Journal of System Simulation

Volume 31 | Issue 11 Article 32

12-13-2019

Microscopic Simulation Based Evaluation of Congestion Pricing for Beijing Urban Area

Jingchen Dai
Department of Civil Engineering, Tsinghua University, Beijing 100084, China;

Ruimin Li
Department of Civil Engineering, Tsinghua University, Beijing 100084, China;

Microscopic Simulation Based Evaluation of Congestion Pricing for Beijing Urban Area

Abstract

Abstract: In order to study the potential effect of congestion charging policy in large-scale road network, a micro-simulation platform Paramics is used to establish a simulation model within Beijing fourth ring road. On this basis, *multiple congestion pricing scenarios are assessed in consideration of charging zones size, charging rate, and travel mode shift*. When the travel mode shift is put aside, the analysis shows that *selecting a larger charging zone is more effective on reducing vehicle kilometers of travel and may increase the total charge revenue. However, congestion pricing appears no potential to significantly affect the average speed of the entire network. Further, taking the travel mode shift into consideration, the speed of external area can be improved and the generalized cost is expected to reduce.*

Keywords

congestion pricing policy, microscopic simulation, traffic impact, large-scale network

Recommended Citation

Dai Jingchen, Li Ruimin. Microscopic Simulation Based Evaluation of Congestion Pricing for Beijing Urban Area[J]. Journal of System Simulation, 2019, 31(11): 2458-2470.

第 31 卷第 11 期 系统仿真学报© Vol. 31 No. 11
2019 年 11 月 Journal of System Simulation Nov., 2019

Microscopic Simulation Based Evaluation of Congestion Pricing for Beijing Urban Area

Dai Jingchen, *Li Ruimin*

(Department of Civil Engineering, Tsinghua University, Beijing 100084, China)

Abstract: In order to study the potential effect of congestion charging policy in large-scale road network, a micro-simulation platform Paramics is used to establish a simulation model within Beijing fourth ring road. On this basis, *multiple congestion pricing scenarios are assessed in consideration of charging zones size, charging rate, and travel mode shift*. When the travel mode shift is put aside, the analysis shows that *selecting a larger charging zone is more effective on reducing vehicle kilometers of travel and may increase the total charge revenue. However, congestion pricing appears no potential to significantly affect the average speed of the entire network. Further, taking the travel mode shift into consideration, the speed of external area can be improved and the generalized cost is expected to reduce.*

Keywords: congestion pricing policy; microscopic simulation; traffic impact; large-scale network

基于微观仿真的北京市拥堵收费研究

戴晶辰，李瑞敏

(清华大学土木工程系，北京 100084)

摘要：为了研究拥堵收费政策在大规模路网内应用的潜在效果，*利用微观仿真平台 Paramics 建立仿真模型，对北京市四环内不同收费区域大小、不同收费费率、不同交通方式分担下的多种拥堵收费方案进行评估。仿真结果表明，在不考虑交通方式转移时，选择较大的收费区域可以有效地减少车辆行驶里程并增加政策收入，但无法显著改善覆盖收费区域内外范围的整体路网的平均速度。当纳入交通方式分担的变化后，收费区外的平均速度会增加，广义成本也有望降低。*

关键词：拥堵收费；微观仿真；交通影响；大规模路网

中图分类号：TP391.9 文献标识码：A 文章编号：1004-731X (2019) 11-2458-13

DOI: 10.16182/j.issn1004731x.joss.19-FZ0278E

Introduction

With the continuous growth of the number of private vehicles, traffic congestion, environmental pollution and other negative effects gradually affect people's travel and life. To recover from a car-dominated development era, measures of traffic demand management (TDM) offer an opportunity to create cost-effective travel choice. Among various TDM strategies, congestion pricing is regarded as a direct and effective method, which has achieved good results around the world[1]. Congestion pricing means charging certain fees to road users in some heavily-trafficked areas during rush hours to alleviate

Received: 2019-05-20 Revised: 2019-07-03;
Fundation: National Key R&D Program of China (2018YFB1601000);
Biography: Dai Jingchen (1994-), female, Hubei, Ph.D, student, Research direction: traffic simulation and modeling.

urban traffic congestion. The idea of a “congestion charge” originated in Singapore in the 1970s. Since then, the applications of congestion pricing in London, Stockholm and Gothenburg have provided helpful references[2].

Considering the convenience, practicality and economy of the policy, cordon-based congestion pricing has been most widely used and studied[3]. When implementing it in other cities, due to insufficient infrastructure conditions and stressful public pressure, it is necessary to investigate all possible impacts of this policy in advance. Although most of the researches have analyzed the charging target, charging method and charging price, the study on the scale of the entire urbanized area of a city is still limited. The main challenges are complicated network structure, simplified assumptions, and limited computational capabilities. As traffic simulation method offers an alternative way to express the linkage of the roads and to evaluate the drivers’ response to charge fee, this paper elaborately constructs a 305 km^2 microscopic simulation platform in Beijing urban area to evaluate the effect of large-scale congestion charging. Taking the uncertainty of the policy into account, we explore the potential effects of cordon-based congestion pricing policies with different charging area, charging rate and travel mode split. In the process of route planning, the combined cost of travel time and charge rate is the selection criteria. And the dynamic traffic assignment model estimates drivers' route choices every two minute. Thus, the characteristic parameters of vehicle kilometers of travel (VKT), speed, generalized cost, and charge revenue inside and outside the charging area can be extracted and analyzed.

Instead of putting forward a brand new and seemingly optimal TDM methodology in theory, this paper focuses on the reaction and effectiveness of various congestion pricing policies in the actual large-scale road network, which is obviously of more practical and operational significance from a practitioner’s point of view. Thus, this paper is organized into four sections.

