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Assessing the contribution of road transport electrification to low-carbon city development using a land use-transport model

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ABSTRACT

Electric vehicles (EVs) are often considered as a promising technology and an attractive solution towards low-carbon future. Thus, it is necessary to model the market penetration of EVs and to detect the role of EV adoption in future urban decarbonization scenarios. This study attempts to develop an integrated land use-transport model to examine the interactions among location choice, land use, transport patterns, energy profiles, and economy when implementing the stringent EV policy. Two scenarios are structured to investigate the long-term (to year 2050) impacts of EV adoption on population distribution, land use patterns, transport demand, energy mix, emission profiles, and social welfare. Scenario simulations show that the energy transition and emission reduction can be realized by the stringent EV adoption. The influences of EV penetration on population distribution, land use changes, and emission intensity draw policy implications for transport engineers and urban planners. More importantly, ambitious market diffusion of EVs exerts significant positive effects on emission reduction in city center, while economic benefits tend to occur in suburban areas, implying that EV adoption plays a special role in the spatial organization and structure of cities. Spatial heterogeneity among zones deserves more attention when evaluating the effectiveness of sustainable urban policies. Since the disaggregated spatial interplays can be handled by this integrated model, such methodology offers a useful tool for sustainable urban planning.

Keywords: transport electrification, electric vehicles, land use, transport, interaction

NONMENCLATURE

Abbreviations

EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IAM	Integrated Assessment Model

1. INTRODUCTION

The ambitions of the Paris Agreement require rapid and massive decarbonization of cities and cities worldwide are becoming agents of climate change mitigation [1-2]. Cities offer some of the best opportunities for decarbonization in few sectors such as buildings, transport, water, and waste [3]. Since urban transport system is one of the sectors that accounts for a huge volume of GHG emissions [4], many countries around the world intend to promote environmentally sustainable transport in hopes of achieving energy-efficient and low-carbon development in cities. However, rapidly growing mobility demand and private vehicle ownership counteract the efforts to reduce the greenhouse gas (GHG) emissions and air pollutants in the regions of large human population such as urban areas. Transport emissions continue to grow, while other sectors decarbonize; thus, the decarbonization of transport sector plays a key role in achieving the target of carbon dioxide-free city.

Transport electrification has been identified as a key strategy to reduce GHG emission [5]. Electric vehicle (EV), which is often considered as a promising solution towards a green future, offers an alternative to conventional internal combustion engine vehicle (ICEV).

The deployment of EVs has been growing rapidly around the world [6], since many governments have been establishing increasingly stringent and ambitious targets in support of EV adoption. Therefore, in the near future, it is not hard to see that EVs could gain a significant market penetration, especially in the city [7]. Since a few of integrated assessment models (IAMs) provide an elaborate representation of transport sector [8-11], the representations of technology improvement and consumer's preference for EVs have been incorporated into global or national IAMs in an integrated manner. However, although IAMs present advantages on analyzing the impacts of mitigation strategies on climate changes, it is hardly to describe the responses of transport system to the urban structure, land use, and location choice at the city scale, and to simulate spatial heterogeneity of impacts on energy consumption and GHG emissions of EV penetration. On the other hand, since the Lowry model developed in 1964, a range of land use-transport interaction models have been applied to urban planning and policy assessment such as ITLUP, MEPLAN, TRANUS, MUSSA, NYMTC-LUM, UrbanSim [12-14], but energy and environmental issues have not been captured in the conventional models.

The objective of this paper is to employ an integrated land use-transport model to examine the interactive mechanisms among location choices, travel activities, energy mix, emission profiles, and economy at the city scale when implementing the stringent EV policy. Model integration of energy system into land use-transport interaction can help enrich the energy representation such as EV diffusion in the urban modeling. Furthermore, it is also possible to investigate how the impacts of EV policies on land use, transport, energy use, emissions, and urban economy are spatially differentiated across zones, since the integrated urban model handles the land use-transport-energy interaction with explicit spatial representations at zonal scale.

