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Author 1: Xiaoyun Zhao
Author 2: Kenneth Carling
Author 3: Johan Håkansson
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Xiaoyun Zhao*, Kenneth Carling, and Johan Håkansson

Abstract
In a city there are hotspots that attract the citizens and most of the transportation in the city arises when citizens move between their residence and the hotspots. However, the evaluation between energy-efficient mobility and urban residential planning has been found to be rather weak. In this paper, we propose an ex-ante evaluation method to quantify the impacts in terms of CO$_2$ emissions induced by intra-urban car mobility due to different residential plans implemented at various urban areas. The method is illustrated by a Swedish midsize city which is presently preoccupied with urban planning of new residential areas in response to substantial population growth due to immigration. On average, the CO$_2$ emissions increase from the continued urban core area (CUCA) to the suburban polycentric area (SPA) to the edge urbanization area (EUA), EUA is almost 3 times more than CUCA. The average travel distances also increase in the same sequence, the overall increase is more than 4 times. Apartment buildings could be more effective in meeting residential needs and mitigating CO$_2$ emissions than dispersed single-family houses.

Keywords: Ex-ante evaluation; Spatial distribution; Urban form; Counterfactual; GPS-tracking data

1. Introduction
   Mobility is inevitable to meet our multiple needs. However, at the same time, mobility is costly: for the individual, it costs time, energy, capital and so on, while for society, costs are commonly regarded external, such as congestions, emissions, resources consumptions and so on. The induced costs are increasing along the urbanization expansion (Fujita and Thisse, 2013). Under the broad definition of cities as urbanized areas (Angel et al, 2005; Satterthwaite, 2008), some 78% of all carbon emissions have been accredited to cities with growing urbanization (Grimm et al., 2008).

* Xiaoyun Zhao is a PhD student in Microdata Analysis, Kenneth Carling is a professor in Statistics and Johan Håkansson is a professor in Human Geography. All are at the School of Technology and Business Studies, Dalarna University, SE-791 88 Falun, Sweden. Corresponding author: Xiaoyun Zhao, e-mail: xzh@du.se, phone: +46-23-778509.
By the end of 2014, global urbanization ratio was 54%, and is expected to be 66% by 2050 (United Nations, 2014a). “Today, the most urbanized regions include Northern America (82% living in urban areas in 2014), Latin America and the Caribbean (80%), and Europe (73%). In contrast, Africa and Asia remain mostly rural, with 40% and 48% of their respective populations living in urban areas. All regions are expected to urbanize further over the coming decades. Africa and Asia are urbanizing faster than the other regions and are projected to reach 56% and 64%, respectively, by 2050.” (United Nations, 2014b). Under this urbanization trend, transport energy use and CO₂ emissions are projected to increase by nearly 50% by 2030 and more than 80% by 2050 (International Energy Agency, 2009). Adoption of new technologies and fuels together with smart urban development are two main courses to mitigate total global energy-related CO2 emissions by 50% from the current level in 2050.

A considerable amount of research has been conducted all around the world to understand the ecological and social consequences of urban development (Pickett et al., 2011; Seto et al., 2011; Wang et al., 2012). Urban form reveals the relationship between a single city and its rural hinterland (Grimm et al., 2008), as well as the impact of human actions on the environment within and around a city (Alberti, 2005; Weng et al., 2007). In particular, there has been an increasing interest in identifying and understanding the effects of transportation pattern in urbanization, as this understanding is crucially important for the design of effective urban planning and management strategies (Dieleman and Wegener, 2004; Schwarz, 2010; Dubovsky et al., 2011; Long et al., 2012; Tavares et al., 2012; Thapa & Murayama, 2010; Li et al., 2013).

