The Urban China Initiative’s grant program

The mechanism and management policies of urban form and urban CO₂ efficiency in China

Associsate Professor Dr. Yong Liu.
College of Management and Economics, Tianjin University, Tianjin, China

Professor Dr. Tong Chen
Institute of Public Administration, Tianjin University, Tianjin, China

Dr. Xiaodong Song
Institute of urban environment, Chinese Academics of Science, Xiamen, China

2012.8
Abstract

The present study aims at exploring whether aspects of urban form are associated with urban CO₂ efficiency in China. Quantitative indicators relating to urban form (form ratio, compactness ratio, and elongation ratio and population density) and urban CO₂ efficiency (CO₂ economic efficiency and CO₂ social efficiency) were selected and quantified using remote sensing and GIS methods. The urban form aspects of form ratio and compactness ratio were positively correlated with urban CO₂ economic efficiency. Conversely, the urban elongation ratio exhibited negative correlations with urban CO₂ economic efficiency. Regarding urban CO₂ social efficiency, no significant correlation is found with urban form. These results indicate that, within China, designing cities to be compact may be lead to increase in urban CO₂ economic efficiency, but if the population density is too high the increased pollution costs will result in a decrease in environmental efficiency. The key point may be less whether policy should favor urban compactness, but rather that policy should account for that above an optimum degree of urban compactness disadvantageous from over-crowding will manifest.
Contents

1. INTRODUCTION .................................................................................................... 4

2. LITERATURE REVIEW ....................................................................................... 5
   2.1 URBAN FORM ..................................................................................................... 5
   2.2 URBAN CO\textsubscript{2} EFFICIENCY ............................................................... 6

3. METHODS ................................................................................................................ 7
   3.1 INDICATORS OF URBAN FORM ............................................................... 8
      3.1.1 Form Ratio .............................................................................................. 8
      3.1.2 Compactness Ratio ................................................................................. 8
      3.1.3 Elongation Ratio ..................................................................................... 9
      3.1.4 Urban Population Density ................................................................. 9
   3.2 INDICATORS OF URBAN CO\textsubscript{2} EFFICIENCY ................................................. 10
   3.3 DATA PROCESSING ...................................................................................... 12

4. RESULTS AND ANALYSIS .................................................................................. 14
   4.1 URBAN FORM ............................................................................................. 14
   4.2 URBAN CO\textsubscript{2} EFFICIENCY .................................................................. 18
   4.3 MECHANISM OF URBAN FORM AND URBAN CO\textsubscript{2} EFFICIENCY .......... 18

5. CONCLUSIONS AND POLICIES .................................................................... 25

ACKNOWLEDGMENTS ......................................................................................... 26

REFERENCES ......................................................................................................... 27
1. Introduction

Urbanization, urban population growth, population dispersion and the spread of settlement patterns have triggered debates on the relationship between urban form and urban sustainable development. Meanwhile, given the growing evidence and scientific consensus about global climate change, urban planning, such as compact city planning and low carbon city planning, is challenged by a multitude of climate change-related risks and opportunities that require measures and assessments. This is especially relevant in China, the world’s largest consumer of energy and emitter of CO₂ (Gregg et al., 2011).

Urban form, which is a term that broadly refers to the layout and design of a city, affects environment and water quality through the consumption or the fragmentation of natural cover (Tang and Wang, 2007). A number of countries, such as the United Kingdom and the Netherlands, have adopted policies of urban planning that better address environmental issues through urban form planning (National Physical Planning Agency, 1991; Department of Environment, 1992). In China, rapid urbanization and urban sprawl have not only consumed precious land resources, but have resulted in increased energy demands and congestion of transportation networks. These factors inhibit Chinese cities away from developing sustainably. Although Chinese governments have paid great attention to urban sustainable development and encouraged innovative policies that utilize changes in urban form to improve the development of low carbon city, until recently there has been a lack of data and
resources to empirically investigate the relationship between various aspects of urban form and urban CO\textsubscript{2} efficiency. Therefore, the aim of the present research is to explore this issue for urban areas within China. The results provide a promising basis for decision-making to support urban planning and policy that lead towards sustainable and low carbon city development.

