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Carbon Reduction Benefits and Carbon Peak Goals of Urban Passenger Transportation Electrification: A Case Study of Shanghai

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Abstract: Urban passenger transportation is an important field of fossil energy consumption and greenhouse gas emissions. Scientifically and rationally setting the goal and supporting policies of electrification of energy structure is of great significance for the positive and orderly transition of the passenger transportation system to the carbon neutrality goals. Taking Shanghai urban passenger transportation tools (including public transportation and individual motorized transportation) as the object, based on the multi-dimensional data such as industry statistics and traffic activity volume, this paper calculates the carbon reduction benefits of transportation structure optimization and energy structure adjustment which takes the carbon emissions generated from energy consumption in the transportation operation stages (indirect emissions at the power generation is considered for electricity) as the measurement caliber. Taking the realization of carbon peak in the near and medium-term as the constraint, the paper focuses on the target requirements of three scenarios for the penetration rate of passenger car electrification transformation. Finally, the paper emphasizes the structural carbon reduction strategy of giving equal priority to energy structure adjustment and transportation structure optimization in the context of incomplete completion urbanization and motorization. At the implementation level, the coordination and connection of industrial, energy, and transportation policies should be strengthened. DOI: 10.13813/j.cn11-5141/u.2021.0041-en

Keywords: urban passenger transportation; carbon reduction; carbon peak; passenger transportation electrification; Shanghai

0 Introduction

To cope with climate change and reduce greenhouse gas emissions, many countries all over the world have made commitments to carbon neutrality, and proposed detailed schedules and measures. China also clearly pledged "to peak carbon emissions by 2030 and achieve carbon neutrality by 2060". Urban areas are the areas with the largest intensity of human activities, as well as the areas with the largest intensity of carbon emissions [1]. Urban passenger transportation is an important field of fossil energy consumption and greenhouse gas emissions, and it is closely related to the travel of residents. With the continuous acceleration of urbanization and motorization, both travel demand and energy consumption show a monotonic growth trend, and the situation of carbon reduction is grim. Unlike developed countries whose development path is to gradually promote peaking transportation carbon emissions and achieve carbon neutrality at the mature and stable stage of urbanization and motorization, China puts more emphasis on the synchronous transformation of transportation, industry and energy. On the basis of continuously tapping into the potential of energy-saving technologies, China has developed a structural carbon reduction strategy that focuses on both the electrification of the energy structure and the construction of the green travel system, to comprehensively improve energy efficiency and the efficiency of carbon reduction. The pledge to peak carbon emissions and achieve carbon neutrality imposes more specific quantitative target requirements for structural carbon reduction of the urban passenger transportation system. At present, objectives for the construction of the passenger transportation system have been clearly defined in the municipal master plan, but the objectives for the energy structure adjustment are still unclear. Energy structure adjustment would cause systematic changes in the automotive industry, power security, transportation system and other fields. These changes should be stable and orderly without being too radical, which in turn

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imposes higher requirements for the rationality of the objectives of energy structure adjustment.

Studying the case of Shanghai and focusing on peaking carbon emissions in urban passenger transportation, this paper sets the objectives for adjusting the energy structure of urban passenger transportation based on multiple scenario analysis. The paper also proposes suggestions on the development and improvement of the integrated transportation system.

1 Carbon emission measurement and calculation method

The carbon emissions of urban passenger transportation mainly come from the energy consumption in motorized travel, including travel made by public transportation modes, such as rail transit, buses and taxis, and travel made by private transportation modes, mainly passenger cars. Based on the overall development requirements of peaking carbon emissions and achieving carbon neutrality, carbon emissions are measured as the CO_2 emissions from fossil energy consumption at the transportation stage and the CO_2 emissions from power consumption (including the indirect emissions during power generation).

