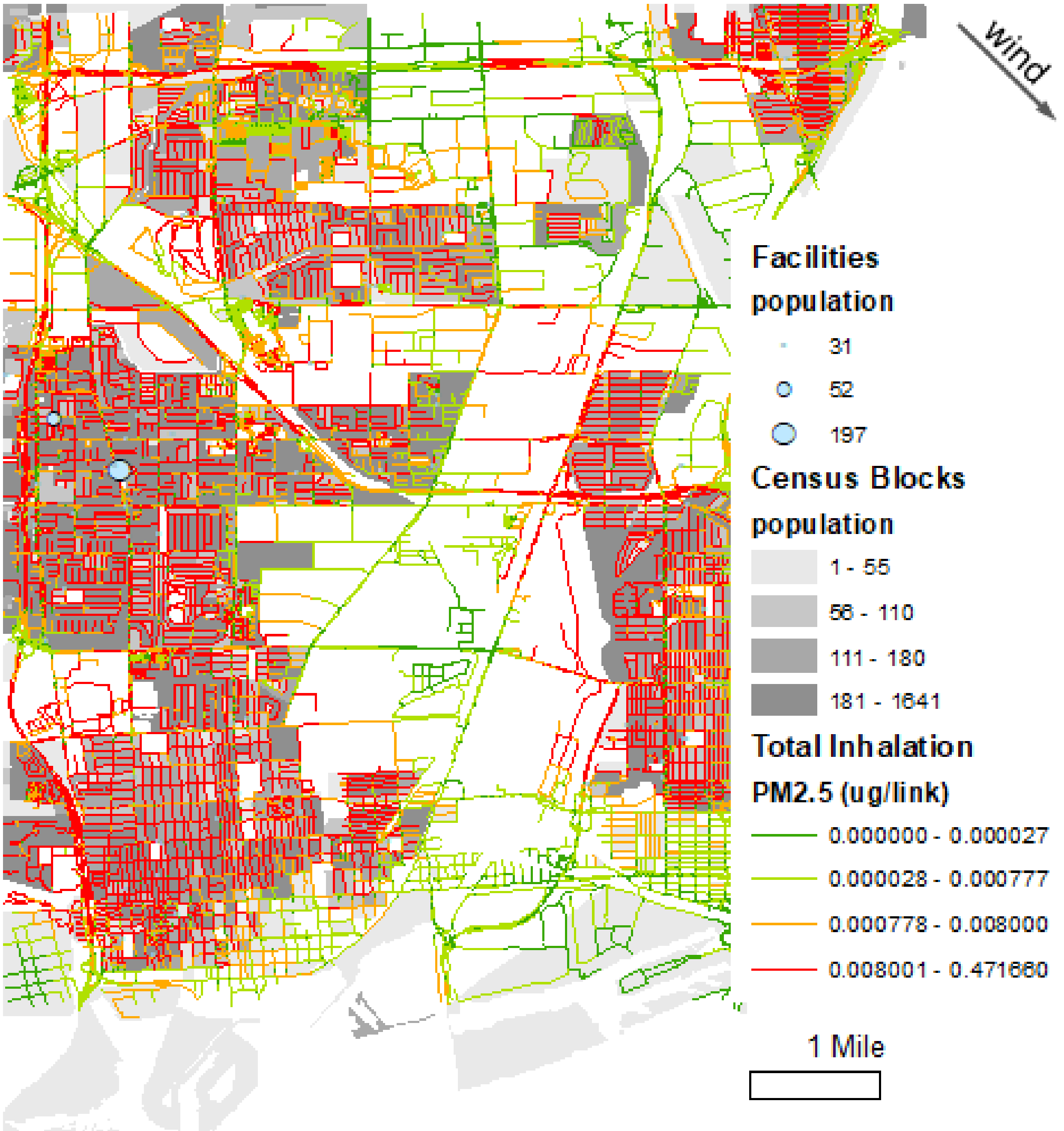



**Figure 3-18. Total inhaled mass of PM2.5 (*μg/link*) at 10 P.M. on May 9, 2016 in Carson**

At the census block level, the population at 10 P.M. is 5 times of that at 10 A.M. scenario (based on the assumption that 20% of population stays at home during working hours). Additionally, the boundary layer condition at 10 P.M. is generally more stable than that at 10 A.M., leading to higher pollutant concentrations near the roadways. However, at 10 P.M., most of the population will be in an indoor microenvironment, in which case an indoor filtration factor can play a role (but not considered in the *IM* calculation in this study). When examining a specific case or route, such detailed factors (e.g., indoor filtration factor, street canyon, high-rise building) can be accounted for.

For each of the 1,100 simulated trips, both the baseline route (BR) and the low exposure route (LER) were determined and their route attributes compared, as presented in Table 3-6 for 10 A.M. As shown in Figure 2-3, the City of Carson designates truck routes throughout the city. For making pickups or deliveries at locations not on truck routes, truck drivers must use the most "direct route" to and from a street on truck routes[5]. Therefore, in determining the BR, it was assumed that truck drivers would normally take the shortest time route when on the truck route network to minimize travel time, and take the shortest distance route when not on the truck route network to comply with the city ordinance.

In Table 3-6, the simulated trips were grouped based on how much longer the trip time of the LER was as compared to that of the BR. The values of route attributes shown in the table are the average value for the trips in each group. It was found that:

- Among the 1,110 simulated trips, the BR and the LER were the same for 669 trips (61%).

- An *attractive* LER with up to 10% longer trip time was found in 257 out of 1,100 trips (23%). On average, the LER for these trips would have 3% longer trip time as compared to the BR, but it would reduce the amount of PM2.5 and NOx emissions from the truck inhaled by community members by 50% and 50%, respectively. It would also reduce tailpipe CO2 emission from the truck by 2% on average.

- An *acceptable* LER with 10%-30% longer trip time was found in 142 out of 1,100 trips (13%). On average, the LER of these trips would have 18% longer trip time and generate 10% more tailpipe CO2 emission as compared to the BR, but it would reduce inhaled mass of PM2.5 and NOx emissions by 65% and 62%, respectively.

Figure 3-19 presents the tradeoff between reduction in PM2.5 inhalation and increase in trip time for the simulated trips during 10 A.M. The numbers right above the "Percentage of Trip Time Increase" are the percentage bins of trip time increase. For example, "2" means that the trip time would increase between 0% and 2% (not including 0%); "5" means that the trip time would increase between 2% to 5% (not including 2%). The "Sum" gives the summation of the corresponding column or row. For instance, "29" (first number of the bottom row) means that the LER would increase trip time by less than or equal to 2% in 29% of the 1,100 simulated trips.

[5] https://ci.carson.ca.us/publicworks/truckroutes.aspx

**Table 3-6. Comparison of route attributes at 10 A.M. on May 9, 2016 in Carson**

| May 9, 2016, 10 A.M. | | Group 1: LER is the same as BR | Group 2: LER is 0%-10% longer | Group 3: LER is 10%-30% longer | Group 4: LER is > 30% longer | All Trips |
|---|---|---|---|---|---|---|
| Number of Trips | | 669 | 257 | 142 | 32 | 1,100 |
| Percent of Trips | | 61% | 23% | 13% | 3% | 100% |
| Baseline Route (BR) | Trip Distance (miles) | 3.8 | 6.0 | 5.2 | 6.0 | 4.6 |
| | Trip Time (minutes) | 8.7 | 11.2 | 9.3 | 9.0 | 9.3 |
| | Trip Speed (mph) | 26.5 | 32.2 | 33.3 | 40.1 | 29 |
| | Inhaled Mass of PM2.5 (µg) | 0.03 | 0.12 | 0.21 | 0.3 | 0.08 |
| | Inhaled Mass of NOx (µg) | 5.7 | 23.4 | 53.1 | 43.1 | 17.0 |
| | Tailpipe emission of CO2 (kg) | 6.9 | 9.9 | 8.4 | 9.1 | 7.9 |
| Low Exposure Route (LER) | Trip Distance (miles) | 3.8 | 5.7 | 5.2 | 6.1 | 4.5 |
| | Trip Time (minutes) | 8.7 | 11.5 | 11.0 | 12.3 | 9.7 |
| | Trip Speed (mph) | 26.5 | 29.8 | 28.5 | 29.9 | 28 |
| | Inhaled Mass of PM2.5 (µg) | 0.03 | 0.06 | 0.07 | 0.1 | 0.04 |
| | Inhaled Mass of NOx (µg) | 5.7 | 11.8 | 20.1 | 23.3 | 9.5 |
| | Tailpipe emission of CO2 (kg) | 6.9 | 9.8 | 9.3 | 10.8 | 8.0 |
| Percent Difference (LER vs. BR) | Trip Distance | 0% | -5% | 1% | 3% | -1% |
| | Trip Time | 0% | 3% | 18% | 37% | 4% |
| | Trip Speed | 0% | -7% | -14% | -25% | -5% |
| | Inhaled Mass of PM2.5 | 0% | -50% | -65% | -69% | -47% |
| | Inhaled Mass of NOx | 0% | -50% | -62% | -46% | -44% |
| | Tailpipe emission of CO2 | 0% | -2% | 10% | 19% | 2% |

| Sum | Percentage of PM2.5 Inhalation Reduction | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 100 | 5.2 | 0 | 0.2 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 |
| 8 | 90 | 6.2 | 0 | 0.2 | 0 | 0.7 | 0.5 | 0 | 0 | 0 | 0 |
| 6 | 80 | 3.3 | 0.2 | 1.2 | 0.2 | 0 | 0 | 0.2 | 0.9 | 0 | 0 |
| 11 | 70 | 2.6 | 1.7 | 3.6 | 1.9 | 0.9 | 0.5 | 0 | 0 | 0 | 0 |
| 12 | 60 | 3.1 | 5.7 | 0.2 | 1.2 | 0.9 | 0.2 | 0.5 | 0.5 | 0 | 0 |
| 13 | 50 | 4.3 | 4 | 0.7 | 0.2 | 1.2 | 0.7 | 1.2 | 0.7 | 0 | 0 |
| 9 | 40 | 1.4 | 1.4 | 1.7 | 1.7 | 0.5 | 0.5 | 0.7 | 0.9 | 0 | 0.2 |
| 23 | 30 | 1.7 | 2.6 | 2.8 | 3.6 | 4 | 2.1 | 2.8 | 2.6 | 0.2 | 0 |
| 10 | 20 | 1.4 | 0.9 | 1.7 | 1.4 | 1.9 | 1.4 | 0.2 | 1.4 | 0 | 0 |
| 2 | 10 | 0 | 0.7 | 0.7 | 0.5 | 0 | 0.2 | 0 | 0 | 0 | 0 |
| | Percentage of Trip Time Increase | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 50 | 60 | 69 |
| | Sum | 29 | 17 | 13 | 11 | 10 | 6 | 6 | 7 | 0 | 0 |

