Multimodal transportation performance certificates (MTPC) for buildings and neighborhoods – comparing methods for benchmarking the effect of built environment on travel

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ABSTRACT

The ambition in Europe is to create cities with integrated, multimodal transportation systems where it is easy to walk, cycle or use public transportation. There is extensive research on urban form and travel, sustainability indicators and rating systems for buildings and neighborhoods and there are new mobility apps, travel planners and websites which provide transportation information, track travel behavior or evaluate and benchmark different transportation modes. This paper assesses three methods to measure multimodality: green building and sustainable neighborhood certification and rating systems, websites that benchmark multiple transportation modes and trip generation tools. It also proposes instituting Multimodal Transportation Performance Certificates (MTPC) as a hybrid method. Three Swedish neighborhoods Munksjostaden and Tenhult in Jonkoping and Haningeterrassen in Haninge, Stockholm, are analyzed and the results show that each method produces different, but fairly reasonable results considering their specific scopes and applications. The conclusive MTPC benchmarking procedure aims to harness the best of each method, though it inherits some of their problems.

1. Introduction

European commission (EC) seeks to break the dependence on oil without compromising the mobility in European cities. The ambition is to create integrated, multimodal transportation systems where greater numbers of passengers are carried jointly to their destination by the most efficient (combination of) modes (EC, 2011, p.5). To achieve this sustainability mobility goal, information on all modes of transportation, on possibilities for their combined use and on their environmental impact, will need to be widely available (ibid., p.13).

Multimodality is defined as ability to travel with a choice of different transportation modes. Modal split is a measure for multimodality in transportation planning and forecasting. It shows the shares of different modes of transportation as percentages of traveled distances or number of trips. Transportation planners commonly use built environment and land use factors to calculate trip generation rates and subsequently modal splits (ITE, 2012; Ewing, et

al., 2013; Weinberger, et al., 2015; Trafikverkets, Swedish Transportation Administration's Trafikalstring tool, see https://applikation.trafikverket.se/trafikalstring/). Many journey planners and web navigation services offer possibilities to see and choose among multiple travel alternatives (by one or many transportation modes). Some journey planners also calculate carbon emissions savings by shifting from private car to public transportation or energy consumption (in pieces of chocolate) if the traveler decides to walk or bike (see http://www.reittiopas.fi/en/). There are new mobile apps which use location tracking and automatic transportation mode detection to analyze movement and calculate modal split for individual mobility (Prelipcean et al., 2014; http://en.trivector.se/it-systems/travelvu/). Walk Score (http://www.walkscore.com/) is a website that calculates Walk, Bike and Transit Scores for different buildings and cities, based on their proximity to destinations (shops, restaurants, cinemas, etc.). The interrelationship between the built environment and travel is the most researched topic in urban planning (Ewing and Cervero, 2010). Within this research tradition, which abridges transportation and urban planning, the built environment 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).

Even though there are links between the research on urban form and travel, sustainability indicators and rating systems for buildings and neighborhoods and the new mobility apps, travel planners and websites, there is no convergence. The information is about multimodal transportation choices to and from buildings (how energy efficient it is, levels of carbon emissions, integration with the built environment, how easy it is to walk, cycle and use public transportation, how often buses or trains depart, what is the transit service quality, are there high parking fees or traffic jams in the neighborhood, etc.) is often scattered. This paper looks at the possibility to develop a method to concisely inform multiple stakeholders: landlords and tenants, real property developers, urban designers and planners about multimodal transportation and the integration of different transportation modes in the neighborhoods. It reviews and compares three methods to analyze or benchmark multimodality and buildings. It also proposes a hybrid method named Multimodal Transportation Performance Certificates (MTPC) to assess multimodality. Three Swedish neighborhoods under development, Munksjostaden and Tenhult in Jonkoping and Haningeterrassen in Haninge, Stockholm are selected as case studies. The methods are described in section 2. Section 3 discusses the theory behind the methods and the possible synergies by combining them. Section 4 and 5 presents the study areas, results, and discussion. The conclusions and future research directions are outlined in the last section.

2. Methodology

The three methods are selected with different scopes, methodologies and abilities to convey information. LEED is a representative of environmental certification and rating systems. They have a strong focus on built environmental factors and ways to categorize and weigh their impact. They are comprehensive in scope, involving laborious analyses with complex benchmarking procedures that rely on expert knowledge. LEED integrates both research on

D-variables (Ewing and Cervero, 2010) and walkable street factors which derive from New Urbanism. Walk Score is a website that provides information about how good the buildings and neighborhoods are integrated with walking, cycling and public transportation. Its scope is narrow with large emphasis on visual information. Walk Score has a focus on network accessibility to destinations, but it also includes two parameters from the Design variable. In the end, Trafikalstring is a travel demand model which calculates trip generation rates and modal split estimations based on types of residences and jobs and location characteristics. It produces a very specialized information which can be used to estimate mobility patterns and environmental impacts from transportation GIS is used to make the methods visually comparable. In urban planning GIS has been utilized to discuss LEED as urban metrics and compare LEED and Walk Score (Talen et al., 2013), for analysis of multimodal networks (Gil, 2015) and land use-transportation integration (Dur et al., 2014). The maps and statistics for demographics and commuting are provided from Lantmateriet (Swedish National Land Survey), municipalities and SCB (Statistics Sweden). The specific methods are described in detail in the following subsections and the Appendix.

2.1   LEED

LEED is an ecolabel for buildings and neighborhoods established by the non-profit organization U.S. Green Building Council (USGBC). It includes different factors grouped in categories: energy use, material and resources, waste, indoor environment, location and transportation and innovation. The factors and categories are organized in scorecards. The weights of the categories and factors vary for different types of building and phases of development (design, construction, operation and maintenance). The LEED certification is done by licensed experts. The building meets certain certification level based on the sum of credits: certified (40–49), silver (50–59), gold (60–79) and platinum (80 points and above).

LEED for Neighborhood Development (LEED-ND) is applied here with certain adjustments. Only transportation-related factors are considered and normalized to fit the original certification levels. In the typical LEED-ND scorecard and methodology (USGBC, 2016) transportation-related factors (including built environment factors that influence travel) sum up to 39 or 35% of the maximum 110 points which can be awarded. A detailed description of the factors included in the LEED analysis are presented in Table A1 in the Appendix. The factors were either measured in ArcGIS or surveyed in the field. Map algebra tools in ArcGIS are used to sum them up and normalize the sum (0-100). The factor for Housing and Jobs Proximity in LEED describes mix of residences and jobs is often captured as potential for less commuting. Here statistics show how many work in the area and how many actually commute. The Walkable Streets factor is also modified. Some conversions between mile and km, intersections and city blocks are accepted. The LEED certification procedure does not produce heat maps in GIS, but instead consultants give medals.

2.2   Walk Score

Walk Score is a web service which provides specialized information about walkability, possibility to bike or ride transit in American cities. The website algorhytm assigns numerical indexes (Walk, Transit and Bike Score) to buildings and cities. Each score is followed by a description. Walk Score between 70 and 89 designates a very walkable area where most errands can be accomplished on foot.

