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RESEARCH ARTICLE

Evaluation of external costs in road transport under the openness of a gated community

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Abstract Residential quarters in Chinese cities are usually walled off from their surrounding roads for security purposes. Recently, the Chinese government has decided to thoroughly open gated residential communities in order to improve traffic capacity and coordinate major roads in the road network, which will inevitably pose challenges, such as environmental pollution, for community members. Unfortunately, before this decision, there were no comprehensive investigations into whether this measure works for road traffic or how much the adverse impact exerts upon residents. Here, we propose a comprehensive method combining microscopic traffic simulation with a vehicle exhaust emission and dispersion model and a noise emission and attenuation model, in addition to a consideration of social cost, to evaluate the possible influence of opening an enclosed residential community to surrounding roads. The validity of the hybrid model was assessed by an assumptive case of two rectangular gated communities under varying traffic flow and five community opening modes. Preliminary results indicate that the opened community outperforms the gated in the most of 49 percent reduction in comprehensive cost. A more detailed analysis reveals that the appropriate extent of openness should rely on the actual situation, and potentially serves as a foundation for the healthy development of communities and cities. Based on the case study results, this paper outlines some strategical suggestions for improving enclosed residential areas by striking a better balance between traffic capacity and environmental risks.

Keywords road traffic, social cost, externality, gated residential area

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1 Introduction

There has been an increasing interest in the land use transportation connection in the past decade, which is motivated by the urban design policies that can be used to control, manage, and shape individual traveler behavior (Badoe and Miller, 2000; Bhat and Guo, 2007; Yan and Wang, 2017). In China, almost all new residential developments, named micro-districts, have been in the form of gated communities since the housing reform during the 1980s (Deng, 2017). Akin to the ‘Neighborhood’ concept originating in the 1920s’ US, gated communities generally point to the residential compound that has strict boundaries with entrances guarded by security and other technology for surveillance (Blakely and Snyder, 1998). For most communities, autos, walkers, bikers, or transit have no right to go across. With the rapid development of urbanization, the construction scale of enclosed residential communities is continuously increasing, and this is leading to more and more adverse effects on residences and is changing the urban landscape with a nationwide effect (Roitman, 2010). Because of transportation privatization, gated communities can destroy the layout of the urban road network (Miao, 2004), reduce road network density (Low, 2001), and lead to traffic congestion (Lv et al., 2012). Moreover, gated communities aggravate residential segregation. Therefore, the Chinese government announced opinions on the further strengthening of city planning and construction from the State Council of the People’s Republic of China in 2016 to encourage the development of a city block system in China, where the existing enclosed communities as shown in Fig. 1 would open their walls to optimize the street network structure and to make the internal roads shared to the public.

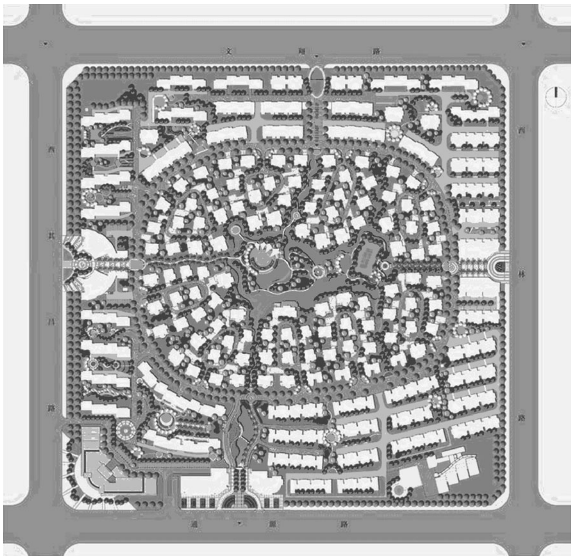

Fig. 1 A typical Chinese gated community.

Closed residential communities are popular over the world, and have been studied due to their unique characteristics in various countries (Webster et al., 2002), such as in America (Blakely and Snyder, 1997), UK (Atkinson and Flint, 2004), Japan (Abdullah et al., 2017), Southeast Asia, (Leisch, 2002) and so on. Current methods for assessing the openness of gated communities are generally divided into two groups. One group focuses on the impact of gated communities on residents. For example, Wang et al. (2018a) analyzed the applicable occasions of closed or open communities and proposed countermeasures for the moderate opening of Chinese urban communities as compared to Chinese and foreign cities. Through the analysis of the flow through the community, some studies also discussed the characteristics, advantages, and disadvantages of the block system and enclosed residential areas from the viewpoint of pedestrians (Wang et al., 2018b) and private car (Sanchez et al., 2005). Surveys reveal that most people have a negative attitude toward the policy because they are worried about security issues, environmental issues, and congestion inside the community (Shi, 2017). The other group often concentrates on evaluating robustness of the road network around closed communities (i.e., heterogeneity, connectivity, accessibility, interconnectivity). By proposing a number of measurable indicators, there are studies exploring the degree of openness of gated communities, such as road capacity, traffic delay, queue length, road service level, and so on (Miao, 2003; Atkinson and Blandy, 2005; Li, 2014). The main methods include random forest algorithm (Chen, 2014), traffic simulation (Wu et al., 2016), the topology probability analysis model (Liao et al., 2018), and other simulation methods. Although these studies tried to analyze the impact of the openness of gated communities, few studies focused on improving the road network with a consideration of the possible environmental impact on dwellers. In addition, it is little known whether community openness can achieve the optimization of the network structure and improve the traffic efficiency. As said in a previous study (Dong et al., 2018), if opening the gated community, the density of the road network will be improved and the road area can increase, a result of which the road traffic capacity is naturally improved. But, people also believe that although the number of passable roads increases due to the community openness, the number of vehicles in the area is bound to increase, which can lower the traffic speed of the road (Yao et al., 2018). People that oppose the openness are also afraid of their dwelling environment that is affected greatly (Shi, 2017). It is unfortunate that there is no earlier work to respond to above opinions and examine what influence can occur with the openness of the community. To facilitate a friendly plan for the residential areas, it becomes important to conduct a comprehensive evaluation on whether it is feasible to make an existing enclosed community public of internal roads, especially from the viewpoint of external costs in traffic efficiency and environment pollution.

