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An integrated analysis of housing and transit affordability in the Chicago metropolitan area

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An integrated analysis of housing and transport affordability provides comprehensive insights into the affordability of different locations in a city. By focusing on transit-based workers, who constitute a significant portion of commuters but are understudied in the affordability literature, this study proposes a new, integrated method for estimating housing and transit (H + T) affordability in the Chicago Metropolitan Area using census data and data from the Google Maps Directions API. Methodologically, the study contributes to the literature by proposing and implementing a new method that estimates H + T affordability in an integrated manner based on census data and data from the Google Maps Directions API across three types of housing occupants (i.e., owners with/without a mortgage and renters). Empirically, the results indicate varying H + T affordability distribution patterns among different types of housing occupants and provide a comprehensive picture of housing and transport affordability in the study area without incurring prohibitive time and cost of data collection. The study indicates that policy-makers should consider expanding the existing concessionary fare scheme to include low-income residents and establishing affordable housing programmes that subsidise not only mortgage/rent but also miscellaneous costs related to housing (such as utilities) in order to improve the overall H + T affordability for different types of housing occupants.

KEYWORDS
census data, Chicago, Google Maps Directions API, housing affordability, transit affordability

1 | INTRODUCTION

Public transit is an integral part of the social and economic fabrics of cities. On any typical weekday in 2018, 4.9% of all workers in the US commuted by transit and the percentage of transit-based commuters reached 6.8% when considering only low-income workers (U.S. Census Bureau, 2018). The percentage of transit-based workers in some of the largest cities in the US – such as New York (55.9%), Chicago (28.3%), and San Francisco (33.5%) – is much higher than the national average (U.S. Census Bureau, 2018). Transit affordability is thus critical for a considerable proportion of the population, especially low-income people who are transit dependent, as low affordability could discourage transit usage and lead to reduced access to socioeconomic opportunities (Guzman & Oviedo, 2018).

Transport affordability is influenced not only by the direct cost of transport (e.g., parking, fuel, and transit fare) but also by the indirect cost incurred by housing (e.g., mortgage, rent, and utilities). In 2018, 25.6% and 12.4% of the average

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household annual income in the US was spent on housing and transport, respectively, accounting for nearly 40% of the average household annual income (U.S. Bureau of Labor Statistics, 2019). Besides, housing and transport costs are negatively related to each other as households tend to make trade-offs between housing and transport expenditures as postulated by classical urban economic models (Alonso, 1964; Mills, 1967; Muth, 1969). Specifically, low-income families that could not afford to live in the downtown area (where housing cost is high but transport cost is low) might choose to live on the urban periphery (where housing cost is significantly lower despite higher transport costs) in order to lower the overall housing and transport costs (Giuliano, 1991). Meanwhile, although traditional housing affordability studies have focused on measuring housing affordability by considering only the share of income spent directly on housing (Bogdon & Can, 1997), recent studies have attempted to examine housing affordability by incorporating transport-related factors such as access to transit (Dong, 2017) because such an approach takes the complex trade-offs between transport and housing costs into account when determining the affordability of different locations in a city. Therefore, considering housing affordability alone is not sufficient anymore. Instead, more emphasis should be put on measuring housing and transport affordability together in order to yield a more accurate picture of the location affordability landscape. However, the relationship between housing and transport costs is more complicated than that because the trade-offs between the two costs are often complex (e.g., it may be influenced by the types of housing available in different areas of a city and factors like discriminatory practices in the housing and mortgage markets).

The objective of this research is to employ a novel data-driven approach that measures transit, housing, as well as housing and transit (H + T) affordability across three types of housing occupants. The proposed approach can better inform policy-makers of the affordability distribution patterns in a large metropolitan area. These patterns are often affected by complex trade-offs between housing and transit costs along with income, especially for low-income neighbourhoods. Specifically, this study proposes a new method for estimating housing and transit cost based only on data from the census and the Google Maps Directions Application Programming Interface (API). The method can yield results for wider areas in a more timely and less costly manner.

2 | LITERATURE REVIEW

2.1 | Transport affordability

Transport affordability has been measured in terms of households' financial burden in purchasing transport services for accessing locations of opportunities (e.g., work, education, healthcare) (Litman, 2020). The existing literature shows that high travel expenditure reduces job accessibility (El-Geneidy et al., 2016; Liu & Kwan, 2020). Many transport affordability studies have been automobile based (Cao & Hickman, 2018; Walks, 2018), which explore the excessive burdens imposed by various exogenous factors such as road pricing, gas price, and parking cost on drivers of low socioeconomic status. However, there are still a significant number of transit-based commuters in many of those automobile-oriented countries (e.g., around 7.6 million transit-based commuters in the US as of 2018) (U.S. Census Bureau, 2018). Therefore, transit-based transport affordability deserves more attention.

Although some studies have examined transit-based transport affordability, they are limited to the context of developing countries (Guerra et al., 2018; Guzman & Oviedo, 2018) or developed countries outside the US (Mattingly & Morrissey, 2014; Saberi et al., 2017). Given the significant number of transit-based commuters in the US, especially in major metropolitan areas like New York, Chicago, and San Francisco, transit affordability in the US should also be examined. Transit affordability measurement is influenced by fare structure (Nassi & da Costa, 2012). Transit-based workers who live in the suburbs but work in the central city and use a zone-based monthly pass to commute may incur higher transport costs than transit-based workers who use a flat-fare monthly pass. Moreover, as urban middle-class professionals seek to shorten their commute time by living closer to urban centres, many low-income workers are priced out and forced to live in urban fringes that are far from their workplaces, and they have to incur substantial travel time costs besides the monetary costs (Lin, 2002).

2.2 | Housing affordability

Housing affordability can be generally defined as households obtaining appropriate housing without incurring excessive financial burden (Bereitschaft, 2019; Isalou et al., 2014; Saberi et al., 2017). The threshold provided by the Department of Housing and Urban Development (HUD) in 2018 for affordable housing is that households should not spend more than 30% of their income on housing.

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Depending on ownership status (i.e., owners with/without a mortgage and renters), housing costs can vary greatly. Hulchanski (1995) compared housing affordability for owners with/without a mortgage and renters in Ontario, Canada. Recently, Saberi et al. (2017) included housing costs for both owners with a mortgage and renters when measuring housing affordability in Melbourne, Australia. However, existing studies measured housing affordability by focusing only on housing costs without considering attendant transport costs, which ignores the inherent effect of housing location on the travel behaviour of residents (Haas et al., 2016). Besides, housing affordability studies that only consider housing costs have limitations in reflecting many other relevant neighbourhood characteristics (e.g., accessibility, quality, and sustainability) (Isalou et al., 2014).

2.3 | Transport and housing affordability

The measurement of either transport or housing affordability alone fails to uncover the full extent of the affordability of specific locations in a city (hereafter, location affordability) (Ganning, 2017; Haas et al., 2016). More studies have started measuring housing and transport affordability to reflect location affordability as location exerts great impacts on both transport and housing costs. Usually, suburban areas have more affordable housing options but may incur higher transport costs in accessing activity sites such as work, education, or healthcare either by private automobiles or public transit. In comparison, central cities usually have fewer affordable housing options but may incur lower transport costs in accessing activity sites either by private automobiles or public transit (Isalou et al., 2014; Saberi et al., 2017). The complementary relationship between housing and transport costs has been stated in the early land rent theory (Saberi et al., 2017). Smart and Klein (2018) found that there are more complicated trade-offs between housing and transport expenditures because, on the one hand, housing options that appear affordable in the far-flung suburbs may be unaffordable when transport expenditure outweighs savings from less-expensive housing in the suburbs; on the other hand, housing options in urban centres that appear expensive may be more affordable compared with the suburban housing options after taking the cheaper transport expenditure into account.

Moreover, the choice of housing location is limited by household income (Goodman, 1988), as many houses located in proximity to transit stations often require a premium (Bartholomew & Ewing, 2011; Zhang et al., 2016). The existing literature has shown that neighbourhoods of lower socioeconomic status tend to suffer from low housing and transport affordability (Saberi et al., 2017). People of lower socioeconomic status are often forced to move to remote locations that usually have lower access to socioeconomic opportunities (e.g., employment, healthcare, and education) as a result of low housing and transport affordability caused by gentrification (Jones & Ley, 2016), which forms a vicious cycle that traps them in long-term poverty.