Makido et al. (2012) found that CO₂ emissions per capita from residential and passenger transport sectors of cities have significant correlations with the spatial variables of urban form, for example, the spatial distribution of the residents and their travel destinations. Urban planning, in particular land use for residential locations, plays an important role in shaping the structure of a city, and subsequently influences the demand for mobility, particularly by private cars. Although urban forms vary in different continents, countries and cities due to the spatial distribution of residents, urban planning policies, landscape, cultural backgrounds and economic status and so on, the relationship between urbanization and greenhouse gas (GHG) emissions has been studied broadly in various contexts, and urban planning and management are found to be crucial in mitigating the adverse impacts on environment (Stead and Marshall, 2001; Schwanen, 2002; Buxton and Scheuer, 2007; Dhakal, 2008; Poumanyvong and Kaneko, 2010; Hamin and Gurran 2009; O’Neill et al., 2010; Ewing & Cervero, 2010; Li, 2011; Li et al., 2013; Naess 2012; Iwata and Managi, 2016).
Various literatures indicate that increasing urban density significantly reduces per capita vehicle travel (Kenworthy and Laube, 1999, Kenworthy, 2003; Mindali et al., 2004), and results in lower fuel consumption and transport-related GHG emissions. Athens (2008) assumed that a general trend towards more compact urban structures of higher densities and limited urban expansion should be adopted in all cases to enhance sustainable travel patterns. The debate between the compact city and dispersed city on energy efficiency and sustainable development can be summarized to a large extent (Holden & Norland, 2005), though the debate is still on going. Tailored and multi-dimensional urban planning is required for each city and country (Dodman, 2009; Corfee-Morlot et al., 2009; Madlener & Sunak, 2011; Hoornweg et al., 2011; Kennedy et al., 2012). City policymakers must choose and introduce urban planning instruments that are appropriate to the corresponding situation (Iwata and Managi, 2016).

However, regardless of urban form adopted, in most urban planning studies, it is commonly assumed that the residential locations are already fixed, and the consequences of locating different types of facilities have been debated (Dieleman et al., 2002; Krizek, 2003; Norman et al., 2006; Perkins et al., 2009; Lindsey et al., 2011; Hong and Goodchild 2014). Studies mainly focus on the analysis of ex-post evaluation of urban planning in influencing the environment, and empirical analyses are mainly based on metropolitan cities. Modifying what Bourguignon and Ferreira (2003) have described in their paper: while the ex-post analysis examine the current stage after urban plans have been implemented, it is important to evaluate the potential impacts of those counterfactual urban plans. It will be helpful for the urban planners to have some estimate of how much each alternative plan would cost, and of which aspect would be affected and by how much, under each alternative.

Höjer et al. (2011) conducted a backcasting study for Stockholm 2050 to show that it’s possible for sustainable energy use by combining of planning, behavioural change and technological development. Given the close relationship between energy use and GHG emissions, little attention has been paid to conducting ex-ante evaluation of the relationship between counterfactual urban plans and the impacts on the environment, particularly the impacts of CO2 emissions induced by cars’ intra urban mobility (Carling et al., 2013).

This paper proposes the ex-ante evaluation method by considering the hotspots in travel as fixed, and examines the induced CO2 emissions of car mobility from counterfactual urban residential plans to the hotspots. The differences of induced CO2 emissions of car mobility among the plans are quantified. The method illustrated by examining a specific urban
residential planning case. To the best of our knowledge, this method has scarcely been adopted in the literature this far.

This paper is organized as follows. Section 2 introduces the methodology. Section 3 describes the data applied in the empirical analysis. Section 4 presents the results of the analysis. Section 5 concludes the paper with concluding discussions.

2. Methodology

2.1 Ex-ante evaluation

Mobility is necessary for people to meet multiple needs, whereby mobility between residential locations and hotspots within the city is a primary part. If we regard the origins as the starting point of a trip and the destination as the end point of the trip, the residential locations and the hotspots will fall in the set of origins and destination. Normally, a residential location is an origin, if we consider a whole round trip, a residential location can also be a destination, but a trip moving from A to B can be very different comparing to a trip moving from B to A.

The proposed ex-ante evaluation method focuses on quantifying the impacts in terms of CO$_2$ emissions induced by intra-urban car mobility due to different residential plans implemented at various urban areas. Essentially, ex-ante evaluation is what if analysis (Bourguignon and Ferreira, 2003). In this paper, two main questions are examined:

1. How different would it be for the city from the current stage?
2. What if some residential plans would never be implemented?

