Exploring the relationship between urban transportation energy consumption and transition of settlement morphology: A case study on Xiamen Island, China☆

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A B S T R A C T

It is important to understand the settlement morphology and its transition process in the rapid urbanization cities of developing countries. It is equally important to learn about the relationships between transport energy consumption and the transition of settlement morphology and its underlying processes. Finally, if the existing transportation technologies are already adequately meeting the environmental challenges of that sector then urban policies can serve as a guide to the transition of settlement morphology, especially for developing countries. Through the application of an integrated land use and transportation modeling system, TRANUS, the paper demonstrates that this transition will bring great changes to the urban spatial distribution of population, jobs and land use, and to residents’ travel patterns, thus resulting in different transportation energy consumption and CO2 emission levels, but that these changes can be managed through appropriate public policies.

Introduction

Urban transport, especially passenger transport, forms a significant proportion of global energy consumption and is also a major contributor to greenhouse gas emissions. The transport sector has thus been identified as one in which energy saving should be encouraged. Commuting patterns and traffic modes will significantly influence energy consumption of the passenger transport sector. In reality, a number of principles, such as location of residences and employment districts, social and economical status and traffic infrastructure, work simultaneously in determining the commuting patterns and trip modal choice. These factors are also related to settlement morphology (Anderson, Kanaroglou, & Miller, 1996). Rapid urbanization and urban sprawl have not only consumed large amounts of natural resources, such as land and fossil-fuels, but have also resulted in the transition of settlement morphology through physical and social forms.

Politicians and researchers are now giving more attention to the discussion of the socioeconomic benefits and the environmental costs of rapidly expanding urban sprawl and believe that environmental sustainability in the megacities of developing countries has become one of the most critical elements of the Millennium Development Goal (MDG) (Zhao, 2010). The impact of this transition on settlement morphology due to urban expansion will therefore be the first focus of this paper.

Many scholars have studied the relationships between urban form and transport energy consumption as a basis for proposals about sustainable urban forms. Based on six case studies in the United Kingdom and the Netherlands, Banister, Watson, and Wood (1997) found that factors such as density, employment and car ownership would affect urban transportation energy use. An empirical study on three cities in the Netherlands (Dieleman, Dijst, & Burghouwt, 2002) found that dependency on private cars was related to the car ownership rate, household type, availability and convenience of public transportation and the urban form of the local residential environment. Many studies have shown that urban form plays an important role in determining mode choice and travel distance (Cervero, 2002; Cervero & Radisch, 1996). For
example, Handy, Cao, and Mokhtarian (2005) found that population density, land use, and mass transit were causally related to per capita passenger vehicle travel. Car dependence and transportation energy consumption per capita for low-density neighborhoods are greater than for compact ones (Kennedy & Van de Wege, 2007; Kenworthy & Laube).

Urban form and urban design are seen as increasingly important in addressing climate change and has been examined by a number of researchers. Marshall (2008) studied the interrelation between urban population density and vehicle-kilometers traveled to build different urban sprawl scenarios to estimate potential carbon benefits. The results highlighted the potential significance of urban design for reducing transport CO2 emissions and suggested that long term climate impacts could result from shifts which could be comparable to those from technological innovation. Previous studies on the relationship between urban form and transportation energy consumption have found a correlation with settlement morphology, especially the physical form of settlements. This relationship is the second focus of this paper.