There are place-based (Mattingly & Morrissey, 2014; Saberi et al., 2017) and person-based (Dewita et al., 2018; Isalou et al., 2014) methods for measuring transport/housing affordability. Because place-based methods can incorporate the housing, socioeconomic, and travel characteristics of all aggregate units covering the entire population in a study area, they can more accurately measure location affordability at a much larger scale such as the metropolitan area. However, place-based analysis assumes that individuals living in the same aggregate unit share similar characteristics since it uses aggregate data to represent individual socioeconomic and travel characteristics (e.g., housing/transport costs, income).

Person-based methods can overcome the limitations of this assumption because they can obtain accurate and detailed individual socioeconomic and travel information directly from survey participants, and this information could be used to determine location affordability at a fine-grained individual level. Despite this advantage (Guerra et al., 2018; Isalou et al. 2014), person-based studies cannot use data that cover all residents in a study area and reveal the detailed distribution patterns of location affordability at a large scale because the travel surveys they rely on tend to have small sample sizes. Besides, travel surveys are costly and time-consuming. As a result, person-based studies have limitations in their accuracy and efficiency (Hentschel et al., 2000). Therefore, this study fills the research gap by proposing a place-based integrated H + T affordability measure that can estimate H + T affordability based on readily available census data and API data, which cover the entire population in the study area in a much more efficient manner compared with travel survey-based studies.

To improve the accuracy of H + T affordability measurement, this research employs a context-based framework to examine H + T affordability at the metropolitan scale by differentiating people by their housing tenures (i.e., owners with/without a mortgage, renters) and income status (i.e., low-income, non-low-income). This is because housing costs vary significantly depending on the types of housing occupants; while income status affects the type of job opportunities one is likely to take up (e.g., low-income people are more likely to take up low-pay jobs and vice versa).

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3 | STUDY AREA AND DATA

3.1 | Study area

We select the Chicago Metropolitan Area (CMA) as our study area because it has experienced significant gentrification in its poor neighbourhoods in recent decades which reduces housing affordability in these places and puts its residents at risk of displacement (Jones & Ley, 2016). Besides, the study area has the second-largest transit system in the US, and around half of their riders are minority residents who tend to be low-income and suffer heavy financial burdens from transit fares. Given the low H + T affordability resulting from gentrification and transit-fare burden for many of its residents, it is appropriate to select the CMA as the study area. The study area consists of Cook County, DuPage County, Kane County, Kendall County, Lake County, McHenry County, and Will County (hereafter referred to simply as "Cook, DuPage, Kane, Kendall, Lake, McHenry, and Will"), located in the northeastern part of Illinois (Figure 1).

In this study, we consider the City of Chicago, the area delineated by the official administrative boundaries, as the central city and the area outside the City of Chicago as the suburban area. In the study area as of 2018, there were over half a million transit-based commuters (i.e., 13.23% of all workers in the study area), among whom 50% are minorities and 41.72% are low-income people (U.S. Census Bureau, 2018). The study area has three main public transit providers, which include the Chicago Transit Authority (CTA), the Pace Suburban Bus and Paratransit (Pace), and the Metra Commuter Rail (Metra).

3.2 | Data source

We use census tract (CT)-level census data and data derived from the Google Maps Directions API to calculate the H + T affordability in the CMA. There are 1,965 CTs in the study area. CT-level demographic information, housing information, employment information, transit time, and transit fare information are collected to measure H + T affordability.

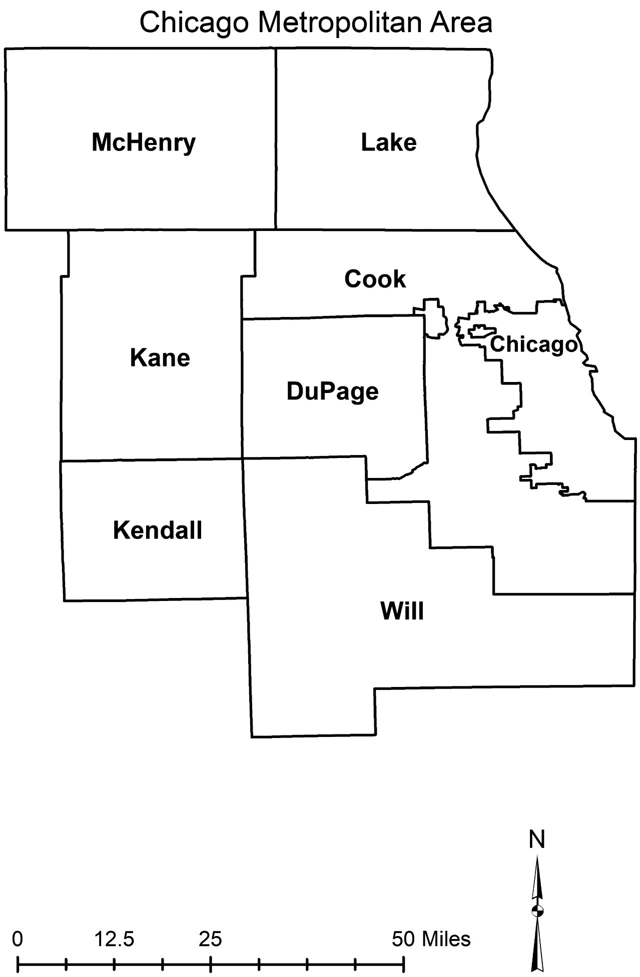

FIGURE 1 The Chicago Metropolitan Area.

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CT-level demographic information

We use the CT-level demographic information based on census data from the 2014–2018 American Community Survey (ACS) 5-Year Estimates, which includes the racial composition of workers; the number of workers who commute by public transit; the per capita income of transit commuters; and the mean commute time of transit-based workers.

CT-level housing information

This study compares H + T affordability across the three most common types of housing occupants (Table 1).

We use the CT-level housing information also based on the 2014-2018 ACS 5-Year Estimates, which includes the average housing cost for owners with a mortgage; the average housing cost for owners without a mortgage; the average gross rent for renters; the average household size of owner-occupied units; and the average household size of renter-occupied units. Since some of the 1,965 CTs in the study area have missing socioeconomic or housing information, we selected the 1,571 CTs (i.e., valid CTs) that have all the required socioeconomic and housing information to calculate their H + T affordability.

CT-level employment information

We derived employment information (e.g., total job number and job number in specific industries) from the latest Census Transport Planning Products (2012–2016), which can be used to identify low-pay jobs and non-low-pay jobs. We define low-pay jobs as jobs from four traditional industries filled with low-pay jobs (i.e., retail, wholesale, manufacturing, and construction) and non-low-pay jobs as jobs from all other industries. Since low-income workers are more likely to work in low-pay jobs, it would be more appropriate to assign higher weights to the transit fare cost for low-income workers with low-pay jobs and vice versa.

CT-level transit cost and transit fare

Transit fare of the CTA and Pace is flat-rate, while the transit fare of the Metra is zone based. As the monthly pass is the cheapest option for regular transit commuters, we only consider the affordability of the monthly pass in this study. As of 2018, the CTA/Pace monthly pass allows unlimited rides on both CTA and Pace services with a flat fare of $105. The cost of a monthly pass for the Metra is based on the fare zones, as shown in Table 2.

We constructed a CT-level centroid-to-centroid transit travel time matrix and a transit fare matrix based on the Google Maps Directions API and the fare information provided by the transit operators, respectively. The departing time is set at 8:30 a.m. on a weekday because this time is within the morning rush hour period, which has the highest transit service frequency and shortest headway of the day. Although some studies have also adopted the General Transit Feed Specification to obtain transit information based on actual schedules and routes, they usually have to assume a certain travel speed to estimate the walking time (i.e., ingress/egress/transfer time) to and from transit stations/bus stops. In comparison, the Google Maps Directions API integrates real-time ingress/egress, transfer, waiting, and on-board time into the travel time.

