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Modeling the Short- and Long-Term Behavioral Impacts of a Low Emission Zone Policy: The Application of an Integrated Model of the Urban Continuum (SimTRAVEL)

Daehyun You ^a, Venu M. Garikapati ^a, Ram M. Pendyala ^{a,*}

^a Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332, USA

Abstract

This objective of this paper is to model the potential impacts of a low emission zone (LEZ) policy aimed at curbing vehicular emissions and energy consumption. Such policies are gaining increasing interest around the world. In this effort, an integrated modeling framework is employed to simulate and analyze the impacts of a LEZ policy. The model system comprises of an activity-based travel behavior model (openAMOS), and a dynamic traffic assignment model (DTALite). DTALite and openAMOS are integrated in such a way that there is continuous communication between the two model systems along the time axis. Every minute, openAMOS sends all of the trips that depart in the given minute to DTALite. DTALite simulates the trips on the network and sends all of the trips that reached their destinations back to openAMOS for determining subsequent activity-travel choices of individuals. LEZ policy impacts are simulated in two incremental scenarios. In the first scenario, people receive incentives for driving cleaner (eco) vehicles in the context of travel to/from LEZs while others (non-eco vehicle drivers) are not subject to any incentive or penalty. In the second scenario, the transit accessibility to LEZs is enhanced with an intent to bring about a mode shift among non-eco travelers (to transit). Results indicate that the LEZ policy does impact activity generation, destination choice, and mode choice in the short term. The longer term impacts of LEZ policies include a move towards acquisition and usage of 'cleaner' vehicles by households. Results of this study can help inform policy makers who are contemplating LEZ strategies to better manage travel demand.

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* Corresponding author. Tel.: +1-404-385-3754

E-mail address: ram.pendyala@ce.gatech.edu

1. Introduction

It is widely recognized that various policy actions have both short and long term impacts on location choices and activity-travel behavior choices of individuals. A policy action of much interest that falls within this domain is that of low emission zones (LEZ). Several low emission zone policies have been successfully implemented in various cities around the world. In the United States, this has become a topic of much interest to researchers and regulatory authorities interested in operational strategies that may curb ever increasing motorized travel and associated emissions. In this effort, the impacts of a low emission zone policy are evaluated through a simulation exercise that deploys an integrated modeling framework where people driving cleaner (eco) vehicles receive incentives when traveling to and from low emission zones while others (non-eco vehicle drivers) receive no such incentives. An eco-vehicle is a vehicle that complies with the emission standards set forth by a low emission zone policy. In order to benchmark a specific type of vehicle as an eco-vehicle in the context of this modeling effort, hybrid, plug-in hybrid and electric vehicle types are considered as eco-vehicles. The overall goal of low emission zone policies is that people would acquire and use cleaner and more sustainable vehicles (eco-vehicles) in the context of their daily travel. In order to encourage sustainable travel behavior among those who cannot or do not shift to cleaner eco-vehicles, transit services to and from low emission zones are enhanced with a view to encourage mode shifts.

In response to low emission zone policies, individuals may alter destination/mode choice in the short term, or change vehicle type (hybrid or electric vehicle) and residential/work location choices in the long term. In the absence of an integrated microsimulation model system that captures the full range of long and short term activity-travel and location choices, it is difficult to forecast the impacts of such policies. The objective of this paper is to present results from the application of a novel integrated microsimulation model system of land use and activity-travel behavior, called SimTRAVEL (Simulator of Transport, Routes, Activities, Vehicles, Emissions, and Land), to analyze the impacts of a low emission zone policy.

The remainder of this paper is organized as follows. The next section presents a description of the test area for modeling low emission zone impacts. The third section describes the framework of the integrated model system deployed in this study. The fourth section describes scenarios for conducting a comparative analysis of low emission zone policies. The fifth section presents results from the application of the integrated model system for different scenarios. The final section provides implications for research and policy.

2. Test Area

The test area chosen for this microsimulation effort is a three city subregion (Chandler, Gilbert and Queen Creek) from the Greater Phoenix Metropolitan Area (see Fig. 1). The highway network follows a grid pattern and the sub-region is served by major highway corridors including the US highway loop 101 running north-south in the west of the sub-region, the US 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. Although the geography chosen for analysis consists of about 500,000 people residing in about 170,000 households, simulation runs were done for a 50% synthetic population (250,000 people residing in about 85,000 households and corresponding travel of 1.1 million trips per day) to keep computational run times reasonable for the sub-region of interest in Maricopa County.

