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Urban Design and Multimodal Transportation – Using Urban Form and Accessibility Factors to Estimate Modal Shares and Energy Use from Transportation

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Abstract

A major urban challenge in European cities is the shift towards more energy efficient environmental friendly transportation modes (walking, cycling and public transportation). To make this possible there is a need to provide information about possibilities to use different modes of transportation in cities and energy use from transportation in buildings. This paper proposes, describes, tests and discusses a model to estimate modal shares of different transportation modes (walking, cycling, public transportation and private automobile) and calculate energy use from transportation based only urban form and accessibility factors. The aim is to visually inform actors and stakeholders such as real property developers, municipalities, public authorities, etc. about how well different buildings are integrated with walking, cycling, public transportation and private car, potential energy use and environmental impacts.

Keywords: urban design; multimodal transportation; urban form; accessibility; modal shares; energy;

Introduction

European commission (EC) seeks to break the dependence on fossil oil in the transportation sector without compromising the mobility in European cities. The ambition is to create cities with integrated, multimodal transportation systems where greater numbers of passengers are carried jointly to their destination by the most energy efficient (combination of) modes. To achieve this sustainability mobility goal, information on all modes of transportation, on possibilities for their combined use and on their environmental impact, needs to be widely available (EC, 2011).

Multimodal defines the ability to travel with a choice of different transportation modes. The perspectives and approaches on measuring multimodality differ greatly. On a societal scale, there is a symbolic struggle among mobility cultures (dedicated motorists versus rail nerds, pedestrians versus bike advocates, etc.). Individuals, on the other hand, are free to make their own everyday travel choices. Modal split is a multimodality measure commonly used in transportation engineering and transportation economics. It shows percentages of traveled distances or (daily or annual) number of trips by different modes of transportation for individuals or locations (buildings, neighborhoods or districts, urban or metropolitan areas). The common approach in transportation engineering and transportation economics is studies of individual travel behavior, discrete travel choices and travelling preferences. To estimate the modal split they create market segments and aggregate individual travel patterns at specific locations. Transportation engineers also use land use factors to calculate trip generation rates and subsequently modal splits (ITE, 2012; Ewing, et al., 2013; Weinberger, et al., 2015; Trafikverket's, Swedish Transportation Administration's Trafikalstring tool, see https://applikation.trafikverket.se/trafikalstring/).

The interrelationship between the land use and travel is the most researched topic in urban planning (Ewing and Cervero, 2010). Within this research tradition land use is conceived through D-variables: Density, Diversity and Design (Cervero and Kockelman, 1996); Distance to transit and Destination accessibility (Cervero et al., 2009); Demand management and Demographics (Ewing and Cervero, 2010). The D-variables are included in green building and sustainable neighborhood certification systems for buildings and neighborhoods such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Methodology). The environmental certification systems produce ecolabels or sustainability indicators.

Accessibility is defined as a potential for interaction between places (Hansen, 1959) or "the extent to which Land Use and Transportation (LUT) systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transportation mode(s)" (Geurs and Van Wee; 2004, p.128). There are different ways of define accessibility and many accessibility measures, indicators or indexes (Hansen, 1959; Handy, 1997; Talen and Anselin, 1998; Van Wee, 2002; 2011; Geurs and Van Wee, 2004; Páez et al., 2012). In Sweden, two private companies Spacescape and Trivector produced a Mobility Index (http://www.spacescape.se/project/mobilitetsindex/) and Accesibility Index, respectably for the Royal Seaport urban development in Stockholm and the municipality of Malmö (Trivector, 2014). Walk Score (http://www.walkscore.com/) is a website that calculates Walk Score, Bike Score and Transit Scores for different buildings and cities, based on their proximity to destinations (shops, restaurants, cinemas, etc.). Walk Score, Bike Score and Transit Score are accessibility indexes for particular transportation modes.

This paper proposes, describes, tests and discusses a model to estimate modal shares and energy use from transportation based only on urban form and accessibility factors. The model utilizes research on travel forecasting based on land use factors (Ewing et al., 2013; ITE, 2012; Weinberger et al., 2015), the link between land use and travel (Ewing and Cervero, 2010) and environmental certification systems. Green building and sustainable neighborhood assessment systems such as LEED or BREEAM include urban form and accessibility factors. It is an continuation of an existing work on measuring multimodality and creating Multimodal Transportation Performance Certificates (MTPC) or transportdeklaration in Swedish (Stojanovski, 2017). The model is developed and tested in Luleå, a small city Sweden, in a cooperation with Riksbyggen, a Swedish real property owner and developer.