3.3 | Methodology

Our study measures H + T affordability based on the transit cost for monthly pass-using transit-based commuters in combination with housing costs for owners with/without a mortgage and renters. As we have gathered the mean travel time for transit-based commuters of each CT from the census data and calculated the CT-level centroid-to-centroid transit travel time matrix of all the CTs in the study area via the Google Maps Directions API, we select the possible destination CTs with centroid-to-centroid transit travel time within a five-minute range of the mean transit travel time from each origin CT and consider the selected CTs as potential destination CTs. We divide all CTs into low-income and non-low-income CTs based

TABLE 1 General housing cost and household size information for different housing tenures

Type of housing occupants	Average monthly housing cost ($)	Average household size	% by housing tenure
Owners with a mortgage	1,839.19	2.95	66.03
Owners without a mortgage	755.03		
Renters	1,352.21	2.74	33.97

TABLE 2 Metra fare zones and the corresponding monthly fare rates (in US$) in 2018

Fare zone	A	B	C	D	E	F	G	H	I	J	K	M
A	116											
B	123.3	116										
C	159.5	123.3	116									
D	181.3	159.5	123.3	116								
E	195.8	181.3	159.5	123.3	116							
F	210.3	195.8	181.3	159.5	123.3	116						
`G	224.8	210.3	195.8	181.3	159.5	123.3	116					
H	239.3	224.8	210.3	195.8	181.3	159.5	123.3	116				
I	261	239.3	224.8	210.3	195.8	181.3	159.5	123.3	116			
J	275.5	261	239.3	224.8	210.3	195.8	181.3	159.5	123.3	116		
K	290	275.5	261	239.3	224.8	210.3	195.8	181.3	159.5	123.3	116	
M	319	304.5	290	275.5	261	239.3	224.8	210.3	195.8	181.3	160	116

on their median annual individual income using the low-income definition of "$43,600 or below" in 2018 for Illinois according to HUD. We assume that low-income workers work in low-pay jobs and non-low-income workers work in non-low-pay jobs. Therefore, for each possible destination CT that falls within the five-minute range of the mean transit travel time from the origin CT, we weight the transit cost to that destination CT based on whether the origin CT is low-income or non-low-income. If the origin CT is low-income, then we weight the transit fare cost to each possible destination CT by the ratio of the destination CT-level low-pay jobs to the total low-pay jobs. If the origin CT is non-low-income, then we weight the transit fare cost to each possible destination CT by the ratio of the destination CT-level non-low-pay jobs to the total non-low-pay jobs. By weighting "the transit fare from low-income/non-low-income origin CT to destination CT" with "the low-pay/non-low-pay job number at the destination CTs as a percentage of total low-pay/non-low-pay job number," we take into account the fact that not all destinations are equal in terms of appropriate job number. Specifically, the average per capita transit cost is calculated by Equations (1) and (2).

$$\overline{\mathrm{TC}_{i(\mathrm{lowinc})}} = \sum_{j=1}^{n} \mathrm{TrC}_{ij} \frac{\mathrm{LE}_j}{\sum_{j=1}^{n} \mathrm{LE}_{ij}} \tag{1}$$

$$\overline{\mathrm{TC}_{o(\mathrm{nonlowinc})}} = \sum_{k=1}^{m} \mathrm{TrC}_{\mathrm{ok}} \frac{\mathrm{NE}_k}{\sum_{k=1}^{m} \mathrm{NE}_{\mathrm{ok}}} \tag{2}$$

where $\overline{\mathrm{TC}_{i(\mathrm{lowinc})}}$ is the average per capita transit cost for low-income CT i; n is the number of destination CTs within the $\pm$ 5 minute time limit; TrC_{ij} is the per capita transit cost for travelling from CT i to CT j; LE_j is the number of low-pay jobs in destination CT j; $\sum_{j=1}^{n} \mathrm{LE}_{ij}$ is the total number of low-pay jobs; $\overline{\mathrm{TC}_{o(\mathrm{nonlowinc})}}$ is the average per capita transit commute cost for non-low-income CT o; m is the number of destination CTs within the $\pm$ 5 minute time limit; $\mathrm{TrC}_{\mathrm{ok}}$ is the per capita transit cost for travelling from CT o to CT k; NE_k is the number of non-low-pay jobs in destination CT k; $\sum_{k=1}^{m} \mathrm{NE}_{\mathrm{ok}}$ is the total number of non-low-pay jobs.

The process of estimating the average transit fare cost for each origin CT is illustrated in Figure 2.

After estimating the average per capita transit fare cost, we obtain the average per capita housing cost for owners with/without a mortgage by dividing their average household housing cost by the average household size of homeowners in each CT; while the average per capita housing cost for renters is obtained by dividing their average household housing cost by the average household size of renters in each CT as shown in Equations (3) and (4).

$$\mathrm{HC}_{i(\mathrm{owner})} = \frac{\mathrm{HoC}_{i(\mathrm{owner})}}{\mathrm{HS}_{i(\mathrm{owner})}} \tag{3}$$

$$\mathrm{HC}_{i(\mathrm{renter})} = \frac{\mathrm{HoC}_{i(\mathrm{renter})}}{\mathrm{HS}_{i(\mathrm{renter})}} \tag{4}$$

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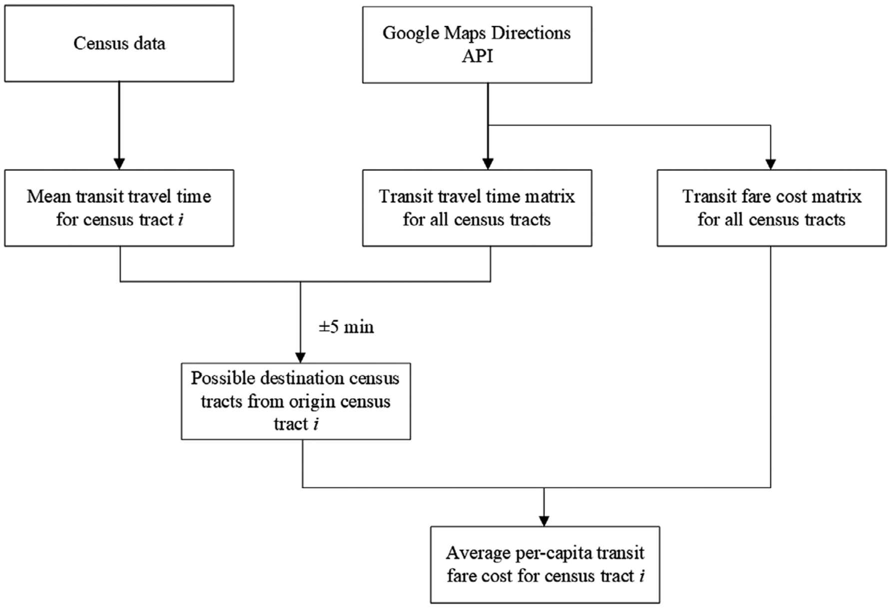

FIGURE 2 Estimating average per capita transit fare cost.

where $HC_{i(owner)}$ is the average per capita housing cost for owners (with/without a mortgage) in CT i; $HoC_{i(owner)}$ is the average household housing cost for owners (with/without a mortgage) in CT i; $HS_{i(owner)}$ is the average household size for owners (with/without a mortgage) in CT i; $HC_{i(renter)}$ is the average per capita housing cost for renters in CT i; $HoC_{i(owner)}$ is the average household housing cost for renters in CT i; $HS_{i(owner)}$ is the average household size for renters in CT i.

Based on the transit cost and housing cost obtained from Equations (1)–(4), we then calculate the transit affordability and housing affordability separately based on transit/housing expenditure–income ratio measures as shown in Equations (5) and (6).

$$\text{TAff}_i = \frac{\text{TC}_i}{\text{TransitINC}_i} \times 100\% \tag{5}$$

$$\text{HAff}_i = \frac{\text{HC}_i}{\text{TransitINC}_i} \times 100\% \tag{6}$$

where TAff_i is the transit affordability of CT i; TC_i is the average per capita transit cost of CT i; TransitINC_i is the per capita income for transit commuters of CT i; HAff_i is the housing affordability of CT i; HC_i is the average per capita housing cost of CT i.

