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Optimization of Passenger Transportation Corridor Mode Supply Structure in Regional Comprehensive Transport Considering Economic Equilibrium

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Abstract: Reasonable transportation network layouts are critical for optimizing a comprehensive transport system. With the gradual development of a transportation industry from quantitative expansion to structural optimization, and transformation of various transportation modes from independent operation to integrated development, traditional comprehensive transport planning theories and methods have not adapted. In this paper, a new planning concept is proposed from the perspective of economic equilibrium with the aim of optimizing a supply structure for a comprehensive transport passenger transportation corridor. An in-depth analysis was conducted of the internal mechanism of the dynamic equilibrium between supply and demand of this corridor, wherein the maximum of the global transportation demand subject customer surplus was taken as a target function, respective interest functions of a demand subject and a supply subject served as constraints to quantitatively optimize the supply structure of the passenger transportation corridor in comprehensive transport, and a Gradient Descent algorithm was designed. The results show that the proposed model better reflects he economic operation mechanism of a passenger transportation market in a comprehensive transport corridor (CTC), and prove that the supply structure of CTC is closely related to passenger flow, travel value distribution, a supply subject's scale rate of return, and travel time. These research results have important academic values in terms of improving passenger transportation corridor structure optimization in region-specific comprehensive transport that conforms to a market economy mechanism. This concept can be extended from single corridor planning to point-to-point and door-to-door transportation supply structure planning, and to comprehensive transport network planning and urban transportation planning without loss of generality.

Keywords: regional comprehensive transport; structure optimization of passenger transportation corridor mode; economic equilibrium; consumer surplus

1. Introduction

Large transport corridors occupy a dominant position in the overall comprehensive transportation system, and pass through densely populated areas and important industrial belts. Reasonable planning of a comprehensive transportation corridor (CTC) is the basic, advanced and critical condition for realizing the real optimization of the comprehensive transport system [1]. On the basis of demand forecast and in combination with the external environment of the system, comprehensive transport corridor planning is to plan the type, composition, construction timing, and the scale of internal transport mode during the planning period, so as to achieve the optimal input–output ratio of the whole integrated transport service system. It is generally believed that CTC planning consists mainly of three levels, namely, corridor selection, corridor system structure determination and corridor internal structure optimization. The corridor system structure is determined after deciding the prior construction of one certain corridor, and on the basis of the status quo adaptability analysis, the composition of the transport mode within the corridor is defined, which is the optimization of the overall CTC infrastructure, so studying the optimization of a supply structure of the CTC is important for promoting the healthy development of the entire comprehensive transport system. The development of traditional transportation planning theory has increasingly matured, especially in urban transportation planning. Transportation planning theory led by four-stage traffic demand forecasting has gradually formed after more than half a century of development [2]. However, broader regional transportation planning theory research lags behind urban transportation planning; even early regional transportation planning practice basically directly copies the four-stage method of urban transportation planning theory. However, with respect to infrastructure, transportation product, and transportation demand, there is a big difference between regional transportation and urban transportation [3]. It is necessary to establish the applicable regional transportation planning theory and method according to the regional transportation demand and network characteristics.

The traditional four-stage traffic analysis and forecast model is the most widely used traffic planning model system in the world. Detailed descriptions and comments on these models can be found in Meyer et al. [4] and Beimborn et al. [5]. Due to its merits of simple data collection and plain models, this model has always occupied a dominant status in traffic analysis, but has many limitations [6–8]. The four-stage traffic demand analysis model belongs to the mathematical analysis and application research of statistical laws, where inductive methods are mostly used, and mechanism analysis is insufficient. Since it separates various stages of transportation planning for modeling, there is no interdependence between models and convergence is poor, heavily discounting its forecast accuracy (Timmermans and Arentze, 2011) [9]. Some scholars integrated the four-stage model into a model, i.e., a combined model, and designed algorithms to solve the model [10–15]. Until now, the combined model research only involved theory and has not been applied in practice. In addition, transportation planning practice faces important challenges globally (Marco teBrömmelstroet, 2017) [7], and regional transportation planning agencies have been endeavoring to revise their planning processes and develop new tools for broader goals and strategies (Aaron Golub and Karel Martens, 2014) [16]. As such, constructing a new transportation planning theory system and developing a model system that meets new requirements of modern transportation planning are urgently required.

The essence of the regional CTC supply structure is the reasonable proportion of various transportation modes (supply). The relevant research on optimization of a CTC supply structure basically imitates the above-mentioned planning theory background. The research mode is relatively fixed, which is the demand–supply method. So, on the basis of traffic demand analysis, an optimal configuration scheme is provided for the CTC (Bhat, 2007, Zhang, 2011) [17,18]. Therefore, the research focus of scholars has concentrated on a demand structure of a CTC. Since a demand analysis model is applied on a large scale during transportation planning, it has gradually developed into two generation models: an aggregate model and a non-aggregate model. Due to the lack of complete theoretical hypothesis, the aggregate model requires the collection of a large amount of data in the application, and the collection result is poor in spatial–temporal transfer, which results in less choice of transportation mode. The non-aggregate model selects an individual as a research object to analyze the response of different travelers to affecting factors of a travel mode, belonging to a research field of travel behaviors, and is thus popular among scholars because of its high data use rate as well as speed and geographical transfer (Sun et al (2016), Bharat (2011), Rashedi (2017), Thrane (2015)) [19–22]. However, the basic guiding ideology of this type of model involves analyzing and forecasting traffic demand, and paying attention to traffic construction to meet increasing traffic demands, which involves planning for passive satisfaction, lacks a traffic demand management concept to solve traffic problems from supply and demand [23], and only meets the demand in terms of quantity.

In a market economy, transactions are realized under the principle of equivalence. Economic equilibrium is the basis of the balance of the quantity, and only the balance of the quantity is insufficient. Some scholars attempted to study passenger transportation supply structure planning of the CTC through Game Theory, which is mainly divided into a game model between passengers (user equilibrium theory) [24–28] and a game model between transportation modes [29–32]. These research results positively affected the development of a structure planning theory for the CTC mode, but do not reflect the inherent economic mechanism of the CTC supply and demand.

Accordingly, existing studies on structure optimization of a CTC mode suffer from the following limitations: (1) the four-stage traffic demand analysis model involves mathematical analysis and application research of statistical laws, is mainly based on the summary of various transportation mode planning methods for CTC mode planning, mostly adopts inductive methods, and lacks a mechanism for research on the inherent correlation between the whole transportation corridor modes. (2) The models generally involve planning for passive satisfaction, lack traffic consideration from the perspective of supply and demand interaction, and only consider the balance of quantity. In a market economy, transaction is merely realizable under the principle of equivalence, and economic equilibrium is the essence of the dynamic balance between supply and demand. Therefore, this paper proposes a new planning concept from the perspective of economics with the aim to optimize a supply structure of a comprehensive transport passenger corridor based on economic equilibrium. Specifically, based on a systematic analysis of an inherent economic mechanism in CTC, the maximization of a main transportation demand consumer surplus was taken as an objective function and respective interest functions of demand and supply subjects were taken as constraints to construct a supply and demand economic equilibrium model. A solution algorithm was designed to quantitatively optimize the supply structure of a passenger transportation mode in comprehensive transport.

