AERIS—Applications for the Environment: Real-Time Information Synthesis

Low Emissions Zones Operational Scenario Modeling Report

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16. Abstract
This report describes the analysis and modeling effort that was conducted to simulate the potential impacts of a Low Emissions Zone (LEZ) strategy. LEZs are designated areas within a metropolitan region where special measures are implemented with a view to modifying traveler behavior and choices so that the energy and emissions footprint of travel associated with the designated area becomes smaller. Within the LEZ modeling effort undertaken in this project, the effects of incentive-based policies where travelers receive a monetary or other benefit for using clean vehicles (low emission vehicles) in the context of travel to the designated LEZ are simulated. The modeling effort involved the use of a novel continuous-time integrated model system that included both an activity-based microsimulation model system of travel demand and a computationally efficient dynamic traffic assignment (DTA) model. The report describes the scenarios considered, the case study area, and the modeling and simulation methodology employed in the project. The report presents detailed results of the simulation study for the specific scenarios considered, and identifies opportunities and directions for further research and analysis. Within the context of the specific scenarios considered in this report, the simulation results suggest that energy and emissions benefits of 3 percent to 5 percent may be achieved with even very modest penetration of eco-vehicles in the market. Coupled with enhanced transit (ET) services, benefits in the range of 15 percent to 20 percent may be achieved, indicating the presence of a strong synergistic effect when ET services are coupled with LEZ strategies.

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Executive Summary

As part of its connected vehicle research effort, the United States Department of Transportation (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) is conducting the Applications for the Environment: Real-Time Information Synthesis (AERIS) program. The focus of the program is to use connected vehicle technology to reduce the environmental impact of road transportation. The AERIS program defined applications that were bundled into logical combinations called Operational Scenarios. This report details the modeling, simulation for the Low Emissions Zones (LEZ) Operational Scenario.

The AERIS program envisions that LEZs may be used by system operators to encourage eco-friendly decisions by travelers helping to reduce transportation's negative impact on the environment. The LEZ Operational Scenario envisions entities responsible for the operations of the transportation network to have the ability to define geographic areas that seek to restrict or deter access by specific categories of high-polluting vehicles into the area for the purpose of improving the air quality within the geographic area. Alternatively, the Operational Scenario may incentivize traveler decisions that are determined to be environmentally friendly such as the use of alternative fuel vehicles or transit. LEZs in a connected vehicle environment would be similar to existing LEZs; however, they would leverage connected vehicle technologies, allowing the systems to be more responsive to real-time traffic and environmental conditions (e.g., a pop-up zone may be implemented for a Code Red Air Quality Day or special event). Connected vehicle technologies provide the ability for entities operating the transportation networks to collect more detailed information from vehicles and infrastructure and better communicate traffic information to travelers directly to in-vehicle systems or handheld devices.

Modeling of the Low Emissions Zones Operational Scenario focused on the management and operation of a LEZ for a metropolitan area. Parameters were established for the LEZ to support air quality improvements within the zone. Parameters considered included the types of vehicles permitted to enter the zone, exemptions for transit vehicles, emissions criteria for vehicles entering the zone, incentives for vehicles and geographic boundaries for the LEZ. As this Operational Scenario involves policy that will affect the way that individual drivers, as well as groups of drivers, react in terms of route and time-of-day choice, the modeling of the LEZ Operational Scenario was undertaken on a regional scale. It is expected that the introduction of a LEZ in the regional concept would result in changes in travel patterns, including destination choice, route choice, mode choice, time-of-day choice, and vehicle-type choice. Even when the LEZ policy does not have a direct temporal element, it is possible that temporal aspects of activity-travel patterns will be affected due to changes in destination and mode choice that arise from the implementation of the LEZ policy. The modeling framework implemented in this study is able to capture such secondary and tertiary effects.

To model the potential impacts of implementing the LEZ Operational Scenario, a regional-scale macro-simulation model of a real-life urban region was used from the Greater Phoenix metropolitan area in Arizona. The Maricopa Association of Governments (MAG) regional model was used because of the considerable support and assistance to this simulation effort through the provision and availability of network files, travel data, traffic volume data, and travel time and cost matrices by time of day period. These files served as the foundation for building micro-simulation model systems of dynamic travel demand and route choice in response to the introduction of a LEZ to the region. The model region covers roughly the entire Maricopa County area with portions of adjoining counties also included in the model area.

For the modeling the LEZ Operational Scenario, an incentive-based approach was used rather than a more traditional pricing scheme. Eligible "eco-vehicles" would receive incentives for their use within the LEZ boundaries. "Eco-vehicles" were defined as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs). Theoretically, as technology improves, high fuel-economy vehicles could be just as "eco" as hybrids of today, but for modeling purposes, the vehicles that were determined to be eco are shown in Exhibit 1.

Exhibit 1: Eco-Vehicles Designated for the LEZ Simulation (Sources:
http://www.toyotainthenews.com/2011-toyota-prius-is-the-no-1-fuel-sipper-in-the-u-s/;
http://gate.its.ucdavis.edu/news/plugctr06;
http://www.colinappleyard.com/blog/customers_fall_for_electric_nissan_leaf)

Two types of incentives were considered for analysis. The first incentive is available to drivers who drive an eco-vehicle. Beneficiaries of these incentives may already own an eco-vehicle or may have decided to purchase an eco-vehicle in response to the implementation of the LEZ. In modeling terms, incentives would be in the form a monetary incentive to travelers as they enter the LEZ in order to simply the models and process. In reality, incentives could exist in many different forms, from coupons and rebates, free parking, to a more "intangible" point system. This incentive is intended to reward the drivers of eco-vehicles, as well as to incentivize the purchase and use of eco-vehicles by travelers that may not currently own such a vehicle. These monetary incentives were considered at multiple levels to determine whether there is any sensitivity in the amount of incentive that is received by each individual user (from $0.50 to $1.50). In addition to the individual eco-driver incentive, a transit-based incentive was also used to provide travelers who choose not to use or buy an eco-vehicle to receive an incentive through mode-shift, thus further reducing non-eco-vehicle trips into the LEZ. This incentive was provided in terms of a reduced transit fare to and from destinations within the LEZ, as well as improvements known as "enhanced transit". The model that was used was able to accurately capture the mode-shift of these travelers using behavioral models calibrated on real-world travel survey data collected by Maricopa Association of Governments (MAG) and Valley Metro in the Greater Phoenix metropolitan region.

As previously stated, the model used for the LEZ Operational Scenario analyses is a regional-scale model of the MAG region in Phoenix, Arizona. The simulation test bed that was used for the analysis includes two models that were tightly coupled to work together to accurately simulate the regional traffic patterns and shifts in response to the LEZ. The first model component is openAMOS, an activity-based travel demand model which produces the vehicle trips and release timing based on activities that are initiated and assigned to individual persons or households. The other component is DTALite, a dynamic traffic assignment (DTA) model which assigns vehicle routes based on dynamic changes in traffic conditions that are monitored by the simulation model in real-time. These two model

components were integrated in such a way that they communicate with one another on a minute-by-minute basis during the simulation period to create a realistic representation of travel patterns and reactions to real-time stimuli throughout the region and the simulation time period. This unique system of integrated modeling components, which was developed as part of a previous FHWA Exploratory Advanced Research Program study and enhanced further for this specific LEZ policy simulation, is explained in significant detail within this report.

To test this new combination of modeling components, which was dubbed Simulator of Transport, Routes, Activities, Vehicles, Emissions, and Land (SimTRAVEL), it was first necessary to test on a smaller, sub-region of the MAG test bed model. For the first set of tests, two smaller LEZs were tested with the incentive-based framework. The smaller LEZs were two areas within the sub-region MAG model with dense retail and residential. The areas used for these analyses are shown below in Exhibit 2.
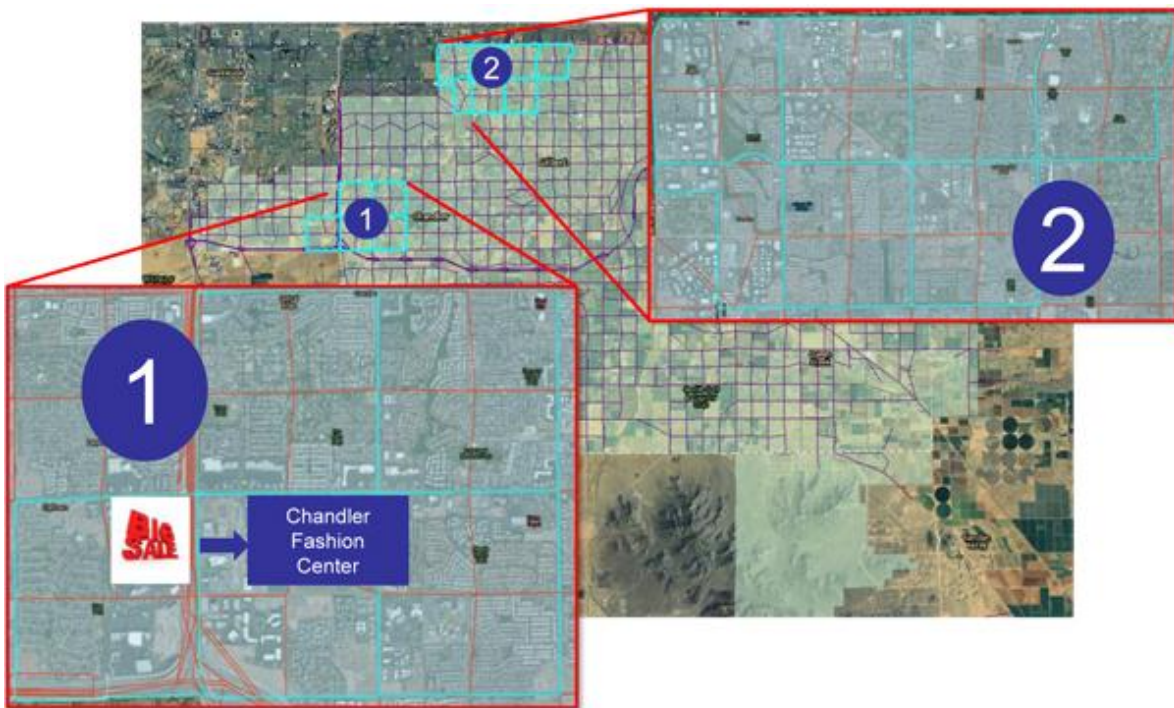
Source: Google Maps (https://www.google.com/maps)

Exhibit 2: Low Emission Zones within the Sub-Area Test Model of the MAG Region

The LEZ was tested for increasing levels of incentive both with and without the additional enhanced transit component. The enhanced transit scenario involves doubling the frequency of transit and reducing the fare by one-half in the context of service to and from the low emission zones. Exhibit 3 shows the impacts of the LEZ and trips to/from the LEZ in relation to the baseline model.

Exhibit 3: Environmental and Mobility Improvements over the Baseline for Trips to the LEZ for the Sub-Region Model Tests

Scenario	Incentive Level	Enhanced Transit	Change in CO_2	Change in VMT	Transit Mode Share
Baseline	$0.00	-	-	-	6.0%
1	$0.50	No	-1.5%	+0.1%	5.5%
2	$1.50	No	-2.4%	+0.2%	5.5%
3	$0.50	Yes	-3.5%	-3.1%	29%
4	$1.50	Yes	-4.2%	-2.3%	28%

As Exhibit 3 shows, the more incentive that is provided, the larger resulting benefit to the LEZ area. As can be expected, only providing an incentive to the eco-vehicles does not penalize non-eco-drivers to avoid the area, so there is no noticeable decrease in vehicle miles of travel (VMT) or mode shift in the LEZ area for these scenarios. However, with the introduction of transit-based incentives for the non-eco-drivers, a large shift to transit can be observed, which results in both a larger reduction in pollution within the LEZ region and a reduction in vehicular miles within the zone via the reduction of non-eco-vehicles on the roadway. This test shows how the combination of incentives can produce better all-around results compared with a single incentive policy.

After the successful test of the SimTRAVEL framework for the subregion test bed, the full regional model was used with the LEZ. The LEZ that was established within the full MAG area regional model consisted of the central business district (CBD) of the city of Phoenix. As a result of the complexity and computational difficulty of running the model based on size, the $0.50 incentive scenarios were not run for the regional case and instead focused on the greater $1.50 scenario. The tests on the sub-region showed enough understanding of the patterns of improvement by increasing level of incentive to ignore this case for the regional modeling. The regional analysis shows the difference between the impacts on the whole MAG region as a result of the LEZ Operational Scenario compared with the analysis of only the region with the LEZ.

Exhibit 4: Environmental and Mobility Results for Trips to the LEZ for the Full Regional Model Analyses

Scenario	Incentive Level	Type	Enhanced Transit	Change in CO_2	Change in VMT	Transit Mode Share
Baseline	**$0.00**	Regional	-	-	-	4.6%
Baseline	**$0.00**	LEZ	-	-	-	7.8%
1	**$1.50**	Regional	No	-1.9%	-0.1%	4.7%
1	**$1.50**	LEZ	No	+0.6%	N/A	7.2%
2	**$1.50**	Regional	Yes	-3.8%	-1.5%	7.3%
2	**$1.50**	LEZ	Yes	-16.7%	N/A	30.4%

As Exhibit 4 shows, the positive impacts on environmental and mobility measures are greater with increasing incentive provided. The results for the larger region of Phoenix are more informative of the LEZ Operational Scenario when looking at the LEZ separately from the entire region. For the scenario that involves only providing an incentive to drivers of eco-vehicles when they enter the zone, there is a very slight increase in VMT and CO_2 emissions consistent with the notion that an incentive-based scheme would induce additional travel demand. . This is a result of the fact that the policy does not penalize non-eco-drivers, so they continue with their usual activity-travel patterns despite the policy of the LEZ. The fractional increase of emissions within the LEZ is a result of the induced demand created by the LEZ. However, when the transit incentive is introduced, there is a significant improvement for both the LEZ and the region as a whole. It can be seen that the transit share increases to around 30 percent within the zone, while the region as a whole also sees a moderate increase. This change in policy results in a nearly 17 percent reduction in carbon emissions within the LEZ as a result of the effects of the mode shift and increased eco-vehicle penetration. Given that the analysis conservatively considered modest penetration of eco-vehicles due to implementation of LEZ policy, most of the benefits in emissions reductions come from mode shift to transit due to implementation of enhanced transit service.

The results of the simulation and modeling analyses of the AERIS LEZ Operational Scenario show that an incentive-based policy of rewarding "eco-driving" and "green" transportation choices results in improved emissions in both a localized and regional context. It should be noted that the analysis considered modest increase in penetration of eco-vehicles as a result of implementing LEZ policy. While the emissions per trip reduces in the low emissions zones, the net impact on emissions is nominal as the reduction in emissions from more eco-vehicles get offset by increase in VMT or induced demand into low emissions zones.   The incremental scenario development structure that was adopted during this analysis allowed for the understanding of impacts at different levels of incentive and implementation, which also shows that this concept has the flexibility to be easily extended to different region sizes. In addition, it can be seen that a combination of incentives (i.e., transit improvements/fare reductions, in this case) amplifies the magnitude of emission and mobility benefits received by the LEZ. Supplemental improvements in transit allowed users that didn't have the access to an "eco-vehicle" the ability to also receive an incentive, therefore providing the system with a corresponding improvement. The following report contains a significantly more detailed approach, modeling techniques, and analysis results to increase understanding of the LEZ Operational Scenario.

Chapter 1.   Introduction

This report is focused on introducing the AERIS Program's Low Emission Zones Operational Scenario and its place in the AERIS program, with a detailed focus on the development of the scenario framework, algorithm development, and application needs for the operational scenario, as well as the modeling and results gained from detailed simulation analysis. The Low Emission Zones Operational Scenario would be used to encourage decisions by travelers that help reduce transportation's negative impact on the environment. The Low Emissions Zones Operational Scenario envisions entities responsible for the operations of the transportation network to have the ability to define geographic areas that seeks to restrict or deter access by specific categories of high-polluting vehicles into the area for the purpose of improving the air quality within the geographic area. Alternatively, the Operational Scenario may incentivize traveler decisions that are determined to be environmentally friendly such as the use of alternative fuel vehicles or transit. Low emissions zones in a connected vehicle environment would be similar to existing low emissions zones; however, they would leverage connected vehicle technologies allowing the systems to be more responsive to real-time traffic and environmental conditions. Connected vehicle technologies provide the ability for entities operating the transportation networks to collect more detailed information from vehicles and infrastructure and better communicate traffic information to travelers directly to in-vehicle systems or handheld devices.

The Low Emission Zones Operational Scenario was imagined as a package of three different regional cordon-based applications that were designed to operate both individually, as well as combined, in order to meet the AERIS program's objective of reducing the environmental impact of surface transportation. Due to limitations in modeling, budget, and time, only one of the applications within the scenario was modeled and are featured in this report in detail. The individual applications of the Eco-Lanes Operational Scenario are shown in detail in Chapter 2 of this report.

This section of the report serves as a general introduction to the AERIS program goals and objective, as well as the past work completed as a part of the program that has led to the scenarios and applications for modeling that are presented in this report. Chapter 1 also contains an overall view of the document and the information that is contained within.

The AERIS Program

The U.S. Department of Transportation's (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) is conducting the Applications for the Environment: Real-Time Information Synthesis (AERIS) program. The focus of the program is to use connected vehicle technology to reduce the environmental impact of road transportation. A connected vehicle setting is used to develop applications that modify traveler behavior or directly reduce fuel consumption of vehicles. The primary objective of developing the AERIS applications is to reduce surface transportation's impact on the environment. This project is dedicated to assessing the benefits of implementing applications that maximize environmental benefits. Benefits are assessed by modeling the applications and evaluating them in a simulated connected vehicle setting.

The AERIS applications are designed to create significant benefits in terms of reductions in emissions (e.g., GHG emissions, criteria pollutants) and fuel consumption, which could ultimately yield environmental and monetary benefits. Most of the environmental benefits can be realized by improving flow, reducing travel times, and encouraging the use of mass transit, carpooling, and fuel-

efficient vehicles. In addition, environmental impacts of surface transportation can be greatly influenced by modifying driving behavior by providing speed or route recommendations and providing incentives to drivers to use fuel-efficient vehicles or other eco-friendly modes.

The main objectives of the AERIS program are:

- Identify connected vehicle applications that could provide environmental impact reduction benefits via reduced fuel use, improved vehicle efficiency, and reduced emissions.

- Facilitate and incentivize "green choices" by transportation service consumers (i.e., system users, system operators, policy decision makers, etc.).

- Identify vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-grid (V2G) data exchanges via wireless technologies of various types.

- Model and analyze connected vehicle applications to estimate the potential environmental impact reduction benefits.

- Develop a prototype for one of the applications to test its efficacy and usefulness.
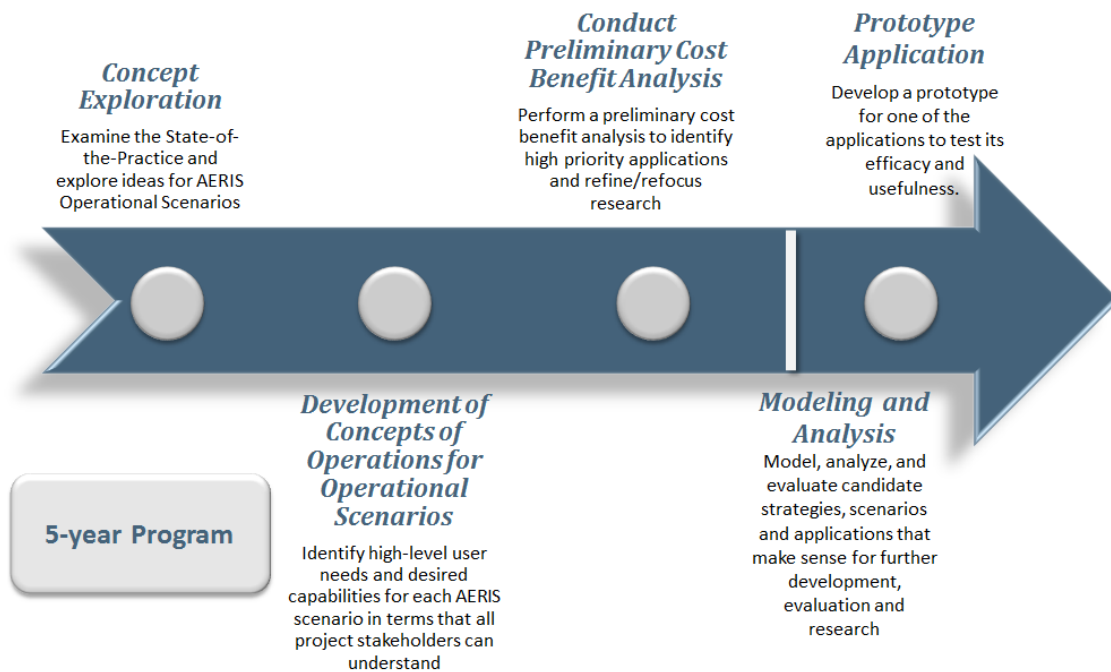
Figure 1: The AERIS approach (Source: USDOT, AERIS Factsheet, http://www.its.dot.gov/factsheets/pdf/AERIS_factsheet.pdf, Accessed on 9/11/14)

The AERIS Program is a five year program consisting of a phased research approach (Figure 1).

- Concept Exploration – The first step was to examine the state-of-the-practice and explore ideas for AERIS research. Five state-of-the-practice reports were developed as part of this phase investigating (i) environmental applications, (ii) assessment of technologies to collect environmental data, (iii) environmental models, (iv) behavioral and activity-based models, and (v) evaluation of environmental ITS deployments. Additionally, six Broad Agency Announcement (BAA) projects were conducted.

- Development of Concepts of Operations for Operational Scenarios – The next phase focused on the identification of environmental applications and the development of Concept of Operations for three of the five Operational Scenarios. Detailed ConOps were developed for the Eco-Signal Operations, Eco-Lanes, and Low Emissions Zones Operational Scenarios. ConOps for the remaining Operational Scenarios will be developed at a later date.

- Conduct Preliminary Benefit Cost Analysis – Once the ConOps were developed, a preliminary benefit cost analysis was performed to identify high priority applications and refine/refocus the research.

- Modeling and Analysis – The high priority applications from the benefit cost analysis were then selected for more detailed modeling and analysis. The result will be a report that documents the potential benefits that may be possible by implementing AERIS connected vehicle applications.

- Prototype Application – Finally, the AERIS Program selected one of the AERIS applications for prototyping. The Eco-Approach and Departure at Signalized Intersections application was selected to test its efficacy and usefulness.

Operational Scenario: Definition

The Applications for the Environment: Real-Time Information Synthesis (AERIS) Program identified five Operational Scenarios or bundles of applications: (1) Eco-Signal Operations, (2) Eco-Lanes, (3) Low Emissions Zones, (4) Eco-Traveler Information, and (5) Eco-Integrated Corridor Management. Each Operational Scenario encompasses a set of applications which individually achieve environmental benefits. By strategically bundling these applications, the AERIS Program expects that the Operational Scenarios can achieve additional environment benefits above those of the individual applications.

Each Operational Scenario is comprised of applications, regulatory/policy tools, educational tools and performance measures. Applications are technological solutions (e.g., software, hardware, interfaces) designed to ingest, process, and disseminate data in order to address a specific strategy. For example, the Eco-Traffic Signal Priority application may collect data from vehicles, send these data to a local processor to determine if a vehicle should be granted priority at a signalized intersection, and then communicate this priority request to a traffic signal controller.

Applications are complemented with regulatory/policy and educational tools to further support the Operational Scenario.

Identification and Evaluation of Transformative Environmental Applications and Strategies Project

Prior to the modeling and evaluation of AERIS applications, three other tasks were carried out as part of the AERIS project. The first task identified applications that could yield environmental benefit and bundle them into Operational Scenarios. This work was completed and is documented in a companion report titled "Identification of the Transformative Concepts and Applications." The second task was an initial benefit-cost analysis (BCA), which used a detailed model that assessed the monetary benefits and costs for each application identified in the aforementioned report. The methodology and results of the BCA are documented in a companion report titled "AERIS Applications for the Environment: Real-Time Information Synthesis Identification and Evaluation of Transformative Environmental Applications and Strategies Project, Initial Benefit-Cost Analysis." The third task prioritized the applications based on criteria such as the benefits of the application, likelihood of deployment, ease of modeling, and data availability. As part of this task, a field experiment was conducted at Turner Fairbank Highway Research Center (TFHRC) to evaluate the benefits of the Eco-Approach and Departure at Signalized Intersections application. The results and the methodology were documented in reports titled *"Identification and Evaluation of Transformative Environmental Applications and Strategies Project, Prioritization Evaluation Report"* and *"AERIS Field Study Application: Eco-Approach to Signalized Intersections."* The fourth task includes detailed modeling and simulation of the prioritized applications. Figure 2 presents the scheme of tasks carried out.
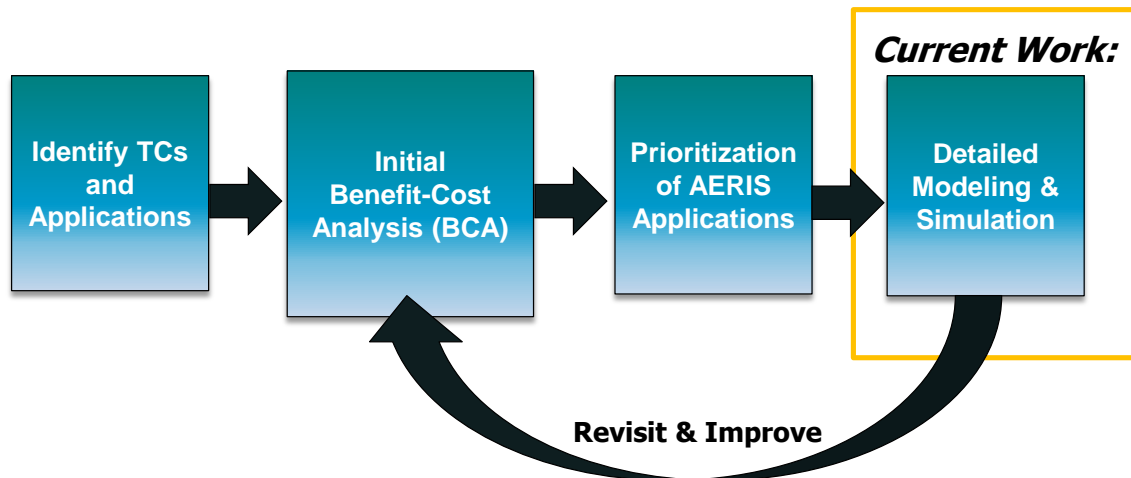
Figure 2: The Role of Modeling and Simulation

Summary of Previous Tasks

Task 1 identified applications and bundled them into five Operational Scenarios as Figure 3 shows. Each Operational Scenario is a bundle of applications that individually are designed to achieve environmental benefits. The applications are bundled strategically with an expectation that the Operational Scenarios can achieve additional environment benefits above those of the individual applications. The five AERIS Operational Scenarios are summarized below:

- **Eco-Signal Operations.** This Operational Scenario uses connected vehicle technologies to decrease fuel consumption and reduce GHGs and criteria air pollutant emissions on arterials by reducing idling, stop-and-go behavior, and unnecessary accelerations and decelerations and improving traffic flow at signalized intersections.

- **Eco-Lanes.** This Operational Scenario includes dedicated lanes optimized for the environment, referred to as Eco-Lanes. Eco-Lanes are similar to managed lanes; however, these lanes are optimized for the environment using connected vehicle data and can be responsive to real-time traffic and environmental conditions.