If we can identify the current origins and the counterfactual origins, the current destinations and the counterfactual destinations; the emissions induced by moving from the origins to the destinations can be estimated. We can then compare the possible residential plans (the counterfactual city) and the current structures of the city (the real city). In this paper the counterfactual destinations are assumed to be the same as the current ones.

Therefore, a network that indicates the induced emissions by the mobility of cars is needed for the quantification. Having this network of induced emissions (NoIEs) constructed, we can compute the emissions between any arbitrary origin to any arbitrary destination. The counterfactual city can then be compared with the real city.

2.2 Emission Estimation Model

In constructing the NoIEs, a model to estimate the emissions based on cars’ mobility is needed. Several models have been used to estimate CO$_2$ emissions, and the external cost induced by vehicles. Stead (1999) suggested using travel length as a proxy for vehicle
emissions due to the ease in collection and computation, but the estimation was insufficient due to the over-simplification. Wielenmann et al. (2005) used the average speed to estimate emissions from road traffic, but they neglected that those different cycles with different driving behaviours and vehicle dynamics can yield the same average speed. Davis et al. (2005) applied the international vehicle emissions (IVE) model, by complicatedly considering the comprehensive conditions of vehicles and circumstance factors. Demir et al. (2014) reviewed factors in fuel consumptions in transportation and models used in calculating energy consumptions and GHG emissions. Factors such as speed, time, distance, acceleration and deceleration are crucial in calculation emissions.

Oguchi et al. (2002) proposed a reasonable model that is well-balanced between preciseness and data requirement. This model is particularly suitable for GPS tracking data that is commonly collected in transportation nowadays. The model estimates CO₂ emissions, considering the instantaneous working conditions of an on-road vehicle, such as speed change in terms of acceleration or deceleration, total travel time $t$ and total travel distance $d$. In this model, change in speed is an important component which is explained by an indicator function $\delta_i$, when speed is greater than that at the previous point, it is 1, otherwise it is 0, which means the acceleration based on the travel speeds $v_i$ and $v_{i-1}$ is considered.

$$e = k_c \times \left[ 0.3t + 0.028d + 0.056 \sum_{i=2}^{n} \delta_i(v_i^2 - v_{i-1}^2) \right]$$

$e$ = CO₂ emission amount (kg)
$t$ = Travel time (sec)
$d$ = Travel distance (m)
$i$ = Number of points where the speeds are observed
$\delta_i$ = 1 (when speed is higher than that at the previous point) or 0 (otherwise)
$v_i$ = Travel speed at point $i$ (m/sec)

Basically, we have inter-urban and intra-urban traveling. In inter-urban traveling, speed is quite constant, as time and distance are highly related; distance becomes the crucial determinant for the emissions. While, in intra-urban travel, constant speed is very difficult to attain, and the relationship between time and distance becomes much weaker, speed changes then become the crucial determinant for the emission estimation. However, the urban planning is tending to be more heterogeneous, the complexity of a city’s road network is increasing, which lead to uneven traffic flow in the city. To estimate the emission for areas with low or even no traffic flow, the speed part in the model might be deactivated, which would lead to insufficient estimation as is discussed in the beginning of this section.
Therefore, a good estimation of speed in all kinds of traffic flows is crucial in deriving the NoIEs.

2.3 Speed profile

We estimate the speed profile based on a symmetric triangle function. The hypothesis is that we can use this simple function approximating the speed profile fairly well. The estimation is applied for each road segment between two intersection points (entrance points into roundabouts are also regarded as intersections). We assume the low incoming speed and the outgoing speed at the intersection points are the same. When the car enters into a road segment, it is expected to accelerate and reach the legally possible highest speed in the middle of the road segment; it is then expected to decelerate when it drives to the outgoing intersection point. As is shown in Figure 1, line CB is a road segment, in which points C and B are the two intersection points which can be both incoming and outgoing intersection points for cars. The distance of road segment CB is known, F is the middle point. Then one travel point between C and F (like H) is sufficient to estimate the peak speed at the middle point. For roads that have no travel point, use of the speed limits is assumed reasonable.