1 Congestion pricing

Since Pigou proposed a taxes on congested roads[4], the effect of different congestion charging policies has been broadly analyzed. Originally, mathematical programming was used to solve this problem, such as first-and second-best pricing models, and Vickrey’s bottleneck model. In this way, one or more system-wide indexes could be optimized to satisfy many equilibrium constraints simultaneously. With the improvement of theoretical basis and solution method, recent research direction has been extensive and close to reality. Traveler information provision[5], traffic mode-split[6], and variable traffic flow and user heterogeneity[7] have also been included in the problem.

Although mathematical methods can be reasonably explained in theoretical and hypothetical scenarios, there is still a lack of research that can be applied to real and large-scale road network. Since the changes of road network operation state after the implementation of this policy can be directly reflected in the simulated traffic model and since it has the advantages of economy, convenience and repeatability, traffic simulation methods gradually become typical approaches to assess the impact of congestion charging, which include macroscopic, mesoscopic, microscopic, and agent-based simulations. Emulating the toll scenarios requires an analysis of the drivers’ route choice principle, and

第 31 卷第 11 期 系统仿真学报 Vol. 31 No. 11
2019 年 11 月 Journal of System Simulation Nov., 2019

most of researches assume that the drivers will select the path with minimal generalized cost. Generally speaking, travel time cost and toll cost constitute the drivers' generalized cost. And the toll cost is usually converted into a measure of time units based on the value of time (VOT). At first, the studies assume single-class vehicle or road users with the same VOT for the sake of simplification[8]. Then, in order to consider heterogeneous users, different VOTs are assigned to discrete users classes for express various pricing evaluation and route choice[9].

While congestion pricing may impose a positive influence on route choice, it may also at the same time change the travel mode and departure time choice patterns. Kottenhoff and Brundell Freij[10] investigated the role of public transit (PT) in Stockholm congestion pricing. The results suggested that PT service was regarded as a viable alternative travel mode and a strong support for congestion pricing schemes. Further, Wu et al.[11] used the logit model to predict the choice between private car and PT. Based on traffic simulation and emissions calculation, they analyzed the traffic and environmental impact of thirteen congestion charging scenarios, and found that the level of PT service may be the greatest pushing hands for reducing emissions. Integrating trip scheduling, congestion pricing and travel time reliability in one model, Zhu et al.[12] confirmed that congestion pricing contributed to the regulation of travel demand and the decrease of random delay. Although existing studies can solve individual problem one by one, there is a lack of discussion covering a variety of possible change factors in congestion pricing, especially for large-scale road networks.

With respect to the consideration of route choice principle, dynamic traffic assignment, user heterogeneity, and travel mode shift, this study focuses on the urban area of Beijing surrounded by the 4th ring road. When comparing scenarios with different charging zones, charging rate and travel mode split, it provides traffic and policy insights of implementing an urban cordon-based congestion pricing scheme.

2 Methodology

By means of a popular microscopic traffic simulation software Paramics[13], we firstly establish and calibrate the urban area of Beijing surrounded by the 4th ring road. Paramics offers fast network construction, dynamic traffic assignment, and detailed output data. On this basis, the requirements of simulation studies for the large scale and multiple scenarios in this study can be met.

To explore the traffic impact of different congestion charging policies, two charging zones, four levels of price and travel mode transfer are considered. Through the concept of toll cost factor, charging price is converted into time units. Also, the market penetration of private cars and the proportion of people with different incomes are adjusted accordingly. Then, dynamic traffic assignment model estimates drivers' route choices every two minutes in terms of “generalized cost”. Finally, a total of thirteen scenarios are analyzed in terms of VKT, speed, generalized cost, and charge revenue inside and outside the charging area.

2.1 Model establishment and calibration

Beijing is chosen principally because it possesses a road network of appropriate size, clear hierarchy, and orderly structure. According to the Beijing traffic report of the first quarter of 2018 released by Amap, the average speed during peak hours is only 24.52 km/h. Meanwhile, traffic congestion is a quite phenomenon in this city downtown. Therefore, it is of practical significance to select the area within the fourth ring road of Beijing as the study area (Fig. 2).

As shown in Fig. 3(a), the established road network covers 305 km^2 land and has a total length of 1 681 km, which comprises 11 465 links, including expressways, major roads and minor roads. The structure of the road network includes physical and connectivity characteristics (Fig. 3(b)). The physical characteristics include specific position coordinates, geomorphological shapes, and traffic signs. The connectivity characteristics include lane connection and specific signal control schemes. The simulation network consists of 130 internal traffic analysis zones (TAZ) and 4 external TAZ. And the total traffic demand is 296,391 veh (Fig. 4), which is collected during the morning rush hours (07:00-08:00) in 2008