Methodology

Urban form and accessibility precondition mobility, rather than determine travel. Driving a car is not possible without parking spaces. Walking needs sidewalks. However, it is also possible to park the car far away, to walk on roads without sidewalks or not to walk on a sidewalk because it is unsafe or boring path. During building booms, specific combination of elements (density, mix of uses, parking standards, street widths and speed limits, sidewalks, transit stops, busways or tramways, parking lots and garages, etc.) become fashionable in urban design practices. When an urban area is developed, it incorporates urban form elements that prioritize particular transportation modes (walking, cycling, public transportation and private automobile). To this historical adaptation to different transportation modes is refered as Level of Integration (LoI).

To measure the LoIs, the method combines urban form and accessibility factors on three scales (visual perception, local accessibility and regional connectivity). The argument is that visual proximity e.g. to a transit stop is as important as local or regional access to destinations. The abundance of bikes on streets, bike racks and bikeways in Copenhagen or Amsterdam have a profound influence on biking share. The factors are weighed arbitrary and included in a composite variables (LoIs for walking, cycling, public transportation and private automobile). LoI measures the effect of different urban form and accessibility factors on the performance of transportation modes. The calculation of the LoI uses the generic formula of a weighted sustainability indicator (Wangel et al., 2016):

$$LoI_m = \sum_{i=1}^{n}(w_i \times c_i)$$

LoI_m	Level of Integration (LoI) of transportation mode m
w_i	weight for criterion/urban form or network access factor i
c_i	criterion/ urban form or accessibility factor i

The factors for the LoIs originate from the research on walkability and D-variables (Cervero and Kockelman, 1996; Cervero et al., 2009; Ewing and Cervero, 2010; Southworth, 1997; 2005) and draw inspiration from Walk Score (https://www.walkscore.com/) methodology and LEED-ND (USGBC, 2017). The LoIs for walking, cycling, public transportation and private car are measures based on few most important factors (urban design elements and accessibility factors) on three scales (visual perception, local accessibility and regional connectivity). If all factors are fulfilled the LoI is at 100%,

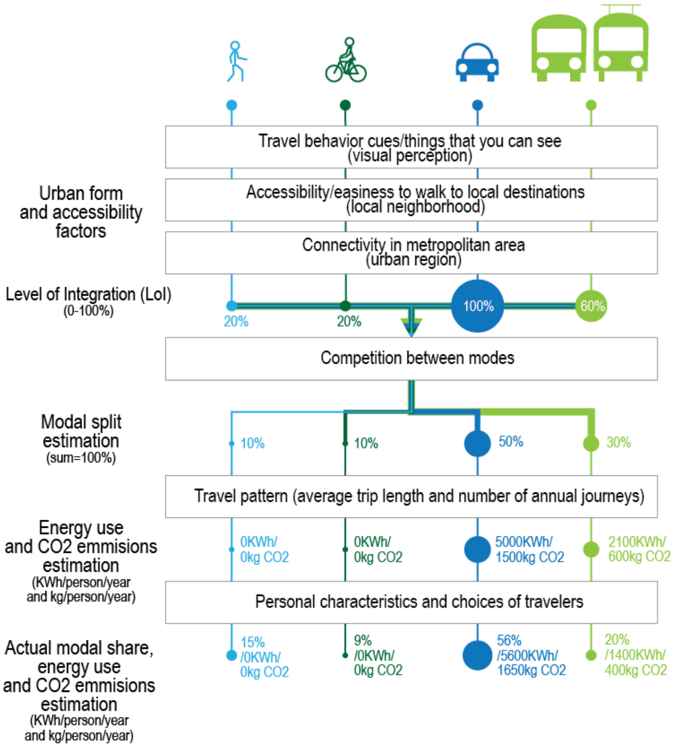

Figure 1: Method to estimate energy use and CO2 emmisions from transportation based only on urban form and accessibility factors

Table 1 shows the urban factors, weights for different factors and the source. The weighting implies 9-point scale commonly used in Multi-Criteria Evaluation (MCE) in GIS where only the top 4 values are used: 9 for extremely, 7 for very much, 5 for moderately and 3 for slightly effects the LoI. The values are arbitrary, but derive from empirical research on the link between built environment and travel (Ewing and Cervero, 2010) and on trip generation based on land use factors (Ewing et al., 2013; ITE, 2012; Weinberger et al., 2015). The proportion between scales in the weighting is arbitrary (10-20% for visual perception, 40-50% for local accessibility and 30-40% for regional scale).

