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Research Article

Guidance Optimization of Travelers' Travel Mode Choice Based on Fuel Tax Rate and Bus Departure Quantity in Two-Mode Transportation System

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This aim of this study is to improve the guidance role of the fuel tax rate and bus departure quantity on travel mode choice. Car and bus travel are chosen as the research object, and a day-to-day evolution model of dual-mode network traffic flow (based on a stochastic user equilibrium model and the method of network tatonnement process) is established. Subsequently, a guidance optimization model of fuel tax rate and bus departure quantity is designed. This guidance optimization model is formulated to determine the comprehensive minimum value among system total travel time of car travel, system total comprehensive cost of bus travel, and the difference between the total operating cost of bus departure increment and the total amount of fuel tax levied on car travelers. Through numerical examples, the validity of this guidance optimization model is verified, and the influence of fuel tax rate and bus departure quantity on the traffic network is analyzed. The results show that a guidance optimization scheme based on fuel tax rate and bus departure quantity can help regulate the proportion of car travel and improve bus service quality.

1. Introduction

Given the diversification of travel modes, attracting more travelers to travel by public transport is an effective method to alleviate urban traffic congestion. Understanding the influence of travel mode choice on traffic flow is the design basis of a guidance method for travel mode choice. Bahat and Bekhor [1] incorporated ridesharing as an optional travel mode, and developed a combined mode choice and static traffic assignment model. Uchida et al. [2] developed a multi-modal transport network model based on the principle of stochastic user equilibrium. An et al. [3] studied the impact of regret aversion psychology on evacuee mode choice behavior, and believed that the regret-based model can more successfully simulate travelers' evacuation mode choice behavior than the utility model. Fu et al. [4] analyzed the influence of day-to-day demand fluctuation on the traveler route and mode choice behavior, and established a reliability-based user equilibrium model for a multi-modal transport network under demand uncertainty. Li and Yang [5] analyzed the day-to-day modal choice of travelers with responsive transit services in a representative period, and established a day-to-day dynamic modal choice model. Guo and Szeto [6] proposed a dynamical system model in which the travelers adjust their modal choice based on the perceived travel and intraday toll on the previous day.

Currently, research on the guidance methods of travel mode-choice is mainly focused on regulating the proportion of car travel and improving the service quality of public transport. The methods of regulating the proportion of car travel mainly include vehicle restrictions, congestion charges, parking charges, tax on fuel, tax on carbon emissions, ridesharing and so on. Liu et al. [7] discussed the influence of vehicle restriction strategies on travel demand and traffic conditions. Ramos et al. [8] believed that the congestion charge policy can significantly change the departure time of travelers. Mei et al. [9] established a simulated model based on system dynamics, and analyzed the role of different parking policies. Qin et al. [10] studied the influence of fuel tax on travel mode, based on travel survey data, and determined that increases in fuel tax can effectively reduce the total car volume on the road. Gupta et al. [11] analyzed the impact of baseline carbon taxes, high carbon taxes, medium carbon taxes, and low carbon taxes on CO_2 emissions from road passenger transport in India. Ma and Zhang [12] investigated the impact of different shared parking charges and ridesharing payments on traffic flow, and indicated that a scheme with dynamic parking charges and a constant ridesharing payment can significantly improve system performance. Zhang et al. [13] believed that the key of the taxi carpooling detour scheme is to determine the appropriate payment ratio and detour payment ratio, and a multi-objective optimization model for taxi carpooling detours was established.

The methods for improving the service quality of public transport mainly include urban rail transit network construction (e.g., Gong et al. [14], Yang et al. [15], and Jiang et al. [16]), bus lane construction (e.g., Yu et al. [17], Si et al. [18], Zhao and Zhou [19], and Liang et al. [20]), bus line optimization (e.g., Zuo et al. [21], Chen [22], Gkiotsalitis and Alesiani [23], and Tang et al. [24]), transfer station optimization (e.g., Liu et al. [25], Khattak et al. [26], and Sancha et al. [27]) and so on. These methods can attract more residents to travel using the large capacity and high occupancy of public transport, but also increase the operating costs of the public transportation companies. Goodwin [28] believed that one-third of the congestion charge revenue can be used to improve public transport. Xu et al. [29] analyzed the change in the total travel cost of the system by redistribution of the toll revenue, and believed that the pricing strategy of the average bus cost is a better strategy when the fixed cost is sufficiently large.

On the whole, regulating the proportion of car travel can effectively regulate car travel demand, and improving the service quality of public transport can attract some travelers to travel by public transport. However, this would increase the operating cost of public transport. To solve this problem, we assume that the government levies a fuel tax on cars and subsidizes the new added operating cost of public transport with the total amount of the fuel tax levied on cars. Obviously, the fuel tax has the same effect on taxi travel, private car travel or ridesharing, which makes some car travelers change to bus by increasing the travel cost. Furthermore, subway travel itself is a type of bus travel. For the convenience of analysis, this study defines car and bus as research objects, attempts to guide some car travelers to take bus based on fuel tax rate and bus departure quantity, and subsidizes the operating cost of bus departure increment with the total amount of fuel tax levied on car travelers. However, the high or low fuel tax rate decides the traffic demand of car travel on the road network, and then affects the total amount of fuel tax levied on car travelers, meaning it affects determining the bus departure quantity. Furthermore, increasing the bus departure quantity on the bus lines can significantly improve the service quality of the bus, and subsequently reduce the traffic demand of car travel, meaning it affects the determination of the fuel tax rate.

In summary, it is not difficult to see that the design of travel mode choice guidance-scheme needs to consider the influence of fuel tax rate and bus departure quantity on the network traffic flow. Hence, in the next section, we establish a day-to-day evolution model of dual-mode network traffic flow to depict the influence of fuel tax rate and bus departure quantity on travelers' travel mode choice. Section 3 presents the design of a guidance optimization model of fuel tax rate and bus departure quantity, and proposes a solution algorithm for this model. In Section 4, the validity of this guidance optimization model and its solution algorithm are verified. In Section 5, the conclusions of this research are drawn.

2. Day-to-Day Evolution of Dual-Mode Network Traffic Flow Considering Fuel Tax Rate and Bus Departure Quantity

To analyze the influence of fuel tax rate and bus departure quantity on the network traffic flow, we divide travelers into car and carless travelers. Further, we suppose that carless travelers can only choose to travel by bus, and car travelers can choose to travel by car or bus. A transportation network $G = (N, A)$ with cars and buses is assumed, where N is the set of all nodes, N_O is the set of origin nodes, N_D is the set of destination nodes, A is the set of all links, and R_{ij} is the set of all paths on an OD pair (i, j) with $R = (R_{ij} : i \in N_O, j \in N_D)$. Suppose that there is direct bus line on OD pair (i, j), where l is the direct bus line on OD pair (i, j) and L_{ij} is the set of direct bus lines on OD pair (i, j), with $l \in L_{ij}$ and $L = (L_{ij} : i \in N_O, j \in N_D)$.