External cost of road transport is an important indicator that can evaluate the impact on bystanders brought by road transport activities, and it plays a significant role in assessing comprehensive value of road transport infrastructures and policies (Bickel et al., 2006; Economic Analysis Directorate of Transport Canada, 2008; Cai and Zhou, 2015). In many previous studies of external cost in road transport, the evaluation methods such as external congestion cost, external accident cost, air pollution cost, and noise cost in road transport are summarized systematically. Keeler and Small (1975) attempted to assess the travel time of motor vehicles and external costs of environmental pollution in the San Francisco area based on a speed-flow curve. Levinson et al. (1996) estimated four kinds of external costs in California road traffic, including congestion, traffic accidents, air pollution and noise pollution, with a lot of literature reviewed. Bickel et al. (2013) established a series of damage functions to evaluate the external cost of traffic accidents, air pollution, noise pollution, and land use. In addition, Barth (2010) systematically studied traffic accidents and external costs such as air pollution and traffic congestion, and provided for the formulation of relevant policies of the continent.

In this study, a hybrid evaluation method is proposed from a viewpoint of external costs in road transport due to the residential area from closeness to openness. This method is intended to assess the change in traffic efficiency, fuel consumption, air and noise pollution. To that end, the method is implemented by an integration of the microscopic traffic simulation, the vehicle exhaust emission and dispersion model and the noise emission and attenuation model. Based on a case study, this paper will propose future development guidelines and design strategies for opening enclosed residential communities.

2 Methodology

2.1 Simulation methods

This section establishes a simulation method for traffic delay, fuel consumption, exhaust, and noise pollution by using the microscopic traffic simulation software. PARAMICS is one of the most widely used microscopic traffic simulation programs. It has one important feature that it allows the user to customize many features of the underlying simulation model through a functional interface or application programming interface (Liu et al., 2005). Through writing a plug-in program, PARAMICS can connect additional models to further calculate the fuel consumption, and exhaust and noise pollution levels.

2.1.1 Simulation of road traffic condition

In PARAMICS, an appropriate microscopic simulation model can be used to represent the lateral and longitudinal movement of an individual vehicle. Such models rely mainly on the use of car-following, lane-changing, and gap-acceptance rules to better describe longitudinal and lateral movements of individual vehicles. This study used the PARAMICS microscopic simulation model to analyze an urban arterial road network of Guangzhou. Results show that the vehicle behavior in PARAMICS shows no difference with actuality, which meets the requirement of microscopic traffic simulation. The microscopic traffic simulation system is a powerful tool to help analyze and evaluate various types of transportation systems. To output valid simulation results, the model parameters need to be corrected before the simulation based on the existing theoretical framework of parameter correction for microscopic traffic simulation systems. To analyze an urban arterial road network of Guangzhou, Li et al. (2008) proposed a systematic, well-characterized parameter correction process, and through the comparison of measured data and simulation results, it was proven to be reasonable. Therefore, we took the optimized calibration parameter according to the literature, i.e., the average time headway is 0.86 s, and the average driver response time is 0.6 s.

To analyze the traffic conditions of closed communities with different kinds of internal road networks after community openness, we simulated the condition of traffic flow and obtained the change situations of average speed, traffic impedance, hold plugging delay, and other traffic parameters in different traffic network demands. The basic input data includes the road network geometry, traffic flow data, the signal timing scheme, and the location of the noise and air pollution receiving point. Ultimately, the travel time of each vehicle is calculated,

$$t_i = t_{e,i} - t_{s,i}, \tag{1}$$

where t_i is the travel time of the ith vehicle, $t_{e,i}$ is the time of arrival of the ith vehicle(s), $t_{s,i}$ is the time of departure of the ith vehicle(s). After accumulating travel time of all vehicles, the total travel time of the vehicle is calculated.

2.1.2 Simulation of vehicle fuel consumption and exhaust pollution

Many previous studies have demonstrated the significant health risk due to vehicle activity in the traffic microenvironment (Wang et al., 2015a, 2015b, 2015c, 2017a, 2017b, and 2018c; Gao et al., 2017 and 2019; Li et al., 2019a and 2019b). Based on the traffic simulation by the PARAMICS, this study calculated the emission factors of CO, HC, NO_x, $PM_{2.5,}$ and the fuel consumption for different types of vehicles using the Comprehensive Modal Emission Model (CMEM) which is widely used in the evaluation of micro-emission emissions from urban road traffic at present (Barth, 2010). Then, we further predicted the above pollutant concentrations for receptors located within 500 m of the roadway by the California Line Source Dispersion Model (CALINE 4) (Zhang, 2001). Based on the Gaussian diffusion equation, this method can employ a mixing zone concept to easily characterize pollutant dispersion over the roadway.

