Traffic & Transportation

Analysis of Traffic Characteristics Based on Multi-Source Data – A Case Study of Jinan

Boqi LV[1], Zhenhua MOU[2], Qingbin WANG[3], Jiangshan PAN[4], Yongming WANG[5], Yuanxi ZHENG[6]

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[1] 513950664@qq.com, Shandong Jianzhu University, School of Transportation Engineering
[2] Corresponding author, mouzhenhua@sdjzu.edu.cn, Shandong Jianzhu University, School of Transportation Engineering
[3] 1021019794@qq.com, Shandong Jianzhu University, School of Transportation Engineering
[4] 1005564299@qq.com, Shandong Jianzhu University, School of Transportation Engineering
[5] 1602272281@qq.com, Shandong Jianzhu University, School of Transportation Engineering
[6] 1742375780@qq.com, Shandong Jianzhu University, School of Transportation Engineering

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ABSTRACT

With the acceleration of urbanisation, the uneven distribution of educational resources has led to many children's school choices, which has increased their school time and occupied a lot of rest time. Taking the Lixia District of Jinan City, China as an example, this paper uses the Thiessen polygon to delineate the scope of school districts, introduces the actual selection weight of children based on the OD data of students, and combines the 4 × 1,767 × 62 data obtained by Gaode API platform to construct the actual and school district accessibility model to study the accessibility and traffic fairness of families with different incomes in the process of school connection. The study identifies disparities in accessibility and traffic equity among income groups, with high-income families experiencing longer school commutes due to school choice behaviours. Compared with the actual general education, the difference in household income in the school district has a greater impact on traffic inequity. Therefore, reasonable school choice can reduce the difference in traffic accessibility between families.

KEYWORDS

actual accessibility; households with different incomes; sense of happiness; transportation inequality; choosing schools far away.

1. INTRODUCTION

In recent years, the school distance of primary school students has been increasing, and the proportion of students who go to school by car has also gradually increased. The school distance generated by children's school choice behaviour is affected by social resources, family economy and travel preferences [1, 2]. According to statistics, more than 50% of students in England choose to enrol in schools [3], and only 18% of students in Tosoweto, Johannesburg, South Africa choose to go to the nearest school [4]. This high proportion of school choice has brought a heavy traffic burden to children and parents and has an important impact on urban traffic. It will form a concentrated school flow in a fixed period of time. The morning and evening rush hours of the working day overlap with the commuting flow of residents in space, which aggravates the traffic pressure of urban roads.

Most cities in China implement the policy of "dividing districts and enrolling students nearby" in the compulsory education stage. Although it can meet the requirements of everyone to go to school, the living space of the city is artificially divided into "school district" and "non-school district", which aggravates the spatial locking of high-quality educational resources and the spatial isolation of different social strata [5]. There is still a huge gap in supporting facilities, school size and teachers between school districts. The "nearby enrolment" policy cannot meet parents' pursuit of high-quality educational resources. The phenomenon of children going to school across school districts and even across administrative districts is still very common.

In the field of transportation, accessibility is understood as the degree of difficulty for individuals or families to reach another space from one space through different modes of transportation. It is a key indicator to evaluate the spatial distribution of transportation facilities and the efficiency of transportation modes [6]. The accessibility model has matured and is divided into accessibility models based on spatial barriers [7, 8], accessibility model based on opportunity accumulation [9], accessibility model based on spatial interaction [10, 11] and derived many refined models, such as the nearest distance model, the Huff model, the kernel density analysis model, the gravity model and the two-step moving search algorithm. Accessibility can be divided into potential accessibility and actual accessibility. Potential accessibility measures that individuals can theoretically achieve opportunities. It is assumed that individuals perform the same behaviour in space and time, ignoring some specific attributes of individual residents, such as behavioural characteristics and choice preferences of residents [12, 13]. The actual accessibility is closer to the actual cognition and feelings of residents and is closely related to people's real travel behaviour [14, 15], which measures the degree to which individuals achieve actual opportunities based on their own needs and realistic factors [16].

With the development of information technology, the data of residents' travel can be recorded and analysed by different media, which provides the possibility for the quantitative calculation of actual accessibility. Some scholars have begun to use taxi GPS trajectory data or mobile phone signalling data to integrate residents' travel behaviour to build an actual accessibility model [17]. However, this kind of data has certain limitations in the application of the general school scene. It cannot accurately distinguish whether the residents' travel is a general school behaviour, only reflects the general school characteristics of a specific family and ignores the overall situation. Subsequently, the methods of geocoding and questionnaire were applied to the actual general study. For example, Zhang et al. [16] geocode the student's address to obtain the student's family spatial location information and distribution; Jiang et al. [18] used the survey data of students to construct the OD matrix between school districts and used the flow ratio between school districts to calculate the accessibility.

The theory of fairness was first proposed and applied in the field of psychology by Adams [19]. Litman [20] applied the theory of fairness to the field of transportation, and divided traffic equity into vertical equity and horizontal equity. Horizontal fairness is absolute fairness, which means that everyone in society can travel fairly and enjoy the distribution of transportation resources fairly. Kim and Wang [21] analysed the accessibility of children to kindergartens in Seoul, South Korea from the perspective of horizontal equity, and found that there are huge differences in the spatial accessibility of children's schooling. Vertical equity is to consider the travel ability and the demand for transportation resources of different income families in society. Different families obtain different transportation resources to ensure that vulnerable families obtain more transportation services [22, 23].

Higgs et al. [24] analysed the impact of different income families on medical accessibility from the vertical equity perspective. They found that vulnerable families of the elderly mainly rely on public transportation to obtain medical services. In addition, some scholars analyse the fairness of transportation modes from the competitive relationship of different modes of travel. Zuo et al. [25] studied the competitive relationship between bicycle and walking in Hamilton County, USA, and found that the accessibility of residents using bicycle + public transportation was 43.7% higher than that of walking + public transportation.

Accessibility can roughly reflect traffic fairness in the process of children's schooling to a certain extent, but a more specific fairness assessment needs to use the evaluation model to quantify the traffic indicators. The Gini coefficient and Theil index are used by many scholars to evaluate fairness. Among them, the Gini coefficient is an indicator to measure the fairness of income distribution in a country or region. It is based on the Lorenz curve, and the numerical range is from 0 (completely equal) to 1 (completely unequal). The smaller the Gini coefficient, the more equitable the income distribution. The Theil index is an indicator to measure the degree of inequality between and within different groups. It has good decomposition and can be used to explain the degree of fairness between and within groups. The greater the Theil index, the greater the gap between the groups, and the higher the degree of unfairness. The Lorenz curve is a linear relationship between the cumulative share of income in a country or region and the cumulative share of the population. It is used to intuitively represent the fairness of income distribution. When the Lorenz curve is close to 45 degrees, the income distribution is fairest. The Gini coefficient is an indicator to determine the degree of distributive justice based on the Lorenz curve [26, 27]. Shinjo and Sang [28, 29] used the Lorenz curve and Gini coefficient to evaluate the fairness of residents' medical treatment. The Theil index has good decomposition, which can explain the contribution degree between groups and within groups and can be used as an indicator to measure the fairness of families with different spaces and incomes. Jin et al. [30] used the Theil index to evaluate the degree of inequality between families and within families and found that inequality between families is more serious than inequality within families in high-level medical services, while the results are opposite in primary and secondary medical services.

Although residents' travel accessibility has received more attention in the field of transportation [31, 32], there are few studies on the accessibility of general education from the perspective of social class and travel mode. The traditional accessibility method assumes that individuals perform the same behaviour in space and time, ignoring the specific attributes of individual residents, resulting in a certain deviation in the analysis results [33, 34]. This study uses the student OD data to construct the actual accessibility model, which can consider the real travel mode, school choice behaviour and traffic congestion to simulate the dynamic travel demand of the city. Two scenarios of actual school access and school access in the school district are constructed to explore the impact of the "nearby enrolment" policy on the accessibility and traffic fairness of families with different incomes. Specifically, this study will answer the following questions: What are the differences in the characteristics of dynamic cyberspace among households with different incomes? How are the relative accessibility differences in different ways distributed in space? How do the accessibility and traffic equity of families with different incomes change in the two scenarios of actual school and school district?