Because of the serious impacts of the transportation sector on both energy use and environmental quality, various methods have been implemented in an attempt to reduce the transportation energy consumption and mitigate the environmental effects of vehicle emissions. Most of these efforts, however, have focused only on efficiency improvements to vehicle and fuel technologies, and the results of these improvements have been largely offset by increased car ownership and use (Cui, Niu, & Wang, 2010; Sandy Thomas, 2009; Zhao & Melaina, 2006). Simultaneously, a general consensus has emerged that prompt development and implementation of new green individual transportation technologies is unlikely, especially in the fast-growing cities of developing countries, where increased consumption has been caused mainly by the affordability of these ‘new’ cars (Assmann & Sieber, 2005; Pridmore & Bristow, 2002; Zegras, 2007). The framework of ASIF (emissions are the product of activity [A], modal share [S], modal energy intensity [I], and fuel type [F]) is the widely recognized methodology for describing the environmental impacts of transportation energy consumption (Schipper, Celine, & Gorham, 2000). Therefore, particularly because of the failure of [I] and [F] to address the problem, it appears that urban authorities of developing countries should make [A] and [S] the urgent priorities for mitigating the environmental impacts of the transportation sector. Benoit Lefevre (2009) built a transportation-land-use model to demonstrate that an emerging city like Bangalore can significantly curb the trajectories of transportation energy consumption with existing technologies from urban public policies such as land use, transportation and economic development. Hence, the third focus of this paper is to look for suitable urban policies to guide the transition of settlement morphology for reducing transportation energy consumption and CO2 emissions, using existing transportation technologies.

According to the three focuses described above, this paper concludes that it is urgent, first, to understand the settlement morphology and its transition process in the rapid development in the cities of developing countries; second, to determine the relationships between transportation energy consumption and the transition of settlement morphology and its underlying processes; and third, to propose that the existing transportation technologies are already adequate to take up the environmental challenges of the transportation sector, if there are suitable urban policies to guide the transitions of settlement morphology. The paper addresses these issues through a case study of Xiamen Island, which is the main urban area of Xiamen City, China.

Methodology

TRANUS, an integrated land use and transport modeling system

TRANUS is an integrated transport-land use model, which de la Barra and Perez have been developing since 1982 (De la Barra, 2005; De la Barra, Perez, & Vera, 1984). This model uses the relationships of dynamic equilibrium between urban transportation and land use to simulate the evolutionary process of cities. It has been implemented in many cities such as Baltimore, Sacramento, Osaka, Caracas and Bangalore and has been shown to have good applicability and operability (Lefevre, 2009; Modelistica, 2007).

The general structure of TRANUS is shown in Fig. 1. There are two main subsystems in TRANUS: activities and transportation. A distinction is made between demand and supply elements that interact to generate a state of equilibrium within each subsystem. The demand side in the activities subsystem is the location of and interaction between activities, showing that activities such as industries and households locate in specific places and interact with other activities. The real-estate market provides activities

Fig. 1. Model structure of TRANUS (Modelistica, 2007).
with land and floor space, thus representing the supply side. The interaction among activities generates travel requirements, and this transportation demand will be exported from activities to transportation. In the transportation subsystem, demand is represented by travel demand (imported from activities, such as people traveling from their households to their work places, or goods being transported from factories to shops), and the supply is the physical transportation facilities (such as roads, railways and maritime routes) and operative entities (transportation operators that supply transportation services, such as buses, cars, trucks and airplanes). Accessibility and transportation costs, which are calculated in the transportation subsystem, will feed back into activities. The activities and transportation are conceived as fully interrelated components with mutual dependencies. The interaction among activities gives rise to travel demand, and accessibility and transportation costs, in turn, affect activity location, interaction and the real-estate system. Each subsystem must trend to a state of equilibrium, and is also affected by the other subsystem. Therefore, based on the iterative operation in the model, TRANUS will maintain a steady state and export the simulation results when both subsystems achieve internal-external demand/supply equilibrium.

TRANUS also has some limitations. First, the structure and level of aggregation of the models is better suitable to statewide than intra-urban modeling; second, the aggregate zonal system (30+ zones) is inadequate for many urban applications; and third, calibration is difficult for lacking a statistical basis. However, TRANUS has integrated many theories of the conventional four-step transportation model (such as graph theory, queuing theory and minimum path search theory), spatial microeconomics theory, and gravity and entropy theory (De la Barra, 2005), and satisfied the analyst’s theoretical and operational requirements. Therefore the present study applied TRANUS to Xiamen Island to explore the transition of settlement morphology in terms of transport energy points.

The application of TRANUS to study area

Xiamen is a coastal sub-provincial city in the southeastern Fujian Province of China, located at 118° 04′04″E and 24° 26′46″N. Xiamen covers a land area of more than 1565 km² and a sea area of 300 km² (Xiamen Municipal Government, 2011). Because Xiamen Island is the fastest growing and most concentrated area of urbanization in Xiamen, it was chosen as the study area for our research. The application of TRANUS to Xiamen Island includes five urban sectors: activities, traffic analysis, residents, transportation mode and the road network.