2. MODEL

2.1 Model structure

Since urban economics forms its normative theory and framework, microeconomic mechanisms have been taken into account for modeling the land use-transport interaction. In this paper, we develop an integrated land use-transport model in the tradition of partial equilibrium model that explicitly formulates the location choices, land use patterns, and travel activities [15] (Fig. 1). The land use-transport model handles the interplays between land use and transport system through a series of market equilibrium conditions under which the behaviors of economic entities are defined explicitly by utility or profit maximization. In this model, the distributions of population and labor force, land use patterns and transport volumes that attain demand-supply equilibria are determined endogenously. Economic agents like households, firms, landowners demand or supply commodities, land, and transport services, and decide the location where their utilities or profits are the highest among all alternative locations. Location choices decide the spatial distribution of residential and business activities, land use pattern, and the transport demand as well, while the transport cost calculated by modal split, vehicle technology selection, and fuel type would enter the household's budget constraint and firm's profit function, which forms the integration of energy system into land use-transport interaction.

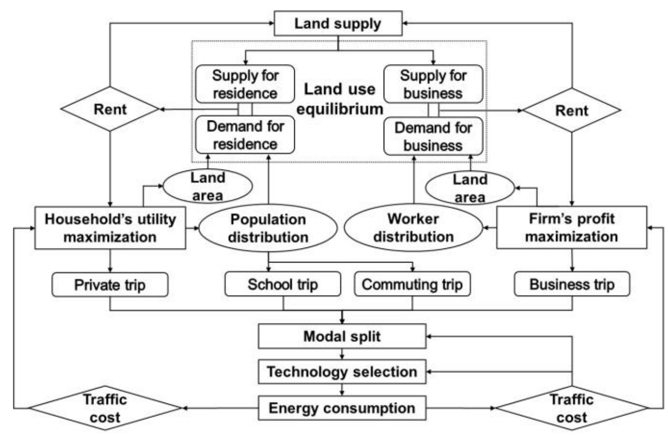

Fig 1 Model structure.

2.2 Data

A case study on Changzhou, China is conducted to investigate the impacts of EV penetration using the land use-transport model. As one of the core cities of the Yangtze River Delta in China, Changzhou is located in the most urbanized and industrialized regions in Jiangsu Province and even in all of China (Figure 2). Data for the parameter estimation and model calibration are mainly collected from the Person Trip (PT) survey in 2008. PT survey divides Changzhou into 6 traffic areas, 40 medium traffic regions, and 438 traffic analysis zones (TAZs). Land use data for all TAZs is processed using ArcGIS 10.3.1 based on a land use map in 2008 obtained from Changzhou Planning Bureau. Socioeconomic data like population, labor force, rent, and wage rate are acquired from Changzhou statistics in 2008. Data for load factor, speed, device cost, fuel price, energy efficiency and emission factors are set based on other relevant studies [16-17]. The integrated modeling in this study is carried out on the basis of 438 TAZs from 2008-2050, with one-year intervals. The model calibration for baseline year 2008 is conducted to make the model predictions such as population distribution, land use patterns, transport demand, and modal structure closer to real evidence in Changzhou.

2.3 Scenario settings

To depict the long-term (to year 2050) energy use profiles and emission trajectories at the urban scale and the impacts of EV adoption across all TAZs, we structured two scenarios in this study: reference scenario (REF) and electric vehicle scenario (EV). In the REF scenario, no stringent policy measures supportive to EV diffusion would be considered, while the EV scenario assumes that the market share of EVs including car, bus, and two wheeler would increase to 70% by 2050 due to city's ICEV ban policy and EV promotion actions. We model the penetration of EVs in EV scenario using a logistic diffusion curve. According to the logistic curve, the adoption of EVs is initially slow owing to technological challenges and then accelerates to 70% by 2050 as the vehicle technology improves. For the underlying socioeconomic conditions like future trends of population, labor force, and wage rate are set based on the Shared Socioeconomic Pathway 2 (SSP2) [18].

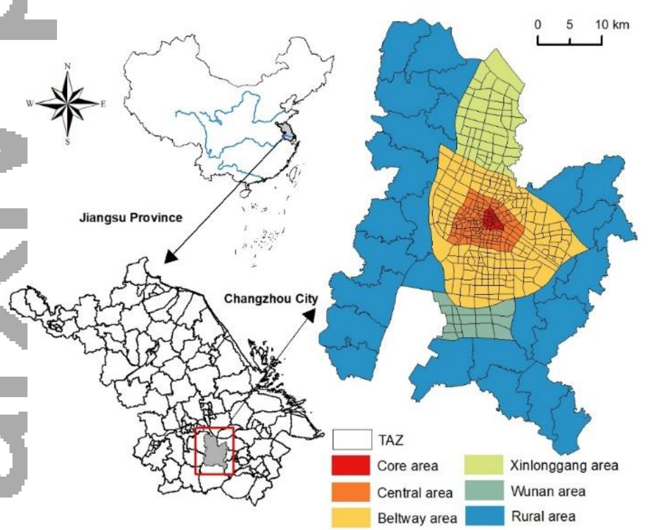

Fig 2 Study area.