2.1. Comprehensive Cost of Car Travel. Suppose that $h_r^c(t)$ is the car flow on path r at day t, then the car flow f_a^c on link a at day t can be expressed as

$$f_a^c(t) = \sum_{r \in R} \delta_{ar} h_r^c(t), \tag{1}$$

where δ_{ar} is the link-path incidence relationship, specifically $\delta_{ar} = 1$ if $a \in r$ and $\delta_{ar} = 0$ otherwise.

Suppose that $y_l(0)$ is the initial departure quantity on direct bus line l, $y_l(t)$ is the departure quantity on direct bus line l at day t, and ζ is the conversion coefficient between bus and equivalent car, then the bus flow f_a^b on the link a at day t can be expressed as

$$f_a^b(t) = \sum_{l \in L} \delta_{al} \zeta y_l(t), \tag{2}$$

where δ_{al} is the link-direct bus line incidence relationship, specifically $\delta_{al} = 1$ if $a \in l$ and $\delta_{al} = 0$ otherwise.

According to Formulas (1) and (2), the total flow f_a on link a can be written as

$$f_a(t) = f_a^c(t) + f_a^b(t) = \sum_{r \in R} \delta_{ar} h_r^c(t) + \sum_{l \in L} \delta_{al} \zeta y_l(t). \tag{3}$$

Suppose that c_a is the travel time on link a, then the travel time c_r on path r can be expressed as

$$c_r(t) = \sum_{a \in A} \delta_{ar} c_a(f(t)). \tag{4}$$

Suppose that ρ_0 is the fuel price not including tax, λ is the conversion coefficient between fuel and travel time, $\rho_a'(t)$ is the fuel cost not including tax of car on link a at day t, $\rho_a'(t) = \lambda\rho_0 c_a(f(t))$, and x is the fuel tax rate, then the fuel cost ρ_a including tax of car on link a at day t can be expressed as

$$\rho_a(t) = (1+x)\lambda\rho_0 c_a(f(t)). \quad (5)$$

Hence, the fuel cost ρ_r including tax of car on path r at day t can be written as

$$\rho_r(t) = \sum_{a\in A}\delta_{ar}\rho_a(t) = (1+x)\lambda\rho_0\sum_{a\in A}\delta_{ar}c_a(f(t)). \quad (6)$$

We define the comprehensive cost π_r^c of car travel on path r on OD pair (i_n, j_n) at day t as the weighted sum of travel time c_r and fuel cost ρ_r. This can be expressed as

$$\begin{aligned}\pi_r^c(t) &= \gamma_{c1}c_r(t) + \gamma_{c2}\rho_r(t)\\ &= \gamma_{c1}\sum_{a\in A}\delta_{ar}c_a(f(t)) + \gamma_{c2}(1+x)\lambda\rho_0\sum_{a\in A}\delta_{ar}c_a(f(t)),\end{aligned} \quad (7)$$

where γ_{c1} and γ_{c2} are the conversion coefficient.

2.2. Comprehensive Cost of Bus Travel. In the transportation network, travelers need to transfer in several stations to reach their destination when there is no direct bus line on some OD pairs. We suppose that there is no direct bus line on OD pair (i_0, j_n), travelers need to transfer multiple direct bus lines $(l_1, l_2, \ldots, l_n)$ to reach the destination j_n, $i_1, i_2, \ldots, i_{n-1}$ are the transfer stations, $j_1, j_2, \ldots, j_{n-1}$ are the getting-off stations, the getting-off station j_{n-1} and transfer station i_{n-1} are the same station (that is to say, the walking time for transfer can be neglected), s is the generalized bus line on OD pair (i_0, j_n), the generalized bus line s consists of multiple direct bus lines, $S_{i_0 j_n}$ is the set of generalized bus lines on OD pair (i_0, j_n), $s \in S_{i_0 j_n}$, $S = (S_{i_0 j_n} : i_0 \in N_O, j_n \in N_D)$, and $h_s^b(t)$ represents the passengers on the generalized bus line s at day t. To this end, the total passengers TP_{al}^b on link a on direct bus line l at day t can be expressed as

$$TP_{al}^b(t) = \sum_{s\in S}\delta_{as}\delta_{ls}h_s^b(t), \quad (8)$$

Where δ_{ls} is the direct bus line-generalized bus line incidence relationship, specifically $\delta_{ls} = 1$ if $l \in s$ and $\delta_{ls} = 0$ otherwise. δ_{as} is the link-generalized bus line incidence relationship, specifically $\delta_{as} = 1$ if $a \in s$ and $\delta_{as} = 0$ otherwise.

We define the in-bus congestion degree CC_{al} on link a on direct bus line l at day t as

$$CC_{al}(t) = \alpha\left(\frac{TP_{al}^b(t)}{y_l(t)B_l}\right)^\beta, \quad (9)$$

Where α represents the conversion coefficient between in-bus congestion degree and travel time, β is the congestion coefficient, and B_l is the maximum passenger capacity of the unit bus on direct bus line l. Then, the in-bus congestion degree CC_l on direct bus line l at day t can be expressed as

$$CC_l(t) = \max_{a\in l}\{CC_{al}(t)\} = \max_{a\in l}\left\{\alpha\left(\frac{TP_{al}^b(t)}{y_l(t)B_l}\right)^\beta\right\}. \quad (10)$$

Suppose that the waiting interval $w_l(t) = 1/y_l(t)$. The comprehensive cost π_s^b of bus travel on the generalized bus line s at day t is the weighted sum of travel time c_s, waiting interval w_s, ticket price P_s, and in-bus congestion degree CC_s. It can be expressed as

$$\begin{aligned}\pi_s^b(t) &= \gamma_{b1}c_s(t) + \gamma_{b2}w_s(t) + \gamma_{b3}P_s + \gamma_{b4}CC_s(t)\\ &= \gamma_{b1}\sum_{a\in A}\delta_{as}c_a(f(t)) + \gamma_{b2}\chi\sum_{l\in L}\delta_{ls}\frac{1}{y_l(t)} + \gamma_{b3}\sum_{l\in L}\delta_{ls}P_l\\ &\quad + \gamma_{b4}\max_{a\in s}\left\{\alpha\left(\frac{TP_{al}^b(t)}{y_l(t)B_l}\right)^\beta\right\},\end{aligned} \quad (11)$$

Where P_l represents the ticket price on direct bus line l, and χ, γ_{b1}, γ_{b2}, γ_{b3} and γ_{b4} are the conversion coefficient.