Based on the energy consumption characteristics of different transportation modes, this paper calculates carbon emissions using the method to estimate carbon emissions of energy activities [2], which is developed by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations. According to the availability of energy consumption data of different transportation modes, a differentiated calculation method is used. The carbon emissions of public transportation are directly calculated based on energy consumption statistics. As the energy consumption data of private motorized transportation are incomplete, the carbon emissions of private motorized transportation are measured based on the activities of fossil fuel vehicles and electric vehicles. Therefore, the total CO_2 emissions from urban passenger transportation in Shanghai are calculated as:

$$C = C_1 + C_2 = \sum_i \left(A_{iC} EF_C + A_{ie} EF_e \right) + \left[Q_j M_j F_j + Q_k M_k W_k EF_e \right] ,$$

Where, C_1 and C_2 are the CO_2 emissions (unit: t) from public transportation and passenger cars respectively; A_{iC} and A_{ie} are the fossil energy consumption (unit: tce) [(1)] and power consumption (unit: MW·h) of the class i public transportation respectively, obtained from industrial statistics (among which, the energy for rail transit is only electricity; the energy for buses includes gasoline, diesel and electricity; and the energy for taxis includes gasoline and electricity); EF_C is the carbon emission factor (unit: $t \cdot tce^{-1}$) of different types of fossil energy, using the latest emission factor data from National Greenhouse Gas Inventory; EF_e is the electricity carbon emission factor (unit: $t \cdot MW^{-1} \cdot h^{-1}$), which is provided by the energy department (in recent years, the proportion of electricity imported to Shanghai has increased, most of which is clean power such as hydropower; and the electricity carbon emission factor shows a downward trend); Q_j and Q_k are the number (unit: vehicles) of fossil fuel vehicles and electric vehicles respectively, obtained through the vehicle management department; M_j is the travel intensity of fossil fuel vehicles (unit: $km \cdot vehicle^{-1}$), obtained through comprehensive travel surveys; M_k is the travel intensity of electric vehicles (unit: $km \cdot vehicle^{-1}$) and W_k is the power consumption per kilometer for electric vehicles (unit: $MW \cdot h \cdot km^{-1}$), and both are calculated based on the electric vehicle data obtained by Shanghai Electric Vehicle Public Data Collecting, Monitoring and Research Center (hereinafter referred to as "EVDATA"); and F_j is the carbon emission factor (unit: $t \cdot km^{-1}$) of fossil fuel vehicles, obtained through the local emission test of motor vehicles in cooperation with the environmental research department.

2 Status and development trend of carbon emissions from urban passenger transportation

2.1 Current status

In 2019, the energy consumption of urban passenger transportation in Shanghai was 7.44 million tce [3], of which fossil energy consumption accounted for 90% and electric energy consumption accounted for 10% (see Fig. 1). From the perspective of electricity consumers, in addition to rail transit, road transportation has shown the initial trend of electrification; buses in built-up areas have basically been electrified; the electrification of taxis has begun to take shape, and Shanghai is leading the world in the promotion of electric passenger vehicles. Based on the carbon emission measurement and calculation method described above, the total CO_2 emission from urban passenger transportation in Shanghai was about 12.9 million tons. Although passenger cars only undertook about 25% of trips, their carbon emissions accounted for 77% and this proportion shows an upward trend. The total carbon emissions of rail transit, taxis and buses accounted for 23%. Passenger cars' travel share is not in proportion to their share of carbon emissions, which is the key to tackle to peak carbon emissions from urban passenger transportation in the future.

2.2 Evaluation of the trend

1) Development trend of urbanization and motorization

China's urbanization has entered the development stage in which urban agglomerations and metropolitan areas are the main forms. The Seventh National Population Census data show that population agglomeration in economically developed regions is still an apparent trend. In 2020, the population of Shanghai permanent residents was 24.87 million, an

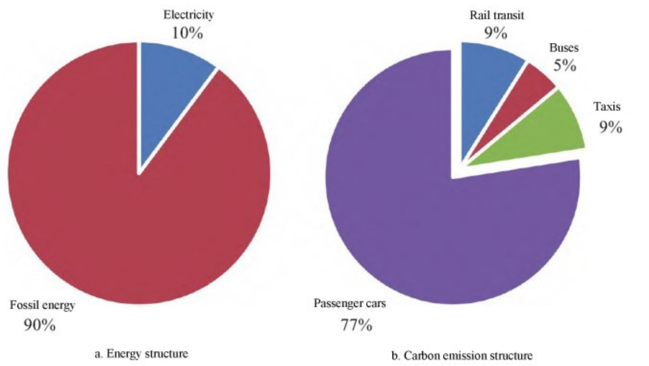

Fig. 1 Energy structure and carbon emissions structure of Shanghai urban passenger transportation in 2019

