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# A Simulation-Based Approach for Sustainable Transportation Systems Evaluation and Optimization: Theory, Systematic Framework and Applications

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## Abstract

Diverse strategies have been proposed and implemented to relieve increasingly serious urban transportation problems. How to evaluate and optimize combined strategies to increase sustainability and improve efficiency of multimodal transportation systems is still a great challenge. This paper proposes a simulation-based systematic framework for sustainable transportation systems evaluation and optimization. Simulation-based optimization (SBO) is incorporated to seek an optimal combination of transportation planning and operations strategies, e.g. congestion pricing for private cars, bus and rail fares, to minimize generalized costs of multimodal traveling in a heuristic way. Applications in a small network of Tianjin Eco-city with multimodal travelers demonstrate the feasibility and applicability of the SBO approach in sustainable transportation systems evaluation and optimization. The objective is to reduce multimodal travel costs subject to a minimum mode share of green transportation. The SBO process also validates that the efficiency of each strategy may be influenced by the strengths of other strategies.

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*Keywords:* Simulation-based optimization (SBO); sustainable transportation; congestion toll; bus fare; rail fare

## 1. Introduction

Multimodal transportation systems are some of the most complex systems that involve millions of travelers, massive network infrastructure and different traveling modes, e.g. private car, bus, rail, bicycle and walk.

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Travelers with heterogeneous characteristics interact in both temporal and spatial dimensions. The complexity also lays on interactions among various transportation modes when we evaluate certain strategies in terms of transportation policy, planning, management and operations. One example is that an increased congestion toll may transfer some private car users who are sensitive to road pricing to other modes. In reaction to traffic congestion, travelers can adjust route, departure time, mode, and/or destination to better achieve personal objectives (e.g. arriving at work in time, making grocery shopping, etc.). Changes in individual travel decisions can then alter the global travel demand pattern in a transportation system, triggering further shifts in individual decisions. In the long term, the emergent travel demand pattern can influence pricing strategies of road operators, network investment decisions of the government, and shift economic activities.

Although there is no standard definition of transportation system sustainability (Jeon & Amekudzi, 2005), it is widely accepted that sustainable transportation systems imply balancing current and future economic development, social qualities and environmental preservation (Shiftan, Kaplan, & Hakkert, 2003; Steg & Gifford, 2005), some externalities of transportation systems significantly impact on vast aspects, including energy, land use, traffic safety, accessibility and economic development. Many initiatives were conducted to develop appropriate indicators for measuring sustainability of transportation systems, e.g. USDOT (2003) set up five strategic goals covering safety, mobility, economic growth and trade, human and natural environment, and national security. Sustainable transportation systems can be maintained by reducing the number of transportation-related pollutants and greenhouse gases released, and improving the sustainability and livability of communities through investments in transportation facilities, especially for transit priority systems, green transportation system and environmentally friendly non-motorized traffic.

In the past three decades, with the rapid economic development, accelerated pace of urbanization, rapidly increasing vehicle ownership, and fast growing travel demands, China's urban transportation systems emerge a serious imbalance between transportation supply and demand. Consequently, it leads to heavy daily traffic congestion, rising accident rates and universally declined speed. Take Beijing as an example, in July 2012, the vehicle ownership had reached 5.12 million, the average travel speed at peak hours was only approximately 20 km/h. To solve urban traffic problems, in addition to efforts in planning and operations (such as public transit planning and signal control system design), integrated/combined strategies are carried out, e.g. congestion pricing and parking fee, vehicle ownership and usage rationing, low or zero bus transit fare. How to evaluate and optimize the combined strategies is still a great challenge because they cover different levels of initiatives such as transportation planning schemes and traffic operations and management. Previously, evaluation and optimization of a certain strategy were considered and implemented separately. To the authors' knowledge, at present, detailed analysis and optimization of various combined strategies in terms of transportation planning and operations to increase the efficiency or decrease social costs of multimodal sustainable transportation systems are seldom studied in literature. The simulation-based optimization (SBO) approach is a powerful tool to fill the gaps aforementioned.

Multimodal sustainable transportation systems are characterized with the following features:

- 1) Travelers' lack of comprehensive understanding of the internal rules in the systems, such that sometimes people can only regard it as a black box;
- 2) The performance of a multimodal sustainable transportation system is a function of many relevant factors, whose implicit relationships are still not fully revealed. In this case, the objective function is hard to be formulated nor optimized in an analytical way;
- 3) Multimodal sustainable transportation systems are of great uncertainty and randomness, thus the only evaluation way may be simulation experiments.