**Figure 3-19. Tradeoff between PM2.5 inhalation reduction and travel time increase at 10 A.M. on May 9, 2016 in Carson**

In Figure 3-19, each number inside the thick box represents the percentage of the total number of trips corresponding to the specific percentage bins of PM2.5 inhalation reduction and trip time increase. All these numbers add up to 100%. It can be seen that there were 15% (5.2% + 6.2% + 3.3%) of the trips where taking the LER would increase the trip time by less than or equal to 2%, but would reduce PM2.5 inhalation by more than 70%. The LER for these trips was very attractive from the perspective of protecting public health without putting a significant economic burden on the truck driver or fleet owner.

Table 3-7 provides the comparison of route attributes between the BR and the LER for the 1,100 simulated trips during 10 P.M. These trips were grouped based on how much longer the trip time of the LER was as compared to that of the BR. The values of route attributes shown in the table are the average value for the trips in each group. It was found that:

- Among the 1,110 simulated trips, the BR and the LER were the same for 399 trips (36%).

- An *attractive* LER with up to 10% longer trip time was found in 258 out of 1,100 trips (23%). On average, the LER for these trips would have 5% longer trip time as compared to the BR, but it would reduce the amount of PM2.5 and NOx emissions from the truck inhaled by community members by 53% and 34%, respectively. It would not change the amount of tailpipe CO2 emission from the truck.

- An *acceptable* LER with 10%-30% longer trip time was found in 312 out of 1,100 trips (28%). On average, the LER of these trips would have 19% longer trip time and generate 11% more tailpipe CO2 emission as compared to the BR, but it would reduce inhaled mass of PM2.5 and NOx emissions by 65% and 43%, respectively.

Figure 3-20 presents the tradeoff between reduction in PM2.5 inhalation and increase in trip time for the simulated trips during 10 P.M. It can be seen that the pattern of this tradeoff matrix is different from the one for the 10 A.M. scenario, which indicates the variation of LER by time of day. For the 10 P.M. scenario, there were 20% (3.7% + 2.9% + 3.6% + 3.1% + 2.1% + 4.1%) of the trips where taking the LER would increase the trip time by 2%-15%, but would reduce PM2.5 inhalation by 20%-40%. The LER for these trips was attractive from the perspective of protecting public health without putting a significant economic burden on the truck driver or fleet owner.

**Table 3-7. Comparison of route attributes at 10 P.M. on May 9, 2016 in Carson**

| May 9, 2016, 10 P.M. | | Group 1: LER is the same as BR | Group 2: LER is 0%-10% longer | Group 3: LER is 10%-30% longer | Group 4: LER is > 30% longer | All Trips |
|---|---|---|---|---|---|---|
| Number of Trips | | 399 | 258 | 312 | 131 | 1,100 |
| Percent of Trips | | 36% | 23% | 28% | 12% | 100% |
| Baseline Route (BR) | Trip Distance (miles) | 3.2 | 5.1 | 5.4 | 5.3 | 4.5 |
| | Trip Time (minutes) | 7.9 | 10.5 | 9.6 | 8.4 | 9.1 |
| | Trip Speed (mph) | 24.3 | 29.1 | 33.9 | 37.8 | 30 |
| | Inhaled Mass of PM2.5 (μg) | 0.17 | 0.86 | 1.05 | 1.4 | 0.72 |
| | Inhaled Mass of NOx (μg) | 50.5 | 148.8 | 161.4 | 183.9 | 120.9 |
| | Tailpipe emission of CO2 (kg) | 6.0 | 8.9 | 8.9 | 8.3 | 7.8 |
| Low Exposure Route (LER) | Trip Distance (miles) | 3.2 | 4.9 | 5.6 | 6.2 | 4.6 |
| | Trip Time (minutes) | 7.9 | 11.0 | 11.4 | 11.9 | 10.1 |
| | Trip Speed (mph) | 24.3 | 26.8 | 29.3 | 31.0 | 27 |
| | Inhaled Mass of PM2.5 (μg) | 0.17 | 0.41 | 0.37 | 0.4 | 0.31 |
| | Inhaled Mass of NOx (μg) | 50.5 | 98.8 | 92.0 | 95.3 | 78.9 |
| | Tailpipe emission of CO2 (kg) | 6.0 | 8.9 | 9.9 | 10.8 | 8.4 |
| Percent Difference (LER vs. BR) | Trip Distance | 0% | -3% | 3% | 17% | 2% |
| | Trip Time | 0% | 5% | 19% | 43% | 12% |
| | Trip Speed | 0% | -8% | -14% | -18% | -8% |
| | Inhaled Mass of PM2.5 | 0% | -53% | -65% | -69% | -57% |
| | Inhaled Mass of NOx | 0% | -34% | -43% | -48% | -35% |
| | Tailpipe emission of CO2 | 0% | 0% | 11% | 30% | 7% |

| Sum | Percentage of PM2.5 Inhalation Reduction | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 100 | 1.4 | 3 | 1 | 0.1 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| 4 | 90 | 0.4 | 1.1 | 1.9 | 0.4 | 0.3 | 0.1 | 0 | 0 | 0 | 0 |
| 6 | 80 | 0.1 | 0.7 | 2.1 | 0.4 | 0.4 | 1 | 1 | 0.3 | 0 | 0.1 |
| 4 | 70 | 0.3 | 0.4 | 0.4 | 0.4 | 0.9 | 0.3 | 0.6 | 0.4 | 0 | 0.1 |
| 7 | 60 | 0.1 | 0 | 1.1 | 0.6 | 0.9 | 2.1 | 0.7 | 1.1 | 0.4 | 0 |
| 12 | 50 | 0.6 | 1.3 | 2.3 | 2 | 0.9 | 1.7 | 1.3 | 1.7 | 0 | 0.6 |
| 22 | 40 | 0.6 | 3.7 | 2.9 | 3.6 | 2.9 | 1.7 | 2 | 3.4 | 0.6 | 0.4 |
| 23 | 30 | 1.3 | 3.1 | 2.1 | 4.1 | 2.3 | 2.7 | 1.7 | 4 | 0.9 | 0.6 |
| 14 | 20 | 0.7 | 0.3 | 2.9 | 2 | 2.9 | 0.9 | 0.9 | 2.7 | 0.9 | 0.1 |
| 2 | 10 | 0.3 | 0.3 | 0.1 | 0 | 0.1 | 0.1 | 0.3 | 0.3 | 0 | 0 |
| Sum | | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 50 | 60 | 69 |
| | | Percentage of Trip Time Increase | | | | | | | | | |
| | Sum | 6 | 14 | 17 | 14 | 11 | 11 | 8 | 14 | 3 | 2 |

**Figure 3-20. Tradeoff between PM2.5 inhalation reduction and travel time increase at 10 P.M. on May 9, 2016 in Carson**

Figure 3-21 illustrates the change of the LER for an example trip at different times of day. The BR remained the same throughout the day, but the LER at 10 P.M. (right side of the figure) was quite different from the LER at 10 A.M. (left side of the figure). The comparison of route attributes is summarized in Table 3-8. At 10 A.M., as compared with the BR, the LER would take 4% longer travel time, but would reduce PM2.5 and NOx inhalations as well as tailpipe CO2 emission by 73%, 31%, and 9%, respectively. At 10 P.M., as compared with BR, the LER would take 11% longer travel time, but would reduce PM2.5 and NOx inhalations as well as tailpipe CO2 emission by 77%, 44%, and 11%, respectively. Based on these comparisons, the truck driver should be encouraged to take the LER for this trip, especially at 10 A.M. when the travel time increase was very small.