Within this sub-region of 175 TAZs, a set of 12 zones was identified for designation as LEZ areas. One set of zones (labeled “1” in Fig. 2) 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 Fig. 2) 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.

The modeling effort was performed for the smaller network to demonstrate the efficacy of the integrated modeling approach prior to implementing the model system and testing the impact of a low emission zone policy for the entire Greater Phoenix metropolitan region network. The Greater Phoenix metropolitan region experiences daily traffic of 14 million trips. Within this study, the full range of activity travel choice dynamics including activity choice, trip chaining, time of day choice, destination choice, mode choice and vehicle type choice are simulated in response to a low emission zone policy.

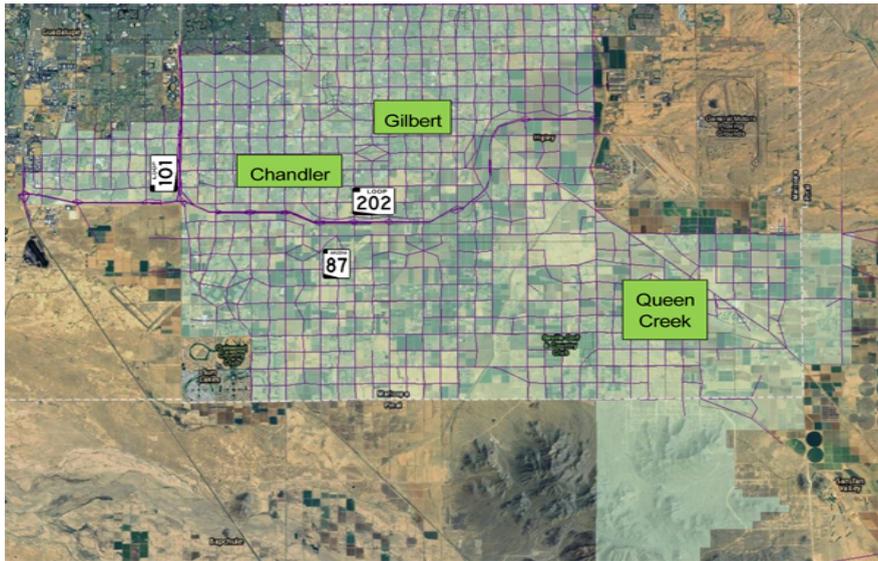
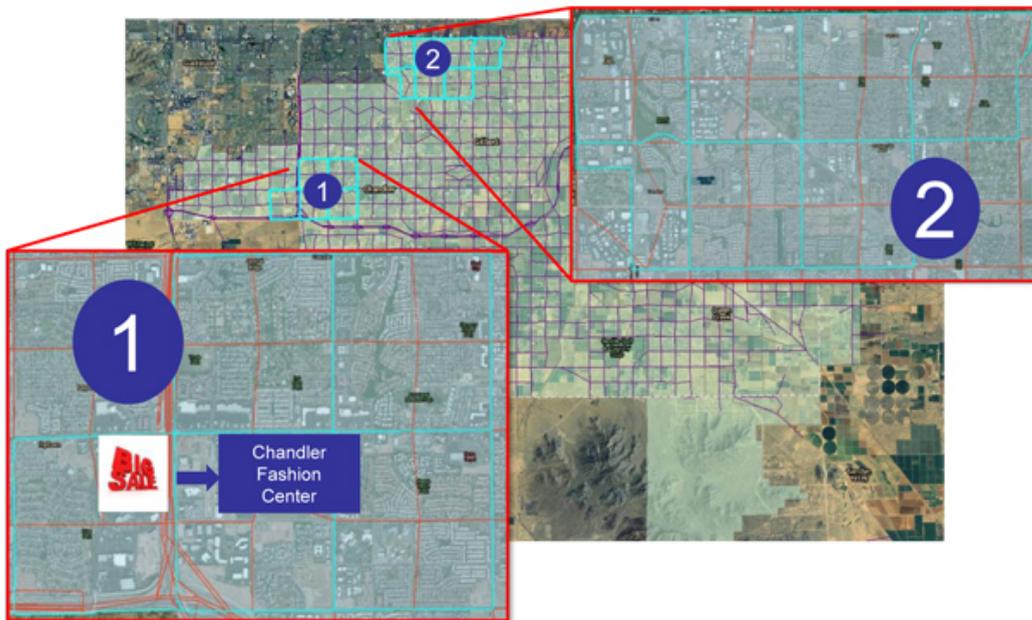


Fig. 1. Map of Three-City Test Sub-Region.