Walk Score includes network accessibility and Design factors. Maximum number of 100 points are awarded for specific destinations for errands, culture, grocery, park, dining and drinking, school and shopping within 5-minute walk (400 m). The score gradually drops and no points are given after 30-minute walk (2400 m). Two Design parameters are included, block length and intersection density which have the strongest effect on walking of all D-variables (Ewing and Cervero, 2010). Transit score uses logarithmic scale based on reference values from stops in the USA with highest frequency of transit service. The value of a transit stop is defined as the service level (frequency per week) multiplied by the mode weight (heavy/light rail 2, ferry/cable car/other 1.5 and bus 1) multiplied by a distance penalty. In the end Bike Score measures: cycling infrastructure (lanes, trails, etc.); hills and slopes; destinations and connectivity; and the number of bike commuters.

To calculate Walk Score, destinations are firstly mapped and coded in GIS, then service area tool is applied to produce polygons with maximum 100 points (within 400 m walking distance from different destinations). Afterwards a cost distance tool is used with 0.05 points per 1 m raster cell (equals 0 after 2000 m) starting from the contours of polygons with maximum 100 points. The methods are described in Table A2 in the appendix. There are some adjustments to the Walk Score methodologies. The website however does not explain how the separate scores are aggregated in the final Walk Score. An average of all the scores is applied. Some conversions between mile and km, intersections and city blocks are accepted. Only the slope is considered as a Bike Score.

2.3   Trafikalstring (Trip Generation) tool

Trafikalstring is a web application created by the consultancy company Trivector for Trafikverket. It estimates the modal split and trip generation levels for a neighborhood based on built environment and land use factors. The assumption behind the trip generation tool is that typical residences and jobs generate consistent travel patterns. These average number of daily journeys by different modes are modified in respect transportation system and mobility management characteristics (Trafikverket, 2011). The formula is:

$N_{daily\ journey}$ (by mode$_{1-n}$) = average$_{daily\ journeys\ by\ residence\ and\ job\ type}$ * location coefficient (modification in respect to other factors)

In this analysis zones of neighborhoods are selected and the input to the models is normalized (100 jobs or residents). The modal splits are calculated by manual input in the web application (different variations of residences and jobs). The results are encoded and visualized in ArcGIS. Pie chart diagrams show the modal split (as preferred by Trafikverket) and bar charts for types of residents and jobs used as input.

2.4   Multimodal Transportation Performance Certificates (MTPC) method

MTPC is a hybrid method which uses Levels of Integration (LoIs) of the built environment with different transportation modes (walking, cycling, public transportation or private car) to estimate the modal split. The factors for the LoIs in MTPC (Table A3 in Appendix) originate from the research on walkability and D-variables (Southworth, 1997; 2005; Ewing and Cervero, 2010; Ewing and Handy, 2009; Ewing et al., 2005) and draw inspiration from Walk Score methodology (for assessing cycling and public transportation) and LEED-ND for walkability. Slope is an important factor in Bike Score, whereas the Transit Score is

calculated in respect to weekly departures and type of transit service (not only as Distance to transit).

The LoIs for walking, cycling, public transportation and private car are measures based on few crucial factors (urban design elements/built environment and accessibility factors) on three scales (visual perception, local accessibility and regional connectivity). If all factors are fulfilled the LoI is 100%. There are two steps in the analysis/benchmarking procedure (Figure 1): calculation of LoIs for specific modes and estimating modal split based on competition between their LoIs. The competition is considered as arithmetic mean between the LoIs for the specific mode. The formulas are:

$LoI_{specific\ mode}$ = Σ weights * urban design elements/built environment and accessibility factors

Modal share$_{specific\ mode}$ = $LoI_{specific\ mode}$ / Σ LoIs for all modes

The weights for different factors are represented on Table A4 in the appendix. The weighing is done accordingly to the 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 some derive from empirical research on the link between built environment and travel and LEED. The proportion between scales in the weighing is assumed arbitrary: 10-20% for visual perception (visible behavioral cues/scripts on the streets), 40-50% for local neighborhood accessibility and 30-40% for regional scale.
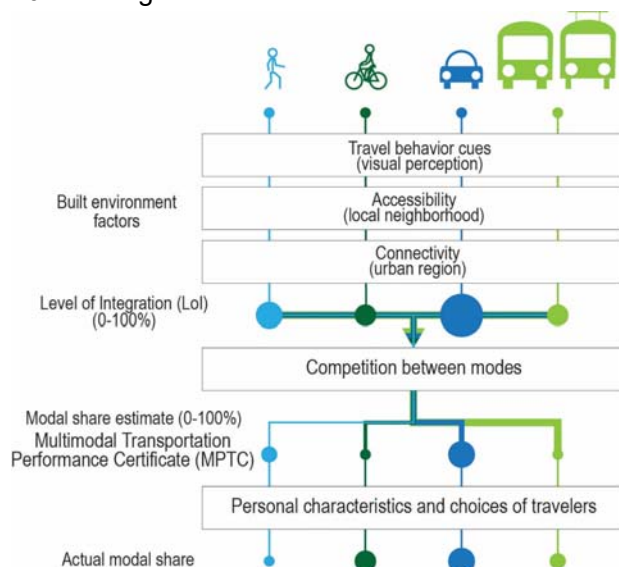

Figure 1. MTPC method including built environment factors on three scales (visual perception, local accessibility and regional connectivity)

3. Theory

The theoretical framework conjoins the aggregated tradition to research the interrelationship between built environment and travel with benchmarking and sustainability indicators in

environmental sciences. The place-node model and mobility environments (see Bertolini, 1996; 1999; and 2017) illustrates the link between the built environment and travel simplistically and deterministically. The place (factors of the built environment) are represented on the x axis, whereas the transportation performance/travel demand variables (modal split, number of journeys generated, etc.) on the y axis. This aggregated tradition is visible in earlier research on public transportation and cities (Pushkarev and Zupan, 1977) and exists in trip generation handbooks and manuals (ITE, 2012).

There is a continuous search for meaningful indicators and performance measures in public policy (Innes and Booher, 2000). Walk Score can be considered as an indicator for walkability and multimodality. Environmental certification systems are also a type of sustainable indicators that also include transportation-related factors. Trip generation forecasts based on built environment factors are compatible with indicators for integration with different transportation modes. As indicators and performance measures LEED and Walk Score can be used to predict trip generation rates and modal splits (as place element in the place-node model).