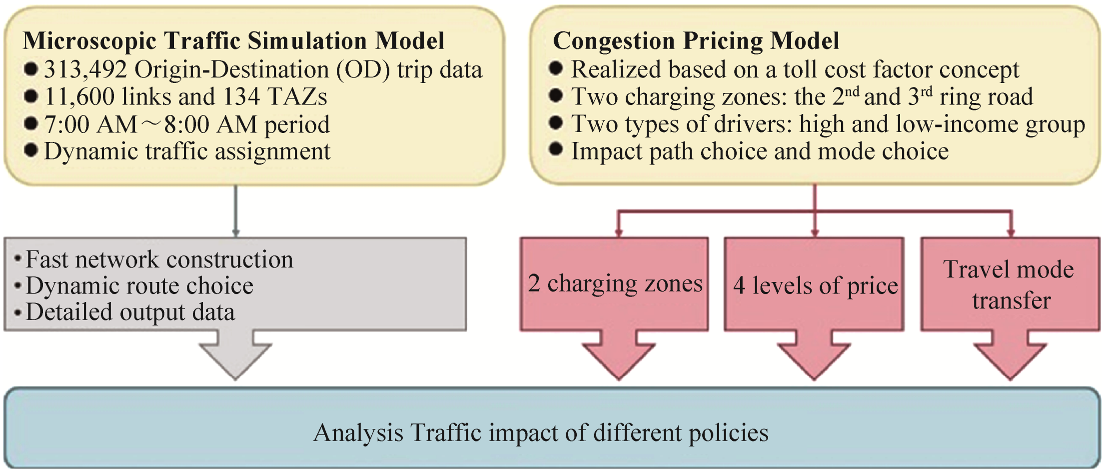


Fig. 1　Technology roadmap for assessing congestion charging policy

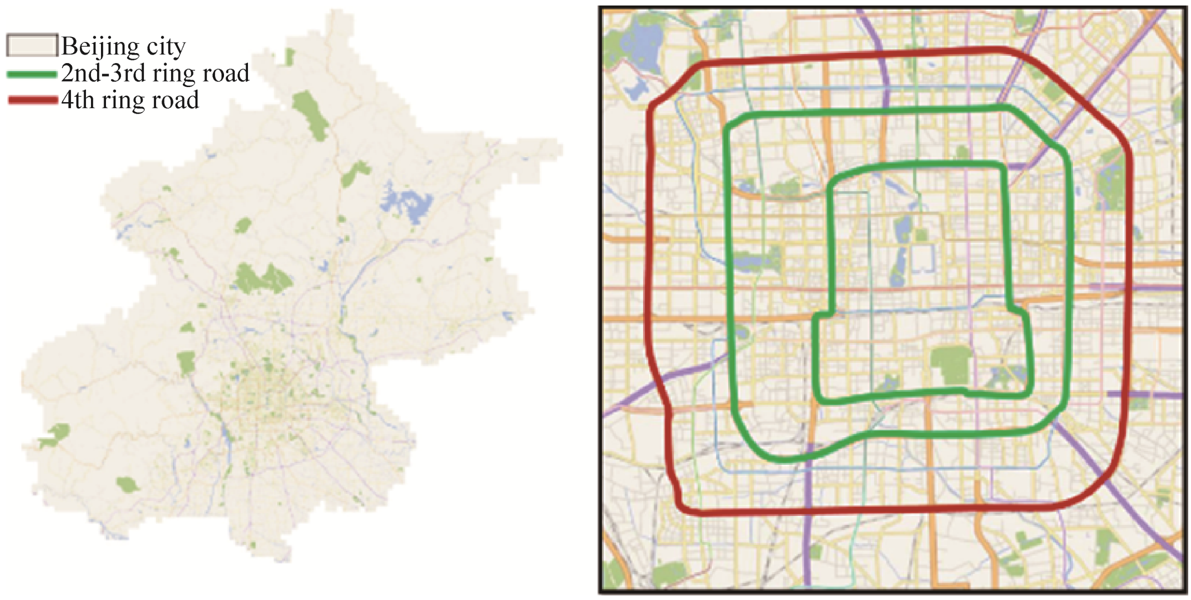
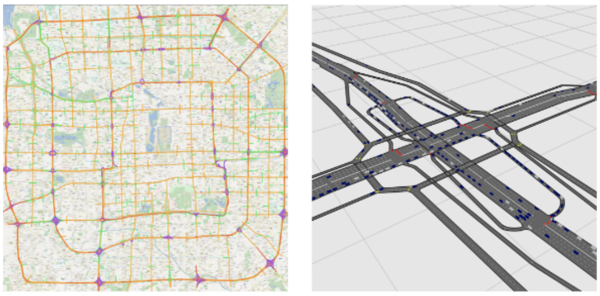


Fig. 2　Study area in Beijing#

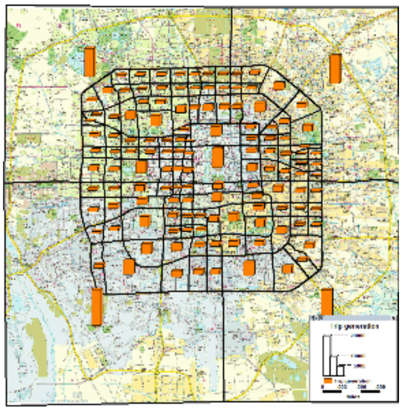
https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/32
DOI: 10.16182/j.issn1004731x.joss.19-FZ0278E

第 31 卷第 11 期　　系统仿真学报　　Vol. 31 No. 11
2019 年 11 月　　Journal of System Simulation　　Nov., 2019

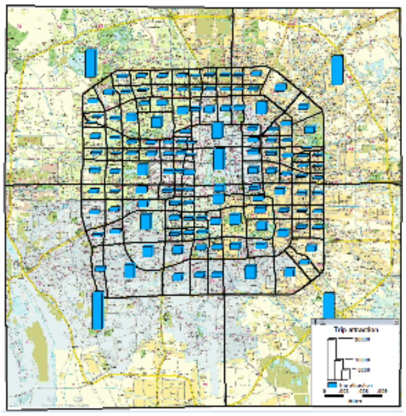


(a) Total road network diagram　　(b) Overpass diagram

Fig. 3　Snapshot of the simulation road network



(a) Trip generation



(b) Trip attraction

Fig. 4　Distribution of trip generation and attraction in simulation platform

Although Paramics comes with fewer parameters to be adjusted than other products, it is believed that the performance of car drivers depends on their aggressiveness and awareness. These two succinct and powerful factors have a major impact on drivers' behaviors, including gap acceptance, acceleration, maximum speed and so on, and they have proven to be sufficient to describe the behavior of most drivers[14]. During the simulation, the distribution of aggression and awareness between vehicle populations on the network defaults to normalization.

