Material stock of infrastructure

Comparative analysis between Swedish and Mexican cities

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

MARCO CRUZ

Department of Civil and Environmental Engineering
Division of Water Environment Technology
Urban Metabolism Group
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis BOMX02-16-92
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Extract of Mexico City urban area (INEGI, 2016 (edited))
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ABSTRACT

The transformation of raw materials into end-use infrastructures in order to meet the needs of connectivity and livability for inhabitants in urban areas is evident. However the transformation of raw materials into their end-use and the change in the morphology of the cities entails major environmental consequences such as climate change. A quantitative analysis of the materials stocked in roads, parking lots, footways, cycleways, tramlines and railways was done. A bottom-up approach was made with Geographical Information Systems (GIS) from OpenStreetMap ArcMap extension tool to calculate the material stocks. The cities of Stockholm, Gothenburg, Malmo and Lund in Sweden were selected as case study, while for Mexico were selected Mexico City, Guadalajara, Monterrey and Puebla. In this study the following results were found: 1.The largest share of materials is stocked in roads in all the cities of both countries. Roads in Mexican cities represent the 85.4 % of the total end-use stock followed by footways (10.6%), tramlines (2.2%), parking lots (1.4%) and rail lines (0.4%), while in Sweden roads are 77.3% of the system, followed by rail lines (10%), parking lots (8.8%), tramlines (2.2%), footways (0.9%) and cycle ways (0.8%). 2. The stone is the material with the largest stock contained within the infrastructure of all cities in both countries, while asphalt, concrete, steel and polymer account for smaller parts in the stocks of the cities. 3. In Sweden, Lund has the largest share of material stock per square kilometer (0.31 million tonnes), followed by Stockholm (0.19 million tonnes), Malmo (0.19 million tonnes) and Gothenburg (0.16 million tonnes), while for Mexico, Guadalajara has the largest share per square kilometer (0.32 million tonnes), followed by Monterrey (0.16 million tonnes), Mexico City (0.14 million tonnes) and Puebla (0.10 million tonnes). 4. Gothenburg is the city with the largest stock of materials per capita (134 tonnes) in Sweden, while in Mexico, Monterrey has the largest stock per capita (47 tonnes).

Key words: Material stock, Infrastructure OpenStreetMap, GIS.

Contents

Preface

This Mater of Science thesis has been carried out between January and June 2016 at the Department of Civil and Environmental Engineering at Chalmers University of Technology in Gothenburg, Sweden.

There are several people who have helped me during the realization of this thesis and to whom I would like to express my gratitude.

First and foremost I want to thank the thesis supervisor Paul Gontia for his time, patience and help throughout the entire project as well as the thesis examiner Yuliya Kalmykova for the valuable comments, feedback and guidance provided during the realization of this thesis.

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A special thanks goes to my family and friends who with their help and support made this thesis possible in spite of the distance.

Last but not least, I would also like to thank the National Council of Science and Technology of Mexico for supporting me during my master´s studies.

Göteborg, June 2016
Marco Antonio Cruz Sandoval

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1 Introduction

Cities occupy only 2.4% of the earth’s land mass but consume 75% of the energy and emit 80% of the greenhouse gas in terms of human activity (Satterthwaite, 2008). The increase in the extraction of natural resources in order to satisfy the livability and accessibility of the people in the cities imposes great challenges in the prevention of climate change.

According to the United Nations (2014) by 2050, the world population is expected to increase from 7 billion to over 9.3 billion and 66% of them will be living in urban areas. With rapid urbanization growth the demand for building and infrastructure construction will increase. Therefore, natural resources will be more difficult, costly and harder to extract and they might be practically inaccessible. Reaching the balance between the well-being and the preservation of natural resources is and will be critical for the sustainability of cities.

Human well-being entails the use of physical services such as food, shelter, and transport, whose provision is based on the in-use stocks in form of buildings, infrastructures and products (Pauliuk & Müller, 2014). These stocks are used during their service lifetime by different type of entities such as households, governments, citizens and industries (Baccini & Brunner, 1991). According to Fischer (2011) , the in-use stocks comprises the ‘‘built environment (infrastructure and buildings)” and they can be split by product type such as buildings, roads, parking lots and railways.

People in urban areas want to be mobile and industries want to be able to transport goods. In order to accomplish this, the construction of infrastructure must be carried out, nevertheless, transport infrastructure constitutes a significantly sized stock of materials (e.g. asphalt, cement, polyurethane plastics, and stone). Stocks and the physical services they provide are normally linked to resource use and emissions generated during the exhaustive extraction of natural resources, the processing of materials, construction and operation and at the end of their service lifetime when demolished, landfilled or recycled (Pauliuk & Müller, 2014). A major challenge therefore is to balance the need for transport infrastructure for better access, but on the other hand to minimize the extraction of natural resources for a better livability.

Over the last decade several researchers have estimated the material stocks in the infrastructure at a national and regional level to improve urban metabolism models, see Table 2.1. The accumulation of materials in urban end-use stocks has brought the attention especially for its links with massive resource extraction, energy consumption and waste generation.

A quantitative analysis of the in-use material stock in the transport infrastructure, especially the composition, could help us to understand resource appropriation, their transformation and the future waste they represent in urban areas. At the same time, the deep knowledge of the interactions of the in-use stocks represent a solid foundation towards a material efficient recycling society.

In this study, a material stock analysis will be carried out to understand the behavior of resource appropriation for transport infrastructure between Swedish and Mexican cities.

The analysis of the material stock seeks to provide guidance to the urban policy makers towards circular systems which aims to minimize new inputs and maximize recycling, and thus to reduce pollution and wastes. The study will be focused on roads, parking lots, cycle ways, footways, tramlines and railways.

2 State of the art

In recent years attention has been gradually increasing to the urban stock from the perspective of urban metabolism. During the last years several estimations of the in-use stock have been done taking into account different kind of spatial and temporal approaches (Gerst & Graedel, 2008). Tanikawa and colleagues (2015) described four methodologic approaches employed in the study of material stock; (1) bottom-up accounting (2) top-down accounting (3) demand-driven modeling and (4) remote sensing approaches. These methods provide us valuable information that help our understanding in temporal and spatial changes in material stock at different levels.

Kennedy (2012) described a model with 25 closed-form equations which express the role of infrastructure in the urban metabolism of 22 cities and found that the density of the transport infrastructure might be relatively invariant between cities 0.10 km ha^{-1}. Tanikawa and Hashimoto (2009) calculated the material stocks accumulated over time in roads, buildings and railways in two urban areas (Wakayama, Japan and Salford, UK) using four-dimensional Geographical Information Systems in order to understand the material accumulation spatially and temporally. Han and Xiang (2012) analyzed ten types of materials stocked in four major infrastructures (roads, railways , water pipelines and residential buildings) in 31 Chinese provinces. The purpose of this study was mainly to use the material stock as an indicator to analyze the intra and inter regional inequality.

Guo and colleagues (2014) obtained the material stocks of the urban road system in China with the purpose of understand and assess the resource appropriation and its potential environmental impacts. Murase and colleagues (2012) calculated the material stocks in Japan in order to understand their material flow and achieve a material-cycling society.

Hashimoto and colleagues (2007) described the flows and stocks of Japan’s construction materials. They calculated the waste generation resulting from material stocks and conclude that the amount of waste generated will be at a lower level than the domestic demand for materials needed for new roads constructions, however a certain imbalance in the supply of crushed stone will likely occur if the construction of roads decreases in 2030.

Wiedenhofer and colleagues (2015) presented a model of stocks and flows for nonmetallic minerals in roads, railways and buildings from 2004 to 2009 in 25 countries of the European Union. Shi and colleagues (2012) forecast the steel and cement demand and related resource consumption and CO_2 emissions for building and transport infrastructure in China. Both studies concluded that a large share of the material inputs are destined in the maintenance of the already existing stocks. The stabilization of existing stocks and the effort in prolonging their lifetime could achieve a major reduction in the resource use.

Tanikawa and colleagues (2015) presented the in-use stock of Japan and its 47 prefectures from 1945 to 2010 describing the distribution of the stocks using geographical information systems to fully comprehend the dynamics and materials balance of the city’s metabolism.

Table 2.1 shows in-use material stock studies and mentioned above, highlighting their various dimensions; author's reference, methodology applied, region, time frame, end-use and materials. As can be seen, the bottom-up approach has been applied more than the other approaches. Regardless of the method, what is being sought is to estimate the different types of materials and define their end-use within a certain infrastructure. These two characteristics are linked to issues of data (Tanikawa, Fishman, Okuoka, & Sugimoto, 2015). The bottom-up approach has the disadvantage in not depicting the spatial distribution of the materials in different types of scales (e.g. regional, district or smaller scale). To overcome this deficiency most authors, such as Tanikawa and Hashimoto (2009), adopted the use of Geographic Information Systems (GIS), which allows them to represent, analyze and display the dynamics of the material stocks in specific areas. However, the lack of either statistical or GIS data availability in some regions, especially in developing countries, has encouraged the use of remote sensing approaches (Han & Xiang., 2012).

Other estimations of the in-use stock have been done in regions where statistics were poor or not available using nighttime light observation data (Takahashi, et al., 2010; Hanwei, Hiroki, Yasunari, & Liang, 2010; Hattori, Horie, Hsu, & D.Elvidge, 2013; Matsuno, Takahashi, & Adachi, 2009).

