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Investigating the Impacts of Urban Built Environment on Travel Energy Consumption: A Case Study of Ningbo, China

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Abstract: The built environment of cities has increasingly affected the travel mode of residents and led to changes in energy consumption, which is crucial to maintaining urban sustainability. Ningbo is a typical representative of urbanization on the east coast of China, and its energy consumption is in a period of rapid growth. Therefore, using the survey data of 22,112 traffic trip samples from nine streets in Ningbo, this paper establishes a regression analysis model, systematically analyzes the relationship between the built environment and domestic energy consumption from multiple dimensions, and reveals the impact mechanism of the built environment on domestic energy consumption. We find that (1) social and economic conditions are the main factors affecting traffic energy consumption. (2) The population density has a significant negative correlation effect on the energy consumption of transportation trips. When the population density increases by 1%, the energy consumption of total transportation trips, commuting trips, high-energy-consumption trips, and low-energy-consumption trips decreases by 0.094%, 0.115%, 0.273%, and 0.124%, respectively. (3) When the degree of mixed use of land increases by one percentage point, the energy consumption of total transportation trips, commuting trips, high-energy-consumption trips, and low-energy-consumption trips decreases by 0.415%, 0.421%, 2.574%, and 1.197%, respectively. (4) The density of road intersections has a significant negative correlation effect on the energy consumption of traffic trips. (5) The impact of the built environment on the energy consumption of transportation trips is greater than that of residential buildings.

Keywords: urban built environment; travel energy consumption; multivariate linear regression; mixed land use

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1. Introduction

In the past 70 years, the world has experienced rapid urbanization. According to the population distribution data released by the United Nations Population Organization (UNPO), as of 2014, about 54% of the world's population lived in urban areas, which is expected to increase to 66% by 2050 [1]. In recent years, China's urbanization rate has increased dramatically. According to the data of the 2016 China Statistical Yearbook, the urbanization rate in 2005 was 42.99%. Nationwide, the urbanization rate of eastern coastal cities is significantly higher than that of western cities. Take Ningbo as an example. By the end of 2015, the urbanization rate of Ningbo had reached 64.62% [2], which is 8.52 percentage points higher than the national average. Rapid urbanization brings economic vitality to cities, but also brings many negative impacts, such as traffic congestion, haze pollution, resource depletion, etc. Among the many negative impacts, energy consumption is the most prominent. According to the sixth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 2022, in terms of energy, due to the rapid growth of demand for refrigeration energy due to population growth, Asian countries have a hotter summer climate. Of the 13 developing countries with large energy consumption in Asia, 11 face energy insecurity and industrial system risks [3]. The International Energy Agency (IEA) estimates that 73% of global energy consumption will come from metropolitan areas in 2030 [4]. Greenhouse gas emissions caused by energy consumption are affecting global climate change, which in the long run will not only threaten the sustainable development of cities, but also seriously affect the living environment of human beings. Therefore, it is important to understand the relationship between energy consumption and population, urban building environment construction, and how to build a better living environment.

Once the urban built environment is formed, it is difficult to change, and its impact on travel energy consumption has a locking role. Therefore, changing people's travel behavior is regarded as the basic measure to reduce energy consumption [5]. The travel theme of residents is the decisive factor to determine the daily travel mode [6]. In this regard, urban planners have always been interested in understanding a variety of factors that can promote positive travel patterns, reduce energy consumption, and promote urban health and low-carbon and sustainable development [7]. North America and Europe have provided a wealth of empirical research on the interaction between the built environment and travel/travel patterns. Newman and Kenworthy conducted research on 32 major cities around the world, and found that urban density was negatively related to per capita annual gasoline use [8]. In the 1990s, Cervero's research on the travel mode of California residents found that residents living within 150 m of the subway station chose to use the subway system, accounting for 30% of all transportation modes, and the farther away from the subway station, the lower the proportion of using the subway [9]. Residents living within 900 m of the subway station choose to take the subway, while only half of them are 500 m away from the subway station. Friedman et al. investigated family transportation in the San Francisco Bay Area [10]. Since the beginning of the 21st century, urban infrastructure and spatial patterns have guided residents' choice of transportation and housing, and influenced their living behavior patterns [11]. At the same time, they also pointed out that the impact of destination accessibility on transport travel is higher at the macro level than at the meso level. Munshi studied the relationship between the building environment and transportation in Ahmedabad, India, and used the work housing ratio index to express diversity in the analysis process [12]. At present, China focuses on the impact of residential building environment on residents' low-carbon cognition. The building environment of residential area is usually described as "5D", i.e. density, diversity, design, transportation, and destination accessibility [13]. In addition, Schwanen and Mokhtarian believe that in the past decade, tourism attitudes and residential choices have played an important role in the relationship between the architectural environment and tourism behavior [14]. The architectural environment can indirectly affect travel behavior by inducing attitude changes and traditional behaviors [15].

In addition, as the core goal of urban development has shifted from spatial expansion to the improvement of residents' living quality, the research on the relationship between the built environment and living energy consumption has gradually become a hot spot [16,17]. Globally, the built environment consumes energy and emits relevant carbon dioxide (CO_2), accounting for 36% of the emissions and final energy use in 2018, of which 11% are the direct consequences of manufacturing building materials and products [18]. When people consider that 44% of the 169 sustainable development targets depend on construction and real estate activities, the importance of the building environment in achieving sustainable development goals is obvious [19]. Therefore, more and more scholars have discussed how to achieve the goal of sustainable development in the architectural environment [20]. For example, Ref. [21] built a high-rise residential building design based on the SDN architecture's low carbon design concept of network energy consumption. The decarbonization of residential energy consumption under collective self-consumption regulations in Italy is discussed in Ref. [22]. Ref. [23] mapped and quantified the energy consumption drivers of Kuwaiti buildings. Ref. [24] believes that improving the efficiency of air conditioning and wall insulation is the best way to save energy consumption in residential buildings. In China, due to the integration of complex morphological changes, demographic changes, local renewable energy production, and electric vehicle absorption, carbon assessment and carbon neutralization potential exploration in the dynamic environment are still challenging, especially in terms of household types and energy consumption behavior, which will significantly affect the carbon performance neutrality of urban areas in the dynamic building environment.

The current research is mostly confined to European and American cities, mainly focusing on the low-density, low-rise building environment. However, the characteristics of China's architectural environment are obviously different from those in Europe and the United States. The differences between China and European and American cities are mainly reflected in the following aspects. The residential types in European and American communities are mainly single houses and apartments, the development density and plot ratio are relatively low, most of the residential buildings in the communities are low-rise, the residential space is relatively large, and there are large green spaces and water systems outside. The residential density and plot ratio in Chinese communities are relatively high. Not only are the residential floors much higher than those in foreign communities, but also the outdoor green spaces and water systems are relatively small. In terms of travel mode, European and American cities need more private cars than Chinese cities. In terms of road network, the road network density of European and American cities is also higher than that of Chinese cities. Whether the existing research results are applicable to Chinese cities needs further verification. Therefore, taking Ningbo City as an example, based on 9 community samples, 598 residential samples, and 22,112 traffic trip samples, this paper reveals the impact mechanism of the built environment on domestic energy consumption, comprehensively evaluates the impact of various indicators of the built environment on domestic energy consumption, and proposes guidance measures for the built environment planning that are conducive to reducing domestic energy consumption. The purpose of the study is to verify the following three questions. First, after controlling for social, economic, and energy saving attitudes and other factors, will the building environment affect travel energy consumption? Second, if there are impacts, will the building environmental energy consumption of different types of vehicles be different? Third, compared with European and American cities, what are the differences in the impact of China's building environment on tourism energy consumption?

