



Need for strategic planning of electric vehicle charging locations in Windsor, Ontario

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ABSTRACT

The paper evaluates the impact of the new additional electric vehicle (EV) charging stations on accessibility to charging in the city of Windsor Ontario. It uses locations and coordinates information of electric vehicle charging stations extracted from the Environmental Canada database combined with details of the new additions by the city, manually abstracted from publications and google. These were spatially aggregated into the city's Ward along with demographic and stations-per-Ward determined.

Point-in-polygon, floating catchment area - FCA, and network level (travel-time) methods were used to understand variations in accessibility across Wards of the city, considering the existing and a combination of existing and new stations. The study found that the point-in-polygon method tends to overestimate the accessibility of Wards with a low population where kinetic (affluents) resides and could lead to improper identification of Wards highly accessible to charging. Findings from FCA and network accessibility methods highlights caution with the use of the point-in-polygon method which favors low-populated areas. Accessibility analysis using FCA, and network level (travel-time) technique revealed that the addition of new stations in the city does not significantly change accessibility levels. The study found that only a few Wards in the city of Windsor will be benefited from the addition of new stations as the median travel times from Wards to stations did not reduce significantly and larger variations exist around the median times suggesting that the new stations are randomly introduced rather than planned. Multicriteria analysis however aided in ranking of Wards based on available charging infrastructures, EV owned, travel time to stations and population density per Ward. The paper recommends data-driven machine learning approach in measuring accessibility and locating charging infrastructures in the city.

1. Introduction

Our society's reliance on transportation modes that uses non-renewable energy significantly contributes to emission and environmental pollution (Ajanovic and Haas, 2020). It is estimated that automobile use alone accounts for about 40% of carbon dioxide and 70% of greenhouse gas (GHG) emission in urban areas (Ajanovic and Haas, 2020; Fadda et al., 2019). This high emission rate is of serious concern and many countries of the world are now faced with the challenges of finding a way to reduce their contributions to global warming caused by

the release of greenhouse gases (Borowska-Stefańska et al., 2021). Nowadays, the implementation of new energy alternatives is seen to address the high dependence of transportation on non-renewable energy. Thus, alternative energy vehicles that use renewable energy as their source of power are now being sought after (Chen et al., 2020; Vaidya and Mouftah, 2020; Zhou et al., 2021). These includes electric, hydrogen, natural gas, methanol, and ethanol powered vehicles. However, of the many alternatives that exists, electric vehicles (EV), which can be pure (battery), hybrid and fuel cell electric types are considered to have the best advantage in terms of environmental and socioeconomic

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benefits (Sechilariu et al., 2019; Sun et al., 2019).

While EV especially the battery powered option has recently regained traction and receiving attention (Jiang, 2019), the concept is not new in its entirety. It has been existing for more than 100 years (Chen et al., 2020) and was first introduced by Thomas Parker in 1884 around the time of industrial revolution. Few years later, Porsche introduced his famous electric car in 1899. At the time of the introduction and compared to fossil fuel vehicles, electric vehicles are known to be quieter and generates less emission. In 1920's, Ford developed the model T version of electric car, which was mass produced, and at the time, enjoyed massive success commercially. Around the time, about 28% of all the vehicles produced in the U.S. were electric. Afterward, the rapid development of conventional fossil fuel car outpaced that of EV and the high cost of production coupled with low range battery, discourages its uptake. The development of EV was however renewed due to increased recognition of the contribution of fossil fuel powered vehicles to environmental degradation (Sun et al., 2019). Nowadays, electric vehicles are seen as viable alternatives to address the environmental problems that are associated with the fossil powered alternative (Ajanovic and Haas, 2020; Canizes et al., 2019; Juda, 2016; Leurent and Windisch, 2011; Sechilariu et al., 2019; Sun et al., 2019).

Numerous advantages could be derived from our societal shift to the use of EV. Compared with the fossil fuel powered alternatives, electric vehicles have low carbon footprints, generates lesser emission, and has low impact on noise level and air quality (Leurent and Windisch, 2011) but are not without limitations. Asides from the limited battery range, and longer time required to charge the battery, limited charging infrastructures has been highlighted as a key factor that influence its acceptance and use. To address these limitations, governments and industry now collaborate through funding policies that support the development of EVs' technology (Bitencourt et al., 2019; Chen et al., 2020; Hanžič et al., 2019; Liao et al., 2017; Sun et al., 2019). Similarly, various cities across the world are introducing incentives and investing in infrastructures to encourage the uptake of battery powered electric vehicles which are expected to phase out fossil powered alternatives in the future. These incentives include discount on vehicle cost, tax exception on development and provision of charging stations, and improved promotion of the sustainable benefit of electric vehicles. (Ajanovic and Haas, 2020; Chen et al., 2020).

Despite these arrays of policies that has been implemented to encourage EV uptake, emissions from the use of fossil fuel dependent vehicles or automobile remains high (Liao et al., 2017). Currently, out of the EV that is globally used for ground transportation, heavy duty commercial vehicle represents a significant proportion. Light weight electric vehicle that are used for commuting accounts for about 2.5% of worldwide vehicle sales (Deb et al., 2021). Nonetheless, the global project of EV suggests that by the year 2030, there will be a significant number of EV using our roadways. With the projected growth in the number of EV in our society, the development and the introduction of new public charging stations have been slow (Ajanovic & Haas, 2020; Deb et al., 2021; Fadda et al., 2019; Juda, 2016; Sechilariu et al., 2019; Zhou et al., 2021). Moreover, the development and full acceptance of EV is dependent on the availability of charging stations that supplies energy and offer maintenance to its operation, and development (Vaidya and Mouftah, 2020). It is therefore important to understand where to place charging stations (Li et al., 2015). Thus, promoting the construction of charging station and strategically locating them becomes critical (Brost et al., 2018; Jiang, 2019).

With electrification of vehicle now considered the way forward to reduce greenhouse gas emission, many cities of the world are planning to increase their fleets of electric vehicles. Increasing EV fleets implies addressing barriers to its market penetration and wider acceptability. Lately, municipal authorities have been reactive and additional charging infrastructures are now proposed to supplement the existing ones. Where these infrastructures already exist or are proposed, situating them is strongly influenced by political rather than planning decisions

(Sechilariu et al., 2019). The idea of politically induced addition of new charging infrastructures neglects the objective that strategic expansion of charging station is important to EV technology (Deb et al., 2021). Thus, the use of EV and its public acceptance is not only faced by challenges that is technological but also legislative or political in nature.

Till date, existing or potentially new buyer of EV are still concern about the short range of distance it can cover before a recharge is required (Juda, 2016). Cities across the world are attempting to address this challenge and are aggressively introducing new charging infrastructures to promote EV uptake. For example, the city of Windsor Ontario, announced additional new charging infrastructures to booster the existing ones and foster more accessibility. However, there is no laid down research findings that supports the need for this additional infrastructures and how it will improve accessibility to charging for current or any potential new owners of EV. Our study addresses this gap and evaluate the likely impact of the new infrastructures on accessibility to charging in the city of Windsor, Ontario.

1.1. Study goal and objectives

Our paper focused on evaluation of the policy decision by the city of Windsor on addition of more EV charging stations within the city and determine improved access (if any) to charging locations.

The specific objectives are to:

- i. Evaluate spatial accessibility to charging stations considering the existing and the new additional EV charging station at Ward level using a) point in polygon method b) floating catchment area analysis (FCA) c) network level analysis.
- ii. Determine the demand–supply relationship between Wards and charging stations.
- iii. Identify the Ward within the city of Windsor that will benefit most from the new stations and emphasize the need for multi-criteria analysis in locating charging infrastructures.

We organized the remainder of our paper as follow. Section 2 give a background on studies that have evaluated accessibility to charging infrastructures across various city of the world and highlights the major findings. Section 3 gives details of our study area, data and the methods used to analyse accessibility to charging infrastructures in Windsor Ontario. In Section 4, the analysis of our result was provided. Section 5 provides the summary of our findings and directions for future research.

2. Literature review

Advances in the development of EV that relies on alternate energy continues to represent a promising direction towards reducing high dependency on fossil fuel and reduction of CO₂ emitted on per kilometer travelled. Recent developments in EV technology have been promising and consistently aligned with the goal of Electric Vehicle Initiative (EVI) that provides a platform for global discussion of EV technologies and infrastructures. The goal of EVI is to make EV the predominant form of transportation in our society through deployment of millions of EV worldwide. However, the global development of EV requires the provision of charging infrastructures that is reliable, diverse and easily accessible. While charging at home seems to be the best solution to address the environmental challenges, the introduction of public charging infrastructures helps address the problem of short range with EV battery. It also grants accessibility to any would be owner that lack access to charging at home. (Mendoza et al., 2016). Currently, majority (about 92%) of EV owners charges their vehicle at stations located in private areas. Therefore, locating EV charging stations in public area is important to random charging events that are unpremeditated (Brost et al., 2018). Otherwise, the populace will continue to fancy the convenience of accessibility to stations and fast refuelling times which promotes the use of fossil fuel powered vehicles. Thus, strategically

increasing the number of charging stations is the way forward to decarbonize transportation (Canizes et al., 2019). It is expected that the availability of adequate infrastructures will be critical to large scale uptake of EVs (Chen et al., 2020).