To address the GIS data availability, OpenStreetMap ArcMap extension tool (Esri, 2016) is proposed as data source to obtain and extract the georeferenced vector data. Since it is constantly updated by its contributors, this tool offers an accurate location of the different types of infrastructures in cities. The information is more accurate than the one provided by private mapping companies since the contributors have a better understanding of their environment. In addition, a variety of attributes and characteristics for each projected element can be modified and adapted to any official standards. Therefore, vector information offered by OpenStreetMap ArcMap extension tool (Esri, 2016) represent a solid and viable open source data for studies where official geo-referenced information does not exist or the public access is restricted by local authorities.

In this study a bottom-method with the combination of GIS is used for the calculation of the total material stock. The model is inspired by previous works of authors such as; Tanikawa and colleagues (2015) , Guo and colleagues (2014) and Han and Xiang (2012), which have used similar methods with changes in the material stock function depending on the amount of the statistic information available such as maintenance, demolition, lifespan and intersections. However, this study as the others, seeks the calculation of the materials contained in the infrastructure through two main variables; the total inventory of the different infrastructures and the material intensity of the materials in them.

Table 2.1 Material stock studies including transport infrastructures at urban-regional scale.

Authors, year	Region	Year	End-use	Material	Method
Hashimoto and colleagues (2007)	Japan	1970-2030	Buildings, roads, airports, parks, fisheries, flood control	Asphalt, cement, sand, gravel, crushed stone, and other aggregates	Bottom-up. MFA
Taniwaka and Hashimoto (2009)	Japan, UK	Japan 1855-2014. UK 1849-2004	Buildings, roads, railways	Wood, brick, steel, mortar, concrete ,stone block	Bottom-up model with 4d-GIS
Matsuno and colleagues (2009)	Global	1996,1999,2000,2003 and 2006	All	Copper	Remote Sensing (Night time light data)
Takahashi and colleagues (2010)	China, Korea, Taiwan, Japan, Australia	1999,2000,2003 and 2006	All	Copper	Remote Sensing (Night time light data)
Shi and colleagues (2012)	China	Buildings 1950-2010. Roads 1986,1999,2002,2006	Buildings and Transportation infrastructure	Steel and cement	Bottom-up
Kennedy (2012)	22 cities	1980-1990	Residential, industrial and commercial buildings, transport infrastructure, sewage infrastructure and drinking water infrastructure	Biomass, metals, non-metallic minerals and fossil fuels	Bottom-up
Murase and colleagues (2012)	Japan	1880-2000	Buildings, Railways, Ports, Bridges Roads, machinery and equipment and Furniture and fixtures.	Steel, Wood and cement	Bottom-up

Han and Xiang (2012)	China	1978-2008	Buildings, roads, railways and water pipelines	Sand, gravel, asphalt, timber, limes, glass, steel, brick, cement, ceramic and plastic	Bottom-up
Hattori and colleagues (2013)	Japan, USA, Germany, UK	2006 to 2010	Civil engineering and buildings.	Steel	Remote Sensing (Night time light data)
Guo and colleagues (2014)	China	-	Roads	Macadam, mineral powder, limes, steel, stone, asphalt, cement, fly ash, atactic polypropylene and polyurethane plastics.	Bottom-up model with GIS
Liang and colleagues (2014)	China	1992-2008	Residential and commercial buildings, roads, railways and pipelines	Steel	Remote Sensing (Night time light data)
Wiedenhofer and colleagues (2015)	EU25	2004 to 2009	Residential buildings, roads and railways.	Nonmetallic minerals	Dynamic Bottom-up approach
Tanikawa and colleagues (2015)	Japan	1947-2010	Buildings, roads, railways, airports, seaports, dams and underground water pipes.	Iron, asphalt, timber, cement, aggregates	Bottom-up with GIS

3 Method

To carry out this study, a series of steps were followed as part of the methodology and they are described as follows:

Step 1. Select the area of study: The selection of the areas in this study correspond to a municipality level. The selection was made based on the different values such as the surface area, number of inhabitants and in the economic importance for the country.

Step 2. Select the type of infrastructure under study: The selected infrastructure in this study is infrastructure that represents levels of accessibility and connectivity in urban areas. Likewise with the selection of the end-use stocks it can be inferred if the stocks belong to infrastructure encouraging sustainable travel habits and to know where the materials are stored in order to reuse them once they have served their lifetime.

Step 3. Define the materials that comprise the infrastructures: The materials stocked in the different types of infrastructures were defined by each country according to their official governmental standards.

Step 4. Calculate the material intensity: Material intensity was calculated after all technical information has been gathered and classified. In order to perform a comparison, the material intensity was presented in units as [kg/m^2] or [kg/m].

Step 5. Extract the spatial information: The inventory of the different infrastructures was made by using OpenStreetMap ArcMap extension tool. With this GIS vector data all the lengths and areas were obtained.

Step 6. Calculate the material stock: Once the inventory and the material intensity of each infrastructure was obtained, the material stock function is applied in order to obtain the total mass by material and by infrastructure type.

Step 7. Check uncertainties and reliabilities: The material intensity values were compared with similar studies and a sensitivity analysis was made in order to define the reliability and the variable with the greatest impact in the final stock.

Figure 3.1 shows the methodology used in this study to calculate the Material Stock (MS).

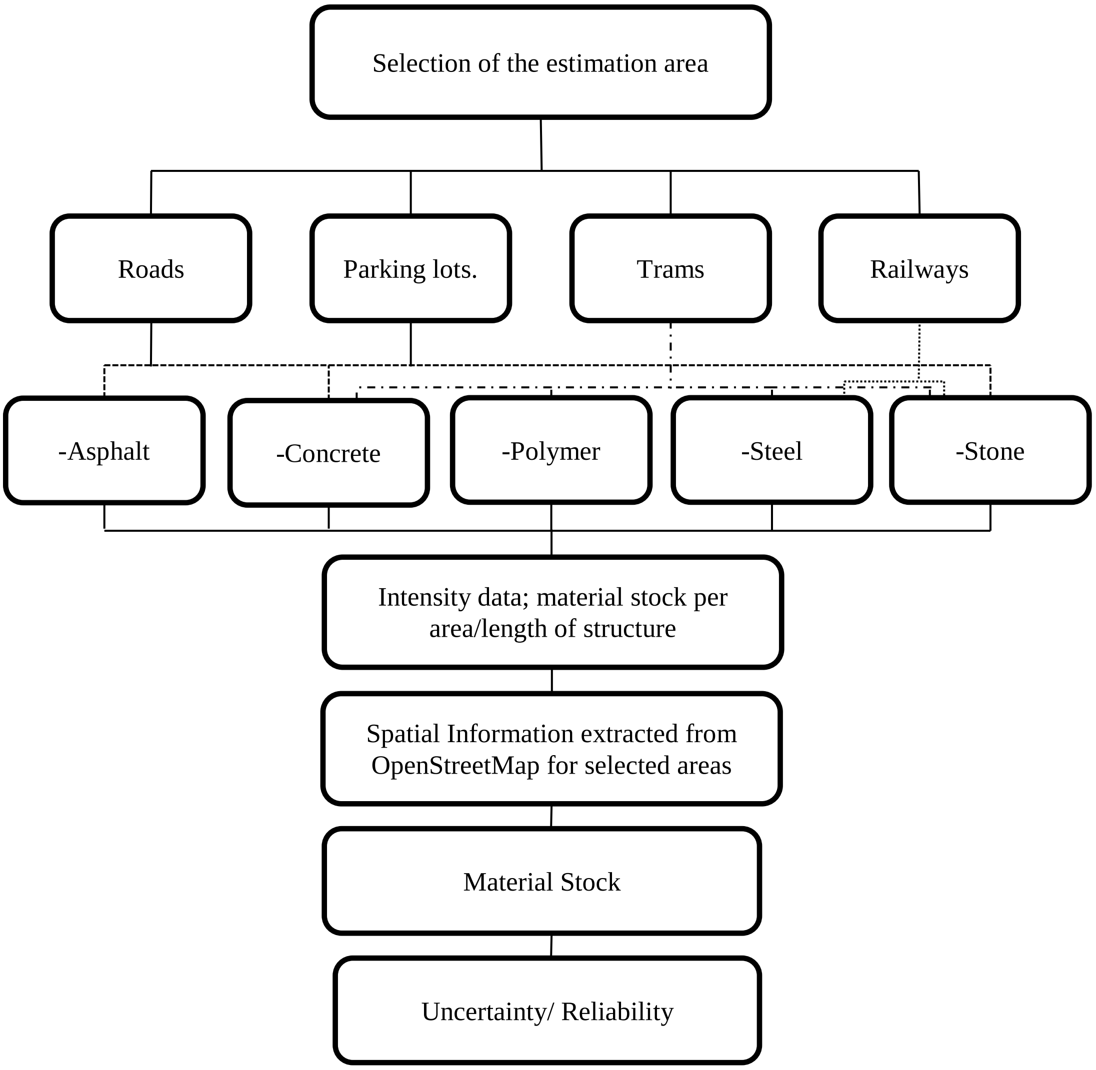

Figure 3.1 Methodology of estimating material stock.