This paper is organized as follows. Section 2 introduces a supply and demand mechanism of CTC. Section 3 constructs the model and presents solution methods. Section 4 lists illustrative examples in which a short-distance passenger transportation corridor and medium- and long-distance passenger transportation corridors are used to illustrate the proposed models and solution approaches. Section 5 outlines the conclusions, contributions, and directions of future research for current study.

2. Analysis of Supply and Demand Equilibrium Mechanism of Passenger Transportation Corridor in Regional Comprehensive Transport

Compared with the general products and services, passenger travel consumption has two salient features: First, it is not the direct object of consumption, but is the measure that has to be taken in order for the demand subject to achieve a specific travel purpose. Therefore, the travel service must be arranged based on the purpose of the trip rather than the journal itself. Second, passengers are just travel entities, not necessarily the demand subject of travel. Transportation demand subject (TDS) refers to the subject directly related to the interests or losses realized by the transportation demand, such as individuals, enterprises, or other property organization. So, in current work, we use the academic term 'TDS' instead of passengers.

Transportation supply is the quantity of various transportation products that the transport producer is willing to offer at a certain moment, at various possible transportation price levels. A regional comprehensive transport system includes five different transportation modes and each transportation mode has different technical and economic characteristics. An interaction process involves many factors, but in a market economy, a primary factor influencing a transaction is economy. Demand and supply each have their own interests, and a demand subject and a supply subject must meet the requirements of their own interests before they can form a real transaction. For the realization of a transportation process, from the perspective of demand, a transportation product is consumed under the principle that a TDS can be satisfied according to its basic interests. From the perspective of supply, a transportation product is provided under the principle that a transportation supply subject can be satisfied according to its basic interests. A transportation supply that meets transportation demand can form an effective supply, and must unify the opposites of all the subject interests involved in transportation demand and supply, that is, the process of economic equilibrium between supply and demand. The external manifestation of an evolution process of a comprehensive transport system is the process of competition and integration of transportation modes, but the inherent mechanism is the economic equilibrium between demand and supply. The whole process of economic equilibrium is the process of transforming transportation supply into effective supply, which is the process of pursuing peak performance. This is the key to constructing an optimization model of a CTC supply structure.

The optimization of the supply structure of CTC is demand-oriented, and the maximum satisfaction of transportation demand is the goal of comprehensive transport. The intrinsic motivation of the TDS to choose a transportation mode is derived from pursuit of maximizing its own interests. Therefore, this paper optimizes a supply structure for corridor transportation by maximizing consumer surplus of a TDS.

A prerequisite for any demand subject to select a certain transportation service is that an expected utility U_i obtained by achieving a displacement is not less than a cost E_j of selecting the jth transportation supply, i.e.,

$$U_i - E_j \geq 0 \tag{1}$$

where i is the TDS, i = 1, 2, 3, ... , N, and j is the category of differential transportation supply, j = 1, 2, 3, ... , m.

Realizing the economic sustainability of transportation supply under a market economy is a constraint for optimizing a supply structure of a CTC. Different transportation modes have different fixed structures, and their operational efficiencies and benefits have different sensitivities to transportation demand characteristics. The core is that implementation of an equilibrium return operation introduces corresponding requirements for a given transportation volume. This is one of the key conditions for rational configuration of transportation modes to clarify the relationship between a price for a transportation mode to implement an equilibrium return operation and a possible transportation volume. Using quantity-cost-profit analysis, for any type of transportation supply j, the transportation price P_j must meet the following condition:

$$P_j - (F_j/Q_j + AV_j) - R_j \geq 0 \tag{2}$$

where F_j is the fixed cost of the jth transportation supply, Q_j is the amount of turnover that the jth transportation supply can bear, AV_j is the unit transportation cost for the jth transportation supply, and R_j is the amount of profit per unit of transportation calculated according to the equilibrium rate of return. F_j and AV_j are determined by the technical and economic characteristics of transportation supply itself, and are usually constant. Under the condition that market competition is relatively ample, the economic significance of Equation (2) is that the possible turnover of the jth transportation supply at the price level P_j in a specific transportation corridor is not less than Q_j. Thus, the transportation supply has sustainable market vitality in the corridor, and vice versa. Based on this, an economically sustainable transportation supply model and its constraint parameters are established.

3. Proposed Models

In this section, the passenger corridor supply structure problem is described and formalized with the notations used briefly summarized in Table 1.

Table 1. Notation.

Set	Definition
I	Set of transportation demand subjects, indexed by i.
J	Set of transportation modes, indexed by j.
Variable	
P_j	Price of transportation mode j.
Q_j	Number of transportation demand subjects (TDS) demanded in transportation mode j.
Parameter	
N	Number of passenger flow.
V_i [a]	Travel value of the ith TDS.
C_{ij}	Travel cost for the ith TDS to select the jth mode.
F_j	Fixed cost of transportation mode j.
AV_j	Unit variable cost of the jth mode.
p_j	Ticket price rate of the jth mode.
L_j	Distance of the jth mode.
R_j	Equilibrium return rate of the jth mode.
t_j	Operation time of the jth mode.
β_i	Time value cost coefficient of the ith TDS.
γ_i	Other psychological cost coefficients of the ith TDS.
$S(P)$	Maximum of consumer surplus with price P.

[a]: We define the travel value is the expected positive effect of the direct or indirect consumption travel service of the demand subject. The greater the expected positive effect, the greater the travel value; vice versa.

3.1. Modeling Ideas and Assumptions

The inherent mechanism of model establishment is that any demand subject i wants to choose a transportation mode that realizes maximum consumer surplus. When the supply of the jth transportation mode is insufficient, only other transportation modes that would achieve the maximum consumer surplus can be selected ($k \neq j$). If the consumer surplus is negative, the demand subject i abandons a trip. Fixed structures of different transportation modes are different, and operational efficiencies and benefits have different sensitivities to transportation demand characteristics. The core is that implementation of an equilibrium return operation R_j introduces corresponding requirements for a borne transportation volume Q_j. When the demand intensity of a certain transportation mode j is insufficient to enable the transportation mode j to realize a capital preservation operation in a planning period, such demand will not be satisfied temporarily. Realization of organic unification of interest functions of a TDS and transportation supply subject themselves are the key constraint conditions for optimizing a supply structure of a passenger transportation corridor mode using comprehensive transport. Under realistic supply conditions, the demand subject would choose to consume a product, applying the principle that the travel surplus is optimal, or sub-optimal, but at least acceptable. With this kind of basic incentive factor, the global consumer surplus maximization is achievable under this circumstance. It further promotes the optimization of supply structure of comprehensive transportation corridor mode. To summarize, the following assumptions were made for the problem.

Assumption 1: There is an origin-destination (OD) set Q composed of only one start point and one end point in a corridor traffic network; the amount of passenger demand N between the OD set is determined; J is set of traffic modes connecting the OD to Q, which is a selection set, where j is an option in the selection set.

Assumption 2: Hypothesis of rational man. A travel demand subject always tends to choose a transportation mode that maximizes travel surplus, and chooses a travel transportation mode according to the principle of maximum travel surplus.

Assumption 3: The general cost of travel for a passenger includes three parts: travel price, travel time cost, and other psychological costs. The travel price is affected by a fixed facility input cost and a unit variable cost, and is inversely proportional to a turnover that a transportation mode may bear.