With these features, we could say that the optimization of multimodal sustainable transportation systems plays into SBO's hand (Wang, 2008). Although some recent studies realized the value of SBO in transportation, they mainly focused on the optimization of signal control system and network (Osorio & Bierlaire, 2009, 2010). This

paper could be the first time that SBO was used in combined strategies optimization for multimodal sustainable transportation systems.

The primary objective of this paper is to propose a simulation-based approach for sustainable transportation systems evaluation and optimization, discuss the systematic framework and then try to seek optimal combination of transportation planning and operations strategies (e.g. congestion pricing for private cars, bus and rail fares) that minimize generalized costs of multimodal traveling. The feasibility and applicability of simulation-based optimization approach to this problem will be discussed as an initiative in detail. We will also validate that strategies not only affect the component cost (a certain mode) of the total cost but other parts of the system in an unexpected way, which was called *ripple effect* by Sheffi (1985).

This paper is organized as follows. *Section 2* mainly presents the literature review of simulation-based optimization and its applications in transportation issues, and some basic concepts that serve as theoretical foundation of the main content. *Section 3* proposes the systematic framework of sustainable transportation systems evaluation and optimization, then the relationship among four main modules (strategies, simulation, evaluation and optimization) in the framework will be addressed. *Section 4* provides a case study of multimodal transportation systems in a small road network to demonstrate how to seek the approximate optimal strategies by using the framework proposed in *Section 2*. Further discussions towards this case study will be shown in *section 5*. Finally, *Section 6* draws conclusions and points out the future research.

## 2. Literature Review

### 2.1. Simulation-Based Optimization (SBO) and its applications in transportation

SBO can be defined as a replicated analysis of the simulation model with different inputs, in an attempt to find out the best pre-defined system performance (Barton & Meckesheimer, 2006). According to this definition, two fundamental parts of SBO, i.e. *search* and *evaluation*, depend heavily on computational resources. To be more specific, how to make a practical allocation between *getting a better evaluation* versus *more iterations to explore the search space*, is a big challenge in SBO (Fu, 1994; Fu, 2002; Fu, Glover, & April, 2005). Fortunately, this challenge has been greatly mitigated due to the fast development of computer techniques. Applications of SBO have been widely discussed in many complex and random systems, such as:

- 1) Complex engineering system (e.g., power supply System, thermodynamic system, dynamic system, etc.);
- 2) Supply chain and logistics system;
- 3) Manufacturing system.

Simulation model is a very useful tool to study the issues in a complex system such as the transportation system with strong sociality (Osorio & Bierlaire, 2010). Travel behaviors, e.g. mode choice, route choice, departure time choice, are influenced by many social factors, so that the process is hard to describe and solve via definite mathematical models. Simulation model provides additional insights when we can't formulate a problem mathematically (Barton, Meckesheimer, 2006; Batz, 2007).

Traffic simulation models can be categorized in three levels: microscopic simulation, mesoscopic simulation and macroscopic simulation. Microscopic model studies individual travel behaviors, where detailed survey data are used to form agent-based traveling demand and assignment model. At this level, even a detailed lane changing behavior could be tracked. While macroscopic model uses integrated data to calculate OD matrix, assign traveling modes and routes. At this level, we are not quite able to trace detailed choice of an individual. Mesoscopic model can provide more information than macroscopic model in some aspects but not as detailed as microscopic model.

Transportation system shares analogical uncertainty and randomness with these complex and random systems aforementioned. Complexity of network traffic flow makes simulation models a proper tool of evaluate the detailed performance of various inputs. Osorio and Bierlaire (2009, 2010) solved a fixed-time signal control

problem for a sub-network in the city of Lausanne using a metamodel algorithm. Bai and He (2007) promoted a BRT network based on Tabu search algorithm. However, applications of SBO in transportation have been rarely explored in this domain. Our work aims to explore more transportation problems that can be handled by simulation-based optimization algorithms to fill the gap of few applications in transportation planning and operations.

Despite of the advantages aforementioned, SBO is regarded as a difficult task, especially its integration with an optimizer. Indeed, a simulator can be regarded as an implicit, stochastic, nonlinear and non-continuous black box. In addition, the number of inputs may be very large, including both discrete and continuous variables (Osorio & Bierlaire, 2009; Kleijnen, 2008). Many traditional optimization algorithms are no longer applicable to a highly nonlinear and complicated system like sustainable transportation systems.