2.3. Day-to-Day Evolution Model of Dual-Mode Network Traffic Flow. Suppose that q_{ij}^n is the travel demand of carless travelers on OD pair (i, j), q_{ij}^o is the travel demand of car travelers, and car travelers choose the travel mode according to their understanding of minimum comprehensive cost between car travel and bus travel. If the understanding error ε_{ij}^c of car travel and the understanding error ε_{ij}^b of bus travel are independent of each other and obey the Gumbel distribution with zero mean, it can be deduced that the travel mode choice of car or bus satisfies the Logit model for car travelers. Then, the car travel demand q_{ij}^c on OD pair (i, j) at day t can be expressed as

$$\begin{aligned}q_{ij}^c(t) &= q_{ij}^o \cdot Pr\left(\mu_{ij}^c(t) + \varepsilon_{ij}^c(t) \le \mu_{ij}^b(t) + \varepsilon_{ij}^b(t)\right)\\ &= q_{ij}^o\frac{\exp\left(-\theta\mu_{ij}^c(t)\right)}{\sum_{m\in\{c,b\}}\exp\left(-\theta\mu_{ij}^m(t)\right)}, \quad \forall i \in N_O, j \in N_D,\end{aligned} \quad (12)$$

where $\mu_{ij}^c(t)$ is the minimum comprehensive cost of car travel on OD pair (i, j) at day t, $\mu_{ij}^b(t)$ is the minimum comprehensive cost of bus travel on OD pair (i, j) at day t, and θ is the sensitivity of car travelers to the minimum comprehensive cost. Hence, the bus travel demand q_{ij}^b on OD pair (i, j) at day t can be written as

$$q_{ij}^b(t) = q_{ij}^n + q_{ij}^o - q_{ij}^c(t). \quad (13)$$

To depict the day-to-day evolution process of dual-mode network traffic flow, this study uses the method of network tatonnement process to simulate the path (or generalized bus line) choice behavior of car travel (or bus travel) according to user equilibrium principle (Huang et al. [30]). The excess travel cost ETC_r^m on path r on OD pair (i, j) at day t is expressed as

$$ETC_r^m(t) = \pi_r^m(t) - \mu_{ij}^m(t), \quad \forall m \in \{c, b\},\ r \in \{R, S\}, \quad (14)$$

where m represents the class of travel modes, $m = c$ represents the car travel mode ($r \in R$), and $m = b$ represents the bus travel mode ($r \in S$).

Rational travelers always choose the path with the minimum comprehensive cost. When the excess travel cost ETC_r^m is positive (the comprehensive cost on path r is greater than the minimum comprehensive cost), path flow h_r^m will decrease because some travelers will automatically move to the less comprehensive cost path, and otherwise path flow h_r^m will increase. To this end, the adjustment principle between path flow h_r^m and excess travel cost ETC_r^m can be expressed as

$$h_r^m(t+\Delta t) = h_r^m(t) - \phi_r^m ETC_r^m(t), \quad \forall \phi_r^m > 0. \tag{15}$$

Considering $h_r^m \geq 0$, Formula (15) can be rewritten as

$$h_r^m(t+\Delta t) = \left\{h_r^m(t) - \phi_r^m ETC_r^m(t)\right\}_+, \quad \forall \phi_r^m > 0, \tag{16}$$

where $\{z\}_+ = \max(0, z)$. Supposing that h_r^m is a continuous differentiability function of t, we know

$$\begin{aligned}\frac{dh_r^m(t)}{dt} &= \lim_{\Delta t\to 0}\frac{h_r^m(t+\Delta t) - h_r^m(t)}{\Delta t} \\ &\approx \eta_r^m\left[h_r^m(t+\Delta t) - h_r^m(t)\right], \quad \forall \eta_r^m < 0.\end{aligned} \tag{17}$$

Applying Formula (16) into (17), we have

$$\frac{dh_r^m(t)}{dt} = \eta_r^m\left[\left\{h_r^m(t) - \phi_r^m ETC_r^m(t)\right\}_+ - h_r^m(t)\right]. \tag{18}$$

The excess travel demand ETD_{ij}^m on OD pair (i, j) at day t is expressed as

$$ETD_{ij}^m(t) = q_{ij}^m(t) - \sum_r h_r^m(t), \quad \forall m \in \{c, b\},\ r \in \{R, S\}. \tag{19}$$

When the excess travel demand ETD_{ij}^m is positive, the minimum comprehensive cost μ_{ij}^m will increase to reduce the potential travel demand; otherwise, the minimum comprehensive cost μ_{ij}^m will decrease. To this end, the adjustment principle between ETD_{ij}^m and μ_{ij}^m can be expressed as

$$\mu_{ij}^m(t+\Delta t) = \left\{\mu_{ij}^m(t) + \varphi_{ij}^m ETD_{ij}^m(t)\right\}_+, \quad \forall \varphi_{ij}^m > 0. \tag{20}$$

Supposing that μ_{ij}^m is a continuous differentiability function of t, we know

$$\frac{d\mu_{ij}^m(t)}{dt} \approx \kappa_{ij}^m\left[\mu_{ij}^m(t+\Delta t) - \mu_{ij}^m(t)\right], \quad \forall \kappa_{ij}^m > 0. \tag{21}$$

Applying Formula (20) into (21), we have

$$\frac{d\mu_{ij}^m(t)}{dt} = \kappa_{ij}^m\left[\left\{\mu_{ij}^m(t) + \varphi_{ij}^m ETD_{ij}^m(t)\right\}_+ - \mu_{ij}^m(t)\right]. \tag{22}$$

Using Formulas (12), (13), (18), and (22), the day-to-day evolution model of dual-mode network traffic flow can be expressed as

$$\begin{aligned}
q_{ij}^c(t) &= q_{ij}^o\frac{\exp\left(-\theta\mu_{ij}^c(t)\right)}{\sum_{m\in\{c,b\}}\exp\left(-\theta\mu_{ij}^m(t)\right)}, \quad \forall i \in N_O,\ j \in N_D \\
q_{ij}^b(t) &= q_{ij}^n + q_{ij}^o - q_{ij}^c(t), \quad \forall i \in N_O,\ j \in N_D \\
\frac{d\mu_{ij}^m(t)}{dt} &= \kappa_{ij}^m\left[\left\{\mu_{ij}^m(t) + \varphi_{ij}^m ETD_{ij}^m(t)\right\}_+ - \mu_{ij}^m(t)\right], \quad \forall m \in \{c, b\} \\
\frac{dh_r^m(t)}{dt} &= \eta_r^m\left[\left\{h_r^m(t) - \phi_r^m ETC_r^m(t)\right\}_+ - h_r^m(t)\right], \quad \forall r \in \{R, S\}.
\end{aligned} \tag{23}$$

