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New Energy Commuting Optimization under Low-Carbon Orientation: A Case Study of Xi'an Metropolitan Area

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Abstract: Low-carbon travel is an important part of low-carbon cities and low-carbon transportation, and low-carbon transportation is an inevitable choice to slow down the growth of carbon emissions in China. All countries in the world are actively promoting new energy vehicles and attach great importance to the application of the new energy industry in urban transportation. Commuting is an important part of urban life, and the choice of travel behavior has an important impact on traffic and environmental protection. Taking the Xi'an metropolitan area as an example, this paper expounds on the integrated development path of the industrial chain of new energy + travel in the metropolitan area and clarifies the energy transformation model of the integrated development of low-carbon transportation and energy. From the perspective of green and low-carbon, 1000 commuters were interviewed using a questionnaire survey, and the cumulative prospect model was used to verify the internal mechanism affecting commuters in metropolitan areas to choose new energy commuting. The results of the study show that new energy transportation modes play an important role in the low-carbon economy, and under different scenarios and assumptions, there are significant differences in the cumulative prospect values of the subway, new energy buses and fuel private cars, and corresponding optimization measures are proposed to increase the proportion of new energy commuting trips. The results will help further promote the development of a low-carbon economy and energy integration in the field of transportation and provide a reference for the sustainable development of public transportation.

Keywords: low-carbon; green travel; metropolitan area; new energy; commuting

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1. Introduction

With the continuous acceleration of economic development and urbanization, the proportion of transportation in national energy consumption and carbon emissions is rising, and it will face increasingly severe resource and environmental constraints. Sustainable development is one of the most pressing challenges facing mankind in the 21st century, among which energy consumption and climate warming have become the focus of global attention and research hotpot, and actively responding to climate change and promoting green and low-carbon development is a key link [1]. A metropolitan area is a new urban regional form with symbolic significance in the process of modern social and economic development and is an inevitable trend of urbanization development in countries around the world. It has become the core area of China's economic development and carbon dioxide emissions. The transportation system has always been one of the main ways to achieve trans-regional large-scale transportation of energy, which profoundly affects the layout of China's energy production. In addition, the accelerated expansion of the transport system and the trend towards re-electrification further strengthen the link between the transport system and the energy system, becoming a key factor affecting the efficiency of the energy system operation [2].

On the one hand, the whole energy industry chain is facing a profound impact. According to the data, the terminal energy consumption of China's transportation sector in 2022 is 820 million tons of standard coal. The total carbon emissions from the transportation industry in Shaanxi Province from 2010 to 2022 were 3.089 million tons. The main types of energy consumption in Shaanxi are gasoline and diesel, which are the main sources of carbon emissions from transportation. The intensity of transportation plays an important role in suppressing the growth of carbon emissions. Specifically, the contribution value of the transportation intensity factor is negative at 2.1724 million tons, with a contribution rate of 0.9601 [3]. The opportunities and challenges brought by "carbon peak" and "carbon neutrality" to the transportation field not only lie in the transportation itself but also penetrate into different business links in the whole industry chain, including not only transportation equipment manufacturing, aviation, railway, road and shipping and other transportation segments, but also sales, transportation, and other service industries [4]. The industrial chain not only needs to pay attention to the proportion of renewable energy, such as non-fossil energy, available in the whole country but also extends from the structure of the energy supply source to the diversity of subsequent energy consumption, which will be affected by low-carbon development ideas. Specifically, the dimensions of the impact of a low-carbon economy on related industries in the field of transportation include differences in the means of transport itself and differences in modes of transport [5]. The former emphasizes the use of a variety of means of transport with a variety of energy structures, such as electric vehicles, diesel vehicles, gasoline vehicles, hydrogen vehicles, natural gas vehicles, etc., while the latter involves the choice of different modes of transport such as ports, railways, highways, and aviation. Therefore, in the field of transportation, to achieve the strategic task goal of "double carbon" as soon as possible, it is necessary to seek feasible solutions from multiple dimensions and implement them around the whole industry chain and the whole process to achieve good results.

On the other hand, transportation commuting, as a kind of generative demand, is the periodic and regular travel behavior of people to and from the workplace and residence. China has entered the metropolitan era of urbanization and quality improvement. The renewal and upgrading of regional spatial structure has also brought new pressure to commuting, with the rapid growth of car ownership and the continuous growth of carbon emissions in the transportation sector [6]. In recent years, the rapid economic and social development of our country has vigorously promoted the development process of urbanization and motorization, and the rapid growth of motor vehicle ownership has become an inevitable trend of social development. The heavy use of motor vehicles is one of the main reasons for the continuous increase in carbon dioxide emissions [7]. At the same time, the pursuit of beautiful and convenient travel demand by urban residents makes the number of motor vehicles continue to increase, the saturation of urban roads is getting larger and larger, and overall traffic congestion has become a common problem in major cities. The traffic carrying capacity of the inner core circle of the metropolitan area obviously exceeds the load, and the efficiency of traffic management is low, which eventually leads to the spread of traffic congestion in a larger area. It has intensified comprehensive problems such as urban environmental pollution.

Based on this, at present, the academic community focuses more on the research vision of the personal will of new energy travel and the development and promotion of new energy. Less attention is paid to the optimization of new energy in commuting. Commuting is an important part of urban life, and the choice of travel behavior has an important impact on traffic and environmental protection. Therefore, this paper takes the Xi'an metropolitan area as an example, summarizes the integration mechanism of the new energy + travel industry chain in the metropolitan area, and clarifies the energy transformation model of low-carbon transportation and energy integration development. From the perspective of green and low carbon, the cumulative prospect model was used to verify the internal mechanism affecting commuters in metropolitan areas to choose new energy commuting.

It is expected that the research results will contribute to expanding the proportion of new energy travel in metropolitan areas in the future.