Source: Google Maps (<https://www.google.com/maps>)

Fig. 2. Map of Delineated LEZs in the Three-City Test Sub-Region.

3. Methodology

An integrated model system is used to simulate impacts of LEZ policies in this study. The components of the integrated model system are estimated on a household travel survey data set from the Maricopa County (Greater Phoenix Metropolitan Area) region of Arizona in the United States. The model system is calibrated and validated to the three-city sub-region of the county where detailed land use, building stock, and socio-economic data are available. The integrated model system, dubbed SimTRAVEL, tightly interconnects an activity-based travel behavior model (openAMOS) and a dynamic traffic assignment model (DTALite). The activity-based travel behavior model and the dynamic traffic assignment model are integrated in such a way that there is continuous communication between the two model systems along the time axis (see Fig. 3).

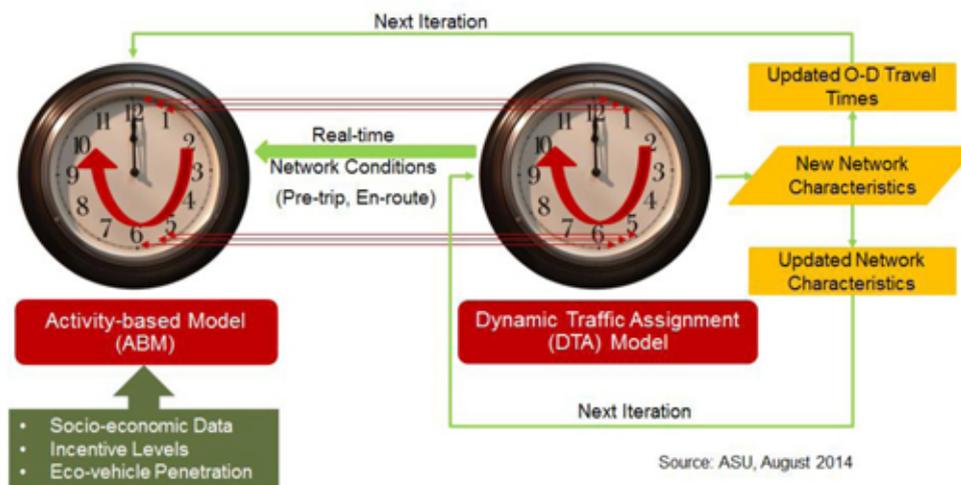
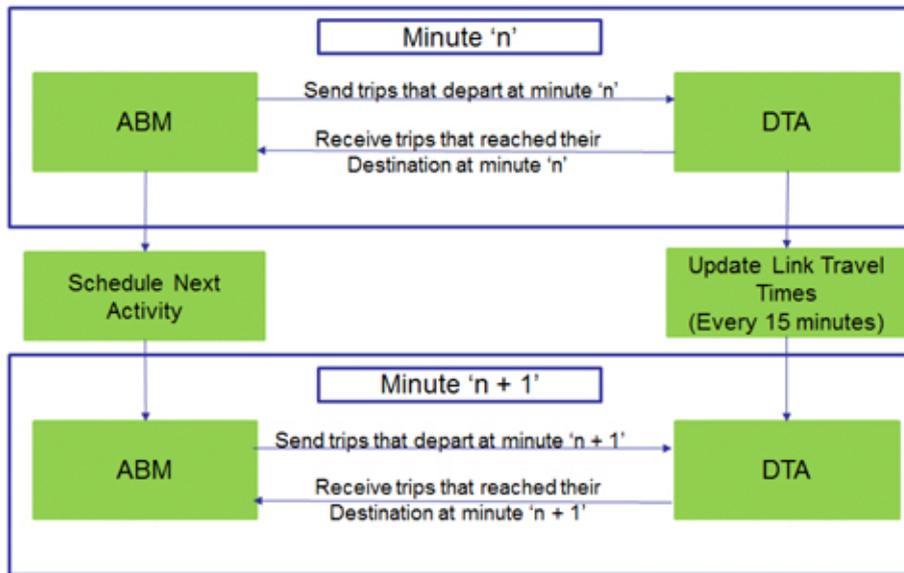


Fig. 3. Illustration of the integrated activity-travel demand and DTA model system.

