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SIMULATING TRANSPORTATION AND ENVIRONMENTAL OUTCOMES OF ELECTRIC VEHICLE ADOPTION SCENARIOS: AN APPLICATION TO THE WINDSOR CENSUS METROPOLITAN AREA

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Introduction

The growth and continuous expansion of Canadian cities over the past six decades increased transportation activities and associated vehicle kilometers travelled (VKT). The upsurge in travel demand not only causes traffic congestion and higher demand for energy, but also impacts the environment through tailpipe emissions. Environment Canada (2014) estimated that Canada will produce 727 megatonnes of carbon dioxide equivalent by 2020. The latter amount will be mainly driven by the oil and gas economic sector (28%) and the transportation sector (23%). While the demand for travel will continue to grow in the future, the dependency on the internal combustion engine (ICE) technology to power vehicles has been an issue of concern. The introduction of alternative fuel vehicles (AFVs), specifically electric vehicles (EVs), is considered as one of the more promising solutions in reducing the demand for fossil fuels and harmful emissions from the transportation sector.

Despite the positive prospects that could be attributed to EVs, their market share has been negligible in Canada with only 18,451 registered EVs in 2015 (Stevens, 2016). Also, little has been done to explore the potential benefits of adopting EVs in Canada. Therefore, this paper devise and simulate the impacts of a number of hypothetical EV adoption scenarios in the Windsor Census Metropolitan Area (CMA), Ontario. The objective is to quantify the reduction in gasoline consumption and tailpipe emissions if a certain portion of the population will own EVs in the near future. We contend that decreasing the demand for ICE vehicles through the choice of EVs is expected to lower the amount of tailpipe emissions and gasoline consumption. However, the expected benefits will be contingent on where EV adoption will occur over space. As such, the conducted analysis will shed light on the relation between electric mobility, urban form and sustainable transportation outcomes.

Included in this paper is a literature review section, which provides an account of the current state of knowledge on the relationship between emission reduction and urban form. This is followed by another section that describes the dataset utilized in the analysis. Next, the results from the conducted simulations are presented and discussed. The final section provides a conclusion and discusses directions for future research.

Literature Review

In recent years, sustainable transportation and its relation to global climate change has been on the top of the agendas of various stakeholders around the world. The main concern is related the negative outcomes that are associated with the ongoing patterns of urban development, namely sprawl, and the increased number and length of daily motorized trips (Handy, 2005). Accordingly, the relationship between urban form and travel behavior has been under scrutiny to curb sprawl and promote smart growth strategies. Kushner (2002) described smart growth as a policy that could be used to steer development towards compactness and restricts further urban expansions. Similarly, Handy (2005) suggested that one of the objectives of such strategies is to limit new developments in rural areas to reduce auto-dependency and long commutes. This concept, which is also known as urban residential intensification (URI), was tested by Behan et al. (2008) in Hamilton, Ontario. The authors utilized an integrated urban model called IMULATE to evaluate the effects of different residential intensification scenarios. Their assessment was focused on various transportation and environmental outcomes such as VKT and tailpipe emissions. This work was extended by Maoh and Kanaroglou (2009) who developed a sustainable sub-module of IMULATE called SUSTAIN to assess progress towards sustainable outcomes under various land use and transportation scenarios.

To date, many studies have been conducted to evaluate the adoption rate of new vehicle technologies, though the methods, scope, and assumptions vary among AFV demand studies. The works of Potoglou and Kanaroglou (2008a), and Al-Alawi and Bradley (2013) provided extensive review on studies regarding potential AFV adoption in recent years. The former focused on different disaggregate automobile demand models such as car ownership models, vehicle-type choice models, vehicle-holdings models, and vehicle-transactions models. The authors also discussed major advantages and disadvantages of revealed and stated choice data for AFV demand. Likewise, the review of Al-Alawi and Bradley (2013) was focused on studies that have used consumer choice models, as well as other complex modelling techniques such as agent-based and market diffusion models, in order to synthesize improved AFV market forecasting. The authors also provide recommendations for improving the effectiveness of the reviewed studies to help stakeholders with their decision making.