3. RESULTS

3.1 Transport demand

As shown in Figure 3a, the total travel demand exhibits upward trends in both REF and EV scenario, as they increased from 3.1 Billon-pkm in 2008 to 5.5 and 5.6 Billon-pkm in 2050, respectively, without and with policy for EV adoption. In the REF scenario, although the travel demand by EVs increased during 2008 to 2050, ICEVs still play important roles in serving the road transport. In consideration of EV policy in EV scenario, the travel demands by electric car, bus, and two wheeler surged to 1.8, 1.5, and 0.6 Billon-pkm in 2050, whereas the demand served by ICEVs fall down to almost 0.8, 0.6, and 0.2 Billon-pkm by 2050. Moreover, compared with REF scenario, the total travel demand rises slightly in EV scenario due to the lower generalized transport cost caused by high market diffusion of EVs, implying that consumers can afford to pay for more transportation services under a certain budget constraint when implementing incentives for EV adoption.

3.2 Energy mix

Figure 3b shows the projected results of total energy demand by mode and fuel type up to 2050. In the REF scenario without EV subsidies, energy consumption required by urban transport sector increased from 89 Ktoe to 156 Ktoe during baseline year 2008 to 2050, with oil continuing to power the vehicles as a dominant contributor. Compared with bus and two wheeler, car travels consume the largest amount of oil, as the oil consumption by ICE car reached 102 Ktoe in 2050 much higher than 40 and 10 Ktoe consumed by bus and two wheeler. EV scenario bought out a substantial change in energy mix that conventional oil fuel no longer dominates the vehicle energy until 2050. Despite the moderate growth of electricity consumption during 2008 to 2050 in REF scenario, dramatically more electricity will be consumed when the targets for the implementation of electrified transport are promoted in the EV scenario. Since EV policy can boost the high electrification rates up for road transport, energy consumed by urban transport increased to a peak value of 127 Ktoe in 2023, followed by a sharp decrease to a relatively stable value of 76 Ktoe in 2050. It implies that strong diffusion of EVs would motivate consumers to choose electrified transport technologies high in energy efficiency, leading a shift from the use of oil to electricity and a transition toward sustainable and energy-efficient urban transport.

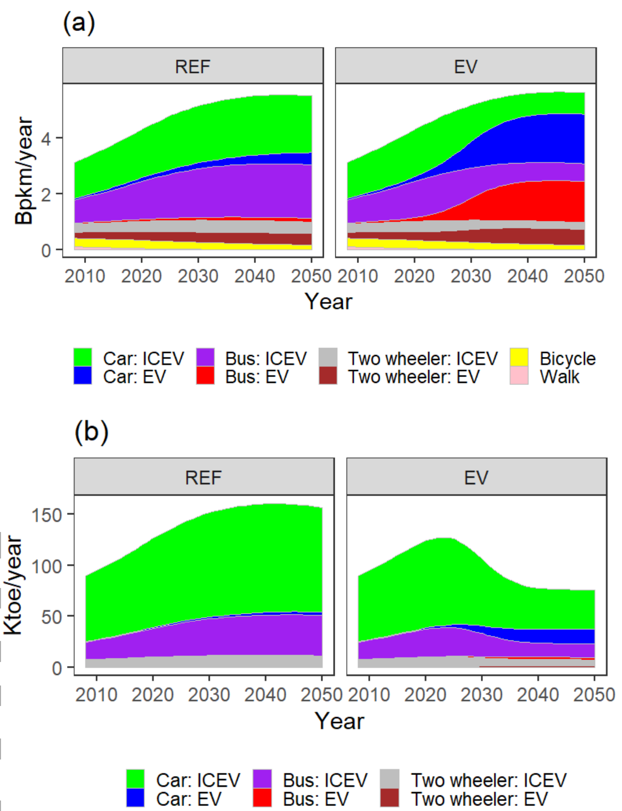

Fig 3 Impacts of EV penetration on the transport demand (a) and energy mix (b).