2. Literature Review

2.1 Urban form

There are various indicators representing urban form. Which indicators are ultimately used for a given analyses depend on the data that are available and the needs of the study. For example, Huang et al (2007) employed five indicators (compactness, centrality, complexity, porosity and density) for a global comparative study. Tang and Wang (2007) used building lot space, road space, green space, water coverage and land consumption per capita to study the link between urban form with traffic and air pollution. Zhang (2005) adopted a gravity model-based measure of spatial accessibility, and took the general form known as the Hansen accessibility model (Hansen, 1959) to look at non-work related travel.

Especially, the most commonly used measures of urban compactness are associated to density grouped by distinguishing between molecular and molar measures (Alexander and Reed, 1988; Newman and Kenworthy, 1989; Burton, 2002). However, according to the opinions of Burton (2002), in terms of policy outcome measurements, the reuse of urban land, rather than the density of new development,
has become the key indicator of compactness. Meanwhile, Burton (2002) also
described the development of a large set of urban compactness indicators used in an
investigation of social sustainability outcomes in twenty-five English towns and cities.
Huang et al (2007) employed the compactness index of the largest patch (CILP) for a
global comparative study. Similarly, though in more detail, Song (2005) developed a
series of indicators (street design and circulation systems, density, land-use mix,
accessibility and pedestrian access) to study the impact of urban growth management.

To analyze the relationship between urban form and walking and bicycling
activity, McMillan (2007) designed indicators presenting urban form, such as
perceived traffic safety, perceived crime safety, actual traffic safety and aesthetics.
Similarly, though in more detail, Song (2005) developed a series of indicators (street
design and circulation systems, density, land-use mix, accessibility and pedestrian
access) to study the impact of urban growth management. Recently a study by
Schwartz (2010) showed that within Europe many indicators of urban form are highly
correlated to each other; however, over large regional scales, urban form, as defined
by these indicators, can be quite heterogeneous.

2.2 Urban CO2 efficiency

Similarly to urban form, the concept of urban CO2 efficiency has been the focus of
a great deal of research, and for which several indicators and definitions have been
assigned. In a broad sense, CO2 efficiency is an index of financial or beneficial
outputs gained with respect to the CO2 emission required (Tahara et al., 2005).
Various indicators of CO$_2$ efficiency have been proposed. For example, Tahara et al. (2005) defined total CO$_2$ efficiency, direct CO$_2$ efficiency and indirect CO$_2$ efficiency; furthermore, they characterized the CO$_2$ efficiency with respect to certain indicators (Producer’s price, Cost, Gross value-added, Direct and indirect CO$_2$ emissions). Gallachóir (2004) compared cars in terms of CO$_2$ efficiency, employing the amount of grams of CO$_2$ associated with each km driven. Similarly, McKinnon (1999), Leonardi and Baumgartner (2004) calculated the CO$_2$ emission efficiency using an indicator metric, tonne-km (tkm) per emitted kg CO$_2$. To calculate the CO$_2$ efficiency of industry, Rao et al (2010) employed the consumption of energy as input, and the CO$_2$ emissions as output. Recently, Perkins and Neumayer (2011) defined a country’s CO$_2$ efficiency: GDP divided by CO$_2$ emissions. In China, Chen and Zhu (2011) proposed Logarithmic Mean Divisia Index (LMDI) model to include Human Development Index (HDI), GDP per person as output indicators, and CO$_2$ emissions per person as input indicator, which is similar to the research of Zhu and Liu (2011).

As can be seen from this survey of the literature, recognized indicators for measuring urban form and urban CO$_2$ efficiency are open to widely differing interpretations and ultimately depend on the aims of the study. Furthermore, there appears to be a lack of research on the relationship between urban form and urban CO$_2$ efficiency indicators, within China and elsewhere.

3 Methods

Data related to urban form and urban CO$_2$ efficiency were collected from four
central municipalities and of the 26 provincial capitals in China (Lhasa and Taipei were not included because of data absence).