There are also studies that explored the interaction between urban development and new vehicle technologies. For example, Hankey and Marshall (2010) predicted plausible urban expansion scenarios for 142 US cities in 2020, and estimated the GHG emissions from private vehicles under these scenarios via Monte Carlo simulations. The authors also tested a scenario where a substantial number of hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) replace ICE vehicles. It was found that complete infill urban form (i.e. constant area distribution) will result in the lowest VKT growth in comparison to the other simulated scenarios. In addition, when complete infill is coupled with significant HEV and PHEV market shares, GHG emission is expected to reduce by about 25% in 2020 relative to the year 2000. A similar study by Zahabi et al. (2013) was conducted in Montreal, Quebec to evaluate the effects of urban form, transit supply, and emerging green technologies on GHG emissions at the household level. The authors estimated GHG emission through a framework that makes use of various datasets, such as travel survey and transit ridership data, and modeling tools like traffic assignment models. Results suggested that improved transit accessibility and passenger vehicle fuel economy provide the greatest GHG reduction.

Our study builds on the existing literature found on the relationship between urban sustainability and AFV demand with an application to Windsor CMA. Reduction in emissions, VKT and energy consumed are considered as the primary performance and environmental measures to assess plausible urban development patterns in conjunction with the adoption of electric vehicles.

Data and Methodology

The Windsor CMA, for which the analysis is performed, is a midsize urban region in the southwestern part of the province of Ontario, Canada. The CMA covers a total area of 1,022 square-kilometers and had 319,246 people in 2011 (Statistics Canada, 2012). As the capital of the automotive industry in Canada, the Windsor CMA grew to depend on the automobile as its primary mode of transportation. The majority (92%) of work trips in the region are conducted by auto (86% auto-drive and 6% auto-passenger), while only 3% make use of public transit. The CMA has evolved to have a number of major highways and freeways that facilitate the mobility of local and through traffic. Moreover, urban sprawl has become more evident in recent years due to the emergence of residential development in suburban areas (Maoh & Tang, 2012).

The population data used in the analysis are based on the projections presented in Gingerich et al. (2014). The Windsor CMA was divided into three main parts: the central business district, inner suburban and outer suburban areas (Figure 1). A multinomial logit (MNL) model was specified and estimated for each area to estimate the probability of developing new dwellings in certain census tracts (i.e. zones), as well as the future spatial distribution of new dwellings at census tract level. The projected new dwellings distribution was subsequently associated with the future population in each zone. Table 1 presents the predicted totals per simulation period.