This paper provides a more comprehensive analysis framework for school accessibility by integrating multiple data sources. However, traditional research may rely on a single data source and cannot fully reflect the actual situation. Multi-source data fusion can provide more accurate school time and mode. In addition, the Thiessen polygon method is used to delineate the scope of the school district. This method can more accurately reflect the geographical boundary of the school district and the actual school access path of the students. At the same time, the actual school access accessibility model is constructed to analyse different income families. Compared with the existing research, this can more truly reflect the traffic conditions and time costs in the process of children's school access and provide an in-depth understanding of children's school access experience under different socio-economic backgrounds. In the evaluation of traffic equity, this paper uses quantitative indicators such as the Gini coefficient and Theil index, which can measure and compare the differences in traffic resource allocation among different households. Finally, the influence of school choice behaviour on school accessibility is discussed, which provides a new perspective for understanding how school choice behaviour affects school time and traffic fairness.

This paper is as follows: Section 1 introduces the research background and literature review on accessibility. Sections 2 and 3 introduce the research data and methods utilised. Section 4 presents the results of accessibility of commuting to school and transportation equity for households with different incomes and different travel modes. Section 5 summarises the paper and discusses relevant policies.

2. DATA

2.1 Research area

This paper focuses on the Lixia District as the research area. As one of the six main urban districts of Jinan, Lixia District is in the central area of Jinan. According to the data from the 7th National Population Census, the resident population of the district is 819,000. Lixia District boasts abundant educational resources, and as of 2021, there are 62 primary school districts (including schools with nine-year system and twelve-year systems). The district includes 14 streets with a total area of 100.9 square kilometres. To reflect the spatial variation characteristics of accessibility in more detailed research units, this paper divides the research area into 1,767 grids measuring 0.25 km×0.25 km and uses satellite image maps and population grid data to remove uninhabited areas, as shown in *Figure 1*.

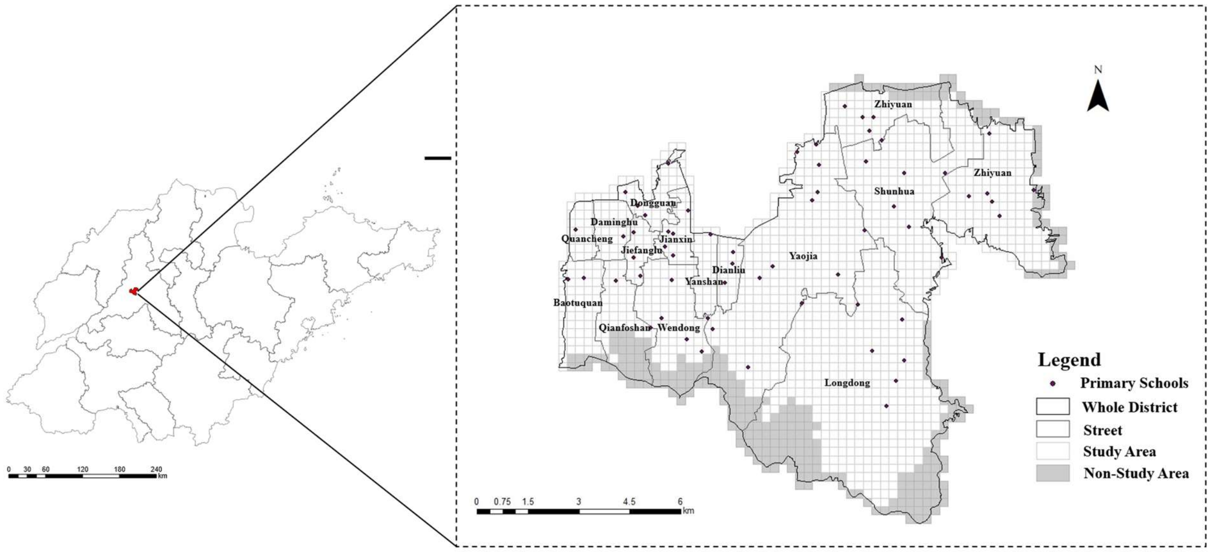

Figure 1 – Study area of Lixia District, Jinan, Shandong Province, China

2.2 Data source

The research data for this study includes students' OD data, travel planning data, administrative division data, demographic data, household income data and school geographical location data, as shown in *Table 1*.

Table 1 – Data source

Data	Representative indicators	Application	Data source
Students' OD data	Travel OD distribution	To establish a weight matrix for commuting to school and an accessibility model of weight calculation	2019 OD Survey of Residents' Travel in Jinan
Travel planning data	Travel time	To generate travel impedance of various travel modes and to improve data accuracy	https://lbs.amap.com/
School geographical location data	The coordinate of latitude and longitude	To divide school districts and to generate travel impedance as the endpoint	
Administrative division data	N/A	Divide the research area	http://www.ngcc.cn/ngcc/
Demographic data	Lattice distribution of the population	Rectify space data	https://hub.worldpop.org/
Household income data	The average house price in communities	Differentiate households with different income	https://anjuke.com/

The OD data of students' study is derived from the 2019 Jinan Residents' Travel OD Survey. The survey selected 2% of residents in 6 urban areas of Jinan City to issue questionnaires, and a total of 87,340 valid questionnaires were collected. The questionnaire covers personal information (such as age, gender, occupation), travel information (such as travel purpose, travel mode, departure time, departure place, arrival place, arrival time) and family information (such as family income, total family population, family monthly transportation expenditure, administrative region, street). In this study, a total of 547 datasets were selected from "6-12 years old", "going to school", "students" and "Lixia District". Through the geocoding tool of the Gaode API platform, this paper obtains the geographic information of students' family residences and analyses the spatial geographic relationship between different income families and schools with different education quality. By excluding the incomplete or abnormal data obtained, the excluded data include data with missing values and extreme values that do not conform to common sense. Among them, there are about 3,500 questionnaires with incomplete data and about 1,800 questionnaires with extreme values that do not conform to common sense. The data of a specific subset of the remaining valid data are selected for analysis. At the same time, the expansion factor is determined according to the proportion of the sample in the population (in this study, the sample is 2% of the population, so the expansion factor is 50), and then the sample data are multiplied by the expansion factor to estimate the corresponding index of the whole group, to expand the questionnaire data in equal proportion. Housing price data come from the Anjuke website. Due to the lack of spatial household income data, the housing price data provide a spatial indicator related to the place of residence, which can reflect the economic conditions of different regions and provide a more consistent measurement standard. This may be more representative than the income data of individual households in space. Housing prices are positively correlated with people's living standards and socio-economic conditions. Therefore, this paper uses housing price data to replace residents' household income. The spatial grid is divided into three different income families by using the quantile method (see *Figure 2*): low-income families (0-25%), middle-income families (25% -75%) and high-income families (75% -100%). According to the Gaode API platform, it covers the traffic big data of almost all cities in China, and the real-time traffic accuracy rate reaches 95%. The travel time is obtained by the path planning interface of the Gaode platform API. Firstly, the coordinates of the centre point of each grid are generated and converted into Gaode coordinates. Then, taking the grid centre point as the starting point and the school as the endpoint, using the path planning interface of the Gaode Map API, the Python programming tool is used to obtain the recommended travel time of the four travel modes of cars, walking, non-motor vehicles and public transportation, and the output results are shown in *Table 2*. Compared with the traditional method, it has the advantages of time-saving, comprehensive elements and high accuracy.

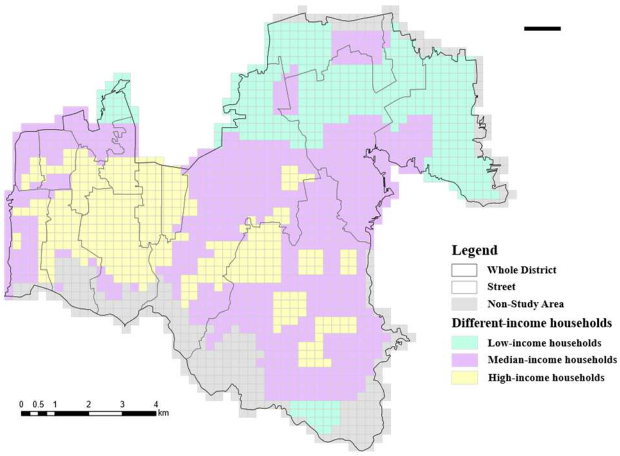

Figure 2 – The different-income households

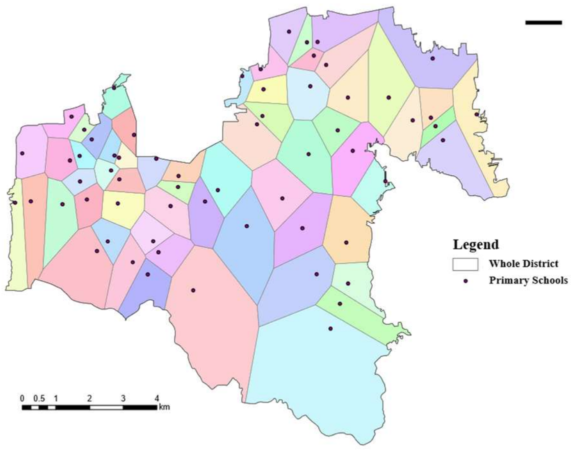

Figure 3 – School district boundaries

Table 2 – Examples of map transportation time

aID	bID	Private car	Bike	Walking	Public transit
0	0	1,200	5,019	13,080	7,997
1	0	1,286	5,185	10,537	6,984
2	0	1,276	5,150	11,564	6,374
……					
1,766	61	1,344	1,869	4,290	2,885

Notes: aID = ordinal number of the grids, bID = ordinal number of the primary schools

In this paper, the housing price data are used to replace the household income of the residents and the natural discontinuity method is used to divide the residential area into three levels, including 266 low-income residential areas (house price 5,800 yuan to 18,946 yuan); there are 432 middle-income communities (house prices from 18,947 yuan to 30,362 yuan); there are 103 high-income communities (housing prices from CNY 30,363 to CNY 116,353). The details are shown in *Figure 4*.