**Figure 3-21. BR and LER for an example trip in Carson at 10 A.M. (left) and 10 P.M. (right)**

**Table 3-8. Comparison of route attributes for an example trip in Carson at different times of day**

| | 10 A.M. | | | 10 P.M. | | |
|---|---|---|---|---|---|---|
| | BR | LER | % Diff. | BR | LER | % Diff. |
| Trip Distance (miles) | 11.9 | 9.3 | -22% | 11.9 | 8.7 | -27% |
| Trip Time (minutes) | 16.4 | 17.0 | 4% | 15.9 | 17.6 | 11% |
| Inhaled Mass of PM2.5 (μg) | 0.3 | 0.1 | -73% | 3.7 | 0.9 | -77% |
| Inhaled Mass of NOx (μg) | 29.9 | 20.6 | -31% | 369.0 | 205.7 | -44% |
| Tailpipe emission of CO2 (kg) | 17.6 | 15.9 | -9% | 17.4 | 15.5 | -11% |

### 3.3.3. Results for East Los Angeles, Boyle Heights, West Commerce

Seven entry/exit points along the boundary of the ELABHWC community and 16 truck trip attractions inside the community, shown in Figure 3-22, were selected and used as the origins and destinations of simulated truck trips. Thus, a total of 7 x 16 x 2 = 224 trips were simulated. Similar to the previous case study, population data were extracted from 2010 Census and 2017 American Community Survey. Population at sensitive facilities and census blocks were projected assuming 20% of census block-level population stay home at 10 A.M. while they all stay home at 10 P.M.

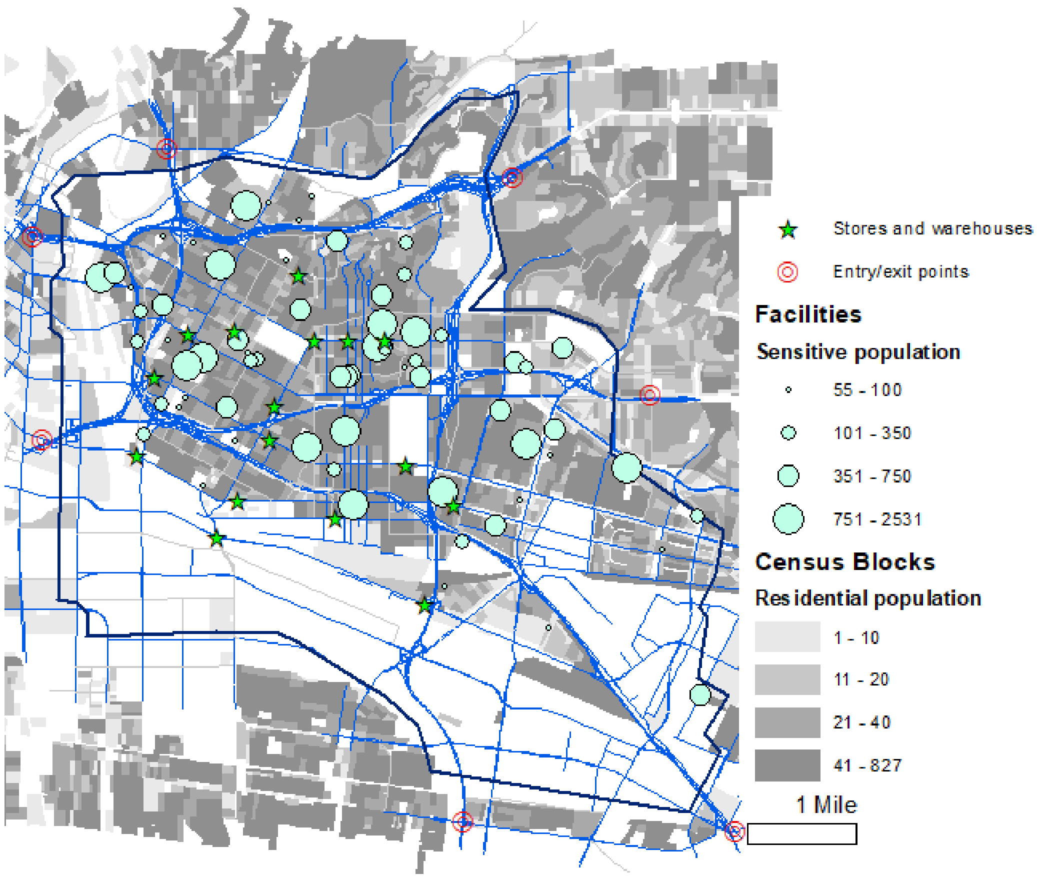



Figure 3-22. Map of population, sensitive facilities, and truck trip attractions in ELABHWC

Figure 3-23 shows the colored map of modeled PM2.5 *IM* values at sensitive facilities and census blocks based on the meteorological conditions at 10 A.M. on May 9, 2016. Figure 3-24 shows the aggregated PM2.5 *IM* values from both sensitive facilities and census blocks. Figure 3-25 and Figure 3-26 show the same information as the previous two figures, but for the scenario of 10 P.M. The differences in population and meteorological conditions resulted in significantly different *IM* values.

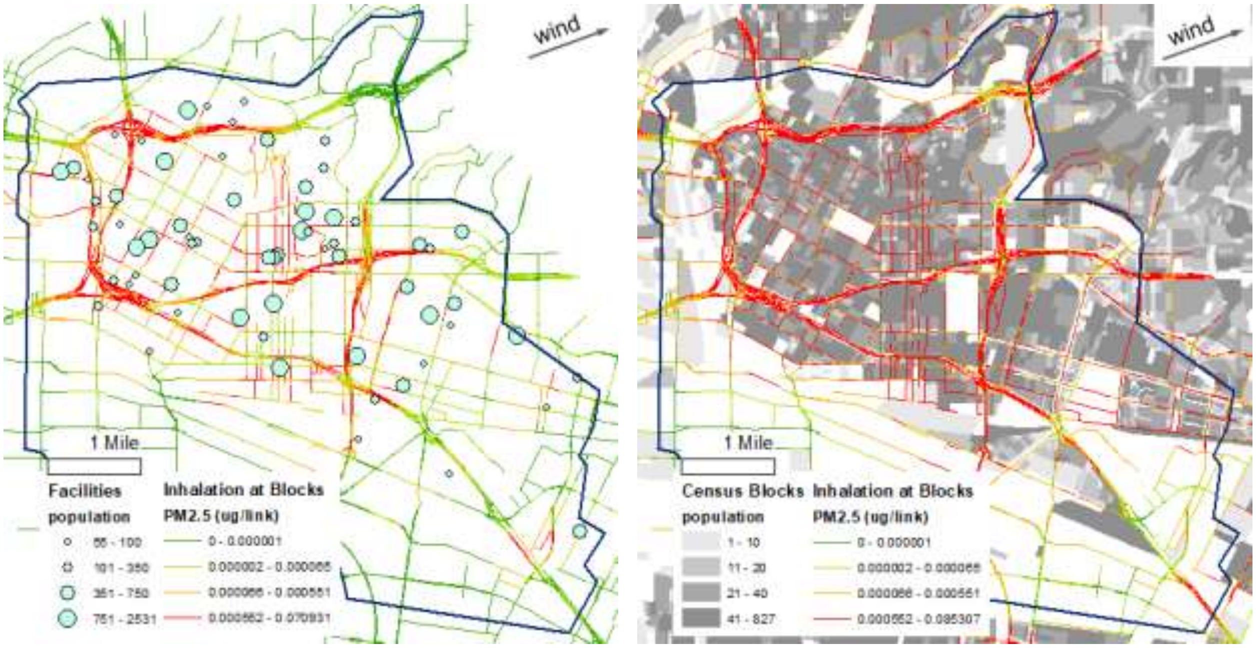



**Figure 3-23. Inhaled mass of PM2.5 ($\mu g/link$) at (left) sensitive facilities and (right) census blocks at 10 A.M. on May 9, 2016 in ELABHWC**