Activities

Activities are divided into exogenous activities and induced activities. The exogenous activities depend on external regional factors, and induced activities are caused by other activities in the region. The main exogenous activities considered in this paper denote the demand on the employed population from the jobs resulting from a variety of industrial land-use zones. According to the travel habits of residents on Xiamen Island, we can see that the main aim of residents’ travel is to and from work (the primary focus of this paper), and that work consists of industrial and tertiary industrial employment. The types of jobs correlate with land-use types in the TRANUS model: the industrial land provides the industrial jobs, and the mixed land-use provides the tertiary industry employment, for the most part. The portion of jobs related to specific land-use types in different streets can be obtained by applying the product of the proportion of the related land use area to the total number of jobs.

Traffic analysis

The Traffic Analysis Zone (TAZ) is the basic unit of traffic analysis and the carrier of the types of social activities by the residents, as they relate to urban transportation. Data for the transportation model are usually gathered by TAZ. The model includes 789 internal zones of the urban built-up area of Xiamen Island and 4 external zones including the Jimei, Haicang, Xiangang and Tongan districts. Internal zones are the main research units in the TRANUS model and are classified by differences in settlement morphology and land-use types (see Fig. 2). The model required that the exogenous employment jobs consume the related land types and the residents who filled the employment jobs live in the communities corresponding with their own identity. Fig. 3 shows the relationships among all the types of employment lands, communities and residential groups. Looking at the residential communities, it can be seen that a particular resident group usually resides in several different community types, not only the one defined as its substitutive consumption by TRANUS model, where the probability is fixed by the choice function.

In the model, industrial land and mixed-use land provide the jobs and settlements provide the population who need jobs, and the balance between the two can be obtained according to transportation network and various modes of transportation. The vehicle flow between any two TAZs generates the energy consumption of residents travel. Under the influence of city planning and other policies, there are some alternations in land development and utilization and urban space pattern that can change the location and number of jobs available at various employment locations as well as the implementation of various policies on transport and social economy. Also, the two aspects influenced the residents’ trips, travel distance, trip mode and so on, and thereby affected the total travel energy consumption.

Residents

The portion of the resident populations considered available for employment was taken to be those in the age range of 18—60. The population the settlements can accommodate was calculated based on the building areas and types in the residential areas, with the population distributed according to the proportion of resident

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carrying capacity per settlement, which varied between the commercial settlement blocks and downtown. The statistical results from the questionnaires showed that 4.9% of the respondents work outside Xiamen Island. Therefore, taking 4.9% of the respondents as the exchange inside and outside Xiamen Island, the number of output laborers from outside to inside the island, and from inside to outside the island, are 44.9 thousand. At the same time, the workers in the TAZ can be distributed among the high-, middle- and low-income groups. Looking only at the second and tertiary (service) industries, the ratios of high-, middle- and low-income groups employed therein was found to be 1: 8: 41, translating to fractions of 0.02, 0.16 and 0.82 for these income groups.

Transportation mode and road network

According to the traffic development status of Xiamen Island, the two commute travel modes can be defined as public transportation and private transportation. The public transportation mode includes BRT, normal bus transit and taxi. The private transportation mode involves compact car, walking and bicycling. Using the TRANUS model, the choice of travel mode is determined by whether the residents have reasonable access to a particular mode, based on a penalty factor and an operation level. Generally, a penalty factor of 1 means that this travel mode is the best choice for a given population. A higher penalty factor indicates that the traffic mode is of less interest. In this paper, the penalty factor was set at 1 for public transportation for all income groups, meaning that it was both available and also the best choice. However, the penalty factor is actually set individually, for different population groups. And related literature and research data on private cars and taxis shows that ownership of a private car creates a discrepancy between the residents of different income levels. Based on these data, the penalty factors for the high-, middle- and low-income groups were individually set at 1, 1.5 and 3 for the private car and taxi aspects, and at 2, 1.5 and 1 for public transportation and walking (Lefevre, 2009).