- **Low Emissions Zones.** Geographically defined areas that seek to incentivize "green transportation choices" or restrict specific categories of high-polluting vehicles from entering the zone to improve the air quality within the geographic area. Geo-fencing the boundaries allows the possibility for these areas to be responsive to real-time traffic and environmental conditions.

- **Eco-Traveler Information.** This Operational Scenario enables development of new, advanced traveler information applications through integrated, multi-source, multi-modal data. Although the AERIS program may not directly develop specific traveler information applications, an open data/open source approach is intended to engage researchers and the private sector to spur innovation and environmental applications.

- **Eco-Integrated Corridor Management.** This Operational Scenario includes the integrated operation of a major travel corridor to reduce transportation-related emissions on arterials and freeways. "Integrated operations" means partnering among operators of various surface transportation agencies to treat travel corridors as an integrated asset, coordinating their operations with a focus on decreasing fuel consumption, GHG emissions, and criteria air pollutant emissions.

AERIS OPERATIONAL SCENARIOS & APPLICATIONS

ECO-SIGNAL OPERATIONS
- Eco-Approach and Departure at Signalized Intersections *(similar to SPaT)*
- Eco-Traffic Signal Timing *(similar to adaptive traffic signal systems)*
- Eco-Traffic Signal Priority *(similar to traffic signal priority)*
- Connected Eco-Driving *(similar to eco-driving strategies)*
- Wireless Inductive/Resonance Charging

ECO-LANES
- Eco-Lanes Management *(similar to HOV/HOT Lanes)*
- Eco-Speed Harmonization *(similar to variable speed limits)*
- Eco-Cooperative Adaptive Cruise Control *(similar to adaptive cruise control)*
- Eco-Ramp Metering *(similar to ramp metering)*
- Connected Eco-Driving *(similar to eco-driving strategies)*
- Wireless Inductive/Resonance Charging
- Eco-Traveler Information Applications *(similar to ATIS)*

LOW EMISSIONS ZONES
- Low Emissions Zone Management *(similar to Low Emissions Zones)*
- Connected Eco-Driving *(similar to eco-driving strategies)*
- Eco-Traveler Information Applications *(similar to ATIS)*

ECO-TRAVELER INFORMATION
- AFV Charging/Fueling Information *(similar to navigation systems providing information on gas station locations)*
- Eco-Smart Parking *(similar to parking applications)*
- Dynamic Eco-Routing *(similar to navigation systems)*
- Dynamic Eco-Transit Routing *(similar to AVL routing)*
- Dynamic Eco-Freight Routing *(similar to AVL routing)*
- Multi-Modal Traveler Information *(similar to ATIS)*
- Connected Eco-Driving *(similar to eco-driving strategies)*

ECO-INTEGRATED CORRIDOR MANAGEMENT
- Eco-ICM Decision Support System *(similar to ICM)*
- Eco-Signal Operations Applications
- Eco-Lanes Applications
- Low Emissions Zone s Applications
- Eco-Traveler Information Applications
- Incident Management Applications

P POLICY CONSIDERATIONS

E EDUCATIONAL TOOLS

Figure 3: AERIS Operational Scenarios (Source: USDOT ITS JPO, www.its.dot.gov/aeris/pdf/AERIS_Operational_Scenarios011014.pdf, accessed April 13, 2014)

In Task 2, the applications were subject to a BCA at a national scale. A BCA model was developed to assess the benefits and costs of each application at a national scale for a period extending through 2055. Most of the steps of the BCA required substantial input from the AERIS team including stakeholders (e.g., Federal Transit Administration [FTA]) and connected vehicle experts (e.g., researchers). The AERIS team collaborated closely to ensure consensus on the baseline assumptions, benefit categories, and cost assumptions. In addition, the approach and assumptions were vetted within the ITS JPO. The baseline assumptions were used to provide a benchmark against which the relative results for each of the applications were compared. The BCA was conducted in two parallel work streams, one for benefit estimation and the other for cost estimation. The results of benefit and cost estimations were then input to the model, which extrapolated results to the entire nation and provided results for each year in the analysis.

Task 3 was prioritization of applications for modeling. To determine the priority order for modeling the AERIS Operational Scenarios, a set of preliminary screening questions were considered.

Key questions pertaining to modeling that were considered include the following:

Are environmental and transportation data required to model the Operational Scenario readily available or easy to collect? The availability and quality of environmental and transportation data greatly impact the ability to model an application, the scale at which the application may be modeled, and the level of effort required to assemble the needed data. Specific data requirements may include vehicle emission information, signal information, and traffic volumes for model validation.

Are algorithms in place—or could they be developed with minimal effort—to model the applications in the Operational Scenario? The availability and readiness of algorithms is important to the accuracy of modeling and evaluating the benefits of the applications and their Operational Scenarios; however, the lack of algorithms does not necessarily mean that the application does not have the potential to provide significant environmental benefits. The availability of algorithms was considered as a part of the prioritization.

Could the Operational Scenario be accurately modeled using existing behavioral, traffic simulation, or environmental models? Similar to the need for algorithms, the ability to use existing behavioral, traffic simulation and environmental models is significant in evaluating the benefits of the applications and Operational Scenarios. The modeling feasibility was considered as part of the prioritization.

Each application was scored using several factors that affect its modeling/testing. Each factor was weighted and the total weighted scores of the applications within each of the Operational Scenarios were averaged to assign a score for each Operational Scenario. The Eco-Signal Operations Operational Scenario was chosen to be modeled first, followed by Eco-Lanes and Low Emissions Zones. The other Operational Scenarios were not considered for modeling owing to the complexity of modeling the applications or the lack of data to model the applications.

Document Overview

This document includes the following chapters:

- **Chapter 1** provides an introduction to the Low Emission Zones Operational Concept, as well as the background and overview for AERIS modeling activities.
- **Chapter 2** presents an overview of the AERIS applications tested as part of this effort.
- **Chapter 3** presents a description of the modeling region and an explanation of the regions and zones established for the modeling area.
- **Chapter 4** describes how the LEZ was modeled and how scenarios were tested. This chapter presents the algorithms developed and used, the hypotheses to be tested, the modeling approach, and the results and findings of the modeling efforts. It also presents and suggests topics for future research. For each of the applications, the following aspects are described:
  a. **Hypotheses.** This section presents the hypotheses and their justification on the anticipated benefits of each application that were made as part of the analysis plan.
  b. **Algorithm.** This section describes the algorithm used to implement the AERIS application.
  c. **Modeling Approach.** This section describes how the model was created to test the AERIS application's hypotheses and how performance measures were generated from the model.
  d. **Scenarios.** This section describes the scenarios modeled.
  e. **Modeling Results.** This section presents the results of the modeling efforts along with a discussion of the benefits of the AERIS application revealed by the model.
  f. **Findings and Opportunities for Future Research.** This section details qualitative findings and suggests topics for future research.
- **Chapter 5** presents observations and conclusions from the entire modeling effort.
- **Appendix A** provides a list of acronyms used in the report.

Chapter 2.   Low Emissions Zones Operational Scenario and Applications

This chapter describes how the LEZ Operational Scenario uses connected vehicle and other technologies to decrease fuel consumption and GHG and criteria air pollutant emissions within a geo-fenced cordon area called a "Low Emission Zone". These LEZs would generally be located in large, dense urban areas, where there is a significant demand destination that results in congestion and increased pollution from vehicles in the area. By incentivizing the use of eco-vehicles by using real-time connected vehicle technologies in these LEZs, the LEZ Operational Scenario hopes to reduce pollution within the LEZ, as well as across the region.

Figure 4 illustrates the LEZ Operational Scenario as envisioned by the AERIS program.
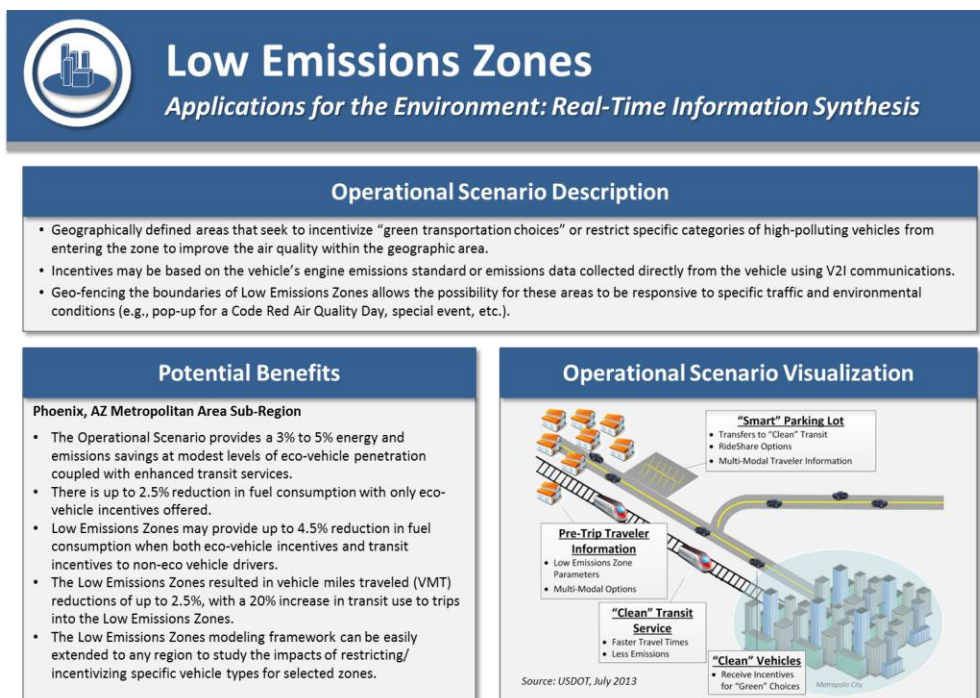
Figure 4: Eco-Signal Operations Operational Scenario

Low Emissions Zone Management

This application supports the operation of a LEZ that is responsive to real-time traffic and environmental conditions. The application uses data collected from vehicles using connected vehicle technologies and from roadside equipment as input to the system. The Low Emissions Zone

Management application supports the geo-fencing of a cordon that may be scalable and moveable (e.g., created for a day, removable, flexible in its boundaries) and would be less dependent on conventional ITS infrastructure. The application would establish parameters, including the types of vehicles permitted to enter the zone, exemptions for transit vehicles, emissions criteria for entering the zone, fees or incentives for vehicles based on emissions data collected from the vehicle, and geographic boundaries for the LEZ. The application would also include electronic toll collection functions that support payments of fees or collection of incentives for registered vehicles.

Eco-Traveler Information Applications

Applications included in the Eco-Traveler Information Operational Scenario apply. Eco-Traveler Information applications provide pre-trip and en-route traveler information about the LEZ. This information includes geographic boundaries of the LEZ, criteria for vehicles to enter the LEZ, expected fees and incentives for their trip, and current and predicted traffic and environmental conditions within and adjacent to the zone. Traveler information messages may be provided to various personal devices and in-vehicle systems and used by travelers to adjust their departure time or select an alternative route. Another key component of these applications is providing travelers with transit options to encourage mode shift as well as parking information in the LEZ or at parking lots outside of the zone. This application was not implicitly modeled separately as a standalone application of the Low Emission Zones Operational Scenario, but rather the application was modeled as travelers receiving pre-trip information about the LEZ zone, which helps them to determine their mode and vehicle choice.

Connected Eco-Driving

The Connected Eco-Driving was identified as a "cross cutting" application that would perform well within multiple Operational Scenarios. This application provides customized real-time driving advice to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. This advice includes recommended driving speeds, optimal acceleration, and optimal decelerations profiles based on prevailing traffic conditions and interactions with nearby vehicles. The application also provides feedback to drivers on their driving behavior to encourage them to drive in a more environmentally efficient manner. Finally, the application may also consider vehicle-assisted strategies where the vehicle automatically implements the eco-driving strategy (i.e., change gears, switch power sources, or use start-stop capabilities to turn off the vehicle's engine while it sits in congestion). While the majority of the LEZ Operational Scenario Concepts are more concerned with the impact of policy on a "regional context," this cross-cutting application would help provide additional environmental savings for connected eco-vehicles once they are within the LEZ. However, this application was not modeled as part of the Low Emission Zones Operational Concept modeling effort.

Chapter 3.   Modeling Region Description

Model Region Description

For the modeling of LEZ applications, a regional network was used to capture the large shifts that result from LEZ policies. This section describes the network and subsets of networks that were used for testing the LEZ applications. Table 1 presents an assessment of how much each application influences the trip chain. The scale of modeling is determined based on the parts of the trip affected by the application.

Table 1: Influence of Applications on Trip Chain and Recommended Modeling Scale

Application	Destination Choice	Mode Choice	Time-of-Day Choice	Route Choice	Lane Choice	Driving Behavior	Recommended Modeling Scale	Comments
Low Emission Zones Management	◐	◐	●	●			Regional level	The application will definitely have an impact on the route and time-of-day choices as a result of the incentives in LEZs. It can potentially affect destination and mode choices as well.
Eco-Traveler Information		◐	◐	◐	◐		Regional level	The application affects demand generation parameters.
Connected Eco-Driving				◕	◐	●	Corridor level	Vehicle trajectories will be affected as a result of the driving recommendation based on user compliance.

Legend:

◕ —Application has a definite influence on the particular trip chain element

◐ —Application has a probable influence on the particular trip chain element

● —Application has only a possible influence on the particular trip chain element

The case study area for the LEZ simulation effort is the Greater Phoenix metropolitan region in Arizona. Maricopa Area Governments (MAG) serves as the metropolitan planning organization for the region and provided considerable support and assistance to this simulation effort through the provision of network files, travel data, traffic volume data, and travel time and cost matrices by time of day period. These files served as the foundation for building microsimulation model systems of dynamic travel demand and route choice in response to LEZ scenarios. The model region covers roughly the entire Maricopa County area (portions of adjoining counties are also included in the model area),

which is one of the largest counties and metropolitan regions in the country. According to the 2010 census, the City of Phoenix is the sixth largest city in the United States and Maricopa County is the fourth most populous county in the country. The county has a multi-modal transportation system including a freeway system with 140 miles of high occupancy vehicle (HOV) lanes and ramp metering; a variety of local, circulator, and express bus services; and a 20-mile light rail line that connects major population and employment centers as well as special event and sporting venues. There are nine cities in the county with a population of more than 100,000, six of which have a population of more than 200,000.

Sub-Region Case Study Area

As a result of the computational challenges associated with performing region-wide simulations, the project team commenced the simulation effort by considering a small test sub-region carved out of the overall model region. This three-city sub-region was chosen as the test site because detailed parcel-level land use data was available for this area, facilitating a rigorous setup of the exogenous land use data and determination of work and school location choice for all of the households within the sub-region. Using the test sub-region allowed the project team to refine the integrated travel model system to ensure that it captured the behavioral phenomena of interest while simultaneously providing the output measures needed to assess the impact of a LEZ scenario. Using the test sub-region for a series of simulation model runs and experiments allowed the team to receive rapid feedback on model sensitivity, which is vital to calibrating and validating the model to replicate real-world conditions and traveler behaviors. Figure 5 shows the entire Maricopa County model region with the traffic analysis zones (TAZ) delineated. There are a total of 3009 TAZs in the model region, with 175 zones falling within the test sub-region. The sub-region covers a three-city area in the southeast part of the Greater Phoenix metropolitan area.
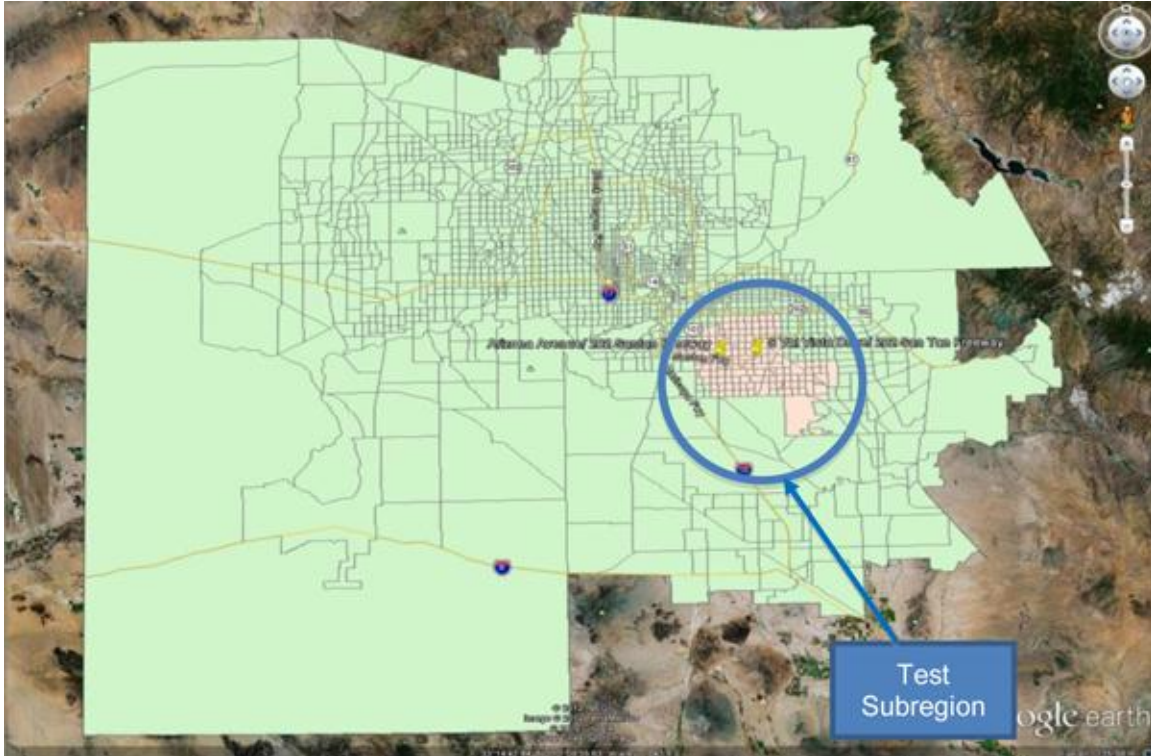
Figure 5: Map of Maricopa County Model Region Showing TAZs and Southeast Three-City Test Sub-Region

Figure 6 shows the three-city sub-region in greater detail with the highway network as an overlay. The three-city sub-region, including the key cities of Chandler, Gilbert, and Queen Creek, has a total population of nearly 500,000 residing in about 170,000 households. The highway network follows a grid pattern and the sub-region is served by major highway corridors including the U.S. highway loop 101 running north-south in the west of the sub-region, the U.S. highway loop 202 running east-west through the middle of the sub-region, and state route AZ-87 running north-south a little west of the middle of the sub-region. All three of these cities are important suburban communities of Phoenix, with Chandler and Gilbert both having a 2010 census population of more than 200,000. Queen Creek has a smaller population of just about 26,000 people, according to the 2010 census.
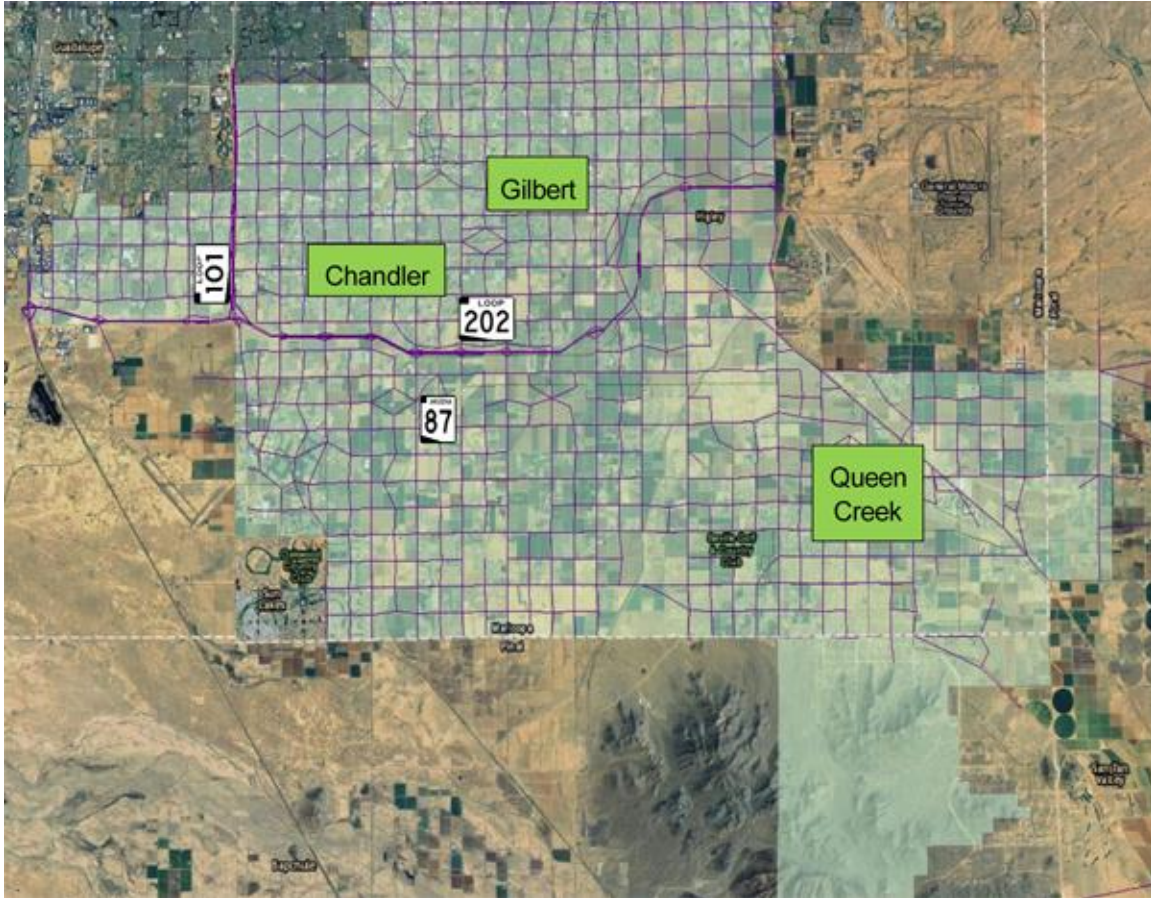
Figure 6: Map of Three-City Test Sub-Region

Within this sub-region of 175 TAZs, the project team identified a set of 12 zones that could be designated as LEZ areas. One set of zones (labeled "1" in Figure 7) corresponds to a major retail center in the heart of Chandler. The Chandler Fashion Center is a large shopping mall that serves as a major destination for shopping trips. The mall employs a large number of individual patrons and is surrounded by numerous other businesses, dining establishments, and offices. Another set of zones (labeled "2" in Figure 7) is to the northeast of the Chandler Fashion Center. This set of zones does not include a singular major attractor of trips but is a high-intensity commercial and retail area with a number of businesses and commercial properties and housing developments. Together, these two sets of zones comprise 12 zones, which is 7 percent of the total 175 zones in the test sub-region.
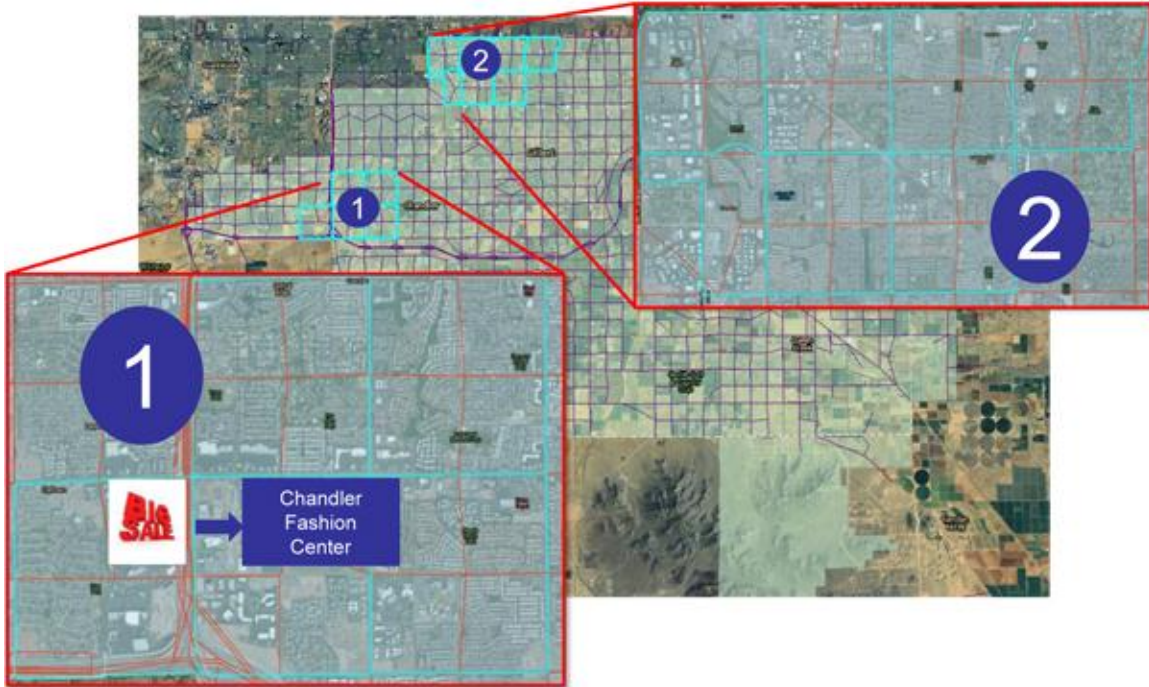
Source: Google Maps (https://www.google.com/maps)

Figure 7: Map of Delineated LEZs in the Three-City Test Sub-Region

Table 2 shows the overall characteristics of the three-city test sub-region and the LEZ areas. The LEZs, although accounting for only 7 percent of all zones in the test sub-region, account for 9 percent of the population and 24 percent of the employment in the sub-region. Thus, the LEZs are areas of high commercial and service activity that serve as a large employment base for the sub-region. The LEZs also include a substantial residential population. This inclusion was done purposefully so that the experimental setup is flexible enough to allow differential treatment of resident population if additional scenarios that treat households and persons residing in the LEZs differently are of interest in future simulation studies.

Table 2: Overview of the Three-City Test Sub-Region

Characteristic	Sub-Region	LEZ Area Only	Percent of Sub-Region
Number of Zones	175	12	7%
Population	505,350	44,418	9%
Employment	171,887	41,237	24%

As mentioned earlier, all scenarios were tested for the smaller three-city test sub-region. The three-city sub-region is not served by light rail but is served by a variety of local and express bus services.