In response, many public charging infrastructures are being implemented across the world. The city of Windsor Ontario is not an exception to these developments. As a matter of fact, announcement have been made on the targeted additions to EV charging stations. In most cases, EV charging infrastructural addition to most cities across the world have been based on either demand or supply. In some cases, they are uncoordinated or the demand and supply across the city is not considerably matched thereby limiting accessibility. If caution is not taken, infrastructures provided within cities especially in urban area will be inadequate (Vaidya and Mouftah, 2020). However, how the recent announcement of additional charging infrastructures will change the accessibility to charging in the city of Windsor remains a question and serves as motivation for our study.

Luckily, the concept of spatial accessibility which provides opportunity to understand how residents can access infrastructures is not new. It measures the ease of accessing services or any form of amenity and has been extensively use in spatial geography, transportation engineering, urban and social sciences. Essentially, it serves as the basis for which cities exist thus it has become a key component of urban transportation models and serves as the performance evaluation of the impact of plans or policies on transportation system (Desjardins et al., 2022; Mahmoudi et al., 2019). It aids in enhancing equity to public services or amenities by helping decision maker identified locations or areas where infrastructures should be provided (Park et al., 2021).

In general, spatial accessibility to amenity in our case charging station is done using two approaches. The first approach measures the ease to which amenities could be access and focused on evaluating the current spatial distribution of infrastructures. It considers accessibility to station at areal level - neighbourhood, Ward, and census tracts. It also provides opportunity to determine the impact of any proposed changes to the numbers of infrastructures, in this case electric vehicle charging stations. A common method that falls in this category is the FCA which has evolved over the years (Zhou et al., 2021). The FCA method is commonly used by researchers because it does not only take into consideration of the level of demand from population placed on infrastructures but also aggregate the level of service considering the catchment area (Paez et al., 2019).

Different modification to the floating catchment analysis (FCA) has been introduced but a popular variation of the technique is the 2 stages floating catchment analysis (2SFCA). The popularity of this method has been based on the advantage of addressing the challenges of solely comparing the supply and the demand within a facility, in our case the demand to charging and the available charging point in a station. Other advantages that made the use of the 2SFCA more appealing to researchers include the ease of interpretation of the accessibility scores as well as implementation in GIS environment. Simply, the 2SFCA considers each location and search all available population, be it charging stations and calculate the ratio of the available facility to population. The second step of 2SFCA, estimates the number of infrastructures that are within a travel distance to a population and sums the ratio of infrastructures to population demand. However, the use of the 2SFCA could be influence by the capacity of each of the infrastructure (Lin and Cromley, 2021). Regardless, it has found applications in the understanding of accessibility in academic literatures (Langford et al., 2021). For example, Sahebgharani & Haghshenas, (2022) used the 2SFCA method to understand accessibility to fires stations by taking into consideration of deterministic transportation travel times. The study used Isfahan, an Iranian city as a study case. Findings from the research suggests that travel time have heterogeneous effects on accessibility. It also highlights spatial inequality and segregation in terms on fire service accessibility. The other derivative or form of FCA is the three-stage floating catchment (3SFCA) analysis. However, the application of

these derivatives of FCA could be limited depending on the knowledge of capacity of the available infrastructures. For example, in a small city like Windsor, Ontario with new charging infrastructures with a capacity of one each being newly proposed to supplement the existing ones, using the derivative of FCA may be inappropriate because capacity is constant over stations. The uniformity of available charging point which represent capacity, defeats the purpose of 2 or 3 stages analysis hence FCA that consider only the first stage of the 2SFCA described above will be suitable.

The other approach to measuring spatial accessibility focused on spatial optimization to determine where best infrastructures can be positioned (Zhou et al., 2021). Spatial optimization examines where the demand, for example charging is generated and takes into consideration of the supply, where available station is located, land use or urban form and available infrastructures – road network. In general, a low accessibility in both spatial distribution and optimization implies disparity between the demand and supply, a barrier to amenities and in the worst-case inequalities especially when areas of socioeconomic disadvantage are affected (Park et al., 2021). Thus, accessibility measures play a great role in understanding the ease to which the populace can access different amenities and it is expected that improved accessibility to charging stations across cities will further enhance the acceptance and uptake of EV (Falchetta and Noussan, 2021). As a result, further research across the world is focused on evaluating and understanding any disparity that exist in spatial accessibility to charging stations.

Hardinghaus et al., (2020) studied the distribution of EV charging infrastructures in the city of Berlin – a European city, to understand the demands for public charging. Findings showed that charging station distribution across the city is unequal and that they are more likely to be in or around the downtown core therefore a higher density of stations are likely to be found in the city center. Their study however suggested that despite the difference in the distribution of charging stations across the city, utilization is relatively the same. The implication of this finding suggests that demands will be unequal and strongly dependent on locations. In line with disparity in accessibility to EV charging stations, Li et al., (2015) developed an optimal charging station deployment method that takes into consideration of the trajectory of EV and determined appropriate locations where stations should be positioned within a city. The main idea of this concept was to minimize the travel time to the nearest charging station and turn-period i.e., the average time required to wait before a charging point is available. The study showed that the travel and average waiting time for charging points to be available could be significantly reduced through spatial optimization. Thus, the research by Hardinghaus et al., (2020) and Li et al., (2015) showed that locating EV stations is a combination of evaluation of spatial distribution (understanding of the demand and supply for charging station) and optimization through operation research. However, obtaining trajectory information of EV as suggested by Li et al., (2015) to conduct spatial optimization analysis is a daunting task and most researchers opts for the study of EV stations accessibility at areal - city, Ward, and census level.

At areal level i.e., regional level, Falchetta & Noussan, (2021) studied accessibility to EV charging infrastructures in Europe. The study used two indicators: the ratio between the number of available EV stations and the average travel time to charging stations. It was found that over the last years, considerable expansion in the number of charging stations have been seen but a great disparity still exists in accessibility to charging infrastructure across countries of Europe. The level of maturity of EV markets was seen to be highly dependent on the local policies in each of the countries that promotes not only the incentives but also charging infrastructures. This was found to varies extensively with the population density and driving habits. In most cases, focus for the provision of these infrastructures have been on larger cities and a great difference exist in the accessibility to charging station in urban and rural areas. Most importantly, the addition of more charging stations was found to be strongly correlated to EV uptake. Therefore, Falchetta &

Noussan, (2021) pointed out that for the overall benefit of the EV to be derived, appropriate strategy must be in place for the provision of charging stations. It was highlighted that about 15% of all populations in Europe live about 30 minutes away from EV charging station but low accessibility still exists in Eastern European countries with low gross domestic produce (GDP). In general, EV stations per 1000 population in Europe was found to be considerably low at 0.5 and recommendation was made that the number of charging infrastructure should be continually increased. Also, emphasized was that rural-urban divide in accessibility should be addressed through extension and promotion of equitable access to EV charging. The study by Falchetta & Noussan, (2021) has some likely implication at the local level. For an example, at the Ward level, which is the focus of our study, it is possible that charging infrastructures may be clustered in affluent neighbourhood and if caution is not exercise, accessibility to charging in less affluent areas may be hampered. This will on the long run create local barrier for EV uptake in the absence of immediate policies.

Consistent with the finding of Falchetta & Noussan, (2021), Hanžič et al., (2019) also found that GDP influences EV uptake and the numbers of stations in European countries. However, besides the GDP, different factors can influence accessibility to charging at the city level. City dynamics relating to population (demographic) as well as the road traffic which influences travel time could affect accessibility to charging infrastructures. Thus, it is important that these factors be taken into consideration when evaluating accessibility to charging infrastructures and on the long run will foster better accessibility and EV uptake. To evaluate the aforementioned, Zhou et al., (2021) studied spatiotemporal accessibility to charging stations in the Province of Nianjing, China. Using multiple data sources: mobile phone records, and route planners, the dynamic effect of population and traffic congestion on accessibility to charging was determined using a derivative of FCA known as the 3SFCA. It was emphasized that population, employment, proportion of residences can restrict accessibility to EV stations. Recommendation was made that population effect and travel time should be considered in measuring accessibility. To account for other factors that may influence spatiotemporal accessibility to charging stations, Park et al. (2021) used Gaussian 2 stages spatial floating catchment (G2SFCA) method to determine accessibility to charging station in Seoul, South Korea. Their study explained that using this method could enable temporal (time) dynamics to be incorporated to EV charging station accessibility in Seoul thus enhancing appropriate policy decisions. However, the resolution of the available data for analysis matters. Due to privacy concerns, information about the time of the day that most EV access charging stations may create a constrain on the usage of the method suggested by Park et al. (2021).