H + T affordability is calculated based on H + T expenditure–income ratio measures used in existing studies (Isalou et al., 2014), as shown in Equation (7).

$$H + \text{TAff}_i = \frac{\text{HC}_i + \text{TC}_i}{\text{TransitINC}_i} \times 100\% \tag{7}$$

where $H + \text{TAff}_i$ is the H + T affordability of CT i; HC_i is the average per capita housing cost of CT i; CT_i is the average per capita transit cost of CT i; TransitINC_i is the per capita income for transit commuters of CT i.

4 | ANALYSIS AND FINDINGS

4.1 | Demographic characteristics in the study area

The study area is known to have a high level of residential and economic segregation with a largely low-income minority-dominated central city and mostly middle/high-income white-dominated suburbs. Table 3 and Figure 3 show the population and median per capita income (MPI) for each area and each population group.

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As shown in Table 3, as of 2018, the study area has a total population of 4,155,231, of which 55.96% are white and 44.04% are minorities (black, Hispanic, Asian, Native American). Although the minority population accounts for less than half of the total population, it takes up nearly 60% of the central city's population; while the white population still dominates the suburbs. Overall, the median per capita income of the minority population is much less than that of the white population. The result confirms that the central city is largely dominated by low-income minorities while the suburbs are dominated by higher-income white people.

As shown in Figure 3(a, b), there is an obvious negative correlation between the minority percentage and the median income for the CTs in the study area. The CMA is residentially and economically segregated, with lower-income minorities being confined largely to the west and south of the central city and higher-income white residents residing in the north of the central city as well as the suburban CTs. Figure 3(c) shows that transit-based workers largely reside in the central city. The west and south of the central city has a population of predominantly poor minority workers, which could indicate higher financial burden in those areas.

4.2 | Analysis of housing and transit affordability

Based on Equations (1)–(7), we calculate CT-level transit commute cost for all CTs in the study area; transit affordability; housing affordability; and H + T affordability. The results are presented and analysed in the following subsections.

Transit cost and transit affordability

We first visualise the geographical distribution of transit cost in the study area. Since the global Moran's I identifies only overall spatial patterns and cannot reveal local clustering, we analyse the spatial patterns of affordability using the local Moran's I via ArcMap because it can identify local clustering patterns in different areas (Liu et al., 2020; Zhang et al., 2008). The results are shown in Figures 4 and 5.

As shown in Figure 4, CTs in the central city generally appear to have low transit cost compared with many CTs outside the central city. Outside the central city, CTs in the entire Cook County and DuPage County, southeast of Lake County, east of Kane County, north of Will County and southeast of McHenry County appear to have higher transit cost than the CTs in the central city.

As shown in Figure 5(a) and (b), the west and south of the central city have huge clusters of less affordable CTs, while the north of the central city has a small concentration of more affordable CTs. In comparison to Figure 4, it can be seen that although CTs in the west and south in the central city have lower transit cost compared with most CTs outside the central city, CTs in the west and south in the central city appear to actually have lower transit affordability compared with their counterparts outside the central city. This can be explained by the fact that although transit-based workers living in the west and south of the central city have low transit cost, they also tend to be low-income workers, as shown in Figure 3(b) and (c). As a result, they may spend a higher percentage of their income on transit fares even when they live in low-transit-cost CTs. Therefore, although fare adjustment can help lower the transit cost (Nassi & da Costa, 2012), it does not necessarily help improve the overall transit affordability as income also plays a critical role in determining affordability.

Housing cost and housing affordability

We then visualise the geographical patterns of housing cost and housing affordability for three different types of housing occupants in the study area and analyse the spatial patterns of housing affordability. The results are shown in Figures 6–8.

TABLE 3 Descriptive demographic and economic statistics of the study area

	Total		White		Minority	
Region	Population	Median per capita income ($)	% of population	Median per-capita income ($)	% of population	Median per-capita income ($)
Metro area	4,155,231	40,643	55.96	51,179	44.04	30,394
Central city	1,487,302	34,300	42.78	54,441	57.22	29,787
Suburb	2,667,929	44,971	63.31	49,967	36.69	31,828

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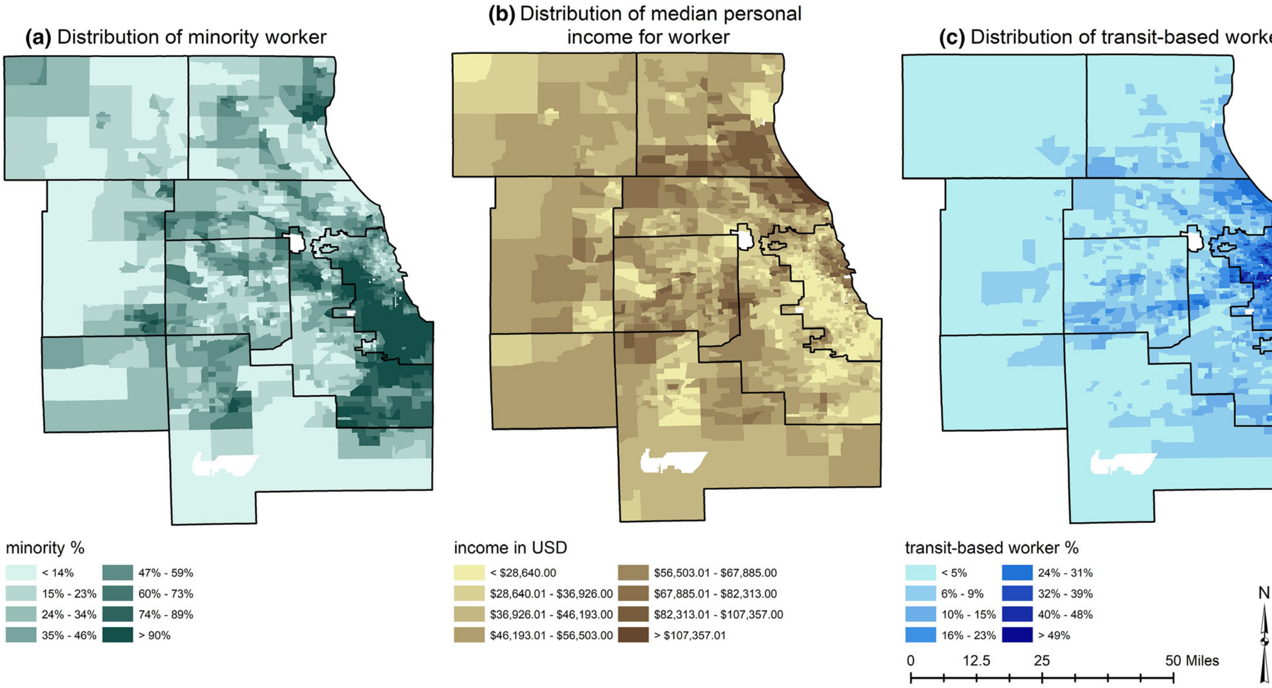

FIGURE 3 Distribution of (a) minority worker, (b) individual worker, median income, and (c) transit-based worker in the CMA. [Colour figure can be viewed at wileyonlinelibrary.com]

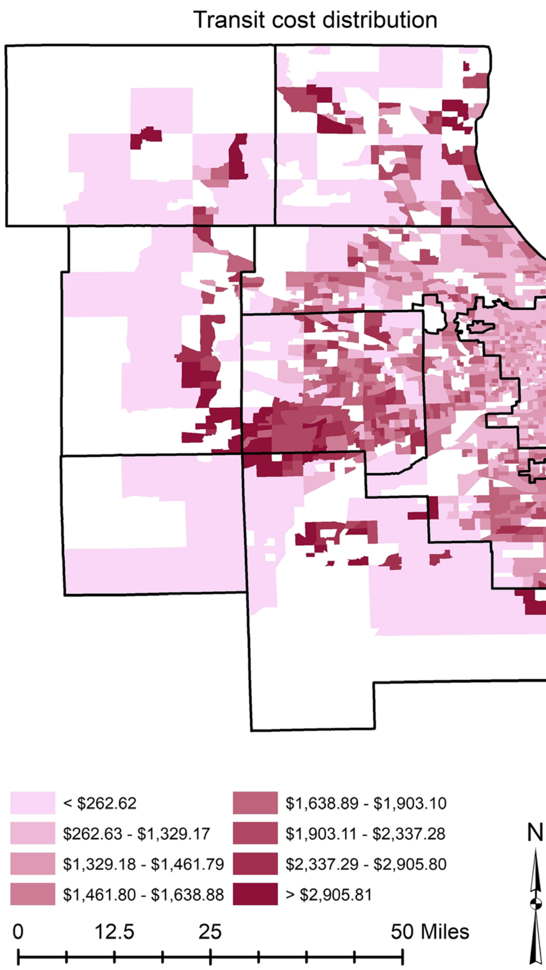

FIGURE 4 Transit cost distribution. [Colour figure can be viewed at wileyonlinelibrary.com]