The energy consumption of motor vehicles can be calculated by a negative exponential function in the model:

$$E_i = E_i^{\text{min}} + (E_i^{\text{max}} - E_i^{\text{min}}) \exp \left( -\mu_i V_i \right)$$

where $E_i$ is the energy consumption of the $i$ traffic mode per unit distance; $E_i^{\text{min}}$ is the minimum energy consumption per unit of distance when the $i$ traffic mode is at free running speed; $E_i^{\text{max}}$ is the maximum energy consumption when the speed of the $i$ traffic mode is close to 0 per unit of distance; $\mu_i$ is the parameter used for

Table 1

<table>
<thead>
<tr>
<th></th>
<th>BRT</th>
<th>Normal bus</th>
<th>Small bus</th>
<th>Private cars</th>
<th>Taxi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_i^{\text{min}}$</td>
<td>0.17</td>
<td>0.17</td>
<td>0.12</td>
<td>0.067</td>
<td>0.067</td>
</tr>
<tr>
<td>$E_i^{\text{max}} (0.067t)$</td>
<td>0.60</td>
<td>0.67</td>
<td>0.46</td>
<td>0.333</td>
<td>0.333</td>
</tr>
<tr>
<td>$\mu_i$</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>
revising the sharpness of the energy consumption curve at the $i$ traffic mode; $V_i$ is the speed of the $i$ traffic mode at the limit of road capacity; $i$ is the type for the travel modes in Table 1. The calculation formula is based on the link-by-link method, because the speed in different roads is link-specific. Also some research indicates that the calculation of the energy consumption of motor vehicles breaks down when the speed surpasses the limited speed in the TRANUS model. However, because there are severe constraints on motor vehicles management in Xiamen Island, all road vehicles can be calculated at the specified speed range. The energy consumption data for all motor vehicles can be found at Table 1.

Based on many years investigation, the California Department of Transportation found that factors affecting vehicle operating costs were primary vehicle type, vehicle speed, speed change and road surface (Bailly & Brinckerhoff, 1999). Empirical research indicates that vehicle operating speed is the dominant factor in determining energy consumption. Graphically, energy consumption decreases as vehicle speed increases, reaching an optimum efficiency point at mid-range speeds, after which point costs will increase as vehicle speed increases further. Fig. 4 shows the shape pattern of the relationship between energy consumption and uniform vehicle speeds, which is reported according to previous research (Bailly & Brinckerhoff, 1999). Based on the fitted exponential equation in Fig. 4, the coefficient of cars (private cars and taxi) and buses (BRT, normal bus and small bus) is 0.058 and 0.021 respectively.

Note: the data is mainly from the Xiamen City Transportation Commission, the research on BRT operating companies, and related literature (Bailly & Brinckerhoff, 1999). $V$ (the speed of the mode based on road capacity) is determined by the road type used by the motor vehicles. BRT has exclusive road rights, and its speed is 60 km/h. The speed for public transportation in a dedicated right-of-way is 60 km/h; for cars in a dedicated right-of-way, 80 km/h; for public transportation on the trunk, secondary roads and link roads, 40 km/h; for cars, 60 km/h. The speed for branch public buses is 20 km/h; for cars, 40 km/h. The speed for public buses on rural roads is 20 km/h; for cars, 30 km/h. Public buses include both normal buses and small buses; cars include private cars and taxis. The public buses all consume diesel fuel and the other vehicles all use gasoline.

Present status of urban settlement morphology in the study area

In order to better understand the settlement morphology, a large-scale survey questionnaire was distributed in Xiamen Island in 2009, targeting more than 3000 residents across the island. The sample areas covered 26 main residential areas and surrounding streets, which were selected by stratified random sampling according to the urban spatial distribution of the island and attributes such as community type and year built (see Fig. 5).

The survey included three aspects: personal attributes, including settlement type, gender, marital status, age, educational level and employment; basic conditions of families, including family size, month income, housing quantity, housing type and area; travel information, including workplace, travel mode, travel frequency and commuting time. In each settlement, 20–60 households were randomly selected and their members directly interviewed. The total number of questionnaire respondents was 1,090, resulting in 952 valid samples. From these, we selected as research objects residents who had journey-to-work trips on working days, obtaining 543 samples after this filtering.