Source: the charts are drawn based on the data in Reference [3].

increase of 8% over the 2010 population based on the Sixth National Population Census. In the context of high-quality integrated development in the Yangtze River Delta, the travel demand of Shanghai will continue to grow along with the concentration of global resources, the upgrading of industrial structures, and the construction of functional platforms such as new towns, Lingang Special Area of Free Trade Zone, Hongqiao International Hub and the Integration Demonstration Area. With further expansion of the urban spatial development from the central city to new towns and the metropolitan area, the average travel distance will be further extended and the proportion of motorized travel will be further increased. It is estimated that the daily average number of trips in Shanghai will reach 78 million by 2035, an increase of 36% over the current level, and the proportion of motorized travel is close to 60% (see Fig. 2). The average distance of commuter trips in Shanghai is expected to be 10 km, which is similar to that in the Tokyo metropolitan area [4]. According to *Shanghai Master Plan* (2017-2035) (hereinafter referred to as the 2035 Master Plan), a multi-mode public transportation system composed of railways, urban rail transit, buses and auxiliary public transportation will be built in the future. The coverage of rail transit stations in new towns with more than 100,000 people will exceed 95%, and the dominant position of rail transit in passenger transportation will be further highlighted. In addition, long-term adherence to the policies of passenger car ownership and use management will support the intensive and balanced development of the transportation structure.

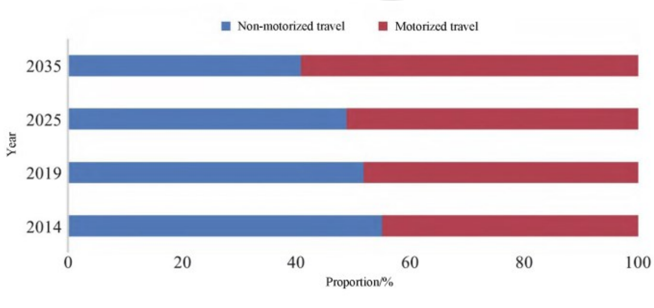

Fig. 2 Growth trends of motorized travel proportion in Shanghai

2) Development trend of energy structure and energy efficiency level

Against the background of peaking carbon emissions and achieving carbon neutrality, China has made more efforts to promote the healthy and sustainable development of the energy-saving and new energy passenger car industry. With the implementation and revision of *Measures for the Parallel Administration of the Average Fuel Consumption and New Energy Vehicle Credits of Passenger Car Enterprises*, energy-saving and new energy passenger cars have developed rapidly, and the overall fuel consumption level of the industry has continued to decline [5]. It is estimated that by 2035, the fuel consumption of passenger cars excluding new energy vehicles will be reduced to 0.04 $L \cdot km^{-1}$, and the fuel consumption of passenger cars including new energy vehicles will be reduced to 0.02 $L \cdot km^{-1}$. The fuel consumption will reduce by 15% to 20% for trucks, and 20% to 25% for passenger cars [6]. With the rapid development of the new energy vehicle industry and the continuous improvement of battery life and charging convenience, the adjustment of the road transportation electrification pattern in Shanghai will accelerate. It is expected that all vehicles used for public transportation will be electrified first during the 14th Five-Year Plan period, and the popularity of new energy passenger cars in private transportation will also increase rapidly [7].

In conclusion, the monotonic growth of motorized travel induces energy consumption, resulting in huge incremental demand for carbon reduction. Introducing systematic adjustment of energy structure before motorization of private transportation reaches the peak would improve energy efficiency and bring carbon reduction benefits, which can provide greater space for the monotonic growth of motorized travel demand. However, when carbon emissions from urban passenger transportation will reach the peak still depends on the competition between the volume of activities and the carbon reduction benefits of alternative energy, as well as reasonable overall investment in the industrial system, energy system, infrastructure, etc.

