USE OF STATEWIDE MODELS AS A DECISION TOOL FOR ZERO-EMISSION VEHICLES DEPLOYMENT

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ABSTRACT

Under worldwide environmental stress, zero-emission vehicles (ZEV) are rapidly coming to market. However, it is not clear how such vehicles reduce vehicular emissions at a spatially explicit level, which is crucial for developing specific policies. This study proposes a quantitative approach to estimate the effectiveness of ZEVs in reducing emissions in order to support investment decisions promoting the usage of ZEVs. The approach utilizes existing statewide travel demand and mobile emission models in an integrated framework. Scenarios are designed to measure the emissions reduction effects of ZEVs at different spatial scales (statewide, county, roadway) and characteristics (densely and sparsely populated counties) and with various levels of market penetration and driving range limits. The results show significant spatial differentiation of the impact of ZEV deployment from county to roadway levels. Offering greater spatial detail and new insights on decision-making process, this study describes an integrated tool for identifying effective strategies for ZEV implementation.

Keywords: Mobile emission; Zero-emission vehicles; Travel demand model; Scenario analysis; Market penetration; Range limits
1. INTRODUCTION

Accounting for a large fraction of total air pollution emissions, transport sector has been recognized as a major target for emission reduction efforts both in the U.S. and international arena (1-4). To reduce transportation-related emissions, the electrification of vehicles has been recommended by the U.S. Department of Energy (DOE) as one of the highest impact reduction strategies (5). The term Zero Emission Vehicles (ZEVs) was first introduced by California as part of its Low Emission Vehicle Program in 1990 (6). The California Air Resources Board (CARB) uses the term to define vehicles that produce no emissions from the on-board power source (e.g., plug-in hybrid electric vehicles (PHEV), fully electric battery-powered cars (BEV), hydrogen-powered fuel cell vehicles, liquid nitrogen vehicles, and solar powered cars) (6-8). Since the term was initially coined, new generations of affordable and high-performance ZEVs have quickly come to the market (9-10).

Following the initiative in California, the governors of seven other states (Maryland, Connecticut, Massachusetts, New York, Oregon, Rhode Island, and Vermont) signed a memorandum of understanding (MOU) committing to coordinate their actions for successful ZEV programs on October 24, 2013. They then established a ZEV Program Implementation Task Force to accomplish the goals of the MOU. As part of this Task Force, Maryland also committed to deploying at least 3.3 million ZEVs and providing adequate fueling infrastructure collectively within these states by 2025 (11). Other actions include establishing a research agenda, reporting the number of registered ZEVs, the number of public electric vehicle supply equipment (EVSE) and hydrogen fueling stations, and available information regarding workplace fueling for ZEVs on an annual basis.

While regulations aim to promote ZEVs, the impacts of ZEVs on overall emissions, particularly on the spatial distribution of hazardous criteria pollutants from mobile sources has yet to be explored, which is crucial for policy development and decision making. Of the limited studies, ZEVs have been found to potentially reduce greenhouse gas (GHG) emissions (in terms of carbon dioxide equivalents, CO$_2$Eq, which mainly consists of carbon dioxide, CO$_2$, methane, CH$_4$, nitrous oxide, N$_2$O, and fluorinated gases) by up to 60% under ideal conditions (12). A few other studies have arrived at similar conclusions with GHG emission reductions, ranging from around 20% to 60% depending on how the electricity that powers ZEVs is generated, which includes coal, natural gas, wind, and nuclear energy (10,13-15). However, a much more detailed analysis is needed to know where the deployment of ZEVs could generate the most benefit, particularly regarding the spatial variation of criteria pollutants (i.e., carbon monoxide, CO, nitrous oxides, NOx, particulate matters, PMx, sulfur dioxide, SO$_2$, ground level ozone, O$_3$ and lead, Pb) that are hazardous to public health; and how these benefits are spatially distributed in the area of concern. One of the main benefits of ZEVs is the opportunity to reduce population exposure to harmful criteria pollutants (12). For example, Skerlos and Winebrake (16) examined the impact of PHEV tax credits finding the credits would be more effective in reducing criteria pollutants if geographically targeted where PHEV technology offers maximum emission reduction. Recently, Holland et al. (17) found considerable spatial variation in the environmental benefit of ZEVs and the vast majority of environmental external benefits from driving a ZEV in one location spill over to many other locations.
This paper proposes a quantitative approach to estimate the effectiveness of ZEVs to assist policy and investment decision making that promotes ZEVs, in the state of Maryland. We developed a modeling platform that integrates a statewide transportation model, the Maryland Statewide Transportation Model (MSTM), and Environmental Protection Agency’s (EPA) MOVES model (18). Evaluation results are summarized in terms of vehicle miles traveled (VMT), vehicle hours traveled (VHT), and the resulting GHG emissions (carbon dioxide equivalent (CO₂Eq)) and criteria pollutants (nitrous oxides (NOₓ) and volatile organic compounds (VOC) as ground-level ozone precursors).