Applying the concept of settlement morphology to the survey results from the questionnaire, the settlement morphologies of Xiamen Island were divided into four types: urban village, old city, upscale commercial settlement and general commercial settlement (see Fig. 2).

The evolution of any system is driven by a combination of internal systemic diversity and external influences of competition and synergy, i.e., it is the combined result of internal and external forces. Human settlements are not only the locations of habitat but also places of growth, association and transmutation among various urban elements. Therefore, according to Yu’s theory (2010) of urban settlement morphology, changes in morphology are driven by two main forces: voluntary individual human judgment in the selection of living space and lifestyle, and the influence of external forces.

The first important aspect is individual’s expectations, which can be seen as the originating impulse behind the transition of settlement morphology. It forms the foundation and direction of the transition process. In contemporary China, the originating impulses of settlement morphology come from changes in the settlement planning concept, with urban residents’ increasing demand for better dwelling environments. By 2008, urban residents’ per capita disposable income in Xiamen City had risen 23,948 Yuan, a 39.8-fold increase compared to 1980 (Xiamen City Bureau of Statistics & Investigation Team of National Bureau of Xiamen, 2009). Thus, the rapid increase in the income level promoted the new housing concepts of urban residents, resulting in the emergence of the commercial settlement morphology.
As for the outside influence aspect, the major driving forces of transition of settlement morphology on Xiamen Island have been the rapid urbanization and Chinese housing reform, which in some respects is even greater than the originating impulse. Housing reform has taken place from 1980 to the present, a period of nearly 30 years. Reform has established a new housing system and brought about housing commercialization, promoting the boom of the realty business. At the settlement scale, housing commercialization has greatly promoted the pluralism and humanization of settlement morphology. Real estate developers have considered many influences on settlement (such as location, green areas, environment, safety, public infrastructures, building management, community culture and so on) in the planning process, trying to consider the consumers' view, truly reflecting the new “people-oriented” approach, thus facilitating the trend of transition in accord with the residents' expectations.

In conclusion, whether it is people's exceptions or outside influences that are promoting the housing system transformation from non-commercial to commercial, the settlement morphology is tending toward commercial settlement. This transition is the major process transforming the urban village and old city into normal-grade or even upscale commercial settlement on Xiamen Island.

Scenario design

This paper constructed three scenarios of the model: business as usual (BAU), transition of settlement morphology (TSM) and transition of settlement morphology with policies (TSMP). The simulation period was morning traffic peak time from 7:00 to 9:00 at 2008 levels. The details for each scenario are presented in the following discussion.

**BAU scenario**

Considering the urban planning, economic costs and other factors, many non-commercial settlement morphologies remain on Xiamen Island, such as the urban village and the old city. Under this scenario, the study is just a simulation of the past, as of 2008, and there are no changes of settlement morphology or policies. The parameters for each sector were directly entered in TRANUS based on Sections Activities Transportation mode and road network. Some of the parameters of this transportation subsystem are shown in Appendix 1.

**TSM scenario**

The purpose of the TSM scenario is to address the second focus in this paper, finding out the changes of transportation energy consumption when the transition of settlement morphology occurred. According to 2.1 and 2.2, there is a transformation trend of settlement morphology from urban village and old city to commercial settlements. (Because the development of upscale commercial settlement involves more risk for developers and is not likely to be the major settlement morphology in Xiamen, this model does not consider that the settlement morphology will transform from urban village and old city to upscale commercial settlements.) Under this scenario, most parameters such as population, employment type for each activity, transportation energy intensity, road network, and so on, are similar to the BAU scenario. The biggest change between TSM and BAU scenarios is that the TAZs of the urban village and the old city have been assumed to transform into normal commercial settlements in the land-use sector of the model. The parameters of transformed zones are changed and re-entered as general commercial settlements, resulting in a different distribution of residents in settlements on Xiamen Island compared with the BAU scenario. The transition of settlement morphology has always accompanied rapid urbanization and the economic boom in China; hence the residents' income levels are higher than that of the BAU scenario. The ratios of high-, middle- and low-income groups were assumed to be 1.20:21.