2. Literature Review

The concept of low-carbon was clearly put forward after 2000; however, the idea of low-carbon travel is not a new concept; it has experienced a long-term evolution, development, and heat process. The transition from private to public transport systems is analyzed, and it is suggested that public transport systems can reduce energy demand, carbon emissions, and air pollutants in local towns. Dällenbach [8] uses cost–benefit analysis to find that a particularly effective strategy to minimize CO_2 emissions from transportation is to replace flights with rail transit, with the same train emitting about 80–90% less CO_2 than an airplane. Fletcher [9] validated that expected travel patterns also have the potential to lock in high-carbon transport and undermine progress by collecting data using an international online survey. Achieving a low-carbon mobility transition must be supported by coordinated efforts by governments and individuals. Shie [10] adopted Porter's diamond model theory to demonstrate that green commitment has a positive impact on low-carbon travel motivation and intention while it has a negative impact on low-carbon travel constraints. Liao [11] used an extended TPB model to investigate the determinants of urban residents' low-carbon travel intentions and found that attitudes, subjective norms, and perceived behavioral control have a positive impact on low-carbon travel intentions. Moriarty [12] proposed to reduce urban vehicle travel by using MSD data to analyze four methods: changing urban land use, reducing the convenience of private car travel, introducing a carbon tax, and using information technology as a travel substitute.

Some scholars' policy studies on traffic governance in the context of metropolitan areas mainly focus on the policy formulation of traffic planning and the development of public transportation, etc., and pay less attention to guiding the change of travel behavior from the level of individual commuters, so as to improve the travel structure and realize the optimization and upgrading of low-carbon traffic environment. P Næss [13], taking Norway as an example, found that reducing travel distances, promoting better transport provision, and imposing tolls on urban roads could effectively save land and reduce car travel. Abdul [14] believes that transforming traditional gasoline vehicles into new energy vehicles is an important measure to achieve low-carbon urban development goals via energy conservation and emission reduction. Electric vehicles, due to their advantages in energy conservation and carbon reduction, will play an important role in this transformation. Broin [15] limiting infrastructure deployment as a complementary policy to carbon pricing reduces the cost of mitigation.

Based on this, this paper improves the cumulative prospect theory model to explore the internal selection mechanism and application scenarios of new energy commuting travel mode selection in metropolitan areas and provides targeted countermeasures and suggestions to guide commuters to choose low-carbon travel and promote the low-carbon development of transportation organizations in metropolitan areas.

3. Integrated Development of Industrial Chain of New Energy and travel in Metropolitan Area

3.1. Relationship between Transportation Energy Consumption and Carbon Emission in Metropolitan Area

The metropolitan traffic environment system is a complex system, and the factors of the system affect and interact with each other. Dual city life, that is, the separation of the place of residence and work, has become a common phenomenon, and traffic congestion and traffic jams in the morning and evening peak have become the norm, which occupies a lot of commuters' living and working time and increases economic costs, which greatly affects the quality of life. The existing travel facilities have been unable to meet people's travel needs [16]. Therefore, the travel structure of residents has changed accordingly. The explosive growth of family cars has not only brought serious congestion of trunk roads and urban traffic but also greatly increased the consumption of oil and other harmful gases and greenhouse gas emissions [17]. The resulting energy shortage, environmental pollution, and deterioration of urban road conditions will restrict economic development and prompt the government to make policy adjustments, control private car travel, raise emission standards, and vigorously develop public transportation, thus affecting people's choice of travel modes, which will, in turn, affect energy consumption, pollution emission, and road construction, forming a complex feedback system [18]. The relationship between transportation energy consumption and carbon emissions in metropolitan areas is shown in Figure 1.

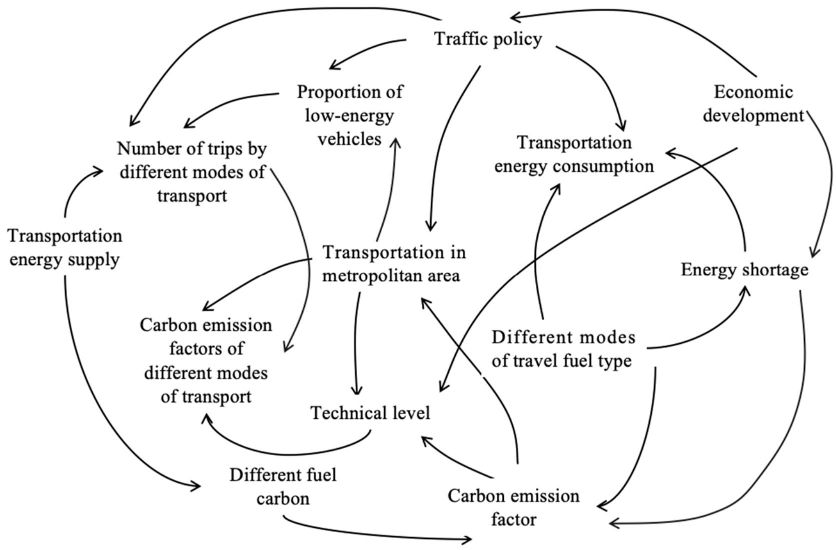

Figure 1. The relationship between transportation energy consumption and carbon emission in metropolitan areas.

3.2. Energy Integration Development of Low-Carbon Transportation

Under the background of energy Internet, the integrated energy and transportation system takes multi-network complementary as the core concept fully integrates the transportation system and deepens its development based on a multi-energy network. To realize the coordinated operation and development of energy systems such as electricity, natural gas, and heat with the railway, wheel transport, electric vehicles, urban electrified rail transit, large-scale hubs, and other transportation systems [19]. The transportation system consumes energy during transportation, so energy consumption is an important attribute attached to the basic attribute. From the energy supply side, re-electrification refers to "electricity as the center", promoting the transformation of the source of electricity from coal power generation to renewable energy power generation to solve the pollution problem in the process of energy production. By optimizing the power supply structure, we should vigorously implement clean energy substitution and electric energy substitution. From the perspective of energy consumption, re-electrification refers to "taking electricity as a priority", increasing the proportion of electric energy in terminal energy consumption, promoting efficient and clean energy utilization, and aiming to solve the problems of pollution and inefficiency in the process of energy consumption [20]. At present, the volume of "replacing oil with electricity" in transportation energy use is still small, but it is developing rapidly. In the future, through the development of electrified transportation, it can achieve "electricity instead of oil", reduce the proportion of oil in the structure of energy consumption, and slow down the growth of oil demand. At the same time, as a green energy storage carrier in the use of new energy vehicles, it is not only the main body of electricity consumption but also the main body of power supply [21]. New energy vehicles can not only reduce exhaust emissions, but intelligent shared electric vehicles can also solve the problem of travel congestion and inefficiency [22]. The energy conversion diagram for the development of low-carbon transport is shown in Figure 2.