Currently, different algorithms have been explored for a variety of SBO problems. For discrete problems, we have Ranking & Selection, Random Search, Branch & Bound, etc. For Continuous problems, we have Stochastic Approximation (SA), Sample Path Algorithm (SPA) and a series of metamodel methods including Response Surface Method (RSM), Regression Spline, Neural Network, etc. Also many algorithms are favored because they can handle both discrete and continuous problems, including a series of metaheuristics algorithms, e.g. Tabu Search (TS), Simulated Annealing (SA), Genetic Algorithm (GA), Scatter Search (SS), Particle Swarm Optimization (PSO), etc. Recently, Ordinal Optimization (OO) is also a hot algorithm recently due to its high efficiency (Ho, Zhao, & Jia, 2007).

## 2.2. Measurements of performance: generalized cost

The proposal of Generalized Cost (GC) for an individual traveler is based on the demand of evaluating the networks' comprehensive quality of service. Evaluation of quality of service always includes travel distance, travel time, travel speed, comfort level, travel cost, etc. The comprehensive evaluation of these components can necessarily reduce the chance of making a partial judgment. Modesti and Sciomachen (1998) proposed a utility-based multi-modal GC analysis. Lozano and Storchi (2001) continued this study and proposed a utility measurement for finding the shortest path in urban multimodal transportation network. Generally speaking, GC is composed of the following parts (Huang, 2008), see Fig. 1.

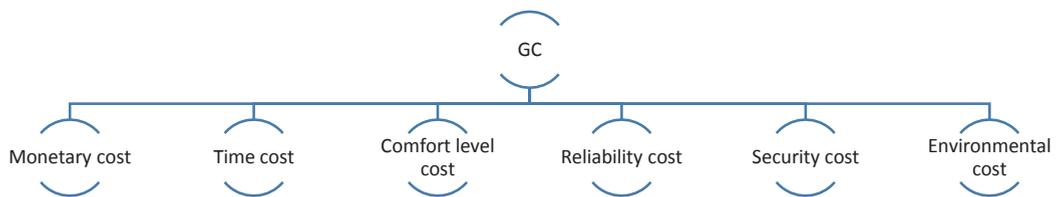


Fig. 1. Generalized cost composition

It's worth mentioning that comfort level of a trip includes many dimensions, e.g. degree of crowdedness, comfort level of a seat, traveling speed, installation of air-conditioner, etc. TCRP (2003) proposed a quantitative analysis of degree of crowdedness in public transit service. Bai (2007) introduced this analysis to China. However, few studies gave quantitative analysis of the other part of comfort level in literature. Studies of reliability cost, security cost, and environmental cost are still in a preliminary process and lack quantitative analysis in the background of China.

### 3. Modeling Framework

As shown in the right of Fig. 2, the process of policy making may include concerns of different-level strategies, with respect of transportation policy and planning, traffic management and control. However, strategies of different levels are always implemented separately. We believe the key to improve the efficiency of sustainable transportation systems is to optimally synthesize and coordinate diverse strategies in a multi-dimensional optimization.

Individual mode choice is based on the mode-specific characteristics, e.g. individual social characteristic and trip characteristics, as shown in the left of Fig. 3. With the fast economic development, private car is getting more and more competitive compared to other sustainable modes. Combined strategies that would change travelers' choice behaviors would guide towards better transportation environment and traffic conditions. Therefore, to obtain optimum combined strategies is of practical significance.