The problem with trip generation forecasts based on built environment factors is the high variation. The built environment preconditions mobility, rather than it determines travel (Figure 2). When a neighborhood is developed, certain urban design elements are embedded in the neighborhood (density, mix of uses, parking standards, street widths and speed limits, sidewalks, transit stops, busways or tramways, parking lots and garages, etc.). These design elements support or hinder travel by specific transportation modes. The actual modal split is a product of personal characteristics and discrete travel choices of individuals. There should be awareness of the limitation of this theory.
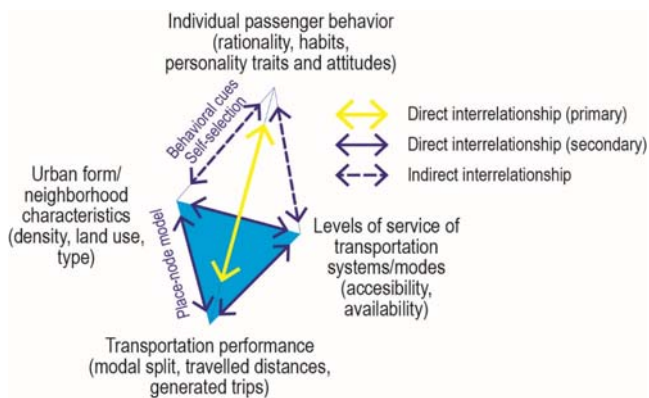

Figure 2: Interrelationship between modal share, built environment, transportation systems and individual behavioral choices.

4. Testing the methods in Stockholm and Jonkoping

Three neighborhoods: Haningeterrassen in Haninge, Stockholm and Munksjostaden and Tenhult in Jonkoping, are selected for the analysis (Figure 3). Haninge, a municipality with roughly 90 000 inhabitants, is a southern suburb of Stockholm, the capital and largest city in Sweden with approximately 2.2 million people living in its metropolitan area.

Haningeterrassen is an infill project close to Handen station (commuter rail). Haninge is a typical suburban neighborhood development project from the 1960-70s with local shopping mall (Haninge Centrum, subsequently upgraded under 1980s) and additional commercial and institutional buildings (library, municipality headquarters, etc.) around commuter rail station. The suburban neighborhood center is surrounded by residential multifamily apartment buildings. Jonkoping is a middle-sized city in southern Sweden with more than 130 000 inhabitants living in the municipality and 350 000 in the region. Munksjostaden is an extension of the southern inner city of Jonkoping, called Jonkoping Soder, along the waterfront of Munksjo, Lake of monks. Jonkoping Soder has a unique inner city character of a middle-sized Swedish city with small shops and services, parks (Idas park) and squares (Torpaplan). Jonkoping University is nearby too. Tenhult is a detached house suburb grown around a railway station from the 19th century. However, the neighbourhood center is not located in proximity to the station despite the fact that the residences create a circle around Tenhult station.

Figure 3. Study areas in Stockholm and Jonkoping

5. Results and discussions

Figures A1-6 in the Appendix show maps illustrating different ways to measure or benchmark multimodality. The heat maps for LEED medals and credits are normalized within the 0-100 interval to be comparable (Figure A1). Walk, Transit and Bike Scores are presented with

adequate descriptions which are comparable to LEED certification levels (Figure A2). The pie charts show the modal shares in Trafikstralning. The modal split estimates in Trafikstralning are shown besides the averaged modal shares and measured in travel surveys (Figure A3). MTPC shows LoIs (0-100%) and modal shares on as heat maps (Figure A4-6). Green means better and red worse on all heat maps.

It is obvious that different methods excel in some aspect, whereas they are disadvantaged in other. LEED focuses in detail on urban elements (building facades, entries to buildings, setbacks, etc.), whereas Walk Score accentuates network access (86% of the score). The visual perception factors under Walkable Streets comprise 25% of the credits in LEED. Regardless, LEED and Walk Score show zones in Jonkoping and Haninge which are highly walkable and zones which are not. LEED seems to be more stringent in sense of awarding credits and produces much more detail. Walk Score results are more even and much higher. The few shops in Tenhult produce very high Walk Score, equally as in Munksjostaden and Haningeterrassen which are located rather centrally in their respective municipalities. Very few destinations boost network access dramatically in Walk Score. The overrating of Walk Score is understandable, since it is a web service and very low scores can affect customer satisfaction (51 out of 100 is acceptable, but 1 out of 100 percent is worrying).

Trafikalstring calculates the modal shares for places (zones) based on the number and type of residents, jobs, etc. within the zone. However, there are some problems. Firstly, Trafikalstring seems to miscalculate walking. The estimated modal shares of 27% car, 8 % public transportation, 14% cycling and 50% walking for Munksjostaden does not coincide with the actual modal share of 44% car, 8% public transportation, 21% cycling and 26% walking in Torpa/Jonkoping Soder (see Jonkoping municipality, 2014). Trafikalstring estimated a high share for walking in Haningeterrassen (13% car, 24% public transportation, 7% cycling and 55% walking) and Haninge municipality is predominantly commuting suburb with 50% car, 32% public transportation, 5% cycling and 10% walking (SLL, 2016). The tool was much better to estimate the modal share in suburban Tenhult 77% car, 4% public transportation, 12% cycling and 5% walking versus 85% car, 7% transit, 3% bike and 2% walking in the travel survey (Jonkoping municipality, 2014). These mistakes might be a limitation because of the choice of zone for analysis. The size of the zones is one or two city blocks. If a wider zone is applied for a specific building where the modal share is calculated by home range as zone, the modal share might change. In the end Trafikalstring relies on manual input of data. The analysis for each building are laborious undertaking. An alternative will be to automate manual input and analysis of number of residences and jobs within the home range.

MTPC as a hybrid method generates reasonable results for LoIs and estimates of modal split (based only on LoIs as indicator of integration with the built environment). The benchmarking procedure produces hot spots for walking and public transportation, and it shows where it is problematic to bike. It identifies steep slopes and terrain depressions where it is difficult to bike. The modal shares estimates are within some reasonable margin of error (not as high as Trafikalstring). Secondly the modal share estimates are shown visually on a map. However, the predictions of mobility patterns based only on built environment factors must be considered with awareness, because travel directly depends on discrete choices of individuals (economic rationality, personality traits, irrational commitment to specific modes,

etc.) and mobility cultures. Some cities like Stockholm have developed a culture where public transportation is prioritized. Other cities like Copenhagen have a cultural cycling bias. Strong mobility cultures influence actual modal shares by boosting specific modes. Mobility management also plays role in shaping everyday travel.

6. Conclusions

The methods produce different, but fairly reasonable results considering their specific scopes and applications. Table 1 shows a summary of the comparison in respect to the benchmarking and evaluation methods and possible problems. Each method excels in something: LEED in detail and comprehensiveness (summarized as medals); Walk Score in visualizing multimodality (multiple scores and heat maps presented online); and Trafikalstring in forecasting modal splits (and subsequently having the possibility to calculate energy use and CO2-emmissions). However, there are some disadvantages. The detail in LEED needs surveying and laborious analysis. Walk Score overestimates its scores to satisfy its customers. Trafikalstring is not very accurate in its modal shares estimations. MTPC combines the best of each method, but it also inherits some of the problems. It remains laborious analysis. The modal share estimations are a bit better than Trafikalstring. There is lots of room for improvement, but also lots of potential to convey information.