![Figure 1: Triangle illustration of the triangle assumption applied for estimating the speed profile on drivers. The point C and B is the incoming/outgoing intersection points for the road segment CB. The point H is a travel point of driver and the maximum speed is expected to reach at the middle point F if there is acceleration.](image)

The following describes the examination of speed profile in detail. Figure 2-1(a) provides an example of the positional recordings in understanding the speeds. The segment indicated by the red line with arrows is a 700-meter road segment that is between one hot spot ICA MAXi and a gas station STATOIL. There were 1225 recordings on this road segment.
Figure 2-1: Example 1: (a) Positional recordings the volunteers have made on a main road (b) Positional recordings that the volunteers have made on arterial roads and private roads.

Figure 2-2: The speed profile for the recordings on road segments in Figure 2-1(a). The thick solid line is the LOWESS line showing the general pattern of the speed changes.

Figure 2-3(a) shows an example extracted from the volunteers and the post-test drivers. The road segments are between the two intersections indicated by the red circles; there is a traffic light, a speed bump, a left turn to a bigger road and a speed bump. Therefore, according to the triangle, we should expect 4 times of accelerations and decelerations. Figure 2-3(b) shows the general pattern from the three drivers. Although we cannot look at the same details for the volunteers due to the different frequencies of measurements, we can take the average driving pattern for all the volunteers who travelled on the same routes, same pattern is observed as is shown in Figure A1-3(c). They first speeded up then slowed down at the traffic...
light; speeded up to about 40, then slowed down for the speeded bump; speeded up to about 40 again, then slowed down for the left turn; speeded up again and slowed down for the speed bump, and then speeded up to 60. A good match between the volunteers and the test drivers with similar triangle pattern was identified.

In the following example, the driver drove out from an arterial road to a collector road. There is one walk/bike path, one speed bump and then the driver came to a roundabout. So we should expect 3 times of accelerations and decelerations. Figure 2-4(b) and Figure 2-4(c) illustrate the average driving pattern of the three drivers and the volunteers. They again behaved in the same pattern, whereby they first speeded up then slowed down for the pedestrians; speeded up then slowed down due to the speed limit change and slowed down at the speed bump; speeded up to 40 again and then slowed down at the roundabout. Overall, the examination shows the triangle estimation for the speed profile is reasonable and consistent.
Figure 2-4: Example 3: (a) The road segments that had recordings from the volunteers and the post-test drivers; (b) The speed profile of the recordings from the post-test drivers; (c) The speed profile of the recordings from the volunteers. The thick solid line is the LOWESS line showing the general pattern of the speed changes.

Figure 2-3 and Figure 2-4 show the good match between the volunteers and the test drivers after the check on collector/main roads. How about the arterial/private road which is shorter and lower speed limit in the residential area? Figure 2-5(a) illustrates that the drivers entered the arterial road from a collector road, and then drove out again. There are 5 intersections in the selected road segment. As is shown in the speed profile in Figure 2-5(b), the car slowed down at the entrance, speeded up, slowed down at the intersection, speeded up, and then slowed down again at the exit. Figure 2-5(b) shows that the triangle form for the speed profile is a reasonable estimation regardless the different driving behaviours.
Figure 2-5: (a) The road segments that had recordings from three volunteers measured by every second; (b) The speed profile of the recordings from the volunteers, the thick solid line is the LOWESS line showing the general pattern of the speed changes.

3. Data

We choose a midsize city Borlänge in Sweden for the empirical analysis in illustrating the methodology proposed above. Sweden’s administration is divided into three tiers: the nation state, the regions (counties), and the municipalities (290 in total). There exist three types of spatial plans: the regional plan, the municipal plan, and the local plan (Larsson, 2006, pp. 245–246). There is no formal institute for spatial planning on the national level (Busck et al., 2008). Spatial planning in Sweden is largely the concern of the municipalities, which is
regulated by law to accommodate certain land use restrictions laid down in the Environmental Code, and must coordinate its actions with other planning bodies; in principle the municipalities have a planning monopoly (Persson, 2013). The two statutory plans at the municipal level are the comprehensive plan and the detailed development plan. Since 1987, every municipality has adopted these two plans for spatial planning of sustainable land use and coordinating the location and development of buildings, infrastructures, and various other spatial landscape elements.