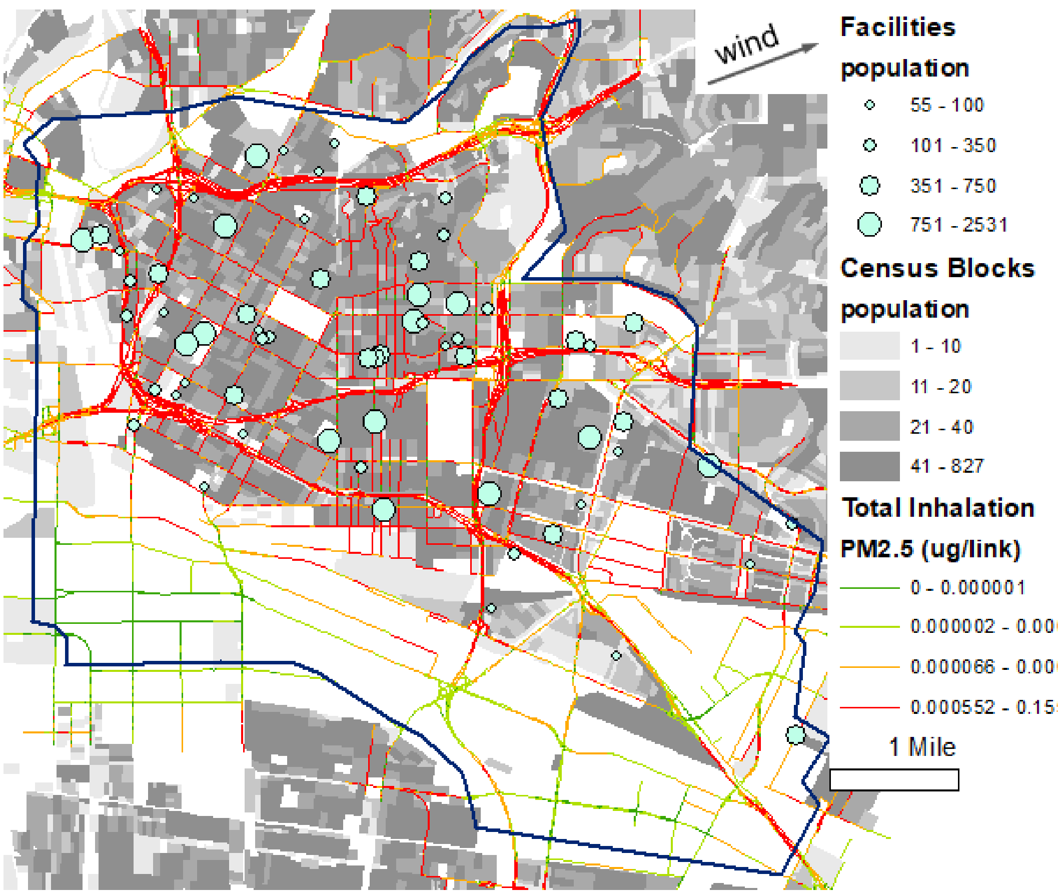



**Figure 3-24. Total inhaled mass of PM2.5 ($\mu g/link$) at 10 A.M. on May 9, 2016 in ELABHW**

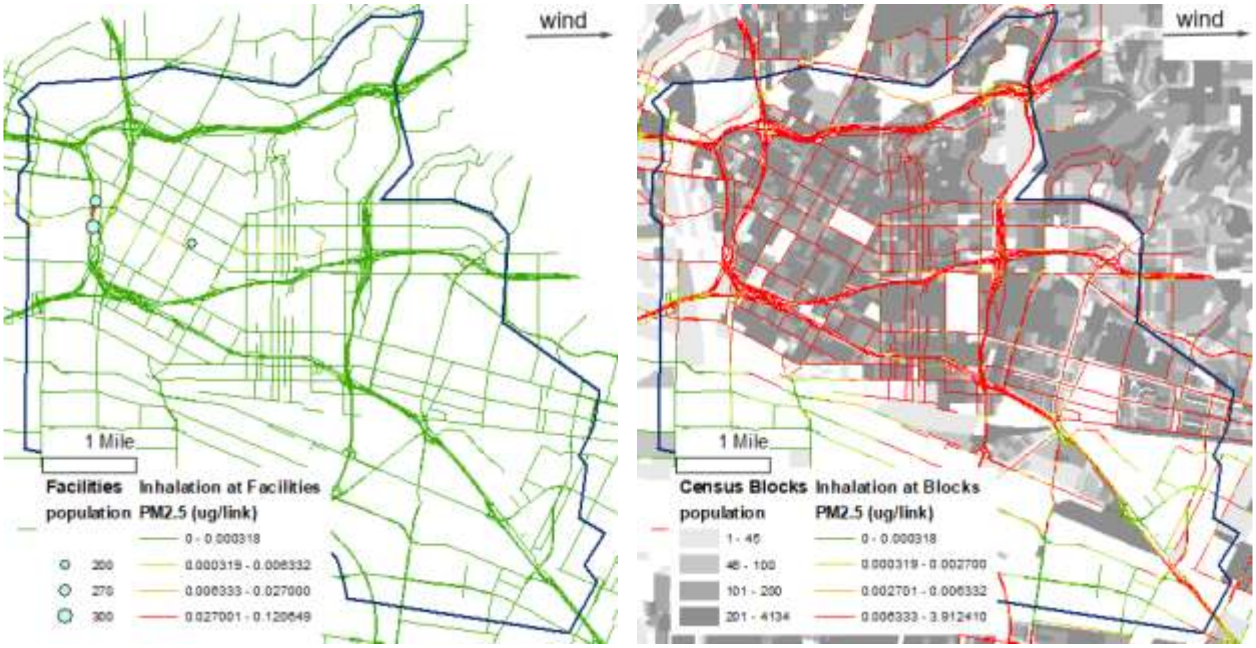



**Figure 3-25. Inhaled mass of PM2.5 ($\mu g/link$) at (left) sensitive facilities and (right) census blocks at 10 P.M. on May 9, 2016 in ELABHWC**

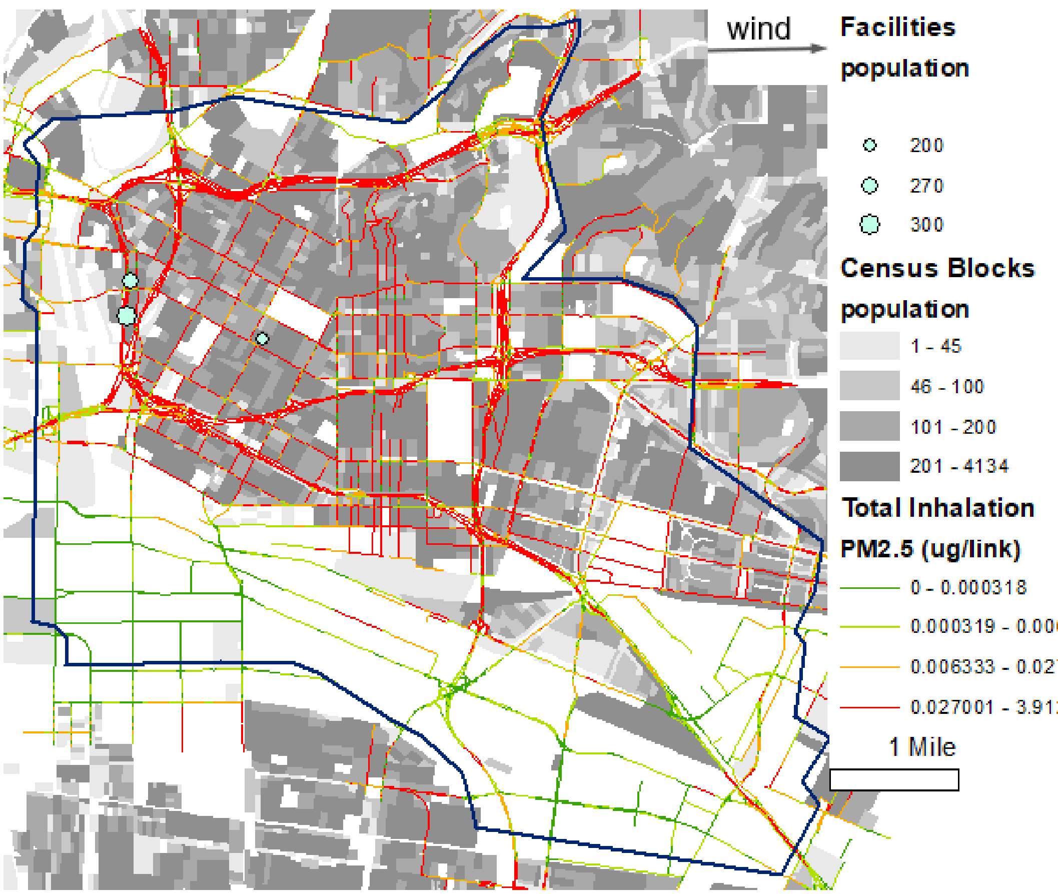



**Figure 3-26. Total inhaled mass of PM2.5 ($\mu g/link$) at 10 P.M. on May 9, 2016 in ELABHWC**

For each of the 224 simulated trips, both the BR and the LER were determined and their route attributes compared, as presented in Table 3-9 for the 10 A.M. scenario. Again, these trips were grouped based on how much longer the trip time of the LER was as compared to that of the BR. The values of route attributes shown in the table are the average value for the trips in each group. It was found that:

- Among the 224 simulated trips, the BR and the LER were the same for 59 trips (26%).
- An *attractive* LER with up to 10% longer trip time was found in 29 out of 224 trips (13%). On average, the LER for these trips would have 5% longer trip time as compared to the BR, but it would reduce the amount of PM2.5 and NOx emissions from the truck inhaled by community members by 41% and 10%, respectively. It would also reduce tailpipe CO2 emission from the truck by 2% on average.
- An *acceptable* LER with 10%-30% longer trip time was found in 65 out of 224 trips (29%). On average, the LER of these trips would have 19% longer trip time and generate 4% more tailpipe CO2 emission as compared to the BR, but it would reduce inhaled mass of PM2.5 emission by 54%. Interestingly, the LER for this group of trips would result in a 3% increase in inhaled mass of NOx emission. This is possible as the values of $w_f$ in Equation (3-4) for travel distance, PM2.5 *IM*, and NOx *IM* were set as 0.5, 0.25, and 0.25, respectively.