	Benchmarking	Evaluation methods	Problems
LEED	Credits and medals	MCE (built environment factors, accessibility)	Not specialized to evaluate multimodality (but much potential). Laborious analysis
Walk Score	Scores, descriptions, and heat maps	MCE (accessibility, built environment factors)	No parking or Driving Score included. Overestimates scores.
Trafikalstring	Modal split	Trip generation and modal split estimation (based on built environment factors)	Inaccurate estimations of modal shares. Laborious analysis
MTPC	LoIs (scores) and modal shares as heat maps	MCE (built environment factors, accessibility) + modal split estimation	Laborious analysis

Table 1: Summary of comparison of methods

MTPC aims to deliver concise and visual information about sustainable transportation to multiple stakeholders: landlords and tenants, real property developers, urban designers and planners. The benchmarking producedure succeeds in that. This information can be used to calculate energy use and emissions from transportation and contribute to increased awareness for unsustainable mobility patterns embedded in the built environment. However, the estimation of modal shares based only on built environment factors must be considered with certain level of doubt. Travel directly depends on discrete choices of individuals and it is skewed by established mobility cultures.

The future research should refine the MTPC benchmarking procedure, automate parts of the analysis and further improve the modal share estimation model. In long term the goal is to create a web application which will automatically recognize urban design elements based on GIS data. MTPC estimates can be additionally verified and calibrated with new travel survey and automated mode detection mobile apps.

Appendix A: Methods

	LEED factors	Method
1	Access to Quality Transit (7 cr.)	Polygons within 400 m around each transit stop are created with service area network analysis in ArcGIS, where each service area as polygon receives number points in respect to frequency of service according to Table 1 and 2 in USGBC (2016, p.19)
2	Bicycle Facilities (2 cr)	Surveyed or assigned
	a. Bikable Location (1 cr.)	Assigned fixed value for entire locality arbitrary
	b. Bicycle Network (1 cr.)	Surveyed and mapped on streets, 1 point is assigned to every block which had a cycle way or bike storage facilities
3	Housing and Jobs Proximity (3 cr.)	As percentage of commuters in residents and jobs calculated from statistics and mapped on blocks: 1) over 75% commuters (0 cr.); 2) between 50% and 75% commuters (1cr.); 3) between 25% and 50% commuters (2 cr.); and 4) under 25% (3 cr.).
4	Walkable Streets (9 cr.)	Each segment of the street is surveyed and credits are awarded for the following factors
	abc. Building facades setback	Setbacks of 5m (1cr.) or 0.3m (2cr.)
	de. Functional entries to buildings	Entries within 9m (1cr.)
	fghkl. Open building façade	Surveyed (3cr.)
	ij. Attractive and continuing sidewalks	Surveyed (1cr.)
	m. Building-height-to-street-width ratio	Surveyed (1cr. If less than 1:3)
	no. Traffic speed for pedestrian safety	Under 30km/h (1cr.)
5	Compact Development (6 cr.)	As residents and jobs per hectare calculated from statistics and mapped on blocks defined by street axes
		1) below 100 (0 cr.); 2) from 100 to 128 (1 cr.); 3) from 128 to 180 (2 cr.); 4) from 180 to 248 (3 cr.); 5) from 248 to 376 (4 cr.); 6) from 376 to 624 (5 cr.); and 7) over 624 (6 cr.)
6	Mixed-Use Neighborhoods (4 cr.)	Polygons within 400 m to entries with different land uses mapped in the neighborhood: shopping, culture, recreation, bars and restaurants, services, education and public spaces; are created with service area network analysis in ArcGIS. With overlay of the generated polygons (intersect tool in ArcGIS) the number of land uses is summed and credits are awarded inspired by Table 1 on in USGBC (2016, p.37)
		1) 0 or 1 uses (0 cr.); 2) 2 uses (1 cr.); 3) 3-4 uses (2 cr.); 4) 5-6 uses (3 cr.); and 5) 7 uses (4 cr.)
7	Reduced Parking Footprint (1 cr.)	Surveyed and mapped on blocks
8	Connected and Open Community (2 cr.)	Number of intersections per sq. mile according to Table 1 and 2 in UGBSC (2016, p.42) is replaced with block density per sq. km and mapped on blocks defined by street axes)
9	Transit Facilities	Surveyed and mapped on blocks
10	Transportation Demand Management (2 cr.)	Assigned fixed value for entire locality arbitrary
11	Access to Civic & Public Space (1 cr.)	Polygons within 800 m to the centroids of public spaces are created with service area network analysis in ArcGIS
12	Access to Recreation Facilities (1 cr.)	Polygons within 800 m to the centroids of parks and other recreation facilities are created with service area network analysis in ArcGIS

Table A1. LEED transportation-related factors

		Method to calculate
	Walk Score	Average of the eight scores described below
1	City block/street segment length score	block length score = 200 - block length (maximum 100 for block lengths lower than 100 m, and minimum 0 points for blocks wider than 200 m)
2	Intersections/city blocks density per km score	block density score = (number of blocks per square km) / 3 (blocks shorter in average than 100 m and longer than 200 m got 100 or 0 points respectably)
3	Errands score	Destinations are firstly mapped in GIS, then service area tool is applied to produce polygons with maximum 100 points (within 400 m walking distance from different destinations). Afterwards a cost distance tool is used with 0.05 points per 1 m raster cell (equals 0 after 2000 m) starting from the contours of polygons with maximum 100 points.
4	Grocery and shopping score	
5	Parks and public spaces score	
6	Dine and drink score	
7	Schools score	
8	Culture score	
	Transit Score	Each transit stop receives a Transit Score based on weekly departures (weight for rail lines is 2, trunk buses 1.5 and standard buses 1). The reference transit score of 100 derives from 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: Transit Score = ln (number of all departures or arrivals per week at the transit stop) / ln (22267). Transit Score incudes distance penalty. Network analysis in ArcGIS is used to delineate polygon within 400 m network distance from each transit stop. This area received the Transit Score calculated for the transit stop. A cost distance tool is applied with decay cost of 0.05 points (as for Walk Score) from this polygon around each transit stop as it was case with Walk Score. Rasters with Transit Scores for different transit stops are overlaid to extract the maximum transit score for each cell (1m long and wide) with cell statistics tool.
	Bike Score	Only the hill factor was analyzed for Bike Score. Spatial access to the central points in the study areas is calculated in respect to impendences caused by degree of slope. Two raster maps with cost distance from the central points are created: 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 travel ratio of 1 would mean no slope obstacles, whereas 2 would mean 0-1% slope. The slope score is normalized (0-100) with the formula: Slope Score = -10 * travel ratio + 110 ratios (the negative values are corrected to 0)