Asides from population, employment that has been identified to influence accessibility to charging, other factors such as technology relating to battery capacity, infrastructure improvement and demographic changes could influence accessibility to charging. For example, Rosik et al., (2021) studied the impact of technological development, road infrastructural improvement and demography on EV accessibility to charging. The study accounts for the distance to labor market considering the range of battery level of EV. Labour market within 30, 60, and 90 minutes in five cities of Poland was considered and spatially analysed using isochrones to determine cumulative accessibility. It was found that technological development for EV charging plays a better role in accessibility than population and infrastructural changes. This effect was seen to be prevalent when travel time of 30 and 60 minutes was considered. The research however emphasizes that population changes, distribution, and road infrastructural development have similar effect on accessibility. Other studies have also made suggestions like Rosik et al., (2021). Kang et al., (2022) studied how charging infrastructural network and spatial urban structure impact demand for charging of electric vehicles. The study focused on Beijing China and used GIS data from EV to develop charging demand indicator. Kernel density analysis was also used to uncover the spatial relationship

between demand and charging infrastructures. Kang et al. found that there is a spatial disparity between demand and supply, and demand during the day and distance travelled by EV. Using spatial lag models, the study confirmed that urban structure in terms of land use and the spatial distribution of charging stations could affect the way charging demands are met. They recommend understanding the supply and demand for charging infrastructures to facilitate informed policy decisions and that EV stations should be in coordination with land use. Essentially charging demand and charging stations should be spatially matched.

Interestingly, demographic features such as race and income class has also been reported to influence accessibility to EV vehicle charging. To this effect, Hsu & Fingerma, (2021) studied the barrier to EV adoption in the state of California United States using location information of public charging stations and community survey data at Census block level. The result from the study was appalling and it revealed that accessibility is generally lower in block with people earning below the median income in the state of California. The pattern was also seen in location with high proportion of Hispanics or African descent. This disparity was more pronounced in locations with multi-unit housing. It shows that blocks dominated by Blacks and Hispanic represent a race that is most likely to have low accessibility to charging stations. The likelihood of not having charging stations in blocks dominated by this group is 70% more likely than block with no predominant race. This finding showed that equity must be enhanced at all levels to boost adoption of EV across board and not only in places with socio-economic advantage is electrification of transportation important. The study recommends that for transportation equity to be achieved, more funds must be allocated to underserved communities for the promotion of EV and development of charging stations to promote accessibility.

It is however worth mentioning that the studies we have reviewed so far in our paper points to need to improve accessibility to promote EV adoption. It focused mostly on the three approaches popularly used while evaluating accessibility to infrastructures. While studies have used FCA - a known method to overcome the limitations of the point in polygon method, other have used 2SFCA and derivatives which requires more additional data. These additional information are not usually available in small cities like Windsor. At best, population in each of the geographic units are incorporated into methods such as point in polygon or FCA methods and used to determine the needs for any improvements such as the provision of additional charging stations. However, method such as the FCA which serves as an improvement to point in polygon by incorporating demand from other nearby areas does not consider network characteristics when measuring accessibility. FCA does not take into consideration of how long vehicles - in our case EV will travel from an area - the city Wards to get charged. Hence, we justified the need for Multiple-Criteria Decision-Making (MCDM) which is a technique used and as described by Taherdoost and Madanchian, (2023) for determining and ranking alternatives. The initial parts of our study compared point in polygon, FCA and travel time accessibility measures to evaluate the improvement the proposed additional charging stations offered. The later uses multiple-criteria methods incorporating the travel time obtained from the network accessibility, the number of stations, electric vehicle charging stations owned per Wards etc. to determine the most accessible Wards. Thus, our paper promotes discussion on the need for small cities like Windsor to conduct detailed accessibility analysis using a multi-criteria approach to facilitate appropriate planning decisions regarding additional charging stations.

3. Study Area, data and method

3.1. Study area

The study area is the city of Windsor. The city is the southernmost in the province of Ontario, Canada. It is bordered in the south by city of Detroit, United States and in the north by LaSalle, Essex County and Amherstburg Ontario. According to Statistic Canada, (2022) the

population of the city was 217,188 in 2016 and grew by 5.7% in recent population census to 229,660. Currently, the city is the third most populated city after London and Kitchener in the southwestern part of Ontario. Bordered by the city of Detroit, the city of Windsor facilitates yearly international crossing between United States and Canada and is the busiest between the two countries. Currently, the city has 10 administrative Wards (see Fig. 1.).

3.2. Data

3.2.1. Windsor Wards

The city of Windsor has 10 administrative planning Wards, and we obtained the shape file from the city's open data platform. The shape file contains the coordinates of each of the city's Ward boundary, councillors as well as the area. We chose the Ward as the spatial unit for our analysis because it is the simplest unit at which the demographic data was provided. This shape file facilitated the understanding of spatial accessibility to EV charging infrastructures in the city of Windsor. The location of the existing and the new station was overlaid on the Wards to determine those that falls within the city limit. Also, the availability of Ward numbers in the shape file database enabled the joining of the demographic information to each Ward, thus, enhancing our accessibility analysis.

3.2.2. Electric vehicle charging stations data

This study used geolocation data of all alternate energy station in the country of Canada, obtained from the Environmental Canada and Transportation database (Natural Resources Canada, 2022) and extracted the record of all the EV charging stations in Windsor. However, all stations that falls within the Windsor-Essex region was tagged Windsor so further analysis was done to extract only the ones that falls within the city boundary. We extracted the location of the new additions to these stations from the city of Windsor website (City of Windsor, 2021). These articles provided the addresses of where new stations will be located. Using these addresses, we were able to generate their geolocation

information i.e., longitude and latitude and then combined them with the existing database that shows the location of old electric vehicle charging stations. We used Google to extract these coordinates because at the point of conducting our analysis, only the addresses were available. In total, our study considered twenty-two (22) electric vehicle charging stations in the city of Windsor. Thirteen (13) of these stations are existing as of December 2021 while nine (9) are among the newly added out of the proposed charging stations which are expected to be completed in March 2022. It should be noted that some of these charging locations are in various centers that are not necessarily a large, designated stations. For example, the ones located at the WFCU centers and Municipal lots are charging points randomly located within a commercial or parking yard but have the same addresses. Therefore, we consider that each of the charging point has a capacity of one despite having the same address (see Table 1).

3.2.3. Demographic data

We extracted the demographic details of the city of Windsor from the published articles by the municipal authorities (City of Windsor, 2018). The demographic data shows the breakdown of population of the city of Windsor for the census year 2016. At the time of completing this research, the detail breakdown of the demography per Wards of Canada for census year 2021 is still scheduled to be released. Also, as earlier stated there was no significant increase in the total population (the city's population only increased by 5.7% in 2021). This increase was not a significant one thus due to the non-availability of the 2021 population breakdown, 2016 data that was available was used and contains the breakdown of populations by Ward. It shows the number of males or females per Ward, the number in each of the age group etc. Our study only uses the total population for each of the Ward. We showed the population breakdown and other demographic information in Table 2.

3.2.4. Number of electric vehicles owned per Wards

We extracted the EV owned in the city of Windsor from <https://data.ontario.ca/dataset/electric-vehicles-in-ontario-by-forward-sortation-ar>

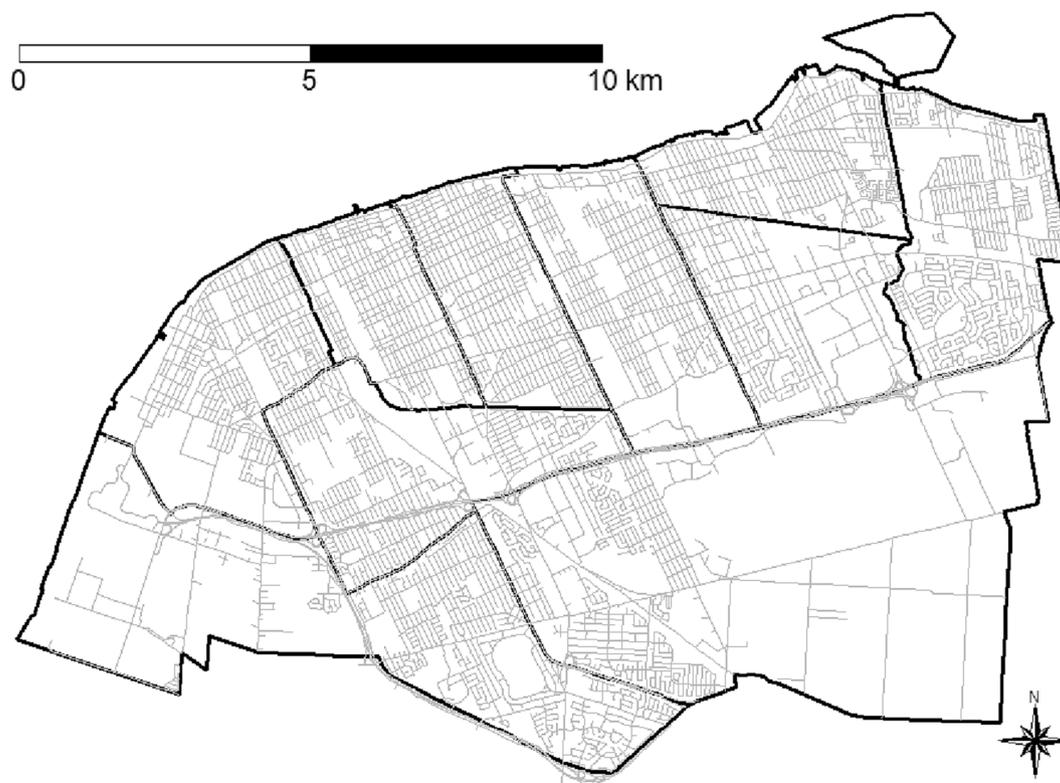


Fig. 1. The City of Windsor showing the Wards.