Regional Simulation Case Study Area

The full region simulation case study area comprises a total of 3,009 TAZs. Figure 8 shows the Maricopa County model region with the downtown Phoenix area designed as the LEZ area. The inset figure shows the downtown area with the lines in magenta delineating the LEZs in the CBD. The Phoenix CBD is served by a number of freeways, has a grid-pattern street network, and serves as a large attractor of trips as a result of the high concentration of jobs and increasing presence of mixed use development including high-density housing. The downtown campus of Arizona State University (ASU) also contributes to a substantial amount of activity in the designated LEZ area. The area is served by local and express bus services as well as light rail.
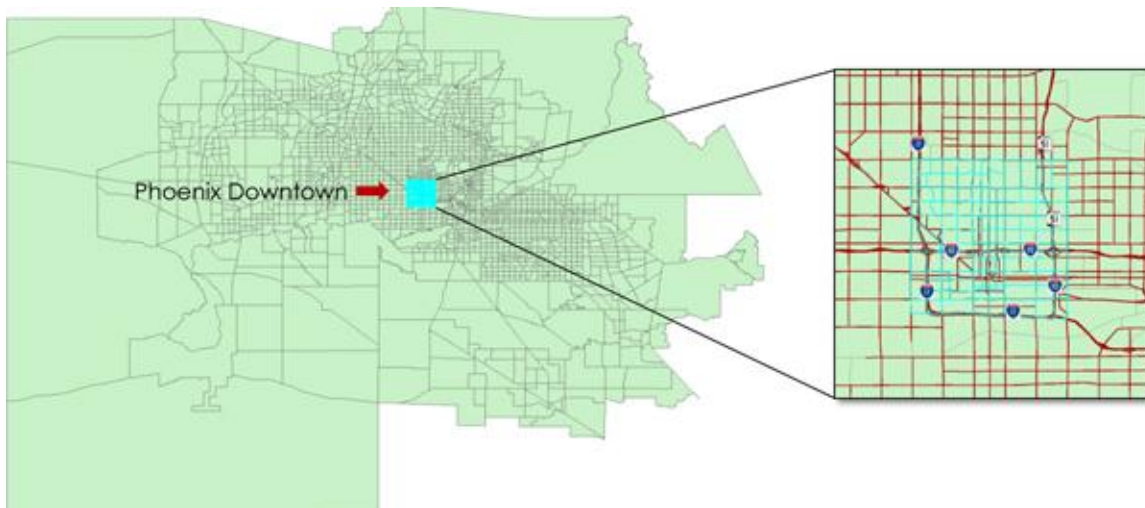
Figure 8: Greater Phoenix Metropolitan Model Region Showing LEZ Area in Phoenix CBD

Figure 9 shows a land coverage map of the delineated LEZ. For clarity, the LEZ is depicted in two parts: the portion that is north of Interstate 10 and the portion that is south of Interstate 10. In the northern section of the LEZ, there is the Phoenix Country Club, a major trip attractor for social and recreational trips. In addition, the St. Joseph's Hospital is a major attractor of both work trips and medical/personal business trips. A variety of other commercial establishments dot the section, many of which account for both work and non-work travel demand. In the southern section, there are a number of key trip attractors. In addition to the growing downtown campus of ASU, there is the Chase Field (home to the baseball team) and U.S. Airways Center (home to the basketball team). In addition, the Phoenix Convention Center, which is one of the largest in the Southwest, is located in this region of the LEZ area designated for this simulation effort. The LEZ area is well served by transit, with light rail lines passing by the sporting venues and the Phoenix Convention Center.
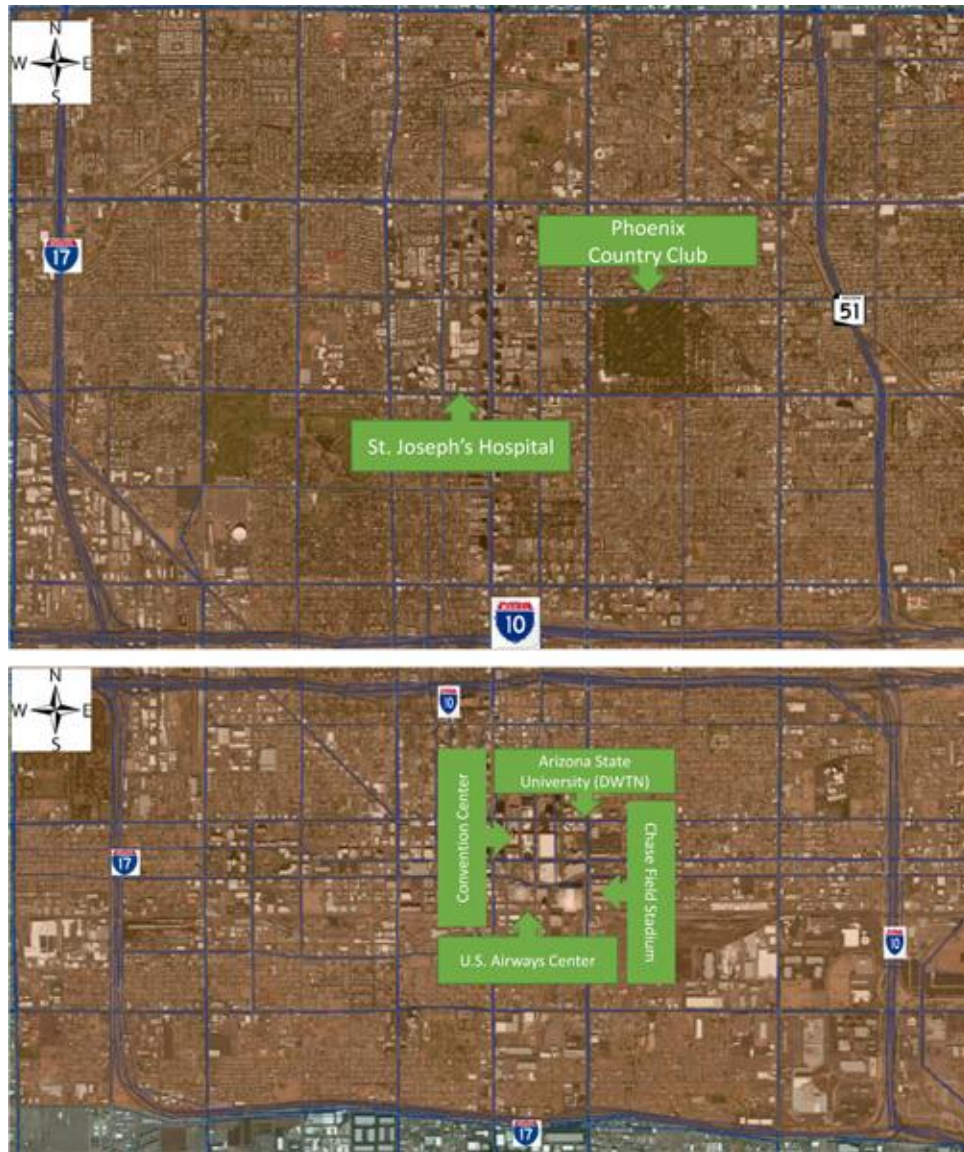
Figure 9: Map of Delineated LEZ in Downtown Phoenix Showing Landmarks

Table 3 presents an overview of the region and the designated LEZ area. The complete region has a population of more than 4 million individuals and 1.6 million workers. The LEZ area encompasses 134 zones (about 4.4 percent of all zones), 3.1 percent of the population, and 11 percent of the employment in the region. The high percent of employment in the LEZ area illustrates the high concentration of economic activity in the LEZ area. The area experiences a high level of congestion, particularly during morning and evening peak periods and on special event days.

Table 3: Overview of Full Region

Characteristic	Region	LEZ Area Only	Percent of Region
Number of Zones	3,009	134	4.4%
Population	4,120,986	127,908	3.1%
Employment	1,640,125	180,124	11%

Chapter 4.   Low Emission Zones Operational Scenario

Application Description

This section provides a description of the AERIS LEZ Operational Scenario. Figure 10 shows an illustration of the LEZ concept. The LEZ Operational Scenario involves the designation of a well-defined geographic subarea of a region that may be targeted through appropriate incentive or dis-incentive schemes to bring about reduction in emissions associated with vehicular travel.
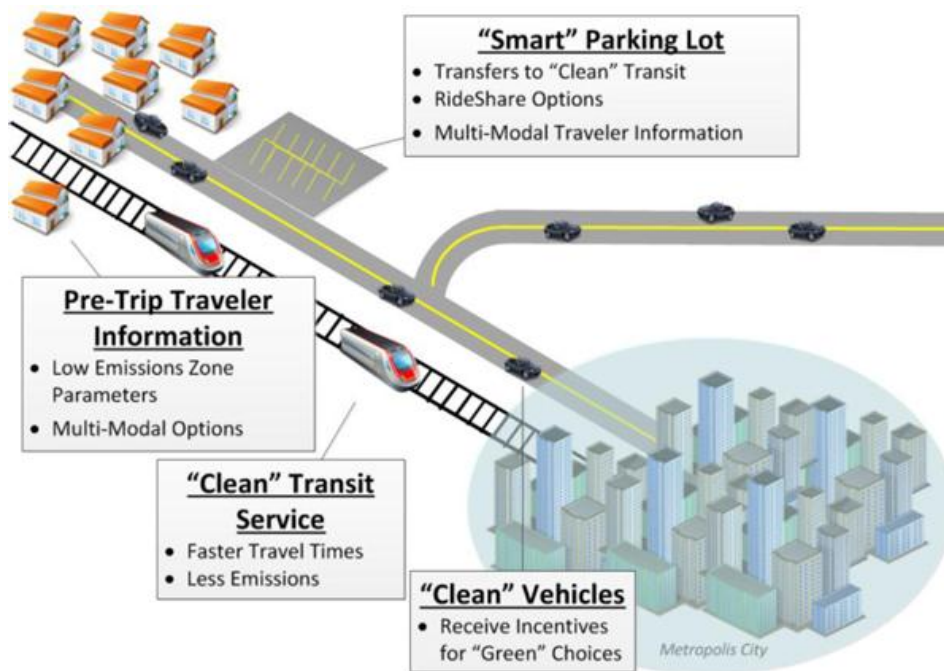
Figure 10: Illustration of AERIS LEZ Operational Scenario

In general, highly developed subareas experiencing high levels of traffic congestion and associated emissions are suitable to be designated as LEZ areas. For example, areas with a large concentration of employment and business/retail activity may be appropriate for designation as LEZs. CBDs and downtown/midtown areas of urban metropolitan regions are prime examples of areas that may be suitable for LEZ designation.

The motivation for a LEZ lies in the desire to target emissions reductions in a sub-area (of a larger region) experiencing high levels of congestion and emissions. The LEZ enables specifically targeting a sub-area that needs relief from congestion and emissions. Another key motivation for the LEZ is that it enables time-of-day and day-of-week adjustments based on traffic and emissions patterns. LEZ parameters such as boundary locations, monetary incentive, and level of enhanced transit (ET) may be adjusted in response to conditions experienced on the network and ambient air quality.

A LEZ may operate in different ways depending on the objectives of the strategy. Travelers may receive incentives, monetary rewards, or other benefits for adopting "green" or environmentally friendly travel choices when traveling to a high-density metropolis designated as a LEZ. For example, travelers may receive a reward for using clean or low emission vehicles when traveling to the LEZ. Travelers who do not have eco-vehicles or low emission vehicles are not prevented from travel through the LEZ, and would not be offered the incentive. In addition, the LEZ may be served by special and "Enhanced Transit" (ET) service with short headways, low (or zero) fares, large span of service, comfortable ride quality, and faster travel times, and premium onboard and station amenities. Travelers who do not have eco-vehicles and therefore cannot take advantage of the monetary incentive may instead take advantage of ET service and realize savings by not having to drive their personal automobile to and from the LEZ. Travelers will be provided information using various forums to enable informed travel choices upfront. Figure 10 illustrates the provision of pre-trip traveler information, where travelers are provided information about the LEZ parameters and the multi-modal options available to them. The information typically provided to travelers includes, but is not limited to:

- LEZ geographic boundary (may vary by time of day or traffic levels)
- Level of incentive associated with "green" travel choices (may vary by time of day or traffic levels)
- Prevailing travel times by various modes of transportation to reach a destination in the LEZ
- Availability and potential monetary savings associated with alternative modes of transportation (primarily transit)
- Real-time updates on the status of park-n-ride lots noting availability of parking, projected wait times for transit vehicle, and transit vehicle load factors or passenger congestion
- Alternative eco-friendly routes to the LEZ showing routes that may not be the fastest but involve a lower carbon footprint (primarily for non-eco-travelers who choose to drive their automobile to the LEZ)

The information provided to travelers may be updated in real-time using connected vehicle technologies, thus affording the ability to dynamically adjust the LEZ boundaries to optimize network performance, target emission reductions where it is needed most, and bring about changes in traveler behavior that are more responsive to prevailing system conditions.

In this study, only the notion of a monetary incentive (associated with a LEZ) has been considered. In reality, incentives may be monetary or non-monetary in nature. For example, it is possible to consider a strategy where travelers earn points for adopting "green" travel choices when traveling to and from LEZs. Travelers can redeem these points, similar to frequent flier miles (in the airline travel context), for various types of rewards. Such reward-based schemes are certainly plausible, but it is often difficult to define or calculate the monetary equivalent of the reward-based scheme. Thus, for the sake of simplicity and ease of simulation, only monetary incentives (or incentives for which a clear equivalent monetary value can be calculated) were considered in this study.

Another important consideration is the cost associated with providing an incentive scheme and ET service for LEZs. Implementing an incentive-based scheme and enhancing transit service and connectivity for LEZs involves a significant cost, and it is important to consider the costs of these strategies from a policy-making perspective. This study does not consider the financial viability and costs associated with implementing the LEZ incentive scheme. It focuses exclusively on travel behavior changes and the associated energy and emissions changes as a result of the implementation of an incentive-based LEZ strategy. However, as has been done in several contexts around the world (e.g., London, several cities in Germany, and several cities in Sweden), LEZs may be implemented with a penalty or toll levied on travelers who do not adopt "green" travel choices. Travelers who choose to drive conventional vehicles (that presumably pollute more than eco-vehicles) would have to pay a toll or penalty for traveling into the LEZs. This strategy is meant to be a deterrent for regular auto travelers, with a view to motivating them to switch to eco-friendly vehicles or modes (transit, bicycling, walking). The revenue collected through such a tolling strategy may be used to offset, at least partially, the costs of an incentive scheme and ET service. A tolling policy has not been considered in this study. The AERIS program focuses on understanding how an incentive scheme, coupled with ET service, may offer energy and emissions benefits. As road-pricing schemes are often viewed as regressive in nature, it is prudent to simulate the impacts of an incentive-based LEZ strategy.

Hypotheses

It is important to specify the types of hypotheses that will be tested and examined through the simulation effort before embarking on a simulation study of this nature. The specification of behavioral hypotheses helps formulate the simulation model runs, define the types of LEZ scenarios to be considered, and identify the output metrics or measures of behavior that need to be summarized, tabulated, and compared across scenarios.

A variety of hypotheses may be postulated in the context of an incentive-based LEZ strategy, with or without ET service. Key hypotheses examined in this study include:

- An incentive-based LEZ strategy will result in reductions in emissions in the targeted LEZ sub-area.
- An incentive-only based LEZ strategy will not result in any appreciable change in traffic congestion. Providing an incentive, while not punishing non-eco travelers will not provide significant reductions in congestion.
- An incentive-based LEZ strategy may result in induced travel demand in the LEZ caused by new trips from eco-vehicle travelers. Without a disincentive for non-eco travelers, they will not change their route or behavior, and therefore will not provide reductions in volume.
- ET service coupled with an incentive-based LEZ scheme will further amplify the emission benefits associated with a LEZ.
- ET service coupled with an incentive-based LEZ scheme will result in reduced automobile travel demand (in the LEZ sub-area) as a result of mode shifts, despite any increases that result from induced travel demand (among eco-travelers).

It should be noted that results of a simulation effort of this nature are sensitive to the scenarios considered and the geographic context for which the simulation is performed. The study team

attempted to test these hypotheses in a way that would provide generalizable results applicable to a wide variety of contexts and scenario specifications. However, there may be situations or contexts/scenarios where additional simulation runs need to be conducted before the veracity of specific hypotheses can be ascertained.

LEZ Modeling Definition and Approach

This section offers an overview of the behavioral and operational aspects of a LEZ strategy. It is invaluable to delineate the operational parameters of interest and the potential behavioral impacts that need to be reflected in the model system used before embarking on a model formulation and simulation effort. These topics are addressed in this section.

Definition of Eco-Vehicle in the LEZ Context

In the LEZ scenarios considered for this study, an incentive is provided to travelers who use "eco-friendly vehicles" (or "clean" low-emission vehicles) in the context of travel to the designated LEZs. To calculate the energy and emissions benefits of such a scheme and the potential market penetration (adoption) of such vehicles, it is necessary to define and designate the vehicle types/classes that would fall into the "incentive-eligible" category. A very strict definition may limit the incentive to travelers who use zero-emission vehicles such as hydrogen vehicles or pure electric vehicles. However, given that the market penetration and refueling infrastructure for such zero-emission vehicles is still rather limited, the study team considered it prudent to use a more relaxed definition of eco-vehicle. Figure 11 presents an overview of the vehicle types and classes considered eligible for the incentive in this study. Hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and pure electric vehicles (EVs) were all treated as "eco-vehicles" in this study and considered eligible for receiving the monetary incentive. No differentiation was made between the different types of eco-vehicles; all eco-vehicle travelers received the same incentive, while those in non-eco-vehicles received absolutely no incentive. However, the operational parameters of the LEZ may be such that different vehicle types (classified by fuel economy, weight class, vehicle body type, fuel type, or a mix) obtain different levels of incentives; such a scheme would give the highest incentive to zero-emission vehicles and the lowest or no incentive to large heavy pure-gasoline vehicles. The model system used in this study includes a detailed vehicle fleet composition and tracking model system; however, for simplicity and in consideration of model run times, a more simple and straightforward incentive structure was used in this study.

Figure 11: Eco-Vehicles Designated in LEZ Operational Scenario Simulation (Sources:
http://www.toyotainthenews.com/2011-toyota-prius-is-the-no-1-fuel-sipper-in-the-u-s/;
http://gate.its.ucdavis.edu/news/plugctr06;
http://www.colinappleyard.com/blog/customers_fall_for_electric_nissan_leaf)

LEZ designation may not necessarily be limited to personal (passenger) travel. The operational parameters of such a zone may also be applied to freight transport vehicles, commercial and service vehicles, and taxis. It is certainly feasible to provide incentives for such non-personal travel if eco-friendly vehicles are being used to access locations in or pass through the LEZ. Different incentive structures may apply in the context of commercial and taxi travel. In the simulation effort conducted for this study, only personal (passenger) travel undertaken by household vehicles is modeled and simulated. The study does not account for freight, commercial, and taxi travel, although origin-destination (O-D) trip tables or matrices reflecting the demand for such travel are loaded onto the network to reflect the effect of their presence on network congestion and travel times. Such demand is treated as background traffic and is not subject to the LEZ designation or treatment in the simulation.

Definition of LEZ Strategy Parameters

In the context of this study, which focuses on an incentive-based monetary LEZ strategy, the most important parameter is the level and nature of the monetary reward for adopting "green" travel choices. The intent of the incentive is to motivate travelers to switch to low-emission vehicles or transit if they are not able to acquire and use a low-emission vehicle. The incentive may be given to a traveler using a "green" travel option when entering the zone. The LEZ may be imagined as having a cordon around it; every time a traveler enters the cordon, his or her transponder will receive a credit if the traveler is using a qualifying low-emission vehicle. A small monetary incentive may be directly deposited into the individual's bank account (on a monthly or quarterly cycle), individuals may receive checks in the mail (similar to receiving bills in the regular mail), or the value could be represented in other forms of incentive, such as coupons or discounts, free parking, or "intangible" point or game systems. Regardless of the method of payment, a traveler would receive the incentive amount every time he or she enters the cordon LEZ area in a low-emission vehicle. This mode of operation raises important questions:

- Should the traveler receive the benefit every time he or she enters the cordon?
- Should there be a daily maximum on the amount of benefit a traveler can earn (to avoid having travelers game the system by repeatedly driving in and out of the cordoned area)?
- Should travelers who live in the area receive the monetary benefit every time they are presumably returning home?

- Should travelers who are merely passing through the cordoned area (i.e., their origin and destination are outside the LEZ area but their path takes them through the area) receive the benefit if they are driving?

These questions need to be answered when implementing the policy in an urban metropolitan region. This simulation study assumed:

- A modest monetary incentive is given to an eco-traveler (traveling in an eco-vehicle) every time he or she crosses into the cordoned LEZ area. No incentive is given for exiting the cordoned LEZ area. No incentive is given for using ET service; the ET service is assumed to provide benefits and no additional incentive is offered for riding ET service.

- The behavioral model adopted in this study will prevent any unreasonable travel patterns where, for example, travelers repeatedly exit and re-enter the cordoned LEZ area in an effort to game the system and maximize their benefits. To further guard against such unreasonable activity-travel patterns from occurring, the amount of incentive is capped at a daily maximum amount.

- The incentive is given to all travelers, including those who live in the LEZ area; thus, travelers returning home would receive the incentive amount every time they return home.

- Travelers passing through the LEZ area receive the monetary benefit when they enter the cordon if they are using an eco-vehicle. The idea is to incentivize travelers to shift to more eco-friendly vehicles if they are going to contribute to traffic and emissions in the LEZ area; hence pass-through travelers are provided the same incentive as travelers destined to zones in the LEZ.

- The nature of the incentive is such that an accurate equivalent monetary value may be estimated. The incentive may be a direct cash benefit or an indirect incentive that may be monetized easily and accurately. For example, incentives may also include free parking (the value of which can be calculated) or rewards that may be redeemed in various ways (again, it is assumed that the monetary value of the rewards can be calculated). Other incentives such as preferred parking, guaranteed parking, discount coupons for use at participating merchants, and eco-traveler points are more difficult to monetize and are hence not explicitly considered in this study.

In addition to defining the level and nature of the monetary incentive for eco-vehicle travelers, it is also necessary to define the nature of the ET service. Regular transit (RT) service in the area may be characterized by certain spans of service, service headways, travel times, dedicated (or not) lanes, and onboard and station amenities. ET service parameters need to be clearly defined because these variables not only affect mode share but also the alternative specific constant in the mode choice utility equations that purport to capture the effect of non-traditional attributes (such as premium onboard and station amenities). At a minimum, the parameters need to define the span of service, the headway or frequency of service, travel times, and fare levels associated with ET to and from LEZs. ET service is assumed to be provided both to and from the LEZs (relative to all other zones in the region). For example, if there are 50 LEZs and 3000 total zones in a metropolitan model region, enhanced service parameters will appear in the 50 x 3000 matrix corresponding to service from the 50 LEZs to all other zones, and in the 3000 x 50 matrix corresponding to service from all zones to the 50 LEZs. If premium service amenities (onboard and at stations/stops) are going to be provided, the alternative specific

constant may be modified (to a modest degree) to reflect the potential impacts of such amenities on mode choice.

Another service parameter is the availability of pre-trip information. In general, with the ubiquitous availability of traffic and transit service information on a multitude of platforms and devices, it is reasonable to expect universal availability of and accessibility to pre-trip information. However, this parameter may be adjusted in the simulation depending on the scenario that is being considered. Although it is reasonable to expect 100 percent of the travelers to have pre-trip information about LEZ designation, multi-modal options, and parking availability, the analyst is free to change this percent to reflect a differing market penetration or use of pre-trip traveler information. In other words, it is possible that not everybody who has access to pre-trip information actually refers to and uses it. So the percent of travelers who access and use pre-trip information at any moment in time may be less than 100 percent. The percent of travelers who have access to pre-trip information is one parameter; among them, the percent that actually use pre-trip information prior to embarking on a trip in the simulation is another parameter.

In a connected vehicle environment (where vehicles communicate with one another and with the infrastructure), it is possible to relay real-time network information to en-route travelers. Real-time travel information may also be relayed through variable/dynamic message signs, dedicated radio channels, subscription-based traffic services available as smartphone applications, in-vehicle navigation and traffic displays, and 511 services. Parameters may be specified to identify the extent to which travelers have access to and use real-time traveler information while they are en-route. This percentage would presumably be less than the percent of travelers who have access to pre-trip information. Nevertheless, as vehicle technology evolves and connected vehicle infrastructure advances, the percent of travelers with real-time travel information on network conditions and multi-modal options may rapidly grow. In the context of real-time travel information provision, it is also necessary to specify the time lag with which the information is provided. In other words, are travelers receiving information in true real-time or does the information lag by 5, 15, or 30 minutes? The lag information provision may affect the percent of travelers who rely on the information to make real-time adjustments to their travel choices. Although this study does not specifically consider real-time traveler information provision through connected vehicle architecture among the scenarios simulated (as a result of model run times), the methodology and findings can be readily extended to such scenarios.

This spatio-temporal variation in the LEZ may occur in a dynamic fashion or a more preset static fashion. In the latter, the LEZ is designed to have preset specifications for different times of the day and days of the week, similar to a pre-timed traffic signal that has different phase and green time allocations for different times of the day (peak hours, off-peak hours, night hours) and days of the week (weekend days versus weekdays). The LEZ may also have pre-specified geographical boundaries, monetary incentive levels, and ET service levels that vary by the time of the day or the day of the week. These parameters are not dynamically adjusted in response to varying traffic and emissions. In the dynamic context, the parameters of the LEZ are determined in real-time and presumably updated every 15, 30, or 60 minutes to respond to prevailing traffic and emissions conditions. Certain boundary conditions such as maximum allowable incentive and minimum allowable incentive may be applied, but the parameters are allowed to vary within these constraints. The spatial and temporal characteristics of the LEZ are adjusted in real-time in response to prevailing conditions to optimize network performance and ensure that emissions in the LEZ remain below a specified (unhealthy) threshold. This dynamic adjustment is similar to a dynamic pricing scenario where tolls on a dynamically priced lane are varied based on travel demand while striving to ensure that a minimum level of service is maintained. The simulation of the impacts of dynamic real-time LEZ

specifications is beyond the scope of the modeling effort conducted for this study, but the methodology and model formulation can be extended to accommodate such a design. The preset static design is easily accommodated within the modeling methodology of this study.

Behavioral Impacts of LEZ Strategy

In a LEZ strategy, a set of zones in a high-activity area (presumably with high traffic and emissions) are designated with the special status to incentivize travelers to use eco-vehicles when traveling to and from the LEZs. Any model system that aims to simulate the impacts of such a strategy should be capable of reflecting the primary, secondary, and tertiary changes in the spatial and temporal characteristics of travel behavior that might occur. This section offers a brief discussion of the potential behavioral impacts that a LEZ strategy may have and the ways in which a model system may be able to account for such behavioral effects.

In response to a LEZ strategy where travelers using eco-vehicles are provided an incentive, it may be expected that households will consider acquiring and using an eco-vehicle, thus bringing about a change in household vehicle fleet composition. Even if households cannot handle the transaction cost of an automobile acquisition in the short term, they may be able to dispose of or trade in an existing non-eco-vehicle and acquire an eco-vehicle over time. In response to a LEZ strategy, it may be reasonably expected that penetration of eco-vehicles in household fleets will increase over time as household vehicle fleets experience turnover. In Maricopa County, Arizona, HOV lanes were opened up to single-occupant hybrid and electric vehicles a few years ago. As a result of this policy, there was a surge in household acquisition of eligible eco-vehicles and the 10,000 specially designated license plates for such vehicles were exhausted within a few months of the announcement of the policy (http://www.azcentral.com/news/articles/2008/05/19/20080519hybridplates0519.html). The program has been so popular that Arizona continues to distribute special license plates (those that are returned or unused from the first wave of the program) to eco-vehicles, but has redefined eco-vehicles to be inclusive of only pure EVs and PHEVs (in the first wave, hybrid vehicles were allowed to participate). In other words, the availability of an incentive is spurring households to adjust their fleet so that they can take advantage of the incentive.

Because the LEZ the scenario modeled in this report involves a monetary-type benefit, it is expected that the impact on vehicle fleet composition may be even larger than in the case of an HOV lane being opened up to single-occupant vehicle drivers in an eco-vehicle. The model system used in this study should be able to endogenously predict within the model system how the percent of eco-vehicles (and therefore, eco-travelers) will change over time in response to the LEZ incentive policy. Very few model systems incorporate such vehicle fleet composition model systems, and it is therefore necessary to adopt a model system for this study that includes such a model component. In addition, the model system should be capable of tracking vehicles through time (over the course of a day) and space so that the traveler in the vehicle obtains an incentive only when he or she travels to the designated LEZ area. An individual may use an eco-vehicle to travel over the course of a day, but will not garner any monetary incentive unless there is travel specifically through the LEZ area. It is imperative that a vehicle-type choice model be included (i.e., if a traveler is going to the designated LEZ area to undertake an activity) so that the traveler is likely to choose the eco-vehicle to undertake this trip. In that case, the eco-vehicle is occupied and unavailable to other household members. Thus, it is necessary to have not only a vehicle fleet composition model (to define the household vehicle fleet) but also a tour-level vehicle-type choice model to identify the specific vehicle in the household that will be used for a specific tour.