Table A2. Walk Score factors

	MTPC factors	Method	Origin
1	Sidewalk design and continuity	Surveyed (assigned arbitrary)	LEED
2	Pedestrian crossings/street segment length/city block width	I_3 = 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).	Ds, LEED
3	Speed limit	Surveyed (I_4 = 100 if speed limit = 30km/h)	LEED
4	Bike parking	Surveyed (bicycle parking racks on a street give I_5 = 100)	
5	Cycling lanes on street/cycleways	Surveyed (street segments with cycling lanes receive I_6 = 100)	
6	Bus line/busway/tramway on street	Surveyed (street segments with bus lines receive I_7 = 50, whereas I_7 = 100 with busways/tramways on street)	
7	Transit stop/station exit on street	Surveyed (city blocks with a transit stop/station exit on the surrounding streets receives I_8 = 100)	
8	On-street parking	Surveyed (assigned arbitrary)	
9	Undisturbed traffic flow (no congestion)	Surveyed (assigned arbitrary)	
10	Building setback	Surveyed (building façade within 0.5 m will yield I_{11} = 100, between 0.5 and 5m I_{11} = 50, and I_{11} = 0 over 5 m)	LEED
11	Building height to street width ratio	Surveyed (if the ratio is 1:3 or lower I_{12} = 100)	LEED
12	Building façade activity/openness	Surveyed (if any part of the building façade is publicly accessible I_{13} = 100)	LEED
13	Lot/block density (residents and jobs)	I_{15} = residents and jobs per ha/100 (if residents and jobs per ha > 100 then I_{15} =100)	Ds, LEED
14	Lot/block land use mix (entropy of residents and jobs)	I_{16} = entropy of residents and jobs /0.7*100 (if entropy of residents and jobs > 0.7 then I_{16} =100)	Ds, LEED
15	Lot/block off-street parking	Surveyed (assigned arbitrary)	
16	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_{19} is normalized (0-100) with the formula: I_{19} = -10 * travel ratio + 110 ratios (the negative values are corrected to 0)	Walk Score
17	Access to everyday activities	GIS O-D matrix network analysis is used to calculate distances from each supermarket, shop, restaurant, bar, etc. to every building in the neighborhood. Interpolation method (IDW) is used to calculate ranges. I_{16} = 100 if building is within 100 m (buffer tool is used), 60 if between 200-400 m network distance, 30 if within 400-800 m network distance.	
18	Access to event-type activities	Same method as in access to everyday activities, just destinations included in this case churches, libraries, etc.	
19	Access to a mix of activities	GIS service area network analysis in ArcGIS is used. Service area polygons within 400 m to entries with different land uses (shopping, culture, recreation, bars and restaurants, services, education and public spaces) are 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).	LEED
20	Access to a local transit stop	GIS O-D matrix network analysis is 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	Walk Score

		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_{20} = weight for proximity to a transit stop (w)*TSPB Interpolation method (IDW) is 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.	
21	Access to a regional transit stop	Same method as for access to a local transit stop	
22	Access to an expressway	I_{22} = 100 if the neighborhood center is within 3 km to an exit to an expressway	
23	Bikable location (regionally)	I_{23} = -20*distance to the metropolitan core (in km) +200 (if distance to the metropolitan core > 10km then I_{23} = 0)	