A bottom-up accounting is the methodological approach used for this study. As a starting point, an inventory of all existing infrastructures has to be performed for all the cities. To accomplish this, the vector information data from OpenStreetMap ArcMap extension tool (Esri, 2016) was extracted. This tool enables to know the exact location of each infrastructure as well as the calculation of their geometrical properties required in the Equation 3.1. The next step is to obtain the amount of materials contained in the infrastructures and calculated by using a coefficient called 'material intensity', Equation 3.2. The material intensity is obtained from the technical standards specified by the normative of each country. In it, the properties of materials, their thicknesses and widths are specified.

This method thus enables to calculate the total in-use stock of a certain material by multiplying its material intensity factor by the total inventory of items in which the material is stocked. The conversion of the inventories of infrastructures into mass units is expressed in Equation 3.1.

$$MS_{x,i} = \sum_{i}^{n} MI_{x,i} * L_i \tag{3.1}$$

Where:

$MS_{x,i}$ = Material stock of a certain material ”x” in [kg], in the infrastructure type ”i”

$MI_{x,i}$ = Material intensity of material ”x” in the infrastructure type ”i” in [kg/m]

L_i = Length of the infrastructure type, “i” in [m]

$$MI_{i,x} = \rho_{x,i} * d_{x,i} * w_i \tag{3.2}$$

Where:

$\rho_{x,i}$ = Density of material ”x” in the infrastructure type “i” in [kg/m3]

$d_{x,i}$ = Depth of material “x” in the infrastructure type ”i” in [m]

w_i = Width of the infrastructure type ”i” in [m]

4 Study Areas

The cities shown in this study were selected for several reasons. First, they represent to a great extent the base of the economy of their countries. Second, they are areas with high population indexes. Third, to observe the differences in the material stock of infrastructure between cities in developed and developing countries. In regards to developed cities, the city of Stockholm, Gothenburg, Malmo and Lund in Sweden will be taken into account, while for developing countries Mexico City, Guadalajara, Monterrey and Puebla in Mexico will be analyzed.

4.1 Stockholm, Sweden

The capital of Sweden, Stockholm, is a municipality located in east central Sweden with 4 708 inhabitants per km^2, see Figure 4.1. It has a population of 881 235 inhabitants and by 2022 it is expected to reach one million people (2016). It is the political and economic center of Sweden in a 187.16 km^2 area. The Stockholm Region contains 37% of the total housing stock in Sweden (Stockholm Stad., 2016). In order to remain as an attractive region, Stockholm must fulfill an efficient housing offer to achieve the long-term development of the region and to guarantee a talent source for industries. More than a third of the companies in Sweden are started in Stockholm, what makes it the most diversified industrial and commercial city. The city accounts for 29% of the Swedish GDP (Business Region Development., 2016). One of every four industries is dedicated to the business consultancy, being the service sector prevalent and the most important in the city region.

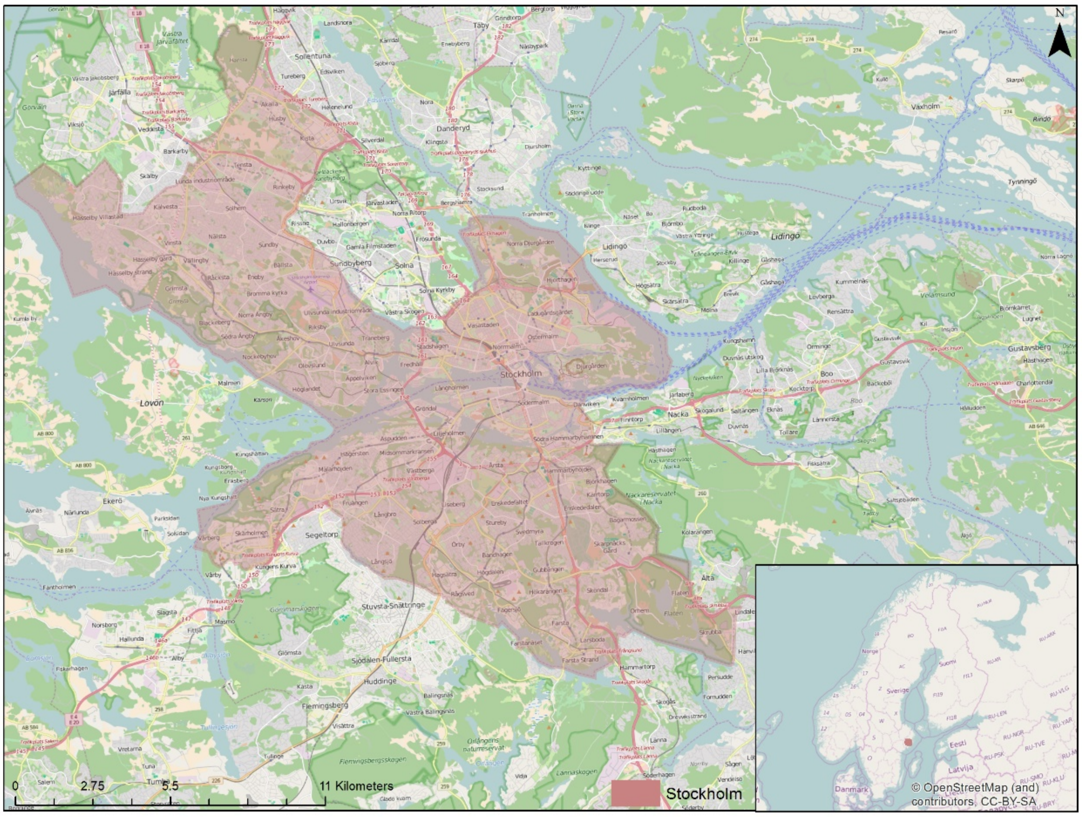

Figure 4.1 Stockholm, Sweden. OpenStreetMaps, 2016 (edited).

4.2 Gothenburg, Sweden

Gothenburg is a port city with a strategic location between Oslo and Copenhagen, see Figure 4.2. It has a population of about 533 000 inhabitants in an area of 447. 76 km^2 and its Sweden's second largest city, having 1 190 inhabitants per km^2. Gothenburg has been growing dramatically and it's preparing to make space for almost 700,000 residents by the year 2035 (City of Gothenburg, 2016). Part of the strategy to adapt to this rapid growth and meet the needs of the future inhabitants consists in the construction of new residential areas, buildings and roads in spaces that were previously used for other purposes. Around 70% of Scandinavia's industry is located within a 500-km radius of the Gothenburg region and 30% of Swedish foreign trade passes through the Port of Gothenburg. Economic growth in Gothenburg is higher than any other place in Sweden and is among the twentieths fasting growing regions in Europe (Business Region Göteborg, 2016) .

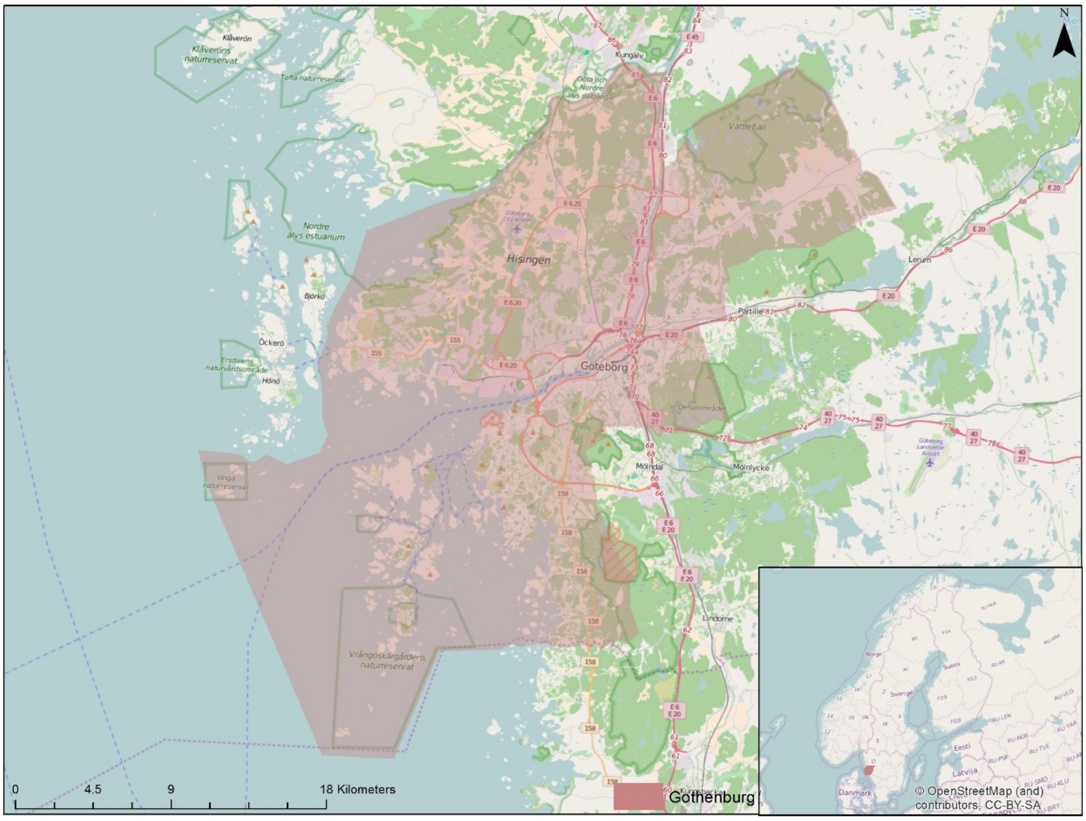

Figure 4.2 Gothenburg, Sweden. OpenStreetMaps, 2016 (edited).