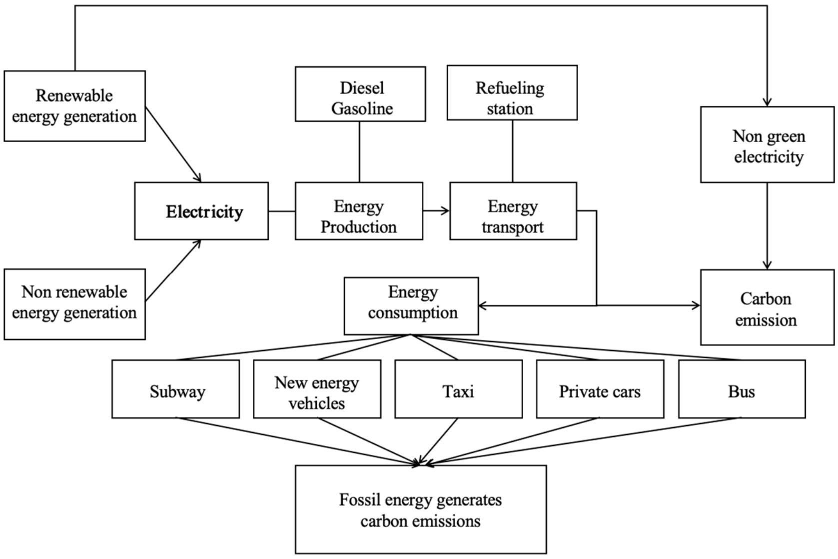

Figure 2. Energy conversion for low-carbon transport development.

3.3. Calculation Model of Average Carbon Emission of Public Trams in Metropolitan Area

In the selection of the transportation carbon emission accounting model, carbon emission is calculated according to different types of vehicle ownership, mileage, combustion per unit mileage, and combustion carbon emission coefficient [23]. The formula is shown as follows:

$$E = \sum_{m,n} Distance_{m,n} \times Consumption_{m,n} \times Density_m \times Calorific_m \times Emission\ coefficien_{m,n} \quad (1)$$

where E represents the total carbon emission of metropolitan traffic in a certain period of time; m represents the type of fuel consumed by transportation in the metropolitan area, including diesel, gasoline, natural gas, etc.; n represents the type of vehicle used for transportation in the metropolitan area. $Distance_{m,n}$ is the distance traveled by the n-type car using m fuel; $Consumption_{m,n}$ is the unit energy consumption of n vehicle using class m fuel; $Density_m$ is the fuel density of m fuel; $Calorific_m$ is the net calorific value of class m fuel; $Emission\ coefficien_{m,n}$ is the carbon emission factor of m fuel. According to this calculation, the average carbon emissions of public trams in metropolitan areas with different fuel types (Table 1) and the per capita energy consumption and carbon emission factors of individual travel modes (Table 2) are obtained.

Table 1. Average carbon emissions of public trams in metropolitan areas with different fuel types [24].

Vehicle Fuel Type	Direct Carbon Emissions (Tons)	Indirect Carbon Emissions (Tons)
Diesel oil	25	29
Natural gas	32	40
Hybrid power	22	27
Gasoline	27	33
Pure electric	0	24

Table 2. Per capita energy consumption and carbon emission factors of each mode of transportation [25].

Item	Walk	Bicycle	Bus	Subway	Taxi	Car
Per capita energy consumption (kg)	/	/	0.47	0.12	9.48	8.52
Carbon emission factor (gCO_2/kJ)	/	/	19.8	7.5	140.2	116.9

Abbreviations: gCO_2/kJ-Grams of carbon dioxide per kilojoule.

Low-carbon transportation is a green transportation development mode characterized by high energy efficiency, low energy consumption, low pollution, low emission, or even zero-emission [26]. In essence, it is an energy revolution, shifting from fossil energy to green electricity as far as possible. Therefore, the core of developing low-carbon transportation is to improve energy efficiency, optimize energy use structure, and improve service level. To achieve low-carbon and green development of the whole cycle industrial chain in the field of transportation.

4. Model of New Energy Travel Mode Selection in Metropolitan Area under Low-Carbon Orientation

Public transportation plays a significant role in reducing carbon emissions. Public transportation has the advantages of low energy consumption, low emission, and high transportation efficiency, and is a green transportation mode [27]. The construction of an urban, comprehensive transportation system dominated by public transportation has become the consensus of all countries in the world. Improving the sharing rate of public transportation and reducing the use of private transportation will significantly promote the reduction in carbon emissions and the protection of the metropolitan environment.

Commuting travel within the metropolitan area is different from regular inter-city travel and family visits. In the context of increasing travel distance and travel time in metropolitan areas, as the choice of each traveler is an individual behavior, commuters have the problem of choosing different travel tools during rush hour.

Subway, new energy buses, and fuel private cars are the three most common ways for commuters to use. Subway mainly refers to the rail transit built in the city with fast, large volume and electric traction. Compared with the ground bus, the subway has stronger transportation capacity and has the unique advantages of punctuality, fast speed, and saving the land use area of the road surface. Bus mainly refers to the conventional ground bus, with the characteristics of large passenger volume, low fare, low per capita energy consumption, and economic and environmental protection travel mode. The travel time of new energy buses and fuel private cars is uncertain to some extent. However, according to the transportation policy in China, new energy buses can use bus lanes, which will increase the driving speed to a certain extent. Additionally, petrol private cars are not allowed. Therefore, starting from the cumulative prospect theory and expected utility theory, this part fully considers the simulation scenario of commuters' travel behavior, assumes departure time, congestion probability, and possible commuting time consumption, builds a travel mode selection model, calculates the cumulative prospect value and perceived travel cost, and explores the direction of guiding travel behavior by comparing the difference of optimal results under different theoretical frameworks [28].