3 Analysis of carbon reduction benefits of electrification

The carbon reduction of urban passenger transportation is mainly affected by the technical performance of vehicles, travel behaviors and transportation organization modes. This paper estimates the carbon emission intensity and behavior characteristics of vehicle electrification, and evaluates its carbon reduction benefits comprehensively.

3.1 Estimates of carbon reduction benefits

From the perspective of transportation structure, carbon reduction benefits mainly reflect the impact of energy structure adjustment on vehicles' carbon emission intensity. The average CO_2 emission intensities of different travel modes are calculated based on statistical and measured data (see Tab. 1). Although the carbon reduction benefits of electrification of different vehicles are different, the carbon emission intensities still decrease by 40% to 60% even if the indirect emissions on the power generation side are considered. The carbon reduction benefits are significant.

Tab. 1 CO_2 emissions intensity of major travel modes in 2019

Travel mode	CO_2 emission per vehicle (10^{-4} t·km^{-1}·vechile^{-1})		Carbon reduction benefits (%)	CO_2 emission per capita (10^{-4}t·km^{-1}·person^{-1})	Carbon reduction rate relative to passenger cars (%)
	Electricity	Fossil fuel			
Passenger cars	1.05	1.74	40	1.21	
Taxis	1.00	2.61	62	2.07	−71
Buses	4.70	8.65	46	0.48	60
Rail transit	18.08			0.33	73

From the perspective of passenger transportation organization, carbon reduction benefits reflect the impact of different passenger flow organization modes on carbon emission intensity. The per capita energy consumption can be greatly reduced due to large passenger capacity of public transportation, which can significantly reduce the per capita CO_2 emissions together with the decline of carbon emission factors brought by electrification. As of 2019, the electrification rate of buses and taxis had been significantly raised, and the average emission intensity of public transportation was 60% to 70% lower compared with that of passenger cars (see Tab. 1). However, if passenger transportation organization is inefficient, the carbon reduction benefits will drop: taxis' emission intensity is higher than passenger cars' emission intensity due to the existence of vacant taxis.

3.2 Change of travel behaviors

This paper estimates the travel intensity and cost of passenger cars that use different types of fuel, and analyzes the impact of electrification on travel behaviors based on travel characteristic data such as previous comprehensive transportation surveys and EVDATA, as well as oil price data and electricity price data. The travel intensity of passenger cars continues to decline: it had decreased to 25 km·d^{-1}[8] according to the sixth Comprehensive Transportation Survey in 2019. This data basically reflects the travel intensity of fossil fuel vehicles since new energy vehicles only account for a small portion (about 7%) of passenger cars. However, the travel data collected by EVDATA in 2019 show that the average travel intensity of battery electric cars was 33 km·d^{-1}, which is higher than that of fossil fuel vehicles (see Fig. 3) due to the low fuel cost of battery electric cars. Since battery electric cars on average consume about 20 to 22 kW·h per 100 km and the electricity price during off-peak periods is 0.307 yuan·kW^{-1}·h^{-1}, the fuel cost of battery electric cars is only about 6 yuan per 100 km. The fuel consumption of fossil fuel cars generally ranges between 0.06 and 0.12 L·km^{-1}, depending on the engine capacity. If the price of #92 gasoline is 6 to 7 yuan·L^{-1}, the fuel cost of fossil fuel cars is about 6.5 to 13 times that of battery electric cars. In the long run, with the popularization of transportation electrification, the operating cost of passenger cars will decline as a whole. However, travel time reliability and parking convenience will be more important than the monetary cost of driving in the choice of the travel mode due to the constraints in road and parking resources. In the context that the intense contradiction between supply (roads) and demand (vehicles) becomes normal, the fuel cost advantage brought by electrification will gradually have less impact on travel behaviors, and travel behaviors will be impacted more by the comprehensive cost whose core values are securing the right of way and ensuring parking for travel connections. In the long term, the rules for the use of fossil fuel vehicles will still be followed.