**TSMP scenario**

Based on the TSM, the TSMP scenario adds in the urban public policies, which were used to guide the transition of settlement morphology and curb the trajectories of energy consumption and CO₂ emissions in the transportation sector. In this scenario, the policies on transportation, land use and economic development have been considered and implemented in the study area. Referring to the Planning of Xiamen or the policies that have been applied successfully in developing countries, all these policies have been implemented or may be implemented in the near future on Xiamen Island. In transportation policies, there are 3 types: giving priority to the development of public transportation (coverage rate of public traffic network is more than 78%, service radius of transit stops is at least as low as 500 m, average waiting time is less than 5 min); these are, in Xiamen, composed of four public transport terminals at the city center or tourist sites and taxi stands in crowded areas; the construction of a four-stage road network system, in which fast roads and main roads are the trunk lines and secondary main roads and branch roads are the subsidiary lines (increasing the capacity and free flow of traffic); and the construction of walkways and cycling roads. The basic principle in land-use policies is controlling the industrial land and improving the mixed-use land. The details of land use policies include: forbidding new industrial zones on the island; integrating the currently existing industrial areas and reducing their number from 20 to 14; and converting the industrial land to commercial mixed-use land (40%). This scenario also includes economic policies to increase car costs and reduce bus costs: fuel tax and increase in parking costs (30%), and fiscal subsidies for bus operation (50%).

**Results and discussion**

**Transport energy consumption of three scenarios**

Note: in the calculation, the densities of gasoline and diesel are 0.725 kg/L and 0.84 kg/L respectively; the transform indexes from gasoline and diesel to standard coal are, 1.471 tce/t and 1.4571 tce/t, the CO₂ emission factor for gasoline and diesel are 3985 g/L and 3149 g/L; the CO₂ emission is calculated as the product of energy consumption and emission factor.

Table 2 shows the result of the main features of the residents’ travel patterns, energy consumption and CO₂ emissions in the different scenarios, computed using the TRANUS model on Xiamen Island. Under the BAU scenario, the energy consumption for the morning peak travel time for Xiamen residents was 53.78 tce in 2008, with CO₂ emissions of 117.87 t, of which travel by private car accounted for 21.5%. When the settlements of Xiamen Island were changed into the commercial settlement morphology under the TSM scenario, the energy consumption per hour of trips was 60.64 tce, and CO₂ emissions were 132.9 t, with the proportion of private car traveling accounting for 31.42%, increasing 13.25%, 12.75%, and 9.58%, respectively, over the BAU scenario. With a combination of various public policies under the TSMP scenario, energy consumption was 51.12 tce, the CO₂ emissions were 112.05 t and the proportion of private car traveling for the residents was 16.75%. Compared with the BAU scenario, energy consumption, CO₂ emissions and proportion of private car traveling for the residents were reduced by 5.22%, 4.94% and 4.59% respectively. Under the BAU
In the TSM and TSMP scenarios, however, trips were reduced slightly to 910,749 and 866,955 respectively. Of all the three scenarios, the longest average trip time for residents was under the TSM scenario, at 0.55 h, while that under the BAU scenario was 0.39 h, and that under TSMP scenario only 0.31 h. On the other hand, residents’ average travel distance was 6.39 km under the BAU scenario, with 6.19 km, 5.92 km, respectively, under the TSM and TSMP scenarios, reductions of 3.13% and 7.36% compared to the BAU.

Through the simulation results, we can conclude that: first, when other socioeconomic conditions are the same and the residential settlement morphology is changed, the proportion of residents traveling by car would increase noticeably, and energy consumption and CO₂ emissions would increase accordingly; second, many relevant public policies (such as promoting public transportation, constructing road traffic facilities, controlling the use of industrial land, improving the ecological land scale, and increasing the cost of car use), can reduce the proportion of residents who travel by car and restrain the growth of CO₂ emissions and energy consumption of residents even under the residential settlement morphology change. Previous studies have proved that the differences in transportation energy consumption under different urban forms could be explained by the evolution of the spatial distribution of homes and jobs (Lefevre, 2009). In this paper, the results, as correlated with the change in spatial distribution for residents, jobs and land uses under the varying scenarios, will be analyzed in detail in the following discussions.