Table 1
Electric Vehicle Charging Stations/Locations in the City of Windsor.

Serial No	Fuel Type Code	Station Name	Street Address	Station Status	Access
1	ELEC	Renewable Energy Technology Centre	1680 Kildare Rd	Existing	Public
2	ELEC	Southwest Detention Centre	4819 8th Concession Rd	Existing	Public
3	ELEC	Trike My Bike	3143 Walker Rd	Existing	Public
4	ELEC	Adventure Bay Family Waterpark	401 Pitt St W	Existing	Public
5	ELEC	Windsor Professional Centre	2462 Howard Ave	Existing	Public
6	ELEC	Devonshire Mall Station 1	3175 Howard Ave	Existing	Public
7	ELEC	Devonshire Mall Station 2	3060 Howard Ave	Existing	Public
8	ELEC	Devonshire Mall Station 3	3100 Howard Ave	Existing	Public
9	ELEC	Premier Chevrolet Cadillac Buick GMC Inc	500 Division Rd	Existing	Public
10	ELEC	Parent Avenue Pharmacy	860, Tecumseh Road East	Existing	Public
11	ELEC	Via Rail Canada Inc. - Windsor	298 Walker Rd	Existing	Public
12	ELEC	Ivy - Windsor	3155 Howard Ave	Existing	Public
13	ELEC	Overseas BMW Fast Charger 01	9425 Tecumseh Rd E	Existing	Public
14	ELEC	City of Windsor/ Aquatic Centre	401 Pitt Street West	New	Public
15	ELEC	City of Windsor/ Garage 2	406 Pelissier Street	New	Public
16	ELEC	City of Windsor/ Lot 10	445 City Hall Square West	New	Public
17	ELEC	City of Windsor/ Lot 35	1031 Elsmere Avenue	New	Public
18	ELEC	City of Windsor/ Lot 4-1	1319 Lincoln Road	New	Public
19	ELEC	City of Windsor/ Mic Mac Complex	1125 Prince Road	New	Public
20	ELEC	City of Windsor/ WFCU Centre-1	8787 McHugh Street	New	Public
21	ELEC	City of Windsor/ WFCU Centre-2	8787 McHugh Street	New	Public
22	ELEC	City of Windsor/ WPL - John Muir	363 Mill Street	New	Public

ea. This is an online open data that classified the number of EV owned per forward sortation areas (FSA). This was merged with the FSA shapefile of the city of Windsor to determine EV owned per FSA. However, there was no common identifying link between the FSA and the Windsor shapefile, and we spatially converted the FSA shapefile that contained the number of EVs to centroids. Through spatial overlay analysis, FSA centroids was overlaid on the Ward shapefile and the number of EVs per Wards of the city of Windsor determined for further analysis (see Table 4). Essentially, we used this as a part of the multi-criteria analysis that incorporated the travel times and other variables for further analysis.

3.3. Method

Our study uses a combination of method to determine the accessibility to charging stations by electric vehicles. The methods include the point in polygon method, the floating catchment area method and the network level accessibility analysis that uses the travel time to reach a

charging station. Lastly, we used a multiple criteria approach to rank the Wards of the city considering travel time accessibility (the existing, a combination of existing and new), charging stations, and EV owned per Wards,

3.3.1. Points in polygon

This is the simplest method to determine the accessibility to amenities or infrastructures, in our case charging stations in a region. It simply involved the aggregation of all stations that falls within each geographic unit. The geographic unit in our case is the city of Windsor's Wards. By overlaying the shape files that gives the longitude and latitude of stations on the Wards in the city of Windsor, the numbers of stations that falls in each Ward can be determined. This represents the simplest method of measuring accessibility to charging stations within the city of Windsor. We describe this using graph principles in Equation (1):

$$W_i = \sum_{j \in A_i} E_j / P_i \quad (1)$$

W_i represents Ward i of interest and E_j is the electric vehicle charging stations that falls in Ward i of interest. P_i is the total population of each Ward. We normalized the sum of the electric station with the total population to gain insight into accessibility to the stations within each Ward and multiply by 10,000 to have the idea of accessibility per 10,000 population of the Wards in the city of Windsor.

3.3.2. Floating catchment area method (FCA)

Floating catchment method has been extensively used to understand accessibility to different amenities. It combines the element of the point-based method that uses the number of stations that falls within administrative units and divide it by the total population. Combined with distance threshold, service catchments are determined and it floats represents a population demand to the other. Accessibility is determined by demand supply ratio estimated from FCA (Langford et al., 2018). These days FCA have been extended to 2SFCA which combines the demand ratio with the demand from other areas within the catchment of the stations, but other methods exist beyond 2SFCA. In our case the supply represents the number of available stations within each Ward and the demand representing the population. The description of this method as adapted from the work by Mercier et al., (2021), Kim et al., (2018) and Zhang, (2021) is given in the next set of equations.

The first step of the 2SFCA uses circular buffer (floating area) to determine the distance at which individuals representing population subset; in our case will need to travel to charging stations to boost their car battery. For a charging station j , the floating area is determined by a threshold distance d_0 . In our study, we used d_0 as 500, 1000, 1500 and 2000 meters. The population located within the area are likely to access charging stations easily. Small floating area implies that population homogeneity is increased. Through the introduction of the supply-demand ratio i.e., the ratio of the number of available charging stations to total population, the level of competition for charging can be determined. We describe this in Equation (2):

$$R_j = \frac{m_j}{\sum_{k \in \{d_{jk} \leq d_0\}} P_k} \quad (2)$$

m_j is the number of charging stations at Ward i . P_k is the entire population at location k , at a distance less than or equal to d_0 from location j . In equation (2), d is the distance between k and j . The second step of the 2SFCA takes into consideration of loads from location i that may find services accessible from set of locations j within a threshold distance d_0 . Thus, accessibility at resident location i takes into consideration of all available nearby stations and it is measured as the sum of supply-demand ratio for each station estimated from equation (2). This is mathematically defined as Equation (3):

Table 2
Descriptive Statistic of Windsor Demography.

Variables	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Total Population	18,487	20,735	21,386	21649.6	23205.25	24,670
Males	8953	10231.5	10589.5	10574.4	11204.75	12,074
Females	9454	10,203	10861.5	11074.3	12,088	12,596
Average age of population	36.9	39.2	41.25	41.07	42.65	45.7
Median age	32	39.05	41.45	41.15	43.175	47.7
Families	4601	5177.25	5786.5	5811.1	6425	7222
Persons per family	2.7	2.8	2.9	2.92	3	3.2
Total couple families	3077	3639	4633.5	4464.7	5164.25	6066
Married couples	2286	2840.75	3894.5	3782.2	4488.5	5499
Common law couples	402	458.25	744	687.4	839.75	1062
Total lone parent families by sex of Parent	863	1114	1430	1344.9	1504.5	1823
Female parent	684	919.5	1143.5	1094	1262.5	1503
Male parent	179	207	239.5	247.4	287.25	336
Households	6785	8065.75	8876.5	9131.9	10818.25	11,418
Persons in private households	18,421	20519.25	20,909	21331.2	22778.5	24,442
Persons per household	1.9	2.125	2.25	2.41	2.675	3
Average household income	43,571	58433.25	71716.5	73301.8	91028.75	105,679
Occupied Dwellings	6769	8072	8879.5	9139.9	10836.75	11,445
Owned Dwellings	3465	4723.5	5836	5804.7	7169	7889
Rented Dwellings	632	1147.75	3512	3334.4	4459.25	7979
Total Battery Electric Vehicle (Total_BEV)	0	22.3	32.5	142.8	75.8	694
Total Plug-in Hybrid Electric Vehicle (Total_PHEV)	0	21.8	34	113.1	58.3	509
Total PHEV and BEV	0	49.8	64	255.9	132.5	1203
Minimum travel time to stations (all_station.min_time)	1.8	3.9	5.1	4.8	5.8	7.3
Number of Wards (n)	10					

$$A_i = \sum_{j \in \{d_{ij} \leq d_0\}} R_j \tag{3}$$

However, in our case, the second step of the 2SFCA method would be unnecessary because the capacity of all the stations is 1 and the service quality of each of the stations is unknown so for this analysis, we focused on the basic floating catchment analysis which takes into consideration of equation (2) only. We chose the first step of the FCA to avoid any methodological challenges that could lead to results that are difficult to interpret. These includes multiple use of the distance decay to determine variation in supply of infrastructures, demand from population and supply demand ratio which could influence accessibility estimates. It is also unclear the advantages of the advance variation of the FCA approach that focuses on methodology has over the empirical method of measuring accessibility (Zhang, 2021). However, study by Paez et al., (2019) have suggested that the inflation of the demand-service ratio: a measure of accessibility could make the interpretation of accessibility quite challenging and in the worst case leads to poor decision making. Thus, it is intuitive to use an easier to understand approach for effective policy decisions. Nonetheless, we further used the network level accessibility based on travel time to evaluate Wards accessibility score and supplement the FCA method.