The paper is organized as follows: studies on ZEV adoption and impacts on emissions are reviewed in Section two. Section three presents the details of the methods we developed to incorporate ZEV analysis capability into the Maryland Statewide Transportation Model (MSTM), which can be used in any four-step modeling framework without loss of generality. A set of scenarios is described in Section four designed to illustrate the impacts of ZEVs at different geographic locations (i.e. counties with different socio-demographic characteristics), scales (from statewide to roadway) and with various levels of market penetration and range limits of ZEVs. Conclusions and policy implications are discussed in the final section.

2. BACKGROUND

Existing literature on ZEVs mainly focuses on two aspects: ZEV market/adoption forecasting and the associated emission reduction evaluations. Many studies have been conducted on modelling the likely adoption of ZEVs based on market diffusion models (10,19,20), consumer choice models (21-23), and agent-based models (9,24,25). One of the latest reviews on the state of the art in ZEV market forecasting is made by Al-Alawi and Bradley (26), providing a comprehensive comparison among existing forecasting methods and the estimated ZEV penetration rates. Although most of these studies concluded that internal combustion engine vehicles (ICEVs) will continue to dominate the automobile market in the immediate future (due to the higher initial cost of ZEVs and limited charging infrastructure), these studies also indicated that under the right conditions (e.g., technology advancement and preferential policies), the introduction of ZEVs is a very promising strategy to significantly decrease transport emissions. Nonetheless, specific forecasts of future ZEV penetration rates in the literature vary widely (ranging from ~3% - ~60%) (22,26-28). Prediction variation arise from the differences in local conditions, data sources, modeling assumptions and methodologies as well as uncertainties in the development of technology and regulations regarding ZEVs.

Many studies have focused on estimating the aggregate environmental impacts of ZEVs from a life cycle perspective including emissions produced by electricity generation (10,14,21,29,30). The results vary from location to location depending on the source of electricity, ZEV market penetration, and the usage of ZEVs. In general, it is widely recognized that ZEVs contribute to emission reductions even in electricity systems with a high fraction of fossil fuel generation, due to the high efficiency of electric motors over internal combustion engines (31).

The aggregate life-cycle studies, however, have not considered the spatial impacts of ZEV deployment on the network, which becomes an increasingly important basis for area-specific environmental policies analysis (17,32). Embedding ZEV trips into travel demand models (macro or micro simulation models) enables researchers to conduct
spatially disaggregated analysis that can help decision makers to weigh policy alternatives. A number of studies have incorporated mobile emission models with travel demand simulation models, e.g. Namdeo et al. (33) and Nejadkoorki et al. (34) in UK, Affum et al. (35) in Australia, Potoglou and Kanaoroglou (36) in Canada, and Goulias et al. (37) and Wei et al. (38) in USA. However, studies that take ZEVs into account under this integrated modeling framework are still quite limited. Based on microscopic traffic simulation results, Xie et al. (39) aggregated a percentage of vehicle fleet as ZEVs in MOVES and estimated emission impacts for a segment of freeway in Greenville, South Carolina. Using both macroscopic and microscopic travel data Amirjamshidi et al. (32) examined the spatial emission dispersal of medium duty diesel truck and ultra-low emission vehicles, and found that higher pollutant concentrations occur along high capacity roadways (e.g., freeways) in the Toronto Waterfront Area. Cho and Hu (40) applied freight travel demand models to analyze the spatial impacts of hybrid trucks on zero-emission lanes of I-710 in California. They illustrated that the emission impacts of freight traffic vary significantly across ZIP code areas as well as among alternative policies (40). These successful advancements demonstrate the necessity and informative value of applying integrated traffic simulation and emission models rather than conventional aggregated models for a more detailed environmental analysis of ZEVs.