**Table 3-9. Comparison of route attributes at 10 A.M. on May 9, 2016 in ELABHWC**

| May 9, 2016, 10 A.M. | | Group 1: LER is the same as BR | Group 2: LER is 0%-10% longer | Group 3: LER is 10%-30% longer | Group 4: LER is > 30% longer | All Trips |
|---|---|---|---|---|---|---|
| Number of Trips | | 59 | 29 | 65 | 71 | 224 |
| Percent of Trips | | 26% | 13% | 29% | 32% | 100% |
| Baseline Route (BR) | Trip Distance (miles) | 3.1 | 4.1 | 5.2 | 5.5 | 4.6 |
| | Trip Time (minutes) | 6.4 | 7.4 | 8.6 | 7.9 | 7.7 |
| | Trip Speed (mph) | 28.8 | 32.8 | 36.2 | 41.6 | 36 |
| | Inhaled Mass of PM2.5 (µg) | 0.10 | 0.18 | 0.31 | 0.4 | 0.25 |
| | Inhaled Mass of NOx (µg) | 35.5 | 39.8 | 49.2 | 49.3 | 44.4 |
| | Tailpipe emission of CO2 (kg) | 5.5 | 6.8 | 8.4 | 8.4 | 7.4 |
| Low Exposure Route (LER) | Trip Distance (miles) | 3.1 | 3.7 | 4.9 | 5.3 | 4.4 |
| | Trip Time (minutes) | 6.4 | 7.8 | 10.3 | 11.6 | 9.4 |
| | Trip Speed (mph) | 28.8 | 28.4 | 28.4 | 27.3 | 28 |
| | Inhaled Mass of PM2.5 (µg) | 0.10 | 0.10 | 0.14 | 0.1 | 0.12 |
| | Inhaled Mass of NOx (µg) | 35.5 | 36.0 | 50.4 | 52.8 | 45.4 |
| | Tailpipe emission of CO2 (kg) | 5.5 | 6.7 | 8.8 | 9.7 | 7.9 |
| Percent Difference (LER vs. BR) | Trip Distance | 0% | -9% | -7% | -3% | -4% |
| | Trip Time | 0% | 5% | 19% | 47% | 22% |
| | Trip Speed | 0% | -13% | -22% | -34% | -22% |
| | Inhaled Mass of PM2.5 | 0% | -41% | -54% | -61% | -50% |
| | Inhaled Mass of NOx | 0% | -10% | 3% | 7% | 2% |
| | Tailpipe emission of CO2 | 0% | -2% | 4% | 15% | 6% |

Figure 3-27 presents the tradeoff between reduction in PM2.5 inhalation and increase in trip time for the simulated trips during 10 A.M. It can be observed that for a large percentage of the trips, the LER would be a long detour, with more than 30% longer trip time than the BR. This is likely because, as shown in Figure 3-22, the dense census blocks, sensitive facilities, and truck trip attractions are distributed over the same areas of the community. Therefore, for these trips the truck would need to take a long detour to avoid passing by dense census blocks and sensitive facilities. On the other hand, there are many trips where the trip time increase would be less than 5%, some of which would reduce the PM2.5 inhalation significantly.

| *Sum* | Percentage of PM2.5 Inhalation Reduction | 2 | 5 | 10 | 15 | 20 | 25 | 30 | 50 | 60 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *8* | **100** | 0 | 3.7 | 0.6 | 2.5 | 0.6 | 0.6 | 0 | 0 | 0 | 0 |
| *5* | **90** | 0 | 0 | 0.6 | 1.8 | 1.2 | 0 | 0.6 | 0.6 | 0 | 0 |
| *8* | **80** | 0.6 | 1.2 | 2.5 | 1.2 | 0 | 0.6 | 1.2 | 0.6 | 0 | 0 |
| *7* | **70** | 0 | 0 | 0 | 2.5 | 1.2 | 0.6 | 0 | 2.5 | 0 | 0 |
| *15* | **60** | 0.6 | 0.6 | 1.8 | 0.6 | 1.2 | 0.6 | 1.2 | 4.3 | 1.8 | 2.5 |
| *17* | **50** | 0 | 0.6 | 0.6 | 1.2 | 3.1 | 0.6 | 0.6 | 6.1 | 2.5 | 1.8 |
| *19* | **40** | 0 | 0 | 0 | 0.6 | 2.5 | 2.5 | 0.6 | 8.6 | 1.2 | 3.1 |
| *9* | **30** | 0 | 0.6 | 0.6 | 0.6 | 0.6 | 1.8 | 0.6 | 3.1 | 0.6 | 0.6 |
| *9* | **20** | 0 | 0 | 0.6 | 0 | 1.2 | 1.2 | 3.1 | 1.2 | 0.6 | 0.6 |
| *3* | **10** | 0 | 0 | 1.2 | 0 | 0.6 | 0 | 0 | 0.6 | 0 | 0.6 |
| | Percentage of Trip Time Increase | **2** | **5** | **10** | **15** | **20** | **25** | **30** | **50** | **60** | **88** |
| | *Sum* | *1* | *7* | *9* | *11* | *12* | *9* | *8* | *28* | *7* | *9* |

**Figure 3-27. Tradeoff between PM2.5 inhalation reduction and driving distance increase at 10 A.M. on May 9, 2016 in ELABHWC**

Table 3-10 provides the comparison of route attributes between the BR and the LER for the 224 simulated trips during 10 P.M. These trips were grouped based on how much longer the trip time of the LER was as compared to that of the BR. The values of route attributes shown in the table are the average value for the trips in each group. It was found that:

- Among the 224 simulated trips, the BR and the LER were the same for 47 trips (21%).
- An *attractive* LER with up to 10% longer trip time was found in 34 out of 224 trips (15%). On average, the LER for these trips would have 5% longer trip time as compared to the BR, but it would reduce the amount of PM2.5 and NOx emissions from the truck inhaled by community members by 30% and 8%, respectively. It would also reduce tailpipe $CO_2$ emission from the truck by 3% on average.

- An *acceptable* LER with 10%-30% longer trip time was found in 73 out of 224 trips (33%). On average, the LER of these trips would have 20% longer trip time and generate 3% more tailpipe CO2 emission as compared to the BR, but it would reduce inhaled mass of PM2.5 and NOx emissions by 50% and 11%, respectively.

**Table 3-10. Comparison of route attributes at 10 P.M. on May 9, 2016 in ELABHWC**

| May 9, 2016, 10 P.M. | | Group 1: LER is the same as BR | Group 2: LER is 0%-10% longer | Group 3: LER is 10%-30% longer | Group 4: LER is > 30% longer | All Trips |
|---|---|---|---|---|---|---|
| Number of Trips | | 47 | 34 | 73 | 70 | 224 |
| Percent of Trips | | 21% | 15% | 33% | 31% | 100% |
| Baseline Route (BR) | Trip Distance (miles) | 3.2 | 3.7 | 4.8 | 5.7 | 4.6 |
| | Trip Time (minutes) | 5.9 | 6.5 | 7.5 | 7.6 | 7.0 |
| | Trip Speed (mph) | 32.6 | 33.7 | 38.7 | 45.0 | 39 |
| | Inhaled Mass of PM2.5 (μg) | 3.48 | 4.53 | 7.99 | 9.6 | 7.01 |
| | Inhaled Mass of NOx (μg) | 1,057.1 | 1,027.9 | 1,211.8 | 1,234.0 | 1,158.4 |
| | Tailpipe emission of CO2 (kg) | 5.5 | 6.3 | 7.9 | 9.2 | 7.6 |
| Low Exposure Route (LER) | Trip Distance (miles) | 3.2 | 3.4 | 4.6 | 5.5 | 4.4 |
| | Trip Time (minutes) | 5.9 | 6.8 | 9.0 | 11.3 | 8.7 |
| | Trip Speed (mph) | 32.6 | 30.3 | 30.9 | 29.2 | 30 |
| | Inhaled Mass of PM2.5 (μg) | 3.48 | 3.16 | 3.96 | 3.2 | 3.50 |
| | Inhaled Mass of NOx (μg) | 1,057.1 | 946.9 | 1,073.9 | 1,136.9 | 1,070.8 |
| | Tailpipe emission of CO2 (kg) | 5.5 | 6.1 | 8.1 | 9.9 | 7.8 |
| Percent Difference (LER vs. BR) | Trip Distance | 0% | -6% | -4% | -4% | -4% |
| | Trip Time | 0% | 5% | 20% | 48% | 24% |
| | Trip Speed | 0% | -10% | -20% | -35% | -22% |
| | Inhaled Mass of PM2.5 | 0% | -30% | -50% | -67% | -50% |
| | Inhaled Mass of NOx | 0% | -8% | -11% | -8% | -8% |
| | Tailpipe emission of CO2 | 0% | -3% | 3% | 7% | 3% |

Figure 3-28 presents the tradeoff between reduction in PM2.5 inhalation and increase in trip time for the simulated trips during 10 P.M. It can be seen that the pattern of this tradeoff matrix is similar to the one for the 10 A.M. scenario in that for a large percentage of the trips, the LER would be a long detour, with more than 30% longer trip time than the BR. On the other hand, there are 7.5% (2.3% + 2.9% + 2.3%) of the trips where the trip time increase would be less than 10%, but the PM2.5 inhalation would be reduced by more than 90%.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *7* | **Percentage of PM2.5 Inhalation Reduction** | **100** | 2.3 | 2.9 | 2.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *6* | | **90** | 0 | 0 | 0.6 | 2.9 | 1.1 | 1.1 | 0 | 0.6 | 0 | 0 |
| *10* | | **80** | 0 | 1.1 | 1.1 | 1.1 | 2.9 | 1.1 | 1.7 | 1.1 | 0 | 0 |
| *11* | | **70** | 1.1 | 1.1 | 1.7 | 1.1 | 1.1 | 0.6 | 2.3 | 1.7 | 0.6 | 0 |
| *13* | | **60** | 0 | 0.6 | 2.3 | 2.9 | 0 | 1.1 | 1.7 | 3.4 | 0.6 | 0 |
| *14* | | **50** | 0 | 0 | 0 | 1.1 | 2.3 | 0.6 | 1.7 | 4 | 1.1 | 2.9 |
| *17* | | **40** | 0 | 0 | 0.6 | 1.1 | 1.7 | 1.7 | 1.1 | 6.9 | 1.1 | 2.3 |
| *7* | | **30** | 0 | 0 | 0 | 1.1 | 0 | 1.1 | 1.7 | 1.1 | 1.1 | 1.1 |
| *11* | | **20** | 0 | 0 | 0.6 | 0.6 | 0 | 0.6 | 0.6 | 5.1 | 0.6 | 2.9 |
| *3* | | **10** | 0 | 0 | 0 | 0 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| *Sum* | | | **2** | **5** | **10** | **15** | **20** | **25** | **30** | **50** | **60** | **86** |
| | | | **Percentage of Trip Time Increase** | | | | | | | | | |
| | | *Sum* | *3* | *6* | *9* | *12* | *10* | *9* | *11* | *25* | *6* | *10* |