3.3.3. Network level accessibility (travel time method)

Our study further uses isochrones map to determine accessibility to charging stations and focus on Wards that gain the least accessibility considering the new additional charging station. Rather than using buffer analysis as the case was with the FCA method, travel accessibility from the Ward centers to the closest station was examined to determine network coverage of each charging infrastructure. However, coverage measures could be Euclidean distance or travel time to charging stations along a network, but the distance method is less preferred due to the possibility of overestimating the size and service area population, thus in this study, travel time was used. The advantage of using travel time is that it provides accessibility measures that is more relatable (Arce-Ruiz et al., 2012). Instead of circular coverage area used by the FCA method, the network level accessibility shows irregular polygon (isochrones) containing all street segments within a travel time threshold.

In this study, isochrone methods described by Biazzo et al., (2019) was used in the determination of travel time accessibility to EV charging

stations in the city of Windsor at network level. Essentially, isochrones method compute accessibility based on travel time under a free flow condition and the matrix of travel times to each of the surrounding stations from the Ward centers could be extracted. To fully understand the changes in travel time to charging stations with the new addition, the matrix of travel times from Ward centers to all surrounding stations was analyzed. This later serves as inputs for our Multiple-Criteria Decision-Making analysis.

3.3.4. Multiple-Criteria Decision-Making (MCDM) for accessibility analysis

We ranked accessibility to the Wards of the city of Windsor using a multicriteria analysis that considered the influence of additional charging stations on accessibility and identify indeed the Wards that will benefit and become more accessible. Thus, network travel time obtained from the network accessibility, population density, the number of electric vehicle owned and charging stations per Wards was used in multicriteria analysis. We formulated our Multiple-Criteria Decision-Making (MCDM) $M_{m \times n}$ matrix where each column represents a criteria for example the numbers of stations, battery electric vehicles etc. aided in the determination of the most accessible Ward considering a combination of criterions (see Table 3).

As part of Multiple-Criteria Decision-Making method, the weight of the criteria for each elements of the alternative are important. We defined these weights based on previously published articles that determines the impact of the criterion considered in our study. For example, population density has been known to have lesser, perhaps no

Table 3
Decision Matrix for Multicriteria Accessibility to Charging in Windsor, Ontario.

Wards	Numbers of Stations (S)	Battery Electric Vehicle (Total_BEV)	Plug in Electric Vehicle (Total_PHEV)	Minimum Travel Time to Charging Stations	Population Density (Pop_Den)
1	x_{11}	x_{11}	x_{11}	x_{11}	x_{11}
2	x_{21}	x_{21}	x_{21}	x_{21}	x_{21}
3	x_{31}	x_{31}	x_{31}	x_{31}	x_{31}
...
n	x_{m1}	x_{m1}	x_{m1}	x_{m1}	x_{mn}

Table 4
Multiple-Criteria Decision-Making (MCDM) Matrix.

Ward	Stations per Wards	Total_BEV	Total_PHEV	old.station.min.time	all_station.min_time	Pop_Den
1	0	694	509	3.75	1.83	8878.07
2	2	34	30	4.95	4.95	17832.38
3	5	20	35	4.23	3.58	3238.46
4	4	0	0	6.09	6.09	3086.23
5	1	29	19	5.73	5.73	16065.21
6	2	31	33	8.95	2.9	2768.05
7	1	60	59	5.13	4.86	18583.13
8	0	14	16	5.84	5.84	17917.24
9	7	465	374	7.3	7.3	5071.62
10	0	81	56	7.17	5.35	17420.84

significant effect on electric vehicle ownership (Brückmann et al., 2021). and presumably on the number of electric vehicles charging stations. The longer the travel time required to access charging, the less likely is EV uptake and more accessible charging stations promotes the switch to alternate energy modes such as EV and has been shown to have positive associations (Sommer and Vance, 2021). These weights are defined mathematically as:

$$W = \{w_1, w_2, \dots, w_n\} \tag{4}$$

We formulated our weight based on the knowledge we derived from published literatures as follows and ensured that the weight summed up as one:

$$W = \left\{ \begin{array}{ccccc} all_stations & Total_BEV & Total_PHEV & all_station.min_time & Pop_Den \\ 0.4 & 0.25 & 0.08 & 0.25 & 0.02 \end{array} \right\} \tag{5}$$

Also, we determine accessibility considering the old stations, therefore all_station.min_time was replaced with the travel time when only the existing stations was considered.

The impact of these variables was also determined based on the reported relationship with EV ownership in published articles as equation (6)

$$W = \left\{ \begin{array}{ccccc} all_stations & Total_BEV & Total_PHEV & all_station.min_time & Pop_Den \\ + & + & + & + & - \end{array} \right\} \tag{6}$$

To evaluate the alternative combination that we have for all the Wards, we used Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) as described by (Ceballos et al., n.d) to evaluate alternate combinations considering the criteria listed on Table 3. As the initial step of TOPSIS, the criteria domain is normalized to adjust for differences in units by substituting elements x_{ij} of the decision matrix with n_{ij} described in equation (7):

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^m (x_{ij})^2}} \quad i = 1, 2, \dots, m, \quad j = 1, 2, \dots, n \tag{7}$$

This is followed by estimation of the normalized decision matrix v_{ij} defined as $v_{ij} = n_{ij} \times w_j$ where w_j is the weight of the j th criterion, $i = 1, 2,$

$\dots, m, j = 1, 2, \dots, n$ and estimation of ideal solutions as well as the distance from every alternative ideal solutions with d_i^+ to positive ideal solution A^+ and d_i^- the distance to negative ideal solution A^- . The relative closeness to both ideal solutions estimated as equation (8) is used to rank alternatives.

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{8}$$

Where $i = 1, 2, \dots, m$. If $R_i = 0$, then $d_i^- = 0$ implying worst possible case. However, if $R_i = 1$, then $d_i^+ = 0$ implies best possible case. In most cases, $0 \leq R_i \leq 1$. The final stage involves ranking alternatives i.e., R_i in descending order. The alternatives with the highest R_i is the best alter-

native. We achieved this using R language package known as TOPSIS (Yazdi and Mahmoud, 2022). The decision matrix used for our study to rank changes in accessibility is shown on Table 4.

We calculated the ranking for each alternative considering the existing stations and the combination of the new and the existing stations to determine any multicriteria effect on accessibility ranking.

4. Result and discussion

4.1. Point in polygon method

The first step of our analysis used the simple point in polygon to understand accessibility to charging station. We normalized the number of Electric vehicles charging stations (old separately and a combination of both the old and the new) to have a quick insight into the likely changes in accessibility to charging station per 10,000 population in each of the Ward. Our analysis showed that there was a considerable change in accessibility to EV charging station for some Wards of the city of Windsor Ontario Canada. The most significant improvement in accessibility per 10,000 population was seen around the downtown area of the city. Before the proposition of new additional stations, only five Wards in the city have considerable accessibility to charging station.