3. METHODOLOGY
An integrated modeling platform that includes two main components, the Maryland Statewide Transportation Model (MSTM) and the MOVES model, is developed for this analysis. The MSTM is a multi-layer model that works at regional, statewide and urban levels, and uses a traditional four-step travel forecasting process with the addition of a time-of-day model which divides trips into four time periods, morning (AM), mid-day (MD), evening (PM) and night time (NT) (41). MOVES was developed by the Environmental Protection Agency (EPA) to estimate mobile source (primarily highway) emissions by using data on climate, fuel economy, and many other variables to develop emission factors. The modelling platform, the Mobile Emissions Model (MEM) (18), integrates the MOVES with the MSTM model. The MEM calculates total emissions by applying emission rates calculated by the MOVES model to the MSTM-produced trip tables and data about travel on links i.e. VMT, speed, and other factors for each network link to estimate the emissions associated with mobile sources. Note that life-cycle emissions i.e. emissions from generation sources such as electricity generation in power plants and distribution or emissions from gasoline production and distribution to refueling stations are not considered in this study (assuming independent with ZEV deployment). Also, we only considered passenger automobiles as ZEVs in this study, which will be extended to include trucks in our future studies.

To model ZEV trips, we assume that the travel behaviour of ZEV users will not show a significant difference compared to the users of conventional internal combustion engine vehicles (ICEV) (42, 43). This assumption may not precisely mirror the differences between the charging behaviour of ZEVs and ICEVs in the real world, i.e. longer charging times and shorter driving range of ZEVs. However, the context of this study, using a statewide transportation model primarily for high-level policy analysis tool rather than for operational purposes, does not require such detail. For example, modelling
charging/refuelling behavior of ZEVs and ICEVs at charging points and gasoline stations. The ZEV analysis capability is developed within MEM platform in the following steps:

Step 1: Define the spatial conditions that identify the locations (e.g., counties) where the ZEVs are deployed. These conditions are defined by restricting origin zones (o) of automobile trips to designated ZEV deployment zones (SMZs- statewide modelling zones) (denoted as O, set of designated ZEV deployment SMZs).

Step 2: Impose driving range limits to ZEV trips. Automobile trips that satisfy the spatial conditions in first step are filtered according to the trip lengths (l) within the ZEV range limits (L).

Step 3: Specify the fleet percentage of ZEVs according to the scenario or exogenous forecast if available. Accordingly, ZEV origin-destination (OD) trips (V_{od}^e) are subtracted in proportion to the given ZEV fleet percentage (p) from the automobile OD trips (V_{od}^g) of all trip purpose and time of the day.

\[ V_{od}^e = p V_{od,l}^g \quad o \in O, l \leq L \]  
\[ V_{od}^g = (1 - p) V_{od,l}^g \quad o \in O, l \leq L \]

where equation (1) extracts ZEV trips from filtered automobile OD trips; and equation (2) updates the OD trip tables to obtains ICEV trips.

Step 4: Assign ICEV and ZEV trips to highway network. An equilibrium model is established to represent the state that no traveler can gain advantage through a unilateral change of his/her route choices:

\[ \left\{ v_{od,r}^m \left( T_{od,r}^m - \min_r \left( T_{od,r}^m \right) \right) = 0 \right\} \]

\[ T_{od,r}^m - \min_r \left( T_{od,r}^m \right) \geq 0 \]

where \( v_{od,r}^m \) is the volume (person/hour) of travelers of type \( m \) of vehicles (i.e., ICEV and ZEV, \( m \in \{g,e\} \)) on route \( r \) between origin-destination pair \( od \); and \( T_{od,r}^m \) denotes the route travel time.

Step 5: In this step, mobile emissions are estimated. Emission factors obtained from MOVES are applied to the assignment results (e.g., vehicle-miles travelled (VMT), congested speeds, and road types) obtained from the previous four steps. Ultimately, emissions are summarized for multiple scales, i.e., statewide, county, and roadway levels.

### 4. SCENARIO ANALYSIS

#### 4.1 Background

This study focuses on the deployment of ZEVs in the state of Maryland (Figure 1). Maryland has been very proactive in identifying strategies that can reduce greenhouse gas emissions (GHG) from mobile sources such as encouraging fuel-efficient and low-emission vehicles. To facilitate and promote the utilization of electric vehicles (EVs) in the State, an Electric Vehicle Infrastructure Council (EVIC) was established in 2011 and has successfully initiated several projects in collaboration with the Maryland Department of Transportation (MDOT), Maryland Transit Administration (MTA), Maryland Public...
Service Commission (PSC), and local governments (44). According to a recent EVIC report (44), there are 5,544 registered PEVs and 611 charging outlets at 250 locations throughout the state.