PARAMICS classifies vehicles on basis of the size of actual traffic flow, while CMEM further subdivides them according to their emission related attribution. To determine a corresponding CEME calculation module for each vehicle in the PARAMICS simulation network, we further established a mapping relationship between the vehicle types in PARAMICS and CMEM. Here, we subdivided the vehicle categories in the PARAMICS according to the CMEM classification criteria. Therefore, the accurate emissions of the exhaust pollutants together with traffic volume, and fuel consumption can be output at the study area when the PARAMICS simulates the traffic running status of the road network till to the simulation stops. Then, the concentration of each pollutant at the observation point is further obtained using the CALINE 4 model.

2.1.3 Simulation of dynamic traffic noise

According to the traffic parameters simulated by the PARAMICS, the dynamic traffic noise is composed of two modules including a vehicle noise emission model and a sound propagation model. To study the noise fluctuation, we used a dynamic traffic noise simulation method to simulate the dynamic noise change. In the calculation, each vehicle on the road network is regarded as a point sound source. The following formulas were used for calculating the sound level of small-size, medium-size and large-size vehicles, respectively, at the corresponding observing point (Zhang, 2001; Cai et al., 2019; Wang et al., 2019).

$$L_{\mathrm{os}} = 12.60 + 33.66\lg V, \tag{2}$$

$$L_{\mathrm{om}} = 4.80 + 43.70\lg V, \tag{3}$$

$$L_{\mathrm{ol}} = 18.00 + 38.10\lg V, \tag{4}$$

where V is the velocity of the vehicle (km/h), L_{os}, L_{om}, and L_{ol} are the emission noise (dB) of the small-size, medium-size, and large-size vehicles, respectively. In Eqs. (2)–(4), the model parameters were obtained mainly according to the classical model proposed by Zhang (2001).

The sound pressure level of the ith second at the receiving point that is emitted by the nth car is expressed as,

$$L_{i,n} = L_0 + 10 \times \lg\frac{d_0^2}{d_{i,n}^2}, \tag{5}$$

where L_0 is the sound pressure level of a single vehicle measured at a standard distance and is calculated by Eqs. (1), (2), and (3), d_0 is the reference distance when measuring the noise emission of a single vehicle, which is 7.5 m in the Chinese Standard "GB 1495-2002," $d_{i,n}$ is the distance from the vehicle to the receiving point (m).

2.2 External cost assessment model

After finishing the dynamic network simulation, we established an external cost assessment of the openness of the gated residential community. Data generated by the PARAMICS for a real-world network were used to develop a cost assessment model, which utilizes comprehensive economic cost to evaluate the influence of the openness of gated communities. The cost evaluation contains five parts: travel time cost, fuel consumption cost, air pollution cost, noise pollution cost, and comprehensive cost. The calculation method is based on assigning monetary costs to vehicle delay, vehicle fuel consumption, air pollution and noise pollution data obtained from the traffic simulations.

2.2.1 Travel time cost

Travel time cost (*TTC*) is assessed by the traveler's willingness to pay for travel time savings (Rakha et al., 2011) and consists of personal travel time costs (*PTTC*) and traffic delays time costs (*ECC*),

$$TTC = PTTC + ECC. \tag{6}$$

Travel can be divided according to purpose into working trips and non-working trips. The unit time cost and value of the two travel modes are based on the recommendation of the World Bank (Gwilliam, 1997). Personal travel time costs and external costs due to traffic delays are calculated by Eqs. (7) and (8), respectively.

$$PTTC = T \times \left(\sum_{j}^{M} p_j \cdot pax_j\right) \times (r_{\mathrm{work}} \cdot VOT_{\mathrm{work}} + r_{\text{non-work}} \cdot VOT_{\text{non-work}}), \tag{7}$$

$$ECC = DT \times \left(\sum_{j}^{M} p_j \cdot pax_j\right) \times (r_{\mathrm{work}} \cdot VOT_{\mathrm{work}} + r_{\text{non-work}} \cdot VOT_{\text{non-work}}), \tag{8}$$

where p_j and pax_j are the proportion of the jth-type vehicle in the traffic simulation and the average carrying capacity of that vehicle, respectively, M is the vehicle type, r_{work} and $r_{\text{non-work}}$ are the average proportions of total trips for work and non-work trips ($r_{\text{non-work}} = 1 - r_{\mathrm{work}}$), respectively. $\mathrm{VOT}_{\mathrm{work}}$ and $\mathrm{VOT}_{\text{non-work}}$ are the time values (US$/h) of work travel and non-work travel, respectively, based on the advice of the World Bank.

2.2.2 Fuel consumption cost

Fuel consumption cost is determined the by oil price as follows (Rakha et al., 2011),

$$FC = M_{\mathrm{F}} \times AFP, \tag*{((9)}$$

where *FC* is fuel costs (US$), M_{F} is the total fuel consumption (kg) generated by motor vehicles during the simulation process, and *AFP* is the domestic average oil price (US$/kg).

2.2.3 Air pollution cost

The cost factor of each exhaust pollutant that is used to reflect the hazard of the exhaust can convert the concentration of three contaminant gases in the air into air pollution cost as follows (El-Shawarby et al., 2005),

$$APC = \sum_{e=1}^{E} M_e \times C_e, \tag*{((10)}$$

where *APC* is air pollution cost (US$), M_e is the average concentration of the eth-species of air pollutant in the study area during the simulation process(ug/m^3), and C_e is the cost factor for the eth-pollutant (US$/kg).