3.1 Indicators of urban form

Based on practicality and the availability of good quality and readily accessible data, four indicators representing urban form were chosen: form ratio, compactness ratio, elongation ratio and urban population density.

3.1.1 Form Ratio

Horton put forward the concept of Form Ratio \((FR)\) in 1932 (Haggett, 1997), which based on the so-called long axis-based method. The formula for \(FR\) is:

\[
FR = \frac{A}{L^2} \tag{1}
\]

Where \(A\) is the urban area and \(L\) is the length of the long-axis of the area. It is generally considered that the inner connection of a city is more accessible when the ratio is from \(1/2\) to \(\pi/4\) (Haggett, 1997).

3.1.2 Compactness Ratio

There is no recognized common practice to which to turn when selecting urban compactness indicators, consequently, current practice may be described as ad hoc and piecemeal (Green and Champion, 1991): there are nearly as many approaches to selecting indicators as there are different studies, but according to the conclusions of Chen (2011), the shortcoming of Horton’s (1932) form ratio is that the standard circle is not taken into account. To remedy this fault, Gibbs gave an adjusted formula by
taking into consideration the standard circle in 1961 (Haggett et al., 1977). This modified form ratio is just Cole’s (1960) compactness ratio and the reciprocal of Stoddart’s (1965) ellipticity index. Furthermore, Cole’s compactness ratio has been widely and successfully used (Chen, 2011). Meanwhile, according to practicality and the availability of good quality and readily accessible data, the indicator related to urban compactness has been chosen. Compactness ratio measures the shape characteristics of a region by employing the minimum circumscribed circle as standard, which was put forward by Cole (1960). The formula is:

$$CR = \frac{A}{A'}$$  \hspace{1cm} (2)

Where \(A\) is the urban area, and \(A'\) is the smallest circumscribed circle of the area. The higher the ratio is, the more compactness a region is.

3.1.3 Elongation Ratio

The Elongation Ration (ER) measures the extended degree of a region. The following equation was proposed in 1969 by Webbity (Haggett, 1997):

$$ER = \frac{L}{L'}$$  \hspace{1cm} (3)

Where \(L\) is the length of the long-axis of a region, and \(L'\) is the length of the short-axis of a region. The more extended the urban shape is, the higher the ratio is.

3.1.4 Urban Population Density

This parameter is calculated as:

$$UPD = \frac{P}{A^*}$$  \hspace{1cm} (4)

Where \(P\) is the estimated population in the built-up area, \(A^*\) is the corresponding
area (Kenworthy and Hu, 2002). Unfortunately, $A^*$ is not an administrative unit on which basic population data are gathered in China. Chinese urban statistical data are collected by administrative units. A city consists of an urban area and counties, towns and rural areas. The normal statistical representations of urban areas or zones in China are referred to as “Quan Shi” and “Shi Xia Qu”, meaning “City-Wide Area” and “City District”, respectively. Suburbs in Chinese cities are mainly rural or peri-urban, and thus generally cannot be regarded as part of the urban agglomeration. Both “City-Wide Area” and also “City District” includes areas of land that are more or less rural in character, and thus are not ideal statistical units for studying urban areas. Built-up areas (“Jian Cheng Qu”), from which $A^*$ is taken, includes residential, commercial, and industrial land etc. as well as roads and streets; meanwhile, it excludes rural land, forests, large areas of contiguous undeveloped or vacant land, and regional scale open spaces (not local open spaces). Under these circumstances, the only way to calculate $UPD$ is through analysis of existing data and estimation where necessary. Therefore, $P$ here is estimated as the non-agricultural population in a City District (Chen et al, 2008).

