Trips and their CO$_2$ emissions induced by a shopping center

Författare 1: Tao Jia
Författare 2: Kenneth Carling
Författare 3: Johan Håkansson
Editor: Hasan Fleyeh

Nr: 2013:02
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Tao Jia\textsuperscript{a,c}, Kenneth Carling\textsuperscript{b} and Johan Håkansson\textsuperscript{b}

(This version: 2013-01-11)

\textsuperscript{a} School of Remote Sensing and Information Engineering, Wuhan University, China
\textsuperscript{b} School of Technology and Business Studies, Dalarna University, Sweden
\textsuperscript{c} Division of Geomatics, University of Gävle, Sweden

Abstract
Most previous studies have focused on entire trips in a geographic region, while a few of them addressed trips induced by a city landmark. Therefore paper explores trips and their CO₂ emissions induced by a shopping center from a time-space perspective and their usage in relocation planning. This is conducted by the means of a case study in the city of Borlänge in mid-Sweden where trips to the city’s largest shopping mall in its center are examined. We use GPS tracking data of car trips that end and start at the shopping center. Thereafter, (1) we analyze the traffic emission patterns from a time-space perspective where temporal patterns reveal an hourly-based traffic emission dynamics and where spatial patterns uncover a heterogeneous distribution of traffic emissions in spatial areas and individual street segments. Further, (2) this study reports that most of the observed trips follow an optimal route in terms of CO₂ emissions. In this respect, (3) we evaluate how well placed the current shopping center is through a comparison with two competing locations. We conclude that the two suggested locations, which are close to the current shopping center, do not show a significant improvement in term of CO₂ emissions.

Keyword: GPS tracking data, trips, CO₂ emissions, relocation planning
1. Introduction

Studies on human trips have been revived in recent years from many aspects. Firstly from the aspect of their relationship with the urban environment, geographers or urban planners have argued that sustainable urban design or planning could reduce the number of trips or miles travelled (Barton et al. 1995, Banister and Marshall 2000, Stead and Marshall 2001). In particular, Giuliano and Narayan (2003) examined their relationship in the US and Great Britain using diary data, and they found that daily trip patterns are highly related to urban form. Secondly, regarding the aspect of human mobility, physicists or statisticians have reported the scaling property or Levy flight characteristic of human travel length with respect to different modes of transportation (Brockmann et al. 2006, Rhee et al. 2011, Jia et al. 2012). And lastly with reference to the aspect of human activity, geographers or statisticians have paid extensive attention to the investigation of urban dynamics via the mining of trip data. For example, Reades et al. (2009) examined the space-time dynamic of urban life for a better understanding of how a city functions, whereas Ahas et al. (2010) found the diurnal rhythm of city life and its spatial difference in Tallinn. Recently, Jia and Jiang (2012a) explored the rhythm of an urban area in Sweden using static points of GPS tracking data.

It is well known that trips consume energy regardless the transportation mode such as walking, biking or travelling by car or bus. The amount of energy cost is further related to the emissions of environmental pollutants such as carbon-dioxide, nitrogen-oxide, and particulates. Hence to fulfill a low emission of pollutants, several studies have tried to establish a relationship between trip patterns and transport emissions. For example, Redsell et al. (1988) reported that an average vehicle speed of 65 km/h could lead to the lowest consumption of energy for petrol cars. Stead (1999) suggested the usage of travel length as a proxy of environmental indicator or vehicle emissions because of its simplicity in collection data and in calculation. Carling et al. (2012) have adopted the travel length as a proxy of CO$_2$ emission to examine the relocation of retail stores. These estimating traffic emissions are so simple that they do not consider other factors included in a trip such as travel speed, travel time, acceleration, or deceleration. Therefore to meet these requirements, a few on-road vehicle emission models have been proposed in the literature such as the IVE model (Davis et al. 2005), the LIISA model (Määttä-Juntunen et al. 2011), and the eco-driving model (Ando and Nishihori 2012).
The above studies are accompanied by advancements in Internet and telecommunication technologies witnessing the usage of digital media or mobile devices with GPS units for recording movement locations. With the availability of these GPS tracking data, we are granted a new opportunity to investigate the trips posing a significant difference from conventional methods relying on questionnaires or diaries. The GPS tracking data not only allow us to perform a micro-analysis of movement patterns, for example, an accurate measurement of CO₂ emissions, but the data also suggest a new way to assess the problem of relocation planning attracting the attention of geographers or urban planners using many location models (Mirchandani 1990, Daskin 1995, Klose and DrexI 2005, Francis et al. 2009, Carling et al. 2012). Importantly, this thinking is in line with the novel idea of urban code (Mikoleit and Pürckhauer 2011) which aims to acquire knowledge from massive crowd-sourced data for promoting a more sustainable urban development.