4.3 Malmo, Sweden

Malmo is the commercial center of southern Sweden, see Figure 4.3. With 312 400 inhabitants is the third most inhabited city in Sweden (Malmö , 2016). It has a surface area of 156.60 km^2 and a population density of 1 995 inhabitants per km^2 (Statistics Sweden., 2016). 76% of households are small one- or two-person households. By the year 2023 Malmö is expected to increase to half million of inhabitants, with this increase, the housing sector and infrastructure is expected to grow to meet the future needs of people living in it (Malmö, 2016). Malmo has a mixed base economy including different kind of sectors. 13 companies/1,000 inhabitants (16-64 years) were founded in Malmö, compared with 16.0 in Stockholm, 11.1 in Gothenburg, and 10.0 in Sweden as a whole (Malmö, 2016). The main working sectors are focused mainly in commerce (16%), followed by business services (14%), followed by health care and social services (14%) and by education (9%) (Malmö, 2016).

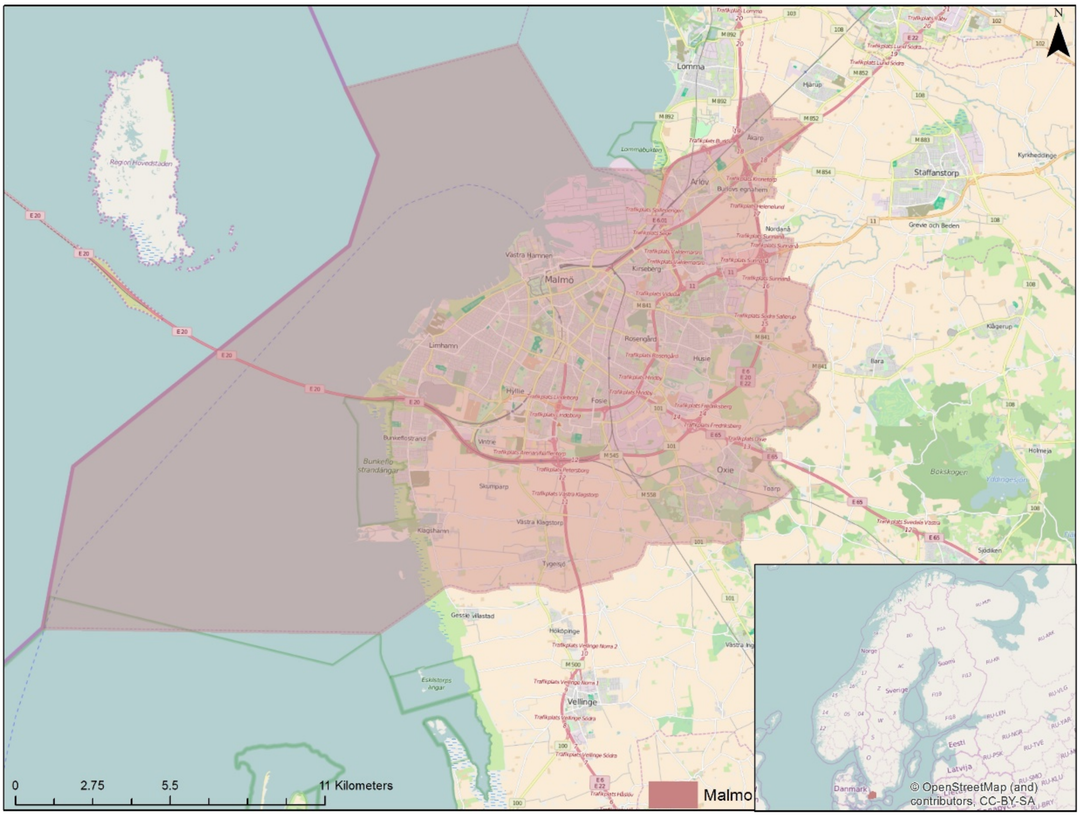

Figure 4.3 Malmo, Sweden. OpenStreetMaps, 2016 (edited).

4.4 Lund, Sweden

Lund is located in the south of Sweden, close to Malmö and the Danish capital Copenhagen, see Figure 4.4. It has a population of 80 000 inhabitants and one third of them are students (City of Lund, Sweden. , 2016). With a 25.75 km^2 area and 3 107 inhabitants per km^2, Lund is one of the oldest and most important cities in the south region (Real State Tax Register , 2016). Over the years, a large number of knowledge-based companies have been developed with the help of the University of Lund and the IDEON Science Park, turning Lund into the Scandinavia's largest center for education and research (Lunds Kommun, 2016).

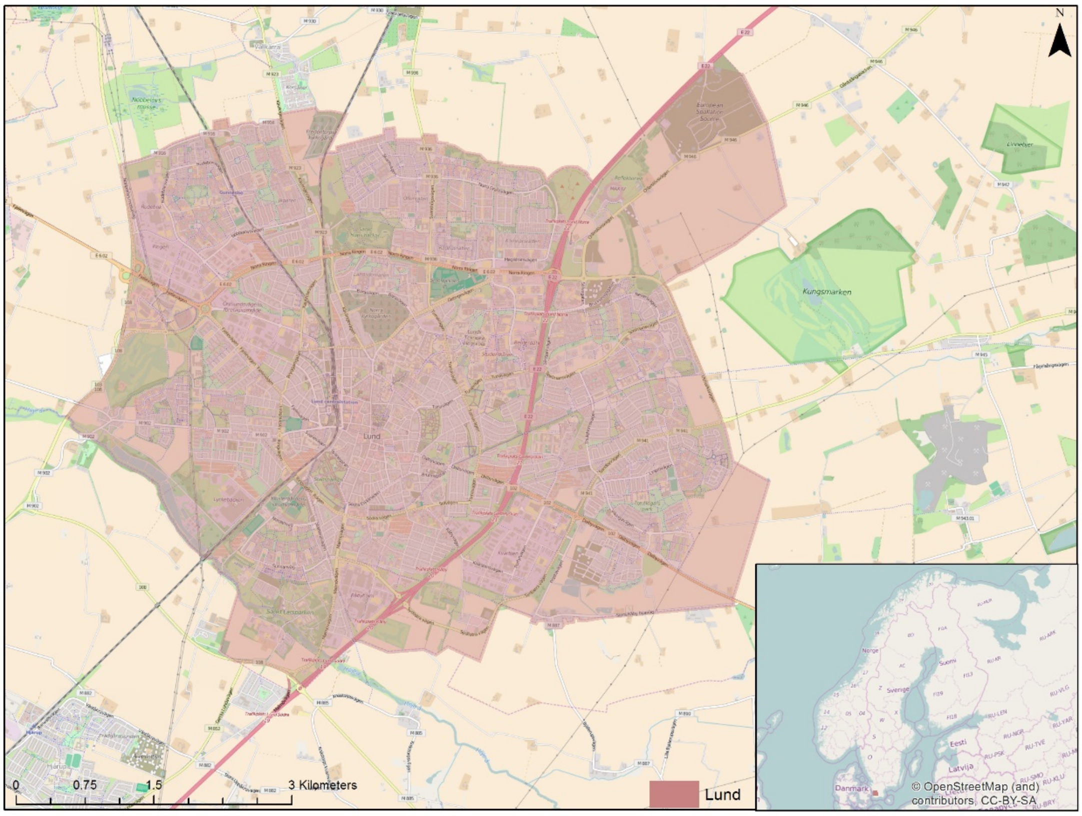

Figure 4.4 Lund, Sweden. OpenStreetMaps, 2016 (edited).

4.5 Mexico City, Mexico

The capital of Mexico, Mexico City, is located in the Southern Center of the territory and is settled in the basin of Lake Texcoco, see Figure 4.5. It is ranked as the eighth-richest urban agglomeration in the world. According to the National Institute of Statistics and Geography, Mexico City has 8 851 080 of inhabitants in an area of 1 499 km^2, having the highest number of inhabitants and the highest population density in the country with 5 905 inhabitants per square kilometer (INEGI, 2016). The lack of water, pollution and poor urban development strategy are the main problems of this city (Forbes, 2016). The large number of vehicles and the lack of an efficient transport system will lead the city to an eminent collapse. Around five million cars are used daily in the city and these are joined by two million cars entering from the metropolitan area of the city (Regeneración, 2015). The city of Mexico has the highest gross domestic product (16.32 %) of the country and its main economic sectors are: commerce, financial services, real estate services and consulting services (Secretariat of Economy, 2016).