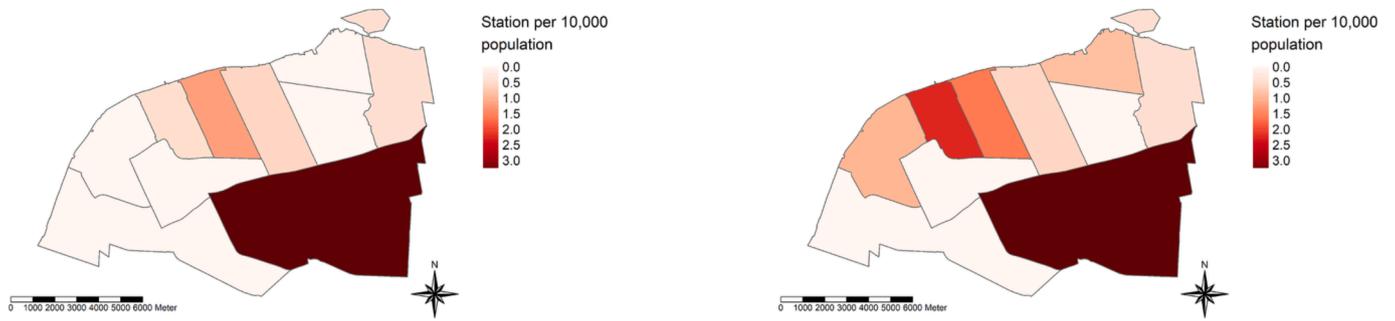
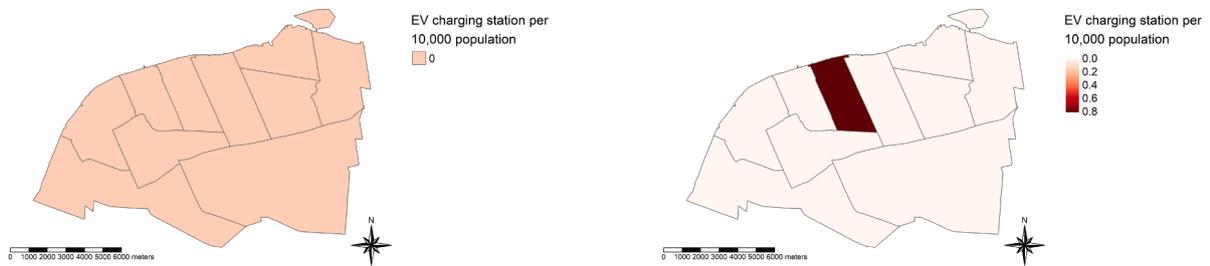
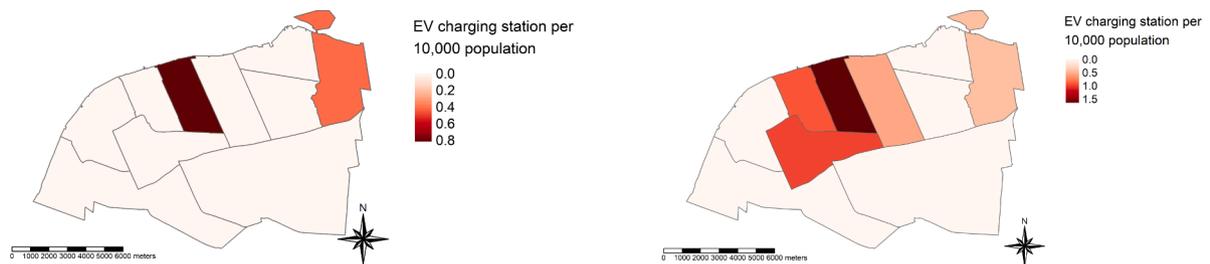


Fig. 2. Electric Vehicle Charging Station per 10,000 Population in City of Windsor, Ontario.



a. 500 meters catchment

b. 1000 meters catchment



c. 1500 meters catchment

d. 2000 meters catchment

Fig. 3. Accessibility to Charging Considering Only the Existing EV stations.

Three of these are near the city center while the other two Wards are near the town of Tecumseh and LaSalle. The rest of the five Wards lack accessibility to EV charging stations. However, it is important to highlight that southern Windsor i.e., Ward 9 has the greatest accessibility to charging which suggest inequalities in access to charging. This pattern could also be indicative of mobility justice issue induced by kinetic elites that of higher socioeconomic classes (see Fig. 2. Higher values show greater accessibility). Surprisingly, western part of the city suffered from poor accessibility to charging station and we suspect this to be influenced by land use or socioeconomics. Using all the station locations (old and the additional stations) that falls in each of the Wards as the basis, accessibility was seen to improve for some Wards while situation remained the same in others. For example, there was a slight improvement in accessibility to charging stations especially in the western part of the city. Accessibility for two of the Wards that are in the downtown core improved greatly. Only two of the Wards remained inaccessible

despite the new additions. Interestingly southern Windsor remained highly accessible to charging stations among other Wards. While the method of point in polygon provided a quick understanding of accessibility at each of the Wards in Windsor, the method is a bit constrained. The method assumes that that only the population within a particular Ward can use the stations that falls within its boundary. It neglects demand from another nearby Wards. Thus, we used the FCA method to understand if accessibility to the two Wards around central Windsor will improve.

4.2. Floating catchment area method (FCA)

The constraint associated with the use of point in polygon method could lead to misinterpretation if caution is not taken. To address this limitation, we evaluated accessibility using FCA method. Our FCA reveal an interesting pattern when accessibility is not limited to the geographic

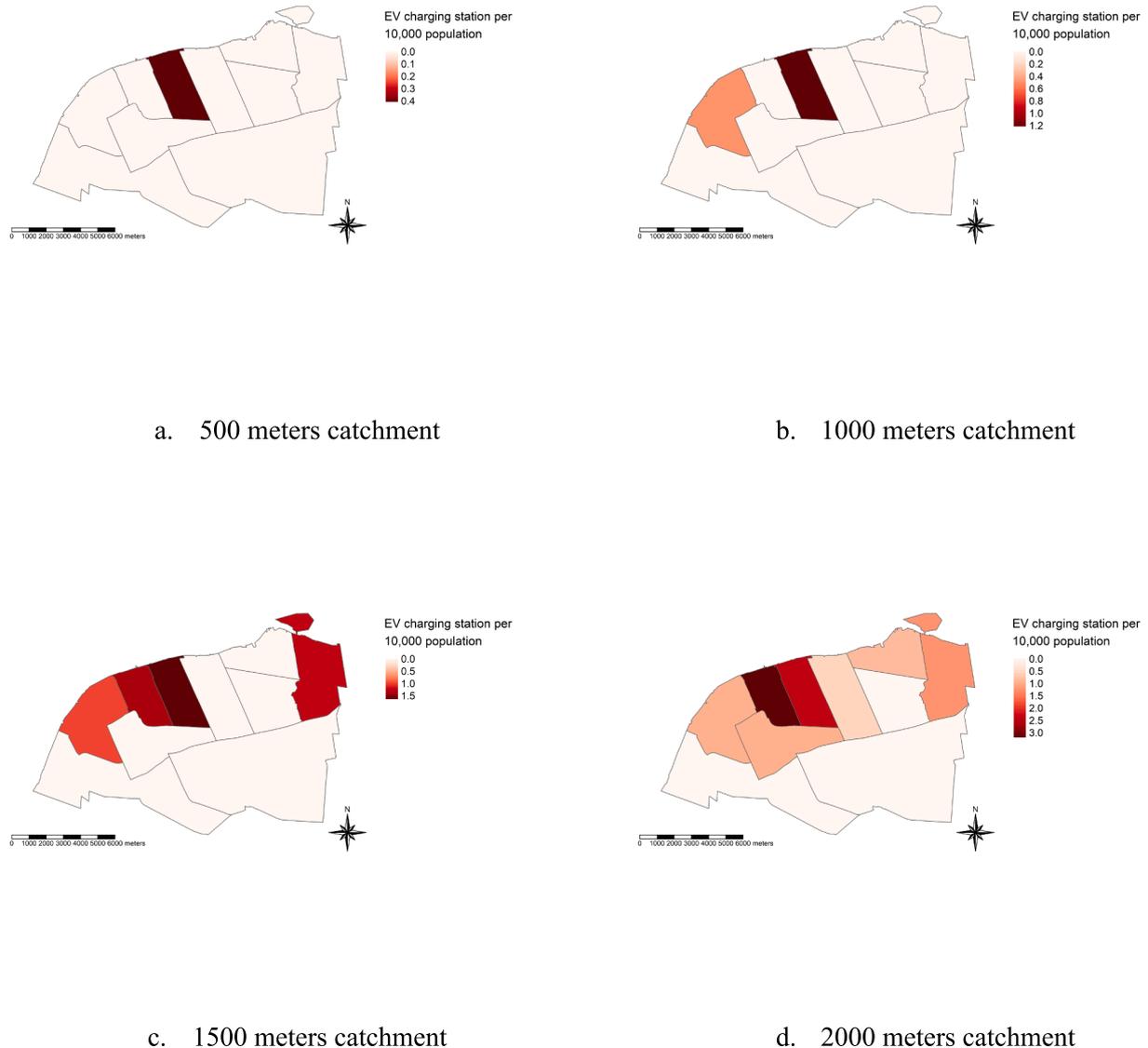


Fig. 4. Accessibility to Charging Considering the Existing and the new EV stations.

boundary of each Ward. We used buffer distances of 500, 1000, 1500 and 2000 meters as our catchment buffer. These buffers determine the distances at which stations are accessible from the center of the Wards which we refer to as the population or demand center in our study. This buffer does not take into consideration of the Ward boundaries.

Fig. 3 shows the accessibility levels considering the catchments areas for both the existing stations and combination of both the new and existing stations.