Most of the previous studies have focused on trips in a geographic area, but a few of them addressed trips resulting from a city landmark and their usage on relocation planning. Therefore, this paper places emphasis on trips induced by a shopping center in an edge-of-town location in Borlänge, Sweden. Using GPS tracking data, this paper firstly analyzes time-space patterns of CO₂ emissions induced by a shopping center, and then it places emphasis on the evaluation of the location of the current shopping center from an energy-efficient perspective. In particular, this paper aims to examine the following questions. (1) How do the CO₂ emissions induced by the shopping center change over time? (2) What is the spatial distribution of CO₂ emissions induced by the shopping center? And (3) how well placed is the current location of the shopping center in terms of CO₂ emissions?, or are there other alternative locations that are better suited than the current one? The answers to the above questions constitute the main findings of this paper, and they will definitely benefit studies in many other fields such as landmark relocation planning, urban planning, and transportation design and management.

This paper is structured as follows. In Section 2, we introduce the trip data adopted and the measurements of their CO₂ emissions. In Section 3, we report the findings around the time-space dynamics of the CO₂ emissions induced by the shopping center. In section 4, we compare the observed trips with optimal ones in terms of the shortest network distance and we further evaluate how well located the current shopping center is in terms of CO₂ emissions. Finally, we draw conclusions in Section 5.
2. Trips and CO₂ emissions measurement

2.1 Trips

In this study, GPS tracking data from March 29 to May 15 in 2011 in three sites of Borlänge were collected by volunteers equipped with BT-338X, a Bluetooth GPS data logger which is a combination of a GPS receiver and data logger with Bluetooth interface, from March 29 to May 15 in 2011 in three sites of Borlänge. Volunteers were recruited from four large sports associations dispersed in our study area with a high compliance and participation rate. They attached the BT-338X to their private cars for around one week. This led to a total number of 262,021 movement recordings contained in 258 GPS logger files with the removal of 5402 invalid records due to the loss of GPS signal. Each volunteer recorded her/his information every 5 or 30 seconds when the GPS signal was received. The information includes longitude (x), latitude (y), time (t), and velocity (v). The longitude and latitude are referenced by the World Geodetic System 84 (WGS 84) and measured with the accuracy of 5 meter according to the BT-338X user manual whereas velocity is measured with the unit of m/s.

To obtain the trip data, we conducted three steps as follows. Firstly, we derive the purposive locations (Jia et al. 2012) from the GPS tracking data. Purposive locations refer to locations with drastic changes in time, distance or angle along the movement trajectories of individual volunteers. They can be identified as two categories including the large time interval locations and the tortuous locations. Secondly, a trip could be obtained by connecting one large time interval location or starting location to the next large time interval location or ending location (Figure 1). Thirdly, we extract the trip samples that start or end at the shopping center from the entire trip data. Thereafter, we obtain a total number of 498 trips induced by the shopping center and which have a total travel length of about 2,481 km from 151 volunteers. Additionally, we show a linear kernel density map of the trips induced by the shopping center in Figure 2, in which the shopping center (known as Kupolen) is marked as a black triangle.

![Figure 1: Illustration of identifying trips in a volunteer movement trajectory](image-url)
Furthermore, we take a look at the statistical descriptions for the trip data. For the number of trips taken by one volunteer, we found that most of the volunteers had two trips during this period which is fairly reasonable since most people would like to go to the shopping mall once a week. As shown in Table 1, during this period around 50% of the volunteers had three trips or less, whereas 95% of the volunteers had seven trips or less. For the number of halts (tortuous locations which are short-time breaks during a trip to the shopping mall) and street intersections in a trip, we reported that 70% of the trips were direct trips to the shopping mall with an average number of 11 street intersections visited (Table 2), which is pretty reasonable since most of the people would prefer to optimize their trips with lower gas consumption by having less stops and crossing less street intersections. In addition, as shown in Table 2, we found that few tips have a large number of halts and the corresponding large average number of street intersections. Therefore, it is assumed that most of the volunteers appeared to have a wise strategy in managing their trips to the shopping center in terms of low energy cost.