Table 1. Weighting of the factors in the LoIs

Urban factors/elements	Walking	Cycling	Public transportation	Private car	Source
Sidewalk design and continuity	(3) 5[1]				LEED
Pedestrian crossings/street segment length/city block width	(7) 15				Ds, LEED, Walk Score
Speed limit	(3) 5[1]				LEED
Bike infrastructures (racks, parking and cycling lanes)		(3) 20			LEED
Bus line/busway/tramway on street			(3) 5		LEED
Transit stop/station exit on street			(3) 5		LEED
Parking				(9) 60	LEED
Undisturbed traffic flow (no congestion)				(3) 10	LEED
Building setback	(3) 5[1]				LEED
Building height to street width ratio	(3) 5[1]				LEED
Building façade activity/openness	(9) 20[1]				LEED
Lot/block density (residents and jobs)	(9) 40[2]		(3) 5		Ds, LEED
Neighborhood topography (slope)		(9) 40			Walk Score
Access to everyday activities	(9) 20				
Access to event-type activities	(3) 5				
Access to a mix of activities	(9) 20				Ds
Access to a local transit stop			(9) 30		LEED
Access to a regional transit stop			(9) 30		LEED
Access to an expressway				(5) 30	
Bikable location		(9) 40			
			Walking (5) 20		
Sum	(51) 100	(24) 100	(27) 100	(20) 100	

[1] assigned to street space
[2] assigned to city blocks/perimeter within building façades

Table 2 describes in detail the methods used to calculate the LoIs.

Table 2. Methods used to assess urban form and accessibility factors.

Urban element	Method
Sidewalk design and continuity	Surveyed (assigned arbitrary)
Pedestrian crossings/street segment length/city block width	I_2 = 200 - city block width (maximum 100 for width lower than 100 m and minimum 0 points for width over 200 m). city block width = city block area ^ (1/2).
Speed limit	Surveyed (I_3 = 100 if speed limit = 30km/h)
Bike infrastructures (racks, parking and cycling lanes)	Surveyed (bicycle parking racks and cycling lanes on a street give I_4 = 100, I_4 = 50 if there are only bike racks or cycling lanes on the street)
Bus line/busway/tramway on street	Surveyed (street segments with bus lines receive I_5 = 50, whereas I_5 = 100 with busways/tramways on street)
Transit stop/station exit on street	Surveyed (city blocks with a transit stop/station exit on the surrounding streets receives I_6 = 100)
Parking	Surveyed (assigned arbitrary)
Undisturbed traffic flow (no congestion)	Surveyed (assigned arbitrary)
Building setback	Surveyed (I_9 = 100 for building façade within 0.5 m from the street, I_9 = 50 for building façade between 0.5 and 5m and I_9 = 0 over 5 m)
Building height to street width ratio	Surveyed (if the ratio is 1:3 or lower I_{10} = 100)
Building façade activity/openness	Surveyed (if any part of the building façade is publicly accessible I_{11} = 100)
Lot/block density (buildings)	I_{12} = number of storeys/3*100 (if number of storeys > 3 then I_{12} =100)
Neighborhood topography (slope)	Two raster maps with cost distance from the central points are created to calculate the travel ratio (TR): 1) without slope; and 2) with slope degree penalty: no penalty was given for 0-0.5 degrees, 50% for 0.5-1, 100% for 1-2, 300% for 2-5, 400 % for 5-10 and beyond 10%-degree slope got 100 times penalty (1000%). By dividing the raster without and with slope penalty it is possible to see how difficult is to reach a destination. A TR of 1 would mean two points on the map connect without slope obstacles, whereas 2 would mean 0-1% slope. I_{13} is normalized (0-100) with the formula: I_{13} = -10 * travel ratio + 110 ratios (the negative values are corrected to 0)
Access to everyday activities	GIS O-D matrix network analysis was used to calculate distances from each supermarket, shop, restaurant, bar, etc. to every building in the neighborhood. Interpolation method (IDW) was used to calculate ranges. I_{14} = 100 if building is within 100 m (buffer tool was used), I_{14} =60 if between 200-400 m network distance, I_{14} =30 if within 400-800 m network distance.
Access to event-type activities	Same method as in access to everyday activities, just destinations included in this case churches, libraries, etc.
Access to a mix of activities	GIS service area network analysis in ArcGIS was used. Service area polygons within 400 m to entries with different land uses (shopping, culture, recreation, bars and restaurants, services, education and public spaces) were created and overlaid to sum up the number of land uses: I_{16} = 0 (0-1 uses); I_{16} = 25 (2-3 uses); I_{16} = 50 (4-5 uses): and I_{16} = 100 (6-7 uses).