2. Materials and Methods

2.1. Study Area and Datasets

2.1.1. Study Area

Ningbo is located in East China, on the southeast coast and the south wing of the Yangtze River Delta. The geographical location is between 120°55′–122°16′ E and 28°51′–30°33′ N (Figure 1). The Zhoushan archipelago in the east is a natural barrier. It is a typical water town and seaport city south of the Yangtze River. It is the seaport at the Henan end of the Universiade and the eastern departure port of the "Maritime Silk Road". The annual cargo throughput of Ningbo Zhoushan port ranks first in the world, and the container volume ranks third in the world. It is a multifunctional and comprehensive modern deep-water port integrating inland ports, Hekou ports, and seaports. By the end of 2021, the permanent resident population of Ningbo was 9.544 million. In 2021, the city's GDP reached 1459.49 billion yuan. It is an important port city along the southeast coast of China and the economic center and energy consumption center of the south wing of the Yangtze River Delta.

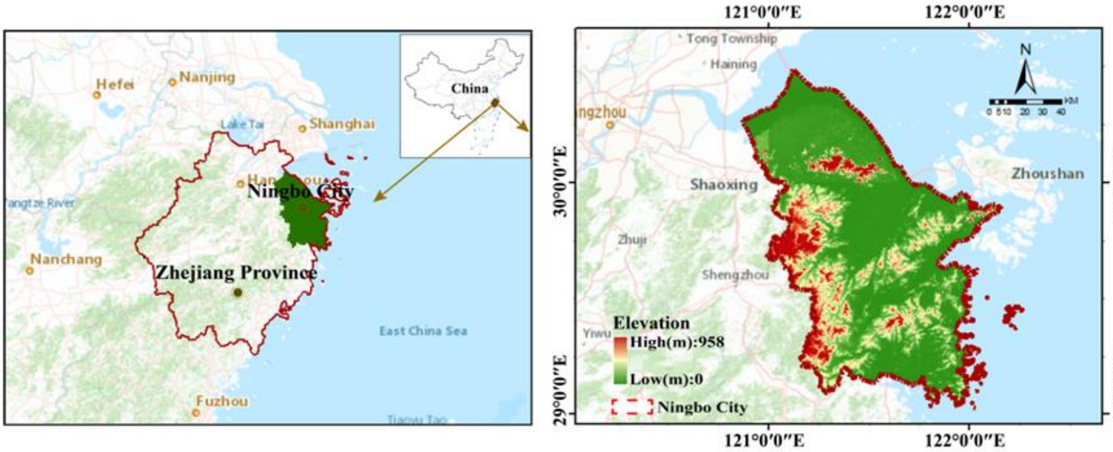

Figure 1. Geographical location of Ningbo City.

2.1.2. Data Sample Selection

Ningbo, with a dense urban built environment, located in the metropolitan region of the Yangtze River Delta, was selected as the case city because of its representativeness. The road network in the downtown area of Ningbo has a square grid and loop layout, and the functional distribution of each block is similar to that of other plain area cities in China. At the same time, Ningbo's population size, economic growth trends, energy consumption levels, etc., are consistent with the overall socioeconomic characteristics of China. Based on the status quo survey and considering factors such as type diversity, uniform spatial distribution, easy access to data, and high occupancy rates, we selected 9 community samples in the downtown area of Ningbo that can reflect the characteristics of the urban built environment (Figure 2). Within the scope of the community sample, considering the occurrence and attraction of traffic, we further obtained 22,112 traffic trip samples.

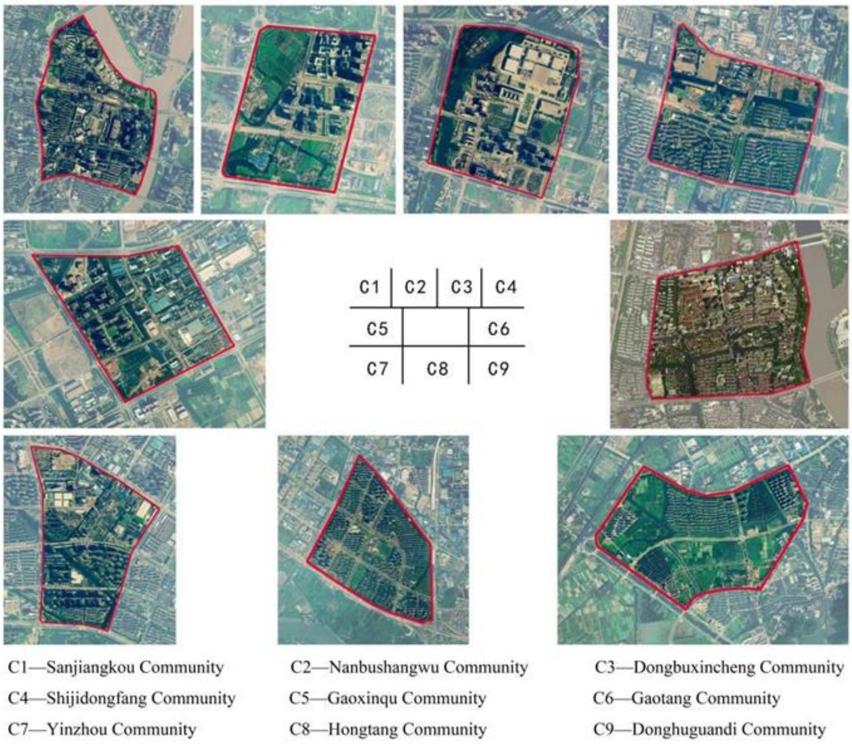

Figure 2. Images of the nine communities across Ningbo used in the study, accessed 12 October 2015. Photograph: Baidu Map.

2.2. Method

An integrated dataset that includes travel energy consumption, the built environment, travel information, travelers' personal and family characteristics, and energy saving attitudes is crucial for this study.

2.2.1. Household Survey Instrument

To obtain first-hand real and reliable data, the household survey instrument was used in this study. The household survey instrument was developed based on previous studies [25], as well as the U.S. Residential Energy Consumption Survey. The data in this study are first-hand data obtained from household surveys. The survey objects are all the permanent residents aged 6 or above and 80 or below who are selected to live together in the family sample. The traffic trips related to the sample community include both outbound trips taking the community as the starting point and inbound trips taking the community as the destination. Therefore, from the perspective of analyzing the occurrence and attraction of traffic, the selection of travel samples should not be limited to nine community samples, but should be carried out in the downtown of Ningbo. The study focuses on the uniformity of the spatial distribution of the samples when selecting the travel samples for families.