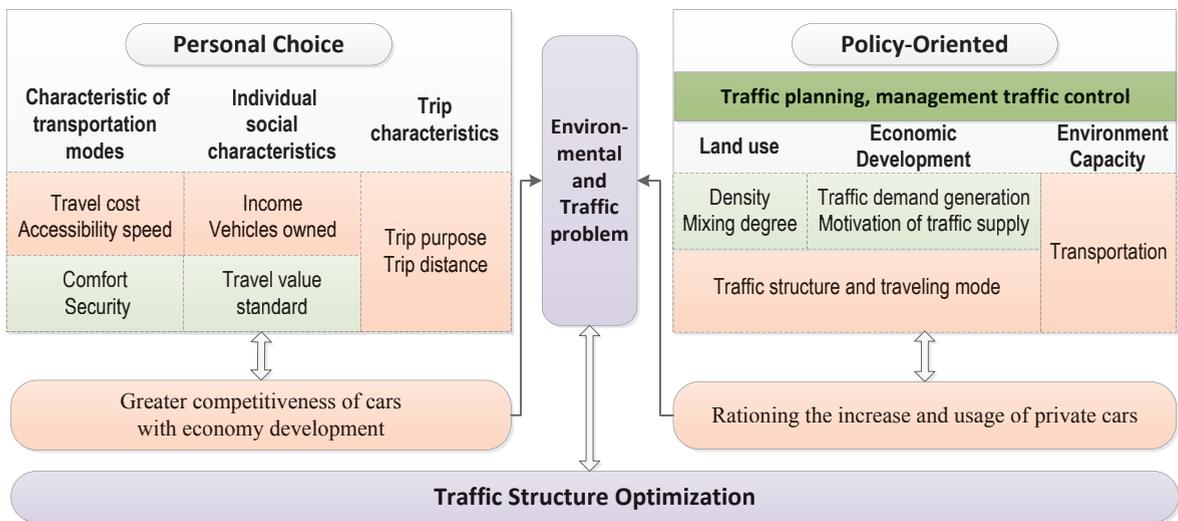


Fig. 2. The influence on traffic structure caused by individual behavior and macro strategies

A systematic framework of the simulation-based optimization approach for sustainable transportation systems is proposed in Fig. 3. There are four main modal: strategy, simulation, evaluation, and optimization. The strategy modal contains abundant sets of strategies to solve transportation and traffic problems in terms of planning and operations. The simulation modal is a description of the transportation network, including infrastructure, travelers, cars and transit. The modal is capable of simulating various traffic conditions under different strategies. The evaluation modal is the judgment of a solution based on the simulation output including such as network conditions and multi-modal transportation shares. The optimization modal is to search the optimum strategies in the choice set based on the evaluation of strategies. The objective of the SBO model is to obtain the feasible optimal strategies and other relevant analysis.

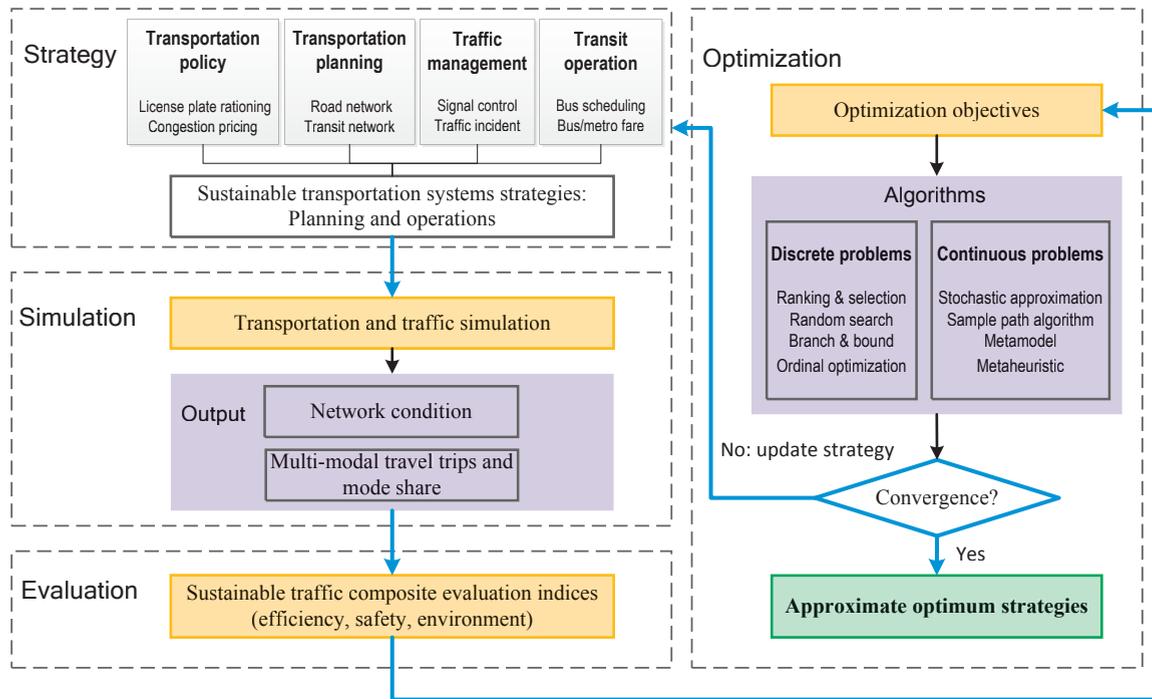


Fig. 3. A systematic framework of simulation-based approach for sustainable transportation systems evaluation and optimization