Access to a local transit stop	GIS O-D matrix network analysis was used to calculate distances from local transit stops to every building in the neighborhood. Each local transit stop received a Transit Stop Performance Benchmark (TSPB) in respect to the frequency and type of service (weekly departures multiplied by 2 for commuter rail/subway/regional bus lines, 1.5 for local trunk buses and 1 for standard buses. The reference for the calculus (TSPB = 100) is Stockholm's busiest transit node (Centralen/T-central/) which has 3374 departures or arrivals per week by bus, 2002 by trunk bus, 6643 by subway and 1302 by commuter rail (weighted sum of 22267). The formula is: TSPB = ln (all weekly departures at the transit stop) / ln (22267). I_{17} = weight for proximity to a transit stop (w)*TSPB Interpolation method (IDW) was used to calculate w: w = 100% if building is within 100 m (buffer tool was used), 60% if between 200-400 m network distance, 30% if within 400-800 m network distance.
Access to a regional transit stop	Same method as for access to a local transit stop
Access to an expressway	I_{19} = 100 if the neighborhood center is within 3 km to an exit to an expressway
Bikable location (regionally)	I_{20} = -20*distance to the metropolitan core (in km) +200 (if distance to the metropolitan core > 10km then I_{23} = 0)

The values for the visual perception in Table 1 are assigned for street spaces (sidewalk design and continuity, speed limit, building setback, building height to street width ratio and building façade activity/openness) and for city blocks (the perimeter within building façades). The LoI for walking on the map is a product of focal statistics, average values of all the values within a 100 m buffer that corresponds of an average zone of visual acuity (Figure 2). Street segment length/city block width replaces the visual perception factor pedestrian crossings in this methodology. Street segment length/city block width correlates with intersection density, a Design variable with strongest effect on walking (Ewing and Cervero, 2010).

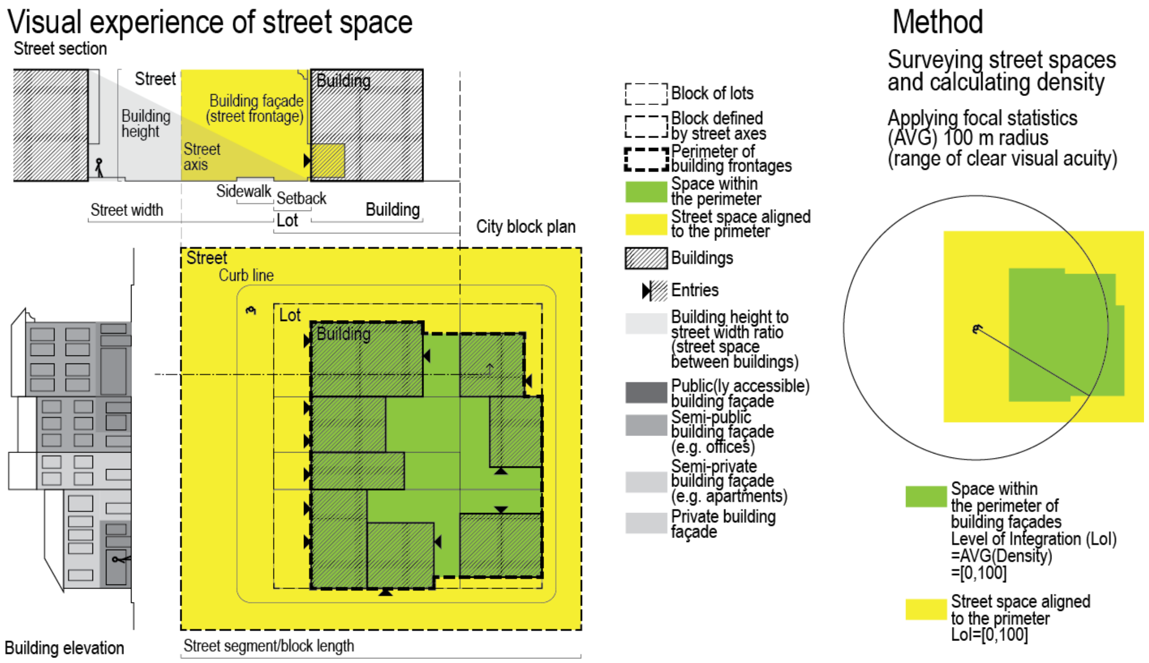

Figure 2: Method for analyzing factors in visual proximity

The method considers competition between modes as proportion of the LoI for a specific mode in respect to the sum of the LoIs for all modes. The formula is:

$$S_m = \frac{LoI_m}{\sum_{i=1}^{n}(LoI_i)}$$

S_m	Modal share for transportation mode m (in percentage/ n
LoI_m	LoI for specific transportation mode m
LoI_i	LoI for transportation modes i

The estimation of modal share allows to calculate the number of annual journeys by different modes by multiplying the modal share percentage with 1000:

$$N_m = S_m \times 1000$$

N_m	Number of annual journeys by transportation mode m
S_m	Modal share for mode m (in percentage)

This assumption is based on travel budgets as invariants of human mobility (Marchetti, 1999). An average person makes 1000 annual journeys (Zahavi, 1974; Banister, 2011). Travel is a fixed sum game where different modes compete for a fixed number of 1000 annual journeys.