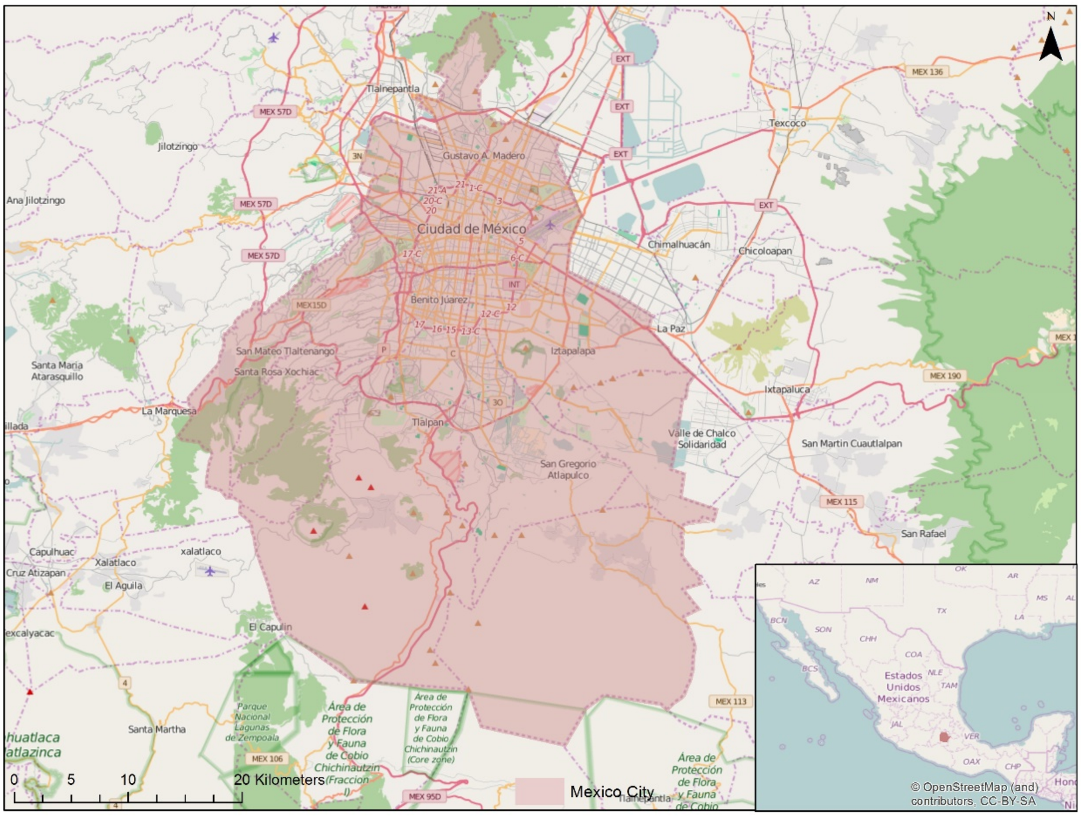

Figure 4.5 Mexico City, Mexico. OpenStreetMaps, 2016 (edited).

4.6 Guadalajara, Mexico

Guadalajara is the epicenter of business and manufacturing in the west of México, see Figure 4.6. According to the Census of Population and Housing in 2013 conducted by the National Institute of Statistics and Geography, Guadalajara has 1 495 189 inhabitants in an area of 151. 40 km^2, having 9 876 inhabitants per km^2 and making Guadalajara the most populous municipality in the state of Jalisco (Jalisco, Gobierno del Estado., 2016). Growing urban sprawl represents new challenges of coordination for the Government which should make a proper planning for a sustainable urban future. Guadalajara is the second largest GDP in México and the second strongest economic potential of any major North American city. 75 % of Jalisco's industries are located in Guadalajara and its economy is based on two main sectors; commerce and industry (Guadalajara's Municipality, 2016).

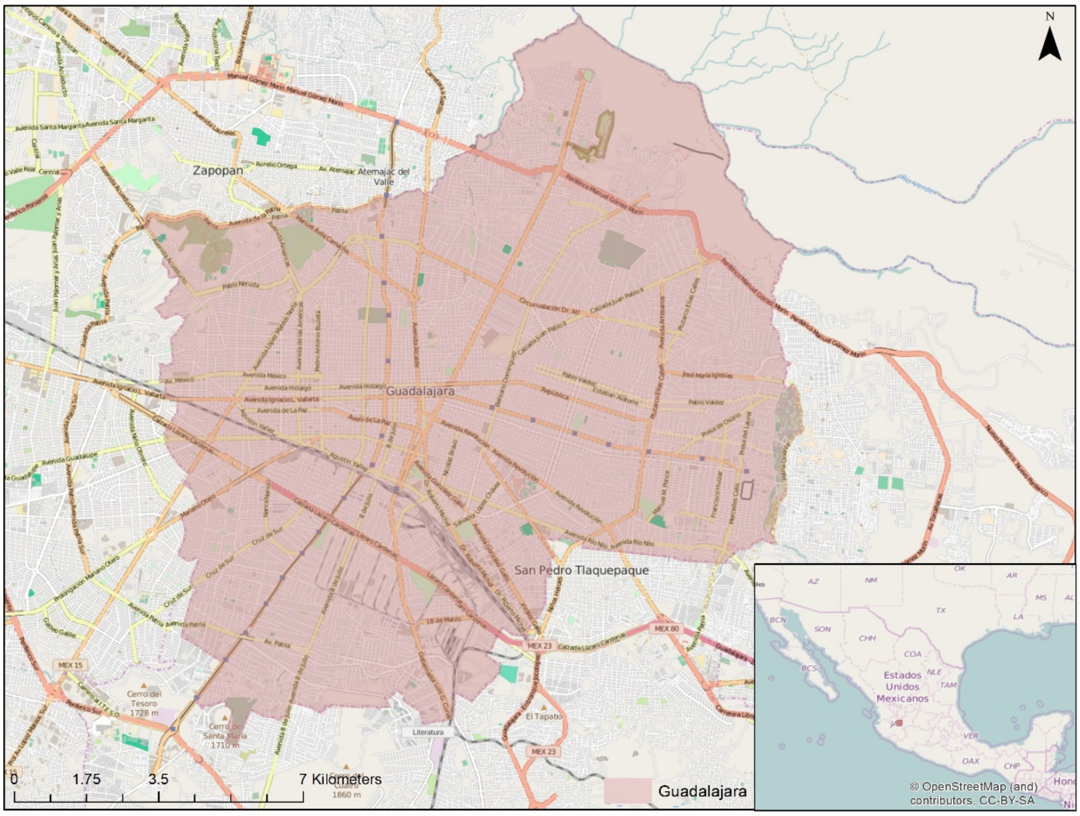

Figure 4.6 Guadalajara, Mexico. OpenStreetMaps, 2016 (edited).

4.7 Monterrey, Mexico

Monterrey is located in the north of Mexico and very close to the border with Texas, see Figure 4.7. It is the third largest city in Mexico with 1 109 171 over 324 km^2 (INEGI, 2016). The population density is 3 423 inhabitants per square kilometer and within its metropolitan area contribute about 7.5 per cent of the gross domestic product of the country (Mexico Tourism Board, 2016). The city stands out in sectors such as steel production, cement, glass and automotive. Its economic wealth is attributed in part to the economic links and its proximity to the United States (Autonomous University of Nuevo Leon, 2016).

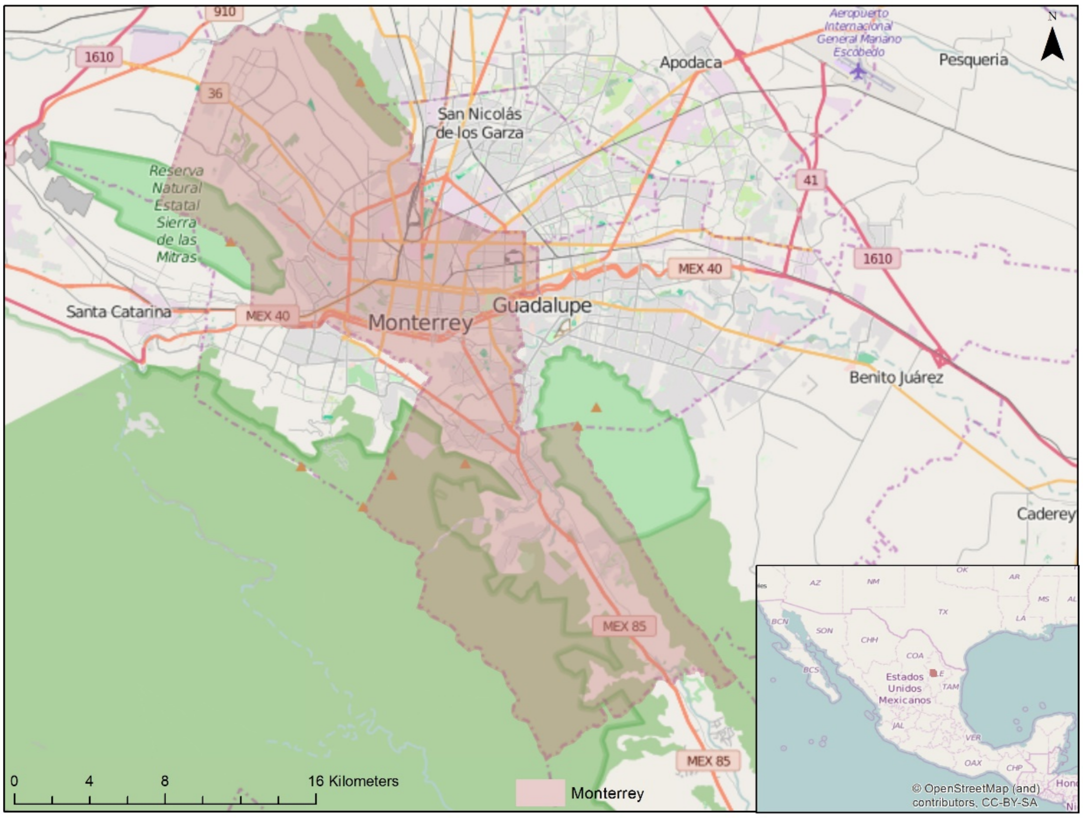

Figure 4.7 Monterrey, Mexico. OpenStreetMaps, 2016 (edited).