In Sweden, 85% of the Swedish population lives in urban landscapes (Statistics Sweden, 2010). By 2050, the Swedish population is expected to grow by 15% (Statistics Sweden 2011). Especially due to the dramatic increase of immigration, over 2 million residence permits have been granted since 1980 (Migrationsverket Sweden, 2016). Urban dwellers move away from the urban cores to the sub-centres (Anas et al., 1998), and to edge areas with rising settlements. This change increases the dependency on car transportation, which leads to an increase of number of cars per household and the distances travelled (Behan et al. 2008), the pollutant emissions due to car traffic are likely to increase. It is therefore challenging to reach the Swedish GHG target: a 40% reduction on 1990 levels by 2020 and a vision of 100% reduction (no net emissions of GHG to the atmosphere) by 2050 (Höjer et al., 2011).

Few studies have focused on the sustainable land and energy use on municipalities with major cities (Höjer et al., 2011; Phdungsilp, 2011). However, midsize cities are facing more challenges in urban planning for adapting the substantial increase of residents due to immigrants and for mitigating the pollutant emissions.

The whole municipality of Borlänge is the administrative area for Borlänge city. It is 220 km northwest of Stockholm. The area is about 35 square kilometres, with approximately 50,000 residents. The municipality is the labour market centre and commercial centre for the whole Dalarna region. Simultaneously, the continuous growth of immigrants and the economic growth lead to an increase demand for urban residential development. As a consequence of the above, many residential plans have arisen to cope with the development of the municipality.

Borlänge city is built up around a steel rolling mill on both sides of the Dalecarlia River and a large railway yard in the city's south-western part, which act together as barriers for the development of residential areas in the city. Together with the old central business district along Stationgatan in the city core, the areas of Norra Backa, Domnarvet, Kvarnsvenden are sub-centres shaping the city in a heterogeneous polycentric pattern (Kloosterman & Musterd, 2001). The sub-centres have gradually become incorporated into an expanded but coherent
urban area built around the original urban core. Other areas are newly spawned at nodes of the transportation network far from the urban core to sprawl the urbanization to the edge area that is tangent to the city. We therefore categorize the city as follows: continued urban core area (CUCA), suburban polycentric area (SPA) and edge urbanization area (EUA).

Figure 3: The distribution of geographical locations of current origins in Borlänge. The embedded map is the zoomed in part is the highest density of residents in the CUCA and SPA.

Borlänge’s development trends and housing styles tend to be quite typical in Sweden. The relatively compact central core and suburban sprawl pattern is also common to many midsize cities in Europe. The digital representation of residence and road network of Borlänge is detailed by the municipality and the National Road Data Base (NVDB). The 46,942 current residents of the city are geo-coded into grids of 0.0625 square kilometres. We identify the 1291 centroid points of the grids, assign the corresponding residents’ number to the centroid points as the weight and regard them as the current origins. Figure 3 illustrates that the residents of the city are unevenly distributed in the three defined areas.
Figure 4: The planned residential locations in Borlänge according to the municipality’s land planning office. 12 locations planned for apartment buildings for about 5000 residents and 38 locations planned for single-family houses for about 200 residents.

Figure 4 illustrates the detailed development plan (next 5 to 15 years) for residential locations according to the municipality’s land plan office. Overall, the plan is to build new apartment buildings, single-family houses in the CUCA, SPA and EUA, by reusing abandoned places, parking lots and unexploited locations. 2156 apartments are planned to be built at 12 locations to accommodate approximately 5000 residents. 38 vacancies are planned to be developed into single-family houses for approximately 200 residents. In the CUCA, 4 apartment buildings that provide more residential units and in a more compact pattern are planned to be located. 7 apartment buildings and 25 single-family houses in a highly concentrated pattern to the current structure are planned in the SPA, while in the EUA, there are plans for 1 apartment building and 13 single-family houses, which are dispersedly distributed in the north, south, and east of the area.

In total, the plan is to meet the need for a population growth of 2% per year, which is a dramatic population increase compared to the average 0.4% annual population growth in the
The mobility data of private cars is also required in constructing the NoIEs. 303 volunteers registered as residents of Borlänge were recruited through 4 sport clubs. Each volunteer was equipped with a GPS receiver (BT-338X) in the car to record their daily in-car movements, under 5 or 30 seconds frequency for one week or two weeks. The data collection lasted from March 29 to May 15 in 2011. There were 309,263 recordings after removing 5402 invalid recordings due to signal loss (for details, c.f. Zhao, 2015). The 154,579 valid recordings inside Borlänge are used for the data analysis in this paper.