The energy use is calculated by using average traveled distances for a journey with private automobile or public bus and assuming energy efficiency. The average traveled distances are based on the numbers from national travel survey in Sweden, whereas the energy efficiency is estimated by fuel efficiency for Swedish gasoline and diesel mix (Swedish Energy Agency, 2017) . Average consumption of fuel is 8 l of gasoline for a private car and 40 l of diesel for a public bus. An average journey by a public bus is 15 km with fuel use of 7KWh/km, whereas a journey by private car averages 18 km and consumes 10KWh/km.

$$E = \sum_{m=1}^{n} (Nm \times l_m \ \times e_m)$$

E	Energy use from transportation
N_m	Number of annual personal journeys by transportation modes m
l_m	Average traveled distances for a journey for transportation modes m
e_m	Energy efficiency (KWh/km) for transportation mode m

The CO2 emmisions are calculated by using average values for Swedish gasoline (2.75 kg/l) and diesel mix (2.78 kg/l) for average traveled distance:

$$CO2 = \sum_{m=1}^{n} (Nm \times l_m \ \times c_m)$$

CO2	CO2 emmisions from transportation
N_m	Number of annual personal journeys by transportation modes m
l_m	Average traveled distances for a journey for transportation modes m
c_m	CO2 efficiencty (kg/km) for transportation mode m that derives from average CO2 emmisions (kg/l)

The methodology is applied and tested in two neighborhoods in the Swedish city of Luleå.

Case study

The study areas

Luleå is a small coastal city in northern Sweden. It is the seat of Luleå Municipality and the capital of Norrbotten County. The city houses roughly 75 000 inhabitants in a county of 250 000. Luleå is also known as the Steel City. It is a Swedish center of metallurgy and steel research and a creative hub. Luleå University of Technology has 15 000 students.

Two neighborhoods are selected for the study, the downtown of Luleå and Kronan (Figure 3). The downtown of Luleå is a typical urban core of a small Swedish city. It has a grid street plan with a rectangular pattern of city blocks with courtyards. Kronan (The Crown) is a proposed urban development neighborhood project roughly 2 km from the downtown. The new plan for Kronan includes residential buildings with courtyards, a new square, commercial and public buildings. When completely finished Kronan will house 7000 inhabitants. Today, roughly 1500 people live in the area. Six residential towers and new student apartments were recently built on the hill westward from the newly planned buildings.

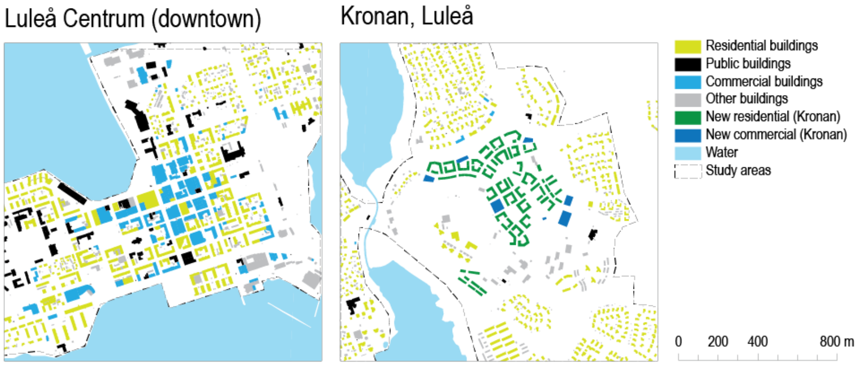

Figure 3: The study areas in Luleå

Results and discussion

Figure 4 and 5 illustrate the urban from and accessibility factors from Tables 1 and 2, LoIs and modal shares for walking, cycling, public transportation and private car for Luleå Centrum and Kronan respectibly. The LoIs for walking, cycling and automobile are very high in Luleå downtown. In Kronan there is a walkability hotspot around the future square, but it quickly dissipates along the residential buildings. Bikeability also decreases in Kronan. The hill on the east of the new development poses difficulties for bikers.

The travel survey for Luleå Municipality from 2010 shows that the shares for walking, cycling, transit and automobile are roughly 50%, 15%, 5% and 30% in the downtown and 25%, 10%, 10% and 55% in the areas surrounding the downtown (like Kronan) (Luleå Municipality, 2010). The modal share estimates show similar results as in the travel survey for future Kronan, but they underestimate walking in the downtown. The walking share is higher in multimodal environments by the actual modal split. With a low frequency of local transit and no regional service, the LoI results in low share of transit. The poor integration of public transportation is especially visible in Kronan.

The results somewhat correspond to the actual travel patterns in Luleå, with a certain error of 10% (20% for walking in the downtown). The expectations are that the actual modal split and the predicted would differ within 10-20%, because the results are based only on urban form or accessibility factors. Travel directly depends on discrete choices of individuals (economic rationality, personality traits, irrational commitment to specific modes, etc.). Mobility management also plays role in shaping everyday travel. The model does not capture this variation. Instead, it measures physical integration of the urban form with transportation modes (walking, cycling, public transportation and private car) and illustrates the interplay between the LoIs as modal share.