Changes in the spatial distribution of the residential population, jobs and land use on Xiamen Island

Fig. 6 shows the residents’ spatial distribution on Xiamen Island under the different scenarios. In the BAU scenario, there is no residential morphology transition or changes in the land use form; hence the residents and the jobs provided remain stable in each area. At present, Xiamen Island’s developed area covers more than 70% of the area of the entire island. Aside from development outside the island, the other way to enhance the land use would be to increase the intensity of development on the island. Fig. 6 shows that under the BAU scenario, residents are concentrated mainly in the southwest of the island, in the area around Xiamen University, Xiamen Port and parts of the old city. The island’s north villages are concentrated urban villages, and there are many industrial zones. The development intensity is low, and the residential population relatively scattered. Under the TSM scenario, the overall land use pattern is similar to the basic scenario, but the residential population has increased because the original residential house has

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Trips</th>
<th>Average distance (km)</th>
<th>Share of private cars (%)</th>
<th>Average time (hour)</th>
<th>Energy consumption Gasoline(L)</th>
<th>Diesel(L)</th>
<th>Sum(tce)</th>
<th>CO₂ Emission(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>949,936</td>
<td>6.39</td>
<td>21.50</td>
<td>0.39</td>
<td>45838</td>
<td>3987</td>
<td>53.78</td>
<td>117.87</td>
</tr>
<tr>
<td>TSM</td>
<td>910,749</td>
<td>6.19</td>
<td>31.42</td>
<td>0.55</td>
<td>53605</td>
<td>2821</td>
<td>60.64</td>
<td>132.9</td>
</tr>
<tr>
<td>TSMP</td>
<td>866,955</td>
<td>5.92</td>
<td>16.75</td>
<td>0.31</td>
<td>42502</td>
<td>4723</td>
<td>51.12</td>
<td>112.05</td>
</tr>
</tbody>
</table>

![Fig. 6. Residents’ spatial distribution of Xiamen Island under the three different scenarios.](image-url)
changed into the commodity house, and additional infrastructure and residential facilities have been built. Therefore, the residential living environment has been improved. As the TSMP scenario is based on the TSM scenario, this new reform also attracts a large population. Affected by public policy, not only residential living environments but also many travel conditions have greatly improved. Therefore life has become more convenient, and residents are more concentrated than in the TSM scenario.

Fig. 7 shows spatial distribution of employment on Xiamen Island under the different scenarios. In the BAU and TSM scenarios, there is no special policy for land use, and industrial jobs still keep their original distribution in the major industrial parks. Tertiary industry is distributed in the main business districts and residential areas. Except for the growth of service jobs associated with the reconstruction of the northern residential settlement in the TSM scenario, total employment remains stable in other areas. In contrast, although the process of the TSMP scenario is the same as for the TSM scenario, jobs distribution has changed because of different public policies, especially the land-use policy. In this scenario, Xiamen Island’s industrial land is restricted, and additional industrial parks are no longer being approved. In addition, measures such as integrating existing industrial parks, no longer approving garden-type industrial parks, and reusing lands that were idle and inefficient, have been put into practice. Compared with other scenarios, industrial parks have been reduced from their original 20 to 14, the average building scale has been reduced from 8.64 km² to 5.52 km², and the previous industrial land has been converted to residential or mixed-use land. The reduction of industrial land would also reduce the number of industrial jobs. Simultaneously, the increase in mixed-use land area and residential facilities would provide more employment opportunities in the tertiary industries, such as service and retail jobs. The nature of this type of work would lead to a more scattered jobs distribution in the TSMP scenario is than in other scenarios.