2.2.4 Noise pollution cost

Road traffic noise leads to not only high blood pressure and myocardial infarction but also general anxiety among the affected population. Road traffic noise pollution cost is generated by these kinds of effects. Based on the work of Bickel and other scholars (Bickel et al., 2006; Li et al., 2009), the emotional impact is much greater than the impact on personal health. So, this study employs the noise anxiety cost to estimate the noise pollution cost as follows,

$$NPC = \frac{(L_{\mathrm{eq}} - L_{\mathrm{limit}}) \times WTP \times N_{\mathrm{House}} \times T_{\mathrm{Sim}}}{720}, \tag{11}$$

$$WTP = 0.11 \times L_{\mathrm{eq}} - 3.05, \tag{12}$$

where NPC is noise pollution cost (US\$), L_{eq} is the average equivalent noise of all the observed points in the study area (dB), L_{limit} is the noise limit of the study area (dB) based on the Environmental Quality Standard for Noise (GB3096-2008) (Ministry of Ecology and Environment of the People's Republic of China, 2008), N_{House} is the number of families affected by the noise, T_{Sim} is the simulation time (h), WTP is the money an average tenant would be willing to pay to reduce the sound pressure level at this level noise, per household per mouth $(\mathrm{US\$} \cdot (\mathrm{dB} \times \mathrm{month} \times \mathrm{House})^{-1})$.

2.2.5 Comprehensive cost

We further combined the above four costs to obtain a comprehensive cost evaluation of the study area,

$$AVGC = \frac{TTC + FC + APC + NPC}{N_{\mathrm{veh}}}, \tag{13}$$

where average comprehensive cost ($AVGC$) is average transportation cost of each vehicle during simulation time (US\$), N_{veh} is the number of vehicles in the road network during the simulation. Based on the comprehensive cost, the openness of the enclosed community can be assessed from the perspective of economic costs and benefits.

3 Case study

3.1 Hypothetical simulation scenarios

3.1.1 Simulation conditions of a community

Many factors usually determine whether the community opening can achieve an optimization of road network structure, improve traffic efficiency, or lead to additional environmental issues. This study mainly focused on three kinds of factors, i.e., the structure and scale of a community, the degree of openness of a community and traffic volume on the road, to predefine simulation conditions of a community.

1) Structure and scale of a community

According to the Chinese urban residential area planning and design standard GB 50180-93 (Yao and Wei, 2012) (see Table 1), residential area is divided into three levels: residential district, residential quarter and residential group. Residential district always has an area over 50000 ha, and is consist of residential quarter and residential group. Residential quarter is often in an area of 500 m × 500 m, and is consist of residential group. There are many residential districts in a city, especially outside the center area of a city. Residential groups are typically independent groups that have no need to share the road in the first stage.

2) Degree of openness of a community

As Fig. 2 illustrates, vehicles should detour outside the community when the community is closed, while vehicles can directly pass through the community with various path selections after opening the community.

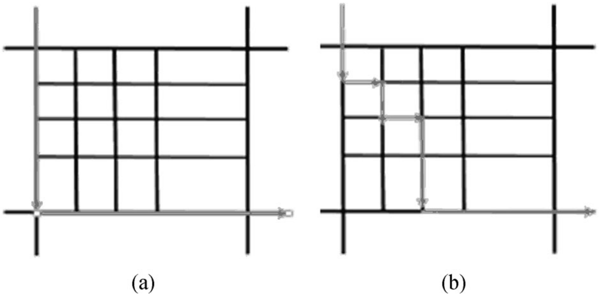

Fig. 2 The possible path for vehicles before (a) and after (b) opening a gated community.

For this, we defined the opening index δ as,

$$\delta = \frac{z}{s}, \tag{14}$$

where z is number of entrances, s is area of the community.

3) Traffic volume on the road

In residential areas, vehicle volumes often change greatly due to geographical location and time period, which usually determine the road traffic situation around the community. Besides, private cars are a main contributor to the negative impact on public health and environment in communities (Song, 2014). Therefore, it is necessary to consider how the varying traffic volumes affect the traffic efficiency and residential environment if opening the community.

Table 1 Chinese urban residential area planning and design standard GB 50180-93 (2016 edition)

Item	Residential district	Residential quarter	Residential group
Number of households	1000–16000	3000–5000	300–1000
Number of population	30000–50000	10000–15000	1000–3000

3.1.2 Multi-scenario simulation for opening an enclosed community

Based on above considerations, we assumed a closed residential district with an area of 2000 m × 2000 m and residential quarters with an area of 500 m × 500 m. Next to the residence, there are four external two-way roads with four lanes for each road. Corresponding to the road network structures of different communities and their different surrounding environments, five hypothetical opening scenarios together with the original closed community model are constructed, and are respectively named the two-block network model, the four-block network model, the six-block network model, the nine-block network model and the twelve-block network model.

Figure 3 shows the original gated community and five opening scenarios. The hybrid method proposed in Section 2 was used in these hypothetical scenarios to evaluate their external costs. The evaluation process is divided into the following steps:

Step 1: Assume there is a closed residential quarter with an area of 500 m × 500 m, and after changing the traffic flow on the road network, traffic simulation is carried out to explore the influence of varied traffic volumes on each opening mode of the gated community.

Step 2: The five opening models are evaluated against the original gated community using the cost index, and then the applicable scope of the six different communities is analyzed.

Step 3: Assume there is a closed residential district with an area of 2000 m × 2000 m, and repeat step 1 to 2 and then compare the results of the two scales of the communities (i.e., 2000 m × 2000 m and 500 m × 500 m).