3.2. Mathematical Formulation

Assume that the total TDS in a certain CTC is N persons, M transportation modes may be planned, rational supply configuration of various transportation modes in a regional passenger transportation corridor in an equilibrium state maximizes the global consumer surplus of TDS, and a passenger flow Q_j determined by a TDS's choice of transportation supply enables various transportation modes to achieve equilibrium return operations. A regional CTC supply and demand economic equilibrium model is as follows:

$$\max S(\boldsymbol{P}) = \sum_{i \in I} \max_{j \in J}(V_i - C_{ij}) \tag{3}$$

$$s.t. \qquad V_i - C_{ij} \geq 0 \qquad \forall i \in I, j \in J \tag{4}$$

$$p_j - (\frac{F_j}{Q_j} + AV_j) \geq R_j \qquad \forall j \in J \tag{5}$$

$$C_{ij} = P_j + \beta_i t_j + \gamma_i t_j \qquad \forall i \in I, j \in J \tag{6}$$

The objective function in Equation (3) reflects that the overall goal of CTC supply structure optimization is to pursue the peak point of global consumer surplus. The internal mechanism is that the demand subject would choose a preferential traveling tool according to the principle that the travel surplus is optimal, or sub-optimal, but at least acceptable. Motivated by this, the global consumer surplus maximization can be obtained under realistic supply conditions. This shows that the fundamental goal of a supply of CTC is to satisfy demand to the best extent. All the constraints in the model constitute a feasible domain of the model solution. The constraints in Equations (4) and (5) reflect the core of traffic planning: the TDS and the supply subject affect one another, and are mutually unified. The constraint condition in Equation (4) is travel surplus of the ith TDS, reflecting the basic principle through which the TDS i chooses the jth transportation supply for a travel, rendering the travel surplus greater than 0, otherwise the travel is meaningless. The economic significance of the constraint condition in Equation (5) indicates that, in a specific transportation corridor, the jth transportation supply should achieve sustainable economic development. The possible turnover accomplished at the price level of P_j should be no less than Q_j; otherwise, this supply will not allow for a normal flow of value. Equation (6) reflects composition of consumer travel costs, and more research on consumer travel costs was reported by Sun (2018) [33].

The above economic equilibrium model is actually an optimization problem with inequality constraints. To solve the model, we define the following:

A value distribution function $V(i) = V(X \leq i)$ is the sum of the travel value of the ith person in the crowd, and thus a value density function $v(i) = V'(i)$ (Figure 1), a price $\boldsymbol{P} = (P_1, P_2, \cdots, P_M)$, and the corresponding price rate is $\boldsymbol{p} = (p_1, p_2, \cdots, p_M)$. The consumer travel cost function in Equation (6) is $c_j(P_j, i) = P_j + \beta(i)t_j + \gamma(i)t_j, j = 1, \cdots, M$, where $\beta(i)$ and $\gamma(i)$ are the time value distribution coefficient function and the psychological cost distribution coefficient function of the traveler i, respectively; t_j is the travel time of the jth traffic mode. The TDS travel surplus function can be denoted as $s_j(P_j, i) = v(i) - c_j(i), j = 1, \cdots, M$, where $s_j(P_j, i) \geq 0, j = 1, \cdots, M$, and thus the total travel surplus can be denoted as $\max s(P_1, P_2, \cdots, P_M, i) = \max\{s_1(i), s_2(i), \cdots, s_M(i), 0\}$, that is, the objective function Equation (3) is $S(P_1, P_2, \cdots, P_M) = \int_0^N \max s(i) di$. The selected passenger flow of the jth transportation mode can be easily obtained as $Q_j = Countif(j; s_j(i) = \max), j = 1, \cdots, M$. For each transportation mode, in order to achieve economic sustainability, it is necessary to meet the basic equilibrium return requirement: $p_j - (\frac{F_j}{Q_j} + AV_j) \geq R_j$ as shown in Equation (5).

Assuming $f_j = F_j + AV_j Q_j - p_j Q_j - R_j Q_j$, the supply and demand economic equilibrium model can be converted to

$$\begin{gathered} \max S(P_1, P_2, \cdots, P_M) = \int_0^N \max s(P_1, P_2, \cdots, P_M, i) di \\ s.t. \qquad f_j \leq 0, j = 1, \cdots, M \end{gathered} \tag{7}$$

3.3. Solution Approaches

As pointed out in Dong et al. [34], the Gradient Descent algorithm is probably the most popular technique for solving systems of nonlinear equations. In this research, we also applied the Gradient Descent algorithm to optimize the passenger corridor supply structure problem. The principle of the algorithm is shown in Figure 1. It is assumed that there are two transportation modes: mode 1 and mode 2. When searching for the maximum surplus S^* of consumers in the whole society, the Gradient Descent algorithm gradually increases the step length of $\boldsymbol{P}$ in the direction of the gradient from the beginning (P_1^0, P_2^0) to the end, and stops when the amplitude of Gradient vector is close to 0. In this case, the corresponding S^*, P_1^*, and P_2^* are the optimization results of the algorithm.

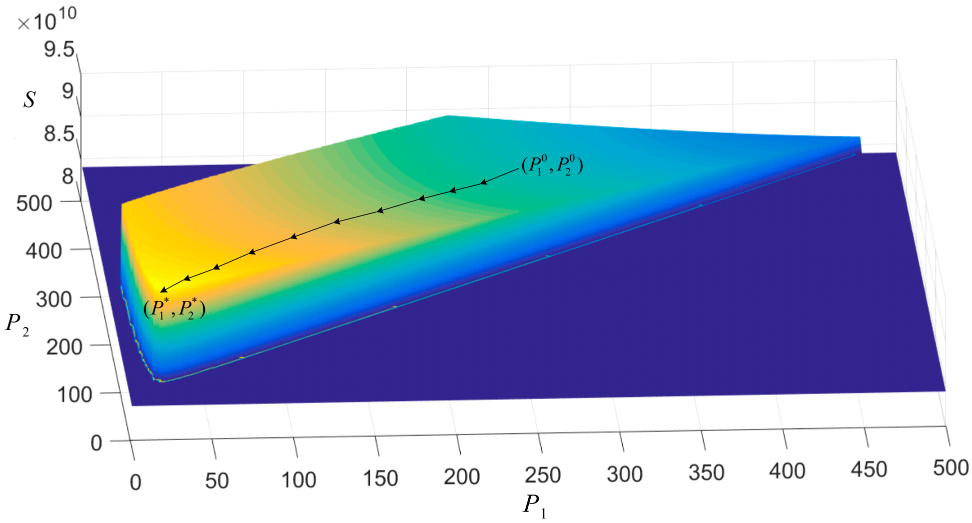

Figure 1. Price-consumer surplus schematic diagram.