## 4. Case Study

### 4.1. Simulation road network

In this section, we study a small road network for the multi-modal transportation system analysis. Fig. 4 shows the network of roads. We define an area with 139 TAZs, each size of which is about 400 m\*400 m. The roads in the area are assumed to be 4-lane two-way. It is worth noting that we set 6 more TAZs as external traffic zones. The economy, population and other social parameters are adopted from Tianjin Eco-city. The strategy set contains bus fare, rail fare and congestion toll of private cars. We try to get the optimum combined strategies to achieve minimum generalized social traveling costs subject to that green mode shares (bus, rail, bike and walk) are greater than 75%. We will demonstrate how to apply the systematic SBO framework proposed in Section 3 in this multi-modal transportation systems to achieve sustainable objectives in both qualitative and quantitative ways.

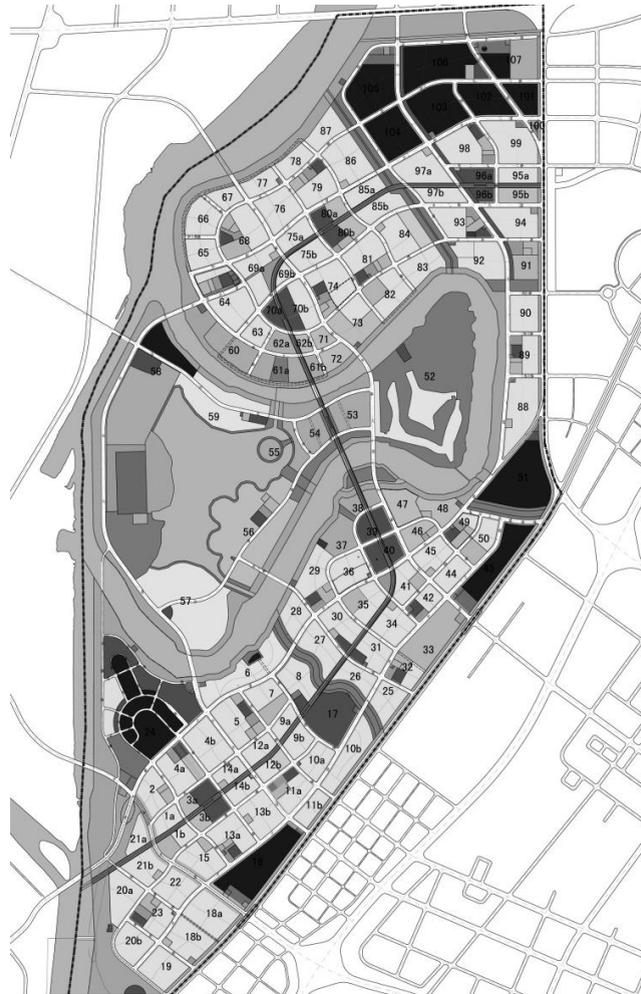


Fig. 4. Study network layout

#### 4.2. Sustainable transportation systems formulation

To formulate this problem, the following symbols, variables, and parameters are first introduced.

##### Nomenclature

Decision variables:

$Tf_1$  bus fare, choice set is [0.2, 3] RMB/trip

$Tf_2$  rail fare, choice set is [1, 6] RMB/trip

$Ct$  congestion toll for private cars, choice set is [0.2, 2] RMB/km

Subscripts and sets:

$I$	set of total trips travelled
$U$	set of different bus routes
$V$	set of different rail routes
$bs \in I$	trips by bus
$r \in I$	trips by rail
$c \in I$	trips by private car
$bk \in I$	trips by bike
$w \in I$	trips on foot
$u \in I$	routes of bus
$v \in I$	routes of rail
Input parameters:	
$Vot_i$	time value of passengers by the $i$ th mode, e.g. bus, rail, private cars, bike and foot
$Ccr$	crowdedness cost rate of public transit
$Umo_i$	unit mileage overhead of the $i$ th mode, e.g. bus, rail and private cars
Outputs from the simulation model:	
$D$	distance traveled in a certain trip
$T$	time traveled in a certain trip