3.2 Indicators of urban CO2 efficiency

Urban CO$_2$ efficiency indicators consist of combinations of input and output

---

1 The A in Form Ratio and Compactness Ratio is calculated by Landsat images and related thematic maps, and does not exclude contiguous undeveloped or vacant land and open space, which is good for depicting urban form roundly. However, $A$ is not fit for calculating Urban Population Density because it does not exclude contiguous undeveloped or vacant land and open space. Consequently, $A^*(built-up\ area)$ is employed to calculate urban population density.
indicator. To design these indicators, an initial list of indicators was developed based on earlier researches mentioned in the literature review. Furthermore, according to practicality, data availability, and cost effectiveness, the final list of indicators have been selected. The input indicator was total amount of CO₂ emissions (tons). According to the results of IPCC (2007) and Chung et al (2009), CO₂ emissions are mainly from fossil energy consumption. Therefore, the total amounts of CO₂ emissions of urban area were estimated from the amounts of energy consumption (Liu et al., 2010; Li and Li, 2010; Hu et al., 2004; Wang et al., 2011). This indicator is calculated as:

$$C_{it} = \sum E_{ijt} \eta_j$$  \hspace{1cm} (5)

Where $C_{it}$ is the estimated CO₂ emission of $i$-th city in $t$ year, $E_{ijt}$ is the $j$-th energy consumption of $i$-th city in $t$ year. $\eta_j$ is the emission factor of $j$-th energy. According to the Chinese energy statistical yearbook, the end-use consumption of energy is sorted to nine categories, including coal, gasoline, diesel fuel, natural gas, kerosene, fuel oil, crude oil, electricity and coke. Unfortunately, urban area is not an administrative unit on which basic energy data are gathered in Chinese energy statistical yearbook, therefore the energy consumption data were collected from Chinese urban statistical yearbook (1986, 1997 and 2008). Because of different statistical regulations from 1980s to 2000s, the nine categories of energy cannot be collected fully. Under these circumstances, the only way to calculate $C_{it}$ is through analysis of existing data and estimation where necessary. So, $E$ here is including the consumption of coal gas, electricity and Liquefied Petroleum Gas.
The output indicators were included GDP (RMB), social welfare (average number of doctors per 10 thousand inhabitants, total amount of students, and total amount of employee). All the data were collected from Urban Statistical Yearbook of China (2008), China Statistical Yearbook (2008) (See Table 1).

### Table 1. Indicators for Urban CO₂ Efficiency

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of CO₂ emissions</td>
<td>10⁴ ton</td>
</tr>
<tr>
<td>Co₂-electricity</td>
<td></td>
</tr>
<tr>
<td>Co₂-coal gas</td>
<td></td>
</tr>
<tr>
<td>Co₂-Liquefied Petroleum Gas</td>
<td></td>
</tr>
<tr>
<td><strong>Output indicators</strong></td>
<td></td>
</tr>
<tr>
<td>GDP</td>
<td>10⁴ yuan</td>
</tr>
<tr>
<td><strong>Social welfare indicators</strong></td>
<td></td>
</tr>
<tr>
<td>Total amount of students</td>
<td>10⁴ person</td>
</tr>
<tr>
<td>Average number of doctors per 10³ inhabitants</td>
<td>Person</td>
</tr>
<tr>
<td>Total amount of employee</td>
<td>10⁴ person</td>
</tr>
</tbody>
</table>

#### 3.3 Data processing

The urban area term, \( A \), is defined as that within the urban land boundary, as identified here using Landsat images and related thematic maps. 30 Landsat TM images (from 2006 to 2007) were employed to interpret urban land areas, using ERDAS IMAGING 9.1 and ArcGIS9.3 for data processing. According to visual
interpretation of satellite images and auxiliary thematic maps, with the assistance of administrative boundary maps, the urban land boundary was interpreted. A popular TM band combination of five, four and three in RGB (Red, Green and Blue) color space was used to facilitate the difference of urban land and non-urban land (Guindon et al, 2004). Beijing is presented as an illustrative example in Figure 1.