The Lagrange Multiplier λ is introduced, denoted as $\boldsymbol{\Lambda} = (\lambda_1, \lambda_2, \cdots, \lambda_M)$, an auxiliary function $L(P_1, P_2, \cdots, P_M, \lambda_1, \lambda_2, \cdots, \lambda_M) = -S(\lambda_1, \lambda_2, \cdots, \lambda_M) + \sum_{j=1}^{M} \lambda_j \cdot f_j$ is constructed, then $\boldsymbol{P^*}$, corresponding to the minimum value is

$$\begin{cases} \nabla_{\boldsymbol{P}} L(\boldsymbol{P}, \boldsymbol{\Lambda}) = 0 \\ \lambda_j f_j \geq 0 \\ \lambda_j \geq 0 \end{cases} \tag{8}$$

or

$$\begin{cases} \nabla_{\boldsymbol{P}} L(\boldsymbol{P}, \boldsymbol{\Lambda}) = 0 \\ \nabla_{\boldsymbol{\Lambda}} L(\boldsymbol{P}, \boldsymbol{\Lambda}) = 0 \\ \lambda_j \geq 0 \end{cases} \tag{9}$$

The detailed algorithm is summarized as follows:

Step 1: Initialization. Initialize $\boldsymbol{P} = \boldsymbol{P}_0, \boldsymbol{\Lambda} = \boldsymbol{\Lambda}_0$, learning rates being α_1, α_2;

Step 2: Solve $L(\boldsymbol{P}_0, \boldsymbol{\Lambda}_0)$. Solve $L(\boldsymbol{P}_0, \boldsymbol{\Lambda}_0)$ corresponding to $\boldsymbol{P}_0, \boldsymbol{\Lambda}_0$;

Step 3: Compute $L(\boldsymbol{P}^{(j)}, \boldsymbol{\Lambda}), L(\boldsymbol{P}, \boldsymbol{\Lambda}^{(j)})$.

Let $\boldsymbol{P}^{(j)} = (P_1, P_2, \cdots, P_j + \varepsilon, \cdots, P_M), \boldsymbol{\Lambda}^{(j)} = (\lambda_1, \lambda_2, \cdots, \lambda_j + \varepsilon, \cdots, \lambda_M)$, solve partial derivatives and obtain $L(\boldsymbol{P}^{(j)}, \boldsymbol{\Lambda}), L(\boldsymbol{P}, \boldsymbol{\Lambda}^{(j)}), j = 1, \cdots, M$;

Step 4: Solve $\nabla_{\boldsymbol{P}} L, \nabla_{\boldsymbol{\Lambda}} L$.

Let $\begin{cases} \frac{\partial L}{\partial P_j} = \frac{L(\boldsymbol{P}^{(j)}, \boldsymbol{\Lambda}) - L(\boldsymbol{P}, \boldsymbol{\Lambda})}{\varepsilon} \\ \frac{\partial L}{\partial \lambda_j} = \frac{L(\boldsymbol{P}, \boldsymbol{\Lambda}^{(j)}) - L(\boldsymbol{P}, \boldsymbol{\Lambda})}{\varepsilon} \end{cases}, j = 1, \cdots, M,$

Then, compute a gradient $\nabla_{\boldsymbol{P}} L, \nabla_{\boldsymbol{\Lambda}} L$. $\nabla_{\boldsymbol{P}} L = \left(\frac{\partial L}{\partial P_1}, \frac{\partial L}{\partial P_2}, \cdots, \frac{\partial L}{\partial P_M}\right), \nabla_{\boldsymbol{\Lambda}} L = \left(\frac{\partial L}{\partial \lambda_1}, \frac{\partial L}{\partial \lambda_2}, \cdots, \frac{\partial L}{\partial \lambda_M}\right);$

Step 5: Cyclic calculation and stopping criteria.

Let $\begin{cases} \boldsymbol{P}^{(j+1)} = \boldsymbol{P}^{(j+1)} - \alpha_1 \cdot \nabla_{\boldsymbol{P}} L \\ \boldsymbol{\Lambda}^{(j+1)} = \boldsymbol{\Lambda}^{(j+1)} + \alpha_2 \cdot \nabla_{\boldsymbol{\Lambda}} L \end{cases}$, adjust the learning rates α_1, α_2;

If $\|\nabla L\| \leq \varepsilon$, then output the solution vector $\boldsymbol{P}$ and stop, otherwise continue to return to Step 3.

4. Illustrative Examples

In this section, a numerical example is provided to illustrate the applicability of the proposed method for solving the problem. Note that this example is not intended to show extreme scenarios. These data and distribution assumptions used in our examples are for experimental analysis only and do not represent their authenticity. Here, we simulate the equilibrium configuration of a CTC supply structure for short-, medium-, and long-distance corridors.

4.1. Short-Distance Corridor Mode Structure Configuration Simulation

For the time being, the short-distance corridor does not consider air transportation due to the short distance. This paper mainly focuses on public passenger transportation on highways, and does not consider private cars because the current work considers the supply issue in infrastructure for CTC chiefly from an economic perspective. Short-distance car trips usually concentrate on the quality of the travel, rather than the economic efficiency. However, as a public infrastructure supply planning problem, private vehicles are important users of highways for short corridors, so we need to consider the noneconomic consuming behavior on the basis of detailed discussions on economic category. As a consequence, how to incorporate this particular subject behavior into a more rational mathematical model would be a major concern of our future research work, and therefore beyond the scope of current analysis. In this example, when only three kinds of transportation supply, highway, ordinary rail, and high-speed rail (HSR), are used, the relevant parameters of various transportation modes are assumed as shown in Table 2: passenger travel value distribution v(i), time value coefficient distribution β(i), and other cost coefficients γ(i) are assumed to be consistent with Figure 2.

Table 2. Main parameter assumptions for short-distance corridor transportation mode.

Transportation Mode	Highway	Rail	HSR
Construction cost (10^8¥)	72	25	212
Operation and maintenance fees (10^8¥/year)	2.2	0.2	2
Sharing fixed cost F (10^8¥ /year)	4.6	0.62	5.5
Unit variation cost AV (¥/person km)	0.068	0.025	0.076
Travel time t (h)	3	4	2.75
Distance L (km)	145	147	150

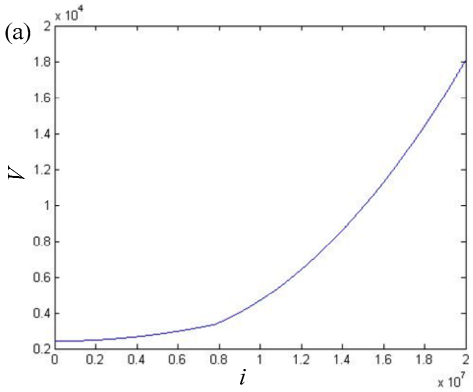

Figure 2. *Cont.*

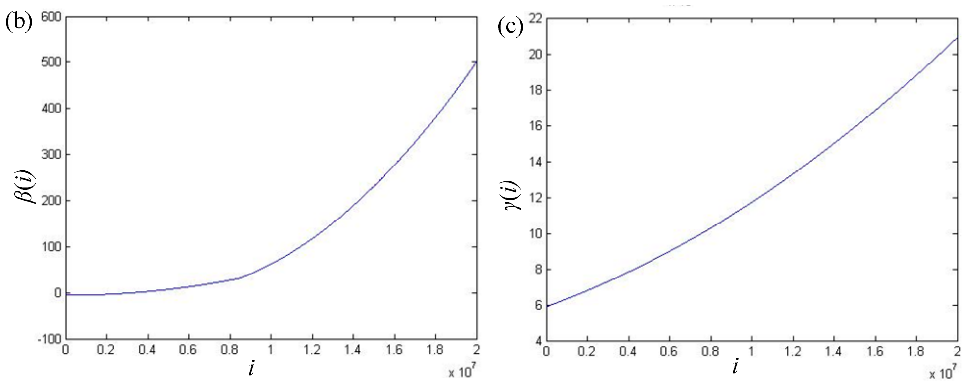

Figure 2. Distribution function assumption: (**a**) Travel value function $v(i)$, (**b**)time value coefficient distribution function $\beta(i)$, and (**c**) other cost coefficient functions $\gamma(i)$.