In this study, the ZEV deployment analysis is conducted for a typical weekday in the year 2030 with socio-demographic data derived from multiple sources such as the Baltimore Metropolitan Council (BMC), Metro Washington Council of Governments (MWCOG), and Census-based population forecasts (41).

4.2. Scenario Design
Scenarios were designed to illustrate the impacts of ZEVs at different geographies and various levels of market penetration and driving range limits. Two scenarios were developed; low and high market penetration scenarios with 20% and 60% ZEVs in the vehicle fleet, respectively. We determined market penetration levels for each scenario based on the literature discussed in Section 2 (10,27,45). These penetration levels are assumed to reflect various realizations of the technological developments in vehicle technology and infrastructure deployment as well as socio-economic factors that affect the adoption and usage of these technologies. For instance, it is expected that the high penetration ratio in the neighborhood of 60% could be reached in some forecasts under ideal conditions (27). For the driving range values, we not only took into account the vehicles’ technical characteristics such as how far it can travel with a full tank or fully charged battery, but also driving behaviour and trip purpose of the users (14, 46).

Since widely available ZEVs are currently electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) (assuming they run on all-electric mode), the range limits are incorporated in the scenario design to reflect these available vehicles’ ranges (42). With the rapid development in battery technology, the driving ranges of EVs and PHEVs in the current market is around 60-150 miles for EVs (up to 300 miles for particular vehicle models) with a full charge, and 10-50 miles for PHEVs on all-electric mode (8,42). The actual driving range of ZEVs, however, is not only determined by the battery technology
limits but also by factors including: (i) vehicle population distribution (e.g., age and vehicle model of ZEVs) in the planning year, which would significantly affect the average driving range; (ii) range anxiety of ZEV drivers, who would prefer not to drive the vehicles to the range limit but leave some safety buffer (47); and (iii) driving conditions, e.g., congested urban area with dense intersections generally cause a decreased all-electric range. Thus, two scenarios are designed in this study with low and high driving range settings to reflect BEV and PHEV all-electric mode ranges, respectively. The low scenario adopts a driving range of 30 miles for ZEVs that can be assumed PHEVs on all-electric mode, or BEVs which may be mainly used for commuting when the access to charging facilities is limited (12, 42, 48). In the high scenario, range is assumed unlimited (or rather comparable to ICEVs) and it is assumed that the fast charging facilities are installed widely across the study area and with the improvements in battery technology, ZEVs become a perfect substitute for ICEVs for all driving activities.

4.3. Scenario analysis

Figures 2(a) and 2(b) illustrate the travel patterns of ZEV deployment under two market penetration levels. ZEVs in the high scenario spread more widely across the network than in the low scenario. The majority of ZEV trips are concentrated in urban areas (e.g., Baltimore City and Frederick City) and along major corridors (e.g., I-270, I-95).

(a) Low scenario - 20 percent market penetration, 30 mile driving range
As emission impacts can differ by geographic area depending on ZEV driver travel patterns, we conduct our analysis at multiple geographic scales: statewide, county, and roadway facility type, for better policy guidance and decision making.

### 4.3.1 Statewide level

Table 1 summarizes the statewide network performance under the base case and two ZEV penetration levels in terms of VMT (of all vehicles), zVMT (VMT by ZEVs), and resulting emissions (including CO2Eq, NOx, and VOC).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base case</th>
<th>Low</th>
<th>High</th>
<th>Percentage changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>VMT (million)</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>zVMT (million)</td>
<td>0</td>
<td>4.10</td>
<td>16.81</td>
<td>-</td>
</tr>
<tr>
<td>CO2Eq (ton/day)</td>
<td>103,225</td>
<td>93,062</td>
<td>63,459</td>
<td>-9.3% 38.5%</td>
</tr>
<tr>
<td>NOx (ton/day)</td>
<td>495</td>
<td>450</td>
<td>313</td>
<td>-8.5% -36.7%</td>
</tr>
<tr>
<td>VOC (ton/day)</td>
<td>61</td>
<td>54</td>
<td>36</td>
<td>-10.5% -40.7%</td>
</tr>
</tbody>
</table>