Based on the notation, the following objective can be formulated:

$$\begin{aligned}
 \min \quad & \text{UserCost}_{bs} + \text{UserCost}_r + \text{UserCost}_c + \text{UserCost}_{bk} + \text{UserCost}_w \\
 = \quad & \sum_{bs} (Vot_1 \times T_{bs} + Ccr \times D_{bs}) + \sum_r (Vot_2 \times T_r + Ccr \times D_r) + \sum_c [Umo_3 \times D_c + Vot_3 \times T_c] \\
 & + \sum_{bk} (Vot_4 \times T_{bk}) + \sum_w (Vot_5 \times T_w) \quad (1)
 \end{aligned}$$

Subject to

$$(bs + r + bk + w) / (bs + r + c + bk + w) \times 100\% > 75\% \quad (2)$$

In this simple case, we chose three decision variables: bus fare, rail fare, and car congestion toll, to find out the best combination of the three strategies. Our objective is to minimize the generalized costs for travelers ( $\text{UserCost}_{bs}$ ,  $\text{UserCost}_r$ ,  $\text{UserCost}_c$ ,  $\text{UserCost}_{bk}$  and  $\text{UserCost}_w$  are for travelers by bus, rail, private car, bike and on foot, respectively). At the same time, it maximizes total travel efficiency with certain traffic demand and it considers the change of service levels for multimodal transportation generalized costs (travel time, in-vehicle congestion cost). The constraint shows our wishes to keep percentage sharing among different modes to be rational. To put it in another way, we hope green traveling shares could be greater than 75% in the sustainable transportation systems. Although the decision variables are not directly reflected in the objective function, the

transportation simulation fully considers these variables, which affects mode shares. So the decision variables indirectly affect the objective function.

The coefficients in the objective function are listed in Table 1. Value of time of each mode is estimated by using a conversion rate of per capita GDP. Readers may refer to (Zhao et al., 2009; Zhang, Zhao, & Tian, 2012) for more details. Estimate of the unit mileage overhead for private car is calculated as the life cycle cost divided by its total mileage. Estimate of unit mileage overhead for bus and rail include additional operation cost like operator's salary. Bai (2007) introduced crowdedness cost rate for China's scenario and estimated  $Ccr$  by an interpolation.

Table 1. Setting of input parameters

$Vot_1$	$Vot_2$	$Vot_3$	$Vot_{4,5}$	$Umo_3$
RMB/hour	RMB/hour	RMB/hour	RMB/hour	RMB/km
9.40	18.23	31.79	9	1.7

### 4.3. Simulation model

The transportation simulation model conducts travel distribution, mode choice and traffic assignment with a certain amount of traffic demand, and finally it gives the traffic states on the road network under specific strategies. In this case, we select VISUM as the simulation model. As one of leading software programs for transportation analyses and travel demand forecasting worldwide, it can simulate and calculate various network parameters (such as ODs of different modes, trip time and trip distance, etc.) which are needed in the measurements of performance in the evaluation modal, supporting decision makers and transportation planners to develop appropriate measures and determine their benefits, effects and impacts.

It's well known that there could always be an alternative-specific constant in the random utility function, reflecting a relative preference for each mode (Ben-Akiva & Lerman, 1985). This preference may include individual concern about safety, comfort level, etc. The opposite concept of utility is impedance. The higher this *constant value* is, the more impedance it contributes to and the fewer people are likely to choose it. The *constant value* plays an important in macroscopic simulations. It can be calibrated via SP/RP household travel survey.

### 4.4. SBO algorithm

In this optimization modal, we chose Genetic Algorithm (GA) as the optimizer. It takes advantage of Darwin's evolutionary theory, a parent candidate solution with a higher pre-defined fitness will be chosen with a higher probability. After mutation and crossover within the chosen parent population, offspring population will be generated. Parent population and their offspring will form the new generation. GA preserves the elitism and converge quickly, thus it's our primary choice as an optimizer in this study. Though GA may get easily entrapped in local optimum, we enlarge the population size and increase crossover and mutation possibility to get rid of local optimum within the computational budget, and in this article there are 10 iterations (generations) with 30 population in each generation.

#### 4.5. Results

We gained the optimum solution (0.2, 3.66, 2), representing a bus fare of 0.2 RMB/trip, a rail fare of 3.66 RMB/trip and a congestion toll charge rate of 2 RMB/km for private cars. The convergence process is illustrated in Fig. 5.