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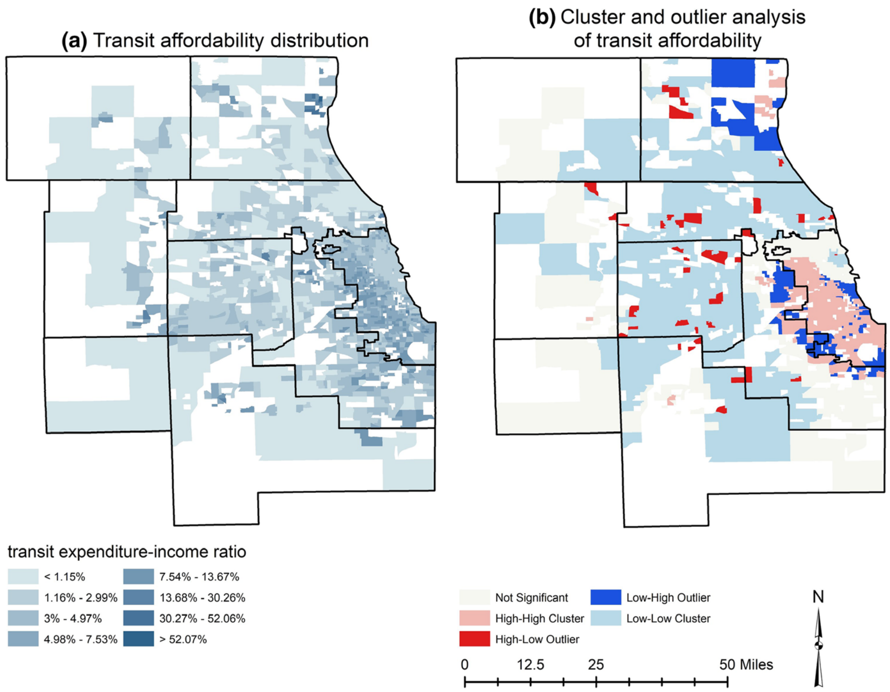

FIGURE 5 (a) Transit affordability distribution; (b) cluster and outlier analysis of transit affordability. [Colour figure can be viewed at wileyonlinelibrary.com]

As shown in Figure 6(a), for owners with a mortgage within the central city, CTs in the west and south have lower housing cost than those in the north. Outside the central city, most CTs tend to have higher housing cost than those in the west and south of the central city, except those to the immediate south of the central city. As shown in Figure 6(b), for owners without a mortgage, there is a clear central city/suburb divide, with most CTs inside the central city having lower housing cost than those from outside the central city. As shown in Figure 6(c), for renters within the central city, CTs in the west and south have slightly lower housing cost than those in the north. Outside the central city, there is no apparent cluster of CTs with either high or low housing cost. Instead, CTs with high and low housing cost are mixed and spread around.

Overall, Alonso-Mills-Muth economic models (Alonso, 1964; Mills, 1967; Muth, 1969), which postulate that housing price decreases as the distance from the city centre increases, only fit well with the renters' housing cost distribution pattern but not with the owners' housing cost distribution pattern. The housing cost for renters decreases as the distance from the city centre increases. This could be explained by the fact that the central city has better transit coverage and transit-based workers prefer living there. However, as many transit-based workers are low-income, they can only afford to rent and thus drive up the rental demand and cost. Moreover, the housing cost distribution patterns for owners actually contradict the Alonso-Mills-Muth economic models as the housing cost for owners generally increases as the distance from the city centre increases, which can be explained by the preference of middle/high-income workers to reside in the suburbs, as shown in Figure 3(b), driving up the demand and cost for house ownership in the suburbs.

By comparing Figures 7(a) and 8(a) with Figure 6(a), it can be seen that for owners with a mortgage, although CTs in the west and south within the central city have lower housing cost than most CTs outside the central city, CTs in the west and south within the central city appear to have lower housing affordability compared with the CTs outside the central city. This can be explained by the fact that most CTs in the west and south of the central city are resided by low-income minority workers (Figure 3(a) and (b)). Although they have lower housing cost, they also have lower income at the same time, which translates into lower housing affordability. This highlights the important point that lower housing cost does not necessarily lead to higher housing affordability after taking income into account.

By comparing Figures 7(b) and 8(b) with Figure 6(b), it can be seen that for owners without a mortgage, although central city CTs generally have lower housing cost than those outside the central city, CTs in the south within the central city appear to have lower housing affordability compared to many CTs outside the central city. Outside the central city, CTs in Cook to the immediate southwest of the central city have high housing cost and low housing affordability. This can be explained by the fact that most CTs in the south within the central city and to the immediate south of the central city are

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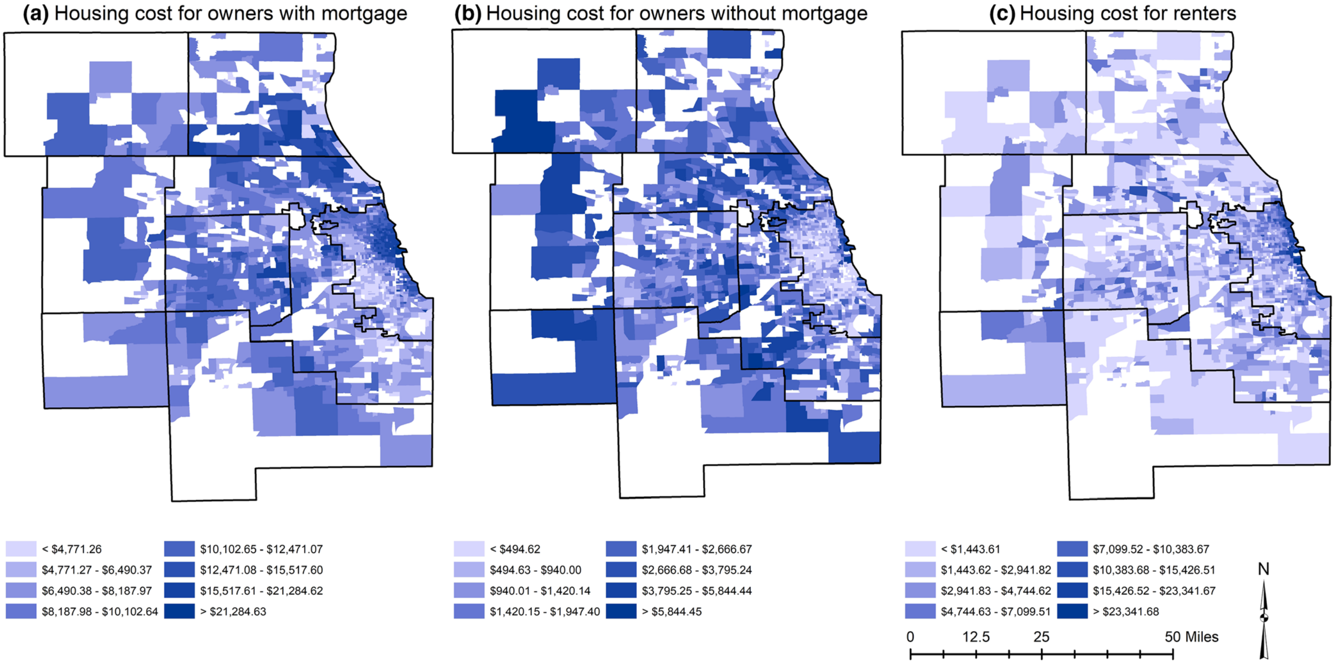

FIGURE 6 Housing cost for (a) owners with mortgage; (b) owners without mortgage; and (c) renters. [Colour figure can be viewed at wileyonlinelibrary.com]