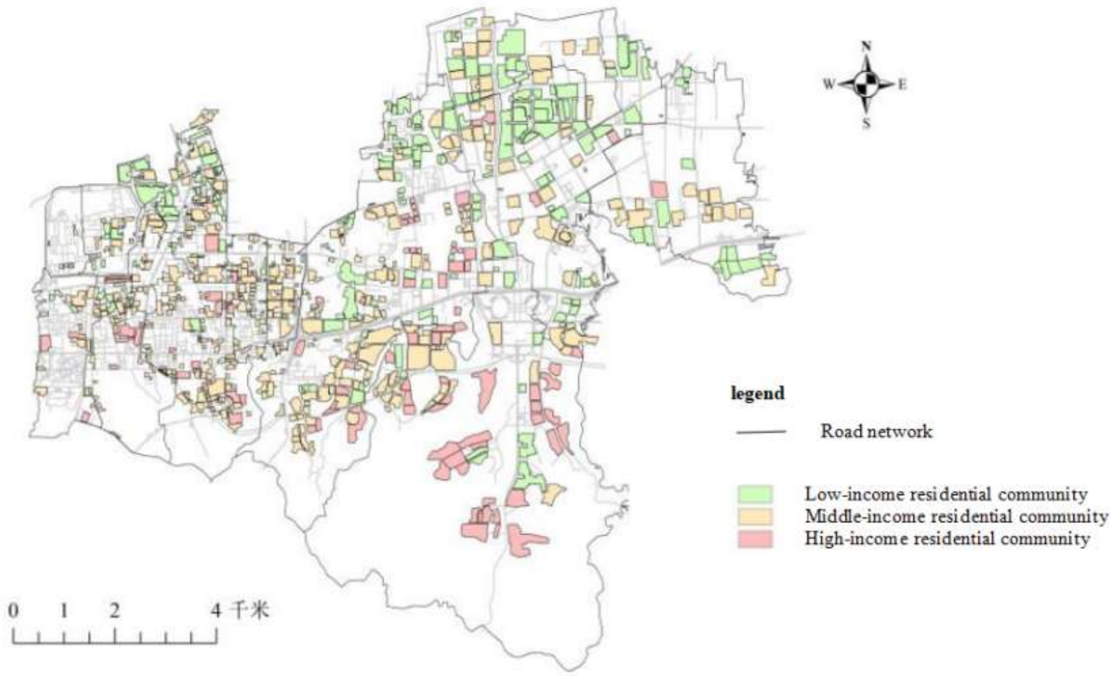

Figure 4 – Distribution of residential areas with different incomes

3. RESEARCH METHODS

The research methods include the Thiessen Polygon Method, the model of actual accessibility to commuting to school, the model of accessibility to commuting to school within school districts, the school selection influence coefficient, the accessibility gap index and the Theil index, so as to understand the meaning and function and explain the relevant indicators as shown in *Table 3*.

Table 3 – Explanation of important terms

Indicators	Names	Explanation	Dimension
T_{kj}	Weight matrix of commuting to school	The ratio of the actual number of commuting to school from a student's school district to other school districts to the total number of commuting to school within a student's district, which truly reflects students' preference for school selection.	N/A
A_i^1	Actual accessibility of commuting to school	It refers to the actual difficulty of children's travel from their place of residence to school. Compared with the traditional potential accessibility, the introduction of the weight matrix of school commuting and the weight of travel mode under school commuting distance can truly reflect children's school commuting behaviour.	min
A_i^2	Accessibility to commuting to school within school districts	Time of commuting to school spent by students attending nearby schools; only the weight f_1^w of travel modes under the distance of commuting to school is introduced.	min
C_i^S	School selection influence coefficient	The proportion of time spent more in actual commuting to school than that in school districts, which can reflect students' school selection efficiency of commuting to school.	N/A
MAG	Accessibility gap index	The index to assess the equity of travel modes in actual commuting to school.	N/A
T	Theil index	The index evaluates the transportation equity between households with different incomes, which, with good decomposition, can be used to explain the equity between and within households with different incomes.	N/A

3.1 Thiessen polygon method

The principle of "nearby enrolment" is an important basis for the division of school districts. Many studies have adopted the method of treating all the spaces closest to the school as the service area of the school. The realisation of this method mainly depends on the Thiessen polygon, that is, the vertical bisector connecting the adjacent school points is used to form a polygon covering the entire research area, and the linear distance between each point in the polygon and the school is the shortest. This method can intuitively represent the area served by each school, that is, each point is divided into the nearest school, which is consistent with the principal of "nearest school" and can adapt to various complex geographical environments. It can also deal with the continuity of geospatial space and help identify the scope of school enrolment. Compared with other methods, the Thiessen polygon can accurately divide the service area of each school, ensure that the residents of each area are as close as possible to their schools, help to achieve a fair distribution of educational resources and ensure the accuracy and fairness of the research. This study uses the Thiessen polygon function of ArcGIS10.6 to divide the 62 primary schools in the study area into school districts, as shown in *Figure 3*, in order to judge children's school choice and enrolment behaviour and provide a basis for constructing the school weight matrix and the school accessibility model in the school district.

3.2 Actual accessibility model and Theil index

Due to the actual needs of children, the opportunities for each school to be selected are different, and there is competition between each school. There are many complex factors in this competitive relationship, such as national policies, teaching environment, teachers, children and parents' psychological activities, etc., which cannot be simply described by models. Although it is difficult to quantify the specific schooling behaviour of children affected by many factors, we can use the actual accessibility model to evaluate the actual difficulty of children's schooling based on the actual travel data of residents. The model considers the weight matrix of general education and the weight of different travel modes, which truly reflects the children's choice preference for schools in a certain area. The Theil index is used as an index to evaluate the fairness of traffic between families with different incomes. Compared with the cost-benefit model, Wilson entropy model and Gini coefficient, it has good decomposition and can be used to explain the fairness between groups and within groups. The larger the Theil index, the greater the gap between the grids, and the more obvious the unfairness.

The detailed formulas and calculation methods are shown in Appendix A. *Formulas 1-10* describe in detail the calculation method of the actual school accessibility model. *Formulas 11-13* describe the calculation method of the Theil index in detail.

Due to the different needs of families, the opportunities for each school to be selected are also different. When a school's comprehensive strength is stronger, the more attractive it is to the students enrolled. Therefore, this paper selects the number of students, the number of classes and the number of teachers as indicators for comprehensively evaluating the service capabilities of educational facilities. First, the indicators are standardised. According to *Formula 5 to Formula 9* in Appendix A, the weight of the number of teachers is 0.30817, the weight of the number of classes is 0.31281, and the weight of the number of students is 0.37903. The comprehensive service ability of school j is obtained by *Formula 10*, and the results are shown in *Figure 5*.