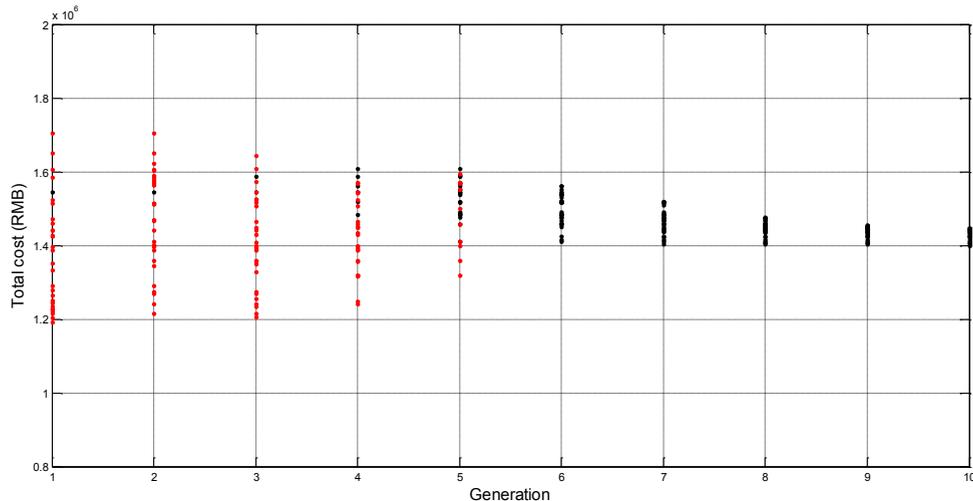


Fig. 5. Convergence process of the Genetic Algorithm

As shown in Fig. 5, there is an obvious trend of convergence when the generations increase. The objective range of feasible solution (black dots) in the first generation was from 1.45 to 1.65 million RMB, while it is almost totally around 1.4 million RMB in the last generation. We gained a good result with a good convergence rate. Final percentages shared among travel modes are 25% for private car, 37% for bus, 26% for real, 7% for bike, and 6% for walk. This structure of mode shares is reasonable for such a small transportation network.

In the next section, we will prove the rationality of our results with more evidence and validate the feasibility and applicability of the proposed SBO framework in sustainable transportation systems.

## 5. Discussions

### 5.1. Correctness of optimization

Fig. 6 shows that when one decision variable is settled, the other two variables found by the optimizer are correct. Fig. 6(a) shows when the bus fare is settled at 0.2 RMB/trip, the optimum solution is (0.2, 6, 0.2), which seems to have violated the solution found by our optimizer, i.e. (0.2, 3.66, 2). This is because when private car congestion toll charge is 0, the violation of constraint would always exist. The only feasible region is the deep blue region in Fig. 6(b). Keep this in mind, we could check the corresponding region in Fig. 6(a) and find that (0.2, 3.66, 2) is truly the optimum feasible solution. The same illustration goes when the other two variables are settled, and is omitted in this paper.

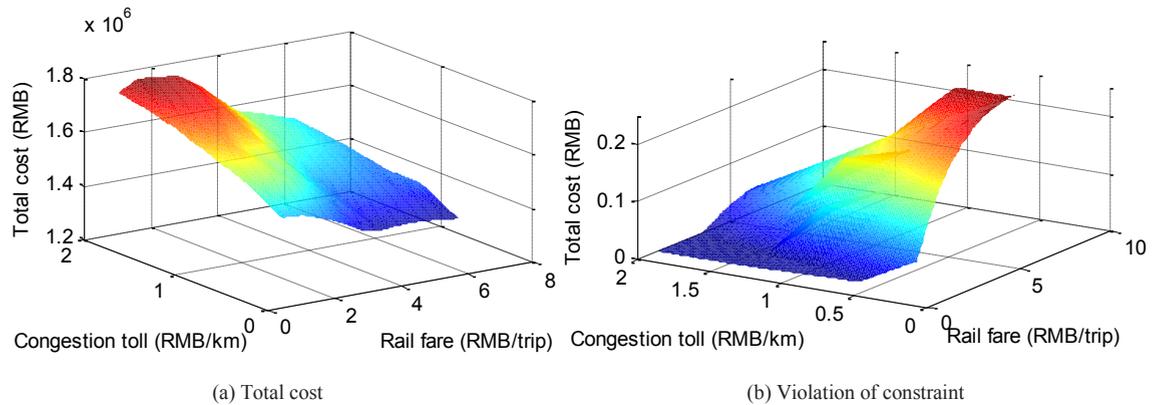


Fig. 6. Total cost sensitivity of joint private cars congestion toll and the violation of constraint.