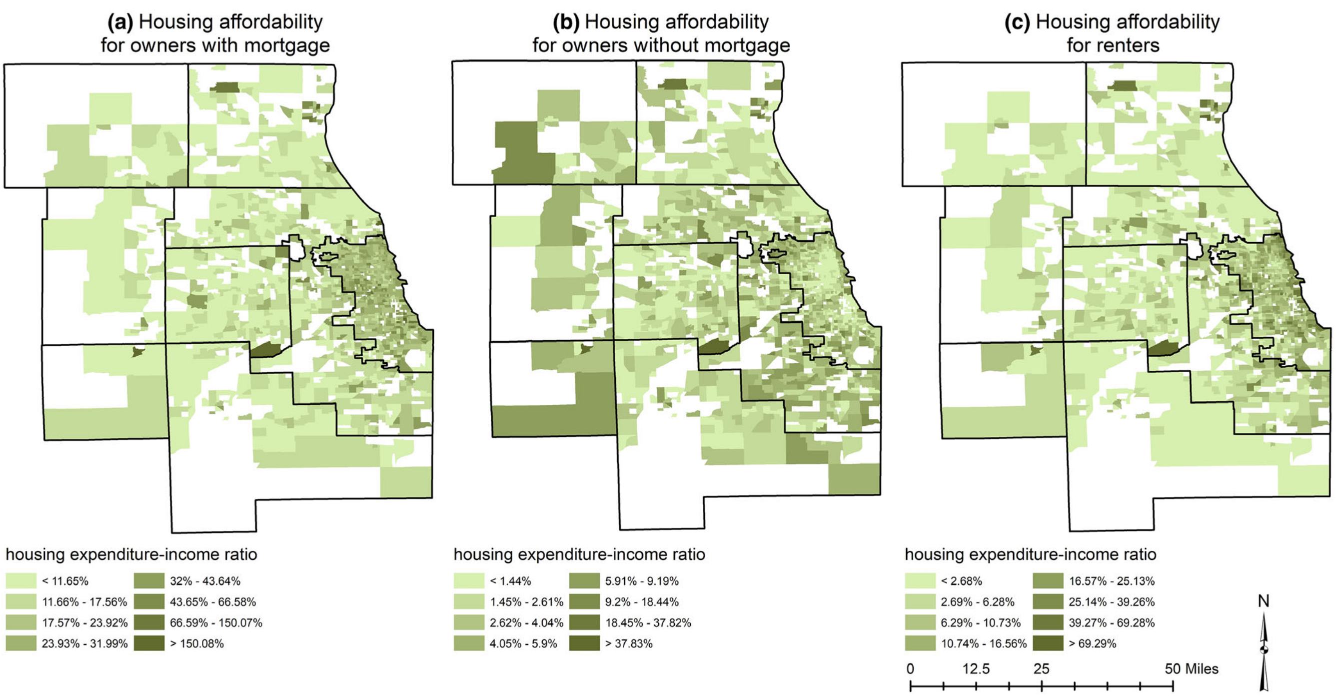

FIGURE 7 Housing affordability for (a) owners with mortgage; (b) owners without mortgage; and (c) renters. [Colour figure can be viewed at wileyonlinelibrary.com]

resided by low-income minority workers, as shown in Figure 3(a) and (b). For CTs in the south of the central city, although they have lower housing cost, they also have lower income at the same time, which actually translates into lower housing affordability. This indicates that lower housing cost does not necessarily mean higher housing affordability after taking income into account. For the CTs located to the immediate south of the central city, because their residents face higher housing cost but have lower income, it is unsurprising that they have low housing affordability.

By comparing Figures 7(c) and 8(c) with Figure 6(c), it can be seen that for renters, although CTs in the north of the central city appear to have higher housing cost than CTs in the west and south of the central city, they have higher housing

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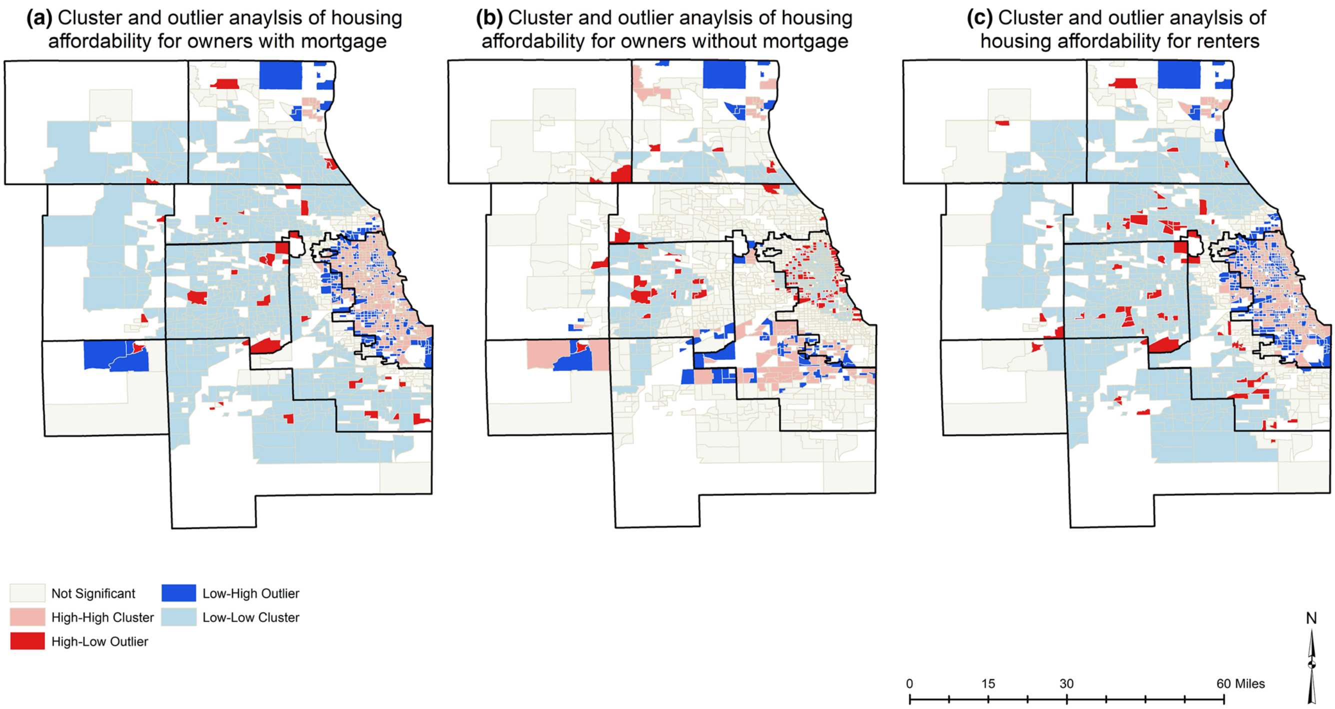

FIGURE 8 Cluster and outlier analysis of housing affordability for (a) owners with mortgage; (b) owners without mortgage; and (c) renters. [Colour figure can be viewed at wileyonlinelibrary.com]

affordability than those in the west and south of the central city. Outside the central city, CTs with housing cost similar to those in the south and west of the central city turn out to have higher housing affordability. This can be explained by the fact that most CTs in the south within the central city and to the immediate south of the central city are resided by low-income minority workers while CTs in the north of the central city and outside the central city are mostly resided by higher-income white workers, as shown in Figure 3(a) and (b).

In summary, findings from this section indicate that the geographical patterns of housing affordability for different types of housing occupants vary significantly. The existing literature that considers housing affordability from the perspective of either owners (Gan & Hill, 2009) or renters (Edmiston, 2016) overlooks the heterogeneity of housing occupants. Even for housing owners, the affordability patterns for housing owners with a mortgage appear to be very different from those for housing owners without a mortgage.

Housing and transit cost, and housing and transit (H + T) affordability

Finally, we visualise the H + T cost and H + T affordability for three different types of housing occupants in the study area before analysing the spatial patterns of H + T affordability. The results are shown in Figures 9–11.