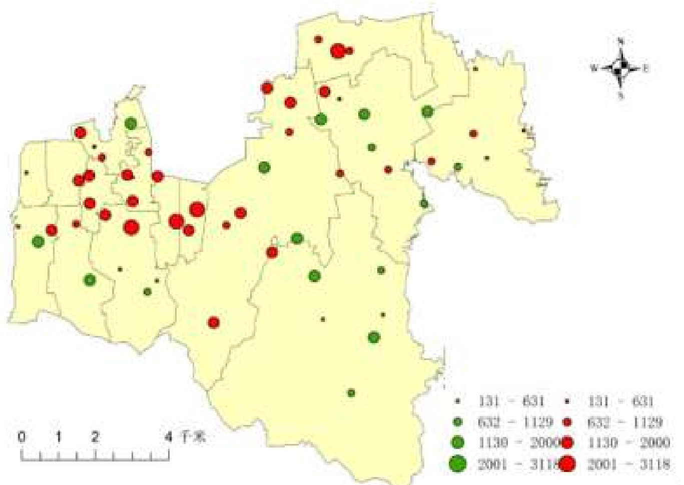

Figure 5 – The distribution of comprehensive service ability of primary school facilities

3.3 Modal accessibility gap

Accessibility gap index

$$MAG = \frac{A^w - A^v}{A^w + A^v} \tag{14}$$

It can be used to identify which modes of transportation perform better or worse in providing accessibility, helping planners and decision-makers understand the impact of different modes of transportation on residents' travel opportunities in a specific area. For example, if the MAG value is large, it indicates that a certain mode of transportation has obvious advantages or disadvantages in providing accessibility compared to other modes. But you need to pay attention to its symbol and size. A positive value may indicate that the accessibility of one mode of transportation is higher than that of another, while a negative value is the opposite. The size of MAG can reflect the extent of the gap.

In this equation, A is the data set for travel modes; A^w, A^v are the accessibility to children's commuting to school by using travel modes w, v; MAG is the modal accessibility gap between travel modes w, v. The value of MAG is between -1 and 1, and the closer it is to 0, the smaller the modal accessibility gap between A^w, A^v; when $A^w \neq 0, A^v \neq 0$, $MAG = 1$, which indicates that transportation mode w is not involved in children's commuting to school; when $A^w = 0, A^v \neq 0$, $MAG = -1$, which indicates that transportation mode v is not involved in children's commuting to school.

3.4 School selection influence coefficient

The influence coefficient of school choice can reflect children's school choice degree and efficiency. If parents send their children to the nearest school according to the national policy, there is no case of school choice, so the influence coefficient of school choice is zero. However, because the current enrolment policy of Jinan City requires that primary school enrolment is usually carried out according to the published school district division in terms of school district division, the right of school-age children to receive compulsory education in the jurisdiction is guaranteed. It is also mentioned that parents need to register their children for school according to the school district where they live, but the specific implementation of the policy may be flexible, allowing a certain degree of school choice behaviour, especially for high-income families. When the family conditions are superior and the gap between the quality of education in the recent school and the expected school is large, parents may choose to send their children to schools farther away to obtain higher quality education services, and the influence coefficient of school choice is due to children's school choice behaviour. To understand the characteristics of children's general education, this study draws on the relevant theories of Horner (2002) and proposes indicators such as school accessibility and school choice influence coefficient in the school district.

1) The accessibility of school commuting in the school district. School commuting in the school district means that children in the study area choose the school closest to their home to go to school. The calculation formula is as follows:

$$A_i^2 = \sum_w \sum_l k_l^w t_{ij,l}^w \tag{15}$$

2) School selection influence coefficient. It refers to the ratio of time that actual commuting to school takes longer than that in school districts. If $A_i^1 = A_i^2, E_i^r = 0$. The higher the coefficient is, the higher the degree of children's school selection and the lower the efficiency of commuting to school. Due to residents' school selection, the actual time of commuting to school will be greater than the minimum theoretical time of commuting to school, leading to higher actual accessibility than the accessibility within school districts. The calculation formula of the school selection influence coefficient is as follows:

$$E_i^r = \left(\frac{A_i^1 - A_i^2}{A_i^1}\right) \times 100\% \tag{16}$$

In this equation, A_i^2 is the accessibility to commuting to school within school districts, E_i^r is the school choice influence coefficient.

4. RESULTS

4.1 Children's school selection behaviour

This section uses the students' OD data to analyse the children's nearby enrolment and school choice enrolment. The proportion of transportation modes under different school distances is shown in *Figure 6*. The choice of children's way of schooling is closely related to the distance of schooling. With the increase in school distance, the number of car trips is increasing, and the number of walking trips is decreasing. In the short-distance (≤ 1,000 m) school, the number of children walking or choosing non-motor vehicles is higher; in the long-distance (≥ 3,000 m) school, because the car has the advantages of flexibility, convenience and fast speed, the number of children riding in a car to school is more than half.

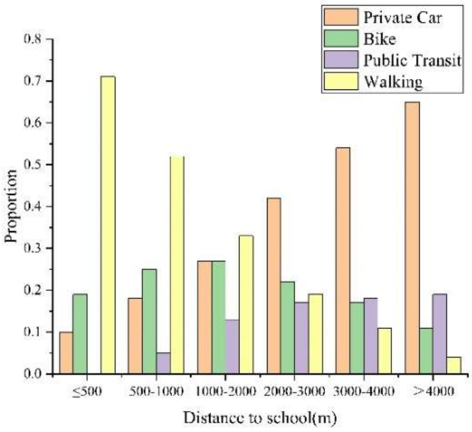

Figure 6 – The proportion of travel modes by different travel distances

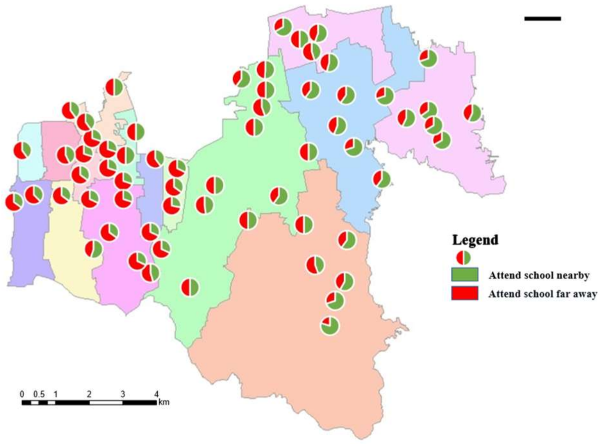

Figure 7 – The situation of non-local school attendance in each school district

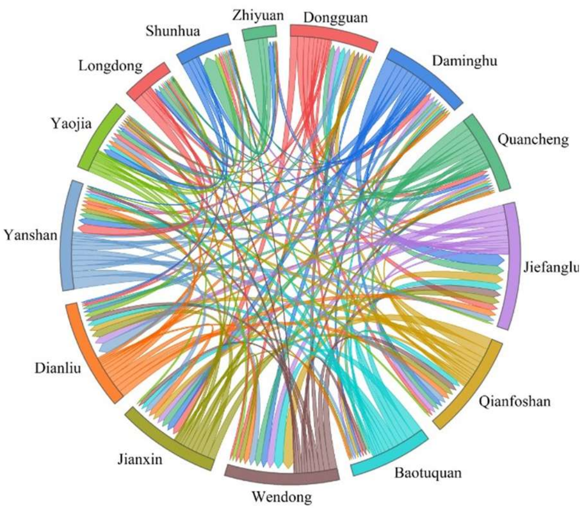

Figure 8 – The proportion of students commuting within Lixia District

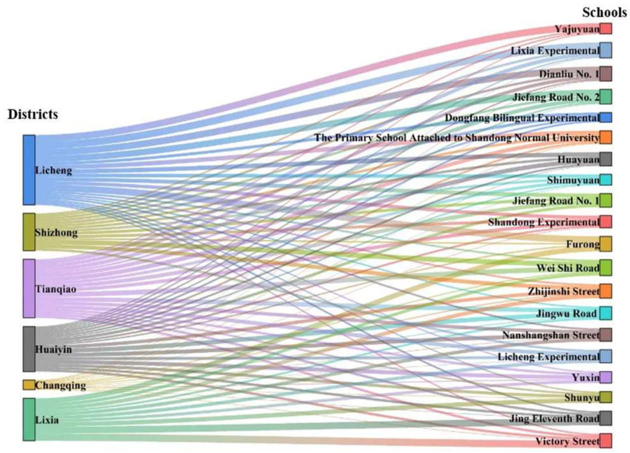

Figure 9 – The proportion of students commuting across administrative districts

The study found that only 49.39% of children in the region chose to go to the nearest school. The situation of nearby enrolment and school choice enrolment in each school district is shown in *Figure 7*. Among them, the red part of the pie chart represents the number of school choice enrolments, and the green part represents the number of nearby enrolments. In the relatively low-economic areas such as Zhiyuan Street, Shunhua Road Street and Longdong Street, the proportion of children entering a school located nearby is higher. In the relatively economically developed areas such as Jiefang Road Street, Wendong Street, Yanshan Street and Dianliu Street, the proportion of children's school choice is higher. It can be seen from *Figure 8* that the participation rate of children's school mobility in areas with relatively high economic levels is higher, the flow intensity is stronger, the flow range is larger, and the communication between regions is more frequent. The participation rate of children in the relatively low-level areas is low, and the flow range is also large, but the long-distance flow intensity is weak. This shows that high-income families have higher capital accumulation, higher requirements for children's education, children and parents need to spend more energy to deal with school choice and family life and other issues, need longer time in the process of communication, and increase their traffic burden.