### 5.2. Constant value effects

In the experiments, it is interesting that the optimum result is very sensitive to how much people would like/dislike biking and walking. For simplicity, we call the relative “alternative-specific constant” of non-motorized modes as the “C value” (see Section 4.3 for its meaning), so as to distinguish that of motorized modes. Here “C value” is an important input parameter in the traveling impedance of simulation. We studied the optimum solutions varying with different “C”, and how “C” influenced the total generalized cost curves.

When C is big enough, the optimal solution has the lowest ticket prices of bus and rail, and lowest car congestion fare. It’s easy to understand because with big non-motorized traffic impedance, there is no chance to transfer the motorized traffic OD to non-motorized traffic OD, and the only way to reduce total cost is to reduce the unit cost of each mode. When C is small enough, the optimal solution has the highest ticket prices of bus and rail, and highest car congestion fare. With small non-motorized traffic impedance and cost, it’s very easy to transfer the motorized traffic population to non-motorized traffic population by increasing unit cost of motorized modes to both satisfy the constraint and to decrease total cost.

From the varying of optimal results with different C, it’s obvious that the traffic environment for non-motorized modes is a key factor for reasonable policies. How to define the environment and how to make a quantitative evaluation of the environment is a valuable issue with further research that is out of the scope of this paper.

### 5.3. The relevance of strategies

Fig. 7 shows how the objective varies when one of the three decision variables changes with a certain rail fare and different car congestion toll. The decision variable is bus fare, the y-axis is the generalized total cost, and different curves represent different car congestion tolls. We could see that the curves were in similar shape but not simple up-and-down translational, because the slopes of different curves at the same bus fare are different. That’s to say, with different rail fares, the impacts of bus fare would vary accordingly. This declares that with different strengths of one specific strategy, another strategy would have different influences on traffic. So when optimizing strategies, we should consider the relevance among them by such sensitivity analyses. And that’s why a combination of strategies in our problem couldn’t be optimized independently but need a simulation-based optimization to consider them together.

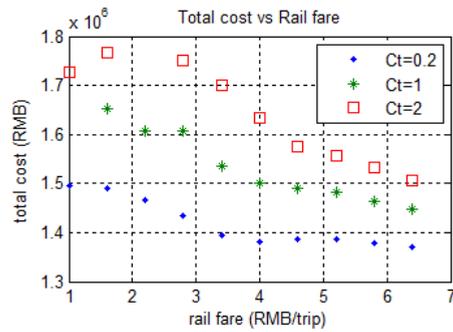


Fig. 7. Influences of private car congestion toll rates on total costs

## 6. Conclusion and Further Research

With serious traffic problems, sustainable urban transportation pattern has been the goal of improving. Solving traffic problem with SBO method which considers diverse strategies together, has been proved to be an effectively method. This paper proposes a simulation-based approach for sustainable transportation systems evaluation and optimization, discuss the systematic framework and then try to seek optimal combination of transportation planning and operations strategies (e.g. congestion pricing for private cars, bus and rail fares) that minimize generalized costs of multimodal traveling. The inner relevance contributes to combined strategies together. SBO method provides an approach to finding the optimal combined strategies via multimodal transportation simulation.

Applications of the SBO framework in solving traffic problem still meet some issues that should be explored further. For example, how to define the indicators which can't be quantized or how to quantize them is a valuable issue with further research. With strict parameter calibration and a real network of a bigger city, we expect to gain particular insights in this system through the process of SBO including our analysis above.

Although GA is a widely used algorithm and proved to output a valid optimum solution in our experiment, its computational efficiency is not that high. We look forward to trying more efficient algorithms (e.g. Ordinary Optimization, OO) and comparing the "relative efficiency" among different algorithms. We will also try to propose our own algorithms that can fit for this problem to the greatest extent. It's also our plan to formulate multi-objective optimization problems to obtain more comprehensive insights into sustainable transportation systems.

We leave some items in the objective function as future work that can perform a more complicated combination of strategies (e.g. headways of bus and rail may be selected as decision variables in the future study).

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