The designation of a LEZ area could directly impact destination choice for discretionary and flexible activities. Although individuals may not have the ability to alter destination choice for more fixed and mandatory activities such as work and school, they may be able to alter destination choice for discretionary and flexible activities such as shopping, personal business, dining, and social-recreation. If the LEZ is designed in such a way that the specially designated zones and the incentive levels vary by time of day, the scheduling of activities may also change. Departure time choice is affected by the time-varying conditions of the LEZ. If a larger incentive is provided during the off-peak period, the eco-traveler may choose to adjust departure time to travel during the off-peak period and realize the higher level of incentive. By varying the spatio-temporal characteristics of the LEZ, it is possible to influence the spatio-temporal patterns of activity-travel demand. Any model system used to simulate the impacts of LEZ policies must be capable of reflecting changes in destination choice (primarily for discretionary and flexible activities) and departure time choice (activity scheduling) that may occur.

Spatio-temporal shifts must, however, be accommodated with due consideration for time–space prism constraints that govern and influence activity-travel patterns. A key strength of the activity-based modeling paradigm is that there is explicit recognition of travel being derived from the need and desire to pursue activities that are distributed in time and space. Thus, travel is a derived demand, and modeling activity generation and engagement provides a robust framework for modeling travel demand. One of the key tenets of human activity-travel engagement is that activity-travel patterns are constrained by three-dimensional time–space prisms that define the action space within which individuals are able to engage in activities and travel. The concept of time–space prism constraints provides a powerful framework for modeling activity-travel demand while explicitly accounting for phenomena such as induced and suppressed demand. Figure 12 illustrates in a simplified form the notion of a time–space prism.
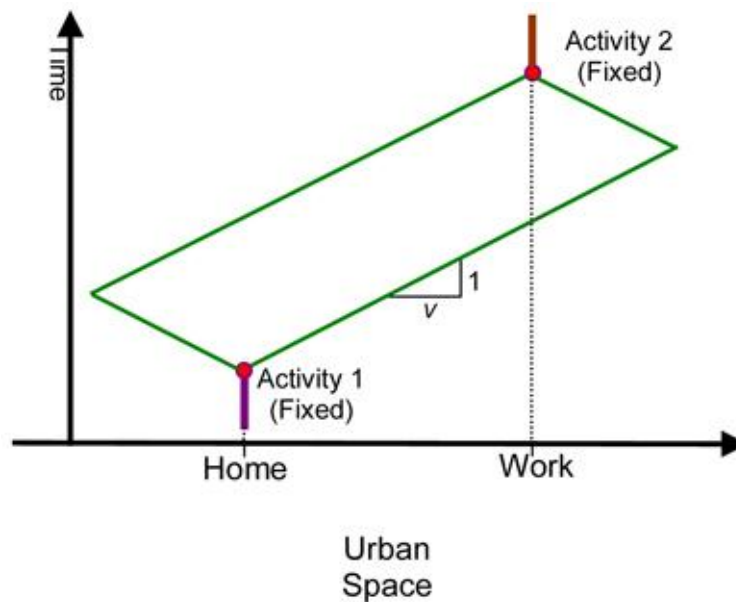
Figure 12: Simplified Representation of Time–Space Prism Concept

Consider an individual who must be at home until a certain time of day (say, to take care of children or simply because the individual needs to sleep and does not want to start the day before a certain time). Activity 1 (Fixed) at the home location represents this idea. Suppose the individual must also be at the next fixed activity location, work, by a certain time as the result of a rigid work schedule. The individual

must be at the location noted as Activity 2 (Fixed) by a certain time. These two points in time and space represent the vertices of a time–space prism within which an individual may engage in discretionary activities and travel. The size of the prism is dictated by the slope of the lines, which represent the speed of travel. If the speed of travel is fast, the prism is large and the individual can indulge in more activities (activities that are located farther away) or spend more time at activities. If the level of service is poor, the speed of travel is slow, and the size of the prism shrinks. This may lead to elimination of non-essential activities, reduced travel times by visiting destinations that are closer, and reduced time expenditures (durations) at the activities themselves. In other words, when there is an improvement in the level of service of the system, the prism expands and the activity model simulates the additional activity engagement and time use (whether travel or activity) that might take place. The model is capable of capturing induced demand effects. When the speed of travel worsens and the prism contracts, the model is capable of representing the reduced activity engagement that must result because of the shrinking time–space prism. The time–space prism constraints dictate the extent of the action space, the range of destinations that can be visited, and the amount of time that can be spent at the activity locations. In other words, the model is capable of capturing suppressed demand effects.

The incorporation of time–space prism constraints is extremely important from the standpoint of simulating activity-travel patterns in a LEZ context. For example, an individual with an eco-vehicle might want to travel to the LEZ for a discretionary trip to take advantage of the incentive. In a model that does not adequately account for time–space prism constraints, the traveler would be allowed to travel to the LEZ location to undertake the activity. However, in reality, the traveler may not be able to travel to the LEZ destination for a discretionary activity because of time–space prism constraints. If the LEZ does not fall within the allowable time–space prism, the individual cannot visit the LEZ location without violating a time–space prism constraint. In such a situation, the traveler will have to forego the activity (forego visiting the LEZ location), visit an alternative non-LEZ location, or reschedule the trip/activity to the LEZ location to a different time of the day when the time–space prism can accommodate the visit. The model system used in this study explicitly models and simulates time–space prism constraints and effects in forecasting activity-travel patterns.

With the potential introduction of ET service as part of the LEZ (where ET service is coupled with the incentive for eco-vehicles), mode choice is a key behavioral trait that must be reflected. In response to a LEZ (where there is an incentive for using eco-vehicles), it is not very likely that travelers will switch to transit. Travelers would be more likely to choose to drive their eco-vehicles to and from the LEZ area to take advantage and realize the monetary benefit/incentive. Nevertheless, there may be a few travelers who might still opt to use transit in light of the enhanced level of service. However, travelers who are driving regular vehicles do not realize any benefit from driving their personal vehicle to the LEZ. They are also not penalized, so they may continue to drive their regular vehicle as they did prior to the introduction of the LEZ and ET service. However, some travelers may switch to transit (taking advantage of the ET) and realize indirect savings; the ET service may come at a greatly reduced or subsidized fare, thus driving the out-of-pocket costs of taking transit lower than the cost of driving (a regular vehicle) to the LEZ area. By switching to transit, travelers are saving money, which might, at least indirectly, be viewed as an incentive to adopt a more eco-friendly mode choice. The model system that is used in the simulation effort must be capable of reflecting mode choice behavior at the tour level, recognizing that an individual who chooses transit for a trip to the LEZ area is likely to remain captive to transit (for the most part) for all trips within the trip chain (until the individual returns to the home anchor and can switch to a different personal mode of transportation). Modal dependency across trips in a tour or chain is an essential ingredient to simulating mode shifts. When mode shifts occur, time-of-day choice (departure time choice) may be affected, as individuals attempt to

synchronize their schedules with transit schedules. Also, transit travel times are different from auto travel times, and these differences may bring about changes in activity durations and destination choice.

Shifts in destination choice (e.g., choosing to travel to the LEZ) will have secondary and tertiary impacts on route choice and activity sequencing (i.e., the order of tasks one completes over time). When individuals choose alternative destinations for their activities, the routes they follow will naturally change and evolve. These changes in route choice must be reflected in the simulation model system. If passing through the LEZ area offers an incentive for eco-travelers, eco-travelers may purposefully attempt to pass through the area to take advantage of the incentive as long as the deviation from the shortest path or route is not larger than a certain threshold. The model should be able to capture modest deviations from the shortest path to accommodate such behavior. This functionality can be accomplished in Dynamic Traffic Assignment (DTA) models that consider and identify multiple shortest paths between O-D pairs, and route eco-travelers on the paths that pass through the LEZ area.

As a multitude of behavioral dimensions experience change in response to a LEZ, the way people sequence (chain) their activities and the types of activities pursued may change as well. Trip chains may be rearranged to accommodate the fact that an eco-traveler now chooses to the visit the LEZ area to undertake a discretionary trip. If an individual is now traveling farther or longer to visit the LEZ area and take advantage of the incentive, the remaining available time in the time–space prism may shrink. As a consequence, an activity that would have otherwise been undertaken may be rescheduled to a different time of day or dropped altogether. These types of cascading changes impact the entire trip chaining pattern, daily activity-travel pattern, and suite of activities undertaken by a person. The model system needs to incorporate an activity type choice model to simulate the set of activities (activity types or purposes) that will be pursued and the sequence or manner in which the activities will be chained together in a LEZ scenario. Accounting for both induced demand and suppressed demand is critical to successfully simulating the impacts of a LEZ scenario.

Modeling Approach

After gaining an understanding of the technical requirements and policy changes induced from the implementation of the LEZ, a new and unique approach to model it was devised. This section provides a detailed description of the modeling approach that has been used in the simulation of the impacts of such a LEZ. The previous section outlined the various behavioral considerations that the model must be capable of reflecting. In the context of modeling LEZ impacts, it is also necessary to consider heterogeneity in behavior across households and persons. To best capture the heterogeneity in user behavior, and reflect the multitude of behavioral dimensions described in the previous section, the project team has adopted the micro simulation paradigm for modeling behavioral impacts of LEZ scenarios. In the micro simulation paradigm, individual travelers are tracked through the course of a day, thus facilitating a fine-grained analysis of activity-travel patterns while accounting for trip chaining, time–space prism constraints, and household interactions. In the micro simulation framework adopted for this study, time is treated as a continuous entity (at the resolution of 1 minute) and activity-travel patterns evolve over the course of a day subject to time–space prism constraints and experienced network conditions. Within the context of this study, simulation of connected V2I systems at the temporal resolution of 1 second was not undertaken because of the additional computational burden that such a simulation would entail. In addition, the study did not address the potential longer-term land use impacts of a LEZ. In response to a LEZ incentive policy and ET service, it is possible that households and businesses will relocate, bringing about a change in the land use pattern and accessibility indices capturing access to destinations. It is not yet clear as to the extent to which a LEZ

would impact longer-term location choices and land use patterns; for this reason, modeling land use change in response to LEZ scenarios was not undertaken as part of the effort. The remainder of this section presents a description of the model system and the special modifications that were introduced to address LEZ-specific simulation requirements.

Integrated Model System of Activity-Travel Demand and DTA

The simulation test bed used for the LEZ analysis includes a tightly coupled activity-based travel demand model system (produce vehicle trips and release timing based on "activities") and a DTA model system (assign vehicle routes based on "dynamic" changes in traffic conditions). The activity-based travel demand model system is called openAMOS and the DTA model system is called DTALite. These models are integrated in such a way that they communicate with one another on a minute-by-minute basis. Two-part Figure 13 shows a simplified schematic of this tight coupling.
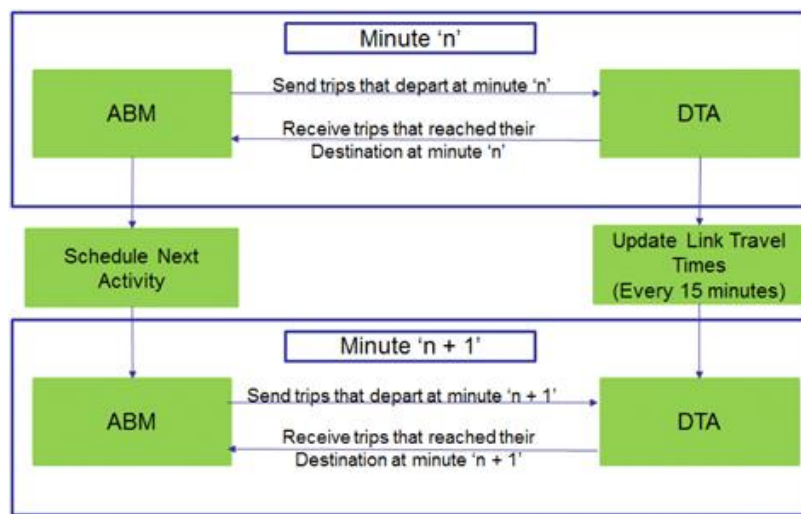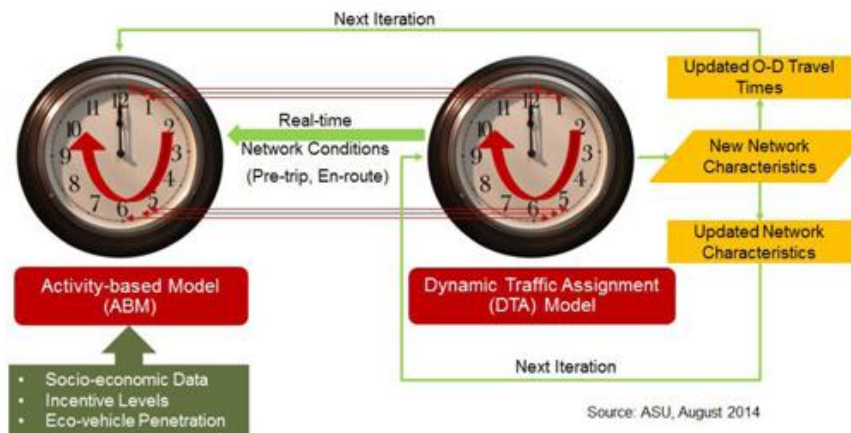
Figure 13: Illustration of the Integrated Activity-Travel Demand and DTA Model System

The integrated model system is one in which the activity-based travel demand model simulates activity-travel (demand) choices along the continuous time axis. In each minute of the simulation, openAMOS generates the set of trips that are going to depart in that minute with attributes such as mode choice, destination choice, vehicle-type choice, activity purpose, and travel party composition. These choices are simulated while explicitly considering the constraints that affect activity-travel patterns, including time–space prism constraints, household coupling constraints (for example, a dependent child cannot be left unattended), and mode and vehicle constraints (subject to availability). The trips that are departing in any minute of the day are transferred to DTALite, the DTA model, for assignment and routing on the network. The DTA model will assign, route, and simulate the trips through the network to their respective destinations. In each minute of the simulation day, a number of trips will reach their designated destinations. DTALite will send to openAMOS (in each minute of the simulation day), the set of trips that have reached their destination. Based on the arrival time of the traveler, openAMOS will then simulate what the individual will do next in terms of activity duration and subsequent activity engagement. This minute-by-minute communication between openAMOS and DTALite provides a robust framework for simulating the evolutionary process underlying the formation of activity-travel itineraries.

Activity-travel choices are simulated by openAMOS according to the traveler's expectations about network performance, where network travel times and costs are represented by O-D travel times and cost "skims." Travel paths are typically the shortest paths generated using generalized cost as the impedance. To develop a better understanding of the parameters that influence path assignment and travel behavior, parameters such as travel time, travel distance, and fares or costs are accrued or summed for all the network links along the travel path to create O-D skim matrices. These skim matrices are typically used by destination- and mode-choice models. Generalized cost functions may be developed to capture the composite impact of travel time and cost (or, in the case of the LEZ scenarios, an incentive). At the end of a 24-hour simulation run, DTALite will save time-dependent O-D travel times (O-D skims) in 15-minute time slices. The resolution of the time-dependent skims can be changed, so it is theoretically possible to save skims at 1-minute resolution, but that comes with heavy computational demands. At the end of each iteration of the integrated model system, new skims are generated and openAMOS will use the latest set of skims in simulating activity-travel choices in a subsequent iteration. In other words, each iteration of the integrated model is representative of an accumulated knowledge or experience gained by the traveler about the network conditions at various times of the day. This iterative process is continued until convergence is achieved both on the demand and network side. Network skims should show no appreciable change from one iteration to the next and the demand (as represented by time-dependent O-D matrices) should be stable from one iteration to the next. Once both of these entities show stability, the model is said to have converged and is terminated.

The integrated modeling framework offers considerable capabilities for simulating the impacts of real-time policies and strategies. As noted previously, openAMOS reads time-dependent or time-varying skims provided by the network model to simulate activity-travel choices (demand). For example, mode choice and destination choice—in addition to activity generation—are sensitive to network travel times at the time that the individual is scheduled to depart on an out-of-home activity. In the current configuration of the integrated model system, activity-travel choices may be simulated by openAMOS using network conditions saved from prior iterations (representing accumulated knowledge or experience of the travelers that constitutes "expectations" on the part of travelers regarding network conditions at various times of the day) or using prevailing network conditions as computed by DTALite within the current iteration of the integrated model run. In other words, if a traveler is being provided real-time pre-trip traveler information about network conditions and travel times, the integrated model system is able to reflect such a scenario. Rather than simulate choices based on travel times stored

from prior iterations, openAMOS will simulate demand choices based on time-varying network conditions and travel times of the current iteration. Thus, a traveler departing at 7:18 a.m. will be provided information about average zone-to-zone travel times and costs (incentives) in the period of 7 a.m. to 7:15 a.m. so that the traveler may make activity-travel demand choices according to the most recent updates of network conditions. Travelers making choices in the time period of 7:30 a.m. to 7:45 a.m. will do so based on network information for the period of 7:15 a.m. to 7:30 a.m. In other words, travel time information is updated every 15 minutes and travelers have the most recent 15-minute information at their disposal when making travel demand choices. The resolution of this time interval can be changed with finer granularity placing greater computational burden.

The integrated activity-travel demand and DTA model systems include a series of model components to capture the behavioral phenomena described in the previous section of this report. Figure 14 offers a simplified illustration of the model components with a focus on the activity-based travel demand model system because the impacts of a LEZ are likely to occur to a greater degree on those travel choices covered by the activity-travel demand model. The DTA model essentially deals with route choice and simulation of person/vehicle movement through the network. The DTA model is able to route trips through the network considering time-dependent shortest paths (i.e., the routing algorithm accounts for the fact that the shortest path between an O-D pair is dependent on link travel times that prevail at the time that the traveler traverses the link). For example, consider an individual departing to a destination at 7:00 a.m. The shortest path is not necessarily the series of links that have the smallest travel time at 7:00 a.m. Instead, the shortest path is time dependent, recognizing that some time will elapse between the moment the traveler departs the origin and arrives at a subsequent link; if a traveler is expected to arrive at a downstream node at 7:15 a.m., the shortest path is determined based on the expected travel time on the downstream link at 7:15 a.m. (rather than at 7:00 a.m.). This time-dependent shortest path algorithm captures the influence of network dynamics on route choice and ensures that routing of trips through the network reflects traveler expectations of travel times on various links. The DTA model routes travelers through the network and computes a gap function at the end of each iteration to determine the difference between experienced travel time and best (shortest) travel time; this gap function is computed for each trip and aggregated over all travelers to determine the extent to which travelers could potentially improve their route choice and travel time. If the gap function is larger than a preset tolerance value, another iteration is performed to reroute travelers and improve experienced travel times. This process is continued until the gap function falls below a pre-specified tolerance value. At this point, it may be conjectured that travelers cannot realize any additional (meaningful) savings in travel time through changes in route choice.
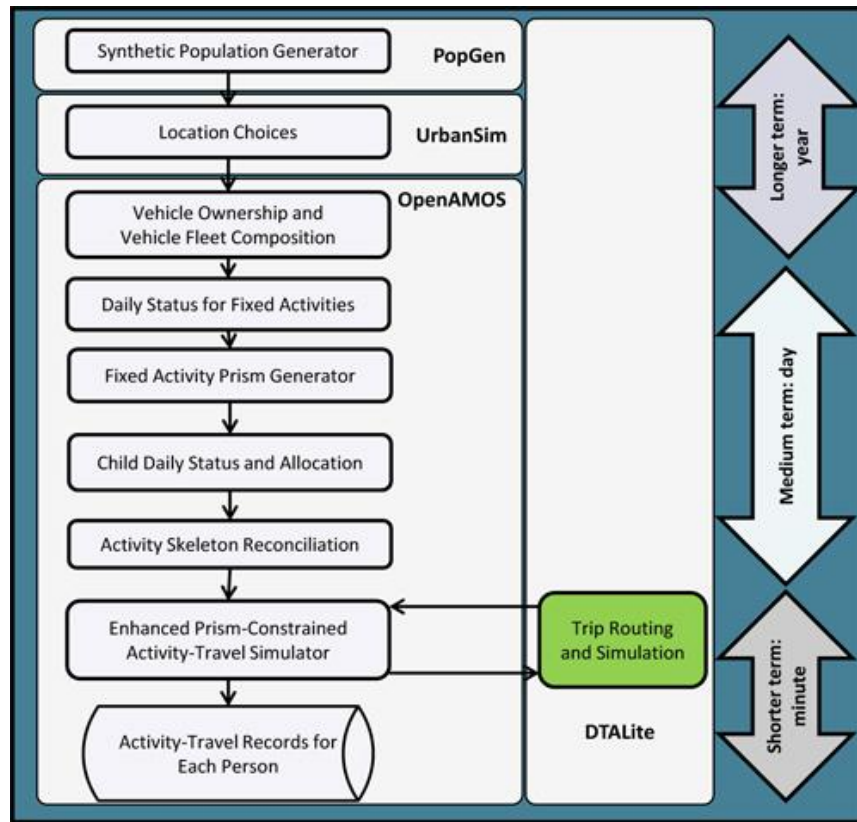
Figure 14: Key Components of the Integrated Activity-Travel Demand and DTA Model System

A challenge arises in the context of the integrated activity-travel demand and DTA model in that the demand model will generate different activity-travel patterns for each traveler in each iteration because each iteration constitutes one realization of an underlying stochastic behavioral process. This can create an endless loop where new activity-travel patterns inevitably produce new network conditions, and the process does not readily converge. To help facilitate rapid convergence of the integrated model system (across iterations), the method of successive averaging is applied to the O-D trip tables (derived from the activity-travel demand model at the end of each iteration). Although the activity-travel patterns for each individual traveler may vary from one iteration to the next, it is expected that O-D flows will eventually exhibit stable behavior and averaging successively across multiple iterations will ensure convergence on the demand modeling side of the integrated model. Thus, convergence in the integrated model is achieved when two conditions are satisfied: first, the gap function in the DTA model is smaller than a specified threshold value, and second, successively averaged O-D trip tables show stability across iterations of the integrated model system (a threshold or tolerance value is specified for the demand-side convergence of O-D trip tables as well). These tolerance values are user-specified; a rather relaxed set of tolerance values would provide for more rapid convergence and faster model run times, while a tighter set of tolerance values would lead to a larger number of iterations to achieve convergence and consequently longer model run times. Setting of tolerance values constitutes a tradeoff reflecting a compromise between the desire to achieve reasonable model run times and the desire to realize high levels of stability in network conditions and flows across iterations of the integrated activity-travel demand and DTA model system.

The integrated activity-travel demand and DTA model system starts with the generation of a synthetic population for the model region under consideration. A synthetic population is a complete and

comprehensive enumeration of all agents (households and individuals within households) in the model region. The activity-travel demand and DTA models simulate activity-travel patterns at the level of the individual traveler while explicitly considering intra-household interactions and vehicle allocation and usage behavior. The synthetic population is an exhaustive listing of all agents in the region complete with socio-economic and demographic characteristics (variables) that enter the choice model specifications. The synthetic population records are generated by weighting and expanding the American Community Survey—Public Use Microdata Sample (PUMS) such that the resulting synthetic population exhibits the same characteristics as the actual population in the region. The Census Bureau provides a series of tabulations and distributions on a large number of socio-economic and demographic characteristics for the entire population of a region. The PUMS records are weighted, expanded, and replicated to form a synthetic population such that the distributions of socio-economic and demographic characteristics in the synthetic population exactly replicate those found in the actual true population (as reflected in the census tabulations).

The integrated activity-travel demand and DTA model system includes a land use microsimulation model called UrbanSim. This model system is able to capture longer-term changes in residential and business location choices in response to changes in transportation network conditions and accessibility measures. Although it is conceivable that a LEZ strategy could lead to changes in longer-term location choice and land use, such aspects were not explicitly captured and considered within the context of this simulation effort. Residential and firm location choices were considered fixed and all land use patterns were treated as exogenous to the modeling effort. In other words, the simulations performed in this study may be treated as reflective of the near-term impacts of a LEZ (rather than reflective of longer-term evolutionary impacts).

The activity-travel demand model system includes a number of key components to reflect the various travel choices that may be impacted by a LEZ. These components of the travel demand model are intended to capture medium- and shorter-term changes in travel characteristics that arise from the implementation of a LEZ. The vehicle ownership and fleet composition model component is capable of forecasting the mix of vehicles that each household will own. The model is sensitive to socio-economic characteristics, built environment attributes (such as mix and density of land use), and network attributes (accessibility measures). The vehicle ownership and fleet composition model may be made explicitly sensitive to price signals (such as LEZ monetary incentive); however, in the absence of real-world data about such price signals, it is difficult to modify the specification of the model to reflect the impacts of a LEZ monetary incentive on vehicle fleet composition (i.e., the acquisition of an eco-vehicle). As a result of this challenge, the project team used a special method to endogenously determine the eco-vehicle market penetration levels in response to LEZ scenarios, and used the model to verify and validate the eco-vehicle market penetration rates derived from the alternative and simpler procedure. The alternative procedure is described later in this section.

The model system includes a set of choice models to capture the medium-term choices of households and individuals. A series of work and school location choice models assign a work and school location for every man, woman, and child in the synthetic population, depending on their work and school status (i.e., whether employed, unemployed, retired, school-age). Because the synthetic population is generated at the level of the census block group, the home location of each household is known and mapped to a corresponding TAZ of the model. For any simulation run (representing a day in the life of an individual), a series of choice models determine the daily status of an individual (such as whether the individual is going to work or school on that particular day) and the time–space prism constraints associated with the daily status. This setup leads to the development of an activity skeleton for each individual identifying blocked periods (such as those associated with fixed work and school activities)

and coupling constraints where adults need to block periods to take care of dependent children. Adults are tasked to chauffeur or be with children depending on availability of open blocks of time.

The prism-constrained activity-travel simulator is the core engine of openAMOS, the activity-based travel demand model system. Within the activity-travel simulator, activities and trips are generated and a complete slate of choice dimensions is estimated. An activity is generated with trip purpose, passenger accompaniment is modeled, destination and mode choices are simulated, and the trip is sent to DTALite for routing and simulation on the network. Once the trip arrives at the destination, openAMOS will simulate the activity duration (time use) and model the subsequent activity participation decision. Thus, activities and trips are simulated along the continuous time axis with due consideration to time–space constraints and modal availability constraints. The mode choice set is constrained to include only those modes that are physically available and accessible to the individual at any decision point; thus, an individual who has used transit for the first segment of a trip chain would not have the ability to switch to the drive-alone mode in the next segment of the trip chain. Similarly, the destination choice set is constrained to include only those zones that have the land use type consistent with the activity purpose (thus preventing, for example, an individual from visiting a purely residential zone for a shopping trip) and can be visited by the mode(s) available without violating time–space prism constraints. If an individual experiences congestion on the network and delay, subsequent activity participation and time use will be affected as a consequence. Thus, the integrated activity-based travel demand model system is able to capture secondary and tertiary impacts of experienced network conditions on activity-travel engagement, including the ability to account for induced and suppressed travel demand effects that may arise from an improvement or deterioration in level of service. At the end of the simulation, the model system outputs detailed activity-travel records for each person; the DTA model retains route information for every trip at a level of temporal resolution specified by the user; however, that data is not vital to the LEZ scenario analysis because route choice is not a behavioral dimension that is expected to be impacted in any substantial way as a result of the LEZ implementation.

Following the completion of the activity-travel simulation process, output activity-travel data are input to the emissions estimation module of the integrated travel model system. The DTA model system includes an efficient emissions estimation model component called MOVESLite. MOVESLite is a computationally efficient emissions estimation model that uses statistical regression equations to estimate various energy and emissions metrics. The statistical regression equations have been calibrated such that the output of MOVESLite closely replicates what the full-fledged MOVES emissions model would have produced had it been deployed. Thus, for all practical purposes, the energy and emissions estimates obtained from the integrated travel model system used in this study closely mimic those that would have been produced by MOVES.