Compared with the flow of children in the region, the flow of children across long-distance administrative regions has a more far-reaching impact on urban traffic. In this study, the top 20 schools in the main urban area of Jinan City were selected for analysis, and the results are shown in *Figure 9*. There are many primary schools with high education quality in Lixia District and Shizhong District, with 10 and 6 primary schools, respectively. There are 2 primary schools in Tianqiao District; Huaiyin District and Licheng District each have one primary school, while Changqing District has a relatively low quality of education, and there is no primary school with the highest quality of education. Cross-administrative school choice mainly shows the flow characteristics of low education quality areas to high education quality and school-intensive areas. The outflow of students in Tianqiao District, Huaiyin District and Licheng District is serious.

At the same time, this paper takes the morning rush hour of the working day as the school time of the study. According to existing research, the sensitive conditions of bad weather and high-pass congestion are set. We assume that under the baseline conditions, the average school time of children in a certain area is 20 minutes, and the influence coefficient of school choice is 58.60%. Under the condition of bad weather simulation, it will increase the school time by 20%, and the new school time = 20 minutes * 120% = 24 minutes. Traffic congestion simulation during peak hours will increase the school hours by 30%, and the new school hours = 20 minutes * 130% = 26 minutes. Through sensitivity analysis, we can see that under the conditions of bad weather and peak hours, the increase in school hours may lead to a significant increase in the impact coefficient of school choice. This means that if children need to go to school under these adverse conditions, the inconvenience and time cost of school choice will be more prominent. This analysis helps decision-makers and planners understand the changes in school accessibility under different conditions and the potential impact on transport policy and planning.

4.2 Accessibility of different travel modes

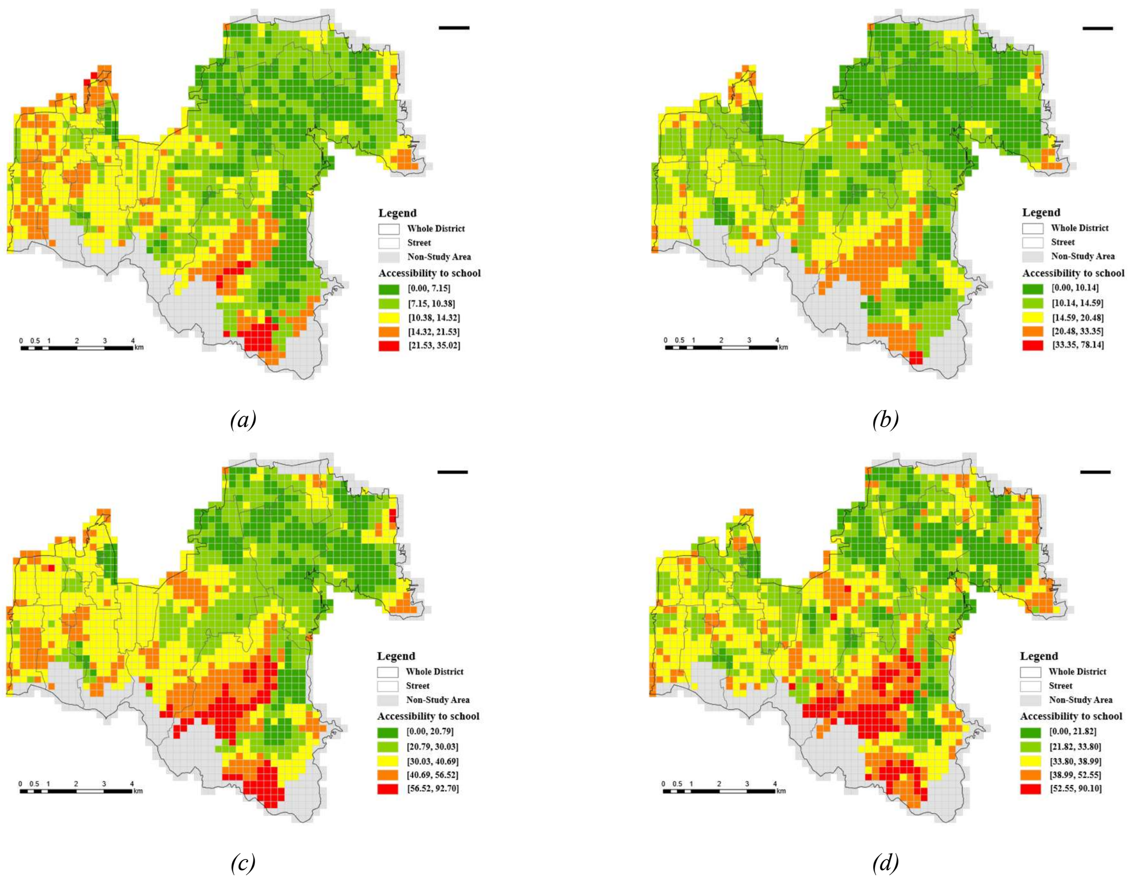

Figure 10 – The actual accessibility of different travel modes: a) private car; b) bike; c) walking; d) public transit

The actual accessibility of different travel modes is shown in *Figure 10*. In the spatial pattern, the accessibility of the entire study area shows a decreasing trend from Northeast to Southwest. Among the four travel modes, the accessibility distribution of walking and non-motorised vehicles is relatively concentrated, while the accessibility of cars and buses is relatively dispersed. This may be because cars and buses are more susceptible to urban road network structure and actual traffic conditions.

According to *Table 4*, in different spaces of the same travel mode, the accessibility difference of cars in each street is the smallest, and the accessibility difference of walking is the largest. From the perspective of different travel modes in the same space, the average travel time of cars is lower than that of other travel modes, and the accessibility of children using cars to go to school is the best. Interestingly, on Shunhua Road Street, the average accessibility of children's walking is less than the average accessibility of taking a bus. There are two main reasons for the analysis; first, the education quality of Shunhua Road Street is higher than that of the surrounding adjacent streets. Children are closer to school, and walking is more flexible than buses. Children can walk directly from their place of residence to their school, without considering the arrival and stopping time of buses. Secondly, Shunhua Street is an independent innovation demonstration area in Jinan City, which provides more employment opportunities for residents. During the peak period, many trips will cause traffic congestion, and children's bus travel is vulnerable to traffic congestion.

Walking and non-motorised vehicles compete in children's short-distance commuting; there is a competition between buses and cars in children's long-distance communication; this paper uses MAG to analyse the fairness of different modes of transportation in space as shown in *Table 4*. The MAG of walking and non-motorised vehicles is concentrated between 0.39-0.44, indicating that the spatial gap between the two modes of travel is not obvious. In contrast, the MAG of cars and buses is concentrated between 0.39-0.56, and the Eastern region is higher than the Western region, which indicates that low-income families are more dominant in choosing cars in the process of school commuting and improving public transport services in the Eastern region is the key to promoting the transfer of children's school commuting. The fairness gap between buses and cars in the Western region is small, and the perfect public transportation system guarantees relatively fair traffic in the region.