Besides, link characteristics are important prerequisites to ensure the simulation accuracy. For example, as shown in Fig. 5, when approaching the intersection or the end of the ramp, the headway that the driver can accept will decrease. Then, the headway factor of the regulated link is set to 0.5. Secondly, traffic signs will be placed on the road to remind drivers to choose the right lane. Therefore, the signpost distances are adjusted in accordance with the signpost location.

Fig. 5　Detailed adjustments in Paramics

Given that the traditional static traffic assignment is inadequate to reveal the time variant of the road network, the dynamic traffic assignment model is used[15]. To fully load the traffic demand on to the road network, the released traffic volume is counted and compared with the real OD matrices after each simulation. By modifying the link and driver characteristics for the sections with significant disparities, the average travel demand error is 7.6%, which is less than 10%. Accordingly, the model is deemed to be validated and the congestion pricing policies could be applied.

2.2 Study area and charging scenarios

In view of the real-world low-tech requirements and the expected benefits, the cordon-based congestion pricing implemented in Singapore is chosen, where drivers are charged for entering downtown (Fig. 6). This paper aims to study the effectiveness of different congestion pricing policies to alleviate traffic congestion. Results obtained through simulations will enable policymakers to better understand potential impact before implementing congestion pricing in any other city.

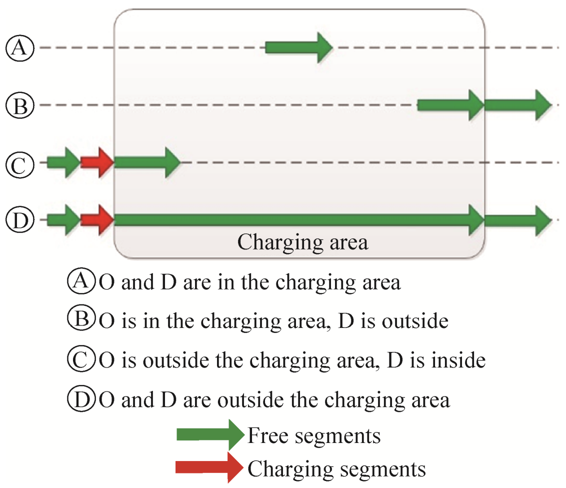


Fig. 6 Cordon-based traffic congestion pricing in simulation#

Charging zone, charging rate, and toll sensitivity are three important factors in congestion pricing policy. Traffic performance index (TPI) is referred to define the charging area as described in previous study[11]. The closer to the city center, the more prominent of traffic congestion problem. Therefore, the areas within the 2nd and 3rd ring roads are selected as the charging zones.

As for charging rate, the congestion price is converted into the time units by the concept of toll cost factor. Dynamic traffic assignment model estimates drivers' route choices every two minutes in terms of "generalized cost", a combination of time, distance, and toll cost. The generalized cost for links is calculated using the following equation.

$$GC = a \times T + b \times D + c \times P \times \beta$$

where GC is the generalized cost (s); a is the time coefficient; b is the distance coefficient; c is the toll coefficient; P is the toll cost factor; β is the toll sensitivity factor. The default values for a, b and c are 1, 0, and 1, respectively.

In view of the difference in sensitivity of various income groups to time value, drivers are divided into low- and high-income groups, which account for 70% and 30% of the total, respectively. And the toll sensitivity factors for the low- and high-income groups are 1 and 0.6, respectively.

To obtain a reasonable toll cost factor to simulate, this study applies some correlational results which study the congestion fees based on the real cities in China (Tab. 1). Taken the people's acceptance, per-capital GDP, and the hourly income level of Beijing residents[16] into account, the pricing standard of 5, 10, 15, and 20 yuan per entry are adopted.

The charging fee not only increases the cost of using private cars into the toll area, but also directly affects the mode choice. In the past, some scholars used questionnaires[26], disaggregate methods, random utility theory[27], cumulative prospect theory[28], and agent-based model[29] to study the impact of congestion pricing on travel modes and drew many useful conclusions. In reference to the existing research results[28-30], this paper could conclude the proportion of cars transferred to other traffic modes (Tab. 2) and the changed proportion of low-income and high-income drivers (Tab. 3) after the implementation of 2nd ring congestion pricing.

Finally, thirteen congestion pricing scenarios are established, including a reference scenario (no congestion pricing), eight pricing scenarios with two types of pricing zones and four levels of pricing rate, and four pricing scenarios with travel mode change (Tab. 4).

https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/32
DOI: 10.16182/j.issn1004731x.joss.19-FZ0278E

第 31 卷第 11 期 系统仿真学报 Vol. 31 No. 11
2019 年 11 月 Journal of System Simulation Nov., 2019