3.3 Emissions

Figure 4 presents the emission trajectories in two scenarios. In line with the overall trends of the energy consumption profiles, CO_2 emissions in REF scenario would keep increasing from 246 Kt in 2008 to its peak of 436 Kt in 2040 and then decline to 422 Kt in 2050. Although EVs would gradually diffuse into the marker in REF scenario, the vast majority of vehicles are almost powered by the fossil fuel when no supportive EV polices would be carried out, leading to an upward trend in emissions. As a result of changing energy mix and reducing energy consumption, CO_2 emissions in EV scenario might peak up a decade earlier in 2022, well ahead of the peak in REF scenario. The emissions in 2050 would be reduced to 160 Kt and by 62% compared with 422 Kt in REF scenario.

3.4 Welfare

The land use-transport model is developed according to the microeconomic theories in the tradition of urban economics; thus, it can evaluate the EV polices consistently with economic system, particular, with welfare economics and cost-benefit analysis. As shown in Figure 5, along with the market diffusion of EVs, a considerable social welfare in terms of equivalent variation would grow to 2 billion RMB in 2050, implying a positive impact on economic system due to the technological improvement in transport sector.

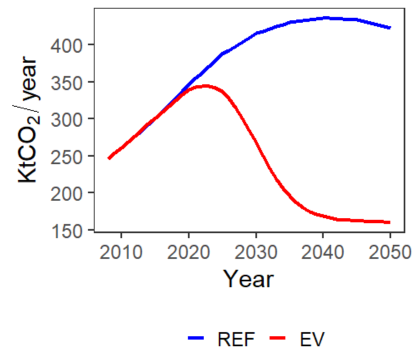

Fig 4 Emission trajectories.

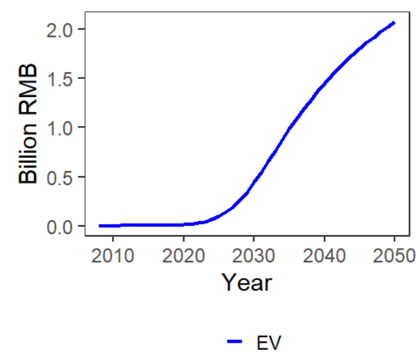

Fig 5 Social welfare.

3.5 Changes in location choices and land use patterns

Figure 6 displays the spatial differentiation on the impacts of EV policy compared with the reference scenario in 2050 across all zones. With the stringent penetration of EVs, population and labor force would migrate from beltway areas to other areas where they can obtain higher utilities or profits. It denotes that the adoption of EVs facilitates both the urban agglomeration in city center and population mobility to suburban areas. Figure 6c and 6d show the changes in land use patterns with EV diffusion. Land for residence and production increased in most of zones across the city except the decreases in beltway areas, which is consistent with the changes in population and workforce distributions. Particularly, remarkable rises in land for residence and production occur in peripheral zones, indicating that EV penetration helps promote the urban land expansion and land use conversion in rural areas. The reason might be more budgets can afford the expenditures of land use because of lower transport cost owing to high diffusion of EVs.

3.6 Spatial differentiations on policy effectiveness

Similar to the changes in land use patterns, transport demand increased significantly both in central and peripheral zones but decreased in beltway areas, implying that the transport demand in city center and rural areas are more sensitive to the lower transport cost. As illustrated in Figure 6f and 6g, the policy effectiveness of EV adoption to mitigate transport emissions varies across different areas. The noticeable emission reduction and decreases in emission intensity was observed in city center and north suburban zones, while south suburban areas have relatively moderate policy effectiveness in emission reduction. In case of large scale EV adoption, high social welfares are mainly concentrated in the peripheral areas, but both northern and southern suburban zones have low values of social welfares (Figure 6h). Spatial differentiation of social welfare highlights that the penetration of EVs can contribute to improving social welfare in rural areas.

4. CONCLUSIONS

In this paper, the integrated urban model, which is consistent with the microeconomic theory, estimates the transport demand, modal split, technology selection as well as energy consumption and the welfare level based on the framework of land use-transport interaction. Energy use and emission profiles are coupled with location choice decision, urban mobility, and land use equilibrium to investigate the influences of EV penetration and how impacts spatially vary across the urban space. Since the disaggregated spatial interplays can be handled by the integrated urban model, such methodology offers a useful tool for transport planning and energy policy making.