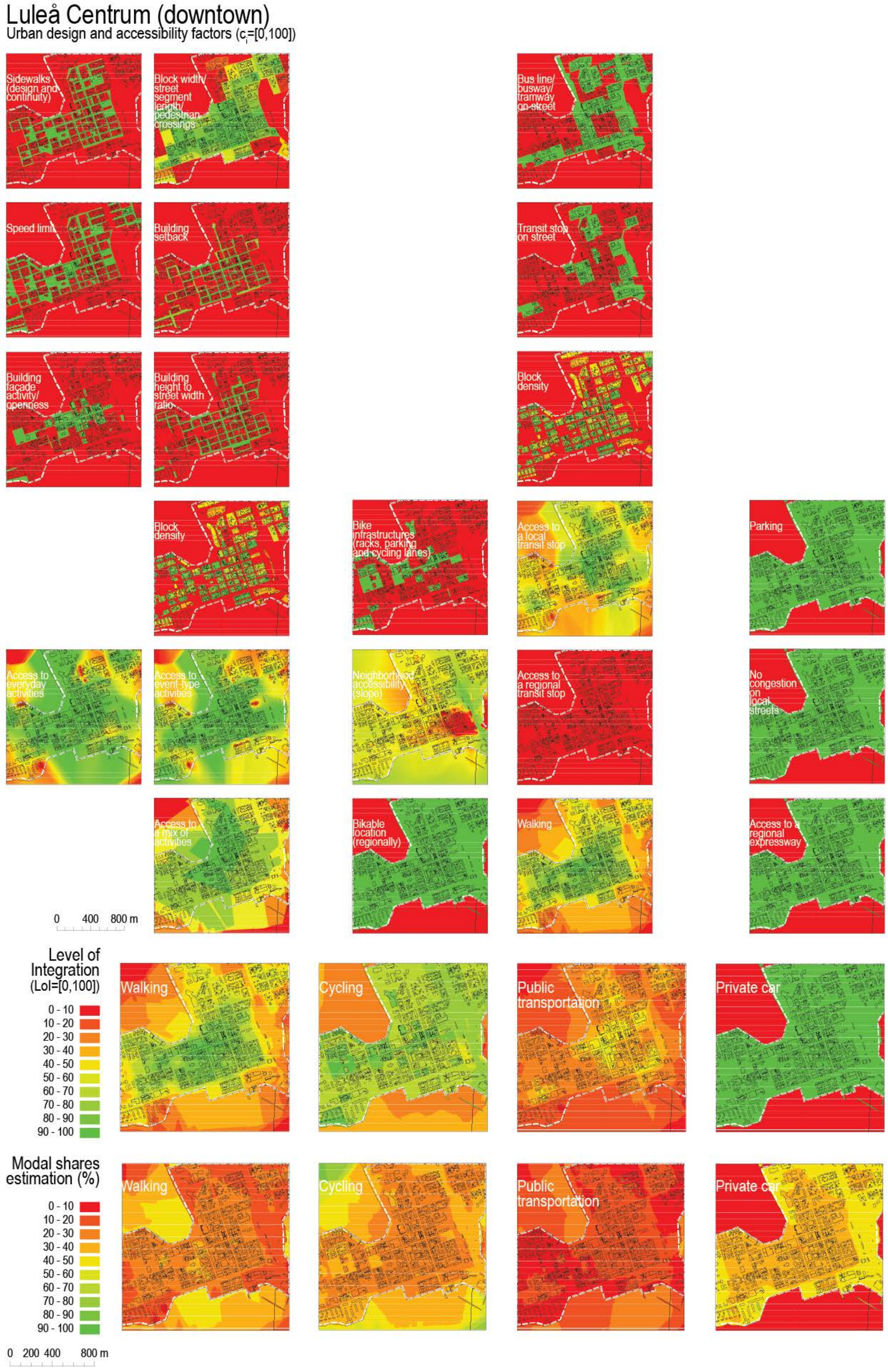

Figure 4: Results for the modal share estimation based on LoIs in Luleå Centrum (downtown)