First of all, based on the division map of Ningbo traffic districts, the number of households in each traffic district is counted and numbered to determine the sample number of each traffic district. Secondly, determine the sample size in each traffic zone. When the confidence is 95% and the error limit is 0.05, assuming that the sample variation in the population is the largest, that is, $p = 0.5$, the population size is 50, 100, 500, 1000, 5000, 10,000, 100,000, 1,000,000, and 10,000,000, and the required sample size is 44, 80, 222, 286, 370, 385, 398, 400, and 400, respectively. It can be seen that with the increase in the overall size, the increase in the required sample size gradually decreases to zero. When the overall size is $\geq$1,000,000, 400 effective samples can meet the demand for sample size. This study draws on this practice to determine the sample size in each traffic zone. If the overall size of the traffic zone is less than 50 or is not an integer, the sample size required by the nearest integer is converted proportionally. Finally, the corresponding interval K value is calculated by dividing the total size by the sample size in each traffic zone, and the samples are randomly selected by the method of equal interval sampling. In this survey, 42,411 questionnaires were actually collected (each family shared one questionnaire), of which 40,927 were valid, with an effective rate of 96.5%. After statistics and screening, 22,112 pieces of traffic travel information related to the sample communities were finally determined. In order to successfully interview the households that need to be surveyed, the survey was conducted from 19:00 to 21:00 every day. In addition, if there was no one in a family during the survey, it was replaced by families with adjacent numbers. The questionnaire is composed of four parts: the first part mainly involves the respondents' family conditions, including the number of permanent residents, ownership of transportation vehicles, etc.; the second part mainly involves the basic personal information of the interviewees, including gender, age, education level, annual income, etc.; the third part mainly involves the personal travel of the interviewees, including starting and ending points, travel purposes, travel modes, etc.; the fourth part mainly involves the respondents' attitudes towards improving the urban transport system.

In order to ensure the quality of the survey, each investigator on the research team must attend a half-day training seminar. During the training, one of our questionnaire designers explained and discussed every question in the questionnaire for each investigator, and each investigator received training on sampling strategy and interview skills. In June 2015, we conducted a pilot survey on 20 families to find out any situation that may affect the accuracy of the survey, including misunderstanding of the survey questions, ambiguity of the answers to the questionnaire, or other questions. According to the feedback from the pilot survey, we slightly modified the survey method, and then conducted a formal household survey in July 2015.

As for the calculation of travel distance, we used the Traffic Analysis Zone of Ningbo to carry out the calculation. The calculation of travel distance is divided into three steps: the first step is to obtain the starting point and destination of residents' travel within the traffic zone through household survey; second, calculate the distance between any two traffic zones based on ArcGIS10.8 software, and import the calculated data into Excel software; third, use the VLOOKUP(Microsoft office professional plus 2013) function of Excel software to match the distance between the starting point and the destination of residents' travel, and then calculate the distance of a single one-way trip. It should be noted that since the travel route only knows the starting point and the end point, it is impossible to obtain its specific travel path. According to people's previous travel habits, we calculated residents' travel distance according to the optimal path, that is, the straight line distance between the center point of the traffic community where the travel starting point is located and the center point of the traffic community where the end point is located is the traffic travel distance, as shown with Equation (1):

$$E_i^m = TD_i^m \times EI^m \tag{1}$$

$$EI^m = FU^m \times EC^m \tag{2}$$

where:

E_i^m refers to the travel energy consumption of the i-th household interviewee in a single one-way trip (MJ).

TD_i^m refers to the travel distance of the i-th household interviewee using mode m of transportation (KM).

EI^m refers to the energy intensity factor of mode m, as detailed in Table 1.

Table 1. Table of energy intensity factors for different traffic modes.

Traffic Modes	Fuel Economy Factor	Fuel Calorific Value Factor	Energy Intensity Factor
private car	0.092 L/km	32.2 MJ/L	2.962 MJ/km
taxi	0.083 L/km	32.2 MJ/L	2.673 MJ/km
bus	0.3 L/km	26.6 MJ/L	10.680 MJ/km
motorcycle	0.019 L/km	32.2 MJ/L	0.612 MJ/km
e-bicycle	0.021 kWh/km	3.62 MJ/kWh	0.076 MJ/km

FU^m refers to the fuel economy factor of mode m, as detailed in Table 1.

EC^m refers to the fuel calorific value factor of mode m, as detailed in Table 1.

It can be seen that EI (energy in intensity factor) is the key to calculating the energy consumption of transportation, which is mainly determined by Fu (fuel economy factor) and EC (fuel energy content factor), as shown in Formula (2). The energy intensity factors of different means of transportation are different. For example, in Jiang Yang's research [26], they pointed out that the fuel economy factor of private cars is about 0.092 L per km, and the calorific value factor of fuel per liter is about 32.2 MJ (see Table 1 for details).

When sorting out the survey information, it was found that the number of trips of some travel information was not just for one of the respondents; that is, the respondents had accompanying people on a single trip. For example, on weekends, many people in a family travel at the same time for shopping. In the process of such travel, family members have the same travel mode, travel distance, and travel purpose. Therefore, it is necessary to consider introducing the factor of "same journey carrying rate" into Equation (3). The modified formula is:

$$E_i^m = \frac{TD_i^m}{TO_i^m} \times EI^m \tag{3}$$

where:

TO_i^m refers to the number of peers in the i-th household interviewee when using mode m to travel, which is 1 when only interviewees travel on their own.

According to the distance from the workplace and the total number of people in 22,112 survey data points, combined with the energy intensity factors of different travel modes in Table 1, the energy consumption values of different travel modes were calculated using Formula (3). With the help of Kepler GL, the energy consumption distribution map of five travel modes was obtained (Figure 3). The results show that the travel energy consumption of the nine surveyed communities is mainly for buses and private cars.

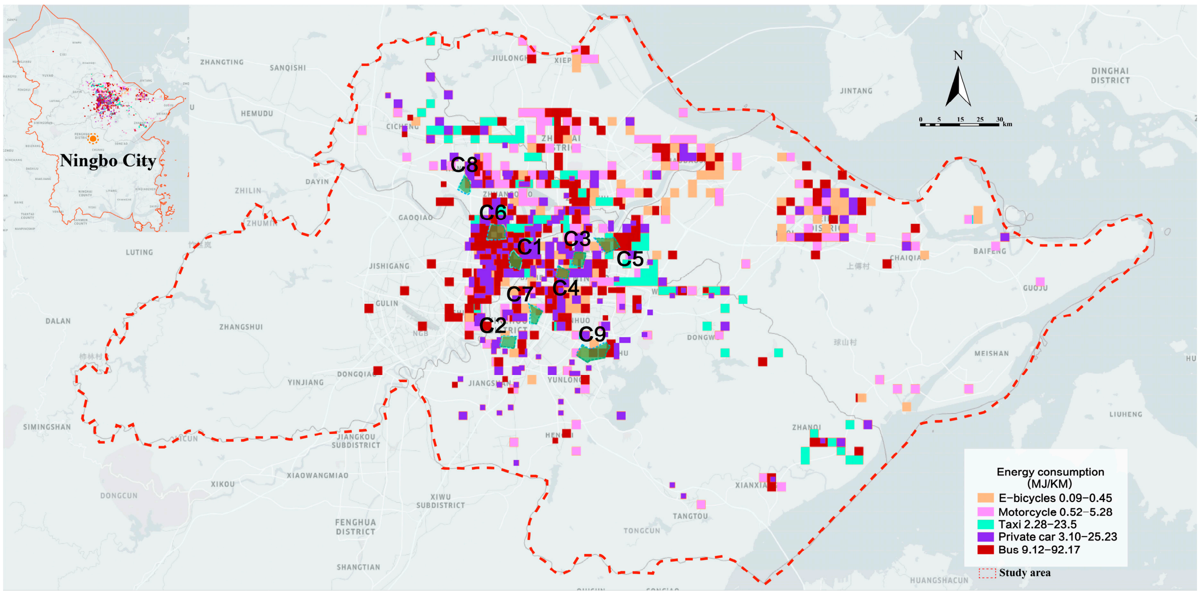

Figure 3. Spatial distribution of energy consumption of five travel modes.