After inputting the road network geometry, road traffic, vehicle type, and other basic information to the PARAMICS, the entire road network model was established. The simulation time was one hour, and, in order to reflect the random changes in the real-world road network, the simulation was performed 10 times, and the average value was used for the analysis. The coordinate origin is the center of the community and the observation points for noise and toxic gas were placed evenly every 25 m, with a total number of 40 × 40.

After the sealed community is opened, vehicles run through the residential community and emit a large amount of waste gases which are harmful to the residents. To analyze the influence of the pollution gases, CALINE 4 was employed to simulate the diffusion of the pollution gases and to compute the pollutant concentration at each observation point.

In the case study, the social cost measures the sum of the economic losses and environmental impact caused by travel time delay, fuel consumption, and air pollution and noise pollution, which are the external costs that are not internalized (Tong et al., 2000). The results include the air

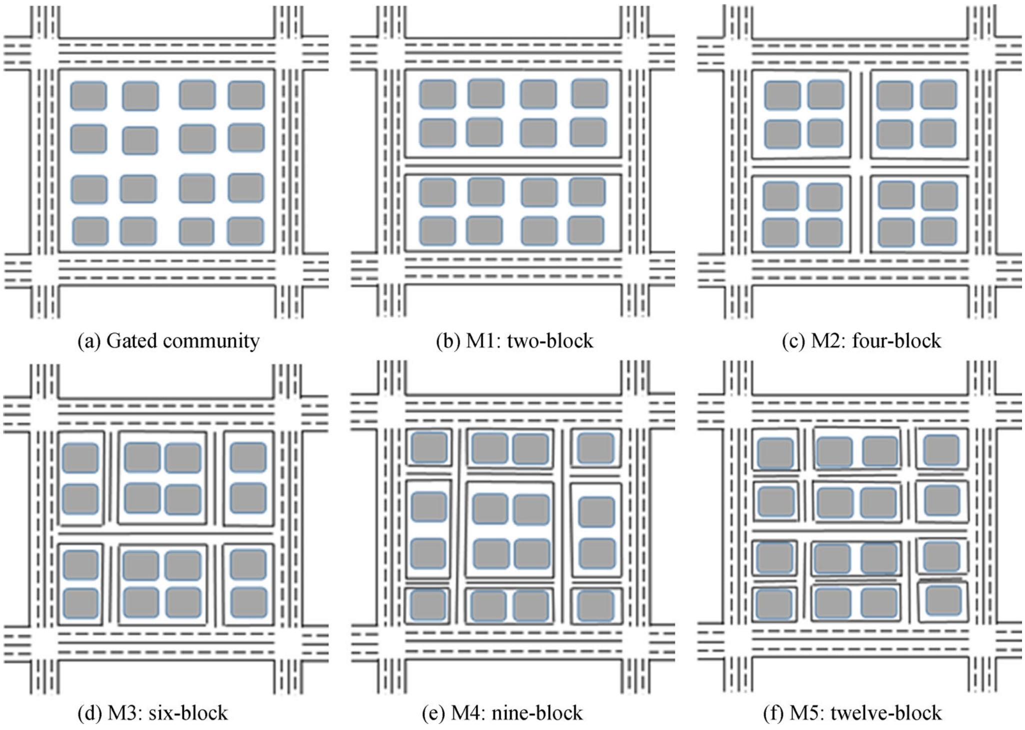
(a) Gated community
(b) M1: two-block
(c) M2: four-block
(d) M3: six-block
(e) M4: nine-block
(f) M5: twelve-block

Fig. 3 The gated community and its five opening ways. (a) Gated community; (b) M1: two-block; (c) M2: four-block; (d) M3: six-block; (e) M4: nine-block; (f) M5: twelve-block.

pollutant inventories and the social costs. Social costs include the cost of travel time, fuel consumption, air pollution and noise pollution; Emissions include four types of air pollutants (NO_x, $PM_{2.5,}$ HC, and CO).

3.2 Results and discussion

3.2.1 Variations of time, fuel, air and noise costs with traffic flows

Figure 4 shows the evolution of time cost, fuel cost, air pollution cost and noise pollution cost with increasing traffic flow. It is clear that time cost and fuel cost follow highly similar trends, which can generally be divided into two stages: a stationary period and a growth period. In the stationary period, the time cost on the road and the fuel cost remain stable when the traffic volume increased, remained around \$0.05 and \$0.15, respectively. It is because the driver often chooses a higher speed with the low traffic volume in the network. Since the external road can meet the demand of the traffic growth, the difference in the time cost with or without the added road is not significant. In other words, the openness of the gated community has little effect on the time and fuel costs over this period. In the growth period, the road traffic volume increases, and the roads become congested. As a result, the travel time and delay time increase rapidly with increasing traffic volume. The time cost depends on the delay time and the salary level. As reported in the past, the transient driving modes (i.e., acceleration and deceleration) produce more consumption than the steady-speed driving modes (Tong et al., 2000). Frequent parking, shifting, acceleration, and deceleration can cause road congestion and increase the fuel cost. This why time and fuel costs grow rapidly in this period. On the whole, the time and fuel costs decline after the community is opened, and the six-block community is the lowest cost scenario.