A market equilibrium state is obtained by a regional short-distance passenger transportation corridor supply and demand equilibrium model as shown in Tables 3 and 4.

Table 3. Scenario simulation results of short-distance comprehensive transport corridor (CTC) supply and demand equilibrium (R = 0).

Passenger Flow (10,000 Persons)	Equilibrium Price (¥)						Market Share (%)			Total Surplus
N	$P_{Highway}$	δ^2	P_{Rail}	δ^2	P_{HSR}	δ^2	$N_{Highway}$	N_{Rail}	N_{HSR}	S
1200	88.62	0.005	34.94	0.000	–	–	59	41	–	7.53×10^{10}
2000	56.57	0.042	16.66	0.043	–	–	59.9	40.2	–	1.26×10^{11}
5000	37.8	0.006	14.72	0.003	42.72	0.01	35.73	11.2	53.07	3.158×10^{11}

Table 4. Scenario simulation results of short-distance CTC supply and demand equilibrium for R = 10%.

Passenger Flow (10,000 Persons)	Equilibrium Price (¥)						Market Share (%)			Total Surplus
N	$P_{Highway}$	δ^2	P_{Rail}	δ^2	P_{HSR}	δ^2	$N_{Highway}$	N_{Rail}	N_{HSR}	S
1200	96.89	0.037	44.46	0.049	–	–	59.6	40.4	–	7.516×10^{10}
2000	62.33	0.000	18.37	0.000	–	–	59.75	40.25	–	1.259×10^{11}
5000	40.64	0.000	13.11	0.001	–	–	74.95	25.1	–	3.155×10^{11}

4.1.1. Impact of Passenger Flow

In order to analyze the impact of TDS travel demand on the short-distance passenger transportation corridor supply structure configuration, Table 3 provides the analysis of corridor supply configuration, in which the total travel demand in a corridor gradually increases from 12 million persons to 50 million persons under the premise that various transportation supplies pursue capital preservation operations (R = 0). The simulation results show that when the total TDS demand is different, the supply structure configuration of each CTC mode should also be different. In order to smoothly transfer value, various transportation modes have met the requirements of the transportation volume of the equilibrium return operation, which is one of the key conditions for configuring the supply of the CTC mode in this paper.

In the case of the established parameters, when R = 0 and N = 12 million persons, the equilibrium price of a middle highway and an ordinary rail in the short-distance passage is basically stable at 88.62¥ and 34.94¥ (Figure 3a) and variances are 0.005 and 0.000, respectively. The supply capacity configuration ratios are 59% and 41%, respectively (Figure 3b), which not only maximizes the global TDS travel surplus, i.e., 75.3 billion, but also realizes the capital preservation operation of highway and ordinary rail (Figure 3c). Due to the low demand for TDS who choose high-speed rail, it is difficult for high-speed rail to meet the capital requirements. This part of the TDS group has to choose highway with suboptimal travel surplus.

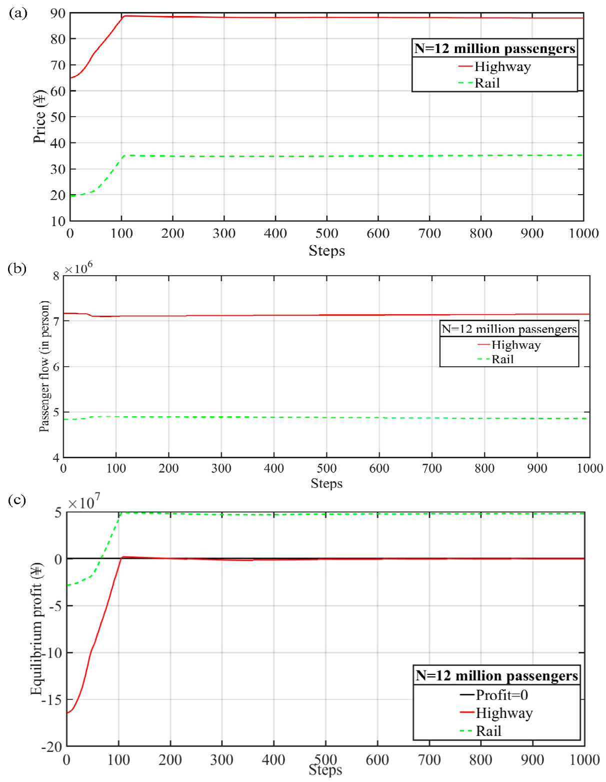

Figure 3. Scenario simulation results with N = 12 million persons: (**a**) equilibrium price, (**b**) equilibrium passenger flow, and (**c**) equilibrium profit.

When R = 0 and N = 20 million persons, in order to maximize travel surplus of the entire CTC and ensure that transportation supply can achieve a capital preservation operation, the corridor should be configured with two modes: highway and ordinary rail. Compared with the case of 12 million persons, the prices of highway and ordinary rail in the equilibrium state slightly decrease to 56.57¥ (variance is 0.042) and 16.66¥ (variance is 0.043), respectively. That is, 59.9% of travel demanders will choose highways, 40.2% of TDSs will choose ordinary rails (Figure 4a,b), and the TDSs who are willing to choose high-speed rail are still not met. This shows that, in the short-distance transportation market, highway and ordinary rail are the main travel modes.

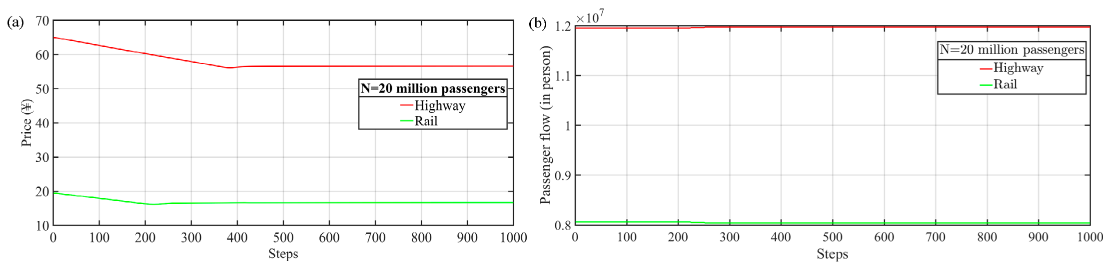

Figure 4. Scenario simulation results with N = 20 million persons: (**a**) equilibrium price; (**b**) equilibrium passenger flow.