In addition, as far as bus travel is concerned, the carrying rate is 27 people on the same journey. These data are mainly calculated based on the information in the Ningbo Traffic Statistics Yearbook 2016 [27]. Among them, the total mileage of buses in the Ningbo urban area is approximately 104.2125 million km in the whole year, the annual passenger volume in the urban area is approximately 199.5735 million, and the per capita mileage of a single trip by bus is approximately 13.91 km. From this, it can be calculated that the same-distance carrying rate of buses is (19,957.35 × 13.91) ÷ 10,421.25 = 26.6, approximately 27 people per ride.

The built environment data were collected from two sources, ArcGIS10.8 analysis and household surveys [28]. In this study, we used population density, land use mixture, service facility accessibility, distance from work sites, and road intersection density to characterize the built environment. Population density refers to the sum of the residential population density and the working population density in each sample community. Referring to Rajamani's [29] method of calculating mixed land use when studying the impact of urban morphology on travel mode choices, entropy was computed to represent the land use mixture with Equation (4). The ratio of the total area covered by various service facilities to the area of the community was computed to represent the service facilities accessibility with Equation (5) [30]. Distance from work sites means the distance between home and the workplace of each travel sample. The road intersection density refers to the ratio of the number of road network intersections to the area of the sample community.

$$M_i = 1 - \left\{ \frac{\left| \frac{r_i}{T_i} - \frac{1}{4} \right| + \left| \frac{c_i}{T_i} - \frac{1}{4} \right| + \left| \frac{m_i}{T_i} - \frac{1}{4} \right| + \left| \frac{o_i}{T_i} - \frac{1}{4} \right|}{\frac{3}{2}} \right\} \tag{4}$$

where:

M_i refers to the degree of mixed land use in the i-th community.

r_i refers to the residential land (R) area in the i-th community (KM2).

c_i refers to the business facilities (B) area in the i-th community (KM2).

m_i refers to the public service facilities (A) area in the i-th community (KM2).

o_i refers to the area of land other than residences, businesses, and public service facilities in the i-th community (KM2).

T_i refers to the total occupied area of the i-th community (KM2).

$$S_i = \frac{A_{Pi} + A_{Mi} + A_{Ci} + A_{Bi}}{A_i} \tag{5}$$

where:

S_i refers to the proximity of service facilities in the i-th community (KM2).

A_{Pi} refers to the coverage area of primary school in the i-th community (KM2).

A_{Mi} refers to the coverage area of middle school in the i-th community (KM2).

A_{Ci} refers to the coverage area of the health service station in the i-th community (KM2).

A_{Bi} refers to the coverage area of small and medium-sized supermarkets in the i-th community (KM2).

A_i refers to the area of the i-th community (KM2).

2.2.2. Variable Description

In recent decades, with the consumption of urban energy, urban carbon emissions have increased significantly. Therefore, urban space may be an vital factor affecting travel energy consumption among individuals. At the same time, this potential transformation of low-carbon behavior is affected by low-carbon ideas and values. Therefore, increased attention is given to the awareness of low energy consumption and low carbon consumption. Energy consumption can be calculated because it follows the conventional calculation rules in the low-carbon cognition of building energy use, daily travel, and daily consumption. These variables consider the willingness, attitude, and awareness of quantifying energy-saving behavior [31]. An integrated set of variables that includes travel energy consumption, built environment, travel information, travelers' personal and family characteristics, and energy saving attitude is collected for this study. Among these variables, travel energy consumption is a dependent variable, and the other variables are independent variables. It is worth noting that travelers' personal characteristics and energy saving attitude variables are dummy variables. In the regression analysis process, dummy variables are represented by 0 and 1, respectively; 0 represents the negative form of the variable, and 1 represents the positive form of the variable. For example, among the energy saving attitude variables, if respondents believe that it is necessary to adjust the bus line value, the variable is 1; otherwise, it is 0. Table 2 provides detailed information on the variable names and descriptions.

In order to reveal the relationship between the built environment and the energy consumption of transportation trips in detail, we not only analyzed the relationship between the built environment and the overall energy consumption of transportation trips, but also further analyzed the impact of the built environment on the energy consumption of different travel purposes and different travel modes. In order to propose the optimization design strategy of the built environment under the guidance of low-carbon development, the energy consumption of different travel modes in this study is divided into high-energy-consumption and low-energy-consumption travel modes based on the use of vehicles.

When conducting traffic travel research, the travel modes are divided into 9 categories for the respondents to choose from, namely walking, cycling, electric vehicles, motorcycles, buses, shuttle buses, driving cars, taking cars, taxis, and others. This study mainly analyzes the impact of the built environment on the energy consumption of transportation trips. Since walking and bicycle trips are inefficient, the study needs to exclude these two types of travel samples, and then classify them according to the level of energy consumption of different travel modes. According to the energy intensity factors of different transportation modes, the energy consumption of private cars and taxis is relatively high, while that of buses, shuttle buses, and electric vehicles is relatively low. Therefore, the transportation modes in this section are divided into high-energy-consumption mode and low-energy-consumption mode.

Table 2. Variables and variable descriptions.

Variable Categories	Variable Name	Variable Description
Travel energy consumption	Overall travel energy consumption	All traffic travel samples
	Commute travel energy consumption	Travel to work, school, and home
	Non-commute travel energy consumption	Trips other than commuting trips
	High-energy-consumption travel energy consumption	Travel by cars
	Low-energy-consumption travel energy consumption	Travel by buses, e-bicycle, and motorcycles
Built environment	Population density	The total number of living and working people per square kilometer
	Land use mixture	The measure of the composition of residential, commercial, public service facilities and other land uses within each community
	Service facilities accessibility	The ratio of radiation coverage of various service facilities to community area
	Distance from work sites	Distance between residence and workplace
	Road intersection density	The number of road intersections per unit area
Travelers' family characteristics	Household size	The number of household members
	Travel tools	The number of bicycles, e-bicycle, motorcycles, and automobiles in the household
Travelers' personal characteristics	Gender	1, if respondent is male; 0, otherwise
	Age	Under 18, 18–60, 60 or higher
	Education	Elementary school or below, junior high school, high school, university, graduate school or above
	Occupation	Students, workers in enterprises and institutions, self-employed persons, retired, unemployed
	Annual income	Under 20,000, 20,000–50,000, 50,001–100,000, more than 100,000
Energy saving attitude	Reconstruction and expansion of urban road systems	1, if respondent agrees with the view; 0, otherwise
	Shorten bus departure intervals	1, if respondent agrees with the view; 0, otherwise
	Adjust bus routes	1, if respondent agrees with the view; 0, otherwise
	Speed up rail transit construction	1, if respondent agrees with the view; 0, otherwise
	Increase pedestrian crossing facilities	1, if respondent agrees with the view; 0, otherwise
	Increase parking facilities	1, if respondent agrees with the view; 0, otherwise
	Strengthen traffic violation management	1, if respondent agrees with the view; 0, otherwise