Table 1: Distribution of the number of trips per volunteer

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Mode</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>25</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>75</td>
<td>95</td>
<td>2</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 2: Number of halts (tortuous locations) and street intersections per trip (Note: for the first column in this table, we can observe that 351 trips have zero halt with an average number of 11 street intersections visited)

<table>
<thead>
<tr>
<th>Number</th>
<th>Trips</th>
<th>351</th>
<th>126</th>
<th>11</th>
<th>8</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halts</td>
<td>0</td>
<td>1</td>
<td></td>
<td>2</td>
<td></td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Intersections</td>
<td>11</td>
<td>19</td>
<td>24</td>
<td>41</td>
<td></td>
<td>49</td>
<td></td>
</tr>
</tbody>
</table>

2.2 CO₂ emissions measurement

To estimate the energy cost of each trip quantitatively, we adopt the amounts of CO₂ emissions as a proxy in this study. As the most important greenhouse gas, CO₂ emission is the main causal factor of global warming and consequent climate change. The primary cause is the combustion of gasoline fuels (Steed 1999), and hence, the higher the energy consumption the higher the amount of CO₂ being emitted. In addition, there are several models existing in the literature (Stead 1999, Oguchi et al. 2002, Davis et al. 2005) that can be used to estimate CO₂ emissions of vehicles. For instance, Stead’s model (1999) is so simple in that it only considers the travel length, whereas Davis’ model (2005) is so complex as it adopts binning technology with both the micro-working conditions of vehicles and the surrounding environmental factors like wind direction and road slope. Through comparison, Oguchi’s model is adopted in this study because it is neither simple nor complicated, and more importantly it is highly suitable for the GPS tracking trip data.

This model considers the instantaneous working conditions of an on-road vehicle such as speed change in terms of acceleration or deceleration, total travel time, and total travel length (Equation [1]). It is specifically used for the gasoline-powered vehicles which also agree well with the situation in this study.

\[
E_{\text{trip}} = K_C \times (0.3T + 0.028D + 0.056 \sum_{i=2}^{n} \delta_i \times (v_i^2 - v_{i-1}^2))
\]

Where \( E \) is the estimated CO₂ emission amount (Kg), \( K_C \) is the CO₂ emission coefficient with the value 0.002322, \( T \) is the total travel time (second), \( D \) is the total travel length (meter), \( v_i \) is the velocity at GPS location \( i \) (m/s), \( n \) is the number of GPS locations in the trip, and \( \delta_i \) is an
indicator with value 1 \((v_i > v_{i-1})\) or 0 \((v_i \leq v_{i-1})\). By applying this model to the trip data, we can calculate the amounts of CO\(_2\) emitted by each trip, and which is explored from a time-space perspective in the following section.

3. Time-space patterns of CO\(_2\) emissions

In this section, we present the time-space patterns of CO\(_2\) emitted from the trips induced by the shopping centre. Temporal patterns are examined through the changes of CO\(_2\) emissions over time. Spatial patterns are investigated with the distribution of CO\(_2\) emissions in spatial areas and street segments respectively.

3.1 Temporal patterns

Trips induced by the shopping centre may have dynamic properties in terms of the traffic CO\(_2\) emissions occurred on street network over time. To examine this dynamic, the CO\(_2\) emissions of trips are chopped and aggregated in a time slot, for example one hour. Furthermore, trips can be categorized as either in-trips to the shopping center or out-trips from the shopping center, and hence the corresponding CO\(_2\) emissions are considered as in-traffic emissions and out-traffic emissions respectively. Therefore, we present the traffic emissions dynamics from the aspects of in-traffic emissions, out-traffic emissions and total traffic emissions on an hourly basis for both weekday and weekend.

On one hand, Figure 3a shows the temporal patterns on weekdays, and traffic emissions per hour are averaged over five weekdays from Monday to Friday. One observation from this demonstrates that there is a general pattern of the change of total traffic emissions over time. For instance, total traffic emissions start to rise around 10am in morning and decline around 8pm in evening among which there is one obvious peak occurred around 3pm in afternoon. Another finding is that there is a difference between in-traffic emissions and out-traffic emissions with respect to change over time. For example, in-traffic emissions come to a peak around 3pm during afternoon, whereas out-traffic emissions go to a peak around 4pm during the afternoon.