The air pollution cost considers pollutants of HC, NO_x, CO, and $PM_{2.5}$. Air pollution cost of five kinds of modes is almost the same in the early stage. However, when the traffic flow is over 1100 vehicles per hour, the air pollution cost increases rapidly. This agrees with previous study results that in a congested area where vehicles frequently stop and go, tailpipe emissions can be three times higher than when driving is smooth (Song, 2018). Obviously, the openness of the community generally leads to much more air pollution than the gated community. Because the noise level is always related to the number and speed of vehicles (Li et al., 2017), the evolution of noise pollution cost is found significantly different from the other types of costs. When the traffic volume increases, the noise level increases rapidly at the early stage. However, when the road becomes congested, the noise level starts to steadily decrease due to a declining vehicle speed although the traffic volume increases.

3.2.2 Comprehensive external costs under different openness patterns

Figure 5 shows the comprehensive external costs of five opening scenarios and the closed mode as a function of traffic flows. When the community is entirely gated, the comprehensive cost is between \$0.2 and \$2.5. When adding shared roads, the time cost and fuel cost can lessen, but the air pollution and noise pollution costs increase. In general, the six community modes can be arranged in a descending order by an average cost as follows: enclosed, two-block (M1), four-block (M2), nine-block (M4), twelve-block (M5) and six-block (M3). It implies that increasing the openness of the gated community will reduce the comprehensive external cost. When the traffic flow is less than 2000 vehicles per hour, the evolution of the comprehensive cost is nearly identical across all five community types. It suggests that it is not necessary to open all the enclosed communities in the city. Instead, each individual community should be evaluated based on its surrounding road and traffic flow situation.

Overall, the travel time cost, fuel cost and comprehensive cost of a twelve-block community are higher than that of a six-block community (see Figs. 4 and 5). This may be a Braess's paradox phenomenon that a road network alteration for improving traffic flow can produce the reverse effect and impede traffic through it (Mak et al., 2018). To be specific, a road added to a congested road traffic network could increase the overall journey time, and when the moving entities selfishly choose their own route, adding extra capacity to a network can reduce overall performance. This also implies a Nash equilibrium. In the transportation network, if everyone does not consider the impact of their own actions on other people's travel, the traffic delay will not decrease although the road number is increased (Acemoglu et al., 2018). If the designer does not take into account the travel demand and the user's principle of path selection, an excessive pursuit of adding roads in the network will lead to the reduction of the overall capacity of the road network, thus increasing the travel time on the road network. In our case study, the number of added gates changes gradually from one to ten. The time cost and fuel cost increase first and then decrease at different opening degree, and reach a lowest value when adding 3 lines and 6 gates (i.e., six-block community). Therefore, the travel time cost and fuel cost of twelve-block community are higher than that of six-block community.

As shown in Fig. 6, the travel time cost and fuel cost remain the most important attributes for the comprehensive cost because of the high conversion standard of vehicle delay and fuel. As known, the average price of gasoline and average salary is gradually increasing in China. The fuel cost becomes larger, when the traffic flow becomes smaller. As the traffic flow increases, the time cost starts to outweigh the fuel cost because of a higher delay time.