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 transmitted 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 in response to network dynamics.

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 based on generalized cost as the measure of impedance. At the end of each simulation iteration (spanning a 24-hour period), travel times and costs are computed and saved for each 15 minute period of the day, thus yielding a full set of origin-destination (O-D) skim matrices. These skim matrices are typically used by destination and mode choice models in the subsequent iteration. 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). Essentially new time-dependent skims are generated at the end of each iteration 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 flows 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.

This tight coupling between both model systems provides a robust framework to test policies that are static as well as dynamic in nature. The model system simultaneously reflects impacts of policy actions on both demand and network related choices, as well as the interactions between demand and network phenomena, in a robust and behaviorally realistic way. In this research effort, the SimTRAVEL model system is applied to see how a low emission zone policy would impact activity-travel patterns on the demand side and route choice on the network side. A detailed description of SimTRAVEL and its components is available in Pendyala et al. (2012).

4. Scenario Development

An incremental scenario development scheme was adopted, starting with an incentive-only policy for low emission zones. Under this policy, eco-vehicle drivers receive a monetary incentive because they use clean vehicles for travel to/from low emission zones, whereas non-eco travelers do not receive any incentive or penalty. The incentive may be monetary such as a fixed dollar amount for each trip made to a low emission zone or a non-monetary one such as free or reserved parking. The intent of this scenario is that individuals would acquire and utilize their eco-vehicle in the context of travel to low emission zones and realize the benefits of the incentives provided. The level of incentives and corresponding market penetration of eco-vehicles is estimated based on existing (limited) research in this topic area (BenDor and Ford, 2006). Table 1 presents an overview of the incentive scenarios considered in this simulation effort. Two levels of incentives are tested: \$0.50 and \$1.50 per eco-trip (trip made using an eco-vehicle) to the low emission zones, with an annual cap for each of the incentive levels. 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. In the Greater Phoenix region, current travel survey data (including the National Household Travel Survey supplement) suggests that the current penetration of eco-vehicles 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 *eco-vehicle* category as designated for this analysis. 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, 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. The expected outcome of such an incentive only scenario is higher but cleaner vehicle miles of travel (VMT), as this policy will encourage purchase and utilization of ‘cleaner vehicles’.

Table 1. Incentive values and eco-vehicle market penetration.

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

Next, in addition to the incentive policy, transit service is enhanced to LEZs with an intent to encourage modal shift to transit for non-eco travelers. This market segment represents the majority of travelers in the region (95%) even under the assumption of an aggressive market penetration of eco-vehicles. In order to reduce the emissions from personal travel of this segment, an ‘attractive’ transit option is provided. Table 2 presents further details on the scenarios which are 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 (ET) service. Thus, the incentive level can be combined with no enhancements to transit, implying that current regular transit (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 doubled when compared with 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.

This enhanced transit service is available to all travelers alike, with an expected higher impact on the non-eco traveler segment. 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 utilize their eco-vehicles for travel to and from 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 enhanced transit service, but it is possible that a small number of eco-vehicle travelers may also choose to ride the ET service, depending on the competitive travel time/cost advantage (if any) that ET service may provide.

Table 2. Incremental Scenario Development.

Scenario Label	Incentive (\$)	Transit	Scenario Description	Eco-Vehicle Penetration
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%

The incremental scenario development approach allows the clear identification of the benefits of an incentive only policy versus a combination of policies. Such an incremental scenario based analysis approach provides decision makers with a variety of options, enabling the identification of policies that cater to the region's environmental as well as financial goals.

5. Modeling Results

This section presents modeling results for the LEZ scenarios, conducted through repeatedly exercising and running the integrated travel model system for all of the 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. The results of the policy simulation exercise are provided in this section. The first sub-section presents a series of disaggregate trip-level, tour-level, and person-level outputs. In the second and third sub-sections, key highlights with overall summary measures of travel and emissions are presented, respectively.