On the other hand, Figure 3b shows the temporal patterns over the weekend, and the traffic emissions per hour are averaged over two weekends on Saturday and Sunday. First, one common pattern shows that traffic emissions last from around 10am in the morning to around 5am in the afternoon regardless of total traffic, in-traffic or out-traffic. Second for the
emissions of total traffic and out-traffic, there are two clear peaks around 12pm in noon and 4pm in the afternoon respectively and one nadir appeared around 2pm in the afternoon; for the emissions of in-traffic, the pattern seems to be relatively stable compared with the other two patterns, and only one peak is observed around 4pm in the afternoon. How the temporal patterns uncovered can be useful to the fields of traffic management or landscape design needs further investigation, but it is believed that they, at least, reflect the rhythm of the local residents to the shopping center which contributes to the study of human geography.

![Figure 3](image-url)

**Figure 3**: Plot of hourly-based traffic CO2 emissions for weekdays and weekends

Besides, it is found that the temporal rhythm bears a remarkable resemblance with the real situation in terms of the opening hours for the shopping center. For instance, the shopping center opens from 10am to 8pm during workdays, whereas it opens from 10am or 11am to 5pm Saturdays and Sundays. This suggests that the landmark or especially its marketing strategy has a non-trivial influence on the temporal dynamic of local traffic and the corresponding environmental emissions. However, they cannot tell us how the emission patterns induced by the shopping center distribute in space. To achieve this goal, spatial patterns are presented in the following section.
3.2 Spatial patterns

In this section, we continue to explore the patterns of CO₂ emissions in terms of their spatial distribution in areas and street segments respectively. It is important to identify the exact potential market or service areas related to the location of a shopping mall or retail store in retailing or marketing research, but few researches have considered the CO₂ emissions from these potential areas. Similarly in this study, due to the fact that CO₂ emissions are produced by vehicles traveling to the shopping center, it is also important to understand how CO₂ emissions distribute in individual street segments.

![Figure 4: Map of observed CO2 emissions from different areas visualized with three categories: low emission, medium emission, and high emission](image)

To investigate the distribution of CO₂ emissions in different areas, we firstly extract the origin and destination locations of all trips, and then we further remove the locations inside the shopping center. Secondly, using these locations, a kernel density map is produced to extract the spatial areas influenced by the shopping center. Thirdly, we assign the CO₂ emissions to each area by summing the emission values of the trips that start or end with this area. As shown in Figure 4, it is reported that a total of 32 areas with two landuse types are impacted by the shopping center which includes residential landuse and commercial landuse (retail areas with a mixture of cars selling, restaurants, toy shops, and supermarkets). This indicates
that two types of trips to or from the shopping center can be identified, namely ones directly coming from or going home (note that most of the home locations of the volunteers are within the residential areas) and others coming from or going to another place of interest (e.g., retail stores). Besides, it is found that traffic emissions resulted from neighborhoods areas constitute around 67% of the total traffic emissions whereas the ones resulted from retail areas constitute about 33%.

To explore the distribution of CO$_2$ emissions in individual street segments, we assign the emission value of each trip to the corresponding street segments according to Equation [2], which is similar to the process of linear kernel density estimation.

$$E(t_i, s_j) = \sum \frac{1}{\text{dist}(t_i, s_j)} \cdot (1-u) \cdot \frac{\text{len}(s_j)}{\text{len}(s)} \cdot u \cdot E(t_i), \quad \text{dist}(t_i, s) < r$$

Where $t_i$ denotes a trip $i$, $s_j$ denotes a street segment $j$, $\text{dist}(t_i, s_j)$ is the nearest distance between $t_i$ and $s_j$, $\text{len}(s_j)$ is the length of $s_j$, $r$ is the bandwidth within which the street segments will be influenced by trip $t_i$, $u$ is a weight parameter to determine the relative importance of distance or length, $E(t_i)$ is the emission value of trip $t_i$, and $E(t_i, s_j)$ is the emission value assigned to the street segment $s_j$ by trip $t_i$.