Modifications to Integrated Model System to Accommodate LEZ Analysis

Over the course of the simulation effort, several enhancements had to be made to the integrated travel model system so that it is responsive to system changes that may be brought about through the future deployment of a LEZ Operational Scenario. Many of these enhancements involved refining the model components so that they are sensitive to key variables and reflect changes in a number of behavioral phenomena while fully accounting for time–space prism constraints, modal and vehicle availability constraints, and household coupling constraints (interactions). Two key enhancements were made specifically to facilitate the simulation of LEZ scenario impacts. This section provides a description of these two key features of the enhanced model system.

First, the model system was enhanced to facilitate the inclusion of the LEZ monetary incentive in the generalized cost calculations. In prior versions of the integrated travel model system, destination choice was essentially determined based on travel time and the attractiveness of the destination (in addition to traveler socioeconomic and demographic characteristics). However, with the implementation of a LEZ scenario, it is essential to model destination choice in such a way that it is responsive to generalized cost that incorporates the LEZ monetary incentive. In other words, destination choice is influenced not only by travel time, but also by the amount of incentive provided. As a result of the incentive, it is likely that a zone will become more attractive as a destination than it had been prior to the introduction of the incentive. Consider two alternative zones that have similar land use characteristics, both 20 minutes away from the origin. In the absence of a LEZ and monetary incentive associated with eco-vehicle driving, both of these zones would be viewed as equally attractive for a shopping trip. However, for a traveler who has access to an eco-vehicle, the zone that falls in the LEZ area will become more attractive than the non-LEZ area zone after the introduction of a LEZ monetary incentive for eco-vehicle use. In other words, the generalized cost or burden of traveling to the eco-zone would be less than the impedance associated with traveling to the non-LEZ, all other things being equal. This needs to be reflected in the skim value used for destination choice modeling.

To reflect the influence of the LEZ monetary incentive on generalized cost of travel, the monetary incentive was converted to an equivalent travel time reduction using a personal value of time (VOT). In the synthetic population file, each household and each person is associated with an income variable. In cases where an adult may not have a personal income (because he or she does not participate in the labor force), the household income can be divided by the number of adults to obtain a personal income for each person in the household. Using the annual income value, an hourly wage rate is computed for each person and the VOT derived as a fraction of the wage rate. For work and school trips, the VOT is taken to be 50 percent of the wage rate; for discretionary trips such as shopping and social-recreation, the VOT is taken to be 33 percent of the wage rate. These percentages are user specified and can be altered in the context of any simulation run. In general, these default values are consistent with VOT–to–wage rate ratios reported in the literature. By using personal income as the basis for computing VOT, population heterogeneity in value of time is accommodated, with high-income individuals having a higher VOT than low-income individuals. A minimum (VOT = $4/hour) and maximum (VOT = $100/hour) value can be imposed to ensure that outlier values are not encountered.

Upon computation of the VOT, any monetary incentive can be converted to equivalent time units. If the VOT is $30/hour ($0.50/minute) for an individual, then a monetary incentive of $1 per trip would correspond to an equivalent perceived travel time (cost) reduction of 2 minutes. An incentive of $1.50/trip would correspond to an equivalent reduction of perceived travel time of 3 minutes. Thus, any monetary incentive can be converted to an equivalent perceived reduction in travel time, with the perceived reduction in impedance proportional to the amount of the incentive. Although it can be postulated that there is a non-linear relationship between incentive and perceived attractiveness (reduction in travel time) of a LEZ destination, it is likely that the relationship is approximated to be linear within the band of likely incentive amounts.

The perceived travel time used for destination choice analysis and modeling would then be lower for LEZ zones that have incentive compared with competing zones (of equal distance and travel time) falling in non-LEZ areas. The modified modeled travel time is then:

$$MTT_{LEZ} = \text{Actual travel time} - \$ \text{ incentive (converted to equivalent travel time)}$$

An eco-traveler choosing between two destinations, one of which falls within the LEZ area, may be enticed to choose the LEZ to take advantage of the incentive. This could result in a modest level of induced travel demand, with the LEZ area experiencing a slight growth in travel demand, but the growth would be virtually exclusively limited to eco-vehicle travelers with much less adverse emission implications as a result.

Although eco-travelers now choose destinations based on a modified modeled travel time, it should be noted that route choice and network simulation uses the actual and true travel time the traveler experiences when visiting the LEZ. In other words, suppose that the travel time to a destination is 20 minutes and the modified modeled travel time is 17 minutes. The travel time used for destination choice modeling is 17 minutes, but the traveler actually experiences the full 20-minute travel time when the trip is routed and simulated on the network. In this way, there is no artificial shrinkage of actual experienced travel duration and no artificial creation of new activities as a result of additional time windows becoming available in the time–space prism constraints.

A second key modification to the model system involved the use of a more simplified approach to determine endogenously the penetration of eco-vehicles in the market in response to the LEZ incentive. Although openAMOS includes a vehicle fleet composition and ownership model system, the model could not be easily re-specified to include a LEZ incentive as an explanatory variable because no data are available to estimate such a coefficient. Rather than assert a coefficient with no basis in the specification of the vehicle fleet composition model (and potentially raise questions about the reasonableness of the projected market penetration of eco-vehicles as a result of the LEZ), the project team used an elasticity-based approach. The elasticity-based approach uses information available from existing literature. BenDor and Ford (2006) studied the impacts of "feebates" and incentives on vehicle fleet composition and emissions reduction. They found that a composite incentive of $10,000 would increase the market share of electric vehicles to 17 percent in the State of California. The same "incentive-to-market penetration" elasticity is used in the current study because of the absence of similar research in the State of Arizona (where the case study area is located). Incentive levels of $0.50, $1.00, and $1.50 per trip were considered within the scope of this study. It was assumed that travelers would make, on average, one-half of their total trips to LEZs in light of the incentive provided. The logic behind this assumption is that, when an incentive is provided, travelers would potentially choose LEZs to the extent possible for their non-mandatory (shopping, social-recreation) travel to take advantage of the incentive provided to them. The average person trip rate, derived from the National Household Travel Survey (NHTS) and a series of preliminary model runs, is 4.5 person-trips per day. We also assumed that the incentive was provided only on weekdays, as the integrated model represents the travel that individuals undertake on an average weekday. Using these assumptions (all of which are parameters that the user can change for any scenario model run), the total incentive that an individual can realize in a year can be computed as:

$$Incentive\ (\$) \ \times \ Average\ trip\ rate\ to\ LEZ \ \times \ Number\ of\ weekdays\ in\ a\ year.$$

For example, at the $0.50-per-trip incentive level, an individual can potentially earn up to $281 per year.

It is somewhat questionable as to whether an individual would or should be able to collect the incentive indefinitely. In other words, just as an incentive or rebate is provided at the time of purchase of a zero-emission vehicle, it may be appropriate to cap the total incentive that an individual can garner. The project team established a user-specified parameter by which the user can dictate the maximum accumulation of incentive for a traveler over his or her lifetime. For the $0.50-per-trip incentive, the project team (arbitrarily) set a lifetime cap of $1,800. With an individual earning $281 per

year at this incentive level, he or she will reach the cap in about 6.4 years. The eco-vehicle market penetration is computed based on the total maximum possible incentive ($1,800 in the current example) and the elasticity measure derived by BenDor and Ford (2006) as:

$$Incentive\ (\$1800)\ \times\ Elasticity\ (17/10000)\ \cong\ 3.1\ percent.$$

In other words, the market penetration of eco-vehicles would reach a level of 3.1 percent in a period of 6.4 years.

Market penetrations for other incentive levels are computed in a similar fashion and rounded to the nearest integer value. Different cap values can be used for different incentive levels. At a higher incentive level, it is reasonable to set a higher maximum or cap value. This will in turn lead to a higher vehicle penetration rate (of eco-vehicles) and a lower period of time in which the estimated eco-vehicle penetration rate would be achieved. For example, at the $1-per-trip incentive level, an individual could earn $562 per year. With a cap of $2,400 (as opposed to the previous $1,800), an eco-vehicle market penetration of about 4.1 percent would be achieved in 4.3 years. In other words, at a higher incentive level, adoption of eco-vehicles would happen at a faster rate, and the level of market penetration would be higher than at lower incentive levels. These indications are quite reasonable and consistent with expectations regarding consumer behavior; hence, the simplified methodology adopted in this project provides a basis for endogenously estimating eco-vehicle penetration rate as a function of incentive level and incentive cap, both of which are user-defined parameters. By treating these parameters as user defined, the model system affords maximum flexibility for the analyst to test and consider a range of scenarios and incentive structures.

Use of MOVESLite Emissions Model

Following the completion of the activity-travel simulation process, output activity-travel data are input into the emissions estimation module of the integrated travel model system. The DTA model system is coupled with an efficient emissions estimation model component called MOVESLite. MOVESLite is a computationally efficient emissions estimation model that uses simplified representation of drive cycles and emission rates to estimate various energy and emissions metrics. The equations and rates embedded in MOVESLite have been calibrated such that the output of MOVESLite closely replicates that of the full-fledged MOtor Vehicle Emission Simulator (MOVES) emissions model. In MOVES, emissions associated with highway vehicular travel are determined for a variety of pollutants based on very detailed information on vehicular characteristics and trajectories. Highway vehicle operations are stratified into 21 operating mode bins defined by speed ranges (less than 25mph, 25mph to 50mph, and greater than 50 mph) and vehicle-specific power (VSP). The VSP is an estimate of engine load based on vehicle speed, acceleration, and road grade. For each vehicle in a simulation, the time spent by the vehicle in each operating mode bin is determined based on the second-by-second vehicle trajectory output by a traffic simulation model. Through a detailed characterization of the drive cycle, MOVES is able to accurately estimate emissions associated with vehicular travel in a network. In addition to second-by-second vehicular trajectories such as those output by traffic micro simulation models, MOVES is able to take as input average link speeds such as those output by macroscopic and mesoscopic traffic models. MOVES includes an extremely comprehensive and disaggregate set of emission rates specific to a detailed representation of operating conditions including VSP, vehicle type and age, operating mode bin, fuel type and properties, road grade, and ambient conditions of temperature and humidity. In view of the very detailed manner in which MOVES processes vehicular travel data and computes emissions, it is a very computationally intensive microscopic emissions

model system. Integrating MOVES with activity-travel micro simulation models and DTA models (that are computationally intensive in their own right) has proven to be a formidable challenge.

To address this challenge, the study team has used MOVESLite in this research effort. MOVESLite is a computationally efficient emissions estimation model that closely mimics the calculations of MOVES without using the same level of detail and drive cycle fidelity that MOVES uses. Similar to MOVES, MOVESLite uses the VSP-to-operating mode conversion process and considers average emissions rates stratified by vehicle type, age, and vehicle operating mode. The major emission metrics include energy, Carbon Dioxide (CO_2), Nitrous Oxide (NO_x), Carbon Monoxide (CO), and Hydrocarbons (HC). Unlike MOVES, which models more than 10 vehicle types, MOVESLite considers only a limited number, 6 vehicle types, that represent 95 percent of the on-road fleet, namely, passenger cars, passenger trucks, light commercial trucks, single unit short-haul trucks, and combination long-haul trucks. By using a limited number of vehicle types, MOVESLite is able to significantly reduce the number of operating mode bins, thereby dramatically decreasing the complexity of the emission rate search process and improving calculation efficiency. Correction factors are introduced to take into account variations in simulated driving cycles with respect to a base emission rate provided in MOVES for each pollutant-vehicle age-vehicle type combination. The simplified model contains a base emission rate that accounts for site-specific characteristics such as fuel-type mix, ambient conditions of temperature and humidity, presence or absence of a vehicle emissions inspection and maintenance program, and a cycle correction factor that accounts for speed trajectories and operating mode bin emission rates. Speed trajectories can be obtained from empirical data or predictions of a travel demand model (as in this study). The approach is ideally suited for integration with a travel demand model as average link speeds output by the travel model can be converted through mapping (embedded in MOVESLite) to a corresponding drive schedule/cycle. A distribution of operating mode bins can be inferred from the drive schedule/cycle, thus providing the basis for calculating emissions. MOVESLite includes a series of equations that tie cycle average emission rates (by pollutant) to a base emission rate and a cycle correction factor that accounts for vehicle type and age and ambient conditions. MOVESLite is able to approximate the emissions output of MOVES very closely. Frey and Liu (2013) report, for example, less than 1-percent error in emissions outputs using MOVESLite for a 5-year-old gasoline passenger car. Zhou et al (2014) illustrates how the simplified emissions model, MOVESLite, can be effectively integrated with the DTA model, DTALite, to efficiently evaluate emissions impacts of traffic management strategies.

Low Emission Zone Scenarios

This section describes the LEZ scenarios that we considered in the analysis of the LEZ Operational Scenario. As mentioned earlier, many of the user-defined parameters and LEZ settings can be changed, thus creating a potentially large number of scenarios. Because computational run times for the integrated travel model system are substantial, it was necessary to control the number of scenarios while ensuring that the scenarios for which we performed simulation runs were defined in such a way that they were both realistic and offered key insights into travel behavior changes that could potentially result from the implementation of such a strategy.

Table 4 presents an overview of the incentive scenarios considered in this simulation effort. The baseline scenario corresponds to the case where the incentive is equal to zero and there is consequently no incentive cap (maximum amount) that would apply in the baseline case. As previously explained, the Greater Phoenix metropolitan region served as the case study area for the LEZ scenario analysis and modeling effort. In this region, current travel survey data (including the NHTS) suggests that the penetration of eco-vehicles (as defined in this study) in the market is at just

about 2 percent—that is, about 2 percent of all personally owned or leased household vehicles fall into the definition of *eco-vehicles* as designated for this analysis in previous sections. This baseline scenario is simulated for both a test sub-region and for the entire Greater Phoenix metropolitan region.

Table 4: Incentive Values and Eco-Vehicle Market Penetration

Incentive ($/trip)	Incentive Cap ($)	Eco-Vehicle Market Penetration (%)	Sub-Region	Full Region
0.00	0	2.0 (baseline)	✓	✓
0.50	1,800	3.0	✓	
1.50	3,200	5.0	✓	✓

For the analysis of the AERIS LEZ Operational Concept, we considered two incentive scenarios. The first is an incentive of $0.50 per trip; the other is a higher incentive of $1.50 per trip. The incentive is credited to the traveler's account if the traveler is using an eco-vehicle to travel to a LEZ (i.e., a LEZ is a destination). No incentive is given when an eco-traveler is exiting the LEZ area (i.e., the incentive is given only for one-way travel into the LEZ). With the incentive cap values used in this study (which the analyst can change for alternative scenarios), the eco-vehicle market penetration was estimated endogenously to be 3 percent in the $0.50 incentive case and about 5 percent in the $1.50 incentive scenario. These are modest levels of eco-vehicle penetration. To avoid exaggerated projections of eco-vehicle penetration in the market, the study team purposefully set low incentive cap values and estimated modest levels of increase in eco-vehicle penetration levels. Because the transaction cost associated with turning over a vehicle can be substantial, it was considered prudent to project modest levels of eco-vehicle penetration in response to the LEZ. In reality, it is likely that higher levels of eco-vehicle penetration will be realized, particularly as households dispose of, trade in, and acquire vehicles over a period of time. For the full region simulation, only the baseline and the $1.50 incentive scenarios were considered in view of computational run times for the integrated travel model systems.

Table 5 presents further detail on the scenarios that we constructed for the simulation study. In addition to the incentive level of $0.50 and $1.50 per trip, the scenarios involved enhanced transit service to and from the LEZ, which was called *enhanced transit service.* Thus, the incentive level can be combined with no enhanced transit, implying that current RT service prevails. Alternatively, the incentive can be combined with ET for travel to and from the LEZ area. The ET service involves the following changes:

- Frequency of service is made twice that of existing RT service (in other words, headways are reduced to one-half of current regular values).
- Transit fare for travel to and from the LEZ area is reduced to one-half of the existing regular transit fare.

Table 5: Incremental Scenario Development

Scenario Label	Incentive ($)	Transit	Scenario Description	Eco-Vehicle Penetration	Full Region Simulation
Baseline	–	Regular (RT)		2%	✓
$0.50, RT	0.50 for Eco	Regular (RT)		3%	
$1.50, RT	1.50 for Eco	Regular (RT)		5%	✓
$0.50, ET	0.50 for Eco	Enhanced to LEZs (ET)		3%	
$1.50, ET	1.50 for Eco	Enhanced to LEZs (ET)		5%	✓

Note: Model runs were performed for all scenarios for the smaller sub-region.

All travelers in the model can take advantage of the ET service. In general, it was expected that non-eco-vehicle travelers would shift to transit in greater proportion than eco-vehicle travelers. Eco-vehicle travelers have an incentive to drive their eco-vehicles to the LEZ area because of the incentive. Non-eco-vehicle travelers, in contrast, have no incentive to drive and may find it quite attractive to ride the ET service, but it is possible that a small number of eco-vehicle travelers may choose to ride the ET service, as well, depending on the competitive advantage (if any) that ET service may provide.

All scenarios were simulated for the smaller test sub-region. However, in view of long computational run times for the integrated model system, only selected scenarios were simulated for the full region. In addition to the baseline scenario, the two transit service scenarios corresponding to the highest incentive level of $1.50 per trip are simulated for the full region. The last column of Table 5 provides an indicator of the scenarios considered for the full region simulation.

Modeling Results

This section of the report presents detailed modeling results of the LEZ scenarios conducted through repeatedly exercising and running the integrated travel model system for a number of scenarios identified earlier. A series of preliminary test runs were completed to obtain a robust set of time-dependent network travel times (skims) at fine-grained temporal resolution (1 hour). After completing the set of preliminary runs, the integrated travel model system was run for the various scenarios to determine how a LEZ may affect traveler behavior and vehicular emissions. Because of the nature of the integrated travel model system, it provides a wealth of disaggregate trip-level, tour-level, and person-level outputs. Synthesizing and summarizing all of the information output by a comprehensive microsimulation model system is a formidable challenge; as such, key highlights with overall summary measures of travel and emissions are presented in this report. However, it should be noted that a wealth of additional information (by demographic segment, time of day, network link, and trip purpose) can be obtained by mining the large datasets output by the integrated travel model system.

The modeling effort in this study covers only personal travel internal to the region. In both the sub-region and full-region simulations, the integrated travel model system does not account for external travel (where one or both trip ends are outside the model region), taxi and truck trips, or travel

undertaken by visitors to the region (non-residents). Ignoring this travel demand (which is significant in a region such as Greater Phoenix) can result in an inadequate representation of congestion on the network (because these trips would not be simulated in the integrated travel model system and would never show up on the network). To overcome this issue, the project team obtained origin–destination trip tables from the MAG for these portions of travel demand, as output by the current four-step travel demand model in use at the agency for planning purposes. These O-D matrices are disaggregated temporally through the use of a continuous time-of-day distribution to create trip lists for each temporal element in the day (1 minute in this study). These trips are loaded in the background along with the personal travel that the integrated travel model system simulates. In this way, the congestion patterns in the region are reflected in the simulation. The continuous time-of-day distributions are derived from survey data and information available in the literature. Although this process does ameliorate any issue arising from ignoring congestion resulting from portions of travel that the integrated travel model system does not cover, we recognize that the procedure adopted in this study is approximate. In an integrated travel model system with feedback, a spatial reallocation of travel happens across iterations in response to changes or updates to network travel times and congestion patterns. However, in this simulation effort, the spatial patterns of truck and taxi trips, external trips, and visitor travel are held constant across iterations, potentially amplifying congestion patterns in certain pockets of the network. None of the trips in these matrices are affected by the LEZ designation and scenario. This aspect of the simulation should be kept in mind when interpreting the results of the simulation effort.

The integrated travel model system was subjected to an intensive calibration exercise. It was desired to ensure that the model system is able to replicate existing traffic conditions on the network reasonably well. The project team devoted considerable time and effort to calibrating the integrated travel model system, but given the large number of model components, it is a challenging endeavor to fine-tune all of the elements in the model system to replicate ground conditions. In view of the specific objectives of this project and the scope and resources of the effort, the project team calibrated the model system to the degree necessary to allow comparisons across scenarios. To compare network performance and travel demand characteristics among different LEZ scenarios, it is not necessary that the baseline model (reflecting existing system conditions) replicate traffic patterns exactly. It is sufficient to have the integrated model system approximately replicate network conditions over the course of a day, with differences between scenario runs providing measures of change that would be attributable to the introduction of LEZ scenarios. In the simulation results presented in this section, it should be noted that some of the travel demand characteristics are not exactly as they appear in the real world. For example, the estimated transit mode share in the baseline model is higher than the actual transit mode share. Although this may present a problem in certain planning application studies, it does not present an issue in the scenario analyses of this study, where the focus is on the *changes* in behavior and emissions in response to LEZ implementation.

Results for the Sub-Region Case Study Area

In view of the computational difficulty associated with running an integrated travel model system for an entire region the size of Greater Phoenix, the project team began the study with a focus on a smaller sub-region, as described earlier. The sub-region case study considered a 24-hour LEZ with the scenario parameters noted previously in this report. In view of the simulation being artificially limited to internal trips, origins and destinations of all trips had to fall within the three-city sub-region. In reality, many trips may have an origin or a destination outside the three-city sub-region; however, because the simulation does not deal with external trips in a time-dependent modeling framework; all trips had to be constrained to having origins and destinations within the model sub-region. This constraint resulted in trip lengths that are smaller than one would expect to see in reality, while average trip

lengths are generally close to 10 miles, according to regional household travel surveys; the average trip length in the sub-region simulation is less than 7 miles. Nevertheless, as mentioned earlier, the important aspect within this simulation effort is the ability to measure and quantify differences in the presence of the LEZ. The full-region simulation (results provided in the next section) provides a more realistic depiction of trip lengths but at the expense of computational burden constraining the number of scenarios that could be considered and analyzed.

A major benefit of the microsimulation approach is that it is possible to examine the activity-travel patterns of individual travelers before and after implementation of a LEZ. To illustrate the capabilities of the modeling framework and the potential range of behavioral adjustments that may occur in response to a LEZ, the project team isolated a random individual in the synthetic population and examined her activity-travel pattern before and after the implementation of a LEZ scenario. The individual becomes an eco-traveler after the implementation of the LEZ scenario and has a residence that is in reasonably close proximity to the LEZ area, as depicted in Figure 15. This individual is employed, 56 years of age, and a single-person household. The individual departs home at 6:47 a.m. and arrives at a personal business activity destination at 6:55 a.m. The individual departs the personal business location at 7:04 a.m. and returns home at 7:12 a.m. After a home sojourn, the individual leaves for work at 8:09 a.m. and arrives at work at 8:18 a.m. The individual leaves work at 2:02 p.m. and proceeds to a shopping activity, where she arrives at 2:14 p.m. After spending an hour at the shopping activity, the individual departs the store at 3:14 p.m. and returns home at 3:32 p.m. The individual undertakes no additional activities for the day.

Figure 15: Activity-Travel Pattern of Random Individual before LEZ Scenario Implementation

Figure 16 shows the new activity-travel pattern the individual adopts after implementation of the LEZ scenario.

Figure 16: Activity-Travel Pattern of Individual after LEZ Scenario Implementation

The activity-travel pattern shows some significant changes from the baseline pattern in response to a LEZ scenario. Not only is there a change in destination choice (presumably to take advantage of the LEZ incentive), but several secondary and tertiary changes in travel characteristics ostensibly arise from the shift in destination choice for non-work activities. The individual now undertakes the personal business activity in the post-work period in the afternoon as opposed to the pre-work period of the morning. The individual departs home for the first time of the day later than in the non-LEZ scenario. The individual now leaves home at 8:43 AM and arrives at work at 8:52 AM. It should be noted that the work location is not allowed to change in the simulation. The individual arrives later at work than in the pre-LEZ scenario. The individual leaves work at the same time—2:02 p.m.—and proceeds to shopping, but shifts the shopping location to the LEZ area. This shopping location is in the northern part of the sub-region as opposed to the location previously chosen in the central/eastern part of the sub-region. After shopping for 10 minutes, the individual departs at 2:22 p.m. and arrives at a second shopping location at 2:29 p.m. It is possible that the shopping location in the LEZ area does not fulfill the needs of the individual as well as the shopping location chosen in the pre-LEZ scenario; hence, the individual chooses to make a second shopping stop in a non-LEZ area. After shopping from 2:29 p.m. to 2:34 p.m., the individual pursues personal business in another LEZ. The individual arrives at the personal business activity location at 2:43 p.m. and spends considerable time at the activity. The individual departs this location after 2 hours and arrives home at 4:51 p.m. It is possible that the open-ended time–space prism in the post-work period allowed the individual to spend a long time at the personal business activity. In the pre-LEZ activity-travel pattern, the individual was constrained by the need to go to work in the morning; hence, the personal business activity in the pre-work period had to be short in duration (within a tight time–space prism constraint). The individual returns home at 4:51 p.m. and ends the day. This example illustrates how the model is able to simulate adjustments in activity-travel patterns and capture the full range of changes in vehicle type choice, destination choice, time use and activity durations, activity sequencing, and activity scheduling (time-of-day choice). After making several checks of this nature on individual activity-travel patterns (before and after LEZ implementation) and fine-tuning the integrated travel model system to provide behaviorally robust and consistent activity-travel patterns, the project team analyzed aggregate activity-travel characteristics for different market segments.

Table 6 presents aggregate travel characteristics for the sub-region of the population considering all travelers (i.e., both eco- and non-eco-travelers).

Table 6: Aggregate Travel Characteristics for All Travelers—Sub-Region Analysis

Indicator	Baseline	$0.50, RT	$1.50, RT	$0.50, ET	$1.50, ET
Population	505,998	505,998	505,998	505,998	505,998
Total trips	2,271,798	2,272,802	2,270,974	2,252,068	2,259,754
Total auto trips	2,173,030	2,173,404	2,173,088	2,100,848	2,110,704
Total transit trips	98,768 (4.3%)	99,398 (4.4%)	97,886 (4.3%)	151,220 (6.7%)	149,050 (6.6%)
Total travel distance (miles)	15,562,844	15,584,178	15,581,050	15,513,408	15,601,756
Average trip rate	4.49	4.49	4.49	4.45	4.47
Average trip length (miles)	6.85	6.86	6.86	6.89	6.90
Average travel speed (mph)	29.40	29.31	29.25	29.74	29.59

Travel characteristics are output and furnished in the table for the approximately half-million people residing in the sub-region. In general, it was found that the changes in travel demand are consistent with expectations given that the penetration of eco-vehicles in the population varies from about 2 percent in the baseline to 3 percent at the $0.50 incentive level and to 5 percent at the $1.50 incentive level. The baseline transit mode share is derived to be 4.3 percent, which is about twice that of the actual transit mode share in the region. Although the model system could have been further calibrated to replicate actual mode shares in the region, it was considered it prudent to move forward with the existing version of the model because the additional fine-tuning of the model to replicate actual transit mode shares would come at a considerable cost without necessarily adding substantial benefit in terms of sensitivity analysis. The model is responsive to the introduction of a LEZ, and the focus of the analysis is on the differences in mode share relative to the baseline as opposed to the actual mode shares themselves. At the aggregate level, considering all travelers across the sub-region, the changes are modest. There is no appreciable evidence of any induced demand (resulting from LEZ scenario implementation) at the incentive levels considered in this study. The trip rates, in the presence of RT service, remain largely unchanged. The transit mode split, in the presence of RT service, also remains largely unchanged (as expected). The average trip length shows considerable stability, thus suggesting that—in the aggregate—any induced demand effects are virtually negligible at low levels of eco-vehicle market penetration.