![Figure 1. Example of urban growth boundary interpretation in Beijing](image)
Urban CO₂ efficiency plays a key role in expressing how efficient the economic activity is with regard to CO₂ emissions. According to the definition, CO₂ efficiency is measured as the ratio between the values of what have been produced (such as wage, jobs, GDP etc) and the CO₂ emissions of the product or service. Two types of ratio-based urban CO₂ efficiencies were measured: CO₂ economic efficiency and CO₂ social efficiency. CO₂ economic efficiency (Eq. (3)) was measured by the ratio of the GDP to the total CO₂ emissions, and CO₂ social efficiency (Eq. (4)) was measured by the ratio of the social welfare indicators (the sum of total amount of students, average number of doctors per 10 thousand inhabitants, and total amount of employee).

\[
CO_{2}\text{economic efficiency} = \frac{GDP}{Total\ amount\ of\ CO_2\ emissions} \tag{6}
\]

\[
CO_{2}\text{social efficiency} = \frac{Social\ welfare\ indicators}{Total\ amount\ of\ CO_2\ emissions} \tag{7}
\]

4. Results and analysis

4.1 Urban form

Calculated urban form indicators for all 30 Chinese urban areas considered here are presented in table 2 and figure 2-4. As can be seen from table 2, the average population density of these cities was 0.95 people / km², and 13 of the cities had population densities above 10,000 people / km². (See table 2 for more details).
<table>
<thead>
<tr>
<th>Cities</th>
<th>Estimated population in built-up area (10k persons)</th>
<th>Built-up area (km²)</th>
<th>Population Density (10k persons/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>901.96</td>
<td>1289</td>
<td>0.6997</td>
</tr>
<tr>
<td>Changchun</td>
<td>254.17</td>
<td>285</td>
<td>0.8918</td>
</tr>
<tr>
<td>Changsha</td>
<td>183.56</td>
<td>181</td>
<td>1.0141</td>
</tr>
<tr>
<td>Chengdu</td>
<td>395.8</td>
<td>408</td>
<td>0.9701</td>
</tr>
<tr>
<td>Chongqing</td>
<td>617.66</td>
<td>667</td>
<td>0.926</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>155.32</td>
<td>170</td>
<td>0.9136</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>636.76</td>
<td>844</td>
<td>0.7545</td>
</tr>
<tr>
<td>Guiyang</td>
<td>154.98</td>
<td>132</td>
<td>1.1741</td>
</tr>
<tr>
<td>Haikou</td>
<td>91.48</td>
<td>91</td>
<td>1.0053</td>
</tr>
<tr>
<td>Hangzhou</td>
<td>269.3</td>
<td>345</td>
<td>0.7806</td>
</tr>
<tr>
<td>Harbin</td>
<td>344.37</td>
<td>336</td>
<td>1.0249</td>
</tr>
<tr>
<td>Hefei</td>
<td>166.38</td>
<td>225</td>
<td>0.7395</td>
</tr>
<tr>
<td>Hohhot</td>
<td>86.67</td>
<td>150</td>
<td>0.5778</td>
</tr>
<tr>
<td>Jinan</td>
<td>330.26</td>
<td>315</td>
<td>1.0484</td>
</tr>
<tr>
<td>Kunming</td>
<td>173.43</td>
<td>253</td>
<td>0.6855</td>
</tr>
<tr>
<td>Lanzhou</td>
<td>184.62</td>
<td>176</td>
<td>1.049</td>
</tr>
<tr>
<td>Nanchang</td>
<td>176.59</td>
<td>109</td>
<td>1.6201</td>
</tr>
<tr>
<td>Nanjing</td>
<td>456.34</td>
<td>577</td>
<td>0.7909</td>
</tr>
<tr>
<td>Nanning</td>
<td>133.47</td>
<td>179</td>
<td>0.7456</td>
</tr>
<tr>
<td>Shanghai</td>
<td>1174.05</td>
<td>886</td>
<td>1.3251</td>
</tr>
<tr>
<td>Shenyang</td>
<td>415.17</td>
<td>347</td>
<td>1.1965</td>
</tr>
<tr>
<td>Shijiazhuang</td>
<td>237.73</td>
<td>187</td>
<td>1.2713</td>
</tr>
<tr>
<td>Taiyuan</td>
<td>232.15</td>
<td>238</td>
<td>0.9754</td>
</tr>
<tr>
<td>Tianjin</td>
<td>548.1</td>
<td>572</td>
<td>0.9582</td>
</tr>
<tr>
<td>Urumchi</td>
<td>171.94</td>
<td>202</td>
<td>0.8512</td>
</tr>
<tr>
<td>Wuhan</td>
<td>451.61</td>
<td>451</td>
<td>1.0014</td>
</tr>
</tbody>
</table>
Xian 326.92 268 1.2199
Xining 72.21 65 1.1109
Yinchuan 73.96 107 0.6912
Zhengzhou 202.17 321 0.6298

maximum 1174.05 1289 1.6201
(Shanghai) (Beijing) (Nanchang)
minimum 72.21 65 0.5778
(Xining) (Xining) (Hohhot)
average 320.637667 345.866667 0.954746667
std.dev 251.754291 275.439553 0.23282714