Table A3. MTPC factors

|	MTPC factors	Scale	Walking	Cycling	Public transportation	Private car
1	Sidewalk design and continuity	Visual	(3) 5[1]			
2	Pedestrian crossings/street segment length/city block width	Visual	(7) 15			
3	Speed limit	Visual	(3) 5[1]			
4	Bike parking	Visual		(3) 10		
5	Cycling lanes on street/cycleways	Visual		(3) 10		
6	Bus line/busway/tramway on street	Visual			(3) 5	
7	Transit stop/station exit on street	Visual			(3) 5	
8	On-street parking	Visual				(3) 10
9	Undisturbed traffic flow (no congestion)	Visual				(3) 10
10	Building setback	Visual	(3) 5[1]			
11	Building height to street width ratio	Visual	(3) 5[1]			
12	Building façade activity/openness	Visual	(9) 20[1]			
13	Lot/block density (residents and jobs)	Local	(9) 20[2]		(3) 5	
14	Lot/block land use mix (entropy of residents and jobs)	Local	(9) 20[2]		(3) 5	
15	Lot/block off-street parking	Local				(9) 50
16	Neighborhood topography (slope)	Local		(9) 40		
17	Access to everyday activities	Local	(9) 20			
18	Access to event-type activities	Local	(3) 5			
19	Access to a mix of activities	Local	(9) 20			
20	Access to a local transit stop	Local			(9) 30	
21	Access to a regional transit stop	Regional			(9) 30	
22	Access to an expressway	Regional				(5) 30
23	Bikable location	Regional		(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 A4. MTPC weighing
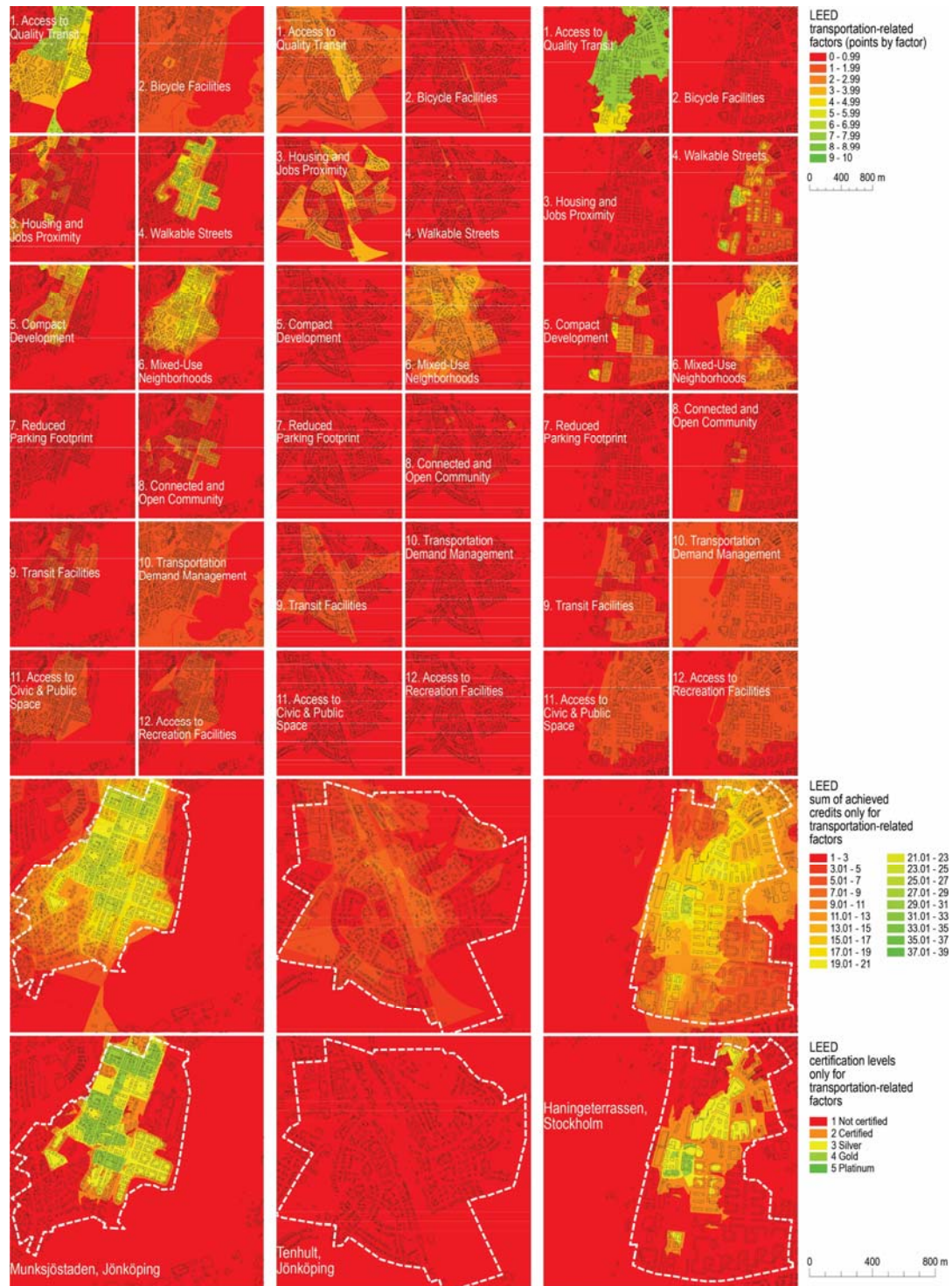
Figure A1. LEED maps
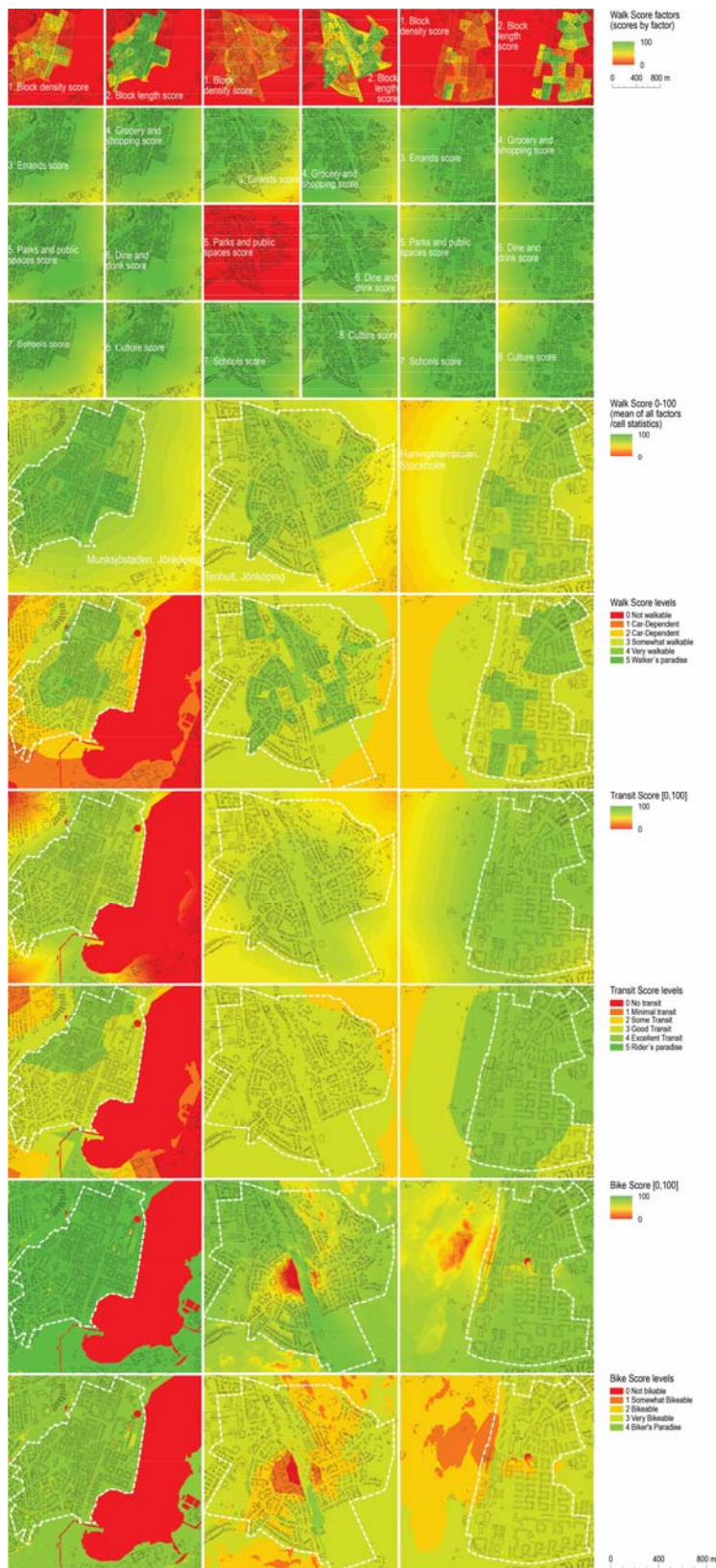
Figure A2. Walk Score maps