2.2.3. Model Specification

Multivariate linear regression is a statistical method that can describe the degree of simultaneous association between multiple variables and a continuous result [32]. The application of multivariate linear regression in travel energy research began in the 1950s [33], and this method has been widely used in many research fields, including sociology, economy, and health [34]. In this study, based on the impact mechanism of the built environment on travel energy consumption (Figure 4), we propose a multivariate linear regression model framework that describes the relationship among the built environment, travelers' family characteristics, personal characteristics, energy saving attitudes, and travel energy consumption.

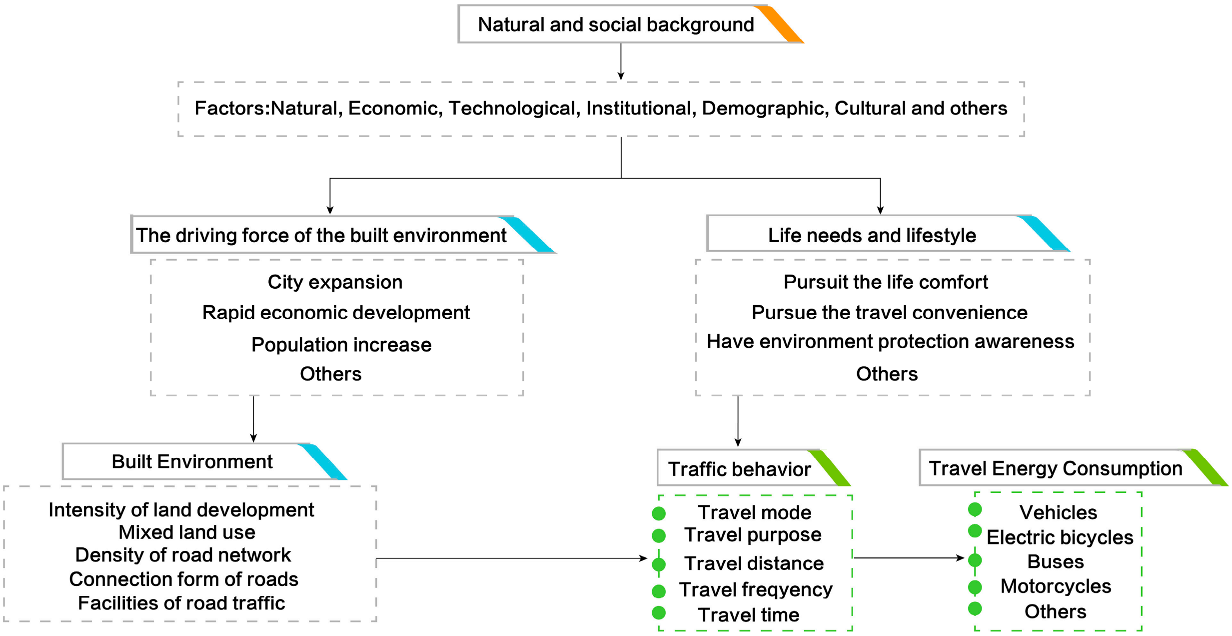

Figure 4. Conceptual framework describing the impact mechanism of built environment on travel energy consumption.

Assuming that the travel energy consumption is affected by these factors, the multiple linear regression model in this study can be written as follows:

$$\mathrm{Ln}\left(\mathrm{E}_\mathrm{i}^\mathrm{T}\right) = \beta_0' + \beta_1'\mathrm{J}_\mathrm{i} + \beta_2'\mathrm{F}_\mathrm{i} + \beta_3'\mathrm{P}_\mathrm{i} + \beta_4'\mathrm{A}_\mathrm{i} + \varepsilon_\mathrm{i}' \quad (6)$$

where:

$\mathrm{E}_\mathrm{i}^\mathrm{T}$ refers to the average energy consumption of residents on a single trip.

J_i refers to the various variables that can describe the urban built environment.

F_i refers to the various variables that can describe the family socioeconomic status.

P_i refers to the various variables that can describe the personal lifestyle characteristics of residents.

A_i refers to the various variables that can describe residents' attitudes towards energy conservation.

ε refers to the random error term of the regression model.

To systematically reveal the impact of the built environment on travel energy consumption, we divided the surveyed traffic travel energy consumption data into three categories: overall travel energy consumption, travel energy consumption for different purposes, and travel energy consumption for different modes. Among them, according to different travel purposes, it can be further divided into commute and non-commute travel. According to different travel modes, it can be further divided into high-energy-consumption travel (such as driving) and low-energy-consumption travel (such as taking a bus or riding an e-bicycle). In this study, we build analytical models separately to examine the impact of various variables on different travels.

It is worth noting that due to the large span of the research sample regarding age, education, occupation, and income, we classified these four dummy variables during regression analysis. When there are categorical dummy variables in the regression analysis, it is necessary to set the control variables and then import other variables except the control variables into the regression model [35]. In this study, the control variables are people under eighteen years old, with primary school education or less, retirees, and people earning less than 20,000 yuan per year. All estimations and computations of regression analysis are carried out by using SPSS Statistics 21.0.

3. Results and Findings

Multivariate linear regression results for overall travel, different travel purposes, and different travel modes' energy consumption are presented in Table 3. In each case, the model includes the built environment, travelers' family characteristics, personal characteristics, and energy saving attitude variables. The regression results reveal the effects of built environment variables on travel energy consumption.

Table 3. Overall travel, different travel purposes and different travel modes regression results.