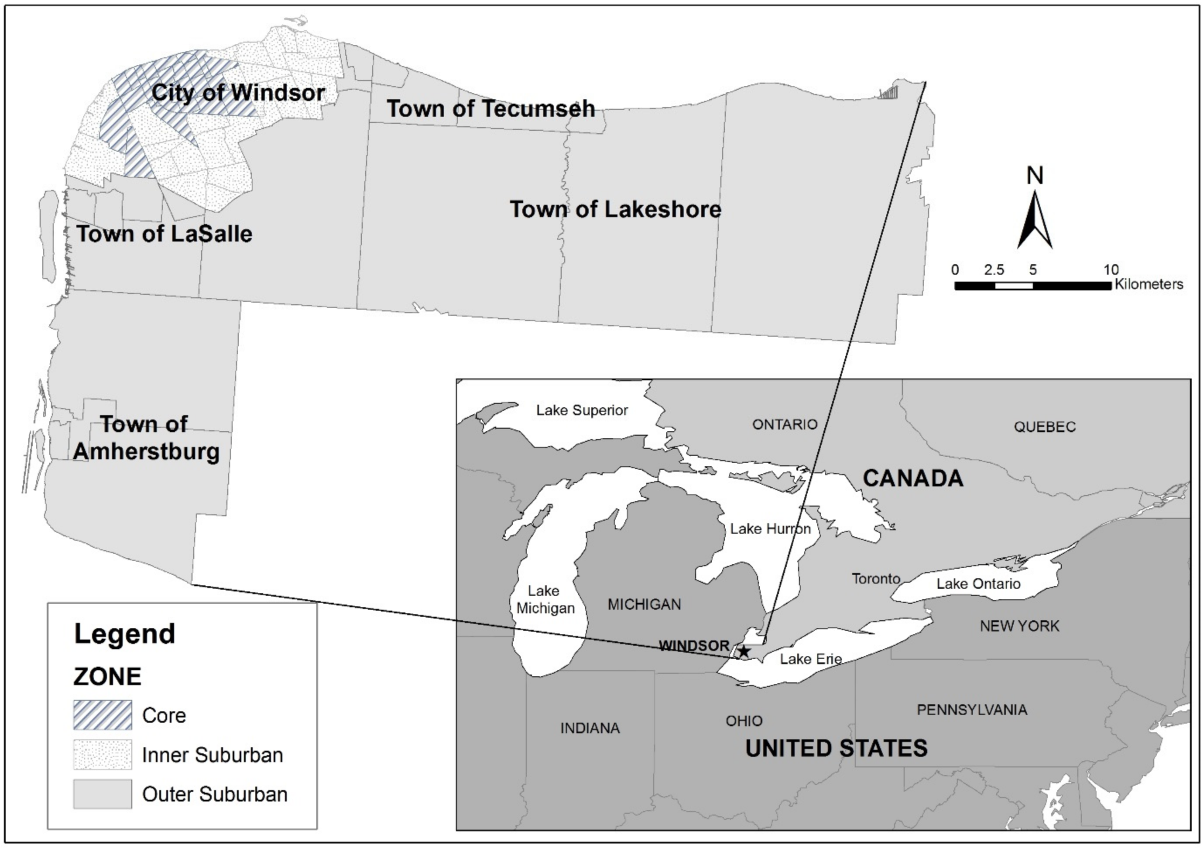


Figure 1. Windsor Census Metropolitan Area

Table 1. Projected dwellings, population and employment figures for 2011 – 2031

	2006*	2011	2016	2021	2026	2031
New Dwellings	11,330	13,317	14,887	16,458	18,028	19,599
Population	323,342	357,564	395,822	438,110	484,434	534,792
Jobs	162,180	141,120	147,214	155,461	165,397	179,428

** Values for 2006 are observed*

Next, the vehicle related data were obtained from R.L. Polk and Company for the year 2010. The total number of registered vehicles in the CMA is found to be 199,436, where each vehicle was georeferenced to its respective census tract. The future number of vehicles per census tract is predicted in proportion with the projected population. This approach provides a simple yet intuitive approach for the notion that the increase in population will lead to a direct increase in the number of vehicles. The summary of the estimated number of vehicles for the various simulation periods is shown in Figure 2. The estimated vehicles per census tract is then used to estimate an origin-destination trip matrix for the 4 -5 pm period of a typical weekday. The data used in this exercise were based on 2011 trip productions and attractions that were estimated for the study area. To be able to calculate the origin-destination matrices for ICE vehicles and EVs, linear regression models were estimated to predict the total O_i and D_j at the zonal level for the year 2031 as a function of total number of vehicles V_i. The two linear equations for trip productions and attractions are as follows:

$$\underset{(16.77)}{O_i = 0.284\ V_i} \qquad R^2 = 0.80$$

$$\underset{(27.14)}{D_j = 0.270\ V_i} \qquad R^2 = 0.91$$

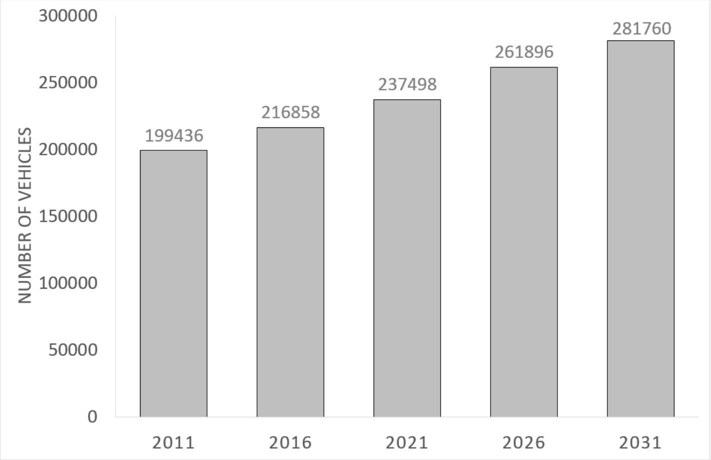


Figure 2. Estimated number of vehicles 2016 – 2031

The GIS-T software, COMMUTE developed at the University of Windsor, is used to estimate the OD matrices and associated traffic flow on the Windsor road network. OD matrices in COMMUTE were based on the Iterative Proportional Fitting (IPF) method, which updated the 2011 OD using the estimated trip productions and attractions for a given scenario and time period. COMMUTE then employed a multiclass Stochastic User Equilibrium (SUE) traffic assignment routine to estimate the traffic flows on the road network. Outputs from any given simulation include the following road link estimates: traffic flows per vehicle class, congested travel time and speed, congestion index, and total energy consumption (i.e. litres of gasoline). For the sake of the analysis, emissions from ICE vehicles were also estimated using the simulated congested speeds and emission factors from MOBILE6C that were obtained for the CMA for a typical winter day in January. The following relationships were derived from the MOBILE6C factors and used to estimate the emissions for carbon monoxide (CO), nitrogen oxides (NO_x) and hydro-carbons (HC) for any given scenario:

CO: $e = -0.00000019\ s^5 + 0.00005895\ s^4 - 0.00691\ s^3 + 0.3798\ s^2 - 9.8541\ s + 110.2639$

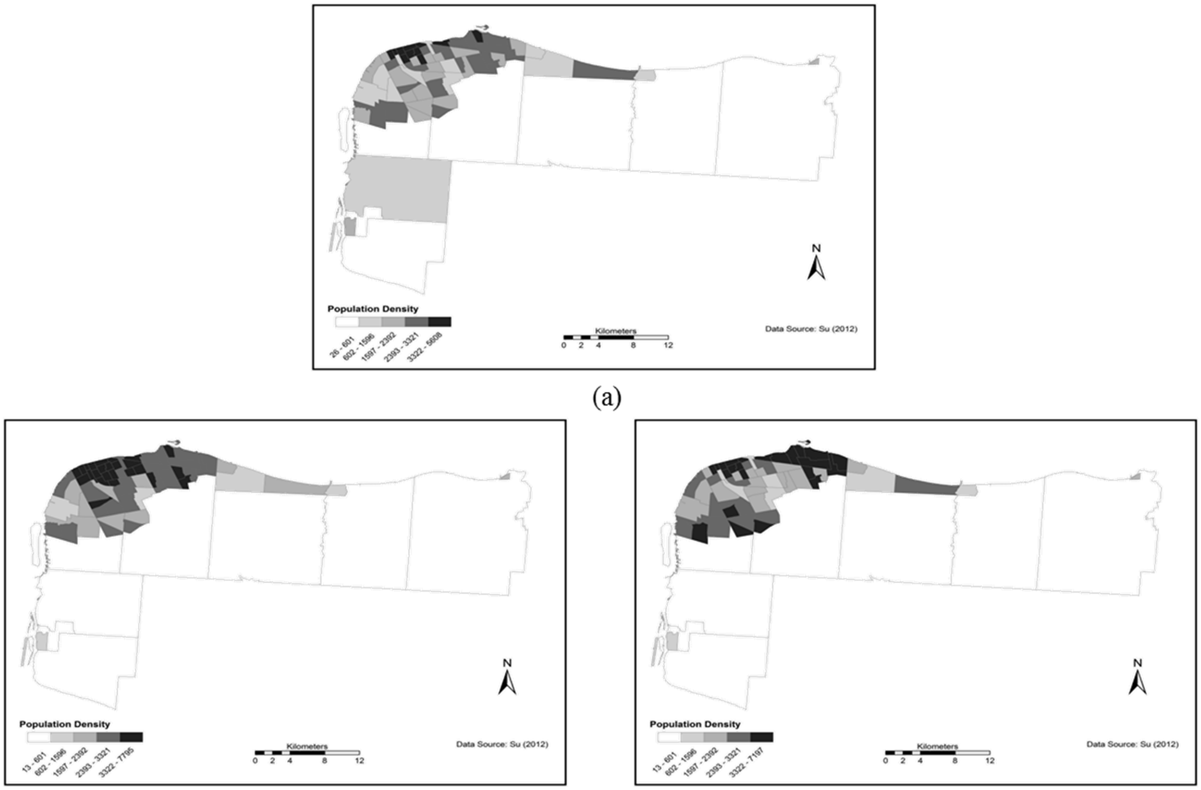
NOx: $e = 0.00000006\ s^4 - 0.00001578\ s^3 + 0.00153\ s^2 - 0.0654\ s + 2.1657$