4.1. Theoretical Model of Cumulative Prospect Theory

Prospect theory (PT) introduces psychology into behavioral science for analysis and is developed from expected value theory and expected utility theory by psychology professors Kahneman and Tversky [29]. When observing the behavior of decision-makers in travel behavior, the important feature of prospect theory is that it mainly focuses on the result that travelers may face, that is, the psychological feeling when they gain or lose. According to the prospect theory, under different risk prediction conditions, when people face gains and losses, they will have different feelings based on different reference conditions. Additionally, believes that human behavior tendencies can be predicted [30].

The theory has been widely used to study attitudes toward gain and loss in decision-making. The main content of the theory is as follows: In the premise of failing to make accurate risk judgment, individual behavior decision is determined using the difference between the result and the prior assumption. The decision is composed of the value function and decision power function. It assumes that the uncertain decision process can be divided into two stages: editing and evaluation. Decision makers divide value into gains and losses based on reference points. Changes in gains and losses will change people's subjective feelings about value and thus affect and change people's preferences. In the evaluation stage, the utility function in the expected utility theory is replaced by the value function, the probability of the expected utility function is replaced by the decision weight of the weight function, and the decision is made based on the change of value rather than the current value.

4.2. Commuter Travel Mode Selection Model

According to the idea of cumulative prospect theory, when commuters are faced with a commuting mode choice, they will make decisions according to the following steps: (1) When there is uncertainty in the travel scene and environment, the perceived cost of commuters for each commuting mode is calculated; (2) Aggregate the perceived cost of each commuting mode; (3) Based on previous travel experience, set a travel reference point, which should be as consistent as possible with daily life; (4) On the premise of the above reasonable travel reference points, the perceived travel cost of each travel mode is reasonably judged; (5) To find out whether a travel mode is a benefit or a loss to an individual, and calculate its value; (6) Calculate the cumulative prospect value of each travel mode, that is, accumulate the prospect value and conduct subjective evaluation; (7) After judging and comparing the commuting modes between residence and work place, choose the mode with the maximum cumulative prospect value to commute, and finally complete the decision-making process.

4.2.1. Edit Stage

① How to select the decision reference point has always been the core parameter in prospect theory, which measures the psychological expectations of decision-makers [31]. In the process of travel decision-making, commuters will judge the gains and losses of behavior with certain measurement standards and evaluate the "loss" and "profit" feelings of gains and losses, respectively. Generally, in order to arrive at the destination on time, travelers need to reserve travel time before traveling. The reserved travel time is determined by the travel time between ODs, travel cost, road network status (number of alternative routes), etc., which can be used as a reference point for path selection decisions. Commuters use this reference point to judge whether they arrive early or late, as well as gain and loss.

In this study, commuting time and cost are selected as the reference points for commuters to make decisions. Generally, travelers will determine the attributes of alternative routes based on their own travel purposes and travel needs, on the basis of the effect judgment of the last trip, combined with experience summary, assuming a decision-making reference point and integrating the commuting time and cost. The mathematical formula can be expressed as Equation (1), M_K is the attribute of K alternative path, N is the set of all paths between OD, and N_K is the set of road sections included in path K, ε_α is the road flow, $M_\alpha(\cdot)$ is time function, $\beta_\alpha(\cdot)$ is the cost function, and P_1P_2 is individual preferences, P_1 refers to the coordination of commuters' travel time and cost based on their choice of path; P_2 is a time value parameter, which refers to the degree to which commuters are willing to invest time or money for this travel:

$$M_K = \sum\nolimits_{\alpha \in N_K} M_\alpha(\varepsilon_\alpha) = \sum\nolimits_{\alpha \in N_K} [P_1P_2M_\alpha(\varepsilon_\alpha) + (1 - P_1)\beta_\alpha(\varepsilon_\alpha)], k \in N \tag{2}$$

Compared with the travel time, if the commuter chooses a certain mode of transportation, the travel cost will be determined accordingly. However, different commuters have different conditions and needs. Therefore, different travel cost reference points will be assumed to select corresponding transportation modes. This paper mainly analyzes the travel choice of public transport and fuel private cars. Based on this, this paper proposes the following hypothesis: office workers have three travel modes: new energy buses, subway, and fueled private cars.

$$CPV = \sum\nolimits_{i=1}^{n} \pi(p_i) \cdot v(\Delta x_i) \tag{3}$$

Among them, CPV represents the foreground value, $\pi(p_i)$ is the probability weight function of the ith state occurrence, and $v(\Delta x_i)$ is the value function.

② The basic feature of the value function is that a normal person with limited rationality has a risk-averse attitude towards gains or gains and a risk-preference attitude towards losses:

$$v[E(X)] > E[v(X)], E[v(-X)] > v[E(X)], X > 0 \tag{4}$$

The value function describes the psychological utility of loss value and returns value to decision-makers. The value function is described as an S-shaped curve specifically: it is a concave function in the income field and a convex function in the loss field; that is, with the increase in loss value and income value, the marginal utility decreases. This phenomenon is summarized as "decreasing sensitivity". The inflection point of the S-shaped curve, that is, the reference point of decision-making, means that what plays a role in the decision of the decision-maker is not the absolute value of losses and gains but the relative change value relative to the reference point. This feature is summarized as "reference point dependence". The value function is steeper in the loss field than in the income field, which shows that the psychological utility of equal loss is greater than that of income; that is, the decision-maker is more sensitive to loss, which is defined as "loss aversion" [32]. The formula of the value function is shown in Formula (5).

$$v(\Delta x_i) = \begin{cases} \Delta x_i^{\alpha}, \Delta x_i \geq 0 \\ -\lambda(-\Delta x_i)^{\beta}, \Delta x_i < 0 \end{cases} \tag{5}$$

where parameter λ It means that the loss has more influence on the decision-maker than the gain, $\lambda > 1$. Parameters α Additionally, parameters β. It represents the slope of the value curve when facing gains and losses, also known as the risk sensitivity coefficient ($0 < \alpha \leq 1$, $0 < \beta \leq 1$). The recommended parameter values proposed by Kahneman and Tversky are $\alpha = \beta = 0.88$, $\lambda = 2.25$. The specific parameter values are shown in Table 3 [32,33]. X_0 is the decision reference point, Δx is the value of x deviating from the reference point.