One question is: to what extent do the spatial distribution of the volunteers corresponds to the spatial distribution of the population in Borlänge in general? As can be seen from Figure 5, the volunteers are spread throughout the city in a pattern similar to the overall population's settlement, although with a higher density in the SPA and EUA. In checking the induced CO₂ emissions of cars; one basic requirement is that volunteers should be in possession of a car, reasonably, people who live in the SPA and EUA have higher frequency of car possession.

Figure 5: The spatial distribution of the volunteers (filled circles) as well as all the residents in Borlänge.

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than those who live in CUCA. Therefore, the volunteers are less concentrated in the CUCA area than where the population live.

Figure 6: (a) The volunteers’ observed destinations in Borlänge. The lower map shows the destinations in the area around the CUCA. (b) The kernel density map that shows the distribution of the densities of destinations in identifying the hot spots.

One condition by the law for traveling by car is driving on the road network. The GPS recordings however are not always on the road network due to the measurement error. Data cleaning is required before the analysis. According to the manufacturer, the BT-338X should provide a geographical positioning within an error of 5 meters, therefore, a 5-meter tolerance was given in identifying valid recordings. 129,353 recordings out of 154,579 were identified afterwards. 7932 recordings were identified as destinations, of which 4920 were categorized as sub destinations, while 3012 were categorized as end destinations. Sub destinations here are those destinations that the car stopped for less than 30 minutes. Figure 6(a) illustrates the geographical locations of all destinations arrived at by the volunteers on the road network. As expected, trips are heavily concentrated in the centre area of the city, given the distribution of the residential location and facilities, while arterial streets in the residential areas as well as private roads are with no or very low trip flows. The heterogeneity of destinations is related to the daily car-related activities of the volunteers. The destinations vary from job commuting,
dropping off children at kindergarten and school and grocery shopping to frequenting sports-arenas and recreational areas on the edge areas of the city.

Figure 6(b) is the kernel density map with output units of 0.25 square kilometres that shows the distribution of the densities of the destinations. Residential areas are hot spots that have 400 to 500 incidences of destinations, while the hot spots with the highest density are identified in the three main commercial areas: Kupolen in SPA, city centre in CUCA and ICAMaxi in SPA. These destinations become hot spots not only due to the fact that they have concentrated stores for leisure activities, like shopping and dining in attracting customers, but also because they are places for working, particularly due to the labour intensive work in services.

Considering the whole trip, 1432 trips had just one end destination and 0 sub destinations, which is about 46% of all the trips. 45% of the trips have at least 1 but less than 4 sub destinations. If we check the facilities that match the sub destinations and end destinations corresponding to weekdays and weekends: weekdays have about 3 times more destinations than weekends, both for sub and end destinations; 71% and 82% have home as the end destination. An apparent difference between the sub destinations and the end destinations relating to weekdays are public buildings (for example, office buildings), while for weekends, school and church as sub destinations are more visited (Table A1 in Appendix A1 provides more details).

However, the identified 7932 destinations based on the volunteers are mostly home destinations. It is unreasonable to assume people setting other’s home as regular destinations. Therefore, we first exclude the residential locations and then identify those destinations that accumulate more than 90% of the destinations based on the kernel density; at last, 51 locations are identified as hot spots which are the current and the counterfactual destinations in this paper. Figure 7 shows that they are mainly distributed in the CUCA and SPA, while a few locate in the EUA.
4. Results

Based on the data prepared in Section 3, the NoIEs can now be derived. First, the distance information of each road segment can be retrieved from the road network. Second, the volunteers’ recordings are categorized according to their positions: at the intersections, at the middle of the road and in between, given a 5-meter tolerance. The estimation was adjusted due to the category. For recordings at the intersections, the recorded speeds and the speed limits were applied, while for recordings at the middle, the average speed at the intersections and the recorded speeds were applied. For recordings in between the intersection and the middle, the average speed at the intersection was applied as the incoming speed. If the estimated speed at the middle of the road is over 30 km/h higher than the speed limit, then speed limit plus 30 km/h was applied. For the road segments that have no recording, the average speed at the intersection and the speed limits were applied.