Tab. 1 Research results of congestion charging in some cities in China

Research city	Road-based charging method/ (yuan/link)	Distance-based charging method/ (yuan/km)	Cordon-based charging method/ (yuan/per entry)	Others charging method	Per-capital GDP (yuan/ person)
Chongqing [17]	2.14				57 904
Dalian [18]		0.746			97 470
Xi'an [19]	2, 5 or 8				71 647
Shijiazhuang [20]	7.3	0.8	7.3		54 526
Chengdu [21]			10		76 960
Beijing [22]			25		118 198
Beijing [23]				The area within the 2nd ring, the area between the 2nd ring and the 3rd ring, and the area between the 3rd ring and the 4th ring are 40, 30, and 20 yuan/h, respectively.	118 198
Beijing[24]				The base rate is 10 yuan and the floating rate varies between 0.04~0.25 yuan/km according to different emission standards.	118 198
Beijing[25]	The maximum rate is 10.02, and the lowest rate is 0.29.				118 198

Tab. 2 Transfer ratio of driver's travel mode

Charging fee/yuan	Low-income drivers/%	High-income drivers/%	Total/ %
5	19.0	6.0	15.1
10	33.0	14.0	27.3
15	46.0	21.0	38.5
20	54.0	27.0	45.9

Tab. 3 Proportion of low-income and high-income drivers

Charging fee/yuan	Low-income drivers/%	High-income drivers/%
0	70.0	30.0
5	66.8	33.2
10	64.5	35.5
15	61.5	38.5
20	59.5	40.5

Tab. 4 Description of scenarios

Scenario	Pricing zone	Charging rate/yuan	Change travel mode
1	No congestion charging	0	No
2	Area bounded by the 2nd ring road	5	No
3	Area bounded by the 2nd ring road	10	No
4	Area bounded by the 2nd ring road	15	No
5	Area bounded by the 2nd ring road	20	No
6	Area bounded by the 3rd ring road	5	No
7	Area bounded by the 3rd ring road	10	No
8	Area bounded by the 3rd ring road	15	No
9	Area bounded by the 3rd ring road	20	No
10	Area bounded by the 2nd ring road	5	Yes
11	Area bounded by the 2nd ring road	10	Yes
12	Area bounded by the 2nd ring road	15	Yes
13	Area bounded by the 2nd ring road	20	Yes

3 Results and discussions

This section provides the prospects of congestion pricing policy with different charging zones, charging rate, and travel mode. We perform 65 times simulations on 13 charging scenarios. The simulation time is the morning rush hours (07:00-08:00), and the simulation result is averaged after each output. The characteristic parameters of VKT, speed, generalized cost, and charge revenue inside and outside the charging area are extracted and analyzed.

3.1 Analysis of VKT changes

As shown in Fig. 7, the charging rate, charging area, and travel mode have a direct impact on the change of VKT. When the charging rate is 5 yuan, drivers' perception cost does not change greatly enough to change the path choice, which leads to a negligible VKT change in different scenarios. Though the VKT in the external area (the area outside the charging area) initially increases slightly as some drivers are sensitive to the prices, the overall VKT roughly shows a trend of decline. Also, the change of the internal area is more obvious than that of the external area. The greater change within the charging area comes from the improved traffic conditions and fewer vehicles entering.

In addition, the reduction of total VKT is more conspicuous in the large charging zone (Sc 8-9), which is about 2.1 times that of the smaller charging zone bounded by the 2nd ring road (Sc 4-5). This indicates that a larger charging zone is more effective at reducing VKT.

Moreover, when some travelers turn to other modes of transportation (Sc 10-13), the greater VKT reduction is accessible and reasonable. Nevertheless, the magnitude of VKT changes in each scenario is less than the corresponding transfer ratio of driver's travel mode; the effect of reduced private travel demand can only play half of the role at best. This discrepancy represents that congestion charging makes a real difference,and people are likely to change routes to reduce generalized costs despite the longer travel distance.

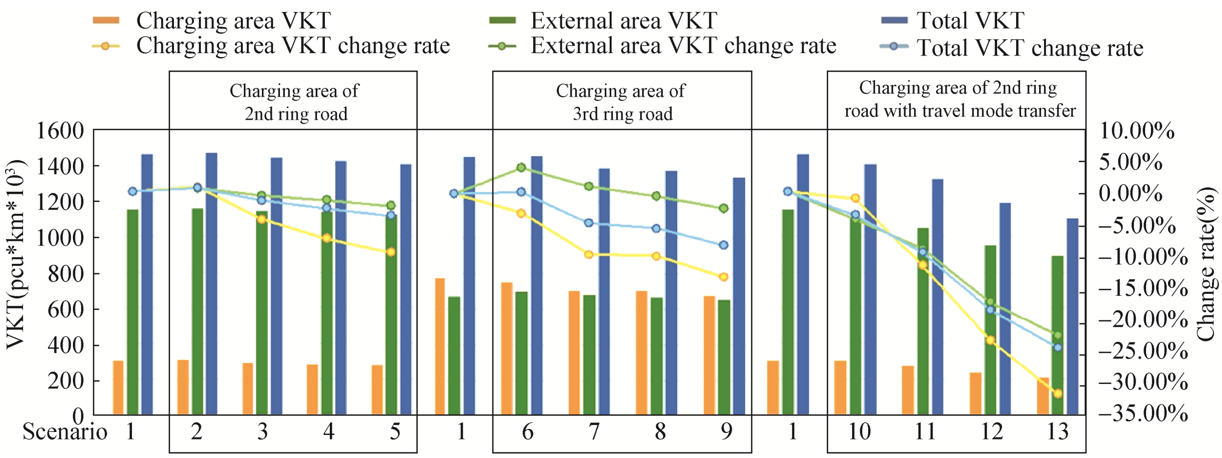


Fig. 7　VKT changes inside and outside the charging area in different scenarios

https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/32
DOI: 10.16182/j.issn1004731x.joss.19-FZ0278E

3.2 Analysis of speed change

Tab. 5 shows the results of speed changes in various grades roads inside and outside the charging area from 07:25 to 07:30. Obviously, the impact on average speed of the expressways is greater than that of the major and minor roads. In the simulation, the speed limits of expressway, major road, and minor road are 80 km/h, 60 km/h, and 40 km/h, respectively. The path choice principle takes an effect that drivers in the external area are apt to use high grade road once they are sensitive to charging rate. In other words, when the vehicles choose to bypass, there will be more traffic volume increase on the expressway than other roads in the external area.