Table 3. The value function with the diagram.

Item	Value
α	0.88
β	0.88
λ	2.25
γ	0.61
σ	0.69

③ The weight function describes the decision-maker's subjective perception of probability, which is a probability monotonic increasing function. The formula expression of the decision weight function:

$$H^{+}(p_i) = \frac{p_i^{\gamma}}{\left[p_i^{\gamma} + (1 - p_i)^{\gamma}\right]^{\frac{1}{\gamma}}} \tag{6}$$

$$H^{-}(p_i) = \frac{p_i^{\sigma}}{\left[p_i^{\sigma} + (1 - p_i)^{\sigma}\right]^{\frac{1}{\sigma}}} \tag{7}$$

4.2.2. Evaluation Stage

The cumulative prospect value is obtained by calculating the cumulative probability of a certain travel mode, taking into account its value function, and the sum of the two products is the cumulative prospect value of the travel mode. The cumulative prospect value of a certain travel mode is as follows:

$$CPV = CPV^{+} + CPV^{-} \tag{8}$$

$$\pi^{+}(p_i) = H(p_i + \cdots + p_n) - H(p_{i+1} + \cdots + p_n); 0 \le i \le n-1 \quad (9)$$

$$\pi^{-}(p_i) = H(p_{-mi} + \cdots + p_i) - H(p_{-m} + \cdots + p_{i-1}); 1-m \le i \le 0 \quad (10)$$

4.3. Generalized Perceived Travel Cost Function

Assuming that all commuters in the metropolitan area are bounded rational, the cost experienced in the whole travel process is composed of travel time cost and delay cost caused by early arrival and late arrival. The definition of commuter travel cost function is:

$$Total\ Cost_{\mu} = C_{Early} + C_{Late} + C_{Trip} + M_{\mu} \quad (11)$$

Suppose $T_{Departure}$ is the departure time of office workers and $T_{Arrival}$ is the arrival time of office workers. $T_{Arrival} = T_{Departure} + T_{Transit}$, T_{Work} is the working hour specified by the work unit, $E_{ArrivelTime} = T_{Work} - T_{Arrival}$ is the time when the office worker arrives at the work unit early, $L_{ArrivalTime} = T_{Arrival} - T_{Work}$ is the time when the office worker arrives at the work unit late. C_{Trip} is the travel time cost of office workers, $C_{Trip} = \phi \times T_{ActualTransit}$, ϕ refers to the value of commuting travel time for different travel modes, and $T_{ActualTransit}$ refers to the actual duration of commuting for office workers. δ_{Early} indicates the unit time value of early arrival of office workers, δ_{Late} indicates the unit time value of late arrival of office workers. M_{μ} is the transportation cost to be paid for choosing different transportation modes. $1-\rho$ is the additional cost factor of late arrival, ρ is the 0–1 variable, which satisfies the following relationship:

$$\rho = \begin{cases} 0, L_{ArrivalTime} \ge 0 \\ 1, E_{ArrivalTime} > 0 \end{cases} \quad (12)$$

Based on this, the generalized travel cost function can be transformed into:

$$Total\ Cost_{\mu} = C_{Early} + C_{Late} + C_{Trip} + M_{\mu} = \rho \times \delta_{Early}(T_{Work} - T_{Arrival}) + (1-\rho)\delta_{Late}(T_{Work} - T_{Arrival}) + \phi T_{ActualTransit} + M_{\mu} \quad (13)$$

When commuters feel profitable:

$$\Delta Total\ Cost_{\mu} = Total\ Cost_{\mu} - Total\ Cost_{\mu 0} > 0 \quad (14)$$

When commuters feel the loss:

$$\Delta Total\ Cost_{\mu} = Total\ Cost_{\mu} - Total\ Cost_{\mu 0} \le 0 \quad (15)$$

Based on this, under the cumulative prospect theory, it is assumed that the budgeted travel cost at the reference point of office workers' travel is $Total\ Cost_{\mu 0}$.

4.4. Spatial Structure of Xi'an Metropolitan Area and Data Sources

Spatial Structure of Xi'an Metropolitan Area

On 21 March 2022, the National Development and Reform Commission of China approved the Development Plan of the metropolitan area, which is the fifth metropolitan area plan after the planning of Nanjing, Fuzhou, Chengdu, and Changchun metropolitan area and the only one in northwest China at present. Xi'an metropolitan area is located at the intersection of the horizontal axis of the land bridge passage and the vertical axis of the Bao-kun Passage in China's "two horizontal and three vertical" urbanization strategic pattern. It is the core area of the urban agglomeration of Guanzhong Plain, one of the regions with the best development conditions and the strongest economic and population carrying capacity in the western region, and plays an important role in the overall construction of a modern socialist country and the construction of a new development pattern. The spatial structure evolution diagram of the Xi'an metropolitan area is shown in Figure 3. Xi'an metropolitan area is the latest emerging metropolitan area in China, so it is innovative to study the characteristics and influencing factors of new energy commuting behavior in this area.