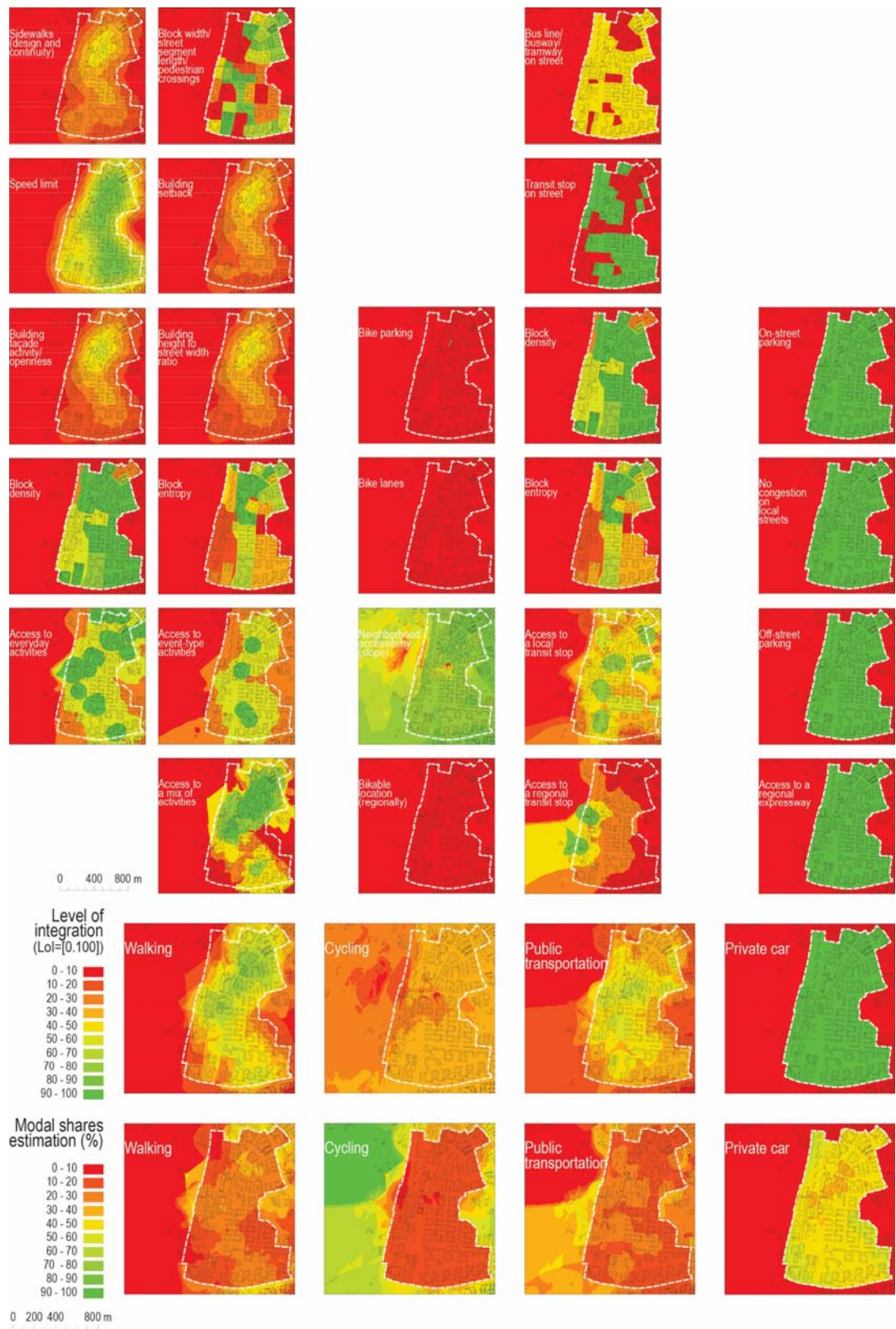Figure A3. Trafikalstring estimates

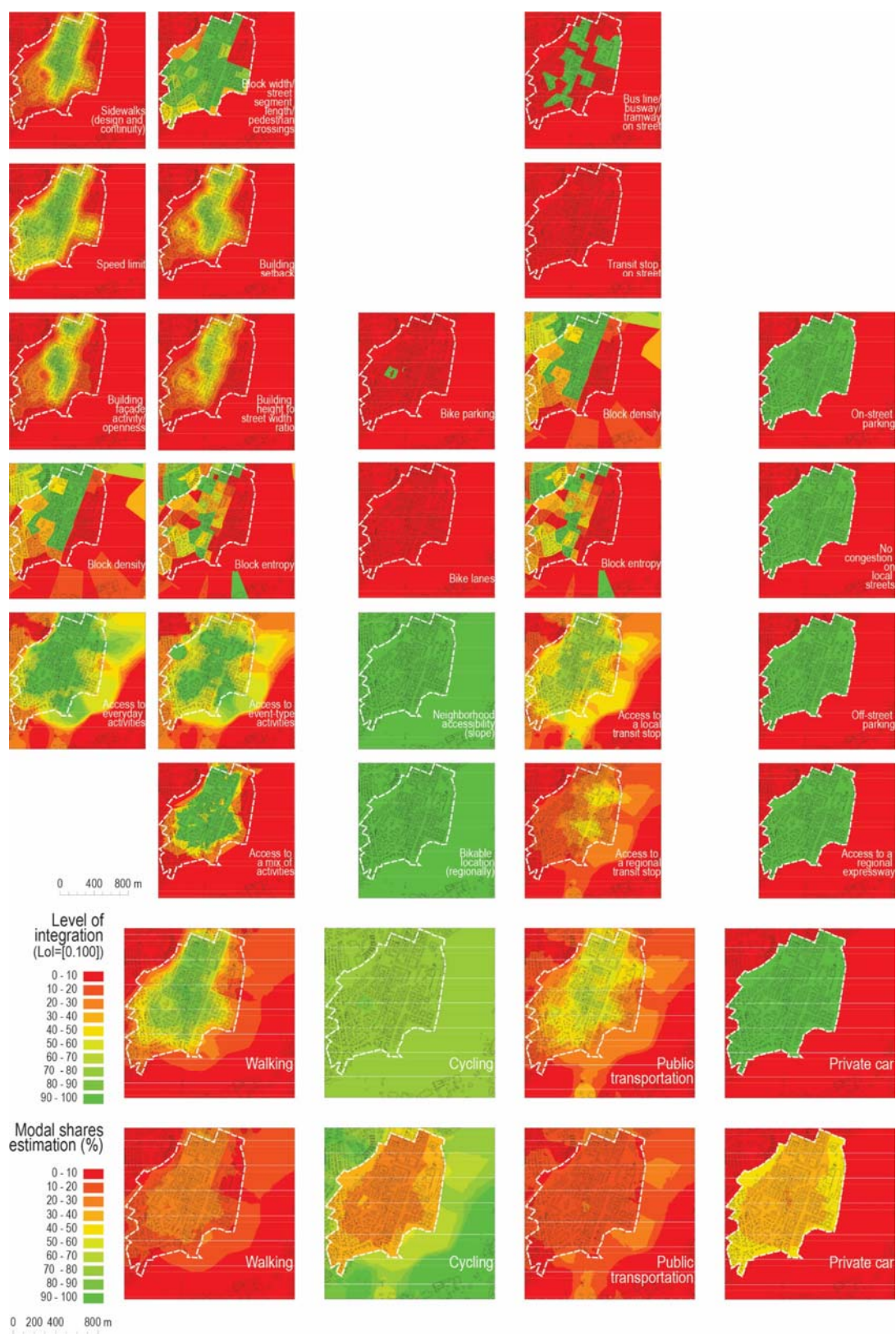Figure A4. MTPC maps of LoIs and modal shares (Haningeterrassen)