3. Guidance Optimization Model of Fuel Tax Rate and Bus Departure Quantity

3.1. Model Formulation. The guidance of travel mode choice based on fuel tax rate and bus departure quantity is expected to guide some car travelers to take bus and subsidize the operating cost of bus departure increment with the total amount of fuel tax levied on car travelers. Based on this, a guidance optimization model of fuel tax rate and bus departure quantity is proposed. This is formulated to seek the comprehensive optimization among system total travel time of car travel, system total comprehensive cost of bus travel, and the difference between the total operating cost of bus departure increment and the total amount of fuel tax levied on car travelers. It can be expressed as

$$\begin{aligned}\min_{x,y_l} SC = {} & \xi\sum_{r\in R} c_r h_r^c + \xi\sum_{s\in S}\pi_s^b h_s^b \\ & + (1-\xi)\left\{\sum_{r\in R} h_r^c\left[x\lambda\rho_0\sum_{a\in A}\delta_{ar}c_a(f)\right] - \sum_{l\in L}\Delta y_l\sigma_l\right\}.\end{aligned} \tag{24}$$

subject to

$$\sum_{r\in R} h_r^c\left[x\lambda\rho_0\sum_{a\in A}\delta_{ar}c_a(f)\right] \geq \sum_{l\in L}\Delta y_l\sigma_l, \tag{25}$$

$$x \geq 0,\ y_l(0) \geq 0,\ y_l \geq 0, \tag{26}$$

$$q_{ij}^c(t) = q_{ij}^o\frac{\exp\left(-\theta\mu_{ij}^c(t)\right)}{\sum_{m\in\{c,b\}}\exp\left(-\theta\mu_{ij}^m(t)\right)}, \tag{27}$$

$$q_{ij}^b(t) = q_{ij}^n + q_{ij}^o - q_{ij}^c(t) \tag{28}$$

$$\frac{d\mu_{ij}^m(t)}{dt} = \kappa_{ij}^m\left[\left\{\mu_{ij}^m(t) + \varphi_{ij}^m ETD_{ij}^m(t)\right\}_+ - \mu_{ij}^m(t)\right], \tag{29}$$

$$\frac{dh_r^m(t)}{dt} = \eta_r^m\left[\left\{h_r^m(t) - \phi_r^m ETC_r^m(t)\right\}_+ - h_r^m(t)\right], \tag{30}$$

where SC represents the objective function, ξ is the weight factor, σ_l is the operating cost of the unit departure quantity on direct bus line l, Δy_l is the bus departure increment on direct bus line l, and $\Delta y_l = y_l - y_l(0)$. The first item on the right side of Formula (24) is the system total travel time of car travel, the second item is the system total comprehensive cost of bus travel, and the third item is the difference between the total amount of fuel tax levied on car travelers and the total operating cost of bus departure increment. Formula (25) is the constraint that the total operating cost of bus departure increment cannot be higher than the total amount of fuel tax levied on car travelers. Formula (26) is the nonnegative constraint for the fuel tax rate, initial quantity of departures, and current quantity of departures. Formula (27) is the constraint for car travel demand. Formula (28) is the constraint for bus travel demand. Formulas (29) and (30) are the day-to-day evolution of minimum comprehensive cost and path flow, respectively.

3.2. Model Solution. The guidance optimization model in Formulas (24)–(30) is a multi-objective nonlinear mixed programming problem, which is very difficult to solve. The fundamental difficulty is how to determine the departure increment of each direct bus line when solving this problem. To determine departure increment of each direct bus line, we assume that the fuel tax rate is known, use the iteration algorithm to find the direct bus line with the minimal Z $\left(Z=\sum_{r\in R}c_r h_r^c+\sum_{s\in S}\pi_s^b h_s^b\right)$, and increase the departure increment of this bus line by one. If the sum of departure increment on each direct bus line equals the total departure increment, we calculate the value of SC. Comparing the value of SC under various fuel tax rates, (x, y_l) is the solution of this model under the minimal SC. The detailed steps are described as follows:

Step 1: Initialization. The iterative tax rate Δx, the initial fuel tax rate x, and the operating cost σ_l of the unit departure quantity are given.

Step 2: Determine the effective path and generalized bus line by the Dial algorithm (Dial [31]), solve the dual-mode network traffic assignment problem, obtain $X=\sum_{r\in R}h_r^c[x\lambda\rho_0\sum_{a\in A}\delta_{ar}t_a(f_a)]$, and set $X_b=X$.

Step 3: Set $x=x+\Delta x$, solve the dual-mode network traffic assignment problem, and obtain X. If $X-X_b<0$, then go to *Step 7*. Otherwise, set $X_b=X$, $k=0$, and go to *Step 4*.

Step 4: Calculate the maximum departure increment $\Delta y_{\max}=floor(X/\min_l(\sigma_l))$, where $floor(\cdot)$ is the floor function. If $\Delta y_{\max}>0$, then go to *Step 5*. Otherwise, return to *Step 3*.

Step 5: Increase the departure increment of each bus line by one in turn, solve the dual-mode network traffic assignment problem, and obtain Z. Increase the departure increment of the bus line with the minimal Z by one, and set $k=k+1$.

Step 6: Solve the dual-mode network traffic assignment problem and obtain $\Delta y_{\max}$. If $k>\Delta y_{\max}$, then reduce the departure increment of the bus line with the minimal Z by one in *Step 5*. Record SC, x, and Δy_l and return to *Step 3*.

Step 7: Compare the value of SC under various fuel tax rates and stop. (x, y_l) is the solution of this model under the minimal SC.

In addition, the solving steps of the dual-mode network traffic assignment problem are described as follows:

Step 1: Initialization. The convergence accuracy ε, the iterative step Δt, the parameters $\xi, \zeta, \chi, \lambda, \alpha, \beta, \theta, \gamma_{c1}, \gamma_{c2}, \gamma_{b1}, \gamma_{b2}, \gamma_{b3}, \gamma_{b4}, \kappa_{ij}^m, \eta_r^m, \varphi_{ij}^m$, and ϕ_r^m, the travel demand q_{ij}^n of carless travelers, the travel demand q_{ij}^o of car travelers, the initial path flow h_r^m, the initial minimum comprehensive cost $\mu_{ij}^m(0)$, the fuel price ρ_0 not including tax, the initial departure quantity $y_l(0)$, the ticket price P_l, and the maximum passenger capacity B_l of the unit bus are given.

Step 2: Calculate the car travel demand q_{ij}^c and the bus travel demand q_{ij}^b according to Formulas (27) and (28), respectively.

Table 1: Direct bus lines.

Direct bus line no.	Links in direct bus line	Direct bus line no.	Links in direct bus line
1	1	2	3
3	6,9,12	4	15,11,8
5	24,20	6	17,21
7	36,32,29,50	8	55,48,27,33
9	41,45	10	57,44
11	72,68	12	63,70
13	39,75,64	14	62,66,74
15	2,7,37	16	38,35,5
17	10,34,42,73	18	76,71,40,31
19	13,25,28,46,69	20	65,67,43,26,23
21	4,16,22,49,53,59	22	61,58,52,47,19,14
23	18,56	24	60,54

Step 3: Calculate the excess travel cost ETC_r^m and the excess travel demand ETD_{ij}^m according to Formulas (14) and (19), respectively.

Step 4: Calculate $d\mu_{ij}^m(t)/dt$ and $dh_r^m(t)/dt$ according to Formulas (29) and (30), respectively.