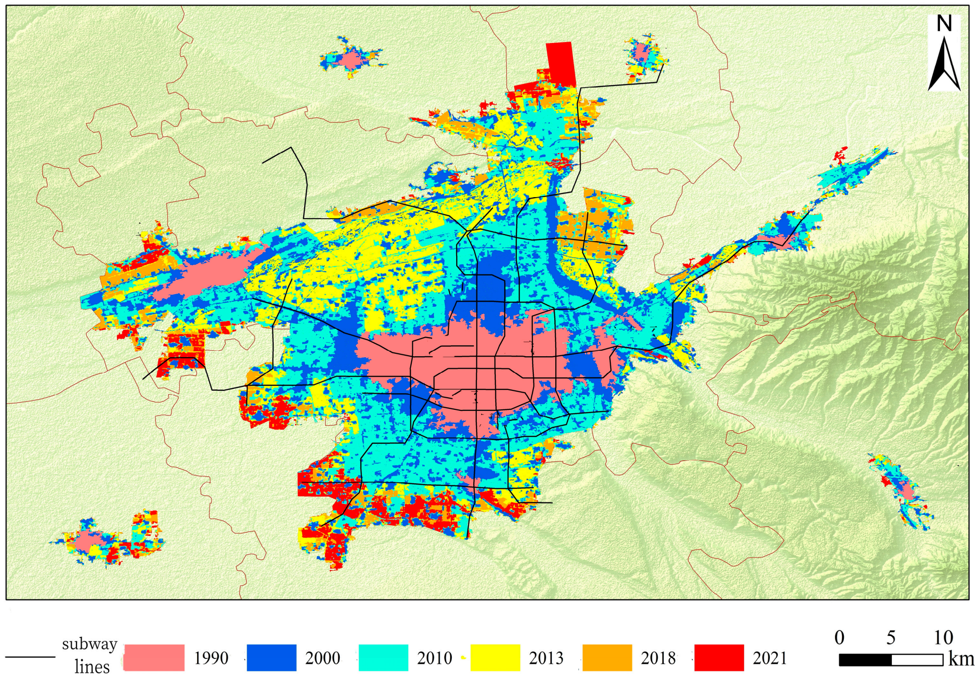

Figure 3. Schematic Diagram of Spatial Expansion of Xi'an metropolitan area.

4.5. Data Sources

In order to comprehensively present the commuting process of commuters in urban areas and link the travel activities of office workers from home to work, this article aims to study the travel behavior of office workers in the context of urban areas. Considering the impact of the epidemic and the limitations of the research scope, an online survey method was adopted for the questionnaire survey. Due to the potential bias or limitations of online surveys, we have adopted two methods in our survey. We have chosen two methods for distributing the online questionnaire. One way is for us to choose locations such as subways and bus stops and directly invite respondents to enter the questionnaire link on-site to fill out the questionnaire. Another method is to select six enterprises distributed in different regions within the Xi'an metropolitan area and entrust their human resources management department to distribute online questionnaires within the enterprises for investigation. The survey was conducted from March 2022 to September 2022, covering the Xi'an metropolitan area. The specific questionnaire design mainly includes understanding the basic information of the respondents, their family economic status, their choice of transportation mode during commuting, as well as the layout of public transportation facilities and personal travel preferences between work and residence. In this survey, the specific investigation content is as follows:

① A survey of basic information about commuter families. This mainly includes the area and street where the household resides, the number of households, the total annual income of the household, and whether the household owns a private car.

② Personal situation survey of commuters. It mainly includes statistics on gender, age, occupation, marital status, registered residence, nature of housing, whether to have a driver's license and length of service.

③ Investigation of personal travel behavior information. This mainly includes the work address of office workers, departure time for commuting, transportation used for commuting, one-way commuting distance and time, one-way commuting fees, and the number of one-way commuting transfers. In actual investigation work, based on the complete process of commuting for a day, the surveyed personnel are required to fill out the entire process from home to work, including the specific location of the stopover location and the means of transportation to be transferred.

5. Result

Then, according to the characteristics of each means of transportation, the commuting time and different possible probabilities brought by the three modes are assumed to compare the selectivity of new energy buses, subways, and fueled private cars in different scenarios.

Mode 1—New energy bus: there is a 70% probability of congestion, travel time is 60 min, there is a 30% probability of no congestion, travel time is 40 min, and the ticket price is 2 yuan;

Mode 2—Subway: The total travel time is fixed at 30 min, and the fare is 4 yuan;

Mode 3—Fuel private cars: the probability of congestion is 60%, the travel time is 45 min, there is a 40% probability of no congestion, the travel time is 35 min, and the cost is 20 yuan;

By setting a scenario, considering the expected possibility of commuters' work time and departure time, the cumulative prospect value of the above method is calculated according to the constraint of the reserved time:

Scenario 1: The commuter's work time is 8:00, departure time is 7:20, and needs to arrive at work within 40 min;

Scenario 2: The commuter's work time is 8:00, departure time is 7:10, and needs to arrive at work within 50 min;

Scenario 3: Commuters start work at 8:00, depart at 7:00, and need to arrive at work within 60 min.

By setting the scenario, considering the expected possibility of the working time and departure time of office workers, according to the constraints of the reserved time, calculate the cumulative prospect value of the above methods, randomly distribute 1000 questionnaires, and recover 860 valid questionnaires, with an effective recovery rate of 86%. According to the minimum living security standard of 740 yuan per person per month for urban residents in Xi'an from 1 October 2020 and the maximum size of conventional families as the standard, families with annual income less than 50,000 yuan are defined as low-income families and other families are classified as non-low-income families.

According to the survey data, 518 men and 342 women commuted among 860 people, accounting for 67.21% and 39.77% of the total, respectively. In terms of age distribution, there are 65 people under the age of 20, 269 people aged 20–29, 314 people aged 20–39, 177 people aged 40–49, and 35 people aged 50–59. In terms of occupational attributes, civil servants account for 14.65%; public institutions staff account for 19.42%; state-owned enterprises 25.93%; private enterprise staff 29.77%; and foreign enterprises 10.23%. From the distribution of seniority, new employees within 2 years accounted for 6.63%, those within 2–5 years accounted for 21.87%, those within 5–10 years accounted for 30.81%, those between 10–20 years accounted for 32.68%, and those over 20 years accounted for 8.02%. The descriptive statistics of the personal survey results of commuters are shown in Table 4.

Tables 5–10 show the perceived costs and cumulative prospect values of traveler decision-making under three different scenarios calculated through the model.

Based on specific data, the following conclusions can be drawn: (1) From Table 5, it is found that under the expected utility theory, commuters believe that the subway is the optimal mode of transportation; (2) From Table 6, it can be seen that commuters believe that new energy bus has the highest returns. (3) From Table 7, it is found that under the expected utility theory, commuters consider the subway to be the optimal mode of transportation (4) From Table 8, it can be seen that commuters believe that the subway has the highest revenue. (5) From Table 9, it is found that under the expected utility theory, commuters consider the subway to be the optimal mode of transportation. (6) From Table 10, it can be seen that commuters believe that new energy buses have the highest returns.