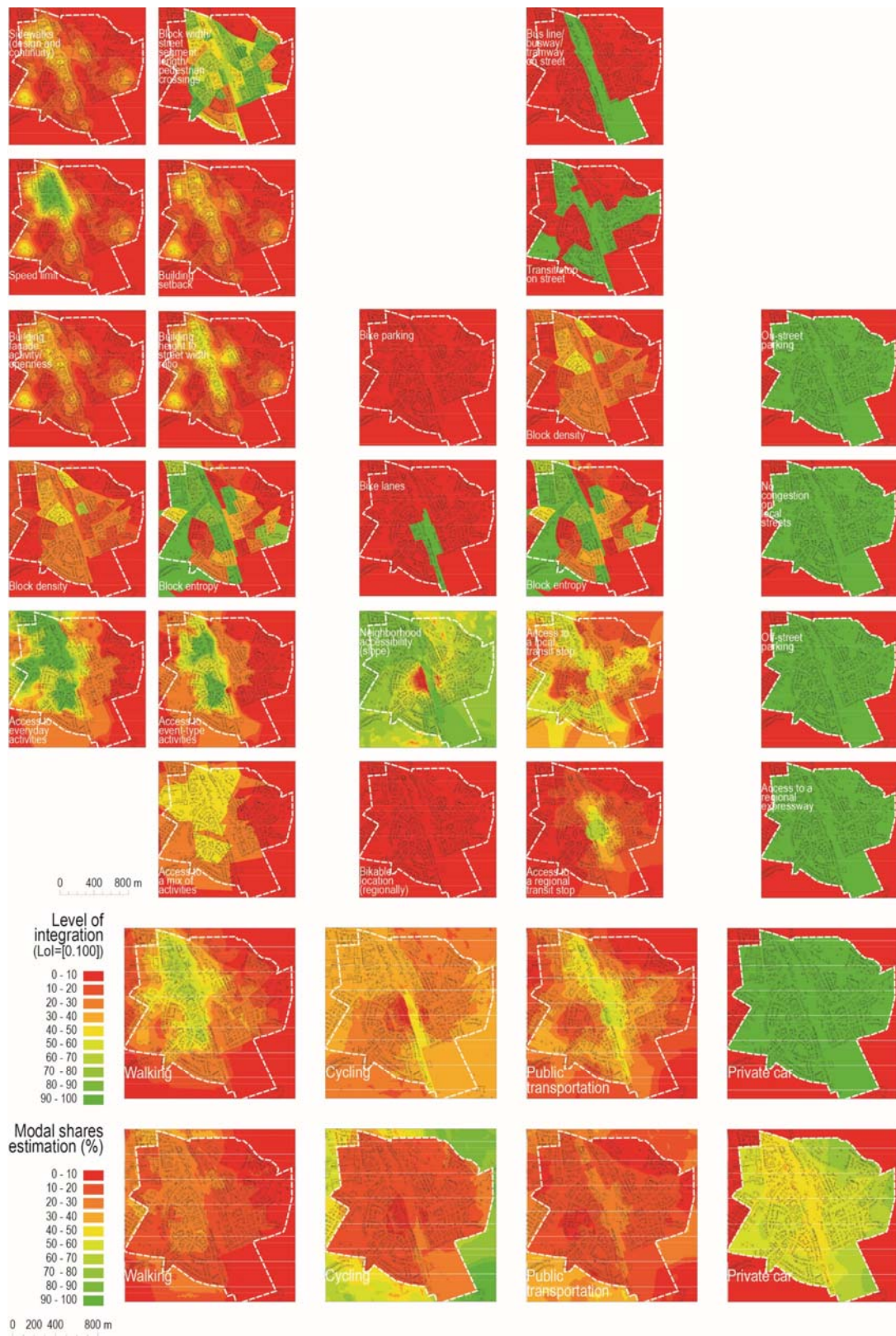Figure A5. MTPC maps of LoIs and modal shares (Muksnostaden)

Figure A6. MTPC maps of LoIs and modal shares (Tenhult)

Acknowledgements

References

Bertolini, L. (1996). Nodes and places: complexities of railway station redevelopment. European Planning Studies, 4(3), 331-345.

Bertolini, L. (1999). Spatial development patterns and public transport: the application of an analytical model in the Netherlands. Planning Practice and Research, 14(2), 199-210.

Cervero R. & Kockelman K. (1996). "Travel demand and the 3Ds: density, diversity, and design", Transportation Research Part D: Transport and Environment, 2(3), 199-219.

Cervero, R., Sarmiento, O. L., Jacoby, E., Gomez, L. F., & Neiman, A. (2009). "Influences of built environments on walking and cycling: lessons from Bogotá". International Journal of Sustainable Transportation, 3(4), 203-226.

Dur, F., Yigitcanlar, T., & Bunker, J. (2014). A spatial-indexing model for measuring neighbourhood-level land-use and transport integration. Environment and Planning B: Planning and Design, 41(5), 792-812.

EC, (2011). White paper 2011. Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system. EC

Ewing, R. & Cervero, R. (2010). "Travel and the Built Environment". Journal of the American Planning Association, 76(3), 265-294.

Ewing, R. Greenwald, M.J. Zhang, M. Bogaerts, M. and Greene, W. (2013). Predicting transportation outcomes for LEED projects. Journal of Planning Education and Research 33(3), 1-15

Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: urban design qualities related to walkability. Journal of Urban design, 14(1), 65-84.

Ewing, R., King, M. R., Raudenbush, S., & Clemente, O. J. (2005). Turning highways into main streets: Two innovations in planning methodology. Journal of the American Planning Association, 71(3), 269-282.

Gil, J. (2015). Building a multimodal urban network model using openstreetmap data for the analysis of sustainable accessibility. In OpenStreetMap in GIScience (pp. 229-251). Springer International Publishing.

Innes, E. J. and Booher. D.E. Indicators for sustainable communities: a strategy building on complexity theory and distributed intelligence. Planning theory & practice 1, no. 2 (2000): 173-186.

ITE (Institute of Transportation Engineers). (2012) Trip Generation Manual. 9th edition. Washington. DC.

Jonkoping municipality (2014). Resvanor i Jonkopings kommun 2014. Accessed from: http://www.jonkoping.se/download/18.2d563fc149c4784291c281/1417172266872/Resvanor+i+J%C3%B6nk%C3%B6pings+kommun+2014.pdf

Prelipcean, A.C. Gidófalvi, G. and Susilo. Y.O. Mobility collector. Journal of Location Based Services 8, no. 4 (2014): 229-255.

Southworth, M. (1997). Walkable suburbs?: An evaluation of neotraditional communities at the urban edge. Journal of the American Planning Association, 63(1), 28-44.

Southworth, M. (2005). Designing the walkable city. Journal of urban planning and development, 131(4), 246-257.

SLL, (2016). Resvanor i Stockholms lan 2015. Accessed from: http://www.sll.se/Global/Verksamhet/Kollektivtrafik/Kollektivtrafiken%20v%C3%A4xer%20me d%20Stockholm/SU/Resvaneunders%C3%B6kningen/resvanor-i-stockholms-lan-2015.pdf

Talen, E., Allen, E., Bosse, A., Ahmann, J., Koschinsky, J., Wentz, E., & Anselin, L. (2013). LEED-ND as an urban metric. Landscape and Urban Planning, 119, 20-34.

Trafikverket (2011). Anvandarhandledning till Trafikverkets trafikalstringsverktyg, version 1.0. Accessed from: https://applikation.trafikverket.se/trafikalstring/docs/manual.pdf

Urry, J. (2007). Mobilities. Cambridge: Polity.

USGBC, (2016). LEED v4 for Neighborhood Development. Accessed from: http://www.usgbc.org/sites/default/files/LEED%20v4%20ND_04.05.16_current.pdf

Weinberger, R. Dock, S. Cohen, L. Rogers, J.D. and Henson J. (2015). Predicting travel impacts of new development in America's major cities: testing alternative trip generation models. Journal of the Transportation Research Board 2500: 36-47.