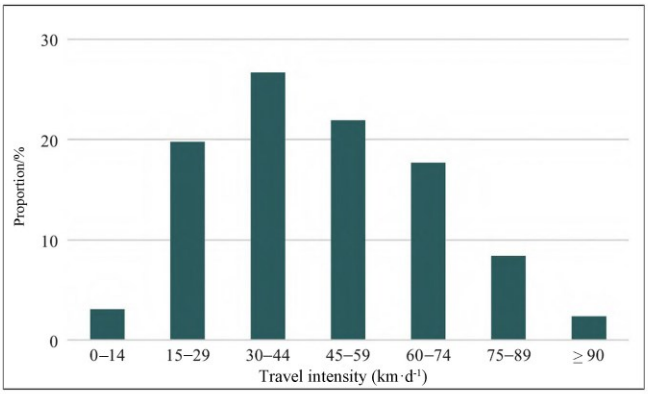

Fig. 3 Travel intensity distribution of pure electric cars in 2019

Electrification can significantly promote the improvement of energy efficiency and the reduction of carbon emissions. With further improvement of energy efficiency and further decline of carbon emission factors brought by clean power, the carbon reduction benefits of electrification still have room for improvement. Under the background of continuous growth of the motorization level, the electrification of energy structure, especially the electrification of vehicles for private transportation, can quickly reduce the carbon emission level of the main transportation modes and accelerate the emergence of the inflection point for carbon emissions. However, when the inflection point can emerge still depends on the penetration rate and the speed of electrification.

4 Setting goals for electrification of energy structure under the constraint of emission peak

4.1 Three scenarios for peaking carbon emissions

Under the constraint of peaking carbon emissions by 2030 and taking whether the transportation structure is in compliance with the 2035 Master Plan as a variable, this paper estimates the energy structure goals and electricity demand,

and develops three scenarios: ideal, enhanced and radical. The three scenarios correspond to different peak emissions, and more requirements are imposed on the electrification of passenger cars sequentially from the ideal scenario to the radical scenario. If the transportation structure deviates from the 2035 Master Plan or the emission peak needs to be reached by 2025, it is necessary to strengthen the adjustment of the energy structure. It should be noted that since buses and taxis will be basically electrified during the 14th Five-Year Plan period, the adjustment of the energy structure is mainly reflected by different development scales and proportion targets of new energy passenger cars.

1) Ideal scenario of 2030

In this scenario, the transportation structure meets the targets specified in the 2035 Master Plan, and the development objectives and requirements of new energy passenger cars are set under the constraint that carbon emissions from passenger transportation would peak by 2030. This scenario imposes relatively loose requirements on the transformation time and the penetration rate of electrified passenger cars: the penetration rate needs to reach 25% in 2030 and about 37% in 2035. The peak CO_2 emissions are about 14.9 million tons, and the carbon emissions will be reduced by 3.0% in 2035 compared with the peak.

2) Enhanced scenario of 2030

In this scenario, the existing transportation structure remains unchanged and fails to meet the targets specified in the 2035 Master Plan, and the development objectives and requirements of new energy passenger cars are set under the constraint that carbon emissions from passenger transportation would peak by 2030. This scenario imposes a higher requirement on the penetration rate of electrified passenger cars: the penetration rate needs to reach 33% in 2030 and about 50% in 2035. The peak CO_2 emissions are about 15.6 million tons, and the carbon emissions will be reduced by 1.2% in 2035 compared with the peak.

3) Radical scenario of 2025

In this scenario, the transportation structure meets the targets specified in the 2035 Master Plan, and the development objectives and requirements of new energy passenger cars are set under the constraint that carbon emissions would peak by 2025. This scenario greatly shortens the electrification time for passenger cars: the penetration rate needs to reach 25% in 2025 and 40% in 2030. The peak CO_2 emissions are about 14.4 million tons, and the carbon emissions will be reduced by 7.0% in 2035 compared with the peak (see Tab. 2 and Fig. 4).