Table 4. Descriptive Statistics of Personal Survey Results for Commuters.

Item	Description	Number (N = 860)	Percentage (%)
Age	Under 20 year	65	7.90
	20–29 years old	269	31.28
	30–39 years old	314	36.51
	40–49 years old	177	20.58
	50–59 years old	35	4.07
Gender	Male	518	67.21
	Female	342	39.77
Occupation	Civil servant	126	14.65
	Public institutions staff	167	19.42
	Staff of state-owned enterprise	223	25.93
	Private enterprise staff	256	29.77
	Staff of foreign enterprise	88	10.23
Working experience	0–2 years	57	6.63
	2–5 years	188	21.87
	5–10 years	265	30.81
	10–20 years	281	32.68
	20 years–∞	69	8.02
Does the family own a car	Yes	475	55.23
	No	385	44.77
Annual household income	0–50,000 yuan	70	8.13
	50,000–100,000 yuan	158	18.37
	100,000–150,000 yuan	193	22.44
	150,000–200,000 yuan	200	23.25
	200,000–300,000 yuan	138	16.05
	300,000 yuan–∞	101	11.74

Table 5. Expected Travel Costs for Different Transportation Modes under Scenario 1.

	Fuel Private Cars	Subway	New Energy Bus
Expected travel time	60 min, 70% 40 min, 30%	30 min	45 min, 60% 35 min, 40%
Perceived travel costs	92.7, 70% 31.6, 30%	56.4	114.23, 60% 53.756, 40%
Expected value of travel cost	63.51	56.4	87.311

Table 6. The cumulative prospect values of different modes of transportation in Scenario 1.

	Fuel Private Cars	Subway	New Energy Bus
Travel cost reference point	24.08	25.55	62.3
Travel cost function value	−84.23, 70% 0, 30%	−40.72	−66.34, 60% 0.85, 40%
CPV	−43.32	−47.43	−35.28

Table 7. Expected travel costs for different modes of transportation in Scenario 2.

	Fuel Private Cars	Subway	New Energy Bus
Expected travel time	60 min, 70% 40 min, 30%	30 min	45 min, 60% 35 min, 40%
Perceived travel costs	70.63, 70% 53.6, 30%	27.5	88.316, 60% 70.481, 40%
Expected value of travel cost	67.4	27.5	72.606

Table 8. The cumulative prospect values of different modes of transportation in Scenario 2.

	Fuel Private Cars	**Subway**	**New Energy Bus**
Travel cost reference point	25.3	32.25	81.4
Travel cost function value	−51.46, 70% −22.37, 30%	−1.66	−9.16, 60% 1.47, 40%
CPV	−24.21	−21.34	−6.2

Table 9. Expected travel costs for different modes of transportation in Scenario 3.

	Fuel Private Cars	**Subway**	**New Energy Bus**
Expected travel time	60 min, 70% 40 min, 30%	30 min	45 min, 60% 35 min, 40%
Perceived travel costs	62.4, 70% 55.42, 30%	51.23	83.27, 60% 77.31, 40%
Expected value of travel cost	56.03	53.141	79.022

Table 10. The cumulative prospect values of different modes of transportation in Scenario 3.

	Fuel Private Cars	**Subway**	**New Energy Bus**
Travel cost reference point	47.3	37.21	76.54
Travel cost function value	−30.4, 70% −26.06, 30%	−12.4	0.636, 60% 0.709, 40%
CPV	−28.15	−13.17	0.68

By integrating the results of the above three scenarios, it can be concluded that under different travel constraints, commuters use travel costs as a reference point, and the cumulative prospect values obtained are shown in Figure 4. The results of the above analysis show that (1) commuters will be affected by reference points in the process of travel behavior selection, which is consistent with the theoretical content of cumulative prospect theory. This is consistent with the results of the study, mainly because commuters may conduct empirical evaluations before choosing their mode of transportation, which proves the importance of further understanding commuters' judgments of the travel environment before traveling [34]. (2) In the simulation, it is found that it is effective to take generalized travel costs as the reference point, and commuters will make rational judgments according to the actual situation. Under the premise of sufficient reservation time and ensuring that there will be no late for work, commuters will prefer to choose the more secure means of transportation with low congestion probability when faced with benefits. This is different from previous studies, which have suggested that commuters are irrational when choosing transportation, and their personal psychological preferences are difficult to change [35]. (3) If commuters reserve a short time and find that they are likely to be late through experience judgment, they will turn into adventurers and form a "gambler's psychology" when faced with losses and are more likely to choose transportation with greater flexibility and a probability of arriving at work in a short time, such as fuel private cars [36]. (4) Different scenarios and assumptions will cause commuters to make different travel decisions. Commuters tend to evaluate different choices through the judgment criteria of utility maximization, and there are differences between traveler choice results and expectation theory.

In summary, it can be found that under the low-carbon orientation, commuters in the Xi'an metropolitan area generally believe that the subway has obvious advantages under different assumptions, which is in line with the current development direction of optimizing transportation energy in the metropolitan area; In addition, in the scenario, due to the support of national energy policies in China, new energy buses have the qualification to enjoy dedicated bus lanes in infrastructure construction. Therefore, they can avoid road congestion during commuting, which is not available in gasoline private cars. Meanwhile, in scenario three, new energy buses and subways, as new energy public transportation modes, have significant benefits.