Step 5: Calculate the minimum comprehensive cost $\mu_{ij}^m(t+\Delta t)$ and path flow $h_r^m(t+\Delta t)$ according to $\mu_{ij}^m(t+\Delta t)=\mu_{ij}^m(t)+\left(d\mu_{ij}^m(t)/dt\right)\Delta t$ and $h_r^m(t+\Delta t)=h_r^m(t)+\left(dh_r^m(t)/dt\right)\Delta t$, respectively.

Step 6: Convergence check. If $\left|\sqrt{\sum_{a\in A}[f_a(t+\Delta t)-f_a(t)]^2}/\sum_{a\in A}f_a(t)\right|\le\varepsilon$, then calculate the objective function SC, Z, and X and stop. Otherwise, set $t=t+\Delta t$ and return to *Step 2*.

4. Calculations and Analysis of Numerical Example

4.1. Test Transportation Network. A transportation network with 76 links, 24 nodes, and 528 OD pairs, as illustrated in Figure 1, is used to verify the validity of this guidance optimization model and its solution algorithm. In Figure 1, we suppose that the direct bus lines are those listed in Table 1, the transportation network only has cars and buses, the travel demand q_{ij}^n of carless travelers is that presented in Table 2, the travel demand q_{ij}^o of car travelers is five times compared with q_{ij}^n, and the fuel price not including tax $\rho_0=6$. The ticket price P_l, initial departure quantity $y_l(0)$, maximum passenger capacity B_l of the unit bus, and operating costs σ_l of the unit departure quantity for all direct bus lines are unified at 2, 25, 30, and 1000, respectively.

In this numerical example, we will make use of the traditional BPR link travel time function of the form

$$c_a(f)=c_0\left[1+0.15\left(\frac{f_a}{K_a}\right)^4\right], \quad (31)$$

where c_0 represents the free flow travel time on link a, and K_a is the capacity on link a. The parameters of the link travel time function for this transportation network are listed in Table 3.

Table 2: Travel demand of carless travelers on each OD pair.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1		1.1	1.1	5.5	2.2	3.3	5.5	8.8	5.5	14.3	5.5	2.2	5.5	3.3	5.5	5.5	4.4	1.1	3.3	3.3	1.1	4.4	3.3	1.1
2	1.1		1.1	2.2	1.1	4.4	2.2	4.4	2.2	6.6	2.2	1.1	3.3	1.1	1.1	4.4	2.2	0.0	1.1	1.1	0.0	1.1	0.0	0.0
3	1.1	1.1		2.2	1.1	3.3	1.1	2.2	1.1	3.2	3.3	2.2	1.1	1.1	1.1	2.2	1.1	0.0	0.0	0.0	0.0	1.1	1.1	0.0
4	5.5	2.2	2.2		5.5	4.4	4.4	7.7	7.7	13.2	15.4	6.6	6.6	5.5	5.5	8.8	5.5	1.1	2.2	3.3	2.2	4.4	5.5	2.2
5	2.2	1.1	1.1	5.5		2.2	2.2	5.5	8.8	11	5.5	2.2	2.2	1.1	2.2	5.5	2.2	0.0	1.1	1.1	1.1	2.2	1.1	0.0
6	3.3	4.4	3.3	4.4	2.2		4.4	8.8	4.4	8.8	4.4	2.2	2.2	1.1	2.2	9.9	5.5	1.1	2.2	3.3	1.1	2.2	1.1	1.1
7	5.5	2.2	1.1	4.4	2.2	4.4		11	6.6	20.9	5.5	7.7	4.4	2.2	5.5	15.4	11	2.2	4.4	5.5	2.2	5.5	2.2	1.1
8	8.8	4.4	2.2	7.7	5.5	8.8	11		8.8	17.6	8.8	6.6	6.6	4.4	6.6	24.2	15.4	3.3	7.7	9.9	4.4	5.5	3.3	2.2
9	5.5	2.2	1.1	7.7	8.8	4.4	6.6	8.8		30.8	15.4	6.6	6.6	6.6	9.9	15.4	9.9	2.2	4.4	6.6	3.3	7.7	5.5	2.2
10	14.3	6.6	3.3	13.2	11	8.8	20.9	17.6	30.8		44	22	20.9	23.1	44	48.4	42.9	7.7	19.8	27.5	13.2	28.6	19.8	8.8
11	5.5	2.2	3.3	16.5	5.5	4.4	5.5	8.8	15.4	42.9		15.4	11	17.6	15.4	15.4	11	1.1	4.4	6.6	4.4	12.1	14.3	6.6
12	2.2	1.1	2.2	6.6	2.2	2.2	7.7	6.6	6.6	22.0	15.4		14.3	7.7	7.7	7.7	6.6	2.2	3.3	4.4	3.3	7.7	7.7	5.5
13	5.5	3.3	1.1	6.6	2.2	2.2	4.4	6.6	6.6	20.9	11	14.3		6.6	7.7	6.6	5.5	1.1	3.3	6.6	6.6	14.3	8.8	8.8
14	3.3	1.1	1.1	5.5	1.1	1.1	2.2	4.4	6.6	23.1	17.6	7.7	6.6		14.3	7.7	7.7	1.1	3.3	5.5	4.4	13.2	12.1	4.4
15	5.5	1.1	1.1	5.5	2.2	2.2	5.5	6.6	11	44	15.4	7.7	7.7	14.3		13.2	16.5	2.2	8.8	12.1	8.8	28.6	11	4.4
16	5.5	4.4	2.2	8.8	5.5	9.9	15.4	24.2	16.4	48.4	15.4	7.7	6.6	7.7	13.2		30.8	5.5	14.3	17.6	6.6	13.2	5.5	3.3
17	4.4	2.2	1.1	5.5	2.2	5.5	11	15.4	9.9	42.9	11	6.6	5.5	7.7	16.5	30.8		6.6	18.7	18.7	6.6	18.7	6.6	3.3
18	1.1	0.0	0.0	1.1	0.0	1.1	2.2	3.3	2.2	7.7	2.2	2.2	1.1	1.1	2.2	5.5	6.6		3.3	4.4	1.1	3.3	1.1	0.0
19	3.3	1.1	0.0	2.2	1.1	2.2	4.4	7.7	4.4	19.8	4.4	3.3	3.3	3.3	8.8	14.3	18.7	3.3		13.2	4.4	13.2	3.3	1.1
20	3.3	1.1	0.0	3.3	1.1	3.3	5.5	9.9	6.6	27.5	6.6	5.5	6.6	5.5	12.1	17.6	18.7	4.4	13.2		13.2	26.4	7.7	4.4
21	1.1	0.0	0.0	2.2	1.1	1.1	2.2	4.4	3.3	13.2	4.4	3.3	6.6	4.4	8.8	6.6	6.6	1.1	4.4	13.2		19.8	7.7	5.5
22	4.4	1.1	1.1	4.4	2.2	2.2	5.5	5.5	7.7	28.6	12.1	7.7	14.3	13.2	28.6	13.2	18.7	3.3	13.2	26.4	19.8		23.1	12.1
23	3.3	0.0	1.1	5.5	1.1	1.1	2.2	3.3	5.5	19.8	14.3	7.7	8.8	12.1	11	5.5	6.6	1.1	3.3	7.7	7.7	23.1		7.7
24	1.1	0.0	0.0	2.2	0.0	1.1	1.1	2.2	2.2	8.8	6.6	5.5	7.7	4.4	4.4	3.3	3.3	0.0	1.1	4.4	5.5	12.1	7.7	