For owners with a mortgage, Figure 9(a) shows that CTs in the west and south of the central city have relatively low H + T cost while those in the north have higher H + T cost. Outside the central city, CTs generally have higher H + T cost than CTs in the west and south of the central city, except for those within Cook to the immediate south of the central city. For owners without a mortgage, Figure 9(b) shows that most CTs within the central city have lower H + T cost compared to most of the CTs outside the central city. However, there are some CTs with low H + T cost outside the central city in the north of Will, northwest of DuPage, southeast of McHenry, and southwest of Lake. For renters, Figure 9(c) shows that CTs along the northeastern border of the central city having higher H + T affordability than other CTs within the central city. The rest of the central city has CTs of different levels of H + T affordability spreading around. Outside the central city, there is also a more mixed pattern within Cook, DuPage, and Kane as CTs of different levels of H + T affordability spread around in these three counties. Most CTs in Will, McHenry, and Lake tend to have a low H + T cost. Overall, the patterns for renters differ from those of owners with or without a mortgage.

As shown in Figures 10(a) and 11(a), for owners with a mortgage, it can be seen that although CTs in the west and south within the central city have lower H + T cost compared with most CTs outside the central city, CTs in the west and south within the central city appear to have lower H + T affordability compared with their counterparts outside the central

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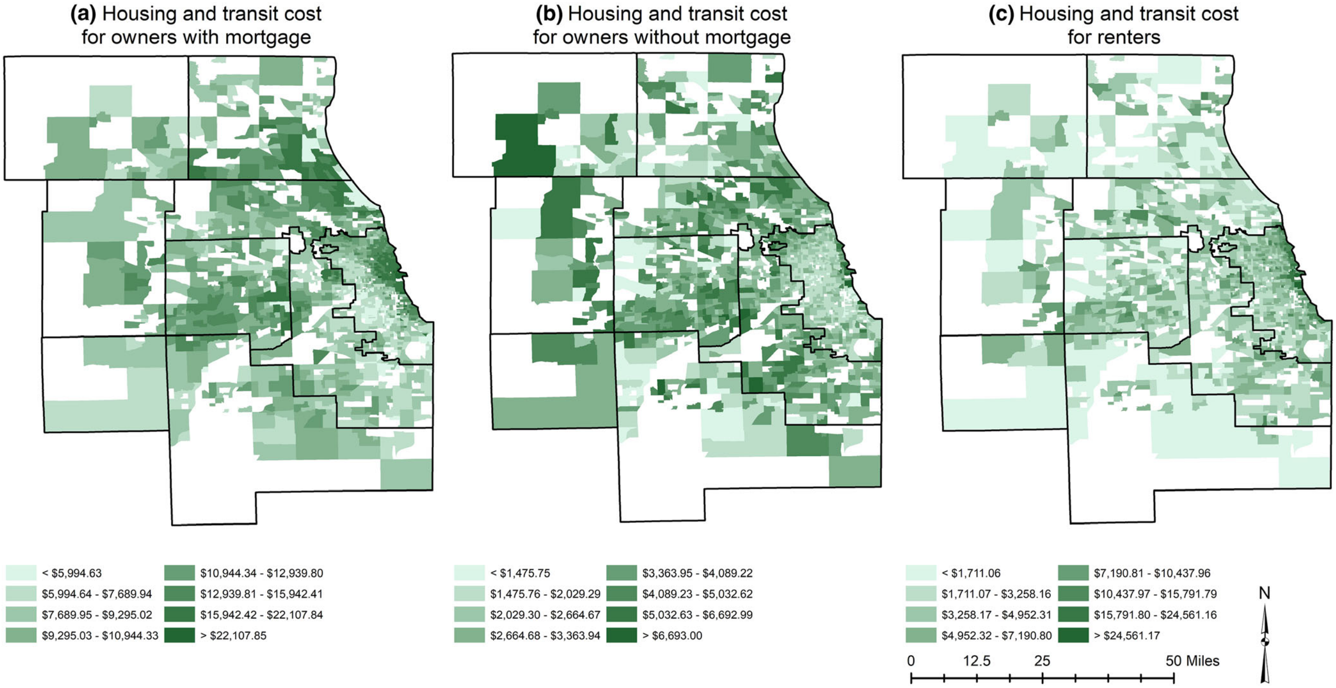

FIGURE 9 Housing and transit cost for (a) owners with mortgage; (b) owners without mortgage; and (c) renters. [Colour figure can be viewed at wileyonlinelibrary.com]

city. This can be explained by the fact that most CTs in the west and south within the central city are resided by low-income minority workers, as shown in Figure 3(a) and (b).

As shown in Figures 10(b) and 11(b), for owners without a mortgage, it can be seen that although most CTs within the central city have lower H + T cost compared with most CTs outside the central city, most central city CTs, except those in the north, turn out to have lower H + T affordability compared with CTs outside the central city. This can be explained by

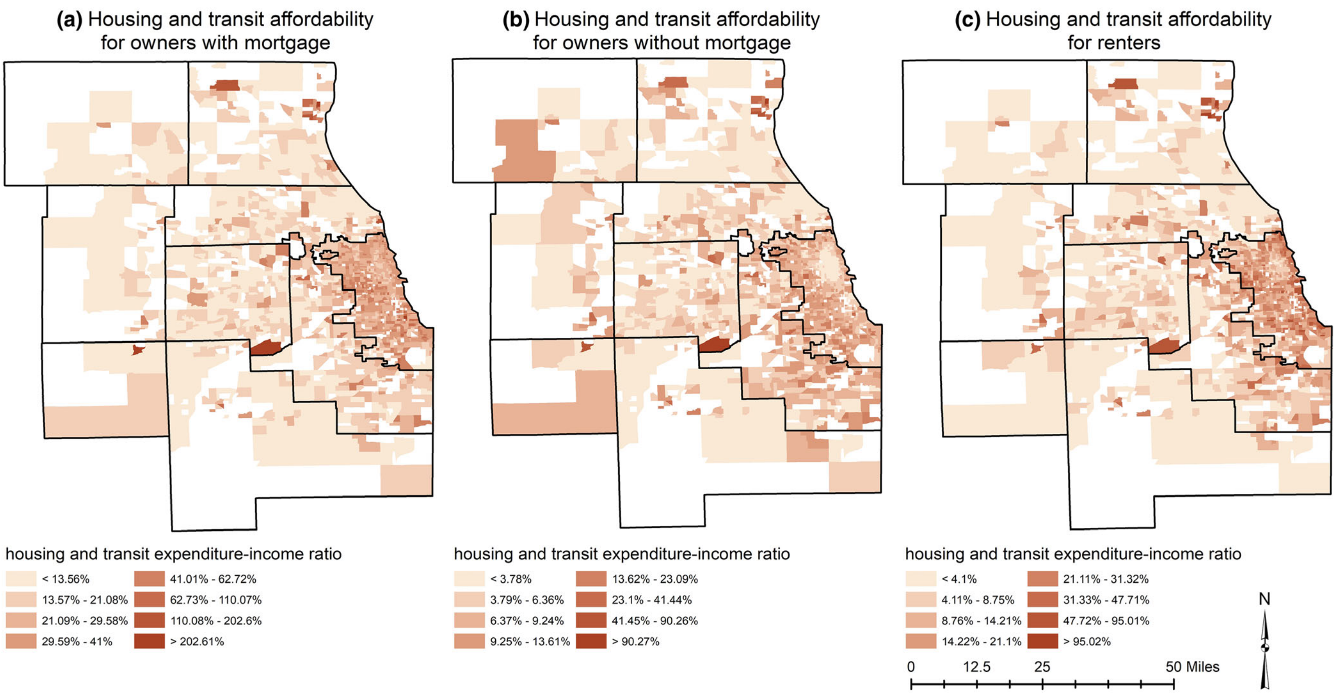

FIGURE 10 H + T affordability for (a) owners with mortgage; (b) owners without mortgage; and (c) renters. [Colour figure can be viewed at wileyonlinelibrary.com]