5.1. Activity-travel pattern of an individual

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 policy, a random individual was isolated in the synthetic population and the person's activity-travel patterns were examined before and after the implementation of a LEZ scenario. The individual became an eco-traveler (eco-vehicle owner) after the implementation of the LEZ scenario and has a residence that is in reasonably close proximity to the LEZ area, as depicted in Fig. 4. This individual is employed, 56 years of age, and a single female. 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.

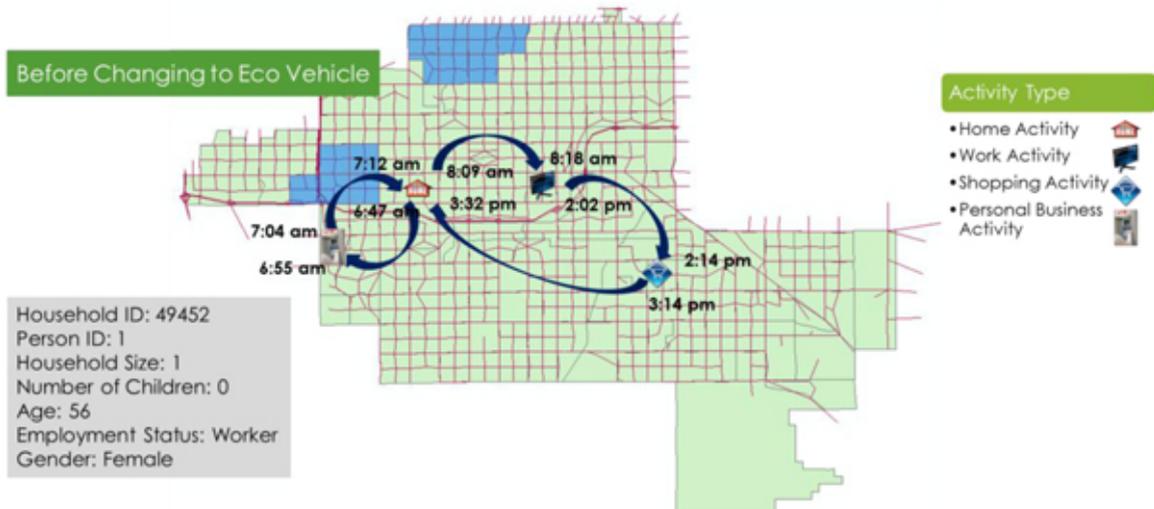


Fig. 4. Activity-travel pattern of random individual before LEZ scenario implementation.

Fig. 5 shows the new activity-travel pattern that the individual adopts after implementation of the LEZ scenario.



Fig. 5. 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).

5.2. Summary measures of travel

Table 3 presents aggregate travel characteristics for the population of the sub-region considering all travelers (i.e., both eco- and non-eco-travelers). Travel characteristics are output and furnished in the table for the approximately quarter-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 predicted 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 unnecessary for this study 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.

Table 3. Aggregate travel characteristics for all travelers.

Indicator	Baseline	\$0.50, RT	\$1.50, RT	\$0.50, ET	\$1.50, ET
Population	252,999	252,999	252,999	252,999	252,999
Total trips	1,135,899	1,136,401	1,135,487	1,126,034	1,129,877
Total auto trips	1,086,515	1,086,702	1,086,544	1,050,424	1,055,352
Total transit trips	49,384 (4.3%)	49,699 (4.4%)	48,943 (4.3%)	75,610 (6.7%)	74,525 (6.6%)
Total travel distance (miles)	7,781,422	7,792,089	7,790,525	7,756,704	7,800,878
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

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 in 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 less 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.

5.3. Measures of energy and emissions

The reduction in energy consumption and emissions relative to the baseline scenario is presented in Fig. 6. The figure 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 scenario (with RT service). The impacts (reductions) 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 seven percent of the zones yields a 1.5-percent to 3-percent reduction in energy and emissions with no enhancements to transit and a 3-percent to 5-percent reduction in energy

and emissions with significant investments in transit. These reductions are certainly context dependent, with the level of reductions sensitive to the magnitude of the incentive, the nature of the built environment, current activity-travel patterns, and socio-economic and demographic characteristics. These reductions were realized with modest incentives of \$0.50 per trip and \$1.50 per trip, with 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.