Higher accessibility score in Fig. 3. and Fig. 4 implies better accessibility at Ward level. When we considered accessibility to existing stations using our four-catchment scenario, we found that at 500 meters, there was no accessible stations from the centre of each of the Wards that our study uses as the demand center. However, this improved slightly when the catchment increased to 1000 meters i.e., one kilometer. Slight improvements was seen around the downtown cores and only one Ward was accessible. At a catchment of 1500 meters, two out of the Wards in the city of Windsor was accessible. These include the Ward that was accessible in the downtown core and the far eastern Ward towards the boundary of the city and Tecumseh. At the catchment of 2000 meters, five Wards became accessible. These includes additional three Wards and the earlier Wards that was identified at a catchment of 1500 meters (Fig. 3). The maximum accessibility score was found to be 0, 0.81, 0.81 and 1.62 for catchments of 500, 1000, 1500 and 2000 meters respectively. An interesting pattern was however seen in the variation in FCA accessibility when we considered the Wards in the southern part of Windsor that we earlier identified as highly accessible. Our catchment analysis revealed that the Ward was among the least accessible. This finding showed that caution should be exercised when using point in polygon to evaluate accessibility.

Our findings were different when the impact of the new additional stations was evaluated with the existing ones and there were higher variations in accessibility scores. Overall, accessibility was improved but we cannot generalize these across the Wards of the city. Downtown Wards benefitted most from the additions (see Fig. 4). At 500 meters buffer, only one Ward was accessible considering the FCA method. This was the same Ward that was earlier identified at 1000 m catchment area when we considered only old stations, but higher accessibility score was seen for this Ward. At 1000 meters catchment, two Wards were more accessible and includes the one located in the downtown core that was earlier identified at 500 meters catchment. The other Ward is in the western part and towards the boundary of the city of Windsor. At a catchment of 1500 meters, four (4) Wards were accessible, these includes the ones identified at a catchment of 1000 m. When the catchment was 2000 meters, most of the Wards i.e., seven (7) Wards in the city of Windsor was accessible and three (3) was not. The pattern seen with the southernmost Ward in Windsor when only the old stations was

considered still exist with the new additions. This Ward was among the three that has the least accessibility to charging stations even at a catchment radius of 2000 meters i.e., 2 km. A maximum score of 0.41, 1.22, 1.62, and 3.17 was found when both the existing and the new addition was compared for the catchment area of radius 500, 1000, 1500 and 2000 meters from the Ward centers.

While our study compared accessibility considering the old and new scenario that includes both the old and new stations, we found that accessibility to charging station is guaranteed from most of the Ward centroid at 2000 meters. Although with the announcement for the addition of EV charging stations in the city of Windsor, equal access to charging is still questionable for the city. Most of the Wards around downtown have better accessibility scores. This is suggestive that most charging stations are clustered around these areas. To promote equality and mobility justice, equal access must be granted to all Wards. To further justify our findings using FCA, we used network accessibility measures to determine the travel time from the city's Wards centroid to the nearest station.

4.3. Network level accessibility

The average travel time was longer when only existing stations were analyzed but the difference was not very large. When only the existing stations were analysed, the average minimum travel time from all Ward centroids was 5.914 minutes. This decreased slightly to 4.842 minutes when the new addition was considered. Wards at or around the downtown of the city of Windsor has better travel time to charging stations. The farther a Ward is from the city center; the more travel is required for charging to be done. Ward 4 was the most accessible to charging station when only the existing station were considered but the addition of more stations changed the dynamic. The travel time to nearby station is about 3.753 minutes, followed by Ward 7 at the time of 4.227 minutes. In the scenario that considered only the existing stations, Ward 2 in Western Windsor is the least accessible at a time of 8.953 minutes under free flow condition, preceded by Wards 6, 1, 10 and 8 at the travel times of 7.168, 7.302, 5.837 and 5.727 minutes respectively. Considering the existing scenario median travel time, Ward 9 and 3 seems to be accessible at the travel times of 6.088 and 5.131 minutes. Fig. 5a shows the minimum travel times from the center of each Ward to the closest station.

Ward 2 benefited most and the travel time which was at about 6.053 minutes dropped significantly. Thus, becoming the most accessible. The travel time from Ward 3 reduced slightly to 4.858 minutes (see Fig. 5b). Also, a reduction was seen in the travel time for Ward 2, 4, 6 and 7 but remained the same for Ward 1, 5, 8, 9, 10. Fig. 6 shows the difference in the travel time when only the existing stations and when both the existing and the new stations were considered. The distribution of travel

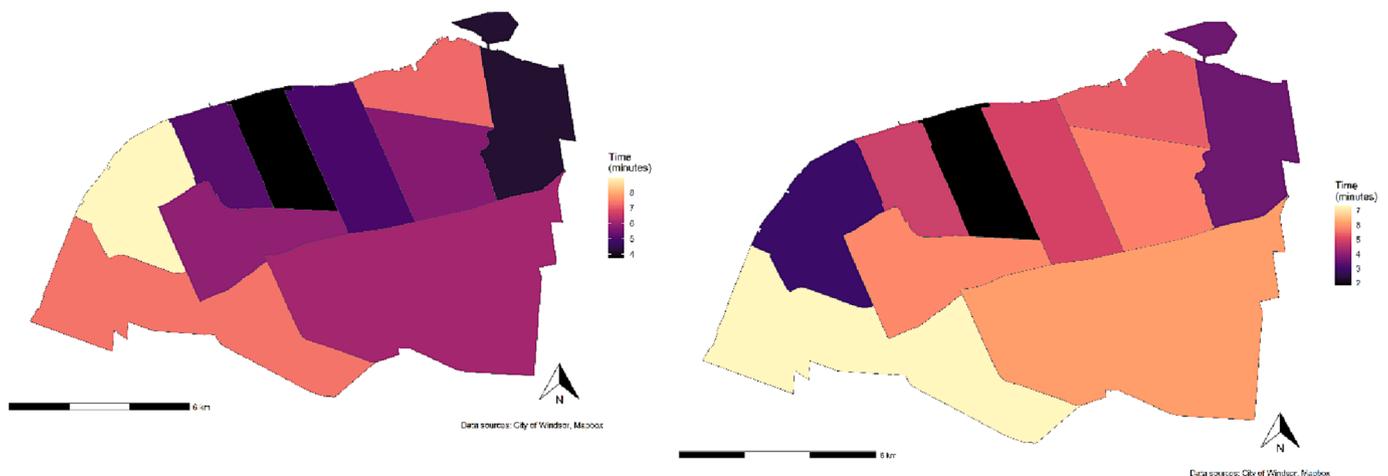


Fig. 5. Change in Network Minimum Travel Time considering a) Existing Stations b) New and Existing Station.

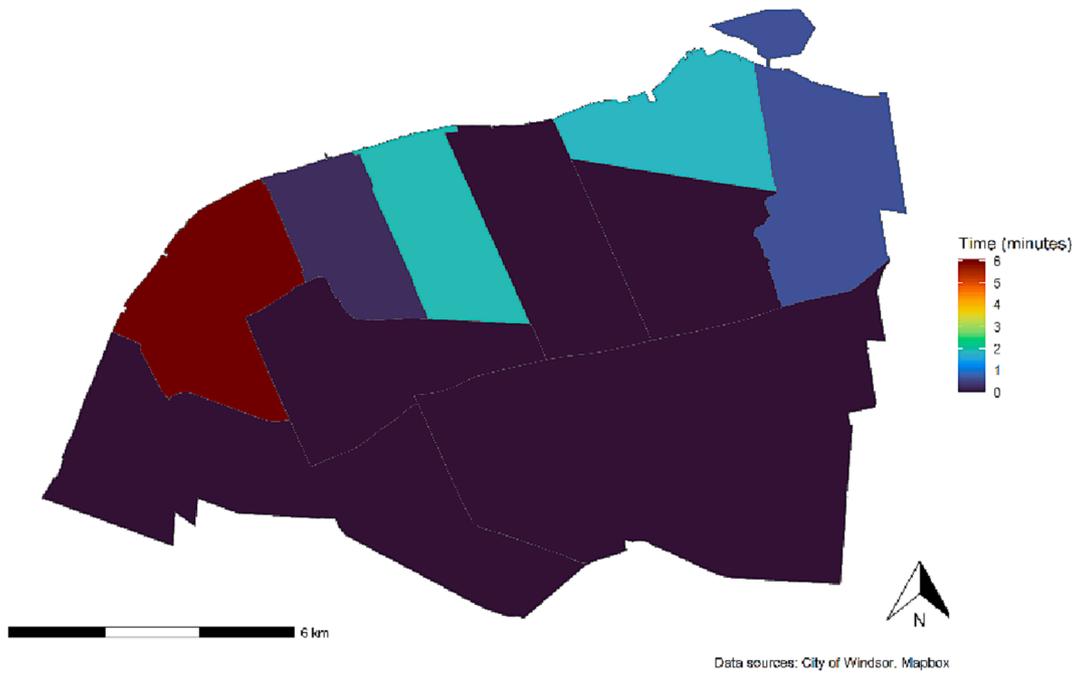


Fig. 6. Change in Travel Time to minimum travel time to Charging Stations.