HC: $e = 10.73\ s^{-0.718}$

Where e is emission factor in grams/km and s is congested speed on a given link. Total emissions on a given road link per pollutant p is then calculated as follows $E_p = e_p \times V \times l$, where V is simulated traffic volume for ICE vehicles, and l is the length (km) of the road link.

In order to evaluate the potential effects of EV adoption on the transportation system and the environment in the Windsor CMA, various hypothetical scenarios are simulated. Different urban forms are constructed:

status-quo, monocentric (compact), and suburban (sprawled) patterns. The 2031 population distribution for the status-quo scenario (Figure 3a) is based on the forecast by Gingerich et al. (2014). The monocentric study area (Figure 3b) is constructed by allocating 50% of the outer suburban population into the inner suburban area. Similarly, 25% of the inner suburban population is moved into the central business district. Lastly, the sprawled urban form (Figure 3c) is fashioned such that 10% of the central business district population and 50% of the outer suburban population are distributed around LaSalle and Tecumseh areas. EV market penetration of 10%, 20%, and 30% are also considered under each urban form scenario. For instance, in a 10% EV adoption case, the number of ICE vehicle related trips are reduced by 10% to create an EV based OD matrix. Next, the 90% and 10% trips pertaining to ICE and EV, respectively, are assigned to the road network via the multiclass traffic assignment. In such case, two classes being ICE and EV are considered.



(a)

(b)

(c)

Figure 3. (a) Status-quo, (b) Compact, and (c) Sprawled Urban Forms

Results and Discussion

The main criteria considered to assess the effectiveness of each simulated scenario for the year 2031 were the total energy consumed, VKT, congestion index and emissions. In order to have consistent comparisons, the values of each criterion were standardized across all scenarios using the following cost function:

$$C_i' = 1 - \frac{C_i}{C_i^{max}}$$

where C_i is the actual value of criterion i, C_i^{max} is the maximum value of criterion i across all simulated scenarios, and C_i' is the standardized value of C_i. The normalized values of each of the considered factors for all the scenarios are presented in Figure 4.