**Figure 3-28. Tradeoff between PM2.5 inhalation reduction and driving distance increase at 10 P.M. on May 9, 2016 in ELABHWC**

Figure 3-29 illustrates the change of the LER for an example trip at different times of day. The BR remained the same throughout the day, but the LER at 10 P.M. (right side of the figure) was slightly different from the LER at 10 A.M. (left side of the figure). This is because several conditions, such as wind direction, traffic congestion, number of population at sensitive facilities, and number of population in census blocks at those times of day were not the same. The comparison of route attributes is summarized in Table 3-11. At 10 A.M., as compared with the BR, the LER would take only 2% longer travel time, but would reduce PM2.5 and NOx inhalations by 74% and 37%, respectively. In addition, taking the LER instead of the BR would reduce tailpipe CO2 emission (and fuel consumption) by 13%. At 10 P.M., the LER would take 12% longer travel time, but would reduce PM2.5 and NOx inhalations by about 80% and 56%, respectively. In addition, taking the LER instead of the BR would reduce tailpipe CO2 emission (and fuel consumption) by 16%. Based on these comparisons, the truck driver should be encouraged to take the LER for this trip, especially at 10 A.M. when the travel time increase was very small.

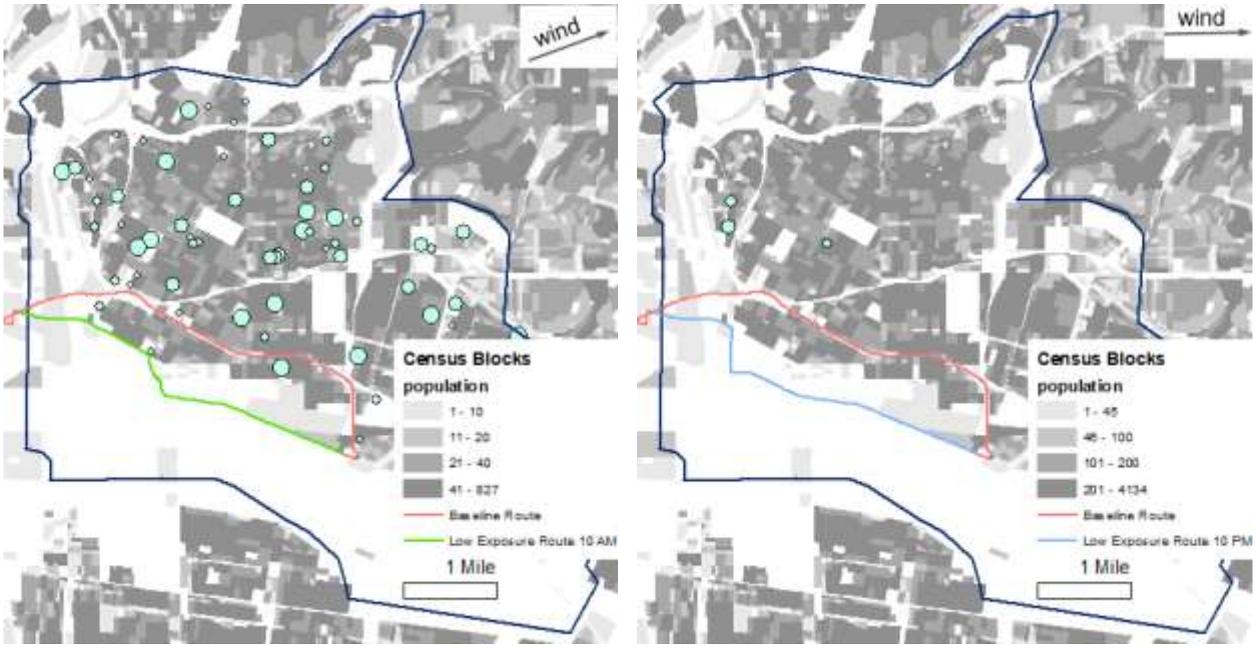



**Figure 3-29. SDR and LER for an example trip in ELABHWC at 10 A.M. (left) and 10 P.M. (right)**

**Table 3-11. Comparison of route attributes for an example trip in ELABHWC at different times of day**

| | 10 A.M. | | | 10 P.M. | | |
|---|---|---|---|---|---|---|
| | BR | LER | % Diff. | BR | LER | % Diff. |
| **Trip Distance (miles)** | 5.4 | 4.1 | -24% | 5.4 | 4.2 | -21% |
| **Trip Time (minutes)** | 8.5 | 8.7 | 2% | 7.7 | 8.7 | 12% |
| **Inhaled Mass of PM2.5 (μg)** | 0.2 | 0.1 | -74% | 6.9 | 1.4 | -80% |
| **Inhaled Mass of NOx (μg)** | 29.7 | 19.7 | -34% | 833.5 | 368.7 | -56% |
| **Tailpipe emission of CO2 (kg)** | 8.4 | 7.3 | -13% | 9.0 | 7.5 | -16% |

# 4. Conclusions

## 4.1. Summary of Findings

The main objective of this research project was to identify and evaluate geofencing strategies in the heavy-duty truck sector that could lower pollutant emissions in disadvantaged communities (DACs) or other areas of poor air quality. For the purposes of this study, geofencing was defined as using a virtual boundary of a specific area within a broader geographic area where strategies can be triggered to reduce air pollutant emissions and adverse public health and environmental impacts. Such strategies can be triggered temporally and spatially. This section of the report discusses project results and the potential use of geofencing to achieve public policies established by the California Governor, Legislature and Air Resources Board related to air pollution control and improved public health.

The research consists of two major parts: 1) Literature Review, and 2) Case Study Modeling and Simulation Evaluation. Two study areas were chosen for the evaluation—East Los Angeles/Boyle Heights/West Commerce (ELABHWC) community and Wilmington/West Long Beach /Carson (WWLBC) community. Both communities are categorized as DACs by CalEnviroScreen and selected in 2018 to participate in the Community Air Protection Program under California law AB 617. In addition, the requisite data for each area was available for both travel demand modeling and air pollution/human exposure modeling. Community concerns in each area regarding local air quality have also well documented, and a number of air quality studies have verified disproportionate environmental justice impacts compared to many other communities in California.

### 4.1.1. Literature Review

As noted above, one major part of the study was an extensive literature review of publications and reports pertaining to geofencing case studies and related transportation and/or air pollution modeling and impact studies. More than 100 such studies were reviewed to assess the state-of-the-science regarding various kinds of geofencing strategies, categorized into three groups—1) transportation network level, 2) vehicle and driver level, and 3) powertrain and emission control system level.

It was difficult to conduct a quantitative comparison of the different geofencing strategies because there were many differences in how they were modeled or implemented, including in different geographic areas and times as well as under different conditions and assumptions. Nevertheless, Table 4-1 provides a qualitative comparison of geofencing strategies reviewed in Chapter 2 of this report. The comparison was made in terms of technology readiness, ease of implementation (from political, institutional, legal, and operational perspectives), benefits (environmental, climate, and public health), and costs (for implementation and operation).

**Table 4-1. Qualitative comparison of geofencing strategies reviewed in this research**

| Geofencing Strategies | Technology Readiness | Ease of Implementation* | Benefits** | Costs*** |
|---|---|---|---|---|
| | | ***Transportation Network Level*** | | |
| **Access Restriction and Pricing** | *High* – Has already been implemented worldwide, so the necessary technologies are available. | *Low* – There could be political, institutional, and legal barriers to the implementation. | *High* – Based on evidence from existing low emission zones in Europe. | *High* – Would require substantial implementation and operation costs, similar to toll roads. |
| **Designating Truck Routes** | *High* – No technology required. | *High* – The process for designating truck routes through local ordinance is established. | *Low* – It would not change the amount of truck traffic in communities, but could move truck traffic away from population. | *Low* – Minimal planning, engineering, and community engagement costs. |
| **Energy-, Emission-, or Exposure-based Routing** | *Medium* – Proven in simulation and prototype, but no large-scale implementation yet. | *Medium to High* – Does not require government approval, but rely on buy-ins from truck drivers and fleet operators | *Medium* – Level of benefits depends on fleet adoption and varies by trip. | *Low to Medium* – Can leverage existing truck routing and navigation technologies |
| **Speed Management** | *High* – Several technologies exist for vehicle speed enforcement. | *High* – Has already implemented broadly for safety reasons. | *Low to Medium* – Level of benefits depends on emission vs. speed relationships for different pollutants | *Low to Medium* – Depends on level of sophistication and supporting technologies. |
| | | ***Vehicle and Driver Level*** | | |
| **Eco-Driving** | *High* – Eco-driving practices have been promoted for a long time. More advanced eco-driving technologies are also available. | *High* – Can be as simple as driver training or incorporated into truck telematics systems. | *Low to Medium* – Level of benefits depends on fleet adoption and varies by truck driver. | *Low to Medium* – Depends on level of sophistication and supporting technologies. |
| **Connected Eco-Driving** | *Medium* – Proven in simulation and prototype, but no large-scale implementation yet. | *Medium* – Process proven, but require traffic signal owner/operators to allow access to real-time traffic signal data. | *Medium* – Level of benefits depends on fleet adoption and varies by trip. | *Low to Medium* – Require medium capital costs up front for implementation, but low operating costs afterward |