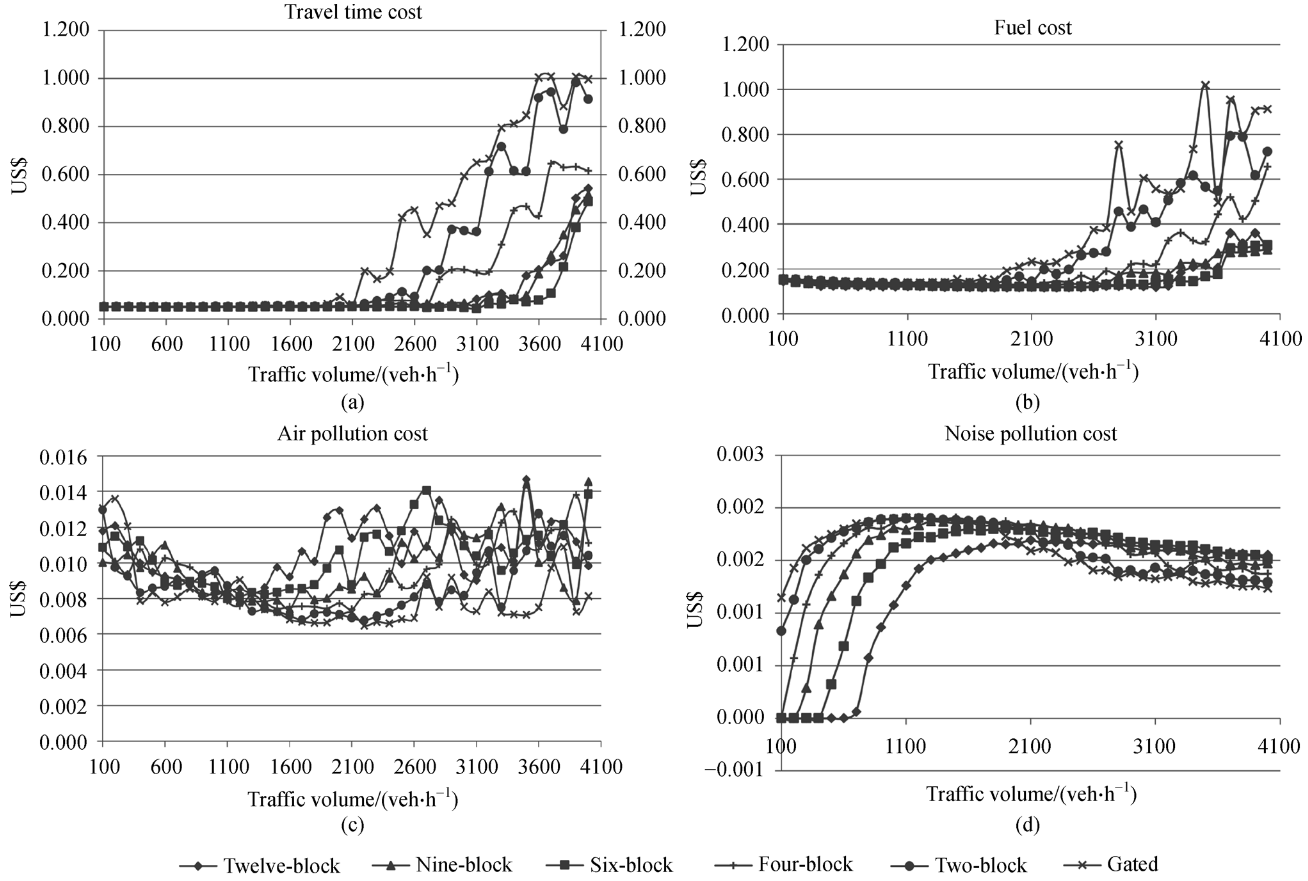

Fig. 4 Change trends of four kinds of social costs with different traffic flows.

Chinese people are willing to spend less money on improving the environment, so the air pollution and noise pollution costs are smaller than time and fuel costs. However, residential quarters belong to the second category of functional areas, whose mandated noise limit is 60 dB (GB3096-2008) (Ministry of Ecology and Environment of the People's Republic of China, 2008). When a crossroad is added into the community, the noise level will exceed the standard at some observation points. At some observation points, the concentrations of CO, HC and $PM_{2.5}$ similarly exceed mandated standards (GB3095-2012) (Ministry of Ecology and Environment of the People's Republic of China, 2012). Therefore, noise limits, as prescribed by the state, should also be considered when re-planning road layouts of gated communities based on residential cost.

To evaluate the influence of the community openness with different scale, we compared the results for two scales of gated communities (i.e., 500 × 500 and 2000 × 2000). As seen from Figs. 5 and 7, when the traffic flow is less than 2000 vehicles per hour, the evolution of the comprehensive cost is nearly identical across two community scales. When the traffic flow is less than 2000 vehicles per hour, the comprehensive cost of both communities increased first and then decreased at different opening degree. The overall trend of the comprehensive external costs for a residential district (2000 m × 2000 m) is similar to that for a residential quarter (500 m × 500 m). When the traffic volumes are in a high level (more than 2000 vehicles per hour), the cost of the twelve-block community is higher than that of six-block community at the scale of 500 m × 500 m, while the cost of the twelve-block community is lower than that of six-block community at the scale of 2000 m × 2000 m. In the previous analysis, we identified this as a Braess's paradox phenomenon. When the cost is the lowest, different scales of communities are often opened with different numbers of open gates and different open roads. For residential quarter at the scale of 500 m × 500 m, the six-block community is optimal, while at the scale of 2000 m × 2000 m, the cost of twelve-block community is lower than that of six-block community. The most suitable opening degree is related to the scale of the community. Urban planning should make a full consideration of the actual situation when transforming the community.

4 Conclusions and policy implications

This paper proposed a comprehensive method, combining the PARAMICS traffic simulation with the vehicle exhaust emission and dispersion model (i.e., CMEM and CALINE

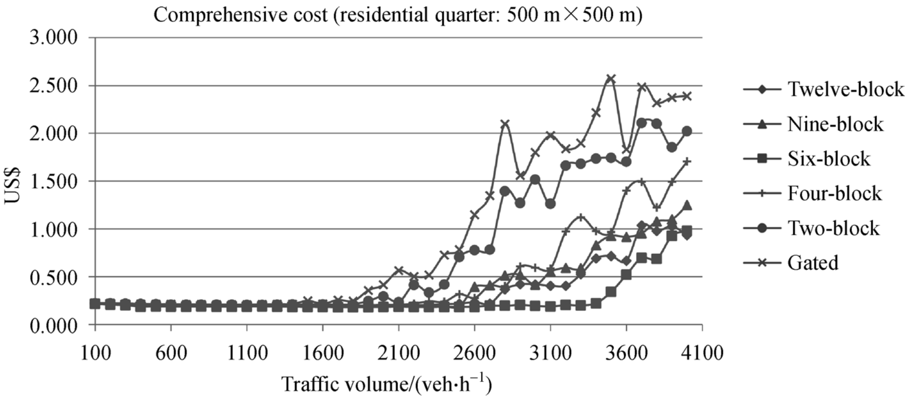

Fig. 5 Evolution of comprehensive external cost with traffic flows in a residential quarter.