Table 4 – The spatial accessibility disparity of different travel modes

	A^{pc} (min)	A^{b} (min)	A^{w} (min)	A^{pt} (min)	MAG_{w-b}	MAG_{pt-pc}
Baotuquan	14.13	15.81	39.40	35.99	0.42	0.44
Daminghu	13.95	14.97	36.09	34.43	0.42	0.42
Dianliu	11.63	13.64	34.21	30.47	0.43	0.45
Dongguan	13.23	14.86	32.98	29.58	0.39	0.39
Jianxin	10.99	11.67	29.16	27.69	0.43	0.42
Jiefanglu	13.02	15.05	37.39	33.11	0.43	0.44
Longdong	11.94	17.22	41.98	40.75	0.42	0.56
Qianfoshan	13.11	14.18	35.20	31.62	0.43	0.41
Quanchenglu	13.30	15.46	38.33	32.36	0.43	0.42
Shunhualu	7.52	9.13	22.21	25.87	0.42	0.54
Wendong	12.04	15.16	37.44	32.74	0.42	0.46
Yanshan	11.26	12.93	33.17	30.58	0.44	0.46
Yaojia	9.12	12.22	31.50	31.90	0.44	0.55
Zhiyuan	8.58	10.22	24.42	26.38	0.41	0.50

Notes: A^{pc} = accessibility to school by public cars, A^{b} = accessibility to school by bike, A^{w} = accessibility to school by walking, A^{pt} = accessibility to school by public transit, MAG_{pt-pc} = modal accessibility gap between private transit and public cars, MAG_{w-b} = modal accessibility gap between walking and riding a bike

4.3 The actual accessibility of commuting to school and accessibility of commuting to school with school districts for households with different income

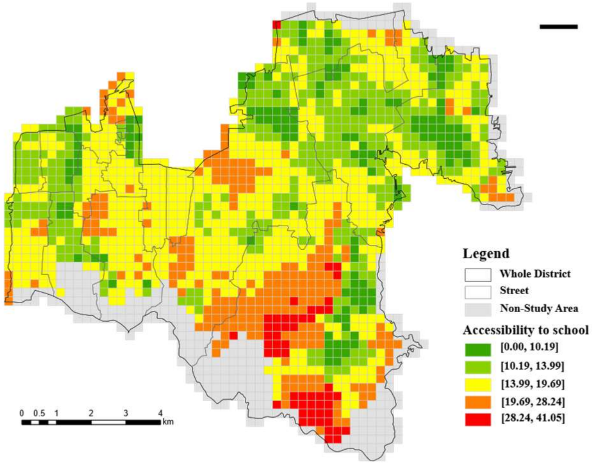

Figure 11 – The actual accessibility of commuting to school

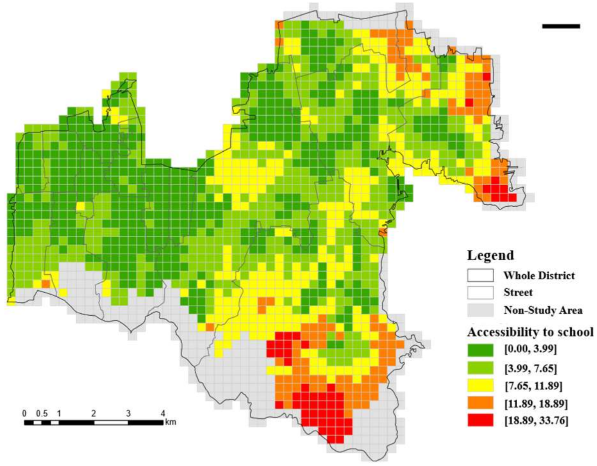

Figure 12 – The accessibility of commuting to school within school district

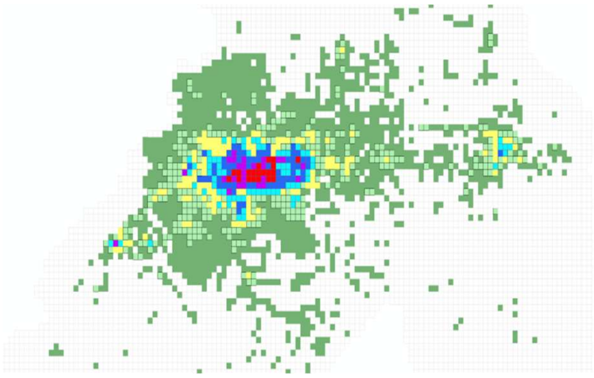

Figure 13 – Spatial distribution of housing prices in 2022

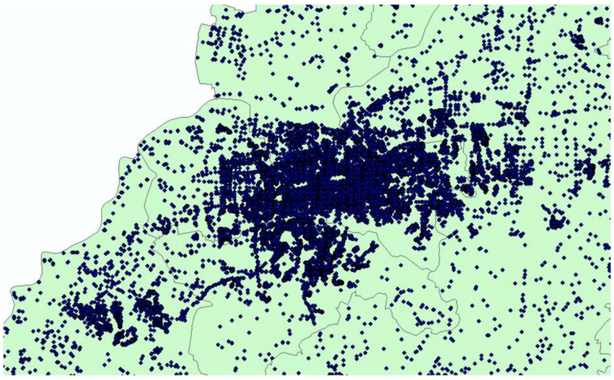

Figure 14 – Residents living point distribution map

As shown in *Figure 11* and *Figure 12*, in the actual school, school accessibility is mainly concentrated in 10 min–28 min, and the area with poor school accessibility is mainly distributed in the Southeast region. The schools in this area are sparsely distributed and the quality of education is relatively poor, so some high-income families choose to go to other schools. In the school district, the accessibility of the school is mainly concentrated in 3 min–12 min, and the accessibility of the school depends on the spatial distance between the family residence and the nearest school, showing a decreasing trend from Southeast to Northwest in space. The school choice degree of different income families is an important reason for the large difference in the spatial distribution of the accessibility of the two scenarios.

Through *Figure 13* and *Figure 14,* we can see the spatial distribution map of housing prices in Jinan City in 2022 and the residential areas of residents.

Because high-income families may live in areas with higher housing prices, they are more inclined to choose schools with higher quality of education and are willing to accept longer school hours to obtain better educational resources, and these areas may have a spatial mismatch with high-quality schools. If high-quality educational resources are concentrated in certain areas, then high-income families living in other areas need to spend more time to reach these schools, which will lead to an increase in school hours, and high-income families may be more inclined to use private cars as a means of driving to school, which may lead to longer school hours when traffic congestion occurs.

It is generally believed that a Gini coefficient of less than 0.3 indicates a reasonable distribution; when the Gini coefficient is between 0.3 and 0.4, the distribution is more reasonable; 0.4 ~ 0.5 indicates that the distribution gap is large; more than 0.5 indicates that the distribution gap is too large. To study the impact of different income regions on actual accessibility, we use the regional average economy to study the low-economic areas and high-economic areas in the regional atmosphere. The results are shown in *Figure 15*. It can be calculated that the Gini coefficient of low economic areas is 0.403; the Gini coefficient of the high economic zone is 0.343, which indicates that the actual accessibility of the low economic zone is unfair compared to that of the high economic zone.

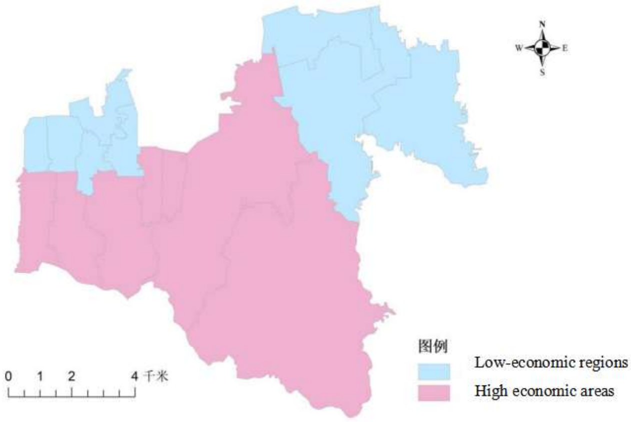

Figure 15 – Schematic diagram of different economic regions' division

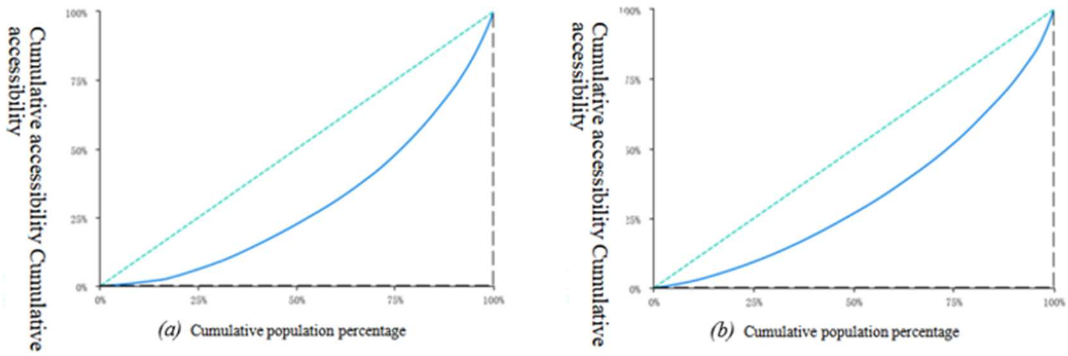

Figure 16 – Lorenz curves of different economic regions: a) Lorenz curve of low economic region; b) Lorenz curve of high economic region