Congestion pricing seemingly has an adverse effect in the external area but has a positive impact in the charging area. Combining these two effects, this policy appears no potential to significantly affect the average speed of the entire network. However, this phenomenon can be reversed when drivers shift their modes of travel. Compared Sc 10-13 with Sc 2-5, the increase of speed with the transfer of travel mode is about 2.63 to 4.98 times as much as that of constant traffic demand.

As seen from Fig. 8, the expansion of the charging area approximately reduces the speed improvement within the charging area by 20%~60% and exacerbates the traffic speed condition by20%~60% in the external area. The smaller the scope of the policy implementation, the less traffic attraction in the internal area and the more alternative routes for vehicles in the external area. Thus, the improvement in the toll area can become increasingly apparent. As for the deteriorating external areas, the vehicles have fewer roads to choose from outside the toll area than in reality and the changed traffic volume is not effectively managed given the incomplete network and unsuited signal timing scheme.

Tab. 5 Speed changes inside and outside the charging area

Area		Charging area			External area			Average
Road type		Expressway	Major road	Minor road	Expressway	Major road	Minor road	
Scenario 1 (cordon 2)	Speed/ (km/h)	37.94	24.98	19.41	46.28	29.23	21.62	31.58
Scenario 1 (cordon 3)		39.29	25.56	21.84	51.92	38.46	27.60	31.58
Scenario 2	Change rate	3.05%	1.96%	5.40%	–4.73%	0.42%	–0.54%	-0.08%
Scenario 3		9.87%	2.41%	5.94%	–6.52%	–1.26%	–2.89%	-0.76%
Scenario 4		16.88%	3.37%	8.56%	–3.76%	–2.86%	–3.80%	0.82%
Scenario 5		17.44%	4.16%	8.74%	–4.24%	–1.92%	–3.29%	0.61%
Scenario 6		6.18%	1.81%	2.29%	–4.92%	–2.65%	0.60%	0.65%
Scenario 7		9.04%	3.35%	4.02%	–5.47%	–2.16%	–2.27%	2.96%
Scenario 8		9.52%	3.27%	3.54%	–7.12%	–4.40%	–1.95%	1.36%
Scenario 9		12.53%	3.83%	2.29%	–9.43%	–4.14%	–3.22%	0.19%
Scenario 10		15.21%	7.79%	8.77%	0.10%	4.21%	1.51%	4.42%
Scenario 11		36.05%	13.51%	12.05%	6.34%	6.63%	6.20%	10.28%
Scenario 12		44.42%	18.94%	15.60%	16.63%	11.63%	11.25%	16.67%
Scenario 13		48.09%	20.99%	18.51%	22.17%	13.07%	13.13%	19.54%

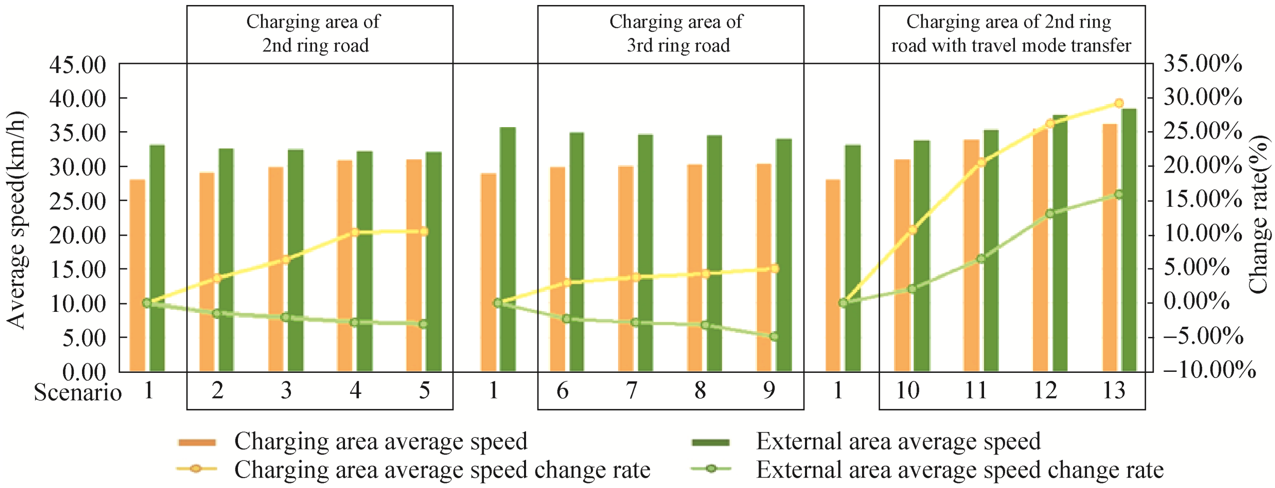


Fig. 8 Speed changes inside and outside the charging area in different scenarios

3.3 Analysis of cost changes

In this section, we first calculate and analyze the overall generalized cost and charge revenue, and then explore the changes in travel costs of different types of drivers.