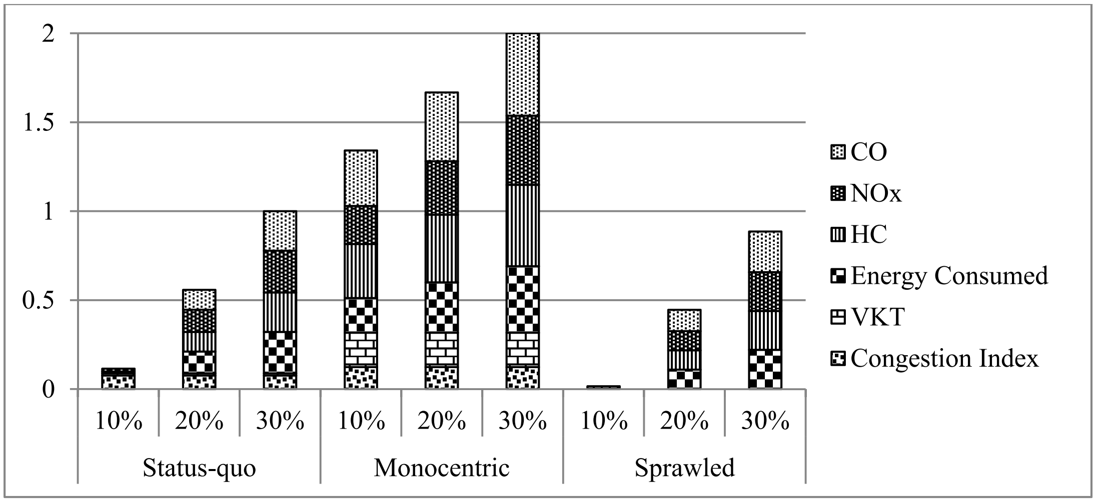


Figure 4. Normalized Values of All Criteria for All Scenarios

Next, a multi-criteria evaluation approach was employed to estimate an overall assessment index for the simulated scenarios. Here, the 6 considered factors are ranked such that the 3 types of tailpipe emissions (i.e. CO, NOx and HC) were the most important because they directly affect the environment and health. All three received the same ranking. The total energy consumption was deemed the second most important criteria for it captures the relationship between urban form and EV adoption rate. Moreover, while VKT and congestion index both impact the performance of the transportation system, VKT was ranked higher because it also contributes to deterioration of the road infrastructure. The overall sustainability index SI_k of each scenario k was calculated using the following equation:

$$SI_k = \sum_i w_i C_i'$$

where w_i is the weight associated with standardized indicator C_i'. The weights were obtained using the rank reciprocal weighting method based on the decided ranking order mentioned above. A high SI_k value (i.e. value closer to one) is indicative of progress towards sustainable outcomes (Figure 5). The estimated values used to calculate the sustainability indices are shown in Table 2.