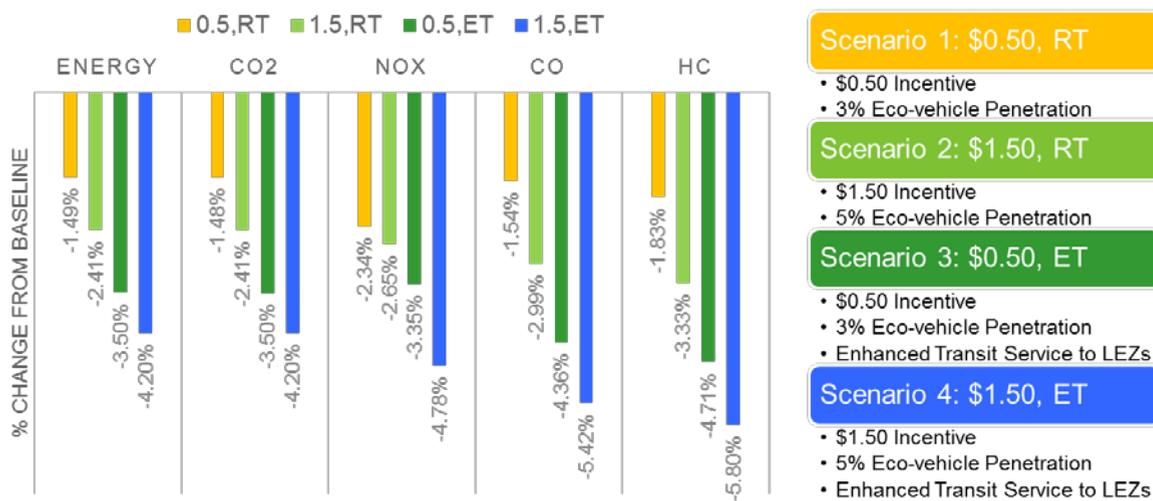


Fig. 6. Reduction in energy and emissions resulting from LEZ scenario implementation.

6. Implications for Research/Policy

This paper describes the application of a new integrated microsimulation model system 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 arising from the introduction of low emission zone (LEZ) scenarios. The integrated model system is capable of reflecting impacts of policy actions in a behaviorally robust framework. The modeling framework and approach is flexible and offers the potential to advance modeling practice in agencies around the world. Moreover, the empirical results of the application of the model to LEZ policy analysis shed light on the impacts of low emission zone policies of different levels on activity-travel behavior and the social equity implications of such policies. The results may be used to help inform policy makers who are contemplating the implementation of low emission zone strategies.

Based on the results of this research effort, it is found that: 1) LEZs may experience a small increase in travel demand resulting from induced travel effects because of the incentive policy. Travelers who have access to eco-vehicles may choose to travel (sometimes farther) to LEZs to take advantage of the incentive policy. 2) Regular zones not subject to the LEZ also experience reductions in energy and emissions because of trip-chaining effects and higher eco-vehicle penetration levels, thus presenting substantial secondary benefits that go well beyond the confines of the LEZs. 3) It was found that an effective low emission zone policy is a combination of incentives for eco-vehicles *and* enhanced transit services to attract non-eco vehicle travelers. It was found that transit enhancements amplified the emission reductions realized from the deployment of a low emission zone policy. This is an intuitive finding, as transit enhancements aim to induce mode shifts particularly among non-eco travelers, thereby contributing to higher emission reductions. Overall, a 3% to 5% energy and emission saving is realized at modest levels of eco-vehicle penetration coupled with enhanced transit services. Pricing or penalizing heavily

polluting vehicles would offset the cost of incentivizing eco-vehicles to some extent, and is a scenario that is worthy of further consideration.

The low emission zone policy tested in this effort is static in nature (fixed zonal boundaries, fixed incentives by time of day), but the concept of low emission zones may be treated as dynamic, where any set of zones can be geofenced during specific times of day with an intent to improve air quality within the designated area. The incentives/tolls in the low emission zones can also be dynamic in nature and the integrated model system described is fully capable of accommodating such dynamic strategies and their impacts on travel.

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