(1) The overall generalized cost and charge revenue

As shown in Fig. 9, because of congestion pricing, the generalized cost grows in different scenarios compared with reference scenario except Sc 12 and Sc 13. Therefore, the generalized cost can be reduced only when the transfer of transportation mode is considered and the congestion charge exceeds 15 yuan. Also, the game between the reduced number of travelers entering the charge area and the increased price of each entry results in a slightly fluctuating trend in the generalized cost. Compared Sc 6-9 with Sc 2-5, the amount of the total charge revenues within the larger charging zone is 1.66 to 1.95 times that of the smaller charging zone. The larger the area of congestion charging, the greater the amount of traffic that will be attracted to the toll area. These travelers who have to pay the fees trigger an increase in the charge revenue, which also reminds us to consider the fair and handy preferential policies while implementing the congestion pricing.

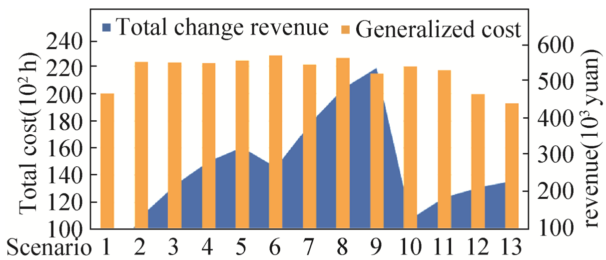


Fig. 9 Generalized cost and total charge revenue in different scenarios

(2) The generalized cost of different types of drivers

Frist, we divide the drivers into four groups based on the different OD pair (Fig. 6). Then, Fig. 10 shows the result of generalized cost change rate for different ODs when 3rd ring is tolled. For Group A, the total cost slightly fluctuates and shows a slight downward trend owing to the improvement of traffic conditions within the 3rd ring toll area. Group B must run to the external area, where the speed is reduced due to congestion pricing. Group C must bear the additional costs of congestion charging such that the total cost increases significantly and may be increased by up to 60%. For group D, the road in the toll area remains the choice of route when the charge is 5 yuan. When the charge rate increases gradually,

https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/32
DOI: 10.16182/j.issn1004731x.joss.19-FZ0278E

第 31 卷第 11 期 系统仿真学报 Vol. 31 No. 11
2019 年 11 月 Journal of System Simulation Nov., 2019

the driver tends to run outside the 3rd ring. Although the congestion pricing causes the average speed outside the toll area to decrease, the average speed in external area is always greater than that of charging area. Therefore, the generalized cost decrease for group D manifests the benefit of the balanced traffic distribution.

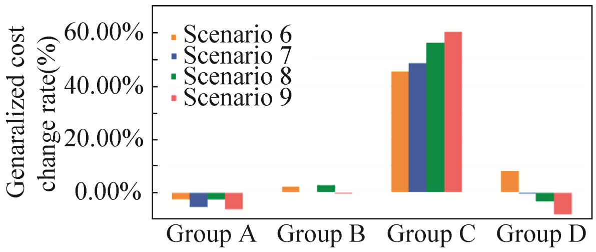


Fig. 10 Generalized cost change rate for different ODs

4 Conclusion

This paper focuses on the reaction and effectiveness of various congestion pricing policies in the actual large-scale road network. To avoid the uncertainty and risk of implementing the policy rashly, a simulated approach is used to assess the effect of these policies on traffic conditions for roads within the 4th ring road in Beijing.

With respect to the consideration of route choice principle, dynamic traffic assignment, user heterogeneity, and travel mode shift, this paper converts the charging rate into the time units, estimates drivers' route choices every two minutes, divides drivers into low- and high-income groups, and adjusts the market penetration of private cars and the proportion of people with different incomes. When the cordon-based congestion pricing is chosen, a total of thirteen scenarios, which differ from each other in charging zones, charging rate, and travel mode, are analyzed in terms of VKT, speed, generalized cost, and charge revenue inside and outside the charging area.

When travel mode shift is put aside, the reduction of total VKT is more conspicuous in the large charging zone (Sc 8-9), which is about 2.1 times that of the smaller charging zone bounded by the 2nd ring road (Sc 4-5). Namely, a larger charging zone is more effective at reducing VKT. Meanwhile, the expansion of the charging area approximately reduces the speed improvement within the charging area by 20%~60% and exacerbates the traffic speed condition by 20%~60% in the external area. However, congestion pricing appears no potential to significantly affect the average speed of the entire network. As for different grades of road, expressways are more affected than major and minor roads owing to the higher speed limit.

The generalized cost grows in different scenarios compared with reference scenario. As congestion charging area expands, more travelers will have to pay for congestion. Perhaps policymakers should give preferential treatment to people working in the toll area, or explore alternative ways of working. In short, there is a need to find a balance between improving traffic conditions and guaranteeing fairness.

Taking the travel mode shift into consideration, the magnitude of VKT changes in each scenario is less than the corresponding transfer ratio of driver's travel mode, which shows that people are willing to take the long way to save money. Although congestion pricing may jeopardize the traffic condition in the external area, but this phenomenon can be reversed when drivers shift their modes of travel. Besides, the generalized cost can be reduced only when the transfer of transportation mode is considered and the congestion charge exceeds 15 yuan. It reminds us to improve the service level of other transportation modes to ensure the effectiveness of the congestion pricing policy.

These results can help to predict the traffic impact of congestion pricing policies in advance, which is obviously of practical and operational significance from a policymaker's point of view. When formulating policies, the effectiveness and fairness are factors that cannot be ignored, and the traffic changes in the charging area, external area and the overall network should be comprehensively weighed and considered. Further, strengthening publicity and promotion, establishing a reward and punishment mechanism, and improving other transportation service levels are necessary supplementary tools.