4.8 Puebla, Mexico

Puebla is situated about 100 km east of Mexico City in the Valley of Cuetlaxcoapan, see Figure 4.8. It is the fourth largest city in México with a population of 1 576 259 in habitants over 545 km^2 (INEGI, 2016). Its population density is 2 892 inhabitants per square kilometer. Its location makes it an important intermediate point on the commercial route between the Port of Veracruz and Mexico City. Puebla contributes 3.2 per cent of the gross domestic product of the country. The main economic sector of the city is the agriculture, followed by the trade, real estate services and education (Secretariat of Economy , 2016).

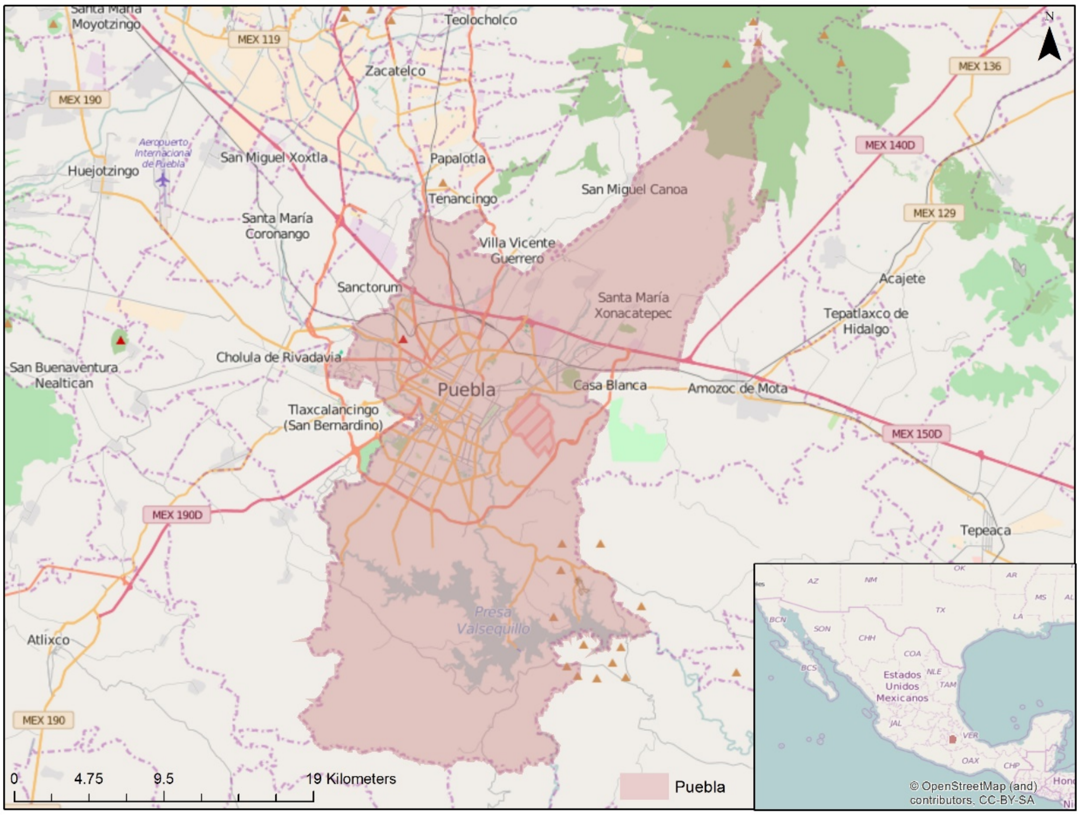

Figure 4.8 Puebla, Mexico. OpenStreetMaps, 2016 (edited).

In Table 4.1 the values of population, surface area and number of inhabitants per square kilometer for all cities are shown. The values shown will be further used to understand the tendency of the extraction and transformation of the natural resources in each city.

Table 4.1 Inhabitants, surface area and inhabitants per km^2 by city.

		Inhabitants	**Surface [km^2]**	**[Inhabitants/km^2]**
Sweden	Stockholm	881,235	187.16	4,708
	Gothenburg	533,000	447.76	1,190
	Malmo	312,400	156.60	1,995
	Lund	80,000	25.75	3,107
Mexico	Mexico City	8,851,080	1,499.00	5,905
	Guadalajara	1,495,189	151.40	9,876
	Monterrey	1,109,171	324.00	3,423
	Puebla	1,576,259	545.00	2,892

5 Data collection

Six infrastructures has been studied; roads, cycle-ways, footways tramlines, railways and parking lots. The data and information obtained for the different types of infrastructures is shown below.

5.1 Roads

5.1.1 Sweden

The materials, layers and thicknesses for the different roads classes were obtained from the software Pavement Management System (Trafikverket, 2016) , a tool used for the analysis and design of road structures comprising Trafikverket (Swedish Transport administration) rules and standards (Trafikverket, 2016) . Pavement Management System (PMS) designs three main layers, the first one correspond to a layer of asphalt and two others of macadam, see Figure 5.1. In order to obtain the materials and the layers for the different road classes PMS needs as input data the road width, number of lanes, lane width, equivalent single axle loads (ESALS), average annual daily traffic per lane (AADT), technical life span, climate, and subgrade below the road.

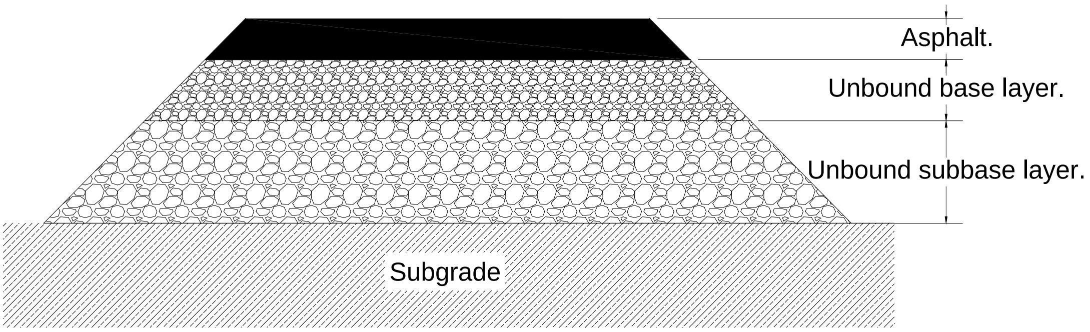

Figure 5.1 Cross section of a road.

The information used to design the roads is the one suggested by the municipality of Gothenburg (Göteborgs Stad Trafikkontoret, 2016) . In its standards, the city suggests a hierarchical classification of the roads under six categories based on their function within the total road network. In order to realize an applicable analysis and following the standards, the roads were classified according to their speed and average annual daily traffic (AADT) in Class III, IV, VI, VII, bike lanes and footways. Equivalent single axle loads for each of the streets can be found in the statistics of Sweden (Tekniska Handbok, 2016).

Table 5.1 describes the properties of roads per class.

Table 5.1 Values according to each road class. (Göteborgs Stad Trafikkontoret, 2016).

	Class III	Class IV		Class VI		Class VII
Function	Main Street			Local Street.		
Speed [km/hr]	At least 70.00	70.00	50.00	50.00	30.00	30.00
AADTK	>6000	At least 6000		3500-6000		<3500
Lanes	At least 4	2-4		2		1
Width [m]*	20.00	15.00		12.00		5.50

*Widths include shoulder's length.

The variable of the climate, which influences the durability of asphalt, is included by PMS software. In the software, Sweden is divided into five climate zones (Vägverket, 2016). Gothenburg, Malmo and Lund lie within climate zone one, while Stockholm in climate zone two.

Concerning the subgrades below the roads, three different subgrades were found, bedrock, clay and mixed grain size. With GIS it's possible to identify whether the road was built on bedrock or clay, see Figure 7.5. In Gothenburg area, bedrock and clay represent a vast majority of the existing subgrade and an important factor to take into account in the design of a road.

The pavement design for the footways and bike lanes was done according to Gothenburg's technical manual (Göteborgs Stad Trafikkontoret, 2016) considering the width of 2.00 [m] for both cases. A mean was done by the latter one between the minimum and maximum value (1.60-2.40) as indicated in the manual.

The pavement designed by PMS Object after introducing the standards values are shown in Table 5.2. The values shown can be double-checked with the proposed values in the design of streets with asphalt in Gothenburg municipality (Göteborgs Stad Trafikkontoret , 2016).

Table 5.2 PMS Road design according to standard properties and subgrade type.