Scenario simulations show that the energy transition and emission reduction can be achieved by the stringent penetration of EVs. More interestingly, changes in population distribution, land use, travel demand, energy use, and social welfare associated to EV adoption would vary spatially across zones, indicating that EV deployment plays a special role in the spatial organization and structure of cities. Spatial differentiation on policy effectiveness deserves more

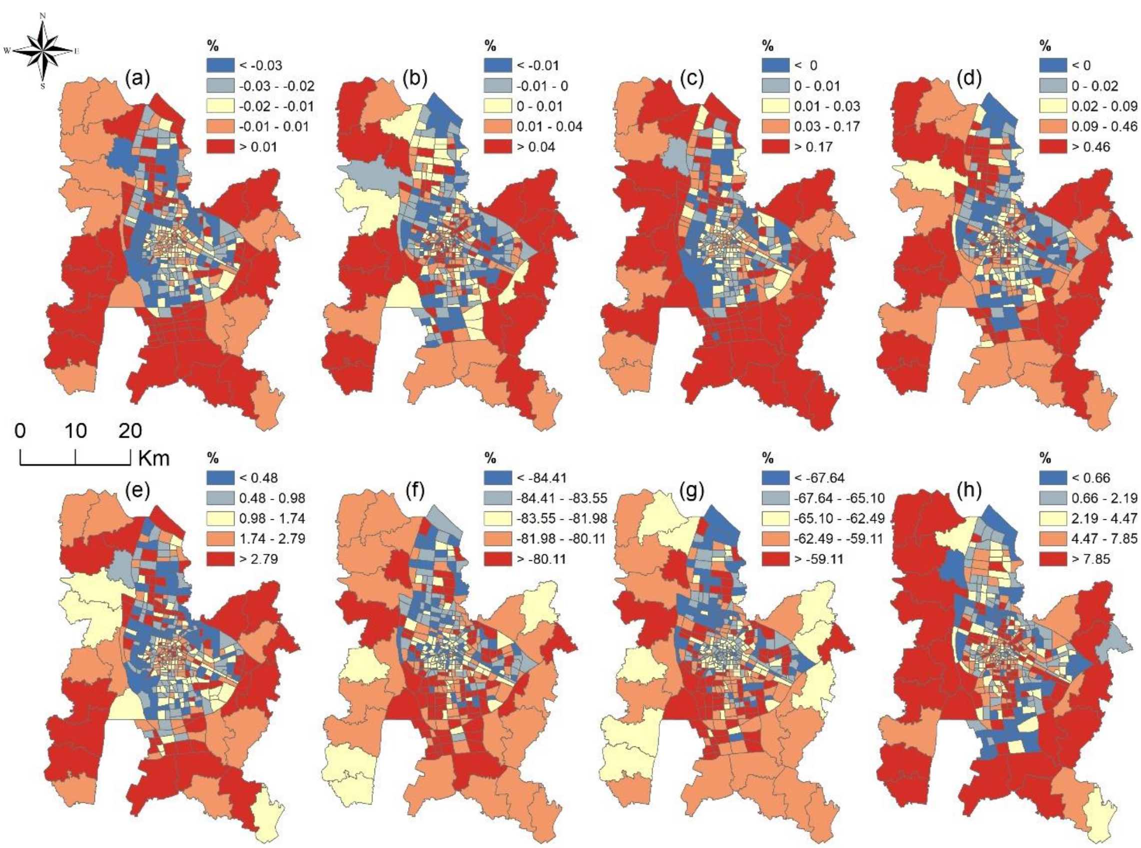

Fig 6 Changes in population (a), labor force (b), land for residential accommodation (c), land for business use (d), transport demand (e), CO2 emissions (f), emission intensity (g), and social welfare (h) between the reference (REF) and electric vehicle (EV) scenarios in 2050.

attention when evaluating the impacts of transport energy policy.

There remain limitations in the current study that could be addressed by future work. Firstly, households and firms that compose the urban economy are assumed to be homogenous and identical with respect to all the relevant characteristics, but it is necessary to classify them into different groups according to education, income, industry types if the detailed data is available. Secondly, the current model formulates the location choice of household based on the indirect utility, without consideration for other determinants such as living comfort and regional environmental quality. Thus, one direction for the future work is to improve the location choice model by including more zone-specific factors. Thirdly, vehicle technologies are currently presented in a simplified form given the lack of reliable data. The long-term impacts of transport electrification policies on the energy use and emission profiles would be more reasonably and accurately projected with considering more detailed EV technologies like hybrid, plug-in hybrid, and battery electric vehicles.

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