Besides, a few limitations in this study could be addressed in the future. Changing drivers' travel behaviors is closely related to the convenience of PT, and some more accurate and detailed considerations of model split can be included. If multi-user classes and the departure time choice patterns are integrated into the simulation, more in-depth insights will be obtained.

Reference:

[1] Lehe L. Downtown Congestion Pricing in Practice[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2019, 100: 200-223.

[2] Brjesson M, Kristoffersson I. The Gothenburg Congestion Charge. Effects, Design and Politics[J]. Transportation Research Part A: Policy and Practice (S0965-8564), 2015, 75: 134-146.

[3] Sabounchi N S, Triantis K P, Sarangi S, et al. Dynamic simulation modeling and policy analysis of an area-based congestion pricing scheme for a transportation socioeconomic system[J]. Transportation Research Part A: Policy and Practice (S0965-8564), 2014, 59: 357-383.

[4] Pigou A C. The Economics of Welfare[M]. London: Macmillan, 1920.

[5] Boyles S D, Kockelman K M, Waller S T. Congestion Pricing under Operational, Supply-side Uncertainty[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2010, 18(4): 519-535.

[6] Meng Q, Liu Z. Impact Analysis of Cordon-based Congestion Pricing on Mode-split for a Bimodal Transportation Network[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2012, 21(1): 134-147.

[7] Tan Z, Yang H, Guo R Y. Dynamic Congestion Pricing with Day-to-day Flow Evolution and User Heterogeneity[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2015, 61: 87-105.

[8] Dong J, Mahmassani H S, Erdoğan S, et al. State-dependent Pricing for Real-time Freeway Management: Anticipatory versus Reactive Strategies[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2011, 19(4): 644-657.

[9] Yang H, Huang H J. The multi-class, multi-criteria traffic network equilibrium and systems optimum problem[J]. Transportation Research Part B: Methodological (S0191-2615), 2004, 38(1): 1-15.

[10] Kottenhoff K, Brundell Freij K. The Role of Public Transport for Feasibility and Acceptability of Congestion Charging–The Case of Stockholm[J]. Transportation Research Part A: Policy and Practice (S0965-8564), 2009, 43(3): 297-305.

[11] Wu K, Chen Y, Ma J, et al. Traffic and Emissions Impact of Congestion Charging in the Central Beijing Urban Area: A Simulation Analysis[J]. Transportation Research Part D: Transport and Environment (S1361-9209), 2017, 51: 203-215.

[12] Zhu S, Jiang G, Lo H K. Capturing Value of Reliability Through Road Pricing in Congested Traffic under Uncertainty[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2018, 94: 236-249.

[13] Cameron G, Wylie B J N, Mcarthur D. PARAMICS-Moving Vehicles on the Connection Machine[C]. Washington: IEEE, 1994.

[14] Paramics Microsimulation S L. S-Paramics 2011 Reference Manual[M]. London, England: Paramics Microsimulation, SIAS Limited, 2011.

[15] Xiong C, Chen X, He X, et al. Agent-based En-route Diversion: Dynamic Behavioral Responses and Network Performance Represented by Macroscopic Fundamental

https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/32
DOI: 10.16182/j.issn1004731x.joss.19-FZ0278E

Diagrams[J]. Transportation Research Part C: Emerging Technologies (S0968-090X), 2016, 64: 148-163.

[16] Statistics B B O. Beijing Statistical Yearbook [M]. Beijing: China Statistics Press. 2017.

[17] Liao L. Research of Congestion Pricing Considering Environment Carrying Capacity with Combined Travel Modes[D]. Beijing: Beijing Jiaotong University, 2016.

[18] Zhang Y. Urban Traffic Congestion Pricing: The Case of Dalian[D]. Dalian: Dongbei University of Finance and Economics, 2016.

[19] Zhang S. The Road Congestion Pricing of Double Layer Model Based on VISSIM Simulation Research[D]. Xi'an: Chang'an University, 2015.

[20] Zhang J. The Charges Research on Urban Road Congestion[D]. Shijiazhuang: Hebei University of Economics and Business, 2014.

[21] Li Z. Research on Design and Implement-influence of Congestion Charging[D]. Chengdu: Southwest Jiaotong University, 2012.

[22] Zhou L. Study on Congestion Charging in Megacities[D]. Xi'an: Chang' an University, 2017.

[23] Zhu Y. Research on the Traffic Congestion Charge under Travel Value of Time[D]. Beijing: Beijing University of Technology, 2015.

[24] Wu Z. Road Congestion Pricing Strategies based on Vehicle Emissions for Beijing[D]. Beijing: Beijing Jiaotong University, 2013.

[25] FU J. Research on Dynamic Congestion Pricing Based on Road Segment Selection[D]. Beijing: Beijing Jiaotong University, 2017.

[26] Cheng H. Research on Urban Transport Demand Management and Congestion Pricing Policy[D]. Beijing: Beijing University of Technology, 2015.

[27] Shen X. Study on the Congestion Charging and ITS Implementation Effects on the Choice of Resident Trip Mode[D]. Nanjing: Nanjing University Of Finance and Economics, 2015.

[28] Jiang Y. Study on System Optimization based on Travel Mode Choice and Traffic Policies[D]. Beijing: Beijing Jiaotong University, 2016.

[29] Zou M. Research on Agent-based Travel Mode Choice and Departure Time Choice Model[D]. Beijing: Tsinghua University, 2015.

[30] Shao C, Li M, Liu X, et al. Study on the Impact of Congestion Pricing on Private Car Owner Trip Mode[J]. Journal of Beijing University of Technology (S0254-0037), 2014, 40(6): 884-888.