Variables	Overall Model1	Commute Model2	Non-Commute Model3	High-Energy-Consumption Model4	Low-Energy-Consumption Model5
Built Environment					
Population density	−0.094 *** (0.023)	−0.115 *** (0.024)	n.s.	−0.273 *** (0.032)	−0.124 *** (0.021)
Land use mixture	−0.415 ** (0.170)	−0.421 ** (0.184)	n.s.	−2.574 *** (0.224)	−1.197 *** (0.162)
Service facilities accessibility	−0.164 *** (0.024)	−0.128 *** (0.025)	−0.352 *** (0.047)	−0.491 *** (0.036)	−0.154 *** (0.021)
Distance from work sites	0.433 *** (0.064)	0.440 *** (0.069)	n.s.	0.394 *** (0.088)	0.209 *** (0.059)
Road intersection density	−0.079 ** (0.033)	−0.112 *** (0.035)	n.s.	0.091 ** (0.046)	0.020 (0.030)
Travelers' Family Characteristics					
Household size	0.044 ** (0.022)	0.065 *** (0.024)	−0.061 (0.054)	0.025 (0.036)	n.s.
Number of bicycles	−0.118 *** (0.011)	−0.125 *** (0.012)	−0.089 *** (0.025)	n.s.	0.020 (0.010)
Number of e-bicycles	−0.127 *** (0.011)	−0.139 *** (0.012)	−0.067 ** (0.026)	0.064 *** (0.019)	−0.255 *** (0.009)
Number of motorcycles	0.217 *** (0.035)	0.219 *** (0.038)	0.237 *** (0.087)	0.012 (0.058)	0.323 *** (0.029)
Number of cars	0.634 *** (0.015)	0.653 *** (0.016)	0.495 *** (0.037)	n.s.	n.s.
Travelers' Personal Characteristics					
Gender	0.256 *** (0.016)	0.276 *** (0.018)	0.170 *** (0.039)	0.077 *** (0.026)	0.013 (0.015)
Age: Under 18 Years Old					
18 to 60 years old	0.189 *** (0.056)	0.202 *** (0.061)	−0.099 (0.146)	0.331 *** (0.105)	n.s.
More than 60 years old	0.021 (0.062)	0.011 (0.071)	−0.263 (0.150)	0.325 ** (0.145)	0.021 (0.030)
Education: Primary School or Less					
Junior high school	0.224 *** (0.026)	0.240 *** (0.030)	0.162 *** (0.052)	0.202 *** (0.053)	0.111 *** (0.025)
Senior high school	0.375 *** (0.029)	0.395 *** (0.033)	0.295 *** (0.061)	0.146 *** (0.053)	0.166 *** (0.027)
College	0.447 *** (0.031)	0.480 *** (0.034)	0.321 *** (0.068)	0.109 ** (0.049)	0.272 *** (0.028)
Graduate or more	0.554 *** (0.073)	0.619 *** (0.080)	n.s.	n.s.	0.242 *** (0.083)
Occupation: Student	0.197 *** (0.060)	0.117 (0.068)	0.495 *** (0.139)	0.001 (0.136)	0.102 *** (0.037)
Workers in enterprises and institutions	0.276 *** (0.032)	0.223 *** (0.039)	0.184 *** (0.058)	−0.066 (0.097)	0.011 (0.022)
Self-employed persons	0.340 *** (0.033)	0.287 *** (0.040)	0.349 *** (0.066)	−0.044 (0.098)	−0.022 (0.024)
Retirees					
Unemployed	0.197 *** (0.034)	0.164 *** (0.043)	n.s.	0.074 (0.103)	n.s.
Annual income: Under 20000 yuan					
20,000 to 50,000 yuan	0.187 *** (0.022)	0.208 *** (0.025)	−0.006 (0.046)	n.s.	n.s.
50,000 to 100,000 yuan	0.544 *** (0.030)	0.545 *** (0.033)	0.499 *** (0.077)	0.028 (0.030)	−0.019 (0.023)
More than 100,000 yuan	0.764 *** (0.043)	0.792 *** (0.046)	0.348 *** (0.124)	−0.008 (0.038)	0.172 *** (0.060)

Table 3. *Cont.*

Variables	Overall Model1	Commute Model2	Non-Commute Model3	High-Energy-Consumption Model4	Low-Energy-Consumption Model5
Energy saving attitude					
Reconstruction and expansion of urban road systems	0.048 *** (0.017)	0.044 ** (0.018)	−0.002 (0.038)	n.s.	0.011 (0.015)
Shorten bus departure intervals	−0.006 (0.018)	−0.030 (0.019)	−0.003 (0.040)	n.s.	0.100 *** (0.016)
Adjust bus routes	0.082 *** (0.019)	n.s.	n.s.	0.025 (0.027)	0.027 (0.017)
Speed up rail transit construction	−0.043 ** (0.019)	−0.048 ** (0.021)	−0.126 *** (0.043)	n.s.	−0.016 (0.018)
Increase pedestrian crossing facilities	0.101 *** (0.019)	0.092 *** (0.021)	0.056 (0.044)	−0.054 ** (0.027)	−0.013 (0.018)
Increase parking facilities	0.046** (0.018)	0.032 (0.019)	n.s.	n.s.	n.s.
Strengthen traffic violation management	−0.629 *** (0.176)	−0.462 ** (0.192)	0.446 *** (0.162)	2.270 *** (0.266)	0.719 *** (0.153)
Intercept	0.318/0.317	0.336/0.335	0.206/0.201	0.295/0.292	0.202/0.199
R^2/Adj − R^2					
VIF	2.712	2.789	2.499	3.921	2.068
N	22,112	18,337	3775	4950	8636

Note: (1) Standard errors in parentheses. (2) ** $p < 0.05$, *** $p < 0.01$. (3) "n.s." indicates that there is no correlation between two variables.

Firstly, the effects of different variables of each model on its travel energy consumption are compared vertically. When other variables in the model are controlled, all variables of family characteristics will have a significant impact on travel energy consumption in the commuting travel energy consumption model. Except for those over 60 years old and students, other variables of residents' personal characteristics will have a significant impact on travel energy consumption. The range of normalized variables is 0–1. In addition to considering the need to rebuild and expand urban roads, adjust bus lines, speed up rail transit construction, and strengthen violation management, other variables of travel attitude will have a significant impact on travel energy consumption, all variables of the built environment will have a significant impact on travel energy consumption. Among them, the distance from the workplace has the greatest impact on commuting travel energy consumption, while the impact of road intersection density on energy consumption is the least.

In terms of the non-commuting travel energy consumption model, all variables of family characteristics, except the number of permanent residents, will have a significant impact on travel energy consumption. Among the variables of residents' personal characteristics, except for people aged 60 or older, with a graduate degree or above, unemployed, or with an annual income of 20,000 to 50,000, other variables will have a significant impact on travel energy consumption. For the variables of travel attitude, only the people who need to increase pedestrian crossing facilities have a significant impact on travel energy consumption. Among the variables of the built environment, only the proximity of service facilities has a significant impact on travel energy consumption. The results show that with the increase in proximity of service facilities, residents' non commuting travel energy consumption decreases.

Secondly, the impact of built environment variables on energy consumption for different travel purposes is compared horizontally. It can be seen that population density, land mixed use degree, road intersection density, and distance from the workplace will significantly affect the total transportation travel and commuting travel energy consumption, and all variables have a greater impact on commuting travel energy consumption, but they have no significant impact on non-commuting travel.

3.1. Population Density and Travel Energy Consumption

When controlling for other variables, there is a significant negative correlation between population density and travel energy consumption on the whole. This is mainly because communities with higher population density tend to have higher development density, and the corresponding supporting facilities are better. All kinds of travel for residents to meet their daily life are relatively convenient, and the travel distance and time are also relatively short, which can reduce their travel energy. However, if modeling is based on different travel purposes and distinct travel modes, population density has a significant negative correlation with commute travel energy consumption and different travel mode energy consumption but has no significant impact on non-commute travel energy consumption. This lack of impact is because with the improvement of supporting facilities, the travel distance to work and school can be significantly reduced; therefore, it can significantly affect the energy consumption of commute travel, but this effect is not significant for non-commute travel. In addition, the results also show that the increase in population density can reduce travel energy consumption in various ways, and the influence on high-energy-consumption travel is greater than that of low-energy-consumption travel. This is also related to the travel distance; the energy consumption will be reduced accordingly, no matter which mode of travel is adopted when the distance of travel destination is shortened, and some travel can be exercised even without the aid of transportation. Moreover, the influence of population density on high-energy-consumption travel is greater than that of low-energy-consumption travel because residents prefer to choose convenient and economical means of transportation when traveling short distances; therefore, it can greatly reduce the use frequency of high-energy-consumption travel, such as private cars.