In the presence of ET, the transit mode share is found to increase by about 2.3 percentage points. Non-eco-travelers presumably shift to transit to take advantage of the ET service. Eco-travelers can also shift to transit but are likely to do so to a smaller degree considering that they receive an incentive to drive their eco-vehicles in the context of travel to LEZs. Corresponding with the increase in transit mode share, the number of auto trips (and the auto mode share) drops relative to the baseline and the

RT service LEZ scenarios. The total number of trips and the trip rate per capita show a small drop relative to the baseline and the regular transit service scenarios. This finding is consistent with expectations and the tighter time–space prism constraints associated with using a slower and potentially more circuitous mode. The average trip lengths are slightly higher, potentially reflective of the longer travel distances associated with using transit (relative to auto). Because travel speeds are slower for transit, individuals (using transit) are likely to be more constrained in time and space and therefore make fewer trips than in the baseline and RT service scenarios. Average speeds on the network are largely unchanged, although they are somewhat higher in the ET service scenarios. It is possible that the increase in transit mode share and consequent elimination of corresponding auto trips from the network contributed to a small increase in network travel speeds. As noted earlier, trip lengths (at fewer than 7 miles) are lower than expected because of the small nature of the sub-region and the exclusive consideration of internal trips where both origins and destinations are internal to the sub-region in all analyses.

Because the analysis of all travelers masks differences between eco-travelers and non-eco-travelers, the project team analyzed the two groups separately. Table 7 presents aggregate travel characteristics for eco-travelers—that is, individuals who have access to eco-vehicles and use them for all of their travel through the course of a day (regardless of whether they are traveling to LEZs).

Table 7: Aggregate Travel Characteristics for Eco-Travelers—Sub-Region Analysis

Indicator	Baseline	$0.50, RT	$1.50, RT	$0.50, ET	$1.50, ET
Population	10,274	15,362	25,470	15,362	25,470
Total trips	46,654	69,746	115,544	69,302	115,580
Total auto trips	44,586	67,004	111,130	65,736	110,654
Total transit trips	2,068 (4.4%)	2,742 (3.9%)	4,414 (3.8%)	3,566 (5.2%)	4,926 (4.3%)
Total travel distance (miles)	320,630	479,852	811,188	478,184	809,236
Average trip rate	4.54	4.54	4.54	4.51	4.54
Average trip length (miles)	6.87	6.88	7.02	6.90	7.00

The number of eco-travelers in the population increases relative to the baseline consistent with the higher market penetration of eco-vehicles in the presence of a LEZ incentive. Thus, the total trips by eco-travelers (region-wide) increases, but the trip rate remains largely unchanged on a per-capita basis. This finding suggests that there is no appreciable evidence of induced travel as a result of a LEZ incentive from an "additional activity engagement or trip-making" perspective. However, we found that trip lengths rise relative to the baseline for eco-travelers. It appears that eco-travelers are altering their destination choice patterns to take advantage of the LEZ incentive, with higher incentive levels associated with longer trip lengths (on average). Eco-travelers may be willing and able to travel slightly longer distances to the LEZ to take advantage of the LEZ incentive, resulting in the longer trip lengths. As expected, eco-travelers are not attracted to transit to any appreciable degree as a result of the ET service. There is a modest increase in transit mode share when the incentive is small ($0.50 per trip) and transit service is enhanced. The mode share in this specific scenario is about 0.7 percentage points higher than in the baseline case. In the RT service scenarios (with LEZ incentive), it was found

that transit mode share drops to a small degree, presumably because eco-vehicle travelers are now shifting to the use of their eco-vehicles to take advantage of the LEZ incentive. At the highest level of incentive ($1.50 per trip) and in the presence of ET service, the transit mode share is about equal to that in the baseline case, suggesting that the pull toward the use of eco-vehicles resulting from the LEZ incentive is just about neutralized by the pull toward the use of ET, which offers a high quality of service.

Table 8 presents the aggregate travel characteristics for the non-eco-travelers—that is, for the large segment of travelers who do not have access to and do not acquire or use an eco-vehicle even after the introduction of a LEZ.

Table 8: Aggregate Travel Characteristics for Non-eco-Travelers—Sub-Region Analysis

Indicator	Baseline	$0.50, RT	$1.50, RT	$0.50, ET	$1.50, ET
Population	495,724	490,636	480,528	490,636	480,528
Total trips	2,225,144	2,203,056	2,155,430	2,182,766	2,144,174
Total auto trips	2,128,444	2,106,400	2,061,958	2,035,112	2,000,050
Total transit trips	96,700 (4.4%)	96,656 (4.4%)	93,472 (4.3%)	147,654 (6.8%)	144,124 (6.7%)
Total travel distance (miles)	15,242,214	15,104,144	14,769,860	15,034,888	14,792,520
Average trip rate	4.49	4.49	4.49	4.45	4.46
Average trip length (miles)	6.85	6.86	6.85	6.89	6.90

As expected, non-eco-travelers show no change in travel behavior after the introduction of a LEZ incentive. Non-eco-travelers are not affected in any way by the introduction of the LEZ incentive and therefore have no reason to change their travel behavior. As shown in Table 5, the change in network travel speeds is virtually negligible, so non-eco-travelers do not have to change their daily activity-travel choices relative to the baseline case. Trip rates and average trip lengths remain largely unchanged relative to the baseline for the RT service scenarios, but in the case of ET service scenarios, the transit mode share shows a considerable increase—to the tune of about 2.3 percentage points. With the increase in transit usage among non-eco-travelers comes a slight drop in average trip rates and a slight increase in average trip lengths. Both of these results are consistent with expectations. When travelers use a slower mode such as transit, they are more constrained and cannot pursue as many activities and trips as they would have had they been using a faster mode of transport. Transit routes tend to be slightly more circuitous (and involve access and egress legs), thus leading to slightly longer trip lengths. In addition, the choice of transit mode for tour-making may entail some adjustments in destination choice, further contributing to changes in trip length.

In addition to analyzing the aggregate travel characteristics of market segments (eco- and non-eco-travelers), the project team examined the composition of trips to and from the different types of zones. Table 9 presents an analysis of trips to better understand how ET service to and from the LEZs affects the share of trips by mode. The top half of Table 9 shows the number and percentage of auto trips, while the bottom half of the table shows the number and percentage of transit trips. There is a

difference between LEZs and regular zones with respect to transit mode share even in the baseline case. Because the LEZs are in areas of higher development density and intensity, it is not surprising that trips to and from these zones enjoy a higher transit mode share in the baseline scenario. In the LEZ scenarios where RT service is maintained, the modal shares do not show any appreciable change. In fact, the transit share for LEZs drops slightly in the RT scenarios relative to the baseline case (6.57 percent → 6.47 percent → 6.08 percent). This drop is consistent with expectations; as the LEZ incentive rises in value, eco-travelers are going to take advantage of the incentive by driving their eco-vehicles. Eco-travelers who were previously using transit may actually opt to use the auto in the RT service scenarios.

Table 9: Composition of Trips by Zone Type

Scenario	Low Emission Zones	Regular Zones	All Zones
Baseline (Auto Trips)	219,424 (93.43%)	1,953,606 (95.91%)	2,173,030 (95.65%)
$0.50, RT (Auto Trips)	221,676 (93.53%)	1,951,728 (95.87%)	2,173,404 (95.63%)
$1.50, RT (Auto Trips)	225,016 (93.92%)	1,948,072 (95.90%)	2,173,088 (95.69%)
$0.50, ET (Auto Trips)	164,128 (70.69%)	1,936,720 (95.88%)	2,100,848 (93.29%)
$1.50, ET (Auto Trips)	170,238 (72.05%)	1,940,466 (95.90%)	2,110,704 (93.40%)
Baseline	15,436 (6.57%)	83,332 (4.09%)	98,768 (4.35%)
$0.50, RT (Transit Trips)	15,328 (6.47%)	84,070 (4.13%)	99,398 (4.37%)
$1.50, RT (Transit Trips)	14,564 (6.08%)	83,322 (4.10%)	97,886 (4.31%)
$0.50, ET (Transit Trips)	68,036 (29.31%)	83,184 (4.12%)	151,220 (6.71%)
$1.50, ET (Transit Trips)	66,050 (27.95%)	83,000 (4.10%)	149,050 (6.60%)

After the introduction of ET services, the proportion of transit trips jumps dramatically for LEZs. The LEZs are served by a substantially higher quality of service (half the fare and twice the frequency) of transit, so travelers shift to the transit mode in a significant way. Much of the increase in transit share of trips can be attributed to non-eco-travelers taking advantage of the ET service, but a small part of the increase can also be attributed to eco-travelers choosing to use transit in the ET scenarios

(consistent with the results reported in Table 9). Regular zones, which do not see any change in transit service quality, show no appreciable change in transit mode share.

Energy and emissions benefits are expected to be realized in a LEZ scenario through the enhanced market penetration, adoption, and use of eco-vehicles, particularly in the context of travel to and from the LEZs. By virtue of the nature of trip chaining, we expect that even regular zones—particularly those within the vicinity of the LEZs—will also experience a higher level of eco-vehicle travel, potentially yielding energy and emissions benefits for regular zones in the proximity of designated LEZs. Figure 17 shows the mix of vehicle types for trips to and from the LEZs in the sub-region. Relative to the baseline scenario, it is readily apparent that the share of eco-vehicle trips increases as the level of LEZ incentive rises. The share of non-eco-vehicles decreases (correspondingly); the share of transit remains largely unchanged, although a modest decrease is discernible. This modest decrease in transit share is likely the result of a few eco-travelers choosing to use their eco-vehicles to a larger extent (rather than take transit) to take advantage of the LEZ incentive.
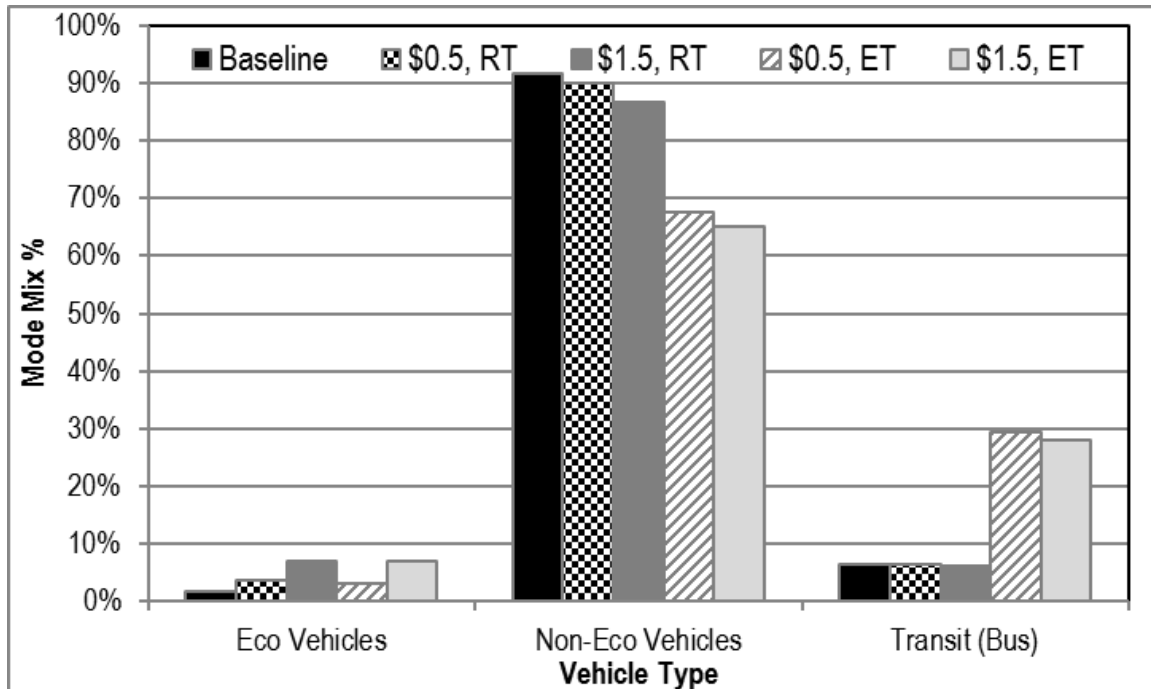
Figure 17: Vehicle and Mode Mix for LEZ Trips

In the ET service scenarios, the share of transit rises dramatically as non-eco-travelers shift in significant numbers to the ET service for travel to and from LEZs. The share of eco-vehicles drops in the scenario where the incentive is small ($0.50 per trip) and is similar to that for the corresponding scenario with RT service. The eco-traveler percentage remains steady between the two $0.50-scenarios, with non-eco-travelers showing a substantial shift from driving non-eco-vehicles to using transit. In the scenario where the incentive is $1.50 per trip, the percentage of eco-vehicle trips is once again replicating that in the corresponding regular transit scenario. The percentage of transit use shows a modest drop in this last scenario (relative to the lower incentive, ET scenario) presumably because some eco-travelers may choose to use their eco-vehicles rather than transit when presented

with a higher incentive. The shifts in vehicle mix and mode use constitute the sources of energy and emissions benefits that may be realized through the implementation of a LEZ.

To further understand the impact of LEZ scenarios, trip intensity maps were generated. These maps provide a means of examining the changes in vehicle travel patterns from a spatial perspective. Figure 18 shows LEZ maps of the sub-region, with the color variation depicting the differing numbers of eco-vehicle trips to the various zones. The figures highlight the LEZs specifically so that the numbers of eco-vehicle trips to and from LEZs (and their immediate surroundings) can be clearly discerned.
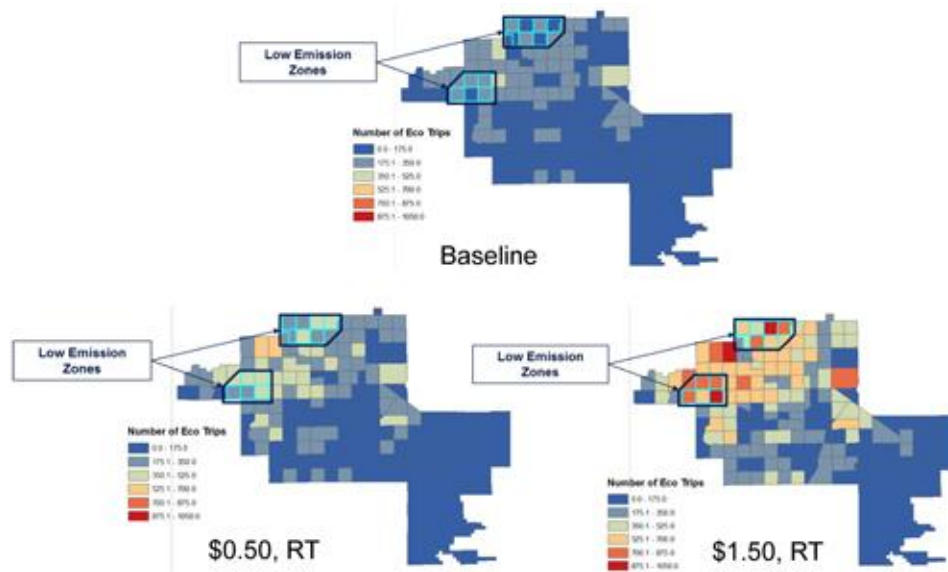

Figure 18: Maps of Eco-Trip Intensity by Traffic Analysis Zone—Sub-Region Analysis

The first figure shows the intensity of eco-trips in the baseline scenario. The LEZs do not show any unusual eco-trip activity relative to the other zones. In the low-incentive scenario ($0.50, RT), a considerable shift in eco-trip patterns appears. The LEZs show a higher number of eco-vehicle trips, as expected. In addition, however, many of the zones in the vicinity of the LEZs also experience higher numbers of eco-vehicle trips. This finding is consistent with expectations. As eco-vehicle travelers visit the LEZs (to take advantage of the incentive), they are also likely to visit neighboring destinations (which may fall just outside the LEZ area) to fulfill activities that are part of the same trip chain. If the eco-vehicle travelers visit the LEZs to undertake activities that are part of a multi-stop trip chain, then they are likely to visit destinations that are closer to the LEZs to complete their trip chaining needs. It is unlikely that they will drive across town (say, to the southeast area of the sub-region) for their other activities in the chain. As a result, the zones around the LEZs also see cleaner vehicle miles of travel, and these secondary benefits—although not quantified within the scope of this study— are to be recognized and analyzed to obtain a complete picture of the impacts of a LEZ scenario. The map corresponding to the highest incentive level ($1.50 per trip) shows that the effects are further amplified at higher levels of the incentive. The number of eco-vehicle trips, both in the LEZs and in the zones around the LEZ area, is higher than in the zones that are farthest from the LEZ's sphere of influence.

The next figure (Figure 19) shows the intensity of transit travel in the scenarios where ET service is offered (relative to the baseline scenario). In the absence of ET, no appreciable change in transit travel occurs. The maps showing transit trips in the RT scenarios show no pattern of change in transit trip

making (relative to the baseline), but in the case of ET service scenarios, the number of transit trips increases for the LEZs that ET service serves.
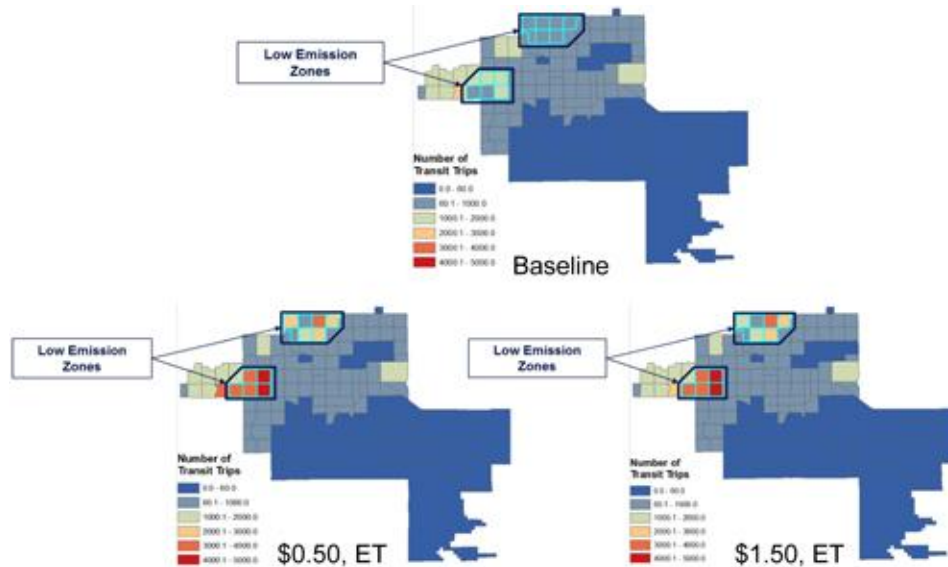

Figure 19: Maps of Transit Trip Intensity by Traffic Analysis Zone—Sub-Region Analysis

It was found that the number of transit trips increased by a substantial amount for the LEZs in which transit service was enhanced. The increase in transit patronage is greater for the LEZs associated with the large Chandler Fashion Center (regional shopping mall), which is consistent with the notion that the mall provides a strong focal point conducive to transit travel (as opposed to a more dispersed land-use development pattern that may entail longer access and egress legs). Hence, the higher intensity of transit associated with the shopping mall LEZs is reasonable. There is no appreciable difference between transit travel in the low-incentive and high-incentive scenarios; indeed, the level of incentive should have minimal if any impact on transit travel, and this is reflected in the findings shown in Figure 20. What is also interesting to note, in contrast to the findings reported in Figure 17, is that secondary impacts on neighboring zones are not discernible in the case of transit travel. In Figure 17, it was reported that eco-vehicular travel increased in neighboring zones, presumably because of trip chaining effects, but in the case of transit travel, such cascading secondary impacts on neighboring zones are not seen. If individuals are using transit in larger numbers to travel to and from LEZs, why is there no appreciable increase in transit travel in the neighboring zones surrounding the LEZ area? The answer lies in the fact that transit, as a mode, is not as conducive to trip chaining (multi-stop journeys) as is the automobile. Although the automobile allows individuals to easily chain together several trips in a single chain or tour, transit is more cumbersome to use in the context of multi-stop trip chains. In the case of transit travel, individuals are more prone to undertake single stop journeys— that is, proceed from an origin to a destination, and then return to the origin, with no other secondary stops. This is amply demonstrated in the findings of this study and consistent with findings on the link between trip chaining and mode choice reported in the literature (Ye et al, 2009).

The ultimate goal of the LEZ is to help mitigate the energy and emissions impacts of automobile travel, particularly within the congested LEZs. Using a suite of tools that mimic the energy and emissions calculations of MOVES, the project team was able to obtain estimates of fuel consumption and emissions for various pollutants under various scenarios. It should be noted that, consistent with the prior discussion, personal VMT does increase slightly in response to the implementation of a LEZ. Because of a small amount of induced travel (where eco-travelers travel longer distances to access

the LEZs and take advantage of the incentive), the overall personal VMT increases modestly for the sub-region as a whole. In the absence of any ET service, there is no shift in travel to transit; hence, the longer distances associated with LEZ-oriented travel will result in greater personal VMT. This is seen in Figure 20.
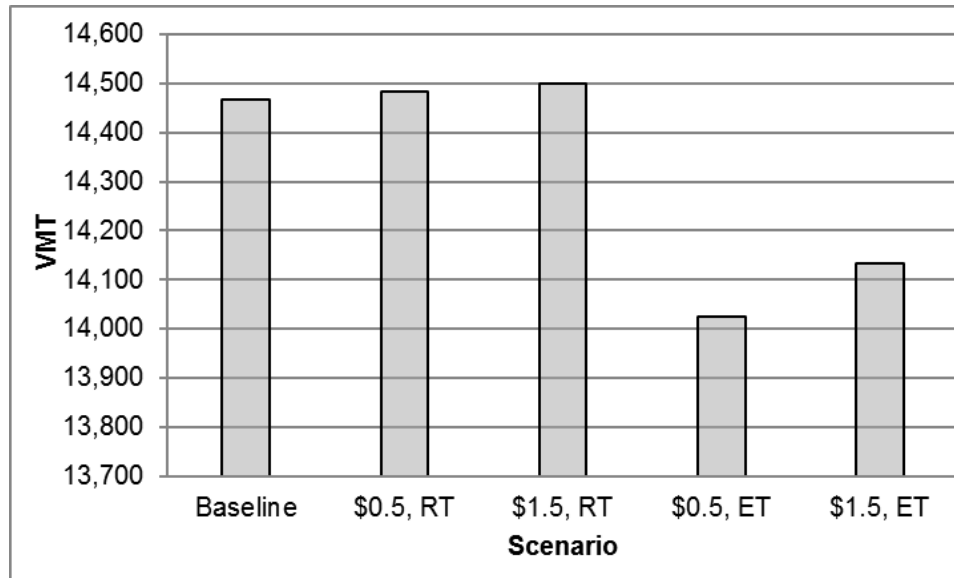

Figure 20: Personal Vehicle Miles of Travel by Scenario

The two scenarios in which RT service is maintained experience slightly higher levels of personal VMT relative to the baseline scenario. The induced travel is sensitive to the level of incentive, with the $1.50 incentive level inducing more VMT than the $0.50 incentive level. However, with the substantial shift to transit in the latter two scenarios characterized by ET service, personal VMT decreases substantially—although, between these two ET scenarios, the scenario with the higher incentive level for eco-travel shows a higher level of VMT (but lower than in the baseline).

Despite this increase in VMT (in the RT scenarios), the implementation of a LEZ does result in reduced energy consumption and emissions output because the VMT, although higher, is cleaner relative to the baseline because of the increased penetration of eco-vehicles in the market relative to the baseline scenario. Indeed, any scenario that has a higher penetration of eco-vehicles will show a reduction in energy consumption and emissions output. However, bringing about a higher market penetration of eco-vehicles in personal fleets often requires an intervention or a price signal that would motivate consumers to switch vehicle types. Based on the analysis conducted for this study, the LEZ is one such measure that can help accelerate the deployment and penetration of eco-vehicles in household fleets, thereby bringing about a reduced energy and emissions footprint from personal vehicle travel. Another key feature of the LEZ is that it is targeted at a specific area or set of zones that is currently experiencing high levels of emissions caused by personal vehicle travel. Through a targeted LEZ, the energy and emissions in the designated area can be reduced, even if the incentive policy brings about a nominal increase in VMT associated with LEZ travel. Thus, the LEZ has the dual benefit of increasing eco-vehicle market penetration and use as well as bringing about energy and emissions benefits to a targeted area that needs it most.
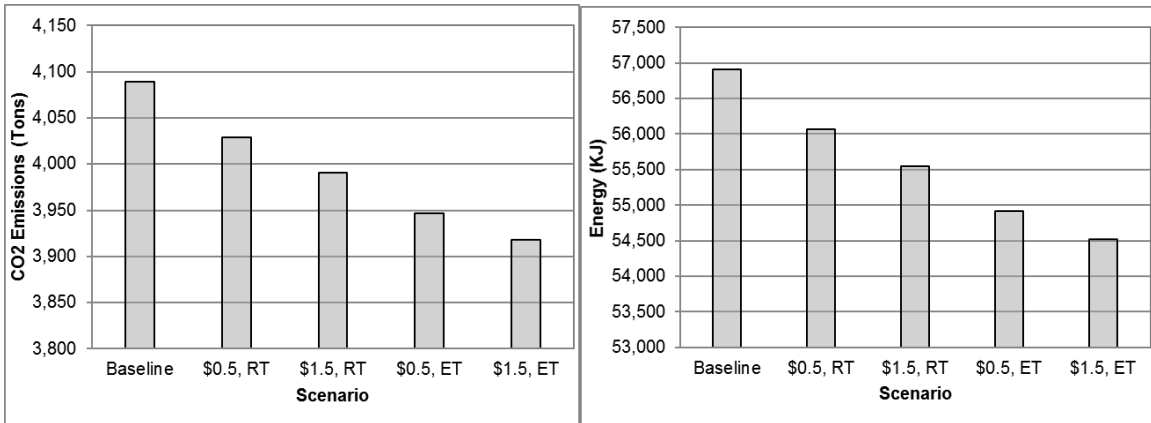
Figure 21 shows the energy consumption and CO_2 emissions associated with personal vehicle travel for the entire sub-region.
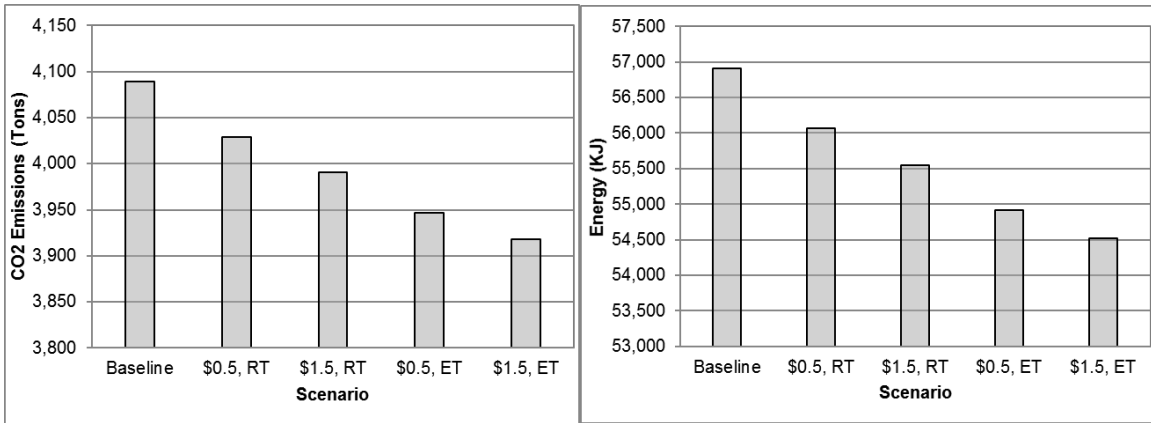

Figure 21: CO_2 Emissions and Energy Consumption by Scenario

The reduction in energy consumption and emissions output relative to the baseline scenario is presented in Figure 22.
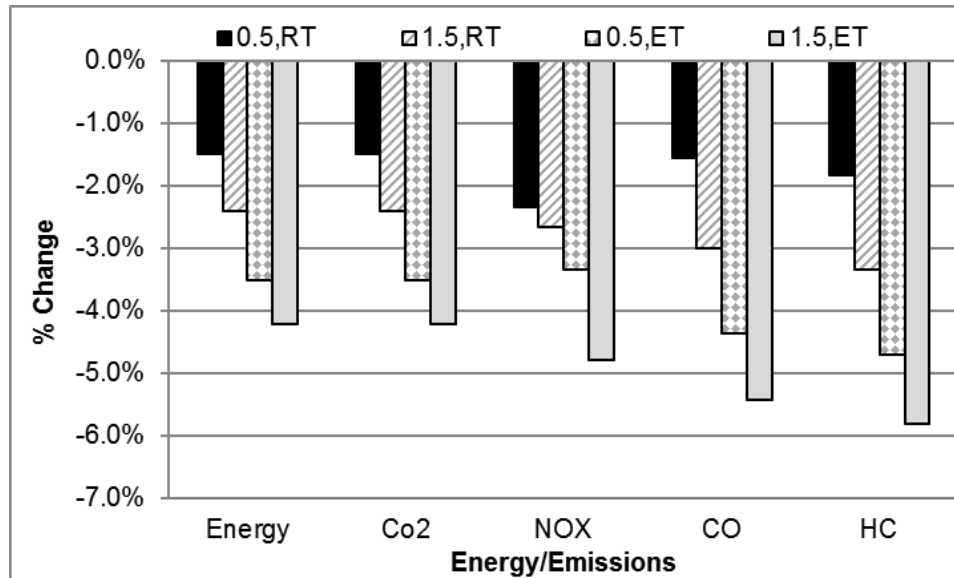
Figure 22: Reduction in Energy and Emissions Resulting from LEZ Scenario Implementation— Sub-Region Analysis

Figure 22 shows that the reductions (benefits) in energy and emissions are commensurate with the level of the incentive and the presence of ET service. Energy consumption and emissions outputs are reduced by about 1.5 percent to 2 percent in the lowest-incentive–level scenario with RT service. The impacts are in the 4 percent to 5.5 percent range at the highest level of incentive with ET service. In other words, in a small sub-region of 500,000 people, the introduction of a LEZ incentive in about 4 percent of the zones yields a 1.5-percent to 3-percent reduction in energy and emissions with no ET and a 3-percent to 5-percent reduction in energy and emissions with ET. These reductions are certainly context dependent, with the level of reductions sensitive to the levels of the incentive. These reductions were realized with modest incentives of $0.50 per trip and $1.50 per trip, with lifetime maximum limits imposed on individuals. The ET service entails doubling frequency and reducing fare to one-half of the original fare for service to and from the LEZs. The model system is able to reflect the secondary and tertiary impacts of a LEZ on travel behavior and vehicular travel, including induced demand effects, and provide an estimate of the energy and emissions benefits that may be realized through a LEZ scenario. Armed with the knowledge that the model system is ready for a larger-scale application, the project team moved to deploying the integrated travel model system to the entire Greater Phoenix metropolitan region. The results of this region-wide effort are presented in the next section.