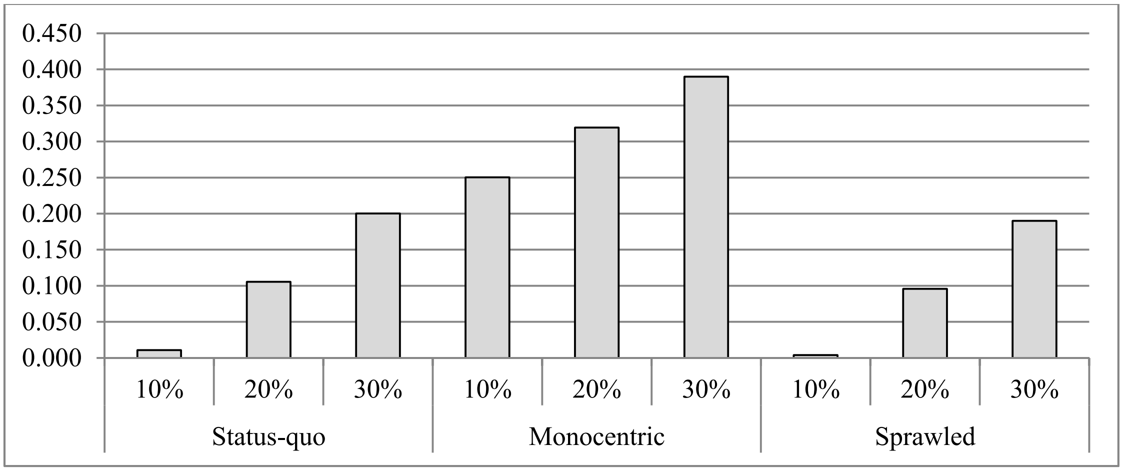


Figure 5. Overall Sustainability Indices for All Scenarios

Table 2. Overall Assessment

Scenarios		2031 Projections						
Urban Form	EV Adoption	Emission (Tonnes)			Energy Consumed (L)	VKT	Congestion Index	Overall Index
		CO	NO_x	HC				
Status-quo	10%	18.47	1.60	0.91	112,296	1,544,153	0.43	0.011
	20%	16.42	1.42	0.81	99,615	1,544,153	0.43	0.106
	30%	14.36	1.24	0.71	87,044	1,544,153	0.43	0.200
Monocentric	10%	12.71	1.28	0.64	91,394	1,261,099	0.41	0.250
	20%	11.32	1.14	0.57	81,338	1,261,099	0.41	0.319
	30%	9.90	0.99	0.50	71,064	1,261,099	0.41	0.390
Sprawled	10%	18.21	1.62	0.91	113,508	1,562,780	0.47	0.004
	20%	16.26	1.45	0.82	101,074	1,562,780	0.47	0.096
	30%	14.24	1.27	0.71	88,462	1,562,780	0.47	0.190

The results shown in Figure 5 suggest that the monocentric urban form scenarios produce the most sustainable outcomes for the year 2031. Based on the figures reported in Table 2, monocentric development will reduce energy consumption by over 18%. On the other the hand, energy consumption levels are similar for the status quo and sprawled scenarios suggesting that the status quo is heading towards sprawled development in the future. With respect to emissions, monocentric development tend to reduce CO, NOx and HC by 31%, 20% and 30%, respectively, relative to the base case. When considering the EV adoption cases, the results suggest that a 30% EV adoption under monocentric development will reduce energy consumption by 22%. The same could be observed for the other patterns of development. When considering the best (30% EV-Monocentric) and worst (10%-Sprawled) cases among all 9 scenarios, energy consumption is expected to decrease by 37%. The picture still holds with a reduction of 36.7% in energy consumption when comparing the 30% EV-Monocentric and 10% EV-Status quo scenarios.

Conclusion and Directions for Future Research

The focus of this paper was to evaluate the potential transportation and environmental impacts from different EV adoption and urban forms scenarios in the Windsor CMA in 2031. The results reinforce some of the previous findings in the literature. It is found that a compact urban development coupled with significant EV adoption can lead to significant reduction in energy and emissions. This in turn will promote sustainable transportation outcomes in the region. While the conducted analysis mainly relied on conventional techniques (linear regression and 4-stage modeling), the results are sensible and shed light on the role that EVs can play to reduce emissions and energy consumption in the future.

Future research will focus on improving the attained results by developing a more comprehensive vehicle ownership model. Unlike the simple approach presented in this paper, vehicle ownership level will be modeled using various socioeconomic factors, mixed density index and mixed land use around residential areas as in Potoglou and Kanaroglou (2008b). Moreover, total vehicle trips generated and attracted are highly dependent on current land use and infrastructure accessibility, as well as modal split; hence, future work will make use of integrated transport and land use models to generate detailed travel demand forecasts. Additional sustainability indicators, such exposure to other harmful emissions (e.g. volatile organic compounds and fine particles) and accessibility to services, will refine the sustainability assessment for the simulated scenarios. Nonetheless, the achieved results are useful as they provide a good benchmark for more extensive work on the topic. Overall, the conducted analysis was successful in disentangling the potential benefits of introducing EVs in a smart growth context.

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