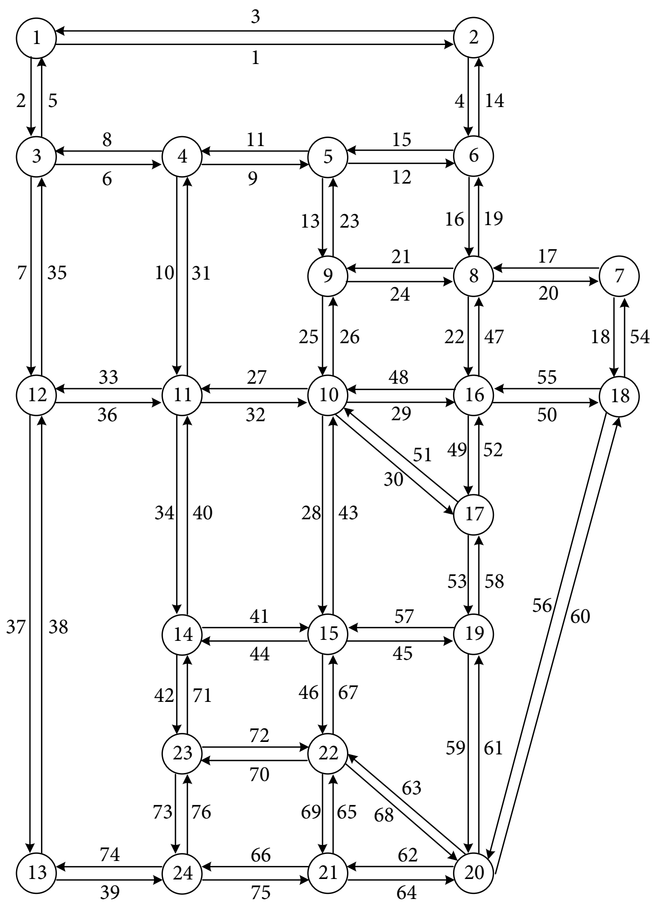

Figure 1: Test transportation network.

Table 3: Parameters of link travel time function.

Link no.	c_0	K_a	Link no.	c_0	K_a	Link no.	c_0	K_a
1 and 3	6	259.002	2 and 5	4	234.035	4 and 14	5	49.582
6 and 8	4	171.105	7 and 35	4	234.035	9 and 11	2	177.828
10 and 31	6	49.088	12 and 15	4	49.480	13 and 23	5	100.000
16 and 19	2	48.986	17 and 20	3	78.418	18 and 54	2	234.035
21 and 24	10	50.502	22 and 47	5	50.458	25 and 26	3	139.158
27 and 32	5	100.000	28 and 43	6	135.120	29 and 48	5	51.335
30 and 51	8	49.935	33 and 36	6	49.088	34 and 40	4	48.765
37 and 38	3	259.002	39 and 74	4	50.913	41 and 44	5	51.275
42 and 71	4	49.248	45 and 57	4	156.508	46 and 67	4	103.150
49 and 52	2	52.299	50 and 55	3	196.799	53 and 58	2	48.240
56 and 60	4	234.035	59 and 61	4	50.026	62 and 64	6	50.599
63 and 68	5	50.757	65 and 69	2	52.299	66 and 75	3	48.854
70 and 72	4	50.000	73 and 76	2	50.785			

4.2. Calculation Results Exhibition. According to the solution algorithm of this guidance optimization model, we select the system parameter $\zeta = 2$, $\alpha = 1$, $\beta = 4$, $\xi = 0.9$, $\theta = 0.1$, $\lambda = 1$, $\chi = 720$, $\gamma_{c1} = 1$, $\gamma_{c2} = 1$, $\gamma_{b1} = 5$, $\gamma_{b2} = 0.5$, $\gamma_{b3} = 0.1$, $\gamma_{b4} = 2$, $\kappa_{ij}^c = \kappa_{ij}^b = 1$, $\eta_r^c = \eta_r^b = 1$, $\varphi_{ij}^c = 0.1$, $\varphi_{ij}^b = 0.1$, $\phi_r^c = 0.001$ and $\phi_r^b = 0.001$. The calculation results are presented as follows.

In Figure 2, we can observe that the objective function *SC* is the minimum value when the fuel tax rate $x = 1.2$. This means that the solution of the model can be derived by this proposed algorithm. When the fuel tax rate $x = 1.2$, the departure increment Δy_l and departure quantity y_l on each direct bus line are shown in Table 4, the system total travel time of car travel is 15073, and the system total comprehensive cost of bus travel is 2823039. Comparing to the system before optimization, the system total comprehensive cost of bus travel has decreased by 47%, and the system total

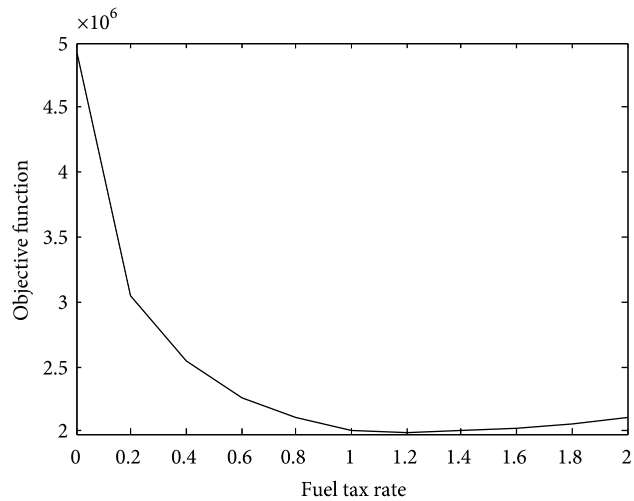

Figure 2: The process of objective function changing with fuel tax rate.

Table 4: Optimization results of direct bus lines when $x = 1.2$.

Direct bus line no.	Δy_l	y_l	Direct bus line no.	Δy_l	y_l
1	0	25	2	0	25
3	0	25	4	0	25
5	0	25	6	0	25
7	11	36	8	12	37
9	0	25	10	0	25
11	0	25	12	0	25
13	0	25	14	0	25
15	0	25	16	0	25
17	4	29	18	2	27
19	1	26	20	3	28
21	12	37	22	9	34
23	0	25	24	0	25

travel time of car travel has decreased by up to 89%. This also reflects the important role of fuel tax rate and bus departure quantity from one side of the traffic demand management.