Results for the Regional Simulation Case Study Area

The software systems embedded in the integrated travel model system were enhanced to accommodate the full region-wide simulation effort. Because of the computational burden associated with simulating the movements of nearly 4 million agents through the course of a day, upgrades were made to the analytical procedures, algorithms, and database management and flow processes within the integrated travel modeling software. Within the scope of this project, it was not possible to completely re-engineer the software systems to take advantage of massively parallel computing architectures. Computational runtimes presented a challenge when simulations were undertaken for the full population of the region, so the project team resorted to sample-based simulations in which the

simulations were performed for a random sample of the synthetic population rather than for the full population. This sample-based simulation procedure is often adopted in large-scale simulation studies to keep computational burden and database management overhead manageable. To ensure that the simulation fully reflects the effects of congestion on activity-travel demand and route choices, we applied special calibration factors to ensure that the sample-based simulation run replicates actual ground conditions (traffic volumes, travel speeds, trip length distributions, and activity frequencies by purpose and time of day) under the baseline scenario. After the model system was calibrated to replicate prevailing conditions in the baseline, we exercised the model system for selected scenarios, as noted earlier in this report. Note that the simulation does not include population in group quarters (such as dormitory students); hence, the population numbers in the tables of this section do not match exactly the population numbers in Table 10. In addition, because the sample-based numbers from the simulation are scaled up using appropriate weights to reflect full population totals, we considered it appropriate to apply rounding procedures for large numbers so that the level of precision in the scaled numbers is depicted correctly.

Table 10 presents the results of the simulation for all travelers in the region. The simulation results include only personal travel internal to the region, not external travel, truck and commercial travel, or visitor and taxi travel.

Table 10: Aggregate Travel Characteristics for All Travelers—Full-Region Analysis

Indicator	Baseline	$1.50, RT	$1.50, ET
Population	3,838,200	3,838,200	3,838,200
Total trips	14,996,600	14,989,900	14,997,100
Total auto trips	14,420,300	14,410,600	14,160,900
Total transit trips	576,300 (3.84%)	579,300 (3.86%)	836,200 (5.58%)
Average trip rate	3.91	3.91	3.91
Average trip duration (minutes)	25.53	25.55	25.74
Average trip length (miles)	9.94	9.94	9.91

The simulation accounts for about 3.8 million persons in the region making nearly 15 million trips. The transit mode share in the baseline is just under 4 percent, which is somewhat higher than the actual value. As explained earlier in the report, we did not perform further calibration of the model to replicate true transit mode shares exactly because it is the difference across scenarios that is of interest in the simulation results. The average trip rate of 3.9 trips per person is consistent with that seen in household travel survey data for the region. The average trip length is nearly 10 miles, once again reflecting a value consistent with observational survey data. The average trip duration of just over 25 minutes per trip is slightly longer than that reported in travel survey data (survey data suggest that average trip lengths are closer to 18–20 minutes in duration); this is presumably because the simulation model system overestimates transit trips (which tend to have longer trip durations because transit is a slower mode). Overall, the travel characteristics seen in the baseline scenario are reasonable and appropriate for a large-scale simulation of this magnitude and nature targeted at understanding the potential impacts of the LEZ Operational Scenario.

The simulation model system considered two scenarios, both at the $1.50-per-trip level (for the LEZs in downtown Phoenix). One scenario had RT service, while the other had ET service. In the ET service scenario, frequency of service is doubled and the transit fare is made one-half of the regular fare for all transit travel to and from the LEZs. In the presence of an incentive, there is virtually no change in aggregate region-wide travel characteristics, which is consistent with expectations that in light of the fact that the LEZs are but a small part of the overall region, the sprawled nature of the Greater Phoenix metropolitan area leads to highly dispersed travel patterns, and travel to and from the LEZ is but a tiny fraction of the overall travel in the region. In the presence of ET, some differences are discernible, with fewer total trips, a higher transit mode share, and modestly higher trip durations. Because of the increased use of transit (which is a slower mode), one would expect the total trip making to drop slightly in view of the smaller time–space prisms associated with transit mode use. The slower transit mode use also contributes to slightly higher average travel times.

To better understand the impacts of the LEZ on travel behavior, the project team isolated the eco-travelers in the simulation and examined their travel characteristics. The results are presented in Table 11.

Table 11: Aggregate Travel Characteristics for Eco-Travelers—Full-Region Analysis

Indicator	Baseline	$1.50, RT	$1.50, ET
Population	79,300	194,300	194,300
Total trips	314,700	777,900	787,400
Total auto trips	302,600	747,100	751,700
Total transit trips	12,100 (3.84%)	30,800 (3.96%)	35,700 (4.53%)
Average trip rate	3.97	4.00	4.05
Average trip duration (minutes)	25.22	25.63	25.57
Average trip length (miles)	9.87	9.99	9.91

The baseline population of eco-travelers corresponds with a 2-percent market penetration of eco-vehicles, while the LEZ scenario population size reflects a 5-percent market penetration of eco-vehicles. The transit mode share with RT remains largely unchanged, while the transit mode share with ET shows a noticeable increase relative to the baseline, despite the presence of an incentive that would motivate eco-travelers to drive. In the context of traveling to and from downtown Phoenix, it is possible that a significantly enhanced transit service is more competitive to the "private automobile with incentive" option for some travelers. In the smaller sub-region considered earlier, traffic congestion and auto travel times may not have been as large an issue because they are in the full-region simulation, where auto travelers encounter substantial congestion when traveling to and from downtown Phoenix. The slight rise in transit mode share in the ET service scenario is associated with a slight increase in trip rate consistent with expectations. In the ET scenario, where there is a larger transit mode share, the higher trip rate may be attributed to the prevalence of transfers in transit trip making. In the case of transit travel to and from downtown Phoenix, travelers will need to undertake additional trip segments (including access and egress trip segments); because the results present "unlinked" trips, the average trip rate will be slightly higher than in the scenarios with lower transit mode share. The average trip duration in the ET service scenario is larger than in the baseline, once

again reflecting the effect of the slower transit mode. Despite the higher transit mode share in the ET service scenario, the average trip duration for eco-travelers is about the same between the two LEZ scenarios. It is possible that eco-travelers are encountering small levels of increased congestion in the LEZ scenario with regular transit likely because of the induced demand effect, where eco-travelers are choosing to pursue discretionary activities in the LEZ area with a higher frequency to take advantage of the incentive. Indeed, this induced demand effect can be seen in the longer average trip length in the middle scenario (i.e., LEZ with RT). The slightly higher mode share for transit in the ET scenario does not contribute to any further changes in average trip duration; the average trip length appears modestly smaller because of the averaging of small access and egress trip lengths (note that this average is computed on unlinked trips).

In contrast to eco-travelers (who are affected by the LEZ), non-eco-travelers show no appreciable change in travel behavior in response to the LEZ incentive but exhibit a higher mode share when presented with ET service. The population of non-eco-travelers drops in the LEZ scenarios because of the higher penetration of eco-vehicles in the market in the LEZ scenarios. The trip rates are largely unchanged across the scenarios. The average trip length is slightly smaller in the ET service scenario, once again because of the averaging of small access and egress trips in the computation of average trip length. The average trip duration rises modestly in the ET service scenario, reflecting the effect of increased mode share on a slower mode of transportation. The transit mode share increases, but the average trip rate shows no change. Although the use of transit is likely to entail transfers and access and egress legs, the overall trip rate does not show a change because any increase (resulting from journeys being split into multiple segments) is offset by the tighter time–space prism constraints associated with using a slower mode. These tighter time–space prism constraints may lead to a small suppression of trips (as evidenced by the slight drop in total unlinked trips). These results are depicted in Table 12.

Table 12: Aggregate Travel Characteristics for Non-eco-Travelers—Full-Region Analysis

Indicator	Baseline	$1.50, RT	$1.50, ET
Population	3,758,900	3,643,900	3,643,900
Total trips	14,681,900	14,212,000	14,209,700
Total auto trips	14,117,700	13,663,500	13,409,200
Total transit trips	564,200 (3.84%)	548,500 (3.86%)	800,500 (5.63%)
Average trip rate	3.91	3.90	3.90
Average trip duration (minutes)	25.54	25.55	25.76
Average trip length (miles)	9.94	9.94	9.91

In addition to examining the travel behavior of eco- and non-eco-travelers, the project team analyzed the impacts of the LEZ on the traffic composition of LEZs and regular (non–low-emission) zones. Figure 23 shows the composition of person miles of travel (PMT) by type of zone. Recall that the percentage of low-emission vehicles in the baseline scenario is 2 percent, while that in the LEZ scenarios is higher, at 5 percent. In the baseline scenario, the percentage of PMT that low-emission vehicles undertake is consistent with the baseline penetration of low-emission vehicles at 2 percent.

The transit percentage is higher in the LEZs in the baseline scenario because these zones are designated in the downtown Phoenix area. The downtown Phoenix area is well served by transit modes (local bus, express bus, and light rail transit) and there is a higher transit mode share for travel to and from downtown Phoenix. In the LEZ scenario with RT, we found that the percentage of PMT that low-emission vehicles undertook is about 4.7 percent for regular zones—a figure consistent with the 5-percent penetration of low-emission vehicles in the household fleet in this scenario. However, for trips to and from LEZs, the percentage of PMT that low-emission vehicles undertake is nearly double, at 9.3 percent, signifying that the travel demand to and from LEZs is "cleaner" compared with travel undertaken to other, regular zones (although regular zones see a benefit, as well). The transit shares in the scenario with RT do not change appreciably, although there is a modest drop in transit mode share for the LEZs (presumably because a few travelers who have access to a low emission vehicle switch from transit to low-emission vehicle use to take advantage of the incentive). In the scenario with ET, we found that the regular zones continue to see a pattern similar to the scenario with RT. The percentage of travel to and from regular zones that low-emission vehicles undertake is 4.8 percent, and transit share holds steady. For the LEZs, however, ET service is associated with a surge in transit mode share. In contrast, the percentage of travel that low-emission vehicles undertake drops slightly to 8.7 percent (compared with 9.3 percent in the RT scenario), presumably because a few eco-travelers choose to travel by transit in the ET scenario.
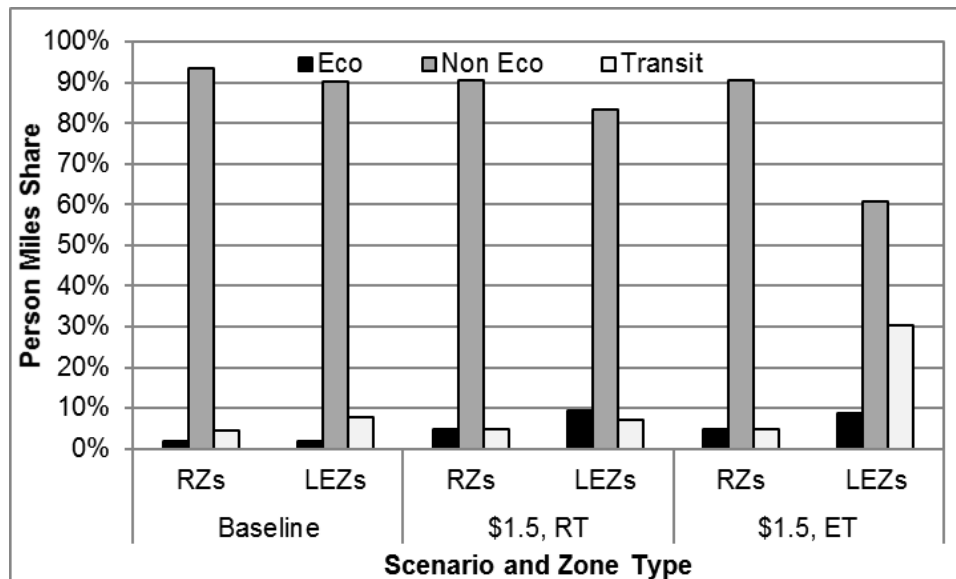

Figure 23: Share of Person Miles of Travel by Zone Type

We performed a similar analysis on the number of trips to the different zone types.

Table 13 shows the split of trips (as opposed to miles, which was the focus of Figure 23) by mode of transportation for the regular zones and LEZs. Auto accounts for the vast majority of trip making in the LEZs and regular zones, although transit mode share is slightly higher in the LEZs even in the baseline (because of the reasons noted earlier). With the implementation of the LEZ, the transit mode share changes substantially only in the scenario where ET service is provided to and from LEZs. In the RT service LEZ scenario, the auto mode share shows a modest increase, and the transit mode share shows a modest decrease (for the LEZs), presumably because some eco-travelers switch to eco-vehicle travel (away from transit) to take advantage of the incentive. In the ET scenario, the share of transit trips shows a striking increase compared with both the baseline and the RT scenarios. The share of transit for travel to regular zones also shows a slight increase, presumably because of modest trip chaining effects where transit travelers are captive to transit for their non-LEZ travel, as well. However, because transit use is not generally conducive to trip chaining, the increase in transit mode share for regular zones is small. Moreover, travelers do not see any enhancement of transit service for travel to regular zones. The number of unique people using transit shows an increase in the ET scenario. Although 372,600 people ride transit in the baseline scenario, 552,500 people ride transit in the ET scenario. This shows that the increase in share of transit trips is not merely attributable to the same individuals making more trips on transit but also to a net increase in the number of individuals using transit for their trip making.

Table 13: Composition of Trips by Zone Type

Scenario	Low Emission Zones	Regular Zones	All Zones
Baseline (Auto Trips)	820,300 (92.5%)	13,600,000 (96.4%)	14,420,300 (96.2%)
$1.50, RT (Auto Trips)	858,800 (93.9%)	13,551,800 (96.3%)	14,410,600 (96.1%)
$1.50, ET (Auto Trips)	618,600 (66.4%)	13,542,300 (96.3%)	14,160,900 (94.4%)
Baseline (Transit Trips)	66,300 (7.5%)	510,000 (3.6%)	576,300 (3.8%)
$1.50, RT (Transit Trips)	63,400 (6.9%)	515,900 (3.7%)	579,300 (3.9%)
$1.50, ET (Transit Trips)	313,400 (33.6%)	522,800 (3.7%)	836,200 (5.6%)

In the presence of induced travel demand, it is possible that VMT associated with LEZ travel will increase as travelers are willing to drive longer distances to take advantage of the LEZ incentive. Regardless of whether VMT increases, there is no reason for VMT to decrease in the absence of a toll or penalty on regular vehicles and in the absence of ET service. In the RT service LEZ scenario, energy and emissions benefits must be realized not through a reduction in trip making or VMT but through a change in the fleet mix associated with travel to and from the LEZs. As the LEZ scenario motivates the use of low-emission vehicles, the share of trips that low-emission vehicles undertake will be considerably higher in the LEZs. Figure 23 shows that the share of low-emission vehicle (eco-) miles is considerably higher in the LEZs compared with the regular zones. In the context of trips (as opposed to miles, which was the focus of Figure 23), a similar trend was observed. In Figure 24, the vehicle mix is shown exclusively for LEZ trips. The percentage of eco-vehicle trips increases to nearly 10 percent in the RT service scenario, with a nearly corresponding decrease in non-eco-vehicle trip share. There is a slight decrease in transit mode share, as well, presumably because there are a few eco-vehicle travelers who switch to driving to take advantage of the LEZ scenario incentive, although that number is extremely small and falls within range of the simulation stochasticity. In the presence of ET service, the share of transit usage surges with a corresponding drop in the non-eco-vehicle trips. There is a slight drop in the eco-vehicle trip share, as well, because a few eco-vehicle travelers switch to ET service in this scenario. In other words, despite the presence of an eco-vehicle incentive, they still find it advantageous to use ET service (because the ET service offers a lower overall generalized travel cost compared with auto even in the presence of the LEZ incentive). It is likely that these travelers experience severe congestion in their travel and so find it worthwhile to switch to ET service.
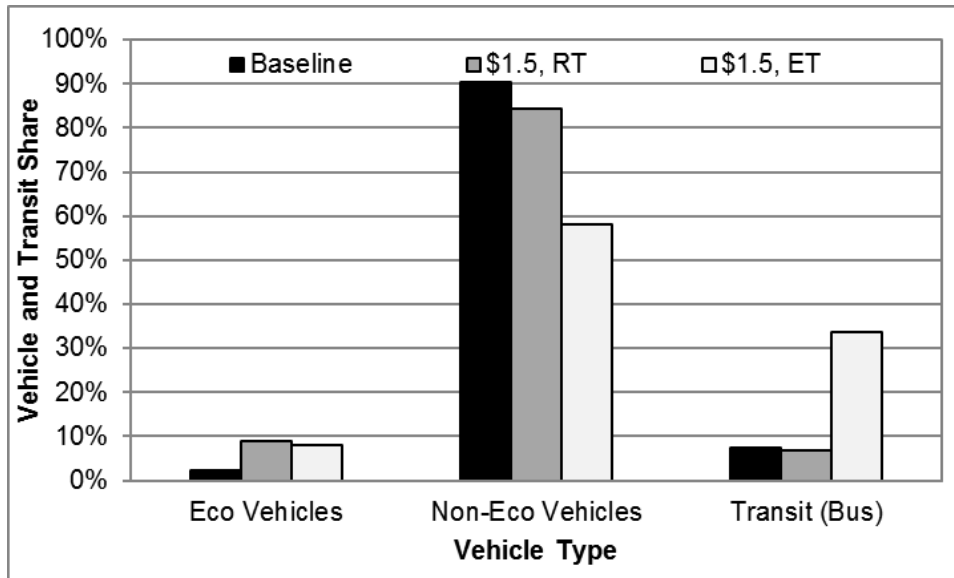
Figure 24: Vehicle Mix and Transit Share for LEZ Trips

Energy and emissions benefits are realized in the LEZ through the increased volume of eco-vehicle travel to the LEZs. In Figure 25, the LEZs are shown with mapping of the intensity of eco-vehicle trip making to the LEZs. A similar mapping can be done for non-eco-vehicle trip making to the LEZs. In the absence of ET service, the non-eco-vehicle trip volumes show no change. A change is seen in eco-trip volumes for the LEZs consistent with the notion that these trips receive a monetary incentive.
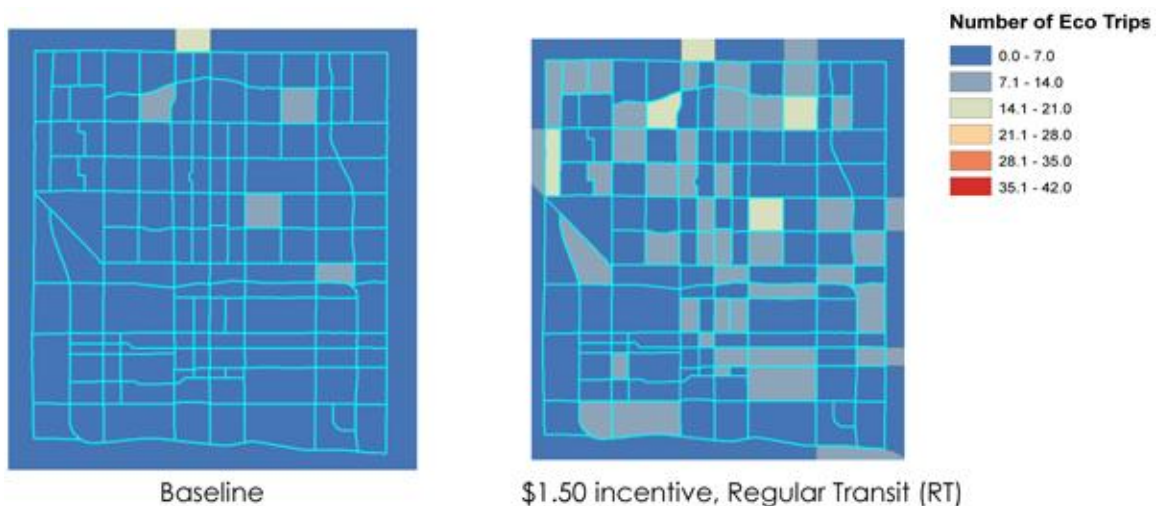

Figure 25: Number of Eco-Trips to Low Emission Zones

The figure shows that the number of eco-trips increases substantially across the LEZ area. Note that the number of eco-trips shows no appreciable change between the RT and ET service scenarios; hence, the map corresponding to the ET service scenario is not shown. The increase in eco-vehicle trip making in the incentive scenario is consistent with results shown in earlier tabulations and charts. Note that there is a small amount of eco-vehicle trip making in the baseline scenario, as well, because there is a 2-percent market penetration of eco-vehicles in the baseline scenario.

Figure 26 shows a similar mapping of trip volumes for transit. The comparison is now performed between the baseline scenario and the LEZ scenario with ET service. The LEZ scenario with RT service does not show any appreciable change in transit trip volumes relative to the baseline (consistent with the notion that transit service is unchanged) and is therefore suppressed. However, in the event of a substantially enhanced transit service (double the frequency and one-half the fare); we see that the number of transit trips increases across the LEZ area in substantial ways. Consistent with this increase in transit trip making, there would be a corresponding decrease in non-eco-vehicle trip volumes as non-eco-travelers switch in large numbers to ET service. The number of eco-vehicle trips is similar to that seen earlier in Figure 25 (despite the small shift of eco-vehicle travelers to transit in the ET scenario).

Baseline $1.50 incentive, Enhanced Transit (ET)

Figure 26: Number of Transit Trips to Low Emission Zones

As noted in

Table 13, the number of auto trips associated with LEZ travel increases in the LEZ scenario (with RT service). In the LEZ scenario with ET service, the number of auto trips drops substantially, but that is because non-eco-vehicle travelers switch to transit in large numbers. In the scenario with RT service, the number of auto trips increases from 820,300 to 858,800 (an increase of 4.7 percent), suggesting that there is a small but noticeable induced travel demand effect that the simulation model system is able to capture. This is not surprising given that eco-vehicle travelers receive a monetary benefit in the incentive scenario for travel to the LEZ. Although there is an increase in auto trips for the LEZs, the cleaner mix of vehicles helps provide the energy and emissions benefits that motivated the designation of the LEZ in the first place. Note that overall auto trip making does not show an increase (in the region as a whole) in the LEZ regular transit service scenario, suggesting that the induced demand effect (in the LEZ area) is the result of a spatial redistribution of travel as opposed to a net increase in travel.