Figure 8 illustrates the NoIEs standardized by the lengths of the roads, in which low indicates the 25 per cent of roads with the lowest emissions, high indicates the 25 per cent of roads with the highest emissions, while the remaining are the roads with medium-level
emissions. Emissions are high on the most frequented roads. This heterogeneity implies that the choices for shortest, fastest or least emitting routes will affect the emission levels from mobility on the road network. In the ex-ante evaluation in this paper, we assume residents opt for the shortest route (Carling et al., 2013; Jia et al., 2013).

![Network of induced CO₂ emissions](image)

Figure 8: Network of induced CO₂ emissions (NoIEs) standardized by the length of the roads.

The origin-destination cost matrixes were constructed based on the NoIEs. For the current stage, the average travel distance is 5.85 km and the CO₂ emission per trip is 1.94 kg based on all the current origins traveling to all the current destinations. Comparing to the current stage, the results of the counterfactual stage show that 8 plans will induce lower CO₂ emissions than the current stage when traveling to the same destinations (detail information in Appendix, Table A2). The 8 locations can meet the needs for 47% of potential residents. Figure 9 shows that, these 8 plans are apartment buildings to be located in the CUCA and SPA. Comparing to the current stage of 1.94 kg, we categorize the 50 residential plans into lower, similar (no more than 15% of 1.94 kg) and higher (more than 15% of 1.94 kg). The 11 similar ones are apartment buildings and single-family houses that are planned to be located in SPA. All the 14 plans in EUA are in the category of inducing high CO₂ emissions.
Figure 9: Distribution of differences of CO₂ emissions between the 50 residential plans and the current stage (1.94kg). The 50 plans are categorized into 3 classes, lower (< 1.94), similar (no more than 15% of 1.94) and higher (more than 15% of 1.94). Comparing to the current stage.

On average, the plans deteriorate from CUCA to SPA to EUA. People who live in SPA will induce 1.95 times more CO₂ emissions per trip than people who live in CUCA. The induced CO₂ emissions per trip from people who live in EUA are the highest, which are 4.32 times more than in CUCA and 2.57 times more than SPA. The average travel distances for people who will live in these three areas also differ to a large extent; people in SPA will travel 1.84 times longer than people in CUCA, while people in EUA will respectively travel 4.11 times and 2.23 times longer than those in CUCA and SPA.

If all the 14 plans in the EUA are not conducted, the remained 36 plans can cover the needs for 54% of the potential residents, and 35% of CO₂ emissions can be avoided. If all the 8 plans that have lower CO₂ emissions and the 11 plans that have similar CO₂ emissions were conducted, 51% of the potential residents’ needs can be met and 72% of CO₂ emissions can be avoided. If the optimization objective is to minimize the CO₂ emissions subject to providing residential locations for at least 90% of potential residents, the 8 plans that have lower CO₂ emissions plus the 1 particular apartment building plan for 2000 potential residents in the EUA in Öster Barkargården can be conducted. These 9 plans can supply places for 92% of the potential residents, and 89% of CO₂ emissions can be avoided.
5. Concluding discussion

In most urban planning studies, the residential location has been considered fixed, and the consequences of where one sets up the different types of facilities has been debated. Literatures mainly focus on the case of ex-post evaluation of relocating destinations, while few studies have focused on conducting ex-ante studies of locating the origins. This paper contributes by proposing an ex-ante evaluation method to quantifying the induced CO\textsubscript{2} emissions of car mobility at the current stage and the counterfactual stage of a city. The results are compared in two dimensions, one is between the current stage and the counterfactual stage, the other is inside the counterfactual stage.