Road Class	**Asphalt [mm]**	**Unbound base layer [mm]**	**Unbound subbase layer [mm]**	**Subgrade material**
Class III	160	80	200	Bedrock
			610	Clay
Class IV	130	80	200	Bedrock
			555	Clay
Class VI	110	80	200	Bedrock
			510	Clay
Class VII	72	80	200	Bedrock
			420	Clay
Bike lanes/footways	40	-	55	-

5.1.2 Mexico

The road system integrating the spatial and urban structure of the city can be found in the geometric characteristics at the second chapter of Guadalajara’s zoning regulations (Urban Development Department., 2001). In its standards, the state classify the roads in two groups; regional and secondary roads. The secondary roads are divided in five classes and their main function is to achieve an efficient interurban mobility and serve as road collectors for the regional roads.

Footways and bike lanes widths are done according to Guadalajara’s zoning regulations under the article 303 and 309 respectively (Urban Development Department., 2001). The width of the bike lanes considered in this study is 1.50 [m] and belongs to the maximum width for one-way lane. Footways are dimensioned according to its minimum width of 2.40 [m]. In Table 5.3 the roads classification and its characteristics in the urban area of Guadalajara considered in this study are shown.

Table 5.3 Guadalajara's roads information (Urban Development Department., 2001).

	Secondary Roads					
	Collector	Minor Collector	Sub-Collector	Local	Bike Lanes	Footways
Speed [km/hr]	80.00	50.00	50.00	40.00	-	-
Total Width [m]	19.00	11.40	10.80	6.50	1.50	2.40
Lanes	4.00	2.00	2.00	2.00	1	-

*Widths include shoulder’s length.

The materials, layers and thicknesses comprising the asphalted roads are obtained from the catalog of structural sections of pavements for the roads of the Mexican Republic (2016). The region's climate and the average annual daily traffic per lane (AADT) are the main variables used in this catalog for the design of the roads. Unlike Sweden information of the AADT is not available to the public and the catalog does not propose thicknesses in accordance with the subgrade materials. The information was requested to Guadalajara’s Secretariat of Pavements and it was obtained that the AADT for design of all the streets is at least a million vehicles (personal communication). Climate areas (as mentioned earlier the climate has an influence in the road's lifespan) are available in the Secretariat of Comunications and Transportation (2016). Once the two main variables are defined, the catalog offers four different sections of road with a twenty years lifespan and with different materials and thicknesses in the base and subbase. The information of roads paved with concrete was provided by the Secretariat of Pavements (personal communication). The information comprising the stoned roads was obtained from the technical manual for rural roads by the Mexican Institute of Transport (Mexican Institute of Transport, 2016).

The materials and layers comprising the bike lanes in this study were taken from the bike lanes infrastructure manual (2016). Materials and thicknesses for footways were taken from Guadalajara’s government public construction work contest (2016).
The Bus Rapid Transit (BRT) lanes and paved with concrete are considered with an average width of 3.5 [m] (MacroBus, 2016). In Table 5.4 the thicknesses and materials considered in this study are shown.

Table 5.4 Roads and layers properties in roads of Mexico.

Road Type	**Surface [mm]**	**Base layer [mm]**	**Subbase layer [mm]**
Asphalted roads	160	250	300
Concrete/BRT roads.	210	200	200
Stoned roads.	150	300	-
Asphalted Bike lanes.	50	100	.
Concrete Footways.	70	100	

5.2 Parking lots

5.2.1 Sweden

The parking lots are dimensioned for a maximum speed of 30 [km/hr] and with heavy traffic vehicles weighing over 3.5 [ton] (Göteborg Stad, 2016). According to the information found in Sweden for road design and linking the speed information (Göteborgs Stad Trafikkontoret, 2016), the parking lots were designed as Class VII. Table 5.5 describes the layering design for parking lots obtained from PMS Object.

Table 5.5 Parking lots design in Sweden.

Asphalt [mm]	Base layer [mm]	Subbase layer [mm]	Subgrade material
45	80	200	Bedrock
		420	Clay

5.2.2 Mexico

The design considered in this study for the parking lots was realized based on the structural design for asphalt pavement manual by the engineering institute of The National Autonomous University of Mexico (2016). In the manual, the Engineering Institute respects and considers all the standards and rules of the Mexican Institute of Transport and the Secretariat of Communications and Transportation. The materials and layers specified in the manual are shown in Table 5.6.

Table 5.6 Parking Lots design in Mexico.

Asphalt [mm]	Base layer [mm]	Subbase layer [mm]
50	150	150

5.3 Tram

5.3.1 Sweden

The design of the tram is dependent on its interaction with other transportation modes on the surface. Depending on its interactions, the design comprises different widths, materials, and thicknesses. The width of 2.5 [m] per lane is suggested by the Swedish norms and standards. (Göteborgs Stad Trafikkontoret , 2016). The material layers and thicknesses used for this study are shown in Table 5.7. The layer properties have also been assumed to not be dependent on the type of subgrade, which have been taken into account for roads.

Table 5.7 Layering design for tramways in Sweden.

Construction components	**Thickness [mm]**
Asphalt	50
Concrete	400
Base ballast	50
Subbase ballast	250
Geotextile	6

Two types of rails can be found in the Swedish tram system. Girder rail is normally used when the tram, traffic and pedestrians interact in the same surface. The Vignole rail, is used when the tram, traffic and pedestrians interact in different surfaces. Girder rail, also known as profile 60Ri2 weights 59.74 [Kg/m] is considered for this study. The clips used to attach the rails weighs 0.350 [kg] per piece and have to be placed every 65 [cm].

5.3.2 Mexico

The design considered in this study was provided by Urban Electric Train System (UETS) through the transparency and citizen consultation tool and showed in (personal communication). The lanes are 7.5 [m] width (double-track tram) and possess their own designated space along its entire length. The material layers and thicknesses used for this study were provided by UETS and are shown in Table 5.8. In this study layer properties are not dependent on the type of subgrade.

Table 5.8 Tram layering design in Mexico.

Construction components	**Thickness [mm]**
Superstructure Ballast	500
Concrete compression layer	250
Substructure ballast 1	300
Substructure ballast 2	200
Substructure ballast 3	200

Carbon steel rail is the one used in this infrastructure, specifically rail RE-AREMA. It weighs 57.04 [kg/m] and is joined by welding approximately every 11.88 [m]. Sleepers used are type B-58 made of concrete with an elastic fastening RNY per piece and placed at each 0.72 [m]. Sleepers weight is 235 [kg] and the weight of the rail clips used is 0.350 [kg] each (Rail One, 2016).

5.4 Railways

5.4.1 Sweden

In Sweden there are approximately 15,000 km of railways (Swedish National Road and Transport Research Institute , 2016). In Figure 5.2 we can see a simplification of a cross section for railway on embankment and its constituent material taken into account for this study.

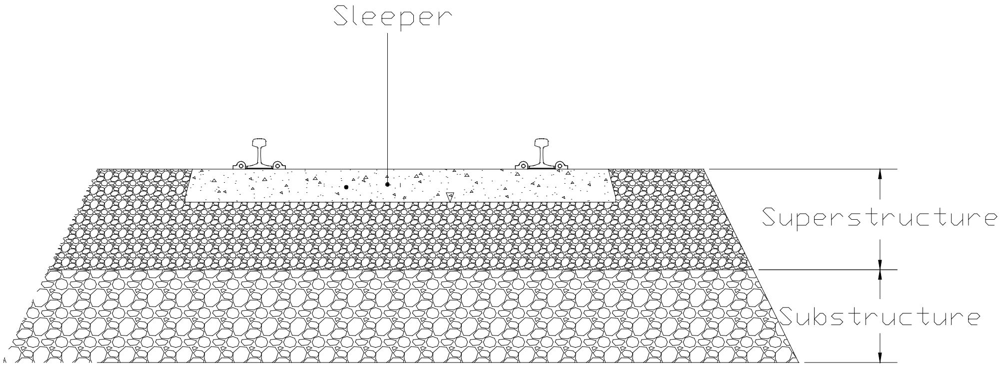

Figure 5.2 Cross section of a railway structure, modified from (Järnväg.net, 2015)

The material in the superstructure and the substructure is ballast, consisting of quality sorted crushed rock. The sub-ballast in the substructure has not as high quality requirements as for the macadam ballast in the superstructure and its thickness depends on the subgrade material (Edvardsson & Hedström, 2015). The Vignole rail, is the most used rail in this infrastructure weighting 50 [kg/m].

Nowadays, wooden sleepers are being replaced by concrete sleepers due to their strength and lifespan. The lane width in the rail system is 2.5 [m] long with concrete sleepers of 183[kg] and placed every 65 [cm]. The rails are fixed to the sleepers with rail clips 0.350 [kg] each (Rail One, 2016) .

The construction components and materials of a simplified railway structure, complied from (Edvardsson & Hedström, 2015) are described in Table 5.9.

Table 5.9 Railway components of Sweden.