The total VMT in the region as a whole and the associated CO_2 emissions resulting from auto travel are shown in Figure 27. The total VMT remains steady (for the region as a whole) between the two scenarios. In other words, induced travel demand did not result in a net increase in VMT at the region-wide level (even if it does increase VMT associated with LEZ travel, consistent with the 4.7-percent increase in trip volumes for LEZs). The auto VMT drops substantially in the ET service scenario, consistent with expectations surrounding the large exodus to transit use in this scenario. The CO_2 emissions show a drop of nearly 2 percent in the RT service scenario and nearly 4 percent in the ET service scenario. In other words, despite no decrease in VMT in the region (in the RT service scenario) and an increase in travel associated with the LEZs, there is a net decrease in CO_2 emissions. This may be attributed to the cleaner vehicle mix associated with travel in the region not only for the LEZs but also for the regular zones that see secondary benefits associated with an enhanced market penetration of clean-fuel vehicles.
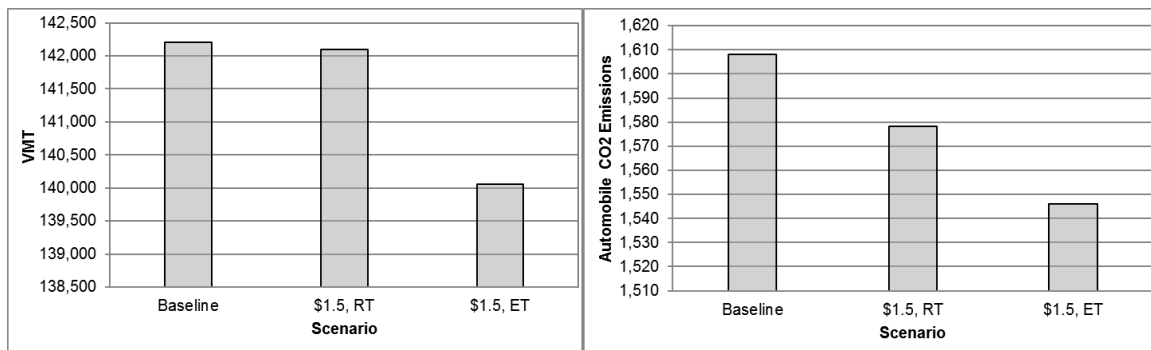

Figure 27: Region-Wide Auto Vehicle Miles of Travel and CO$_2$ Emissions

The total energy consumption in the region drops despite the amount of VMT holding steady in the RT LEZ scenario. The total energy consumption drops substantially in the ET LEZ scenario because of the large shift in mode choice. The drop in energy consumption in the RT scenario is consistent with the discussion earlier that, even though the number of auto trips and VMT remain the same in this scenario, energy and emissions benefits are realized through the turnover in the fleet, with a higher market penetration of eco-friendly vehicles that the LEZ scenario brings about. Figure 28 shows the energy consumption for the region as a whole and for the LEZs. The energy consumption for auto travel associated with regular zones can be calculated as the difference between the region-wide energy consumption and the LEZ energy consumption. The region-wide auto travel energy consumption decreases largely because of the reduction in energy consumption for travel associated

with the regular zones. Because of the induced demand effect that resulted in a spatial reallocation of travel, auto travel associated with regular zones drops by a small amount. This drop, coupled with the higher presence of eco-vehicles in the fleet, contributes to the drop in energy consumption (for regular zones). For the LEZs, however, the total energy consumption remains steady (there is a nominal increase that falls in the range of simulation stochasticity), consistent with the competing forces that neutralize one another. On one hand, an increase in auto travel is associated with LEZs in the RT scenario because of induced demand and spatial redistribution effects. Eco-vehicle travelers may be willing to travel longer distances to avail of the incentive associated with LEZs. On the other hand, the vehicle fleet mix is cleaner and more energy efficient, with a higher percentage of trips to and from LEZs undertaken by eco-vehicles than in the rest of the region. The first contributes to an increase in energy consumption, while the second aspect contributes to a decrease in energy consumption. The net result is the energy consumption associated with LEZ travel holding steady in the RT scenario.
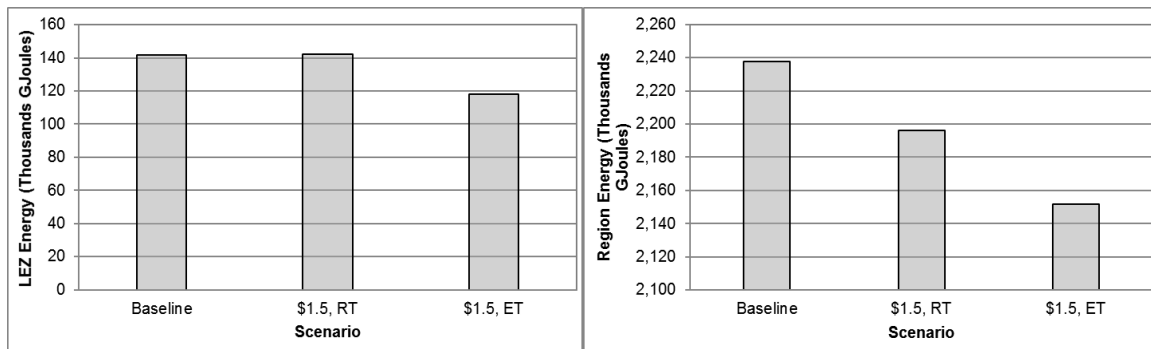

Figure 28: Energy Consumption for Auto Travel

The team performed the energy and emissions analysis of the LEZ scenarios using the MOVESLite component, which is integrated with the DTALite dynamic traffic assignment model. This component provides information not only about energy consumption and CO_2 emissions but also about other emissions of interest in the transportation planning and operations domain. Consistent with the results presented above, we found that the LEZ scenarios offer energy and emissions reductions for the region as a whole. In other words, the region as a whole benefits even though the LEZ is limited to a downtown Phoenix location. Figure 29 shows the percentage of change in energy and emissions for the entire region. The energy and CO_2 emissions reductions are the same as those shown in Figure 27 and Figure 28. With a LEZ scenario that retains regular transit service, the percentage of reduction in these two metrics is just under 2 percent (relative to the baseline scenario). With a LEZ scenario that includes ET service, the percentage of reduction in these two metrics is just under 4 percent (relative to the baseline scenario). These percentage reductions are realized with a $1.50-per-trip incentive, where the trip maker obtains this monetary benefit every time he or she enters the LEZ (users realize no incentive when exiting the LEZ) in an eco-vehicle (hybrid, electric, or plug-in hybrid). The percentage reductions are sensitive to these scenario assumptions, and the integrated travel model system can be applied to test a variety of scenarios in which assumptions are varied, including a maximum allowable daily incentive benefit, differing levels of incentives across eco-vehicle types,

differing treatment of individuals who live or work in the LEZ, and time-of-day varying incentive levels. As such, the percentage reductions seen in Figure 29 should be interpreted and considered in the context of the specific scenario configurations used in this study.
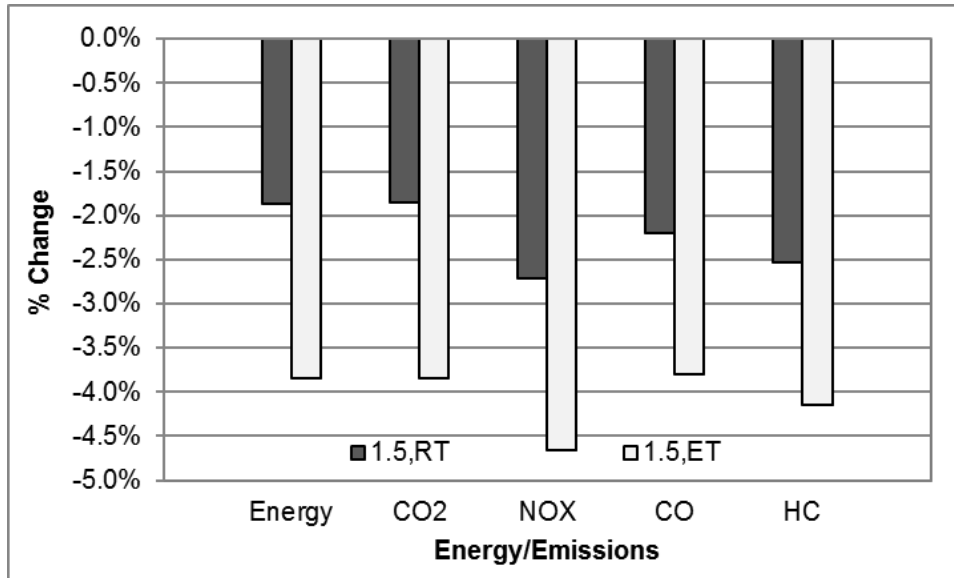

Figure 29: Change in Emissions in LEZ Scenarios Relative to Baseline—Region-Wide

An energy and emissions analysis was performed separately for regular zones and LEZs. Figure 30 shows the change in energy and emissions for regular zones in the LEZ scenarios.
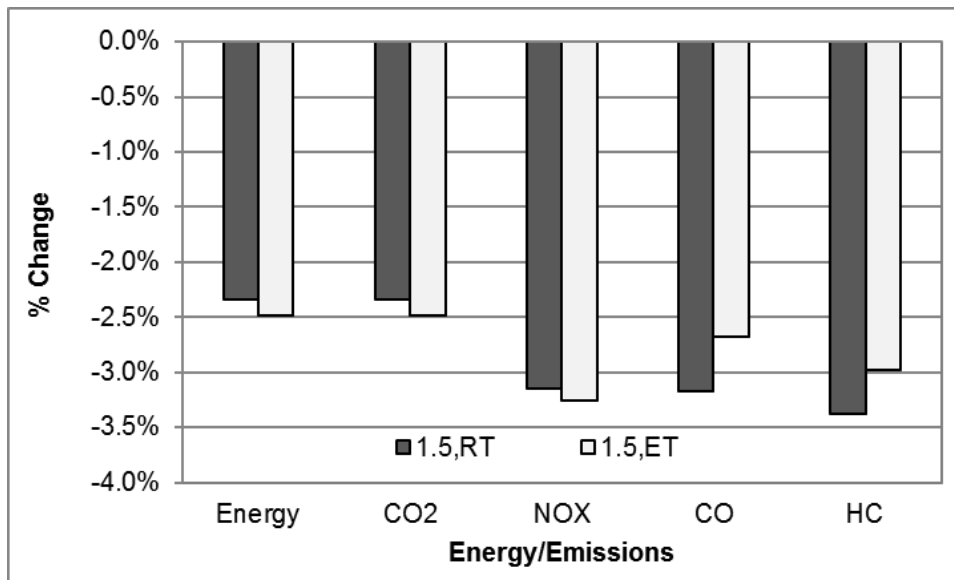
Figure 30: Change in Energy and Emissions in LEZ Scenarios Relative to Baseline—Regular Zones Only

The regular zones experience a reduction in energy and emissions across all pollutants in the presence of LEZ scenarios. The regular zones do not experience much of a change in travel demand when the LEZ scenarios are implemented, largely because the transit service associated with these zones remains unchanged at RT service levels even in the ET service scenario. In the absence of any pricing structure (incentive) or change in transit, the travel demand for these zones is largely unchanged. However, because of a small spatial redistribution of travel (where travel of eco-travelers is redirected to the LEZs) and the higher penetration of eco-vehicles in the fleet, regular zones realize energy and emissions savings. In other words, the introduction of a LEZ scenario has a beneficial impact on not only LEZs but also regular zones.

A slightly different story emerges in the context of energy and emissions analysis for LEZs. Because LEZs experience a slight increase in travel (because of induced travel effects), there is virtually no reduction in energy consumption and emissions of various pollutants in the RT service scenario. The eco-vehicle percentage that was used in the modeling of the LEZ Operational Scenario was quite conservative in order to present a realistic view of a LEZ implementation in the near future. The eco-vehicle penetration rate is simply too small to bring about significant reductions in energy and emissions.

Figure 31 shows the change in energy and emissions resulting from LEZ scenario implementation. In the RT service scenario, the energy consumption and CO_2 emissions show a slight increase, although the increase is so small that it falls within the range of simulation stochasticity. Other pollutants show modest decreases, suggesting that the higher penetration of eco-vehicles for low-emission travel does yield some benefits, despite the 4.7-percent increase in travel associated with these zones. It should be noted that, even though travel associated with these zones increased by 4.7 percent, the energy and emissions for the LEZ area remained largely unchanged, clearly indicating that any induced travel effect is neutralized by the penetration and use of eco-vehicles motivated by the LEZ incentive. In the case where ET service is provided, the LEZs exhibit large reductions in energy and emissions consistent with the shift of non-eco-travelers (and a few eco-travelers) to the transit mode.
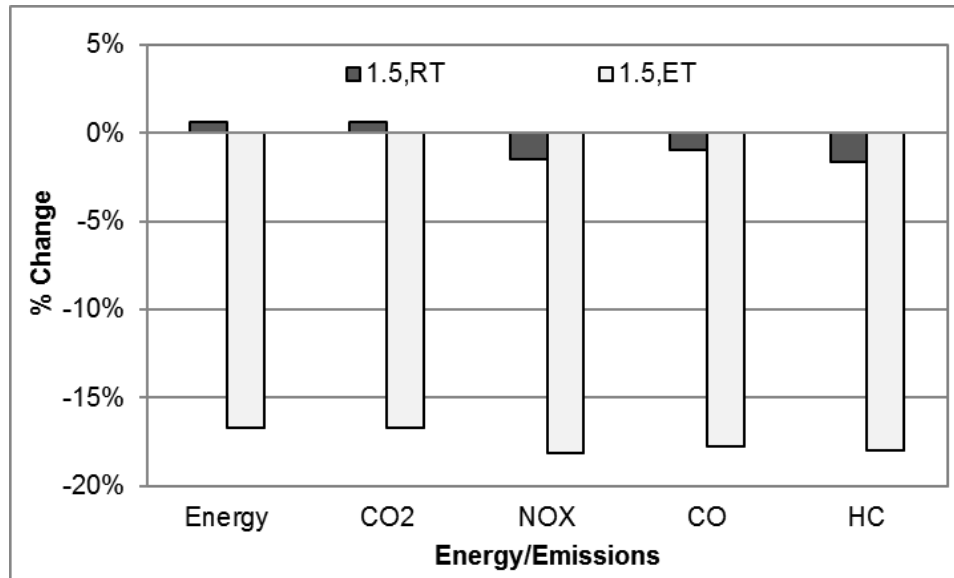
Figure 31: Change in Energy and Emissions in LEZ Scenarios Relative to Baseline—LEZs Only

In view of the slight increase in travel associated with LEZs in the LEZ scenarios, it may be appropriate to examine the energy and emissions changes on a per-trip basis, in order to normalize the output against an appropriate metric. Using the metric of "per-trip," rather than an aggregate method shows a more appropriate comparison between the different analysis scenarios. The results of this analysis are shown in Figure 32, which focuses exclusively on trips associated with LEZs. The energy and emissions per trip decreases, with the reductions ranging between 3.5 percent and 6.5 percent. The reduction in energy and emissions per trip is consistent with expectations. Because the travel demand associated with LEZs is characterized by a higher penetration of eco-vehicle use, the energy and emissions per trip goes down despite the slight increase in travel demand. The nature of the incentive can be refined to help achieve reductions in energy and emissions at an aggregate level, as well.
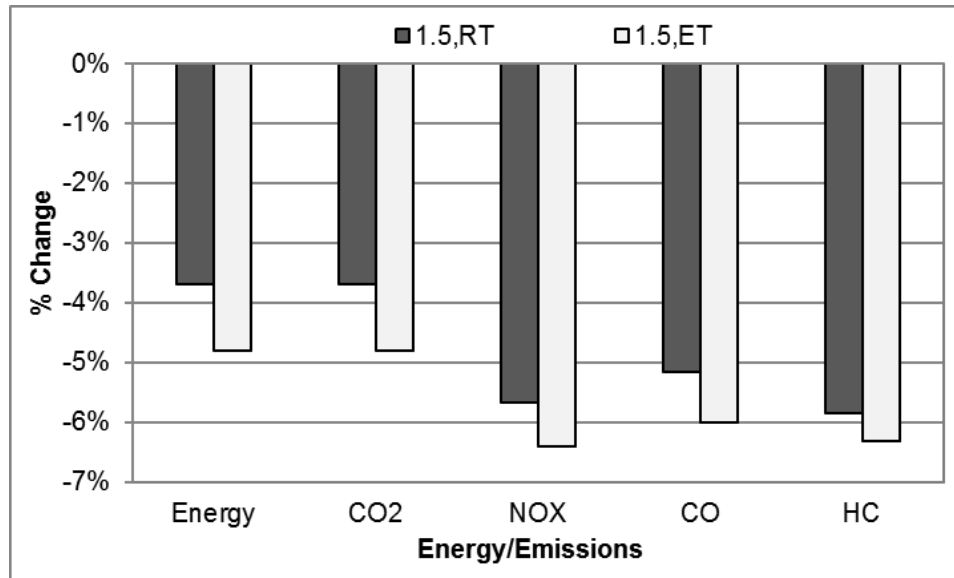
Figure 32: Change in Energy and Emissions per Trip in LEZ Scenarios Relative to Baseline—LEZ Only

The results of the simulation study illustrate the types of reductions in energy and emissions that may be realized through the deployment of LEZ. In this study, consideration has been given to the use of incentives to motivate the enhanced penetration and use of eco-vehicles in the household vehicle fleet mix. By providing incentives for the use of eco-vehicles, the LEZ scenario can enhance market penetration of these vehicles to the extent that regular zones (not subjected to the LEZ) also realize energy and emissions benefits (as seen in Figure 29). Although a toll or penalty on regular vehicles may provide similar benefits, it has the potential to reduce or deter travel to and from the LEZs. This may hurt economic activity because businesses suffer in the face of reduced travel to the LEZs. Businesses may have to relocate out of the LEZs under such a pricing scenario to remain viable, further threatening the vitality of the LEZ areas (which are often high-density business districts). The LEZ incentive simulations performed in this study showed that energy and emissions benefits can be realized without adversely affecting the economic activity in the LEZ area (in fact, there may be a modest increase in activity because of induced travel effects). Although LEZs may experience slightly higher travel and VMT in a LEZ incentive scenario, the transition to a cleaner, eco-friendly fleet (motivated by the LEZ) helps bring about energy and emissions benefits to the targeted area and the region as a whole. These secondary benefits should be taken into account when evaluating the overall impacts of LEZs.

Chapter 5.   Conclusions

Summary of Results

This report has documented a comprehensive effort to simulate the impacts of LEZ scenarios on travel behavior and resultant energy and emissions outputs. A LEZ is characterized in this study as a specifically delineated area targeted for emissions reductions through the use of an incentive to motivate a higher market penetration and use of eco-friendly vehicles in the context of travel to and from the LEZ area. The scenarios considered in this study can be described as follows:

- *Eco-friendly vehicles* are HEVs, PHEVs, and EVs.
- Travelers are offered an incentive equivalent to a monetary benefit on a per-trip basis.
- The incentive values considered in this study include $0.50 or $1.50 per trip (low and high incentive level).
- The incentive is provided only when a traveler enters the LEZ using a low-emission vehicle; no incentive is offered for travelers exiting the zone.
- The monetary benefit that an individual can realize is capped at a maximum allowable lifetime benefit.
- No special treatment is afforded to individuals who reside or work in the LEZs. They are eligible to receive the incentive in the same way as others.
- The monetary incentive may or may not be coupled with enhanced transit service for the LEZs. In this study, *ET service* refers to service that is twice the frequency and one-half the fare of existing RT service.
- The incentive or monetary benefit does not vary by time of day.

An integrated travel model system was used that couples the openAMOS activity-based microsimulation model system of travel demand with the DTALite dynamic traffic assignment model system to simulate the behavioral changes that the introduction of LEZ scenarios bring about. The model system is exercised both for a small test sub-region of the Greater Phoenix metropolitan area in Arizona as well as for the region as a whole. We did this to facilitate rapid testing of the integrated travel model system and to determine whether the results (simulated impacts) vary by spatial scale. The model system included only personal household travel demand, with other travel demand (truck, visitor, external) loaded on the network in the background (these trips are not subject to or sensitive to the LEZ). The activity-based travel model and the dynamic traffic assignment model exchange data continuously throughout the simulation so that the travel choices of travelers in the simulation are sensitive to experienced and prevailing network conditions. The integrated travel model system can capture the myriad impacts that a LEZ incentive policy may have on the range of travel choices, such as destination choice, activity choice, and mode choice. In this study, the LEZ is not likely to affect route choice or time-of-day choice directly, but indirect impacts are fully captured through the integrated travel modeling framework. Any changes in destination and mode choice that could result in modifications of route or time-of-day choices are fully captured in the simulation.

The simulation effort shed considerable light on the types of impacts that can be realized through the implementation of a LEZ incentive-based policy, with and without ET service for the targeted LEZ. Study results suggest the following:

- Given the incentive configurations considered in this study, energy and emissions reductions of 2 percent to 5 percent can be realized for the entire region under consideration (including LEZs and regular zones). The lower end is achieved in the absence of ET service, while the higher end is achieved in the presence of ET service for the LEZs.

- For the incentive levels considered in this study, the market penetration of eco-friendly vehicles may reach about 5 percent in the short term (5–7-year timeframe); this level of market penetration is sensitive to the incentive level and the maximum allowable lifetime benefit.

- Because of the incentive policy, LEZs may experience a small increase in travel demand resulting from induced travel effects. Travelers who have access to eco-vehicles may choose to travel (sometimes farther) to LEZs to take advantage of the incentive policy.

- Although the LEZs may experience some increase in travel because of induced demand, energy and emissions show no significant increase because of the higher level of eco-vehicle penetration and use among travelers accessing the LEZs. Carbon Dioxide remain the same, while there are decreases among other pollutants.

- Because of trip-chaining effects and higher eco-vehicle penetration levels, regular zones not subject to the LEZ also experience reductions in energy and emissions, thus presenting substantial secondary benefits that go well beyond the confines of the LEZs.

- When ET service is available in LEZs, the energy and emissions reductions are amplified substantially and found to be in the range of 15 percent to 18 percent (in the LEZs). Because regular zones do not get ET service, the energy and emissions reductions for those zones remain at about 3 percent to 4 percent in the LEZ scenarios.

- The simulation results show that the range of impacts is similar for both the test region and the full region (as long as the LEZ area is a small fraction of the entire simulation region, about 4 percent to 7 percent in terms of the number of zones), suggesting that the magnitude of the impacts and secondary benefits across the region is robust to spatial scale.

Table 14 presents a summary of the impacts of the LEZ incentive-based scenarios.

Table 14: Summary of Impacts of Low Emission Zone Scenarios

Application	Range of Benefit	Effect on LEZs	Effect on Regular Zones	Effect of Enhanced Transit	Effect on Congestion
LEZ incentive scheme	2% to 5% energy and emissions savings for entire region	Slight increase in travel resulting from induced demand but no increase in energy and emissions because of substantial penetration and use of eco-vehicles	No change in travel demand but secondary benefits in the form of reduced energy and emissions realized because of the higher presence of eco-vehicles in the fleet	Benefits substantially amplified in the LEZs because of ET, with significant shifts of non-eco-travelers to transit	Pure incentive-based scheme not likely to have an appreciable impact on congestion in LEZs or regular zones

Findings and Opportunities for Future Research

This research study has confirmed the hypothesis that the project team postulated at the inception of the project. The study team had hypothesized that, at the levels of incentives considered in this research and with modest levels of market penetration of eco-vehicles, region-wide impacts of LEZ policies would be in the range of a 3-percent to 5-percent reduction in energy and emissions resulting from personal transportation. The study team also hypothesized that the LEZs would see small levels of induced travel demand but would realize energy and emissions reductions in the LEZ scenarios because of the higher level of eco-vehicle usage for trips to and from the LEZs. Finally, it was hypothesized that enhancing transit service for the LEZs would significantly amplify the effects of the LEZ. All of these hypotheses were confirmed in this research effort. Because we performed the case study using the Greater Phoenix analysis, modeling, and simulation test bed, the study team believes that the results would hold true in other geographic contexts (except for areas that are vastly different from the Greater Phoenix area).

Based on the findings from the modeling effort, the research team presents the following recommendations and remarks:

- An incentive-based LEZ can provide beneficial impacts in terms of a reduced energy and emissions footprint. These benefits would be largely realized through the enhanced market penetration of eco-friendly vehicles and the incentive for travelers to use such vehicles when accessing destinations in the targeted LEZs.
- An incentive-based LEZ may not bring about congestion reduction because there is no incentive to suppress travel to and from the LEZ area. In fact, there may be a slight increase in traffic volumes in the LEZ area, but energy and emissions benefits are realized because of the cleaner nature of the vehicular travel.
- Maintaining (or even increasing) traffic volumes to the LEZ area may be desirable from an economic development and vitality perspective because businesses located in the area would benefit from the higher level of patronage.
- Congestion reduction can be realized (without adversely affecting economic vitality of the LEZ area) through the introduction of ET service to and from the LEZs. With ET service, individuals will be motivated to shift mode (from personal vehicle to transit) in the context of travel associated with the LEZs. The shift to transit will not only reduce congestion in the area but also reduce infrastructure

- required for parking and provide substantial energy and emissions benefits to the targeted LEZ and the region as a whole.

- It is advisable to combine an incentive-based LEZ with an ET service provision because the combined effects of these strategies provide substantial benefits in energy and emissions footprint.

- However, neither the incentive-based LEZ nor the provision of ET service comes without a cost. It would be advisable to undertake a comprehensive cost–benefit study to fully assess and quantify the short-, medium-, and long-term costs and benefits of implementing the LEZ schemes. This study did not address the cost implications of these strategies.

- It may be possible to implement a toll or penalty as part of the LEZ wherein regular non-eco-vehicles would be subjected to such a pricing signal for travel associated with the LEZs. Although such pricing schemes tend to be unpopular, they can suppress non-eco-friendly vehicular traffic, encourage mode shifts to transit and other eco-friendly modes, and generate revenue that can be used to pay for the incentive to eco-travelers and ET service provision. The analysis of such toll and pricing schemes is worthy of a future research endeavor. Such research efforts should try to identify the optimal pricing level—just enough pricing to cover the costs of the incentive but without adversely affecting economic activity in the LEZ area.

- It would be useful to analyze the sensitivity of travel demand, including induced demand effects, associated with a variety of additional incentive levels and formats. Incentives in the form of guaranteed, preferred, or free parking; discount coupons for use at merchants and businesses in the LEZ area; and accumulation of frequent eco-traveler points (similar to frequent-flier miles) that can be redeemed for merchandise or cash would be alternative formats worthy of modeling.

- To understand how travelers value non-monetary incentives, perks of different kinds, and other rewards associated with eco-vehicle use, it would be valuable to conduct behavioral surveys and collect data on valuation of and sensitivity to non-monetary instruments. Such data can help inform the specifications of behavioral models embedded in integrated travel model systems and ensure that the model components reflect behavioral choices travelers are likely to make in the real world.

- Future research efforts should examine the impacts of time-varying incentive levels, including those that are fixed but change by time of day as well as those that are dynamically set in response to real-time network conditions and emissions inventories. In the case of dynamic incentive schemes, the simulations can be enhanced to consider the role of real-time information provision (with varying degrees of latency) facilitated by connected vehicle technology.

- In this study, the incentive level and the enhanced transit service configuration are specified exogenously, and the impacts of such system changes are simulated using the integrated model. It would be of value to explore the possibility of determining the desired incentive level and transit enhancements as a function of the desired network performance and emissions reductions. If an area has a target emissions reductions value that is desired, then it would be valuable to have a model system capable of predicting the incentive level (and

transit service changes) that would bring about those desired metrics. Such a research effort would reverse the approach adopted in this study; rather than predict activity-travel impacts of specified LEZ scenarios (as was done in this study), the LEZ scenario parameters would be predicted as a function of the desired activity-travel and emissions performance measures. This type of exercise would be consistent with the notion of performance-based planning.

- Consideration should be given to the differential treatment of travelers (eco and non-eco) who live or work in the LEZ area. Although this study treated such individuals in the same way as the rest of the population, scenarios in which these groups are treated differently may be worthy of investigation. In addition, scenarios with varying definitions of eco-friendly vehicles could be considered in future work. It is conceivable that benefits will be further amplified if the LEZ incentive is provided only to drivers of pure electric vehicles, although the lower penetration of such vehicles in the market may limit the potential benefits or extend the time duration over which benefits may be realized.

- The microsimulation of millions of trips in a large metropolitan region using an integrated travel model system that includes both an activity-based travel demand model and a mesoscopic dynamic traffic assignment model continues to present a severe computational challenge, despite advances in computing architecture and software systems. Further efforts are needed in the domain of parallel computing and processing of big data to facilitate the application of large-scale simulation model systems to the analysis of a large number of scenarios. Although this project has made considerable strides in the design and deployment of such model systems, there is considerable scope for further enhancement of the model architecture and database system design.

Appendix A. List of Acronyms

Acronym	Definition
AERIS	Application for the Environment: Real-Time Information Synthesis
ASU	Arizona State University
BCA	Benefit-Cost Analysis
CBD	Central Business District
CO2	Carbon Dioxide
DTA	Dynamic Traffic Assignment
ET	Enhanced Transit
FHWA	(JPO) and Federal Highway Administration
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LEZ	Low Emissions Zone
MAG	Maricopa Association of Governments
NHTS	National Household Travel Survey
O-D	Origin-Destination
PMT	Miles of Travel
PUMS	Public Use Microdata Sample
RT	Regular Transit
TAZ	Traffic Analysis Zones
TFHRC	Turner Fairbank Highway Research Center
USDOT	United States Department of Transportation
V2I	Vehicle-To-Infrastructure
VMT	Miles of Travel
VOT	Value of Time
VSP	Vehicle-Specific Power

U.S. Department of Transportation