To present the anticipated changes in urban land use in the TAZs, the land-use change distributions under the different scenarios were chosen as indexes, and are shown in Fig. 8. It is clear that the land use change patterns are different under these three scenarios. In the TSMP scenario, the changes in land use are most evident in the decline of industrial land, primarily in the northern and eastern areas of the island. The largest decrease in the area of industrial land is about 20 ha; almost all of the industrial parks would be demolished. Simultaneously, with the transition of settlement morphology, service facilities would be more complete and there would be a slight increase in mixed-use land. While most of increases are smaller than 1 ha, yet they are distributed widely and cover almost all of the residential communities on Xiamen Island. All of the above changes also mean that the jobs in the tertiary industries such as retail, service, etc. would be more widely distributed and be closer to residential settlements.

The impacts of spatial distribution change on transport energy consumption

According to the spatial distribution changes for residents, jobs and land use in these three scenarios, in the TSMP scenario residents and jobs would be more widely distributed and land use would have a greater densification and diversification than under the other two scenarios. Such characteristics can lead to both fewer and shorter trips because it would become easier to find jobs near residential areas; this trend has been proved in previous studies. As noted, trips and average distances under the TSMP scenario are smaller than under either the BAU or the TSM scenarios, and these simulation results also validate the correctness of these views.

Simultaneously, the results also show a different share of private car usage: 21.5% for the BAU scenario, 31.42% for the TSM and

Fig. 7. Spatial distribution of employment on Xiamen Island under different scenarios.

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16.75% for the TSMP. The reasons for this phenomenon are the transformations in settlement morphology, dispersed residents and jobs and the densification and diversification of land uses, and, for TSMP, policy changes. For the TSM scenario, residents would have a higher living standard than for the BAU, but there would be little improvement in traffic infrastructures, especially public transportation, and thus residents would have to buy cars to meet their increasing travel demands. This requirement would result in the greatest share of private car use, of the three scenarios. The policies of the TSMP scenario would encourage the residents to use public transportation, replacing cars (economic policies increase the costs of cars and transportation policies improve the conditions of public transportation), resulting in the lowest modal share of cars under TSMP.

Finally, the TSM scenario has the longest average trip time, which would result in the worst congestion of any scenario. The reasons for this phenomenon are the highest modal share of private cars and little improvement of traffic conditions. The greater congestion generates longer travel times under TSM than under TSMP, and even longer than under the BAU scenario.

In conclusion, the differences in terms of average trip distance and time, modal share of cars, together with the residential, employment and land-use changes, explains the differences in energy consumption and CO₂ emissions, under the three scenarios. For the TSMP scenario, the transition of settlement morphology and land use policies lead to more widely dispersed residential areas and jobs, along with densification and diversification of land use, while transportation and economic policies discourage the increase of private cars, thus reducing the average number and length of trips and discouraging the use of private cars for these trips, compared to both the TSM and BAU scenarios. Hence the TSMP scenario can generate the greatest energy saving and lowest emissions of CO₂.

Conclusion

The settlement morphology in China is undergoing a great transition because of the people’s expectations and outside influences such as housing reform and rapid urbanization. This transition will bring great changes to the urban spatial distribution of population, jobs and land use, and hence to residents’ travel patterns, resulting in different transportation energy consumption and CO₂ emissions. Beyond the case of Xiamen Island, the result shows the great effect of these patterns on transportation energy consumption and CO₂ emissions for residents’ trips, and that energy consumption will increase with the transition of settlement morphology. Simultaneously, the results also reveal that public urban policies can curb this situation, cutting down the energy consumption and CO₂ emissions, having results similar to those of a previous study of transportation-land-use policies (Lefèvre, 2009). Moreover, from the aspect of the ASIF framework, this paper demonstrates that the action of (A) and (S) can reduce the transportation energy consumption under the change of settlement morphology currently occurring in China. Therefore, existing transportation technologies are sufficient for the government to meet the challenges of the growth of transportation energy consumption brought about by the transition of settlement morphology, especially for developing countries.

Acknowledgment

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Appendix 1

Key parameters of TRANUS application to Xiamen Island

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Note: VTT = value of travel time, VWT = value of waiting time, %VA = % vehicle availability, MGTGR = min trip generation rate, MGR = max trip generation rate, DE = demand elasticity, MSE = Model Split Elasticity, MCLS = Model Choice Logit Scaling, PCE = Path Choice Elasticity, PCLS = Path Choice Logit Scaling.

References