Total VMT remains unchanged for the scenarios; this results from the assumption that driving characteristics of ZEV users (e.g., destination choice, route choice, and trip length) are not different than the non-ZEV users. Although the relaxation of this assumption is among our future research plans, our current implementation gives valuable information on order of magnitude. Considering driving range limit also gives an approximation for the travel behavior representation. The zVMT increases more significantly than the increment of ZEV fleet percentage (i.e., 20% to 60%) from low to high scenarios likely due to the increased range limits (from 30 miles to unlimited). Total emissions in the base case consist of CO2Eq (103,225 tons/day, accounting for 99.5%),...
NOx (495 tons/day, accounting for 0.4%), and VOC (61 tons/day accounting for 0.1%). The CO$_2$Eq emissions drop by approximately 9.3% in low scenario, and 38.5% in high scenario. ZEVs produce the largest changes in VOC, while NOx reductions show a smaller change. Note that compared to the high market share (60%) of ZEVs, the zVMT accounts for a relatively low portion ($\frac{16.81}{200} = 8.4\%$) of all VMT in high scenario; this is due to (i) ZEVs are assigned to passenger vehicles only not including freight vehicles and (ii) ZEVs are implemented within the state of Maryland whereas MSTM covers long-range VMTs in/across the states of Delaware, Washington DC, and selected areas in Pennsylvania, Virginia and West Virginia.

In addition, based on the zVMT information, one can also estimate statewide fuel consumption reduction and electricity consumption due to ZEV deployment. For instance, given fuel consumption rate for ICEVs is 0.04 gallon per VMT (50), the estimated fuel consumption reductions are 0.16, and 0.67 million gallons per day for low, and high scenarios, respectively. It is also possible to approximate the increase in electricity consumption in each scenario with the assumptions that ZEVs are powered by electricity and a ZEV consume 0.3 kwh per zVMT on average (adopted from the estimates by DOE (51)) as 1.23 and 5.04 million kwh per day. These estimations are useful for decision makers in assessing not only tail pipe emissions effects but also effects regarding the energy source of ZEVs, which may impact the policy decisions significantly (30).

### 4.3.2 County level

At the county level, results are reported in Figures 3 (a) and (b). Figure 3(a) depicts percent of total Maryland emissions in each county. Note that since the majority of the emissions are CO$_2$Eq, we used this measure for reporting and visualizing the results in our analysis. The results show that the majority of the statewide emissions come from counties in the Washington-Baltimore Metropolitan area including Baltimore County (accounting for 15.2%), Prince George’s (14%), Montgomery (13.9%), Anne Arundel (8.6%), Howard (7.2%), and Frederick (7.1%). Noticeably, Baltimore City generates 6.3% of total statewide emissions, which is more than Harford (5.2%), a 4.7 times larger area than the Baltimore City. Emissions from other counties contribute less than 5%, and some remote ones (e.g., Garrett, Somerset, and Worcester) produce less than 1% of total emissions.
Although considerable emission reductions are observed for all counties, the amount of change differs from county to county, indicating that the emission changes and the magnitude of change differ at the county for each scenario. Figure 3 (b) illustrates emission reduction per zVMT in different counties. The various emission reduction impacts of ZEV deployment in different counties can be attributed to a number of local factors, such as, congestion level and composition of roadway facilities. Generally, dense urban counties have greater congestion, with more stop-and-go driving. Similarly, due to the varied motion characteristics of vehicles, the amount of VMT on different roadway types (e.g., freeway and arterials) imposes different effects on overall emissions.
In addition, it is noted that the deployment of ZEVs under the high scenario reduces slightly less emission per zVMT than the low scenario for most counties. This marginal effect among scenarios may be attributed to the range extension of ZEVs; longer-range trips may be using roadway facilities (e.g., freeways) that provide higher speeds, thus emitting less.

### 4.3.3 Roadway level

Simulation results are further summarized by roadway classification, as shown in Figure 4. Figure 4 (a) indicates the proportions of five types of roadway facilities with respect to length, VMT, and emissions per VMT. We found that although the length of interstate highways accounts for less than 10% of total roadways, the generated VMT and emissions are significantly higher than other types of roadways. The second largest emission source is arterials, of which major arterials with less length produce more emissions than minor arterials. Roadways of collectors, local roads, and ramps (classified into the group of others) also generate a considerable amount of emissions due to the large scale (i.e., 46% of total roadway length). Least emissions come from freeways and expressways. Figure 4(b) presents emission reductions contributed by different roadway facilities under two scenarios. Major reductions are achieved on interstate highways, major arterials, and others. Particularly, emission reductions on interstate highways are higher and the amount of reduction increases from low to high scenarios.