Figure 5 displays a CO$_2$ emission map of the underlying street network. As the trips are induced by the shopping center, we can clearly observe that the emission values of street segments decrease gradually with increasing distances from the shopping center. Besides, several roundabouts connecting streets with different directions are reported to have very large emission values. This map also gives us a scale impression in terms of the distribution of the emission values among street segments, namely that a majority of street segments have a very low emission value, whereas a minority of them has an extremely large emission value. Here, the heavy-tailed distribution of traffic emissions in street segments (Figure 6) is common to many other phenomena in the geographic space (Lämmer et al. 2006) or society (Jia and Jiang 2012a). These patterns may be interesting to urban planners or marketing researchers. As for urban planners, they may inspire another topic of evaluating the location of the current shopping center from an energy-efficient perspective and which will be elaborated in the following section.
4. Optimal trips and evaluation of the shopping center

In this section, we primarily report the results on how well placed the current location of the shopping center is from an energy-efficient perspective. To address this problem, two topics will be investigated sequentially. Firstly, the CO₂ emission of each trip is compared with that of an optimal route in terms of shortest network distance. Secondly, based on the first result,
the current location of shopping center is evaluated through a comparison with two alternative locations suggested in two scenarios.

4.1 Optimal trips with low energy cost

It is interesting to delve into the individual patterns of each trip, and we wonder if every trip is optimized by the volunteer. Optimization here means the trip should have a low emission of CO$_2$ or is energy-efficient. Our previous empirical findings (Section two) seem to suggest that most of the observed trips are optimized due to a small number of halts and street intersections visited. In reality, many other factors are considered as important in shaping the optimization of trips such as speed change like deep acceleration or deceleration, route choice in terms of travel time or length, and other extra physical factors including road slope and engine of car. However, in this study we only consider the route choice behaviors of volunteers, and furthermore, we assume that volunteers would have a mental map to come up with a best route choice.

To test our assumption, we firstly calculate the shortest street network distance for each volunteer using the conventional Dijkstra algorithm considered as an optimal route compared with the observed trip counterpart. Secondly, the CO$_2$ emission value of each optimal route is calculated with Equation [1], where the distance effect is updated and the speed and time effects are unchanged with respect to the observed trip. Finally, we conduct a correlation analysis between the emission values of the observed trip and the optimal route. The results are shown in Figure 7: Figure 7a shows a linear regression curve of their relationship with a high R-Square value equal to 0.96, and only five out of 498 trips are reported to be not

![Figure 7: Comparison of observed emission values with the optimal ones](image-url)
energy-efficient. Figure 7b demonstrates a lognormal distribution of the deviated emission values from the regression curve which suggests a way to select the top five outliers (Jiang 2012). Further, the top five observed trips are reported to have multiple halts. Therefore, we conclude that most of the observed trips are optimal ones.

4.2 Evaluation of the shopping center

As elaborated above, most of the trips are similar to the corresponding optimal ones in terms of CO₂ emissions. In other words, most of the volunteers follow a shortest network distance during their journeys to the shopping center. This imply that the shortest network distance can be adopted to model the human trips to a shopping center when considerations for CO₂ emissions are taken into account when the relocation planning issue on the current shopping center is dealt with. To scrutinize this question further, we need to know whether there are any other competing locations to where the shopping center could be relocated to that minimize the total CO₂ emissions and still satisfy the demands of consumers. In addition to this we need to evaluate the location of the current shopping center from an energy-efficient perspective. To cope with this problem, two strategies are proposed in this section.

The first strategy is to employ the p-median model (Mirchandani 1990) which aims to optimally allocate P facilities among Q demanding points such that the total distance from each demanding point to the nearest facility is minimized. In this context, we select one location \( l \) among the street nodes \( L \) (ending point of street segments) such that the total CO₂ emissions of the optimal trips induced from the observed 498 demanding points (origins or destinations of the trips) is minimized. We give the objective function as follows.

\[
\text{Min}_{l \in L} \left\{ \sum_{i=1}^{N} E(\text{trip}(q_i, l)) \right\}
\]

Where \( l \) is the location of a street node, \( L \) is the whole set of street nodes, \( N \) is the number of demanding points which equal to 498, \( q_i \) is the \( i^{th} \) demanding point, \( \text{trip}(q_i, l) \) is the shortest network distance from \( q_i \) to \( l \), and \( E(\text{trip}(q_i, l)) \) is the CO₂ emission of the trip. By applying this method to our 498 demanding points, we obtain the suggested location \( \tilde{l} \) (black triangle in Figure 9) which is very closely located at around 300 meters to the current shopping center. Besides, we assign CO₂ emissions of all simulated trips to the corresponding street segments using equation [2] (Figure 8). Compared with emissions from the current shopping center
(Figure 5), the emissions from this new location are more concentrated in a small number of street segments; although there is a 9% decrease in terms of the total CO\(_2\) emissions \(((389 - 354) / 398)\).