Tab. 2 CO_2 emissions scope under three scenarios

Scenario	Peaking time	Peak CO_2 emissions (10,000 t)	Increment compared with 2019 (10,000 t)	Proportion demand of electrification by 2030 (%)
Ideal scenario of 2030	2030	1 490	200	25
Enhanced scenario of 2030	2030	1 560	270	33
Radical scenario of 2025	2025	1 440	150	40

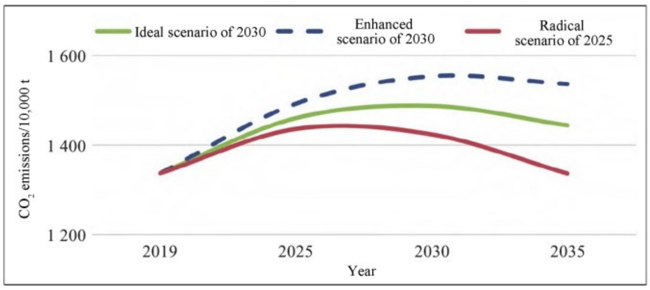

Fig. 4 CO_2 emissions trend under three scenarios

4.2 Determination of electrification goals

Among the three scenarios, the radical scenario of 2025 has the lowest peak CO_2 emissions but the highest requirements on energy structure adjustment, which is difficult to realize. As of the end of 2020, new energy passenger cars only accounted for 7% in Shanghai, and most of them were newly purchased cars. Even if the goal of the 2035 Master Plan, in which battery electric passenger cars would account for more than 50% of vehicles newly purchased by individuals [6] can be reached, it is still difficult to realize the electrification rate required by the radical scenario with the growth of fossil fuel passenger cars. However, among the two scenarios in which carbon emissions would peak by 2030, the ideal scenario of 2030 has lower peak CO_2 emissions under the joint influence of transportation structure adjustment and energy structure adjustment. In addition, it requires a lower electrification rate and a longer time, which is easier to achieve.

From the perspective of power supply, the power consumption will gradually increase along with the increase of the electrification rate (see Tab. 3). Although the power consumption of new energy passenger cars does not account for a big portion of the overall power consumption in Shanghai, the power distribution networks in some areas may become a bottleneck. If the capacity and the capacity margin of the distribution transformers in a community are both small, an excessively high penetration rate of electric vehicles will challenge the electricity distribution capacity of the community.

Tab. 3 Estimation of electrical car power consumption under three scenarios kW·h

Scenario	Power consumption of electric cars (kW·h)		
	2025	2030	2035
Ideal scenario of 2030	2.2×10^9	3.7×10^9	5.2×10^9
Enhanced scenario of 2030	2.4×10^9	5.2×10^9	7.6×10^9
Radical scenario of 2025	3.5×10^9	6.0×10^9	8.5×10^9

In summary, it is possible for the carbon emissions from urban passenger transportation in Shanghai to reach the peak around 2030. While the construction of integrated transportation system is being improved, the electrification rate of passenger cars should be increased to 25% to 30% by 2030 to lay a foundation for the subsequent carbon neutrality.

4.3 Contribution of various factors to peaking carbon emissions

The Logarithmic Mean Divisia Index (LMDI) is used to analyze the contribution of various factors to carbon reduction in the ideal scenario of 2030. Specifically, the carbon reduction due to transportation structure optimization is about 2.14 million tons. The carbon reduction due to energy structure adjustment is about 3.36 million tons, 1.6 times that due to transportation structure optimization. It reflects the enormous benefits of electrification on the improvement of energy efficiency and reduction of carbon emissions (see Fig. 5).