Table 5 – The accessibility for different income groups

	A^{pc} (min)	A^{b} (min)	A^{w} (min)	A^{pt} (min)	A^{1} (min)	A^{2} (min)	E^{r}
Lih	9.22	11.39	26.32	27.86	14.45	7.92	47.08%
Mih	10.49	14.46	35.52	34.39	16.11	7.44	56.02%
Hih	11.65	14.26	35.34	33.12	16.77	4.39	73.81%

Notes: Lih = low-income households, Mih = median-income households, Hih = high-income households, A^{pc} = accessibility to school by public cars, A^{b} = accessibility to school by bike, A^{w} = accessibility to school by walking, A^{pt} = accessibility to school by public transit, A^{1} = actual accessibility of commuting to school, A^{2} = accessibility of commuting to school within school district, E^{r} =school choice influence coefficient

Figure 16 shows the Lorenz curves of different economic regions. The Lorenz curve is usually used to represent the fairness of resource allocation. The closer the curve is to the 45-degree line (i.e. the diagonal line), the more equitable the distribution is. In *Figure 16*, the Lorenz curve is used to analyse the fairness of the distribution of actual school accessibility in different economic regions (low-economic regions and high-economic regions). The shape of the Lorenz curve shows the distribution of school accessibility in different economic regions. The more curved the curve, the greater the degree of uneven distribution. By comparing the Lorenz curve and Gini coefficient of the two regions, it can be seen that the uneven distribution of school accessibility in low-economic areas is higher than that in high-economic areas. This is related to the imbalance of resource allocation in low-economic areas and the lack of transportation infrastructure.

According to *Table 5*, it is found that in the actual school commuting, the average school commuting time of low-income, middle-income and high-income families is 14.45 min, 16.11 min and 16.77 min, respectively. The school commuting accessibility of high-income families is the worst, followed by middle-income families, and the school commuting accessibility of low-income families is the best. This difference is mainly due to the different geographical locations and economic conditions of different-income families. Due to their own economic conditions, higher-income families are more able to pursue high-quality schools, so the proportion of school choice is higher; low-income families live on the edge of the city or in remote areas. Due to their economic conditions, they often cannot choose high-speed and high-price travel modes, so they are more inclined to go to school according to the designated school district. In the school district, the average school time of low-income, middle-income and high-income families is 7.92 min, 7.44 min and 4.39 min, respectively. Compared with the two scenarios, the maximum difference in the average school time of high-income families is 12.38 min. High-income families have more choice power and can choose better resources. Middle-income families and low-income families are vulnerable to school district control and traffic conditions.

4.4 Transportation equity for households with different income

According to *Table 6*, in the actual general education, the Theil index of high, medium and low-income families is 0.06, 0.10 and 0.12, respectively. The Theil index of high-income families is the lowest, indicating that their traffic equity is the best; in the school district, the fairness of middle-income families is the best, followed by high-income families, and low-income families are the worst. By comparing the two scenarios, it is found that children's school choice can improve regional traffic equity. Among them, the gap of the Theil index of high-income families is 0.19, the gap of the Theil index of low-income families is 0.17, and the gap of the Theil index of middle-income families is 0.12. If the government strictly implements the policy of "schooling nearby", it will have an impact on the traffic equity of all families, with the greatest impact on high-income families and the least impact on middle-income families.

In the school district, 82.4% of the unfairness of children's school transportation is caused by differences within the family, and the differences between families with different incomes contribute 17.6%. However, in the actual school commuting process, the contribution of traffic injustice between families only accounts for 8.3%. This shows that children's school choices can reduce the difference in traffic accessibility between families.

After analysing the traffic fairness of different modes of travel, it is found that the Theil index of buses is smaller than that of cars, indicating that the factor of fairness in buses is higher than that in cars. This is because public transport, as a social resource, aims to serve more people, and pays more attention to the fairness of traffic in route selection and site selection. In addition, there is no significant difference in the accessibility of walking and using non-motor vehicles between high-income families and middle-income families, while the Theil index of non-motor vehicles and walking in low-income families is 0.24 and 0.18, and low-income families use non-motor vehicles to drive to schools. The fairness is less than walking.

Table 6 – The transportation equity for different income groups

	T^{pc}	T^{b}	T^{w}	T^{pt}	T^{1}	T^{1}_{WG}	T^{1}_{BG}	T^{2}	T^{2}_{WG}	T^{2}_{BG}
Lih	0.19	0.24	0.18	0.15	0.12	91.7%	8.3%	0.29	82.4%	17.6%
Mih	0.16	0.15	0.16	0.14	0.10			0.22		
Hih	0.08	0.07	0.07	0.06	0.06			0.25		

Notes: T^{pc} = Theil index of the private car, T^{b} = Theil index of the bike, T^{w} = Theil index of walking, T^{pt} = Theil index of the public transit, T^{1} = Theil index of actual accessibility, T^{2} = Theil index of accessibility within the school district, T_{WG} = within-group component of the Theil index, T_{BG} = between-group component of the Theil index

5. CONCLUSION AND DISCUSSION

This study takes the Lixia District of Jinan City as an example to explore the accessibility and traffic fairness of different income families and different modes of transportation. Using the travel time of Gaode API platform path planning to improve the accuracy of school accessibility; using Thiessen polygons to divide the scope of school districts; combined with the students' OD data, the actual school accessibility and the school district accessibility model are constructed. It not only analyses the school time, but also considers multiple dimensions such as transportation mode, family income level and school choice behaviour, and uses the accessibility gap index to evaluate the differences between different transportation modes. The concept of traffic equity is introduced, and quantitative tools such as the Gini coefficient and Theil index are used to evaluate the differences in traffic resource allocation among households with different incomes. Taking the Lixia District of Jinan City as an example, this paper provides specific empirical research results and local evidence for understanding the problem of children's school attendance in urban China. The research results are as follows:

1) There is a big gap between the mobility characteristics and accessibility of different income families, and the dynamic spatial characteristics of children's schooling are affected by income level. Specifically, high-income families have a high participation rate, a strong flow intensity and a large flow range; the flow participation rate of low-income families is low. Although the flow range is large, the long-distance flow intensity is weak. The main reason may be limited by geographical location and economic conditions, only to choose the nearest school. The study found that high-quality educational resources in Jinan are often concentrated in specific areas, and high-income families usually have higher expectations and requirements for their children's education. At the same time, because they usually have stronger economic capacity, they can bear the transportation costs of longer distances. As a result, they may be more inclined to choose schools with good reputations and high teaching quality, even if these schools are far away. This high expectation of educational resources drives families to accept longer school hours, so high-income families have to choose schools farther away in order to obtain better educational resources. This uneven distribution of resources forces families to accept longer school hours, while high-income families may be more inclined to use private cars as a means of driving to school, which may lead to longer school hours in traffic congestion. This may affect the family's quality of life and children's rest time, making high-income families less happy than other families. Therefore, high-income families need to balance the relationship between time cost and the quality of educational resources in their decision-making.
2) There are great differences in the numerical and spatial distribution of the accessibility of the two scenarios of the actual school and the school district. The actual school accessibility is mainly concentrated in 10 min–28 min, showing a decreasing trend from Northwest to Southeast. The accessibility of the school district is mainly concentrated in 3 min–12 min, showing a decreasing trend from Southeast to Northwest. The school choice degree of different income families is an important reason for the large difference in the accessibility of the two scenarios. The Theil index of the actual school is smaller than the Theil index of the school district. The school district control restricts children's school choice behaviour and reduces the traffic fairness of the school. Among them, the gap of the Theil index of high-income families is the largest, and the gap of the Theil index of middle-income families is the smallest. This shows that high-income families have strong subjective initiative and are not easily constrained by school district control.
3) 82.4% of children's traffic inequity in the school district is caused by differences within the family, and the difference between families with different incomes contributes 17.6%. In the actual school, the contribution of traffic inequity between families accounts for only 8.3%, indicating that children's reasonable and orderly choice of school can reduce the difference in traffic accessibility between families.
4) The accessibility gap index between walking and non-motorised vehicles is concentrated in 0.39-0.44, and the accessibility of these two methods is not significantly different in spatial distribution. The accessibility gap index between buses and cars is concentrated in 0.39-0.56, showing a spatial distribution of higher in the East than in the West, indicating that low-income families are more dominant in choosing cars in the process of school commuting. Improving public transport services in the Eastern region is the key to promoting the transfer of children's school commuting. The Theil index of buses is smaller than that of other modes of transportation, indicating that the fairness of children taking buses is higher than that of other modes of transportation. This is because public transportation, as a social resource, aims to serve more people, and pays more attention to the fairness of transportation in route selection and site selection.