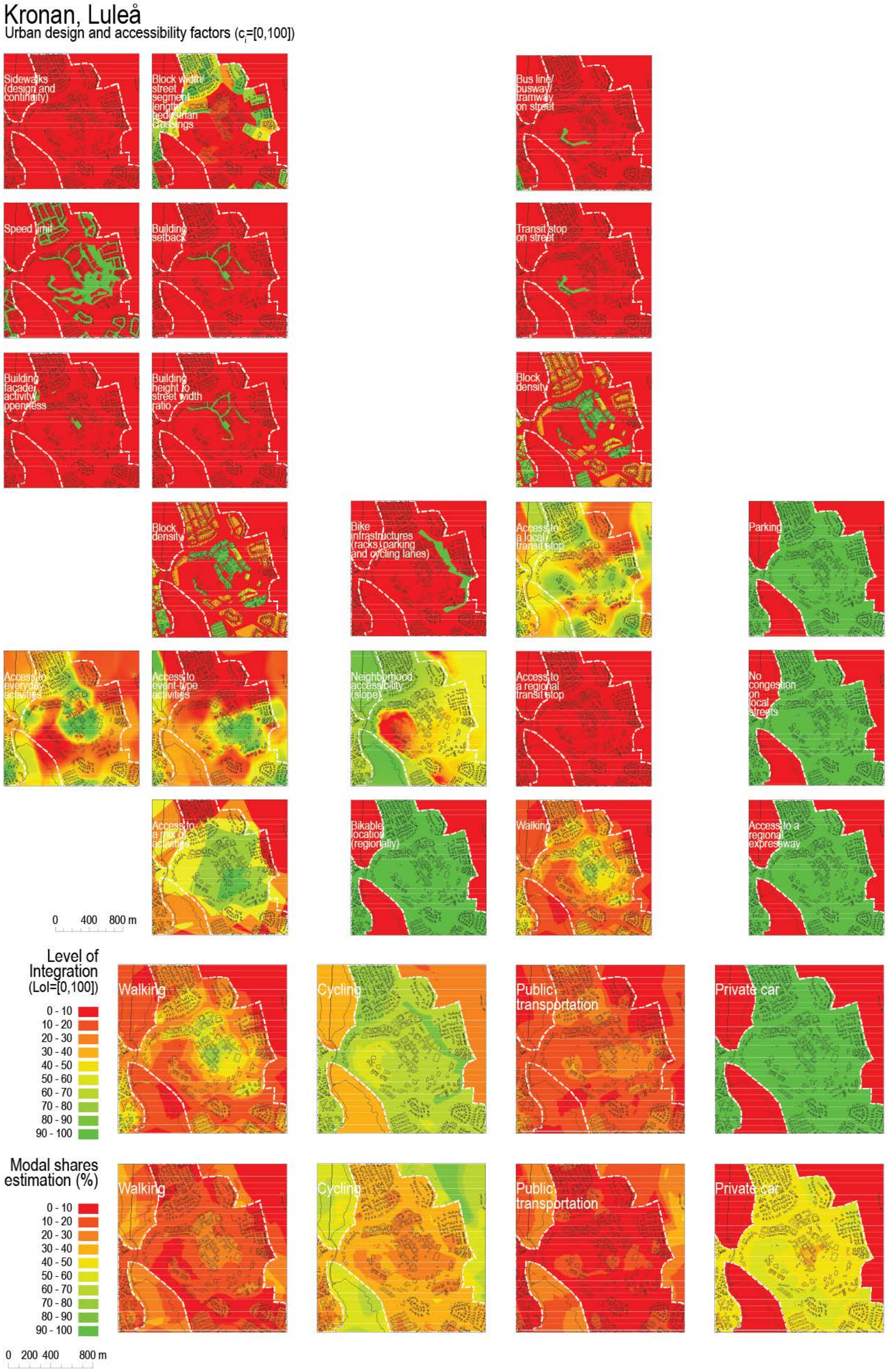

Figure 5: Results for the modal share estimation based on LoIs in Kronan, Luleå

Figure 6 and 7 shows the energy use and CO2 emmision estimation based on the modal shares of public transportation and private car, annual number of journeys and average traveled distances for a journey by public transportation and private car. Annual number of journeys is used because it balances for periodical variation in travel. The travel patterns in terms of number of journeys vary seasonally (less journeys during summer season of holidays than in spring or autumn), but they tend to be more stable and normalize annually (Banister, 2011).