![Map of CO\(_2\) emissions in individual street segments induced by the new location obtained from p-median model](image)

Figure 8: Map of CO\(_2\) emissions in individual street segments induced by the new location obtained from p-median model

However, the street network is not homogeneous in its structure with respect to the importance of street nodes. For instance in terms of accessibility, some nodes may have a more important role than others. Therefore, the second strategy is to adopt the weighted p-median model which considers the relative importance of the street node. Here, the importance of a street node is measured with a network metric Betweenness which is defined as the number of shortest paths between any two nodes that pass through the current node and reflects the accessibility of the current node within the network (Jia and Jiang 2012b). Generally, it is defined as follows.

\[
b_i = \sum_{m\neq i \neq n} \frac{\text{Path}(m, i, n)}{\text{Path}(m, n)}
\]

[4]

Where \(\text{Path}(m, i, n)\) is the number of shortest street network paths through node \(i\) from node \(m\) to \(n\), and \(\text{Path}(m, n)\) is the number of shortest street network paths from node \(m\) to \(n\). We show a kernel density map of the Betweenness value of each street node in Figure 9 where an
observation is that the areas close to the current shopping center have the highest level of accessibility.

Hence by taking into account of the accessibility of street nodes, the weighted p-median model is given as the following objective function.

\[
\min_{i \in L} \left\{ b_i \times \sum_{l=1}^{N} E(trip(q_i,l)) \right\}
\]

Where \( b_i \) is the Betweeness value of a street node \( l \), and other parameters are the same as the ones in [3]. Again, by applying this method to the 498 demanding points, we found that the suggested location is also located very close to the current shopping center with about 320 meters. Further, we found that this new location is along the street of Gjutargatan where urban land is now under construction for an IKEA shopping mall. Assigning the emissions of the simulated trips to the corresponding street segments, we can obtain an emission map shown in Figure 10 which displays an intermediate pattern between Figure 5 and Figure 8 in terms of the concentration of emission on the street segments. In addition, the total estimated CO₂ emissions is about 357 Kg which indicates an 8% ((389 - 357) / 398) decrease compared with the current shopping center.
5. Conclusions
This study investigates trips and their CO$_2$ emissions induced by a shopping center using GPS tracking data. The results uncover a time-space dynamic patterns of CO$_2$ emissions from the trips. Particularly, the temporal patterns suggest a rhythm of traffic emissions which coincides well with the opening hours of the shopping center; whereas the spatial patterns indicate an uneven proportion of traffic emissions from spatial areas with different landuse types and a heterogeneous emission distribution in individual street segments. On the other hand, it is reported that most of the observed trips seem to be optimal ones in terms of the shortest network distance. In this respect, the shortest network distance is adopted as a proxy of human trips to simulate the trip patterns induced by other competing shopping locations. This motivates us to further explore the rationale of the current shopping center location in terms of CO$_2$ emissions. Consequently, two competing locations are suggested by the applications p-median model and weighted p-median model, and both of them are close to the current location of shopping center with a decrease of 9% and 8% CO$_2$ emissions respectively.

This study suggests the usage of crowd-sourced GPS tracking data to investigate issues related to the dynamics of traffic CO$_2$ emissions and relocation planning in urban systems. GPS tracking data show several advantages compared with the conventional human diary or
questionnaire data in transportation research, for instance they are time-saving and economical. In addition, this paper is inspired by the idea of urban code which aims to uncover novel urban patterns from massive crowd-sourced geospatial data. As far as we know, this paper is the first to bear this idea exploring the patterns of traffic CO₂ emissions induced by a shopping center from a time-space perspective and their usage in relocation planning, which might establish an empirical benchmark in this field.

Acknowledgements

Financial support from the Swedish Retail and Wholesale Development Council is gratefully acknowledged. We are grateful to Magnus Bohlin who managed the recruitment and instructions of volunteers, and we thank the anonymous volunteers for their contribution to the GPS logger dataset. Finally, we thank the anonymous referees for their constructive comments.

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