** From political, institutional, legal, and operational perspectives*
*** Environmental, climate, and public health benefits*
*** Implementation and operation costs*

| Geofencing Strategies | Technology Readiness | Ease of Implementation* | Benefits** | Costs*** |
|---|---|---|---|---|
| ***Powertrain and Emission Control System Level*** | | | | |
| **Engine Management** | *Medium* – Over-the-air engine calibration is possible, but not as the truck is being driven yet. | *Low to Medium* – Will require coupling with emission reporting to ensure compliance with emission standards. | *Medium to High* – Can be highly beneficial if managed properly. | *Medium* – There will be additional costs associated with emission reporting. |
| **Hybrid Energy Management** | *High* – Proven in real world. | *Medium to High* – Does not require government approval, but rely on buy-ins from fleet operators. | *Medium to High* – Same benefits as zero-emission truck while in all-electric mode, but requires the truck to have hybrid powertrain. | *Low to Medium* – Requires some incremental costs on top of the cost of hybrid vehicle itself. |
| **Emission Control Management** | *High* – Already be part of emission control systems in newer model year trucks | *Low to Medium* – Will require coupling with emission reporting to ensure compliance with emission standards. | *Medium to High* – Can be highly beneficial if managed properly. | *Medium* – There will be additional costs associated with emission reporting. |

** From political, institutional, legal, and operational perspectives*
*** Environmental, climate, and public health benefits*
*** Implementation and operation costs*

Several observations emerged from the literature review that were important from a policy perspective. First, the information confirmed that a wide variety of strategies fall under the umbrella of access restriction and pricing. These technical/implementation approaches include no drive zones, fees on high emission vehicles, both geographic and temporal controls, limitations on certain fuel types, required vehicle pollution controls, permits, preferred vehicle access, and others. Case studies and technical analyses clearly demonstrate that a variety of approaches have been successfully or could be successfully used around the world (for example, see Section 2.1 and Appendix A). Relative to the United States, including California, there has been more limited use of these approaches to date. The recent use of hybrid diesel electric buses in downtown San Francisco which run on electricity in high impact areas and diesel fuel elsewhere is one such example. High-occupancy lane access for low emission vehicles is another example that has been widely used in California. The Ports of Los Angeles and Long Beach's Clean Trucks Programs, which limit marine terminal access to lower emitting trucks and provides an air quality benefit to the people working in the ports and to the surrounding community, are yet another example. The bottom line, similar to many other pollution control approaches, is that one size does not necessarily fit all. In other words, the geofencing approach needs to be tailored to the specific characteristics of the community, need, compliance with existing laws, vehicle type and duty cycle, public health and environmental impacts, equity and economics, technology feasibility and practicability, public acceptance and politics, possible conflicts or synergistic effects with other public policies, to mention a few. The normal process of consultation with stakeholders and establishing a formal advisory group is thus recommended.

Nonetheless, the fact is that geofencing has been successfully implemented under a variety of circumstances in the past, and new opportunities will arise from ongoing changes in technology. Therefore, an action should be taken to establish a more formal role for geofencing strategies in some of California's premier efforts to reduce local and regional air pollution such as AB 617 community air quality plans, reducing air toxics exposure, achieving federal and state clean air standards, and achieving greenhouse gas reduction targets.

### 4.1.2. Case Study Modeling and Simulation Evaluation

The modeling and simulation evaluation of two selected geofencing strategies was conducted to demonstrate their potential in reducing truck emissions and their impacts inside DACs. One is the emission-based pricing strategy implemented in the ELABHWC community where a $10 emission fee is collected from heavy heavy-duty trucks (HHDTs) that do not meet the 2007 emission standards (model years 2009 and older) when they enter the community, which is considered to be a low emission zone (LEZ). Under the modeling scopes and assumptions used in this research, the effect of the emission fee was found to be significant. It diverted 7% of the 11% pass through HHDTs of model years 2009 and older away from the LEZ.

The diversion of pass through truck traffic through the implementation of the emission fee was found to reduce PM2.5, NOx, and CO2 emissions from HHDTs of model years 2009 and older inside the LEZ by 44%, 48%, and 50%, respectively. In addition, the diversion also reduced PM2.5, NOx, and CO2 emissions from these trucks in the area immediately outside the LEZ but within 5-mile radius from the center of the LEZ by 21%, 24%, and 26%, respectively. On the other hand, the diversion of old truck traffic away from the LEZ caused the emissions from these trucks outside of the 5-mile radius from the center of the LEZ to increase. For the areas between 5-mile and 15-mile radius from the center of the LEZ, the PM2.5, NOx, and CO2 emissions increased by 7%, 6%, and 5%, respectively.

Figure 4-1 shows the changes in emissions when considering all the old and new HHDTs together. According to the figure, the implementation of the emission fee resulted in reductions in PM2.5, NOx, and CO2 emissions from HHDTs inside the LEZ by 38%, 37%, and 25%, respectively. On the other hand, the implementation of the emission fee resulted in emission increases in the areas outside of 5-mile radius from the center of the LEZ, but those emission increases were no more than 6%. Lastly, it was found that the emission fee had minimal impacts on the total emissions in the modeling area. The total NOx and CO2 emissions remained unchanged, while the total PM2.5 emission increased by 1%. These results demonstrate a potential for the emission-based pricing strategy to reduce truck emissions inside DACs with minimal impact on the regional emission inventory. Nonetheless, any issues of equity arising between communities should be addressed through, for instance, AB617 implementation, air quality management plans, and other policy mechanisms.

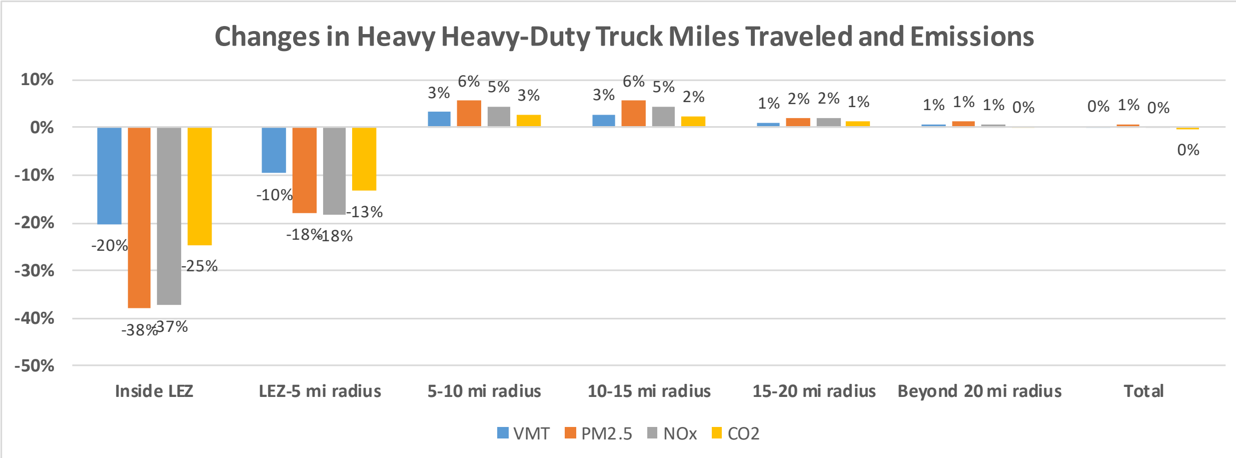



**Figure 4-1. Changes in HHDT miles traveled and emissions due to emission fee implementation**

Another modeling and simulation evaluation effort was made on the exposure-based routing strategy where a HHDT is navigated through a DAC in a way that lowers the total exposure of community members to the pollutant emissions from the truck without significantly increasing travel time. This low exposure route can change dynamically depending on traffic and meteorological conditions, spatiotemporal distribution of population, and other factors. The evaluation was conducted for two case study areas—the ELABHWC community and the city of Carson, CA—and two scenarios—10 A.M. and 10 P.M. on May 9, 2016. The results showed that for some trips, the route that a truck driver would normally take or the baseline route is already the low exposure route. For other trips, the low exposure route is different from the baseline route, and there are tradeoffs among the different route attributes (trip distance, trip time, tailpipe CO2 emission, and human exposure to PM2.5 and NOx emissions) between the two route options. Figure 4-2 shows such tradeoffs for the trips where the low exposure route would take no more than 10% longer trip time.