3.2. Land Use Mixture and Travel Energy Consumption

In terms of the degree of mixed land use, this variable overall has a significant negative correlation with travel energy consumption. However, if modeling is based on different travel purposes and distinct travel modes, the degree of mixed land use has a significant negative correlation with commute travel energy consumption and different travel mode energy consumption but has no significant impact on non-commute travel energy consumption. When calculating the degree of mixed land use, this study mainly considers the land for residences, businesses, and public service facilities, so to a certain extent, this variable can also reflect the job–housing balance in the community and the accessibility of all kinds of facilities.

The results show that with the increase in mixed land use in the community, the total travel energy consumption, commute travel energy consumption, and various modes of travel energy consumption will be reduced. This is mainly because residents in communities with a high degree of mixed land use have a relatively short travel distance and time for work and other purposes, so the energy consumption of using various means of transportation will be reduced. As far as Ningbo is concerned, the improvement of mixed land use can significantly reduce the energy consumption of commute travel, which shows that the job–housing balance can significantly affect residents' daily travel. When the ratio of jobs to housing in the community tends to be balanced, the distance and time of commuting, such as going to work, can be shortened, so the corresponding energy consumption will be significantly reduced. In addition, in terms of different travel modes, the impact of mixed land use on high-energy-consumption travel is greater than that of low-energy-consumption travel because when the travel distance and travel time are shortened, residents are more willing to choose low-energy-consumption travel such as buses or e-bicycle, so the impact on high-energy-consumption travel is more significant. It should be noted that the degree of mixed land use in Ningbo has the highest impact on high-energy-consumption travel, with a coefficient of -2.574. However, relevant studies in Europe and America show that the average influence coefficient of mixed land use on vehicle mileage is −0.09, which is relatively weak. We believe that this weak influence is mainly due to the differences in development methods between cities. European and American cities have a high degree of flattening; that is, the scale of cities is relatively large, the building height is relatively low, the per capita use area in cities is relatively large, the road network system is well developed, and daily travel is highly dependent on cars. Therefore, the degree of mixed land use has a weak impact on choice of travel mode. However, Ningbo is the opposite of most cities in Europe and America, and the degree of mixed land use has a direct impact on people's travel mode and travel distance under the condition of relatively high development intensity. Therefore, the impact of mixed land use on motor vehicle travel in Ningbo is higher than the average level of cities in Europe and America.

3.3. Service Facilities Accessibility and Travel Energy Consumption

Overall, the influence of road intersection density on travel energy consumption has a significant negative correlation with travel energy consumption. The road intersection density reflects the road network density to a certain extent and reflects the connectivity of the road network system. In Ningbo, with the increase in road intersection density in the community, residents' travel energy consumption will be reduced. The main reason is that the increase in road intersections in the community can provide more travel routes for residents, and residents will choose the most energy-saving travel routes according to their travel needs, thus reducing travel energy consumption. Interestingly, if modeling is based on different travel purposes and different travel modes, this variable has a significant negative correlation with commuter travel energy consumption but a significant positive correlation with high-energy-consumption travel energy consumption and has no significant effect on non-commute travel energy consumption and low-energy-consumption travel energy consumption. This is mainly because the road network form in the main urban area of Ningbo is a square grid, which can effectively reduce the travel time because the residents' travel flexibility will be enhanced when the road intersection density increases.

It is worth noting that the road intersection density in Ningbo has a negative correlation with residents' total travel energy consumption, which is lower than other built environment variables, and the coefficient in the model is −0.079. This is obviously distinct from the situation in Europe and America. The relevant research results in Europe and America show that the average influence coefficient of road intersection density on vehicle mileage is −0.12 [36], which is significantly higher than that in Ningbo. This is mainly related to the way people travel. In European and American countries, especially the United States, people are relatively more sensitive to the connectivity of road networks. With the increase in road intersection density, people can optimize their travel routes to effectively reduce the travel distance. In addition, the enhanced connectivity of road networks can also encourage residents to choose travel modes such as walking, thus reducing the frequency of car use. The residents of Ningbo mainly travel by e-bicycle, and the increased road intersection density will reduce residents' travel distance to a certain extent. However, the results of the quantitative analysis show that it not only cannot reduce the low-energy-consumption energy consumption, but also encourages some people to choose high-energy-consumption travel. Therefore, the impact of road intersection density on traffic travel in Ningbo is lower than the average level of other cities in Europe and America.

3.4. Distance from Work Sites and Travel Energy Consumption

The distance from work sites has a significant positive correlation with travel energy consumption. The main reason is that communities far away from work sites tend to be far away from the city center, the development density of these communities is relatively low, and the supporting service facilities are relatively flawed. Therefore, the travel distance of residents will also increase to meet a variety of living needs. However, if modeling is based on different travel purposes and different travel modes, the distance from work sites has a significant positive correlation with commute travel energy consumption and different travel mode energy consumption but has no significant impact on non-commute travel energy consumption. With the increase in the distance from the work sites, the commute travel energy consumption of residents will also increase, while the energy consumption of non-commute travel has no significant change. This is mainly because a greater distance from work sites leads to an increase in commuting distance and commuting time, which in turn affects travel energy consumption, while non-commute travel is not affected. Moreover, with the increase in the distance from work sites, the travel energy consumption of residents who choose different travel modes will increase because residents who live far away from their work sites travel relatively long distances to meet the needs of their daily lives, so regardless of which means of travel they use, they will increase their travel energy consumption.

3.5. Road Intersection Density and Travel Energy Consumption

Based on the analysis results of each model, service facilities accessibility has a significant negative correlation with the overall traffic travel, different travel purposes, and different travel modes. The service facilities of this study include educational, medical, and commercial facilities. When the distance between residents and service facilities is shortened, their travel distances, such as going to school, transportation, seeing a doctor, and daily shopping, will be shortened, thus reducing residents' overall travel energy consumption. At the same time, with the increase in service facilities accessibility, the travel energy consumption of different purposes will be reduced, and the impact on non-commute travel energy consumption is relatively high. With the increase in service facilities accessibility, the travel energy consumption of different modes will be reduced, and the impact on high-energy-consumption travel is greater than that of low-energy-consumption travel. On the one hand, when the accessibility of educational facilities increases, it is beneficial for women and grandparents to pick up students, and this group of people has been indicated to travel with low or zero energy consumption. On the other hand, due to the rich business forms and dense population around the service facilities, idle speed, traffic jams, and other phenomena often occur, which is not conducive to high energy consumption. Therefore, when service facility accessibility increases, high-energy-consumption travel will be reduced.