The results indicated that the average of Form Ratio was 0.2648, and of most cities (66.67%) ranged from 0.08 to 0.39, with only four cities (Beijing, Changsha, Shanghai and Xian) above 0.40. (See Figure 2)
As can be seen from Figure 3, compactness ratio of most cities (66.67%) was between 0.20 and 0.49; meanwhile, the average of urban compactness ratio was 0.337, and also only four cities (Beijing, Changsha, Shanghai and Xian) above 0.50. (See Figure 3)

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic</td>
<td>Statistic</td>
<td>Statistic</td>
<td>Std. Error</td>
</tr>
<tr>
<td>0.11</td>
<td>0.53</td>
<td>0.34</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Finally, the results indicated that Elongation Ratio (1.6 – 17) was consistently greater than both the Form Ratio (0.09 – 0.42) and Compactness Ratio (0.11 – 0.53). The average of the ratio was 4.189, and most cities (73.33%) ranged from 1.00 to 3.90. (See Figure 4)
Figure 4 the results of urban Elongation Ratio

<table>
<thead>
<tr>
<th>Zhengzhou</th>
<th>Yinchuan</th>
<th>Xining</th>
<th>Xian</th>
<th>Wuhan</th>
<th>Urumchi</th>
<th>Tianjin</th>
<th>Taiyuan</th>
<th>Shijiazhuang</th>
<th>Shenyang</th>
<th>Shanghai</th>
<th>Nanning</th>
<th>Nanjing</th>
<th>Nanchang</th>
<th>Lanzhou</th>
<th>Kunming</th>
<th>Jinan</th>
<th>Hohhot</th>
<th>Hefei</th>
<th>Harbin</th>
<th>Hangzhou</th>
<th>Haikou</th>
<th>Guiyang</th>
<th>Guangzhou</th>
<th>Fuzhou</th>
<th>Chongqing</th>
<th>Chengdu</th>
<th>Changsha</th>
<th>Changchun</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Error</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.61</td>
<td>16.99</td>
<td>4.19</td>
<td>0.57</td>
<td>3.15</td>
</tr>
</tbody>
</table>

4.2 Urban CO2 efficiency

According to equation 5, Urban Statistical Yearbook of China (2008) and China Statistical Yearbook (2008), as well as China Energy Statistical Yearbook (2008). The results of indicators for urban CO2 efficiency are presented in Table 3. The average
value of total amount of CO$_2$ emissions was $2224.20 \times 10^4$ ton, and the average value of GDP was $2790.21 \times 10^4$ yuan (see Table 3).

### Table 3. Descriptive Statistics of Indicators for Urban CO$_2$ Efficiency

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Units</th>
<th>Mean</th>
<th>Std. dev.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input indicator</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total amount of CO$_2$ emissions</td>
<td>$10^4$ ton</td>
<td>2224.20</td>
<td>2407.03</td>
<td>10800.00</td>
</tr>
<tr>
<td>Co$_2$-electricity</td>
<td></td>
<td>1864.30</td>
<td>2050.79</td>
<td>9650.00</td>
</tr>
<tr>
<td>Co$_2$-coal gas</td>
<td></td>
<td>325.47</td>
<td>712.99</td>
<td>3610.00</td>
</tr>
<tr>
<td>Co$_2$-Liquefied Petroleum Gas</td>
<td></td>
<td>34.48</td>
<td>57.29</td>
<td>290.00</td>
</tr>
<tr>
<td><strong>Output indicators</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GDP</td>
<td>$10^4$ yuan</td>
<td>2790.21</td>
<td>2669.18</td>
<td>11846.39</td>
</tr>
<tr>
<td><strong>Social welfare indicators</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total amount of students</td>
<td>$10^4$ person</td>
<td>85.58</td>
<td>49.10</td>
<td>203.00</td>
</tr>
<tr>
<td>Average number of doctors per $10^3$ inhabitants</td>
<td>Person</td>
<td>36.24</td>
<td>9.03</td>
<td>38.48</td>
</tr>
<tr>
<td>Total amount of employee</td>
<td>$10^4$ person</td>
<td>106.03</td>
<td>107.06</td>
<td>514.00</td>
</tr>
</tbody>
</table>