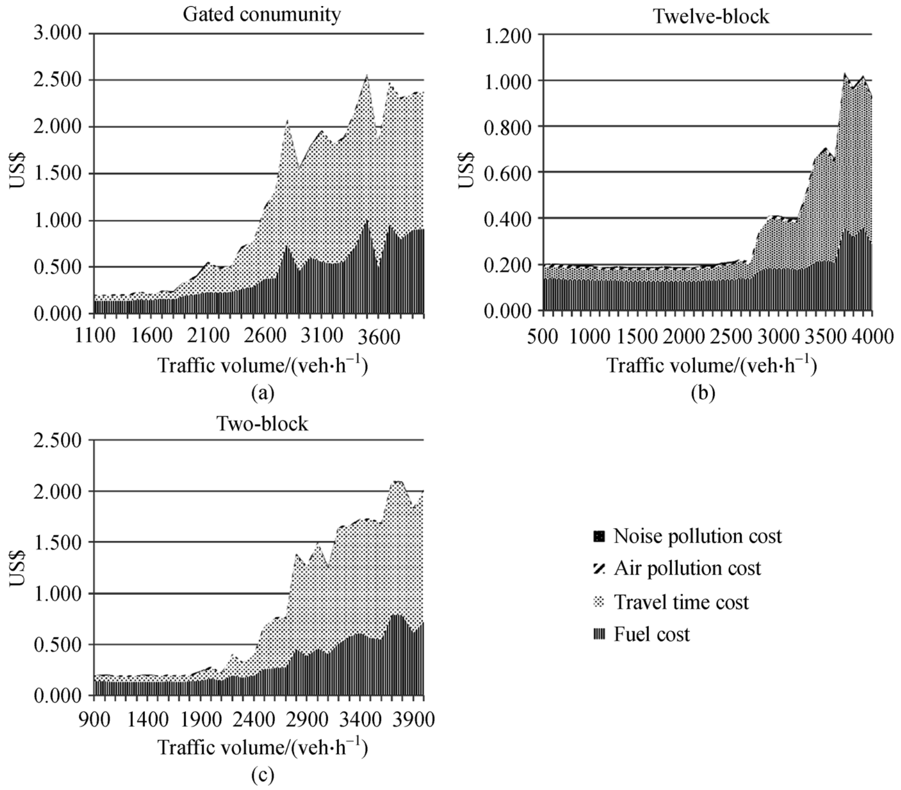

Fig. 6 The proportion of four kinds of costs in different community patterns.

4), and the noise emission and attenuation model, to assess the external costs in road transport before and after opening an enclosed residential community. The evaluation method was applied to an enclosed quadrate community with five opening styles, and was expected to examine the effect of making an existing enclosed community internal roads public from the perspective of traffic efficiency, fuel consumption, air pollution, and noise pollution. The results show some policy implications as follows:

1) The external costs of the opened communities are lower than the gated scenario. As the opening degree of the community increases, the comprehensive cost increases first and then decreases. But, for the closed residential district and quarters, it is not that the higher the opening degree of the community is, the higher the traffic efficiency will be. The suitable opening degree is often related to the structure and scale of the community. Thus, urban planning should make full consideration of the actual situation when making the transformation.

2) Not all of the gated communities need to be transformed when the government re-plans the network. If there is no traffic jam in the road around the gated community, it is of little significance to remove the wall of a closed cell. The community can be opened gradually

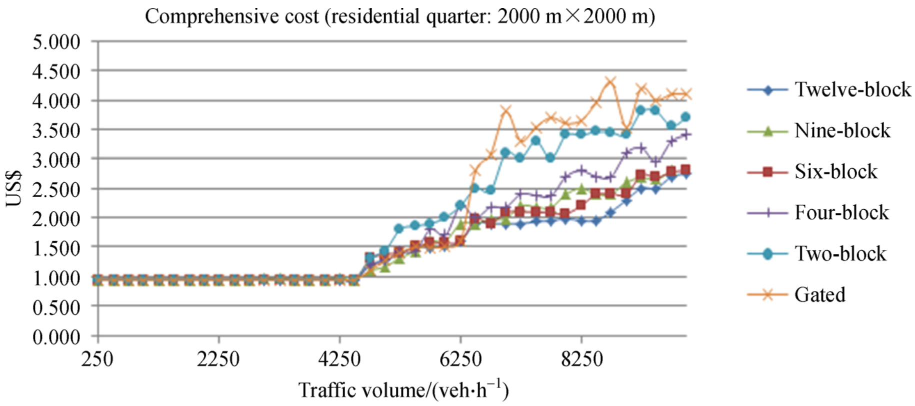

Fig. 7 Evolution of comprehensive cost with traffic flows in a residential district.

rather than in one step. It is recommended that urban planning gives priority to the community surrounded by traffic congestion when selecting the opening target. Besides, the planning department can take into account traffic volumes with a flexible measure to open the wall of the closed cell. For example, the community can share the inner road during morning and evening peak periods, which can reduce the daily impact on community residents.

3) Although the traffic efficiency can be improved to an extent, the openness also brings environmental pollution to the residents once opening the community, especially when a crossroad is added. The air and noise pollution likely exceeds the limit level prescribed by the national environmental protection agency. Therefore, when opening the road network of a gated community, we should seek an appropriate balance of the openness to provide a foundation for the healthy and sustainable development of communities and cities.

The quantitative evaluation and measurement of openness degree are an essential step to analyze the Chinese gated communities and their social impact. Openness of a gated community exists in different forms, as can be measured through time cost, fuel cost, air pollution cost, and noise pollution cost. The quantitative method breaks down the gating phenomenon into more defined sectors, thus making it possible to evaluate the fuzzy region between definite gating and total openness in the compound residence. However, one challenge of this study lies in refining the standardized index that represents the qualified openness degree. Besides, this study just shows a hypothetical community scenario rather than the real Chinese community, which inevitably affects the practical contribution of the study. Another limitation is the model localization and regionalization of the proposed assessment method. The lack of local information contributed to the reluctance to localize the model, and thus errors can inevitably happen to other cases in China. The measurement is a framework that provides the research foundation for follow-up studies, but more samples are further needed in the future to refine the framework.

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