4. Discussion

4.1. Comparative Analysis

Compared with the existing research, our research finds that the building environment has an obvious effect on the energy consumption of residential travel. The five variables of population density, mixed land use, road intersection density, workplace distance, and service facility distance can change the travel behavior of residents to varying degrees, and thus have different impacts on traffic energy consumption [37]. We controlled for other important variables such as travelers' family characteristics, personal characteristics, and energy saving attitude. The density of road intersections can represent the connectivity of the road network, and its impact on the energy consumption of high-energy-consumption mode travel is different from the research results of the overall and community travel energy consumption. This is mainly due to the increase in road network density, which will encourage more people to drive, while the increased traffic volume will lead to traffic congestion, which increases the travel energy consumption when vehicles are idling. The impact of mixed land use on travel energy consumption in Ningbo is relatively important. When the comprehensive utilization of land increases by one percentage point, the energy consumption of total transportation travel, commuting travel, high-energy travel, and low-energy travel decreases by 0.415%, 0.421%, 2.574%, and 1.197%, respectively. In addition, according to the analysis results of each model, from the characteristics of the impact of the built environment on travel energy consumption, commuters' travel energy consumption is more vulnerable to the impact of the built environment, while the travel energy consumption of high-energy-consumption modes such as driving is relatively sensitive to the built environment. This further proves the importance of comprehensive consideration of various types of building environments and low-carbon planning layouts [38]. However, existing studies often focus on the impact of cultural psychological factors and social policy norms. There is little operable space management, so it is difficult to realize the guiding role of low-consumption tourism cognition.

4.2. Limitations

First, there was no survey of residents in residential areas, and there was no memory survey of other types of urban land, such as commercial areas and industrial areas. However, when analyzing urban energy consumption, the unit personnel in commercial and industrial areas are also representative of travel energy consumption, which is often more regular in normal energy use, commuting travel, and travel consumption.

Second, in the regression analysis of the classification of dummy variables, the control variables were set as the people under 18 years old, with primary school education and below, retirees, and people with an annual income of less than 20,000 yuan, while ignoring the investigation of some control variables. According to the purpose of tourism, teenagers and retirees under the age of 18 are also the main groups in urban activities.

4.3. Policy Implication

The findings of this study can provide a new policy entry point for low-energy travel, low-carbon city construction, changing residents' lifestyles, and optimizing the built environment of the city. Our specific policy recommendations are as follows:

- Increase the mixed proportion of land use and improve the guidance of the external environment on residents' behavior.

To promote a low-carbon travel environment, the mixing ratio of land use with different functions should be strengthened at the community, block and building levels, especially to the optimal combination of residential, commercial, and office functions; improve the convenience of residents' travel and optimize the transportation network system; enrich the design of basic supporting services; and strengthen the guidance of human settlements.

- Focus on low-carbon travel and reasonably arrange the road network density.

Considering that the road intersection density has a significant negative impact on overall and community travel energy consumption, it has a significant positive impact on high-energy-consumption mode travel energy consumption. While increasing the density of the road network, Ningbo should also reduce traffic congestion with high energy consumption, such as driving, to ensure smooth operation of the road network. Therefore, the density of the road network should be considered around the promotion of low-carbon mode travel in road design. For example, the layout of road networks in residential areas should be developed around the service radius of bus stations, and road intersections should be designed from the perspective of improving road capacity; for example, the length of transition sections should be increased appropriately when widening the main road intersection to promote urban traffic microcirculation development from the perspective of reducing road congestion, for example, optimizing parking resource allocation, building green wave roads, and other command traffic systems.

- Improve residents' low-carbon awareness and build a built environment assessment system.

Because residents are affected by personal attribute factors such as education level, occupation, age, and values, their low-carbon travel and low energy consumption will not be considered. Therefore, in terms of residents' travel cognition, (1) for the low education population, we should increase the publicity and education of low-carbon travel knowledge and advocate for low energy consumption; we should also improve the basic service facilities in the living environment and enhance the guiding role of the environment in residents' lifestyle. (2) For the built environment, we can consider developing a built environment assessment system for travel energy consumption control in Ningbo, incorporating the built environment variables of this research into the system as evaluation indicators. Simultaneously, we can incorporate the proposed optimization guidance measures of the built environment into the system as assessment content and promote the construction of a low-carbon city in Ningbo from many aspects.

5. Conclusions

This study took the residents of nine districts and 22,112 traffic travel samples in Ningbo as the research objects, adopted the method of multiple linear regression, combined with a large-scale social questionnaire survey, and analyzed if the five variables of population density, mixed land use degree, road intersection density, workplace distance, and service facility distance can change the travel behavior of residents to varying degrees and have varying degrees of impact on traffic energy consumption. Our conclusions are as follows.

First, the urban built environment can have an impact on the total travel energy consumption of transportation. Although its impact is lower than the family socioeconomic characteristics and personal characteristics variables that can measure lifestyle, it is higher than the attitude variables that can improve the urban transportation system. It can be seen that social and economic conditions are the most important factors affecting traffic energy consumption, that the built environment is an important factor affecting traffic energy consumption, and that personal travel attitude is a secondary factor affecting traffic energy consumption.

Second, from the perspective of the impact of population density on transportation travel energy consumption, on the whole, population density has a significant negative correlation effect on transportation travel energy consumption. However, if the modeling is based on different travel purposes and different travel modes, the negative correlation effect of population density on commuting travel and different modes of travel energy consumption is significant, and the impact on non-commuting travel energy consumption is not significant. It can be seen from the coefficient of population density of each model that when the population density increases by 1%, the energy consumption of total transportation travel, commuting travel, high-energy consumption travel, and low-energy consumption travel will be reduced by about 0.094%, 0.115%, 0.273%, and 0.124%, respectively (Table 3).

Third, from the perspective of the impact of the road network system on the energy consumption of transportation travel, in general, the density of road intersections has a significant negative correlation with the energy consumption of transportation travel. Interestingly, if the modeling is based on different travel purposes and different travel modes, it has a significant negative correlation with the energy consumption of commuter travel, and has no significant impact on the energy consumption of non-commuter travel and low-energy travel. However, it has a significant positive correlation with the energy consumption of high-energy mode travel, which is mainly due to the fact that the increase in the density of the road network will attract more people to drive—the increase in vehicles will cause traffic congestion, which will increase the travel energy consumption of vehicles at idle speed. The analysis results show that when the density of road intersections increases by 1%, the energy consumption of total travel and commuting travel decreases by about 0.079% and 0.112%, while the energy consumption of high-energy-consumption mode travel increases by about 0.091% (Table 3).

Finally, through the regression analysis results, it can be seen that after adding the built environment variables, there is a significant impact of the built environment variables on energy consumption in the overall residential energy consumption model. The average value is greater than the total travel energy consumption model, so it shows that the impact of the built environment on travel energy consumption is greater than residential energy consumption. From the perspective of the impact of the urban built environment on travel energy consumption, this paper explores the relationship between residents' travel behavior and the urban built environment and provides scientific and reasonable policy management suggestions. However, the social survey based on some groups does not easily reflect the dynamic images of the overall building environment, personal characteristics, energy saving attitude, and other factors on low-carbon travel and low energy consumption. In the future, further follow-up is needed to reflect the real-time dynamic change data.

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