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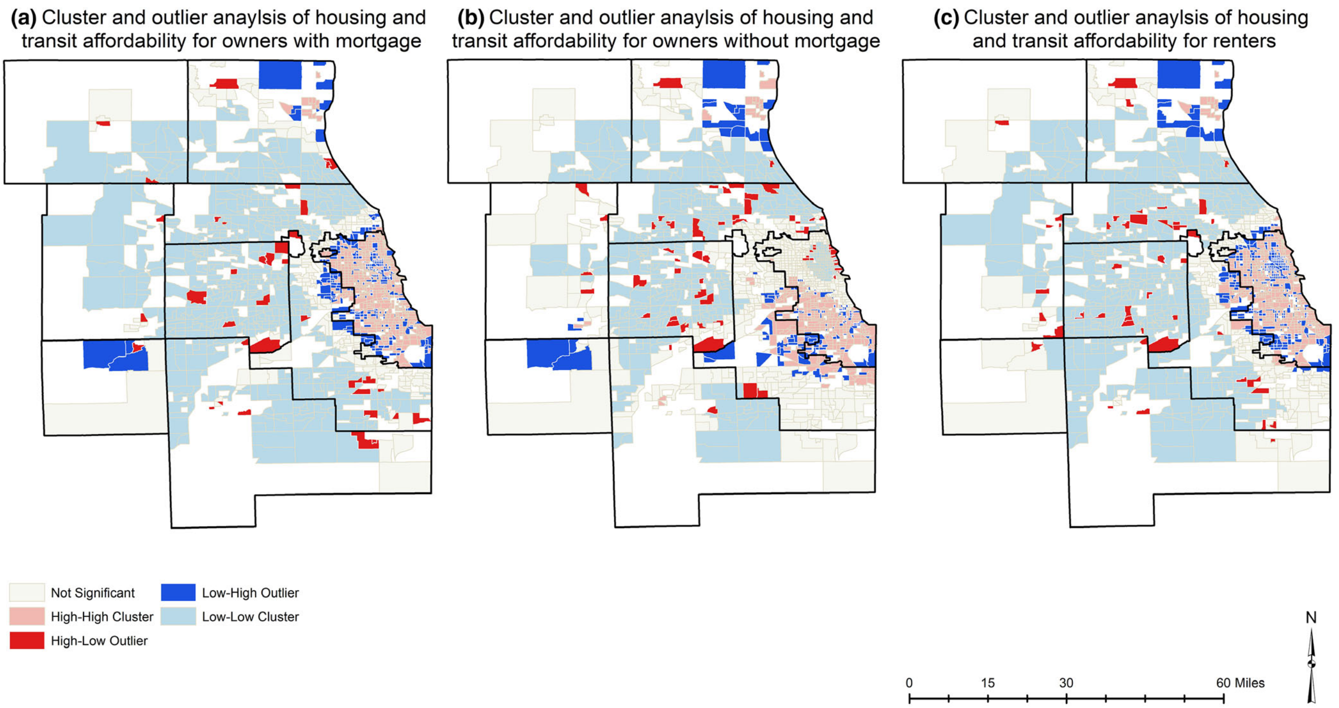

FIGURE 11 Cluster and outlier analysis of H + T affordability for (a) owners with mortgage; (b) owners without mortgage; and (c) renters. [Colour figure can be viewed at wileyonlinelibrary.com]

the fact that most CTs in the west and south within the central city are resided by low-income minority workers while those in the north of the central city, as well as those outside the central city, are mostly resided by higher-income white workers, as shown in Figure 3(a) and (b).

As shown in Figures 10(c) and 11(c), for renters, most CTs in the central city, except a small concentration in the north, have generally lower H + T affordability compared with CTs outside the central city. This again can be explained by the fact that most CTs in the west and south in the central city are resided mostly by low-income minority workers while those in the north of the central city and those outside the central city are mostly resided by higher-income white workers, as shown in Figure 3(a) and (b).

In summary, findings from this section confirm that the measurement of either transport affordability or housing affordability alone cannot reveal the real affordability of a location (Ganning, 2017; Haas et al., 2016). By considering H + T affordability, the geographical patterns of affordability appear to be significantly different from those obtained from considering only transport or housing affordability. Moreover, the findings have also revealed the complex trade-offs between housing and transport expenditures and showed that both housing and transport are integral parts to accurately measuring location affordability. Overall, our findings indicate serious H + T affordability inequality between the central city and suburbs. Besides, there is an evident affordability segregation pattern in the west and south of the central city where the minority-dominated neighbourhoods are the most disadvantaged across all three types of housing occupants. This reflects the reputation of the CMA being one of the most residentially and economically segregated metropolitan areas in the US where neighbourhoods in the west and south of its central city are dominated by poor minorities who also suffer from the worst H + T affordability.

5 | DISCUSSION AND CONCLUSION

This study proposes a new method to estimate H + T affordability based on census and API data, which takes into consideration the socioeconomic, housing, and travel characteristics of all census tracts and covers the overall population in the region. Our results show that the suburbs generally have higher H + T affordability than the central city across all types of housing tenures. This contradicts the findings of previous studies (e.g., Dewita et al., 2018; Isalou et al., 2014), which found that H + T affordability of the central city is higher than that of the suburbs. Besides, the existing literature has found significant differences between the geographical patterns of housing affordability and H + T affordability, which indicates the impact of transport cost on location affordability. In comparison, our results show that for owners with a

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mortgage and renters, the geographical patterns of housing affordability look similar to those of H + T affordability, which suggests that transport cost may be insignificant in influencing location affordability for these two types of housing occupants. Nevertheless, for owners without a mortgage, the geographic patterns of housing affordability appear very different from those of H + T affordability, which indicates that transport cost is significant in influencing location affordability for owners without a mortgage. Our findings, obtained by leveraging much more comprehensive data than previous studies, offer more insights into the complexity of H + T affordability distribution by different housing tenures.

Overall, while the low-income minority-dominated west and south of the central city consistently have low H + T affordability regardless of housing tenure, the higher-income white-dominated north of the central city consistently has high H + T affordability regardless of housing tenure, which aligns well with the geographical patterns of residential and economic segregation in the study area. The unemployment data show that the 2018 average unemployment rate for the study area is 7.85%, with central-city neighbourhoods in the west and south having a staggering unemployment rate of 14.64%, central-city neighbourhoods in the north having a much lower unemployment rate of 4.71%, and suburban neighbourhoods having an unemployment rate of 5.77%. These unemployment rates correlate well with the H + T affordability: white neighbourhoods in the suburbs and north of the central city with high H + T affordability tend to have low unemployment rates, whereas minority neighbourhoods in the west and south of the central city with low H + T affordability tend to have high unemployment rate. The combination of high unemployment and low H + T affordability in these latter areas calls for urgent action to address the predicament in these areas.

Therefore, policy-makers need to channel more funding towards the improvement of H + T affordability for workers living in the west and south of the central city. The funding can take the form of a concessionary fare scheme. The CTA, Pace, and Metra currently provide concessionary fares for disabled people, older adults aged over 65, and Medicare recipients. However, in the study area, low-income people currently do not receive any form of concessionary fare. Expanding the current concessionary fare scheme to include more socially disadvantaged groups such as low-income people would enhance their H + T affordability. Besides, more affordable housing programmes should be rolled out in neighbourhoods with low H + T affordability (e.g., the south and west of the central city) in tandem with the concessionary fare scheme. Since existing affordable housing programmes mainly help subsidise rent or mortgage costs, policy-makers should also consider subsidising other housing costs such as real estate tax, homeowners' or renters' insurance policies, utilities, and condominium fees (as our study has indicated that even for owners without a mortgage, non-mortgage housing costs can still make housing unaffordable). Our results indicate that high transit/housing affordability alone does not guarantee overall H + T affordability. In order to improve the location affordability of minority-dominated poor neighbourhoods, policy-makers should consider reducing residents' financial burdens (which include transit fare burden and housing cost burden) on two fronts: first, by establishing concessionary fare programmes to help low-income residents; second, by implementing affordable housing programmes that subsidise not only rent and mortgage payments, but also other miscellaneous housing-related costs.

Finally, our study has some limitations in terms of data usage. First, we rely on the average cost to measure affordability, which could be affected significantly by extreme values. Due to the use of aggregate data at the CT level, which assumes that all residents within a CT have the same socioeconomic and transport characteristics, the proposed method may have limitations when applied to cities with more mixed neighbourhoods. Future work could explore data-driven methods for measuring H + T affordability for cities with more mixed neighbourhoods and propose corresponding measures that can help improve H + T affordability for mixed neighbourhoods with consistently low H + T affordability.

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DATA AVAILABILITY STATEMENT

The data used in this study are from the U.S. Census Bureau and are available to the public.

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