When a passenger flow of a CTC continues to increase to 48.5 million persons (R = 0), a high-speed rail can operate at a guaranteed cost and maximize travel surplus. Therefore, the CTC should be configured with three types of transportation supply: highway, ordinary rail, and high-speed rail. Taking a passenger flow of 50 million persons as an example, the calculation results show that capacity configuration ratios of highway, ordinary rail, and high-speed rail are 35.73%, 11.2%, and 53.07%, respectively (Table 3), because when the passenger flow is large enough, various transportation modes can realize capital preservation operation. TDS that desire to choose high-speed rail will no longer choose the sub-optimal highway, which maximizes the overall travel surplus, i.e., 315.8 billion. At this time, 24% of the highway passenger flow and 29% of the ordinary rail passenger flow are transferred to high-speed rail, which illustrates that opening a corridor with a large passenger flow, i.e., high-speed rail, creates large competition for highway and ordinary rail. The price is lower than in the previous trip to different degrees, which reduces the travel cost for a traveler. In the equilibrium state, the price for highway is 37.8¥, the price for ordinary rail is 14.72¥, and the price for high-speed rail is 42.72¥, which is the equilibrium price for various transportation supplies to achieve capital preservation operations.

4.1.2. Influence of Equilibrium Rate of Return

The calculations showed that when a scale rate of return is different, the traffic volume borne by various transportation modes to achieve sustainable development is different. Figure 5a,b show a situation where a difference between travel surplus (S1) of the entire corridor with opening of a high-speed rail and travel surplus (S2) without the opening of a high-speed rail at different-scaled rates of return varies with passenger flow. When other parameters are unchanged, the equilibrium rate of return of various transportation supplies is 10%, and a corridor passenger flow required by a high-speed rail to achieve an equilibrium rate of return is approximately 70 million persons. When a passenger flow in a corridor is less than 70 million persons, high-speed rail is not recommended because it cannot achieve an equilibrium rate of return. A passenger flow required for its opening is increased by more than 20 million persons than a passenger flow required when the equilibrium rate of return is 0%. Therefore, the higher the equilibrium rate of return requirement of a transportation mode, the higher the total passenger flow requirement for opening of a corridor. The equilibrium price of various transportation supplies rises compared with an equilibrium price with a rate of return of 0%, and travel surplus of the whole society declines. Taking a CTC with a passenger flow of 20 million persons as an example, when R = 10%, in order to achieve the economic sustainability of various transportation supplies, the equilibrium prices of highway and ordinary rail are 62.33¥ and 18.37¥, respectively, which have risen slightly compared to 56.57¥ and 16.66¥ when R = 0%, respectively. The total travel surplus of the whole society dropped from 126 billion to 125.9 billion (Table 4).

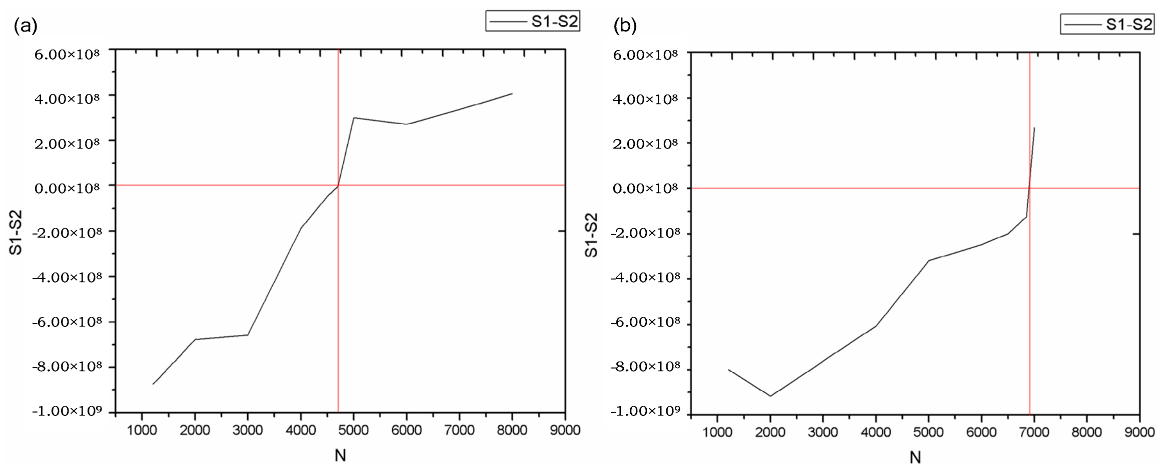

Figure 5. (**a**) Total travel surplus difference before and after opening of high-speed rail (R = 0%); (**b**) total travel surplus difference before and after opening of high-speed rail (R = 10%).

4.1.3. Effect of Travel Value Distribution

In order to simulate impact of passenger travel value distribution on an equilibrium state of a short-distance passenger transportation market, the market equilibrium states of two different travel value distributions (Figure 6) were calculated separately (Table 5).

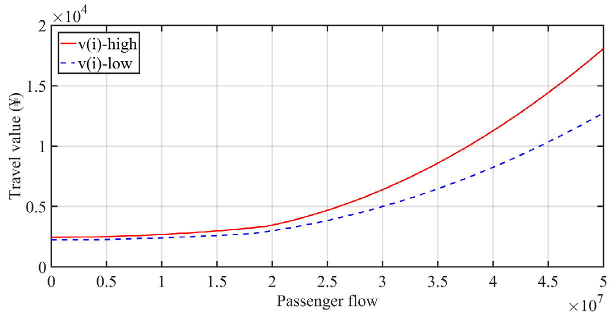

Figure 6. High–low travel value distribution.

Table 5. Scenario simulation results of different travel value distribution supply and demand equilibriums for N = 50 million persons.

Travel Value Distribution	Equilibrium Price (¥)						Market Share (%)			Total Surplus
$v(i)$	$P_{Highway}$	δ^2	P_{Rail}	δ^2	P_{HSR}	δ^2	$N_{Highway}$	N_{Rail}	N_{HSR}	S
$v(i)$-*high*	37.8	0.006	14.72	0.003	42.72	0.01	35.73	11.2	53.07	3.158×10^{11}
$v(i)$-*low*	39.78	0.000	13.2	0.000	–	–	75.08	24.92	–	2.38×10^{11}

The results show that for different travel value distributions, structure configuration of comprehensive transport passenger transportation modes is different. Assume that passenger demand for a short-distance corridor is 50 million persons, and other relevant parameters are determined (Table 2), when the passenger travel value distribution in the corridor is as shown in Figure 6 ($v(i)$-*high*), i.e., the proportion of a passenger group with a large travel value is higher, three kinds of transportation supplies should be configured in the passenger transportation corridor: highway, ordinary rail, and high-speed rail. The corresponding passenger flow sharing rates are 35.73%, 11.2%, and 53.07%, respectively, and equilibrium prices are 37.8¥, 14.72¥, and 42.72¥, respectively. When a passenger group with a smaller travel value dominates ($v(i)$-*low*), the passenger transportation corridor is only configured with two kinds of transportation supplies: highway and ordinary rail, because the passenger traffic that is expected to select high-speed rail is generally a passenger group with a large travel value. The passenger flow of this group is relatively small, which is not enough to guarantee the high-speed rail will operate. Therefore, the corridor is only configured with two kinds of supply, highway and ordinary rail, and their equilibrium prices are basically stable at 39.78¥ and 13.2¥, respectively. The share ratio is generally stable at 75.08% and 24.92%, respectively (Figure 7a,b). When the passenger flow reaches 70 million persons, the opening of the high-speed rail causes the overall travel surplus to be the largest, and the high-speed rail can achieve capital preservation operation. At this time, 40% of the highway and 14% ordinary rail TDSs flow to high-speed rail, and the high-speed rail assumes 53.52% of passenger flow in equilibrium.