![FIGURE 4 (a) Emission of different types of roadway facilities, (b) Emissions reduction on roadway facilities under two scenarios](image)

### 5. DISCUSSIONS AND CONCLUSIONS

This study has shown that the ZEVs, if deployed strategically, can play a significant role in reducing GHG and criteria emissions from mobile sources. However, the magnitude of the reduction depends on the area in which the ZEV operates, and roadways they travel. Our analysis showed that ZEVs provide a greater emissions reduction per zVMT in congested urban areas. In deploying ZEVs as an emissions reduction measure, attention should be given first to areas with significant congestion. Although these result may seem intuitive, quantifying the reductions and the range of potential impacts of ZEV deployment (not only at a spatially aggregated level but also with detailed distribution patterns at network, county and roadway level) is useful to decision makers in developing
area-specific, targeted policies in promoting the adoption of ZEVs and improving local air quality. The results suggest several policy implications:

(i) The fleet percentage of ZEVs in future years directly determines the emission reduction effects, while the changes of range limits of ZEVs (whether dictated by the battery technologies of vehicles or travelers’ trip patterns) amplify the emission reduction for short-distance trips but as battery technology improves ZEVs will have similar effects for trips of any length. With limited driving range, policies that target ZEV use for short-distance and high frequency trips (e.g., commuting trips) would have the greatest effect on reducing emissions. For example, policies to encourage on-road usage of ZEVs, such as employee cash out, travel allowances, and reimbursement programs may be effective (7,52,53).

(ii) The variety of emission reduction effects of ZEVs among different counties suggests that when the deployment of ZEVs is governed by financial and political constraints, priority can be given to counties with higher emission reduction benefits, which are typically in dense metropolitan areas. Investments such as charging infrastructure could be implemented in the identified counties and along corridors.

(iii) Roadway level emission analysis suggests that the environmental benefits (regarding the reduction in harmful criteria pollutants) of ZEVs are closely related to roadway types. In conjunction with ZEV ownership incentive policies (e.g., tax credits), operational strategies such as emission pricing, free/lower cost use of HOV/HOT lanes, and parking permits can be used to encourage the usage of ZEVs on interstates, arterials, connectors, and local roads.

(iv) In developing ZEV related transportation policies, further examination of the effects of electricity consumption should also be done in the future based on statewide results. Emissions related to the source of electricity should also be taken into account in addition to the tail-pipe emissions. While ZEVs reduce tail-pipe emissions regardless of the electricity source, electricity generated from natural gas or non-emitting sources such as nuclear or hydroelectric, when combined with ZEVs will have a greater impact on emissions reduction than energy generated through coal or oil.

It is worth noting that the proposed analysis framework can also apply to an analysis of the effects of other low-emission, alternative fuel powered vehicles. The assignment process in four-step travel demand models remains the same with fleet percentage and range limits substituted by that of the new vehicles, and the mobile emission estimation process adds the new vehicle category in MOVES to obtain corresponding emission rates, which are applied to the assignment results and ultimately generate network-scale emission results. In this case, the corresponding driving cycles should be developed to the specific vehicle fleets upon field studies, as documented by FHWA in a case study in Kansas City (54). Further extensions could also include (i) endogenous vehicle adoption model predicting households’ ownership choices of ZEVs or any other new type of vehicles; (ii) integrated module of spatially differentiated policies favoring (e.g., emission pricing) zero- and low-emission vehicles; (iii) since the modeling platform developed in this paper provides link level emissions and pollutant measures, it is easy to extend the research to hot-spot analysis for specific locations such as around schools, hospitals, parks, transit centers and gasoline stations in future studies. Note that such analysis would be meaningful for criteria pollutants as their effects are local and relevant to public health; (iv) inclusion of other modes such as zero-emission
transit vehicles and trucks is also desirable; and (v) to capture disaggregate behavior of ZEVs/ICEVs, the modeling platform can be changed from a trip-based transportation model to an agent- and activity-based model to simulate charging/refueling behaviors of ZEVs/ICEVs at charging points and gas stations (e.g. 55, 56). This would provide a much finer scale spatial analysis capability for evaluating ZEV benefits.

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