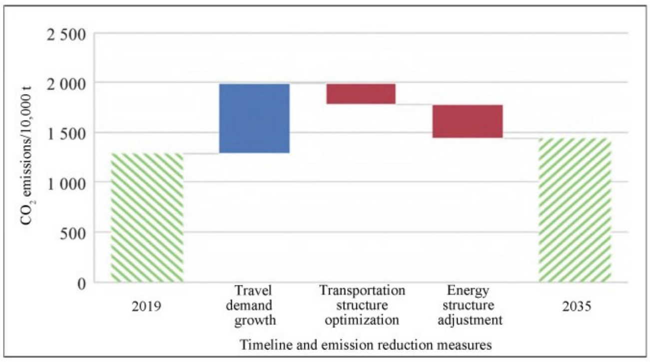

Fig. 5 Contribution of various factors to carbon reduction under the ideal scenario in 2030

With optimization of transportation structure and adjustment of energy structure, the carbon emission structure in the field of urban passenger transportation is gradually optimized (see Fig. 6). Compared with 2019, the proportion of carbon emissions from passenger cars gradually declines, and that from public transportation gradually rises. In the enhanced scenario of 2030, as the transportation structure is not optimized, the optimization of the overall carbon emission structure is limited. In the ideal scenario of 2030, the proportion of carbon emissions from passenger cars has significantly decreased to 59%, while that from rail transit has increased to 32%. These changes show that the overall carbon emission structure of urban passenger transportation is optimized in Shanghai, which is similar to that in London [9].

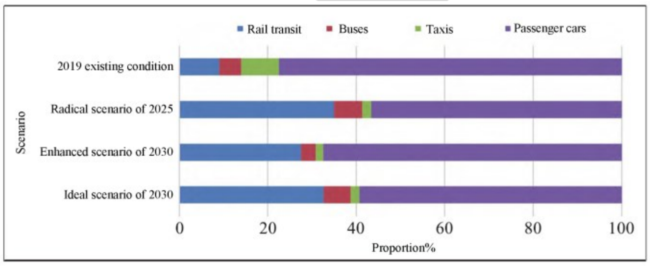

Fig. 6 Evolution of carbon emissions structure under three scenarios

5 Conclusions

In the context of immature urbanization and motorization, it is a great challenge to peak carbon emissions from urban passenger transportation. Efforts should be made from two aspects: optimization of transportation structure and adjustment of energy structure. Optimization of transportation structure can reduce the energy consumption intensity of passenger transportation and adjustment of energy structure can reduce the carbon emission intensity, which would lay a foundation for the subsequent carbon neutrality. However, during the implementation, it is still necessary to strengthen the overall coordination and connection of industrial, energy and transportation policies.

First, the coordination between the policies of energy industry and the development policies of passenger cars should be strengthened. New energy passenger cars can effectively reduce the negative impacts of passenger cars on the environment, but their transportation functions and use characteristics are not essentially different from those of fossil fuel passenger cars since they both belong to individual motorized transportation. At present, new energy passenger cars are still in the industrialization and promotion stage. To support their industrialization, transportation policies have partially deviate from the overall strategic requirements of urban transportation development, such as giving priority to public transportation and managing travel demand. In addition, new energy vehicles have advantages in travel, use cost and intelligent connected vehicles, but these advantages have imposed great incremental impact on the road network and parking. In the context of limited road and parking resources, it is necessary to strengthen the coordination and connection of development and use policies regarding new energy vehicles and traditional fossil fuel vehicles. It is also necessary to pay more attention to the upgrade and replacement of existing vehicles in terms of vehicle promotion, and strengthen the power distribution support in bottleneck areas, with an aim to achieve a win-win situation in industry, transportation and energy.

Second, the coordination between the construction and the efficient operation of the low-carbon transportation system should be strengthened. Transportation structure optimization policies that center on the improvement of the public transportation system are the basic guarantee of the low-carbon development of the transportation system. However, the real improvement of energy utilization efficiency and carbon reduction efficiency relies on the support of matching passenger transportation intensity. The per capita energy consumption and carbon emission of rail transit with low efficiency may even be higher than those of passenger cars [10]. The populations and travel demand densities of different levels of urban systems in a metropolis are significantly unbalanced and their travel scenarios are highly diverse. In view of these features, it is imperative to strengthen the coordination and complementarity of multiple transportation modes, promote the efficient matching of transportation capacity and demand, improve the overall service experience of public transportation travel chains, and maximize the carbon reduction function of high-capacity public transportation.

Annotation

(1) tce means ton of coal equivalent.

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