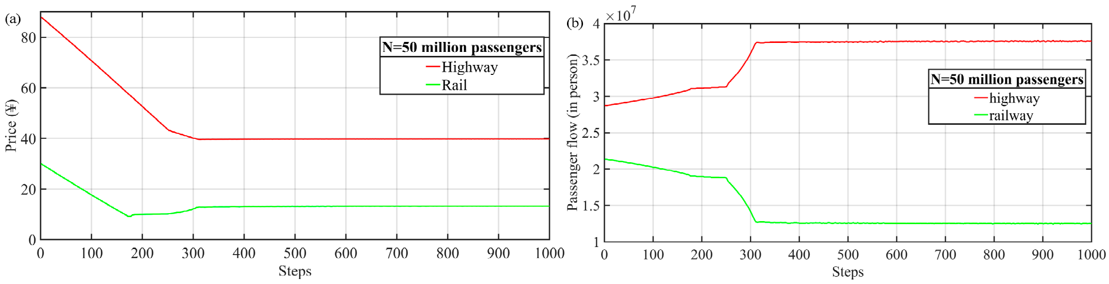

Figure 7. Scenario simulation results with a low travel value (N = 50 million persons): (**a**) Equilibrium price; (**b**) equilibrium passenger flow.

4.2. Medium- and Long-Distance Corridor Mode Structure Configuration Simulation

Given that medium- and long-distance travel has different characteristics from intercity passenger travel, this section simulates an equilibrium state of a passenger transportation market in a CTC in the context of medium- and long-distance. Since the market share of long-distance buses is extremely low, this paper has not considered it in the calculation. Only three transportation modes are considered: ordinary rail, high-speed rail, and civil aviation. The relevant parameters are assumed as shown in Figure 2 and Table 6. The simulation results for medium- and long-distance corridor supply structures are as follows by virtue of a supply and demand economic equilibrium model.

Table 6. Parameter settings for a CTC in medium- and long-distance.

Transportation Mode	Rail	HSR	Air
Construction cost (10^8¥)	153	354	1
Life (year)	60	60	15
Sharing construction cost (10^8¥/year)	2.55	5.9	0.067
Unit variation cost AV (¥/person km)	0.025	0.077	0.52
Travel time t (h)	7.2	4.3	3
Distance L (km)		550	

4.2.1. Impact of Passenger Flow

In order to analyze influence of a corridor passenger flow on supply structure configuration of a passenger transportation corridor in a comprehensive transport for medium- and long-distance, scenario simulation was conducted on a case where the scale rate of return was 0% and passenger flow of the passenger transportation corridor increased from 12 million to 50 million persons (Table 7).

Table 7. Scenario simulation results for a CTC under medium- and long-distance supply and demand equilibrium for R = 0.

Passenger Flow (10,000 Persons)	Equilibrium Price (¥)			Market Share (%)			Total Surplus
N	P_{Rail}	P_{HSR}	P_{Air}	N_{Rail}	N_{HSR}	N_{Air}	S
1200	84.35	–	360.23	29.5	–	70.5	7.06×10^{10}
2000	64.69	–	325.39	24.3	–	75.7	1.183×10^{11}
3000	52.89	–	305.17	20.93		79.07	1.78×10^{11}
4000	41.2	220.66	293.11	17.9	8	74.1	2.378×10^{11}
5000	35.4	212.55	284.26	15.81	8.99	75.2	2.976×10^{11}

The results show that under the assumption of the established parameters, in order to maximize the overall travel surplus of the corridor and achieve economic sustainability of various transportation supplies, when the passenger flow is 30 million persons or less, the corridor only needs to plan two types of transportation modes: ordinary rail and civil aviation. When the passenger flow is 12 million persons, the equilibrium prices of ordinary rail and civil aviation are basically stable at 84.35¥ and 360.23¥, and supply capacity ratios are 29.5% and 70.5%, respectively (Figure 8).

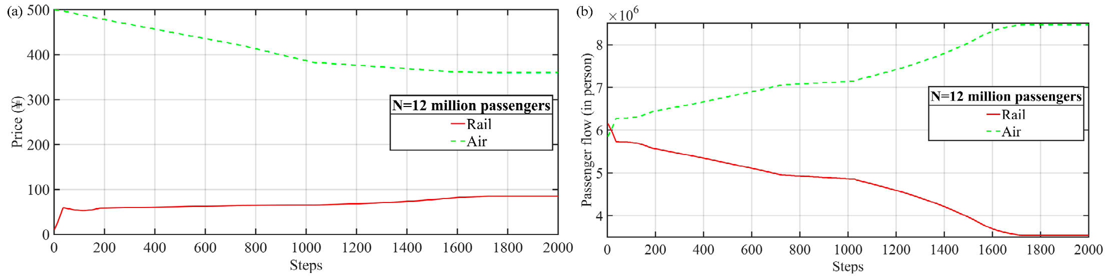

Figure 8. Simulation results with N = 12 million persons: (**a**) Equilibrium price; (**b**) equilibrium passenger flow.

In an equilibrium state, civil aviation occupies 70% of the market share, which results from a too large passenger travel value in a corridor at the time of parameter assumption of a travel demand subject. In this case, the overall travel surplus of the corridor is about 70.6 billion. With the gradual increase in passenger flow to 40 million persons, the passengers who are willing to choose high-speed rail increase gradually, and high-speed rail will be able to realize a capital preservation operation. Therefore, the CTC in the medium- and long-distance should plan for three transportation modes: ordinary rail, high-speed rail, and civil aviation, with capacity configuration ratios being 17.9%, 8%, and 74.1%, respectively; and equilibrium prices being 41.2¥, 220.66¥, and 293.11¥, respectively (Figure 9). When the passenger flow in the corridor continues to increase to 50 million persons, the equilibrium prices of various modes decrease with the increase in passenger flow. The passenger flow of the ordinary rail continues to decline, while the market shares of high-speed rail and civil aviation increase, which is related to the parameter setting of the scenario simulation. On the whole, the scenario simulation results are basically in line with an economic operation mechanism, indicating that the model has certain feasibility.

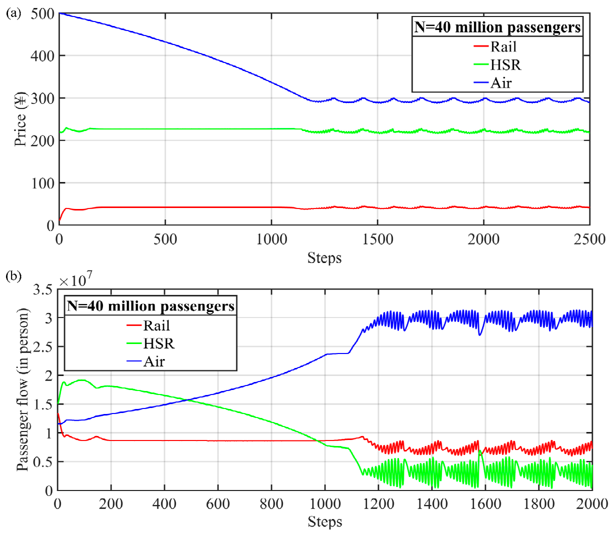

Figure 9. Simulation results with N = 40 million persons: (**a**) Equilibrium price; (**b**) equilibrium passenger flow.