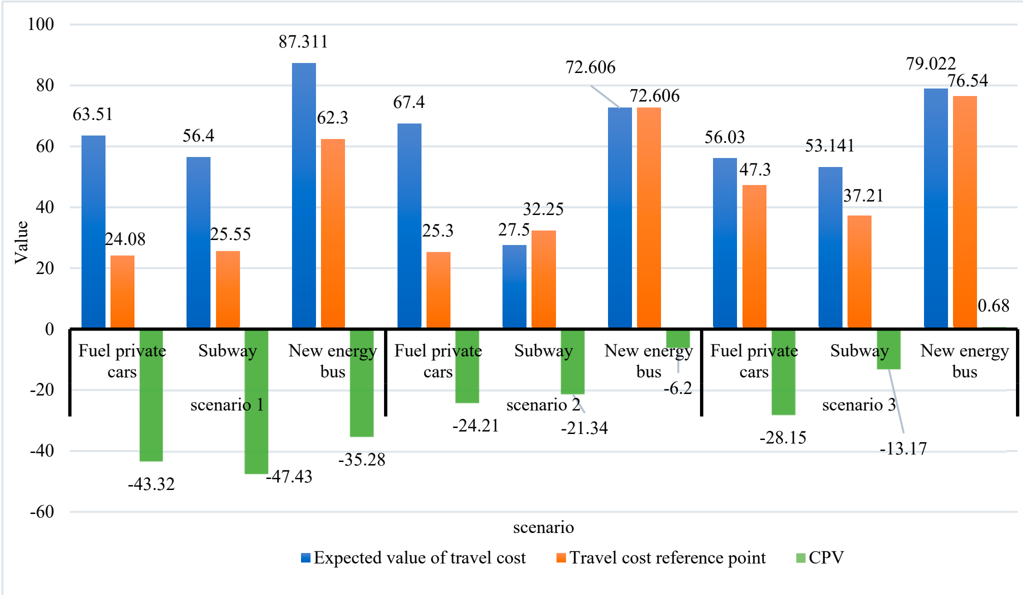

Figure 4. The Cumulative Foreground Model Results in Three Scenarios.

6. Conclusions and Suggestion

This article takes the Xi'an metropolitan area as an example to elaborate on the integrated development path of the new energy + transportation industry chain in the metropolitan area and clarifies the energy transformation model for the integrated development of low-carbon transportation energy. From the perspective of green and low-carbon, the cumulative prospect model was used to verify the internal mechanism that affects commuters in metropolitan areas to choose new energy commuting modes. The research results indicate that new energy transportation modes play an important role in a low-carbon economy, and there are significant differences in the cumulative prospect values of subways, new energy buses, and gasoline private cars under different scenarios and assumptions.

Therefore, we believe that (1) low-carbon-oriented commuting in urban areas is easily influenced by the characteristics of transportation modes. Subways and new energy buses have obvious advantages in energy optimization for commuting, which has become one of the directions for the future development of low-carbon transportation in urban areas. (2) Commuters face a significant threat to the proportion of private fuel cars traveling due to the significant advantages of new energy public transportation in terms of commuting time and cost when facing the choice of transportation tools. In order to expand the proportion of public transportation, such as new energy buses and subways in daily commuting, we need to improve the construction of public transportation infrastructure and increase the burden of using fuel-powered private cars. (3) Accelerating the proportion of new energy in public transportation is the key to reducing carbon emissions from public transportation. New energy public transportation has lower energy consumption and emission levels, which helps promote the application of new energy and low-carbon technologies.

However, it is important to also acknowledge the limitations of this study. In terms of case selection and data investigation, we have focused on China. Taking the newly approved urban agglomeration in western China as an example, although it has some innovation in the research area, we have not taken into account other mature urban agglomerations in China. At the same time, relying on big data methods, the number of data samples can be increased to compensate for the subjective bias in data in order to improve data reliability, which will help to study this topic better.

Based on these findings, we provide the following suggestions for improving the proportion of new energy commuting in the Xi'an metropolitan area:

6.1. Build a Complete Network of Ground Bus Charging Facilities

For large cities in China, the first step should be to take measures to strictly control the growth and use of private cars. Measures such as traffic restrictions, license plate restrictions, differential parking fees, congestion fees, and staggered commuting should continue to be implemented to avoid traffic congestion. A new energy vehicle charging pile is one of the key areas of "new infrastructure", accelerates the construction of the charging facilities network, on the one hand, strengthens the technological innovation of charging facilities, strengthens the digital gene, and promotes the deep integration of traditional charging facilities, ground bus operation network and new technologies such as artificial intelligence, block-chain, and big data [37]. Actively explore the construction of an intelligent network platform from the planning and construction of front-end charging facilities to the deployment of intermediate bus charging needs and then to the management and maintenance of terminal charging facilities. On the other hand, strengthen the innovation of charging operation mode, face the subdivision scenarios of the charging demand of public vehicles and social vehicles at different times, take into account safety, efficiency, and energy saving, create technology applications such as wireless charging of charging piles and customized charging management of vehicles, and form an ecological model of multi-type charging facility investment, diversified charging methods, and diversified profit sharing [38]. Maximize the utilization rate and profitability of charging facilities to match the charging demand and management level.

6.2. Promote the Transformation of the New Energy Travel Structure

The transformation of motor vehicle energy structure is the core of promoting urban transportation emission reduction, and it is also the most potential strategy. To achieve a carbon peak in 2030, first rely on the decarbonization of the energy system and the decarbonization of the energy system depends on the energy storage of new energy vehicles, and the new energy revolution is driven by new energy vehicles [39]. As a representative of new energy vehicles, pure electric vehicles are the integrated products of modern automotive technology, new energy, electronic computer intelligent control, and other high-tech, which do not produce CO_2 during operation and use and have the advantages of environmental protection and pollution-free, high energy efficiency, and low operating costs. The emergence and popularization of pure electric vehicles can not only make the automobile industry get rid of the situation of excessive dependence on gasoline but also reduce carbon emissions, and the emission reduction effect is remarkable [40]. Attention should be paid to the planning and construction of energy supply facilities, improving the power supply and grid capacity of cities, and strengthening the construction of charging facilities.

6.3. Strengthen the Publicity of Low-Carbon Travel and Create a Low-Carbon Travel Cultural Atmosphere

Through the media, the internet, public service advertising, and other advertising media, the government can inform urban residents about the growing problems of traffic congestion, air pollution, and energy consumption and their serious consequences so that citizens can respond to the challenges posed by motorization and make positive contributions to reducing air pollution and traffic congestion [41]. The government should also step up efforts to promote low-carbon living and low-carbon travel to the public, especially the high-income group, and encourage the public to travel using means of transport that minimizes damage to the environment through extensive publicity on energy conservation to reduce carbon emissions and the implementation of low-carbon emission practices.

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