4.3. Comparisons of Calculation Results. To analyze the influence of fuel tax rate and bus departure quantity on transportation network, we will calculate the before optimization scenario ($x = 0$, $y_l = 25$) and after optimization scenario ($x = 1.2$, y_l are listed in Table 4) based on day-to-day evolution model of dual-mode network traffic flow. Selected network equilibrium results are shown in Tables 5 and 6.

In Table 5, we can observe that traffic flow on some links has obviously decreased, and the saturation on some links has decreased by up to 50% after optimization. This means that the guidance optimization scheme based on fuel tax rate and bus departure quantity can regulate the distribution of network traffic flow and decrease the link saturation. In Table 6, we can observe that the total passengers on some links have significantly increased, but the saturation has slightly increased after optimization. This reflects that the guidance optimization scheme based on fuel tax rate and bus departure quantity can not only attract some car travelers to take bus, but also improve the service quality of bus. In summary, the guidance optimization scheme based on fuel tax rate and bus departure quantity can not only help to regulate the proportion of car travel, but also improve the service quality of bus.

Table 5: Link flow and saturation on some links.

Link no.	Link flow		Saturation	
	Before optimization	After optimization	Before optimization	After optimization
13	200.9278	85.9122	2.0092	0.8591
23	209.3689	91.8982	2.0936	0.9189
25	288.8332	140.1156	2.0755	1.0068
26	291.6866	163.3316	2.0960	1.1737
37	258.9613	111.3811	0.9998	0.4300
38	249.7426	110.8453	0.9642	0.4279
50	372.9562	189.2985	1.8951	0.9618
55	347.0723	180.4761	1.7635	0.9170

Table 6: Total passengers and saturation on some links.

Link no.	Total passengers		Saturation	
	Before optimization	After optimization	Before optimization	After optimization
13	493.2327	527.9446	0.6576	0.6768
23	481.9583	556.2356	0.6426	0.6621
25	949.2594	1068.8783	1.2656	1.3703
26	942.0002	1054.5305	1.2560	1.2553
37	626.9092	791.2864	0.8358	1.0550
38	643.6858	756.6255	0.8582	1.0088
50	704.7923	844.8154	0.9397	0.7822
55	811.7225	961.5565	1.0822	0.8662

5. Conclusions

In this study, we established a day-to-day evolution model of dual-mode network traffic flow to depict the influence of fuel tax rate and bus departure quantity on travelers' travel mode choice, proposed a guidance optimization model of fuel tax rate and bus departure quantity, and designed a solution algorithm for this model. The case study demonstrated that the guidance optimization scheme based on fuel tax rate and bus departure quantity can effectively regulate the proportion of car travel, reduce the saturation of urban road traffic, and improve the service quality of the bus.

This research work can help to analyze the influence of travel mode choice behavior on network traffic flow and promote the development of urban traffic demand management methods. In a future study, we intend to consider the influence of multi-user classes and multi-vehicle types on the travel mode choice, the dynamic adjustment mechanism of the fuel tax rate and bus departure quantity.

Data Availability

The data used to support the findings of this study have been deposited in the [program] repository ([https://figshare.com/account/home#/projects/65102]).

Conflicts of Interest

The authors declare that there is no conflicts of interest.

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References

[1] O. Behat and S. Bekhor, "Incorporating ridesharing in the static traffic assignment model," *Networks and Spatial Economics*, vol. 16, no. 4, pp. 1125–1149, 2016.

[2] K. Uchida, A. Sumalee, D. Watling, and R. Connors, "A study on network design problems for multi-modal networks by probit-based stochastic user equilibrium," *Networks and Spatial Economics*, vol. 7, no. 3, pp. 213–240, 2007.

[3] S. An, Z. Wang, and J. X. Cui, "Integrating regret psychology to travel mode choice for a transit-oriented evacuation strategy," *Sustainability*, vol. 7, no. 7, pp. 8116–8131, 2015.

[4] X. Fu, W. H. K. Lam, and B. Y. Chen, "A reliability-based traffic assignment model for multi-modal transport network under demand uncertainty," *Journal of Advanced Transportation*, vol. 48, no. 1, pp. 66–85, 2014.

[5] X. W. Li and H. Yang, "Dynamics of modal choice of heterogeneous travelers with responsive transit services," *Transportation Research Part C: Emerging Technologies*, vol. 68, pp. 333–349, 2016.

[6] R. Y. Guo and W. Y. Szeto, "Day-to-day modal choice with a pareto improvement or zero-sum revenue scheme," *Transportation Research Part B: Methodological*, vol. 110, pp. 1–25, 2018.

[7] Z. Liu, R. Li, X. Wang, and P. Shang, "Effects of vehicle restriction policies: analysis using license plate recognition data in Langfang, China," *Transportation Research Part A: Policy and Practice*, vol. 118, pp. 89–103, 2018.

[8] R. Ramos, V. Cantillo, J. Arellana, and L. Sarmiento, "From restricting the use of cars by license plate numbers to congestion charging: analysis for Medellin, Colombia," *Transport Policy*, vol. 60, pp. 119–130, 2017.

[9] Z. Mei, Q. Lou, W. Zhang, L. Zhang, and F. Shi, "Modelling the effects of parking charge and supply policy using system dynamics method," *Journal of Advanced Transportation*, vol. 2017, Article ID 6463586, 10 pages, 2017.

[10] P. Qin, X. Zheng, and L. Wang, "Travel mode choice and impact of fuel tax in Beijing," *Environment and Development Economics*, vol. 19, no. 1, pp. 92–110, 2014.

[11] M. Gupta, K. R. Bandyopadhyay, and S. K. Singh, "Measuring effectiveness of carbon tax on Indian road passenger transport: a system dynamics approach," *Energy Economics*, vol. 81, pp. 341–354, 2019.

[12] R. Ma and H. M. Zhang, "The morning commute problem with ridesharing and dynamic parking charges," *Transportation Research Part B: Methodological*, vol. 106, pp. 345–374, 2017.

[13] W. Zhang, R. He, Y. Chen, M. Gao, and C. Ma, "Research on taxi pricing model and optimization for carpooling detour problem," *Journal of Advanced Transportation*, vol. 2019, Article ID 3867874, 11 pages, 2019.

[14] X. Gong, G. Currie, Z. Liu, and X. Guo, "A disaggregate study of urban rail transit feeder transfer penalties including weather effects," *Transportation*, vol. 45, no. 5, pp. 1319–1349, 2017.

[15] X. Yang, A. Chen, B. Ning, and T. Tang, "Measuring route diversity for urban rail transit networks: a case study of the Beijing metro network," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 2, pp. 259–268, 2017.

[16] R. Jiang, Q. C. Lu, and Z. R. Peng, "A station-based rail transit network vulnerability measure considering land use dependency," *Journal of Transport Geography*, vol. 66, pp. 10–18, 2018.

[17] B. Yu, L. Kong, Y. Sun, B. Yao, and Z. Gao, "A bi-level programming for bus lane network design," *Transportation Research Part C: Emerging Technologies*, vol. 55, pp. 310–327, 2015.