4.2.2. Influence of Travel Time

In order to analyze the variation in supply capacity configuration of medium- and long-distance passenger transportation corridor mode with change in travel time of a traffic transportation mode, this section simulates various supply capacity configurations of various transportation modes when the passenger flow of a corridor is 40 million persons and the travel time of TDS choosing high-speed rail gradually decreases from 4.3 h to 3.9 h. Results are shown in Table 8.

Table 8. Scenario simulation results of impact of travel time variation on a corridor mode structure for $R = 0$.

Travel Time of High-Speed Rail (h)	Equilibrium Price (¥)			Market Share (%)		
t	P_{Rail}	P_{HSR}	P_{Air}	N_{Rail}	N_{HSR}	N_{Air}
4.3	41.2	220.66	293.11	17.9	8	74.1
4.2	40.21	225.37	293.34	17.49	10.6	71.91
4.1	40.22	231.61	294.55	17.79	11.71	70.5
4	40.98	239.35	295.88	18.14	12.22	69.64
3.9	46.13	–	293.88	18.85	–	81.19

The results show that when the travel time of high-speed rail is in the range of 4 to 4.3 h, the passenger flow sharing rate of high-speed rail increases with the decrease in travel time, due to the operating speed of the high-speed rail. Simultaneously, an increase in the operating costs of the high-speed rail leads to an increase in prices; however, at this stage, under the established parameter assumption, the travel time has a higher impact on TDS travel surplus than the price. Therefore, the share and the price of high-speed rail changes, as shown in Table 8: the share rate of high-speed rail increased from 8% to 12.22%, and the price also gradually increased from 220.66¥ to 239.55¥ due to the increase in operating costs. The passenger flow sharing rate of civil aviation gradually decreased. When the travel time of the high-speed rail declines to 3.9 h, under the established total passenger flow of the corridor, the operating cost of the high-speed rail is large and the price rises rapidly, which makes the TDS travel surplus decline rapidly. It is difficult for the high-speed rail itself to maintain a capital preservation operation, and in this case, the CTC can only be configured with ordinary rail and civil aviation. Therefore, the passenger flow sharing rate for high-speed rail presents a change process: increasing followed by decreasing with the decline of travel time. The sharing rate of civil aviation presents a trend of decreasing followed by increasing with the decline in travel time of high-speed rail. So, for high-speed rail, shorter running time is not a better choice. When the running time is shortened and the operating cost of high-speed rail increases rapidly, high-speed rail will not be able to maintain the capital. Therefore, to design of a supply product in a CTC, a passenger time value level and a supply subject's cost–benefit ratio should be comprehensively considered for scientific decision-making.

5. Conclusions

To summarize, the supply structure optimization of a comprehensive transport passenger transportation mode was examined in this work from the perspective of supply and demand economic equilibrium. An in-depth analysis of the internal mechanism of the dynamic equilibrium between supply and demand of a regional comprehensive transportation passenger corridor was conducted, wherein the maximum travel surplus of a passenger demand subject was the goal, respective interest functions of a demand subject and a supply subject were constraints to optimize the supply structure of the passenger transportation corridor mode in a quantitative manner, and a Gradient Descent algorithm was designed for solution. To demonstrate the proposed models and their associated solution algorithms, they were first implemented in an illustrative example of a short passenger corridor. Analysis results show that (1) under the given circumstances of other relevant parameters, in the pursuit of maximizing travel surplus of the whole society, with the increase in passenger demand, the passenger flow sharing rate borne by different modes of transportation varies. In a short-distance corridor, when the passenger flow is lower, highway and ordinary rail are the main modes of short-distance travel. High-speed rail is not economically viable to operate due to lower passenger flow. TDSs who are willing to choose high-speed rail have to choose a highway with sub-optimal travel surplus. With the increase in passenger flow, the equilibrium prices of highway and ordinary rail decrease and travel costs of travelers reduce. As the passenger flow continues to increase, TDSs who are willing to choose high-speed rail increase, which then supports the capital preservation operation of high-speed rail. A short-distance corridor should be configured with three kinds of transportation supply, and opening the high-speed rail constitutes a large competition for highways and ordinary rail. In order to maximize the TDS travel surplus, equilibrium prices of various transportation supplies present a declining trend, which is basically in line with the economic mechanism. Given that relevant parameters are established, the configuration structures of the CTC in a medium- and long-distance are also affected by the passenger flow, and with increase in the corridor passenger flow, equilibrium prices of various modes decrease. (2) When requirements for the equilibrium rate of return are different, passenger flow sharing rates of various transportation modes are also different. The higher the equilibrium rate of return, the higher the threshold passenger flow requirement for introducing a traffic mode. The equilibrium prices of various modes present an increasing trend. (3) The travel value distribution of a passenger group has a greater impact on structure configuration of a CTC mode. When there are more passenger groups with higher travel values, TDSs tend to choose a transportation mode with high price, fast speed, and comfortable experience. When there are more TDSs with lower travel values, TDSs tend to choose a transportation method with relatively cheaper price and slower speed, so transportation modes with a high price and comfortable experience may struggle to maintain a capital preservation operation due to possible lower passenger flow, and cannot be opened temporarily. (4) The operation time of the high-speed rail has a certain impact on supply configuration of a CTC mode. The passenger flow sharing rate of high-speed rail changes by increasing followed by decreasing with the decline in travel time of high-speed rail until maintaining the operation of the high-speed rail is difficult and cannot be opened. The sharing rate of civil aviation presents a trend of decreasing followed by increasing. Results proved that the model can better reflect an economic operation mechanism of a passenger transportation market in a CTC, which provides reference for the design of supply in a passenger transportation corridor mode and decision-making. On the whole, for a supply plan and the product design of a passenger transportation corridor mode with comprehensive transport, local economic development level, passenger time value level, and a supply subject's scale rate of return and cost, composition should be considered comprehensively for scientific decision-making.

Accordingly, this paper makes contributions to the literature. The research results have important academic value for improving structure optimization theory and methods for passenger transportation corridor modes in a comprehensive transport that conform with a market economy mechanism. The application value is in providing guidance for formulating an implementation for the optimization of a large corridor supply structure in a comprehensive transport. By doing so, other directions for future research include extending the concept from a single corridor to a point-to-point, door-to-door transportation supply structure planning, and further to comprehensive transport network planning and urban transportation planning. A theoretical CTC could be compared with an actual CTC, a partial engineering technology could be used to compensate for deviation, and incremental construction could be used to drive inventory optimization. Any existing partial CTC supply incremental optimization planning is applicable, and existing corridor layouts could be used as constraints for incremental planning.

Due to the wide scope of optimizing a CTC supply structure, this paper only provides a partial exploratory research. The presented approach still has limitations, which might be the subject of future research, such as scheduling transportation mode operations. The optimization of corridor supply structure with multiple ODs still needs further study, and the random selection of a passenger demand subject was not considered. In addition, a combination of a CTC system and an external environment needs to be considered, and it is necessary to introduce factors influencing the external environment in a quantitative research process. It is firmly thought that the proposed ideology could spur interdisciplinary research in regional traffic management, urban economy, and synthetic transportation planning, and create active interactions between transportation economists, product design engineers, and applied mathematicians.

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