The results of the urban CO$_2$ economic efficiency are presented in Figure 5. The average value of CO$_2$ economic efficiency was 1.50. The minimum was 0.22 and the maximum was 3.34. Most of cities (86.67%) ranged from 0.50 to 2.50, and only two cites above 2.50, and two cities below 0.50.
Figure 5. The results of urban CO₂ economic efficiency

The results of the urban CO₂ social efficiency are presented in Figure 6. The average value of CO₂ social efficiency was 0.12. The minimum was 0.02 and the maximum was 0.21. Most of cities (86.67%) ranged from 0.05 to 0.20, and only one city above 0.20, and three cities below 0.05.
As can be seen from table 4, a Pearson correlation matrix of the urban form indicators and urban CO2 efficiency is presented. The urban form indicators: Form
Ratio, Compactness Ratio and Elongation Ratio manifested significant correlation with urban CO₂ economic efficiency. Especially, Form Ratio and Compactness Ratio manifested positive correlation with urban CO₂ economic efficiency, while Elongation Ratio manifested negative correlation with urban CO₂ economic efficiency, indicating that urban compactness could be a contributing factor to urban CO₂ economic efficiency.

<table>
<thead>
<tr>
<th>CO₂ economic efficiency</th>
<th>Form ratio</th>
<th>Compactness ratio</th>
<th>Elongation ratio</th>
<th>Population density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson Correlation</td>
<td>0.387*</td>
<td>0.387*</td>
<td>-0.393*</td>
<td>0.161</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.035</td>
<td>0.035</td>
<td>0.032</td>
<td>0.394</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ social efficiency</th>
<th>Pearson Correlation</th>
<th>Compactness ratio</th>
<th>Elongation ratio</th>
<th>Population density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.193</td>
<td>0.193</td>
<td>-0.332</td>
<td>-0.029</td>
</tr>
<tr>
<td>N</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4 Pearson Correlations Analysis between Urban form and Urban CO₂ efficiency

Urban compactness is characterized by relative high density, mixed land-use and pedestrian-oriented habitation (Burton, 2000). The abovementioned correlation could be rationalized by some causal effects, for example, less private car dependency, hence resources and time required for travelling are saved, and the preservation of green fields and arable land (Williams et al., 2000). Other potential advantages, in terms of economic efficiency, of compact cities are less material and energy use for infrastructure construction per capita, such as reduced length and service run of pipe.
lines, roads, etc, heat and energy preservation from less exposed wall and roof area per capita, and more multi-family houses sharing foundations and resources. Furthermore, an increase in compaction helps exploit economies of scale for resources (Capello and Camagni, 2000). All of these potential benefits, along with others, could play roles in promoting urban CO₂ economic efficiency.

On the contrary, Elongation Ratio demonstrated strong negative correlations with urban CO₂ economic efficiency. This indicates that outward urbanized expansion has an undermining influence on urban CO₂ economic efficiency. This and related trends have been seen for previous studies of Chinese cities, in which the rapid development of urbanization is often viewed unsustainable because of environmental degradation and resource depletion. Zhang (2000) reported how urban expansion slid into urban sprawl, which has resulted in an increasing waste of land resources. Yeh and Li (2000) concluded the patterns of urban sprawl in China took no consideration of urban form, agricultural land use and energy consumption. Urban sprawl, indicated by an increased elongation ratio, is also associated with longer travel distances and thus extra fuel and resource consumption (Yeh and Li, 2000). Regarding urban CO₂ social efficiency, however, only weak, insignificant (at the 0.05 level (two-tailed)) negative correlations could be found with respect to Population density (-0.029) and Elongation Ratio (-0.332).