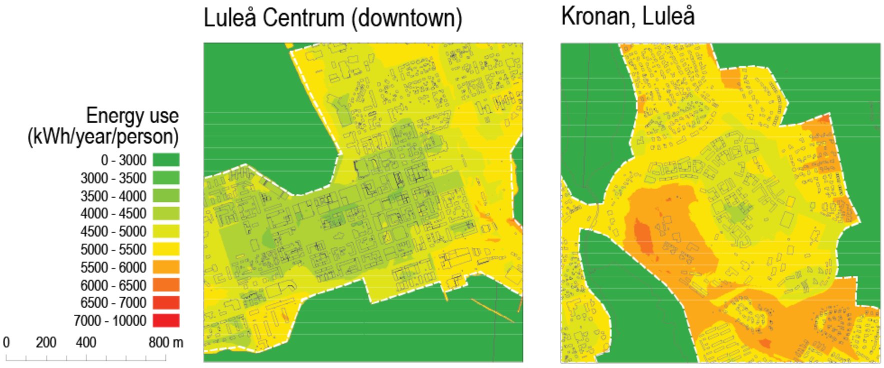

Figure 6: Results for the energy use estimations

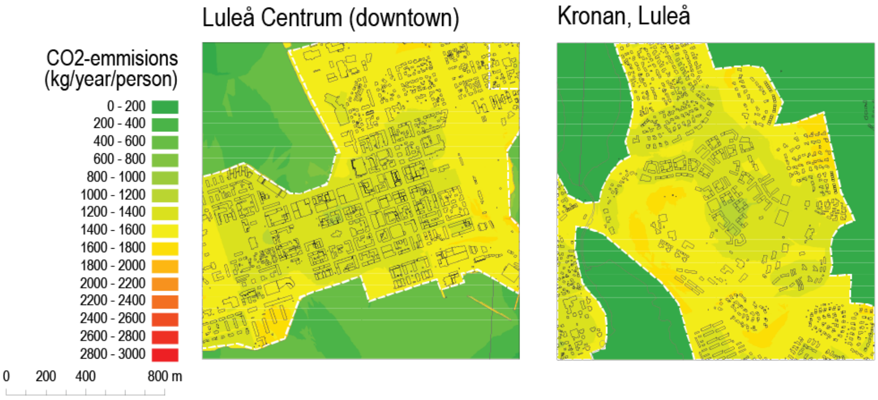

Figure 7: Results for the CO2 emissions estimations

The metrics of kWh/year/person links the model with the Energy Performance Certificates (EPCs). EPC is a European measure of energy performance of buildings based on annual energy use in kWh per square meters of floor space (kWh/m^2/year). EPCs are mandatory for almost all buildings larger than a single-family residence in the European Union (EU). EPCs for apartment buildings in Sweden have an average energy performance of around 140 kWh/m^2/year. The average in Sweden of roughly 50 square meters of floor space per inhabitant would result in a yearly use of 7000 kWh/year/person. The averate CO2 emissions from transportation in Sweden are 1710 kg CO2/year/person. These are two reference values to be used when discussing the results in Figure 6 and 7.

Figure 6 shows that the estimated energy use varies between 3000 and 6000 kWh/year/person in the study areas (between 45% and 85% of the energy used in building for heating and electricity). The areas with 3000 kWh/year/person are along the main street in Luleå downtown, whereas the single houses in the suburbs surrounding the downtown vary within 5000 and 6000 kWh/year/person. Kronan, the new neighborhood reaches the range of 4000 and 5000 kWh/year/person. The estimation suggest that the energy performance from transportation is a bit better from the single house neighborhoods around, but roughly 1000 kWh/year/person. With use of standard energy conversion methods 1000 kWh/year/person would correspond to 120 liters of gasoline per year and person. This will effect some 5000 new residents that would need to pay extra 600 tons of gasoline per year.

Figure 7 also illustrates variation in respect to the reference value of 1700 kg CO2/year/person. The results in Luleå downtown roughly halve the CO2 emissions similarly as in the buildings around the newly planned square.

Conclusions

This paper presents a model to estimate energy use in transportation in buildings by predicting modal shares and calculation energy use as fuel consumption for private cars and public buses. Luleå is a small city where there is no rail transit. The model generates reasonable results for LoI and estimates of modal split (based only on urban form and accessibility factors). The variation of the LoIs for walking, cycling, public transportation and private car correspond to the patterns of movement in the downtown. The most energy efficient areas are along the main street. The main street offers opportunities to walk, bike and use public transportation. The central bus station where all the bus lines meet is located nearby. It also identifies a hot spot for walking around the future square in the Kronan.

The model is based on urban form and accessibility factors. As such, it must be considered with awareness, because travel directly depends on discrete choices of individuals and established mobility cultures. Cities like Stockholm, London and New York have a strong mobility culture that prioritizes public transportation. Cycling is most important in cities like Copenhagen or Amsterdam. Strong mobility cultures influence actual modal shares by boosting specific modes.

In the end, the model works fine in its aims to inform stakeholders and actors (house owners, municipalities, developers, etc.) about the energy performance or CO2 emmisions of buildings in a context of transportation. It introduces a measure for energy use performance from buildings (kWh/year/person) to link with the annual energy consumption with EPC for buildings (measured in kWh/m^2/year). This allows to compare energy performance for electricity and heating in the building and transportation to and from the building. The CO2 emissions can be discussed in a context of average Swedish CO2 emissions. This relates to the fossil free transprotation urban challenge in many Swedish and European cities. Providing this kind of information can contribute to increased awareness about poor integration with energy efficient modes of transportation in respect to the energy used for heating and electricity in buildings.

The future research is to create different future scenarios and test the method in a situation where the public transportation gets higher frequencies or the buildings create main streets that link to the downtown (pedestrian corridors). The other option is to create alternative energy scenarios (hybrid or electric automobile or buses).

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