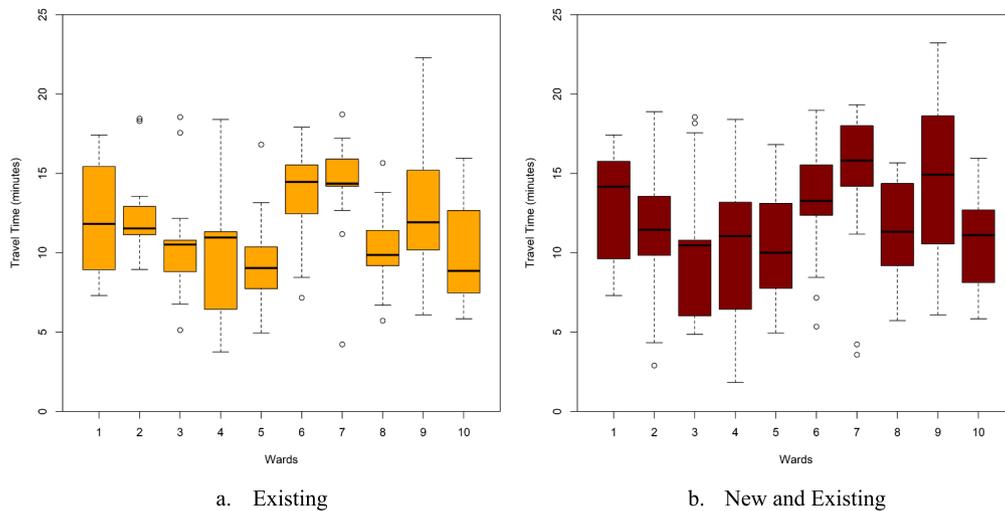


Fig. 7. Travel Time Distribution Considering the Existing and both the New and Existing Charging Locations.

times from the Ward centers to nearby stations are given in the boxplots shown on Fig. 7.

The boxplots of the distribution of travel times around the median for each of the Wards differs when the two-scenario shown in Fig. 7 was analysed. We found that:

1. There was almost a wider variation in the travel times for each of the Wards signifying more alternative stations for charging at a longer travel time.
2. The median travel time for Ward 1 increased significantly with the addition of more stations. Only slight differences were seen with the median travel time accessibility of Ward 2 to charging station when we compared the two scenarios in Fig. 7. However, the Ward has extreme travel times (outliers). It benefitted most from additional stations in travel times.

3. The median travel time to station for Ward 3, and 6 dropped slightly with the addition of more stations, surprisingly the median travel time for Ward 4 and 5, 7, 8, 9, 10 slightly increased but the difference was not significantly larger.

The larger variation from the median of the travel times for most of the Ward is suggestive from our network analysis that location of charging infrastructure might be random rather than planned. We expected that the addition of more charging station should improve accessibility from each Ward centers. Compared to the floating catchment method, we believe the network base accessibility measure could complement FCA method rather than the point in polygon approach. However, a MCDM considering the numbers of electric vehicles owned, available stations, minimum travel times, and population density was used to rank accessibility to Wards.

Table 5
Multicriteria Accessibility Ranking of Wards to Electric Vehicle Charging Stations in Windsor.

Wards	Scores		Rank		Changes in Rank
	All Stations (Existing and New)	All Stations (Existing)	All Stations	Existing Stations	
1	0.453	0.446	3	3	0
2	0.234	0.249	6	5	1
3	0.481	0.483	2	2	0
4	0.387	0.398	4	4	0
5	0.129	0.153	8	8	0
6	0.270	0.216	5	6	-1
7	0.157	0.173	7	7	0
8	0.061	0.099	10	9	1
9	0.741	0.790	1	1	0
10	0.103	0.088	9	10	-1

¹Bold black represents the top 4 Wards and red the least accessible from the MCDM.

4.4. MCDM for ranking accessibility to charging stations

We used the criterion specified in Table 4 in the determination of the Wards that is most accessible in the city of Windsor. It is however worth highlighting that the weight given to each of the criteria varied. For example, and as earlier discussed in the method section i.e., section 3.3.4, higher weights were given to the numbers of stations, the Total number of battery electric vehicle owned per Wards. This was based on the understanding that the number electric vehicles and charging stations owned have been reported to exhibit linear relationships. Lower weights were assigned to population density and plug in hybrid electric vehicles.

The result from the multicriteria decision making process to determine the Ward that is most accessible considering the electric vehicles owned, the minimum travel times to stations and population density revealed interesting patterns (see Table 5). Based on the ranking scores, Ward 9 appears and remained to be the most accessible considering all criteria followed by Ward 3, 1 and 4. Ward 8 was the least accessible across the city.

5. Conclusion and recommendation

Our study evaluate accessibility to EV charging stations in the city of Windsor. It uses the point in polygon, floating catchment, and network accessibility measures to gain insight into the ease at which stations could be accessed from the center of each of the city of Windsor Wards. Although, it is a quick and easy measure, our study found that using the point in polygon method only to measure accessibility could be misleading. We found that the most accessible Ward identified by this method was not quite accessible when demands from nearby Wards was evaluated. We determined this through the floating catchment method.

We used the floating catchment approach considering catchments of 500, 1000, 1500 and 2000 meters and captured changes in accessibility at these distances. At catchment of 500 meters from each of the Ward's centers, no station was accessible when we considered only the existing stations. At 1000 meters, only the Ward at the downtown core of the city was accessible. The numbers of Wards that were accessible to charging station increase to two (2) and five (5) at catchment area of 1500 and 2000 meters respectively. When we considered the existing and the new additional station, accessibility at the catchment of 500 meters mirrors exactly what was seen at the catchment of 1000 meters when only the existing stations were considered. When the catchment area of 1000 meters was considered, two Wards have the most accessibility to charging stations. These includes the Ward identified at the downtown core of the city. The number however increase to 4 at catchment of 1500 meters. At 1500 meters, two of the Wards that were accessible are those earlier identified at 1000 meters catchment and two others: the Wards

near the downtown cores and the easternmost Ward in the city of Windsor. However, at a catchment of 2000 meters, accessibility increased for most of the Wards in the city, but the southernmost Ward and the near eastern Ward's accessibility remained almost the same throughout our analysis. This pattern was consistent when only the existing stations were considered. Surprisingly, this contradicts what was earlier seen with the point in polygon methods for measuring accessibility which identified the southernmost Ward as the most accessible. Our findings showed that caution should be taken with the use of simple measures that counts the numbers of stations in each unit normalized with population. We further compared our findings from the FCA method with the network level analysis to validate accessibility of each Ward to charging stations.

Our network level accessibility analysis measured in terms of free flow travel time again confirmed what was found with some of the Wards using our FCA method. Considering the existing stations, we found Wards in the downtown area are the most accessible. The southernmost Ward in the city is not very accessible in terms of travel time and among the least accessible. Other least accessible Wards include those in the western Windsor and some towards the east. The minimum travel time from the Wards to the stations ranged between four (4) and nine (9) minutes. This however decreased to between two (2) and seven (7) minutes. While this is a slight decrease, improved accessibility extended westward around the downtown core. Ward 2 benefited most in terms of travel time accessibility to charging stations. Overall, accessibility slightly improved across three (3) Wards in the city while the minimum travel time for another four Wards remain the same. We suspect that the addition of new electric stations to the city of Windsor is rather random or possibly influence by political rather than planning decisions. We evaluated our claims by comparing the travel time distribution of the existing station with both the new and existing. Contrary to our expectation that the overall travel times will decrease considerable, we only found evident of slight decrease in travel times to stations from the Ward centers. In some cases, travel time decreased slightly. Overall distribution of travel times for most Wards was wider than when only the existing stations was considered. We deemed this pattern as indicative that each Wards have more access to alternate charging station but required more travel minutes. We expect that a well-planned out station rather than random location should minimize travel to charging stations. We conclude that the location of electric vehicle stations in Windsor Ontario might have been unplanned or rather, influence by political decisions. This was supported by our MCDM that showed minimal changes in the ranking of Wards when we examined both the existing and the combination of the existing and new stations. While our study currently focused on Windsor – a major city in Windsor- Essex metropolitan planning region, at the time of conducting this research, the population per Wards of other towns within the region is not accessible to us. Therefore, future research should study EV station accessibility at Windsor-Essex metropolitan planning level. Also, network optimization approach in determination of locations for EV stations within the region is an interesting research direction. We recommend that with more data collected or that are available, a machine learning approach could be considered to evaluate accessibility to EV charging stations in city. Also, travel and waiting times could be optimized to determine any likely impact on CO2 emission.

CRediT authorship contribution statement

Seun Daniel Oluwajana: Methodology, Formal analysis, Conceptualization, Data curation, Investigation, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. **Tanvir Chowdhury:** Project Administration, Validation, Writing – review & Editing. **Crystal Mingyue Wang:** Validation, Writing – review & Editing. **Olubunmi Philip Oluwajana:** Validation, Writing – review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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