We illustrated the method by applying it on a specific urban planning case. The empirical analysis was based on 1291 aggregated current residential locations, 50 counterfactual residential locations and 51 destinations. The urban plans were categorized into three areas, the continued urban core area (CUCA), suburban polycentric area (SPA) and edge urbanization area (EUA). The CO\textsubscript{2} emissions induced by car mobility of residents who counterfactually live in these three areas to the 51 destinations are quantified. On average, the CO\textsubscript{2} emissions increase from CUCA to SPA to EUA (1.17 kg vs. 2.28 kg vs. 3.00 kg); EUA is almost 3 times more than CUCA. The average travel distances also increase from CUCA to SPA to EUA (3.40 km vs. 6.26 km vs. 13.96 km); the overall increase is more than 4 times.

The quantification results indicate that urban residential plans can significantly influence CO\textsubscript{2} emissions induced by private car mobility of residents. If the plans aim to continuously increase the compactness of former urban cores and to increase the residential density of the developed sub centres, the CO\textsubscript{2} emissions can be mitigated effectively. An apartment building which can accumulate residents in a highly concentrated place could be a preferable building form in reducing CO\textsubscript{2} emissions, which is in line with the advantages of compact city (Burton, 2000; Holden & Norland, 2005). Urban expansion at the edge of cities could bring adverse increase in CO\textsubscript{2} emissions, due to long travel distance to hot spots, restricted accessibility and underdevelopment of public transport. On the other side, when a polycentric city region with several functional gravitation points that serve as destinations for the residents in the relatively peripheral parts, the scenario could be different and the trade-offs between the density and the sustainability need to be adjusted (Naess, 2006; Reginster & Rounsevell, 2006; Westerink et al., 2013).

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relatively peripheral parts, the scenario could be different and the trade-offs between the
density and the sustainability need to be adjusted (Naess, 2006; Reginster & Rounsevell,
2006; Westerink et al., 2013).

To be able to carry out the empirical analysis, certain simplifications, aggregations and
assumptions are found necessary. Firstly, we only had the residents in the city geo-coded with
a precision of 250m, and we could not identify whether one resident owns a car or not.
Secondly, the speed profile used in deriving the network of the induced CO$_2$ emissions is
based on 303 volunteers’ data using triangle estimation. Further empirical check is required in
validating the method. Furthermore, we follow Carling et al., (2013), and Jia et al. (2013) in
assuming residents choose the shortest routes traveling from origins to destinations. However,
in multiple-purpose trips and inter-urban trips, time and cost could be more influential than
the route.

It is also noted that, while this study has given specific consideration to empirical evidence
in the city of Borlänge, it is quite probable that these findings are indicative of a more general
relationship between residential planning, GHG emissions, and energy use in many other
European cities. Beyond residential planning and GHG emissions, city planners have multiple
objectives to be optimized. Urban planning that is solely based on promoting one single
pattern is no longer the solution. Being able to identify the heterogeneous demands and
combine strategies under various contexts is the way for sustainable urban development.
Nonetheless, similar empirical studies in other cities, both within and outside Europe, would
be helpful to move toward a better quantitative understanding of urban planning effects.

References

regional science review, 28(2), 168-192.


Migrationsverket Sweden:


**Appendix**

**A1: Number of sub destinations and temporal distribution of both end and sub destinations**

<table>
<thead>
<tr>
<th>Number of Sub destinations</th>
<th>Count</th>
<th>Facility</th>
<th>Sub destinations</th>
<th>End destinations</th>
<th>Sub destinations</th>
<th>End destinations</th>
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<td>Sub destinations</td>
<td>End destinations</td>
<td>Sub destinations</td>
<td>End destinations</td>
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### A2: The average travel distance and CO₂ emissions in different scenarios

Table A2: The average travel distance and CO₂ emissions per trip per person from all the current residents to the 51 destinations, the average travel distance and CO₂ emissions per trip per person from the three different areas to the 51 destinations, and the average travel distance and CO₂ emissions per trip per person from each residential plan to the 51 destinations.

<table>
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<th></th>
<th>Average travel distance per trip(km)</th>
<th>Average CO₂ emission per trip(kg)</th>
<th>Number of Residents</th>
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<tr>
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<td>1.166777 (0.05)</td>
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<td>13.958923 (1.49)</td>
<td>3.001324 (0.11)</td>
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Note: Standard error is in the parentheses.

Counterfactual stage of each 50 residential plans

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<th>Planned number of residents</th>
<th>Type of area</th>
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