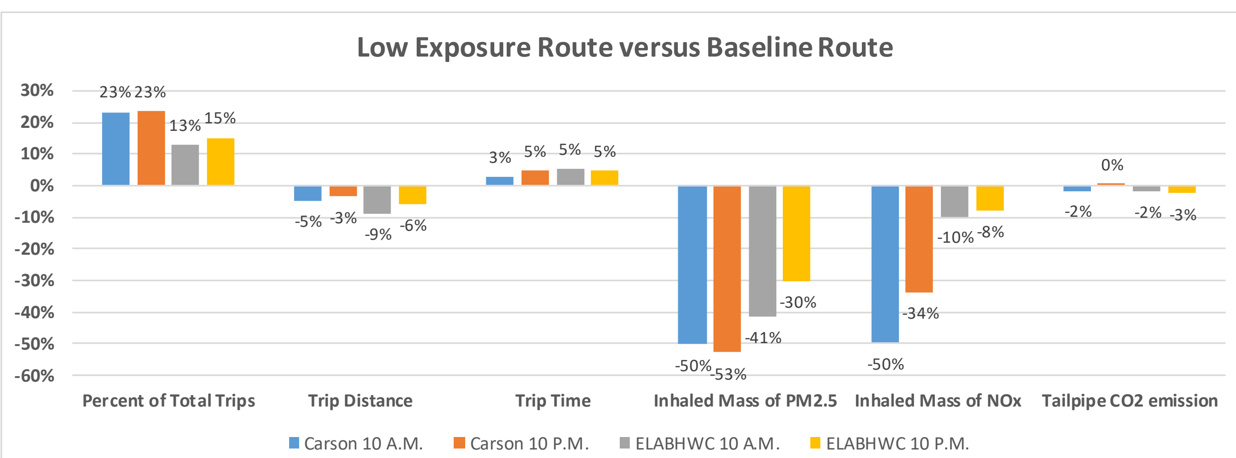



**Figure 4-2. Comparison of route attributes between low exposure route and baseline route**

For the 10 A.M. scenario in Carson, a low exposure route with up to 10% longer trip time was found in 257 out of 1,100 simulated trips (23%). On average, the low exposure route for these trips would have 3% longer trip time as compared to the baseline route, but it would reduce the amount of PM2.5 and NOx emissions from the truck that would be inhaled by community members by 50% and 50%, respectively. In addition, the low exposure route would also reduce tailpipe CO2 emission from the truck by 2% on average. Similar results were observed in the 10 P.M. scenario where a low exposure route with up to 10% longer trip time was found in 258 out of 1,100 simulated trips (23%). On average, the low exposure route for these trips would have 5% longer trip time as compared to the baseline route, but it would reduce the amount of PM2.5 and NOx emissions from the truck that would be inhaled by community members by 53% and 34%, respectively. It would not change the amount of tailpipe CO2 emission from the truck.

The results are quite different for the ELABHWC community. For the 10 A.M. scenario, a low exposure route with up to 10% longer trip time was found in 29 out of 224 trips (13%). On average, the lower exposure route for these trips would have 5% longer trip time as compared to the baseline route, but it would reduce the amount of PM2.5 and NOx emissions from the truck that would be inhaled by community members by 41% and 10%, respectively. It would also reduce tailpipe CO2 emission from the truck by 2% on average. For the 10 P.M. scenario, a low exposure route with up to 10% longer trip time was found in 34 out of 224 trips (15%). On average, the low exposure route for these trips would have 5% longer trip time as compared to the baseline route, but it would reduce the amount of PM2.5 and NOx emissions from the truck that would be inhaled by community members by 30% and 8%, respectively. It would also reduce tailpipe CO2 emission from the truck by 3% on average.

These results imply that the effectiveness of the exposure-based routing strategy varies by community and time of day. It is more likely to be able to find a low exposure route for the trip in, for example, a community that has more route options for the truck, a community where sensitive facilities and dense residential neighborhoods are far away from major roadways, and a community where truck trip attractions are not located near where people live, work, and play. Nevertheless, the results presented in this report demonstrate a potential for the exposure-based routing strategy to help mitigate the impacts of truck emissions on DACs, either in conjunction with or independent of the emission-based pricing strategy.

## 4.2. Policy Implications

The existing policy structure includes Executive Orders, legislation (laws), plans, regulations, policy statements, and budget expenditures (e.g., grants & incentives) among other actions. Examples of major policy directives and implementation mechanisms where geofencing can play a role going forward include regional Air Quality Management Plans, the statewide Scoping Plan for reducing greenhouse gases, Sustainable Community Strategies under SB 375, Regional Mobility Plans, Land Use Plans, and Economic Development Plans.

Geofencing strategies can also be designed in a manner that integrates public health, transportation, climate, equity, and economic factors to derive more optimum solutions to pressing societal issues at the regional and community level. Efforts to implement geofencing strategies should attempt to foster win-win outcomes relative to these multiple policy areas and minimize negative interactions. Much better coordination and cooperation among responsible parties/agencies/stakeholders in research, policy development, and implementation will be a key factor for success.

The California Air Resources Board (CARB)'s mobile source emission control program has been recognized for many decades as an international leader in promoting advancements in pollution control technology/approaches. Among the changes in automotive engineering in response to CARB's regulations was the inclusion of microprocessors to lower pollutant emissions from engine combustion as well as the linking and operation of add-on pollution control devices. This decades old transformative event paved the way for today's incorporation of advanced vehicle operation, monitoring, and communications systems. The availability of these technologies, combined with improved location and mapping software and vehicle communication technologies, has further enhanced and positioned geofencing as a future component of the overall strategy to meet environmental and mobility goals. For example, the current CARB Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments directed at in-use compliance for heavy-duty trucks makes use of some of these improved capabilities. With the automotive industry making significant advancement toward fully autonomous vehicles, which will contain further enhancements that can be used for geofencing and related efforts, the time has come to more fully use this advanced operation and communication technology for air pollution exposure reduction purposes.

It is important to emphasize that science has clearly shown that proximity matters (i.e., near roadway exposure) in relationship to risk of adverse health consequences related to air pollution, especially from air toxics (such as carcinogens) and particulate matter. Geofencing strategies such as emission-based pricing and emission/exposure-based vehicle routing can complement traditional emission control strategies in reducing population exposure to air pollutants in communities with high levels of conventional truck traffic. Moreover, these strategies can be implemented in the near term and utilized over the next several decades until the entire heavy-duty fleet can achieve a zero-emission profile as technology advances and fleet turnover occurs.

## 4.3. Pathways toward Implementation

California maintains a leadership role in environmental management on many fronts, including air pollution control, climate change, environmental justice/equity, and piloting of innovative technologies, policies and programs. Nonetheless, California must redouble its efforts to achieve federal and state clean air standards, reduce greenhouse gas emissions, and reduce disproportionate impacts, which occur predominantly in low income communities and communities of color. Mobile source emissions continue to be a very large source of pollutant impacts on the breathing public and a contributor to climate change. Geofencing strategies provide an array of additional opportunities to reduce pollutant emissions and population exposure to harmful air contaminants. This section of the report makes specific recommendations pertaining to research, policy development, and policy implementation to expedite the further inclusion of geofencing strategies in California's air pollution and climate change programs. While this research project is focused on heavy-duty trucks, the approaches identified could be applied to other vehicle categories.

Recommendations for moving toward implementing geofencing strategies are given in Table 4-2.

**Table 4-2. Recommendations for moving toward implementing geofencing strategies**

| Level | Recommendations |
|---|---|
| **Strategic** | • Initiate parallel tracks of research, policy development and adoption, and implementation.<br>• Strengthen efforts to improve modeling and evaluation methods, including development of guidelines for assessing impacts of geofencing strategies. This should include recommended data sources, calculation methods, models, and desired outputs (e.g., environmental, health, economic, equity, mobility, etc.) for formal policymaking. Development and approval of guidelines should be done through an open and participatory process.<br>• Identification of priority needs to facilitate analysis that raises research approaches to the standards required for use in policy setting by legislative bodies, regulatory agencies, and local government.<br>• Initiate a process to screen geofencing strategies for applicability to CARB's policy programs and readiness for adoption. Place appropriate measures in the California motor vehicle control strategy and CARB's various existing plans and strategies. Make appropriate recommendations for other state agency inclusion in their policies and that of local governments.<br>• Establish demonstration projects for emerging technologies or groups of technologies associated with geofencing that provide new tools for meeting California's air quality, climate change, and equity/environmental justice objectives. Prioritize such projects and locate as appropriate in DACs.<br>• Establish stakeholder engagement plans for above activities, share this research information with DACs and other stakeholders, gather feedback, and implement actions to foster success. |
| **Tactical** | • Identify a model community for pilot implementation.<br>• Conduct transportation-related air pollution audits and determine appropriate geofencing strategies for the model community.<br>• Engage with stakeholders such as community-based organizations, truck fleets and independent owner operators, local governments (cities, counties, metropolitan planning organizations, air pollution management districts or air pollution control districts) early in the process. |

<table>
<tr><td></td><td>
<ul>
<li>Prioritize the use of incentives over regulations, and try to be revenue-neutral.</li>
<li>Start with something simple and predictable to maximize buy-ins from stakeholders.</li>
<li>Explore creative ways for implementation, for example:
<ul>
<li>State level - Through California Environmental Quality Act or State Implementation Plan</li>
<li>Regional level - Through air quality management plans</li>
<li>Local level - Through general plan elements or ordinances</li>
</ul></li>
<li>Align the timeline with the timelines of other programs and regulations, such as Heavy-Duty Omnibus and Advanced Clean Trucks regulations.</li>
</ul>
</td></tr>
<tr><td>Operational</td><td>
<ul>
<li>Designate or update truck routes in the model community by explicitly taking into account human exposure to truck emissions.</li>
<li>Pilot three geofencing strategies in an integrated fashion:
<ul>
<li>Emission-based pricing – Assess an emission fee on trucks of older model years upon entry to the community.</li>
<li>Exposure-based routing – Waive the emission fee if the truck opts in and uses a low exposure route.</li>
<li>Connected eco-driving – Equip traffic signals along truck routes and provide trucks that opt in with free access to connected eco-driving application.</li>
</ul></li>
<li>Create a Win-Win-Win situation for all stakeholders.
<ul>
<li>Community – Experience reduced truck emissions and reduced exposure to these emissions inside the community.</li>
<li>Agency – Use the collected fees to fully (or partially) pay for the implementation costs, and improve public health.</li>
<li>Truck fleets and independent owner operators – Can claim part of the fees paid earlier as credits toward purchasing/leasing cleaner trucks that are not subject to the emission fee.</li>
</ul></li>
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# Appendix A:

# Summary of Relevant Literature

Available in *Appendix A.xlsx*