The study found that there are differences in traffic fairness among families with different incomes in the process of school commuting. In the process of children's school commuting, the proportion of cross-regional school selection, cross-regional school commuting flow and school commuting mode of families with different incomes reflect that the characteristics of school commuting bring a heavy burden to urban traffic. We should improve residents' awareness of schooling and encourage high-income families to pay more attention to the choice of nearby enrolment. At the same time, it provides transportation subsidies or concessions for low-income families to reduce the burden of transportation costs.

Studies have shown that children from high-income families often need longer school hours, which indicates that the current school district division may not fully consider the actual needs of residents. At the same time, it shows that the uneven distribution of high-quality educational resources is one of the main reasons for the increase in school time. The government can improve the educational level of the Eastern region by increasing educational investment, providing more educational resources, scholarships and other educational support measures, optimising the distribution of teachers and promoting the sharing of educational resources. In addition, a school evaluation mechanism is established to evaluate the quality of education in each school, encourage schools to actively improve the level of education, provide better educational resources, and attract more parents and children to choose nearby enrolment to reduce children's school time.

Encouraging children to attend a school located nearby does not mean that any school choice behaviour of children is strictly restricted. On the contrary, the government should take some measures and policies to strengthen supervision and limit illegitimate interests and disorderly school choice. The government can properly implement the system of "multi-school division" and "group school running", reduce the impact of school district control on the fairness of school access and improve the traffic fairness of families with different incomes. At the same time, the educational resources of each school should be adjusted to make them evenly distributed, and the boundaries of school districts should be regularly evaluated and adjusted to reflect population changes and traffic development. To ensure that the division of school districts matches the actual living and travel patterns of residents, establish public participation and feedback mechanisms, and involve parents and community members in the decision-making process of the school district division. This helps to ensure the fairness and effectiveness of the policy.

There are significant differences in the accessibility of different modes of transportation, especially during peak hours. To alleviate traffic congestion, improve traffic efficiency and safety, and increase the traffic equity of children's schooling, the government should establish a sound public transport system and improve public transport services in relatively low-economic areas. In particular, the Eastern region needs to increase investment, increase the frequency and coverage of public transport, optimise routes to connect major residential areas and schools and improve the quality of public transport services. For low-income families, the government can provide transportation subsidies or concessions to reduce their transportation costs. In addition, the government can also vigorously develop customised public transport, ensure customised public transport "one stop to the end" services, improve the convenience and safety of communication, and attract more parents and children to use public transport. It also provides real-time traffic information through mobile phone applications, websites and other channels to help students and parents plan the best route to school. This includes real-time bus arrival information and traffic congestion.

Studies have shown that the efficiency of car commuting during peak hours is not high, and the commuting time is closely related to traffic congestion. The government should consider more walking and bicycle-friendly infrastructure construction and adopt more perfect traffic management measures to disperse traffic pressure during peak hours.

There are also limitations in this paper. The data collection method may be subjectively affected by the interviewees, resulting in inaccurate or incomplete data. This requires more accurate measurement tools and techniques in subsequent studies to improve the accuracy and efficiency of school accessibility research. In future research, research can also be carried out in different cities to understand the differences in school accessibility under different backgrounds, and to better integrate various transportation modes to provide more efficient and convenient school access paths.

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APPENDIX A: FORMULAS AND METHODS OF CALCULATION

A.1 The actual school accessibility model formula

Formulas 1-10 describe in detail the calculation method of the actual school accessibility model.

This paper uses students' OD data to calculate the actual number of commuting to school from the school district k to the school district j and the total number of commuting to school in the school district k and obtains the weight matrix T_{kj} by dividing them. If there are no commuting to school from the school district k to the school district j, then T_{kj} is zero.

$$T_{kj} = \frac{N_{kj}}{\sum_j N_{kj}} (k \neq j) \tag{1}$$

$$T_{ij} = T_{kj}, (i \in k) \tag{2}$$

$$A_i^w = \sum_{j=1}^{m} t_{ij}^w T_{ij} \tag{3}$$

$$A_i^1 = \sum_{j=1}^{m} \sum_{w} \sum_{l} f_l^w t_{ij,l}^w T_{ij} \tag{4}$$

In this equation, i is the grid; j is the public service facilities of schools; w is the data set of four travel modes: car, bike, walking and bus. t_{ij}^w is the time cost of getting to the school j from the grid i by using transportation mode w; N_{kj} is the number of commuting to school from the school district k to the school district j; T_{ij} is the proportion of the number of commuting to school from the grid i to the school j. A_i^w is the accessibility of i by using transportation mode w. l is the dataset of children's actual school distance; f_l^w represents the actual school distance l of children, as shown in *Figure 4*; A_i^1 is the actual accessibility of educational resources at point i.

First, the indicators are standardised.

$$x'_{ij} = \frac{x_{ij} - min\{x_{ij}, \dots, x_{nj}\}}{max\{x_{ij}, \dots, x_{nj}\} - min\{x_{ij}, \dots, x_{nj}\}} \tag{5}$$

$$r_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \tag{6}$$

In the formula: x_{ij} is the value of index j of sample i; x'_{ij} is the dimensionless value of index j of sample i, r_{ij} is the proportion of sample i in j index.

Then calculate the index information entropy, obtain the information entropy redundancy value, and determine the weight of each index.

$$e_j = -\frac{\sum_{i=1}^{n} r_{ij} \ln(r_{ij})}{\ln(n)} \tag{7}$$

$$k_j = 1 - e_j \tag{8}$$

$$w_j = \frac{k_j}{\sum_{j=1}^{m} k_j} \tag{9}$$

In the formula: e_j is the information entropy of index j； k_j is the redundancy value of information entropy of index j; w_j is the weight of index j.

$$S_j = w_1 AQ + w_2 BP + w_3 C \quad (10)$$

In the formula: S_j is the comprehensive service ability of school j. Q is the ratio of teachers to students, according to the 2023 statistical yearbook of Jinan City, the teacher-student ratio is 16.16; A represents the number of teachers, and AQ represents the number of teachers multiplied by the ratio of teachers to students, which is used to evaluate the teacher strength of the school. P is the number of classes. According to the education statistics announcement of Jinan City in 2022, the average class size is 40.76 people per class. B represents the number of classes, and BP represents the number of classes multiplied by the number of classes, which is used to evaluate the class size and teaching resource allocation of the school. C represents the number of students. This indicator directly reflects the size of the school's students and is the basic data for assessing the school's service capabilities.

A.2 Theil index formula

Formulas 11-13 describe the calculation method of the Theil index in detail.

The Thiel index T, intra-group Thiel index T_{WG} and inter-group Thiel index T_{BG} are calculated as follows:

$$T = \frac{1}{N}\sum_{i=1}^{n}\frac{A_i}{A}\ln\left(\frac{A_i}{A}\right) \quad (11)$$

$$T_{WG} = \sum_{m=1}^{M} A_m[\sum_{i\in g_m}\frac{A_{mi}}{A} ln \frac{A_{mi}/A_m}{1/n_m}] \quad (12)$$

$$T_{BG} = \sum_{m=1}^{M} A_m \ln\left(\frac{A_m}{n_{m/N}}\right) \quad (13)$$

In this equation, A_i is the accessibility of grid i, A is the average accessibility of all grids, N is the number of all grids, M is the number of groups, g_m is the data set of the grid of group m, n_m is the number of the grid of group m, and A_{mi}, A_m are the percentage of group m and grid i in the total accessibility.

吕伯淇，牟振华，王庆斌，泮江珊，王永明，郑元玺

基于多源数据的通学交通特征分析-以济南市为例

摘要：
随着城市化进程的加快，教育资源分配不均导致许多儿童选择学校就读，增加了他们的上学时间，占用了大量的休息时间。本文以济南市历下区为例，利用泰森多边形划定学区范围，基于学生 OD 数据引入儿童实际选择权重，结合高德 API 平台获取的 4 × 1767 × 62 数据，构建实际与学区可达性模型，研究不同收入家庭在学校接驳过程中的可达性与交通公平性。研究发现，不同收入群体在可达性和交通公平性方面存在差异，高收入家庭由于择校行为而经历更长的通学时间。与实际的普通教育相比，学区家庭收入差异对交通不公平的影响更大。因此，合理的择校可以减少家庭之间交通可达性的差异。

关键词：
实际可达性；不同收入的家庭；幸福感；交通不平等；选择距离较远的学校。