[18] B. Si, M. Zhong, X. Yang, and Z. Gao, "Bi-level programming model for exclusive bus lanes configuration in multimodal traffic network," *Transportation Research Procedia*, vol. 25, pp. 652–663, 2017.

[19] J. Zhao and X. Zhou, "Improving the operational efficiency of buses with dynamic use of exclusive bus lane at isolated intersections," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 2, pp. 642–653, 2018.

[20] J. Liang, J. Wu, Z. Gao, H. Sun, X. Yang, and H. K. Lo, "Bus transit network design with uncertainties on the basis of a metro network: a two-step model framework," *Transportation Research Part B: Methodological*, vol. 126, pp. 115–138, 2019.

[21] X. Zuo, C. Chen, W. Tan, and M. Zhou, "Vehicle scheduling of an urban bus line via an improved multiobjective genetic algorithm," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 2, pp. 1030–1041, 2014.

[22] Q. Chen, "Global optimization for bus line timetable setting problem," *Discrete Dynamics in Nature and Society*, vol. 2014, Article ID 636937, 9 pages, 2014.

[23] K. Gkiotsalitis and F. Alesiani, "Robust timetable optimization for bus lines subject to resource and regulatory constraints," *Transportation Research Part E: Logistics and Transportation Review*, vol. 128, pp. 30–51, 2019.

[24] C. Tang, A. Ceder, and Y. Ge, "Integrated optimization of bus line fare and operational strategies using elastic demand," *Journal of Advanced Transportation*, vol. 2017, Article ID 7058789, 15 pages, 2017.

[25] Z. Liu, K. Li, and Y. Ni, "Optimization of bus stops layout under the conditions of coordinated control," *Transportation Research Procedia*, vol. 25, pp. 1585–1596, 2017.

[26] A. Khattak, Y. Jiang, and A. Hussain, "Design of passengers' circulation areas at the transfer station: an automated hybrid

simulation-differential evolution framework," *Simulation Modelling Practice and Theory*, vol. 87, pp. 293–310, 2018.

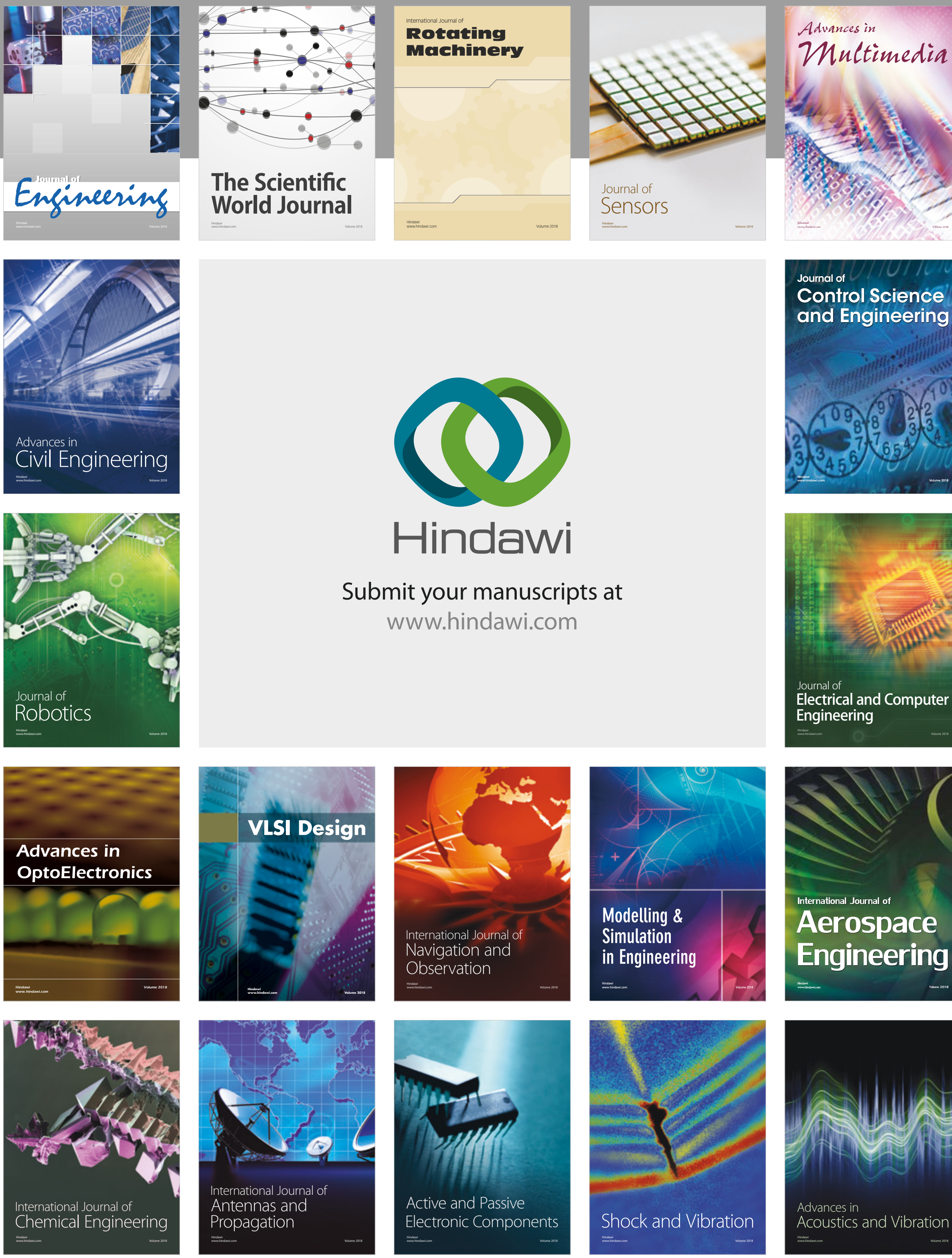
[27] A. R. Sancha, J. M. Mayoral, and L. I. Román, "A novel approach for transit transfer stations design optimization in densely populated cities," *Procedia Computer Science*, vol. 130, pp. 1013–1018, 2018.

[28] P. B. Goodwin, "The rule of three: a possible solution to the political problem of competing objectives for road pricing," *Traffic Engineering and Control*, vol. 30, no. 10, pp. 286–289, 1989.

[29] S. X. Xu, T. L. Liu, and H. J. Huang, "Transit pricing and redistribution of toll revenue with user heterogeneity," *Systems Engineering-Theory and Practice*, vol. 35, no. 7, pp. 1791–1799, 2015.

[30] Z. X. Huang, J. H. Wu, R. Q. Huang, and Y. Xu, "Network traffic flow evolution model based on disequilibrium theory," *Mathematical Problems in Engineering*, vol. 2018, Article ID 8478910, 10 pages, 2018.

[31] R. B. Dial, "A probabilistic multipath traffic assignment model which obviates path enumeration," *Transportation Research*, vol. 5, no. 2, pp. 83–111, 1971.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