The abovementioned results indicate that compact development may have positive urban CO₂ economic efficiency consequences in China, in the absence of considering pollution costs.
Thus, from an urban planning perspective, this could indicate a need to balance city compactness with limits of population density. Compared with other countries, the population densities of Chinese cities are quite high (Kenworthy and Hu, 2002), and moreover, the infrastructure investments are relatively limited, which has exhausted urban environmental carrying capacity (Jenks and Burgess, 2000). In addition, based on the research of Richardson et al. (2000), the higher level of mixed-uses in Chinese cities was accompanied by various social-environmental problems. The combination of rapid urbanization resulting from explosive urban population and high urban densities has made for unsustainable dispersed development practices, and consequently, the urban environment efficiency exhibits a
negative correlation with urban population density (Liu et al, 2012). What this ultimately indicates is a trade-off. When not considering pollution as an input or cost, better urban CO$_2$ economic efficiency is attained by compact cities.

5 Conclusions and Polices

This present research provided a quantitative analysis of the relationship between specific indicators of urban form and urban CO$_2$ efficiency for 30 Chinese urban areas.

The results found that urban form indicators: Form Ratio, Compactness Ratio and Elongation Ratio manifested significant correlation with urban CO$_2$ economic efficiency. Especially, Form Ration and Compactness Ratio manifested positive correlation with urban CO$_2$ economic efficiency, while Elongation Ratio manifested negative correlation with urban CO$_2$ economic efficiency, indicating that urban compactness could be a contributing factor to urban CO$_2$ economic efficiency. However, regarding urban CO$_2$ social efficiency, only weak, insignificant negative correlations could be found with respect to Population density and Elongation Ratio.

Consequently, this indicates that low carbon city policy favoring compact development may have positive CO$_2$ economic efficiency consequences in China. Successful urban development should prioritize the minimizing threats from wasteful use of non-sustainable resources. Furthermore, it should not draw on the resources to an extent that disrupts dynamic equilibrium of urban ecosystem, which would lead to long term environmental consequences. As mentioned above, although there has been
growing support on compact city theories and policies (Williams et al., 2000; Burton, 2001), there are also those who argue against the process of urban compaction on the ground that higher density led to traffic congestion, greater air pollution, noise and overcrowding (Rudlin and Falk, 1999; Tony, 1996). Thus, there is a complex trade-off between benefits of increasing compactness at the same time increasing the population density. According to the conclusions of the present research, better CO₂ economic efficiency can be achieved through more compact living, but population densities may already be too high in Chinese urban areas to be environmentally efficient. Further increases of population density may result in even denser living environments. The impact of these developments on domestic energy consumption and pollution generation requires further study. The crucial point may be less whether policy should favor urban compactness, but rather that policy should account for that above an optimum degree of urban compactness disadvantageous from over-crowding will manifest.

Some limitations are worth mentioning from this study. The indicators of measuring urban form are limited and by no means comprehensive. Thus, the research only provides an incomplete, empirical correlation of certain aspects. However, the findings from this explorative research provide a context and starting point for further investigations on the role of urban form and urban CO₂ efficiency in China.

**Acknowledgments**

The authors are grateful to the UCI.
References


Song, Y. (2005) Impacts of Urban Growth Management on Urban Form: A Comparative Study of Portland, Oregon, Orange County, Florida and Montgomery County, Maryland. National Center for Smart Growth Research and Education University of Maryland


Yeh, A. G. O., Li, X. (2000). The need for compact development in the fast growing areas of China: The Pearl River Delta. In M. Jenks, & R. Burgess (Eds.), Compact cities: Sustainable urban forms for developing countries (pp. 73–90). E & FN Spon.

Zhang, M. (2005) Exploring the relationship between urban form and no work travel through time use analysis, Landscape and Urban Planning. 73, 244–261.