Construction components	Material type	Thickness of the material layer [mm]	Subgrade material
Rail	Steel	-	Not depended
Rail Clips	Steel	-	Not depended
Sleepers	Concrete.		Not depended
Superstructure ballast	Macadam ballast	500	Not depended
Substructure ballast	Sub-ballast	800	Clay
		500	Bedrock

5.4.2 Mexico

The information considered for this study is based on the regulation of conservation of railways and structures for the Mexican Railroads (Secretariat of Communications and Transportation, 2016). The simplification of the cross section for railroad embankment and its constituent materials are shown as well in Figure 5.2, however the specifications with regard to the track width and thicknesses are displayed according to the regulations of Mexico. The lane is 3.04 [m] width and the rail used is a caliber 100 with weight of 50 [kg/m]. The concrete sleepers utilized in the rail system are 2.5 [m] long, weigh 235[kg] and are placed at each 54 [cm]. Rail clips weigh 0.350 [kg] and placed at the same distance as the sleepers (Rail One, 2016). The construction components and materials of the railroad structure according to (Secretariat of Communications and Transportation, 2016) are described in Table 5.10.

Table 5.10 Guadalajara railways construction components.

Construction components	Material type	Thickness of the material layer [mm]
Rail	Steel	-
Rail Clips	Steel	-
Sleepers	Concrete.	-
Superstructure ballast	Macadam ballast	180
Substructure ballast	Sub-ballast	200

Table 5.11 shows the densities of the materials comprising the different infrastructures based on regulations of each country.

Table 5.11 Densities of materials in [kg/m3]

	Material	**kg/m^3**
Sweden	Asphalt	2200
	Concrete	2400
	Geotextile	0.2
	Stone	2000
	Steel	7850
Mexico	Asphalt	2624
	Concrete	2330
	Stone	2000
	Steel	7850

6 Material Intensity

The material intensity is an important parameter affecting the total material stock accumulation. Therefore, the material intensity coefficients shown in this study are based in official standards and regulations of each country, section (5). In Table 6.1 and 6.2 the material intensity data of Sweden and Mexico are arranged by the type of structure and by construction material.

Table 6.1 Construction material intensity of structures in Sweden, [kg/m^2].

Structure Type	Type	Layer	Material	Material Intensity
Roads	Class III	Surface	Asphalt	352.00
		Unbound base	Stone	160.00
		Unbound subbase on Rock	Stone	400.00
		Unbound subbase on Clay	Stone	1220.00
	Class IV	Surface	Asphalt	286.00
		Unbound base	Stone	160.00
		Unbound subbase on Rock	Stone	400.00
		Unbound subbase on Clay	Stone	1110.00
	Class VI	Surface	Asphalt	242.00
		Unbound base	Stone	160.00
		Unbound subbase on Rock	Stone	400.00
		Unbound subbase on Clay	Stone	1020.00
	Class VII	Surface	Asphalt	158.40
		Unbound base	Stone	160.00
		Unbound subbase on Rock	Stone	400.00
		Unbound subbase on Clay	Stone	840.00
Parking lots	Single story	Surface	Asphalt	99.00
		Unbound base	Stone	160.00
		Unbound subbase on Rock	Stone	400.00
		Unbound subbase on Clay	Stone	840.00
Cycleways	Designated	Surface	Asphalt	88.00
		Unbound base	Stone	110.00
Footways	Designated	Surface	Asphalt	88.00
		Unbound base	Stone	110.00
Tram	Street environment	Surface	Asphalt	110.00
		Compression layer	Concrete	960.00
		Base ballast	Stone	100.00
		Subbase ballast	Stone	500.00
		Geotextile	Polymer	0.0012
		Rail*	Steel	119.48
		Rail clips*	Steel	1.08
Railway	Basic structure	Superstructure ballast	Stone	1000.00
		Substructure ballast on Rock	Stone	1000.00
		Substructure ballast on Clay	Stone	1600.00
		Rail*	Steel	100.00
		Rail clips*	Steel	1.08
		Sleepers*	Concrete	281.54

*Intensity units are [kg/m]

Table 6.2 Construction material intensity of structures in Mexico, [kg/m^2].

Structure Type	**Type**	**Layer**	**Material**	**Material Intensity**
Roads	Collector roads; Minor collector roads; Sub-collector roads; Local Roads; BRTs	Surface	Asphalt	419.84
		Surface	Concrete	489.30
		Unbound base	Stone	500.00
		Unbound subbase	Stone	600.00
Parking lots	Single story	Surface	Asphalt	131.20
		Unbound base	Stone	300.00
		Unbound subbase	Stone	300.00
Cycleways	Designated	Surface	Asphalt	131.20
		Unbound base	Stone	200.00
Footways	Designated	Surface	Concrete	163.10
		Unbound base	Stone	200.00
Tram	Exclusive	Superstructure Ballast	Stone	1000.00
		Concrete compression layer	Concrete	582.50
		Substructure ballast 1	Stone	600.00
		Substructure ballast 2	Stone	400.00
		Substructure ballast 3	Stone	400.00
		Rail*	Steel	114.08
		Rail Clips*	Steel	0.98
		Sleepers*	Concrete	326.39
Railway	Basic structure	Superstructure ballast	Stone	360.00
		Substructure ballast	Stone	400.00
		Rail*	Steel	114.08
		Rail Clips*	Steel	0.98
		Sleepers*	Concrete	326.39

*Intensity units are [kg/m]

7 Data collection using GIS

The georeferenced vector data information used for this project was extracted from OpenStreetMaps ArcMap extension tool (Esri, 2016). The information extracted is depicted in form of lines and polygons containing different features according to the infrastructure type, see Figure 7.1 to 7.4. The information comprising the roads, cycleways , footways, trams and railways is extracted from the lines and the parking lots are extracted from the polygons vector data. The infrastructures are classified according to the standards of each country, shown in section (5) by modifying the attribute tables of each extracted layer. Table 7.3 shows the equivalences between OSM classification and the governmental official information of section (5). Once the attribute tables have been modified, the total length and areas of the different types of infrastructure are obtained with "Calculate Geometry" ArcMap tool and shown in Table 7.1 and Table 7.2.

Two additional resources that work as a complement to the extracted information were used. The first one, belongs to the Swedish University of Agricultural Sciences (SLU), which provides vector information data with the types of soil for Swedish cities. The second one, belongs to the National Institute of Statistics and Geography in México which is used to extract information related to the sidewalks.

7.1 Linear vector data

7.1.1 Roads, cycleways and footways

OpenStreetMap (OSM) classifies the roads network of cities in eight types of roads according to their connectivity level within the urban network going from the most to the least connected. Roads referred as "motorways" represent the highest level of connectivity with a restricted access and have at least two lanes. The "trunk" roads are defined as the most connected roads in a country level but not considered as "motorways". "Primary" roads are those connecting large villages and the "secondary" roads connect as well villages but not as large as the "primary" roads. "Tertiary" roads are defined as those that unite small towns or villages. "Roads" have lower classification than tertiary, but serve a purpose other than access to properties. "Residential" roads are those that serve as access to housing and finally the "service" roads are those that are within some complex or industrial park.

Information related to the number of lanes and the permissible speed it's possible to find in the attribute table for each type of road and it's used to reclassify them according to the countries regulations in order to obtain the material contained in each type of road and in the overall network system.

The classification of roads for the Swedish cities was carried out according to the rules of the city of Gothenburg, which in turn is based on Trafikverket federal traffic agency and described in section 5.1, being as follows; Class III roads include OSM roads classified as trunk, motorway and primary roads; Class IV roads comprise the secondary roads; Class VI are the tertiary roads and Class VII roads are now the formerly called roads, residential and service roads.

With respect to the Mexican cities, roads classification was made with the regulations and development plans in Jalisco which in turn are based on the federal agency of the

Secretariat of Communications and Transportation, being as follows; Collector Roads include motorways, trunk and primary roads; Minor Collector Roads include those previously named as secondary roads; Sub Collector Roads are the tertiary roads and Local Roads include those classified by OSM as roads, residential and service roads.

In the case of the cycle ways, OSM classifies them within the section "highways" as "cycle ways" representing all those infrastructures constructed especially for the cyclists. All data belonging to this category is exported from the information for OSM for both cities. The same was done for footways, however the classification used by OSM to categorize tracks built exclusively for pedestrians are classified as "footways". In the case of the Mexican cities the information of the sidewalks was extracted from the National Institute of Statistics and Geography, the difference is that in Mexico the exclusive areas for pedestrians are only the sidewalks. The information provides the location of the blocks in the cities which is used to obtain their perimeter.

For cities in Mexico with special infrastructure for the BRT's, OSM identifies them as special infrastructure of buses in the "route" section. Identified once, they're removed from OSM tables and represented separately for their length calculation.

7.1.2 Tramlines

Tram infrastructure has a special distinction within OpenStreetMap (2016) attribute tables and can be identified in the "route" and "railways" sections with the "tram" value. For all of the cities this criterion was applied and the corresponding lines were extracted. The lines drawn were verified with the OSM ArcMap base map in order to verify the number of the lanes projected and to be able to perform the calculation for the number of rails, sleepers and clips.

7.1.3 Rail lines

The railway lines considered by OSM are mainly those tracks that have their independent structure and which do not allow the interaction in the surface with any other type of transport (e.g., vehicles, buses, pedestrians, etc.). The lines extracted from OSM for railways have as main function the provision of transport for goods and passenger trains on a regional, state and national level. These are extracted from the attribute "rail" within the section of "railway". As well as the tram lines, the projected rail lines are verified with OSM base map in order to perform the correct calculations for the rails, sleepers and rail clips.

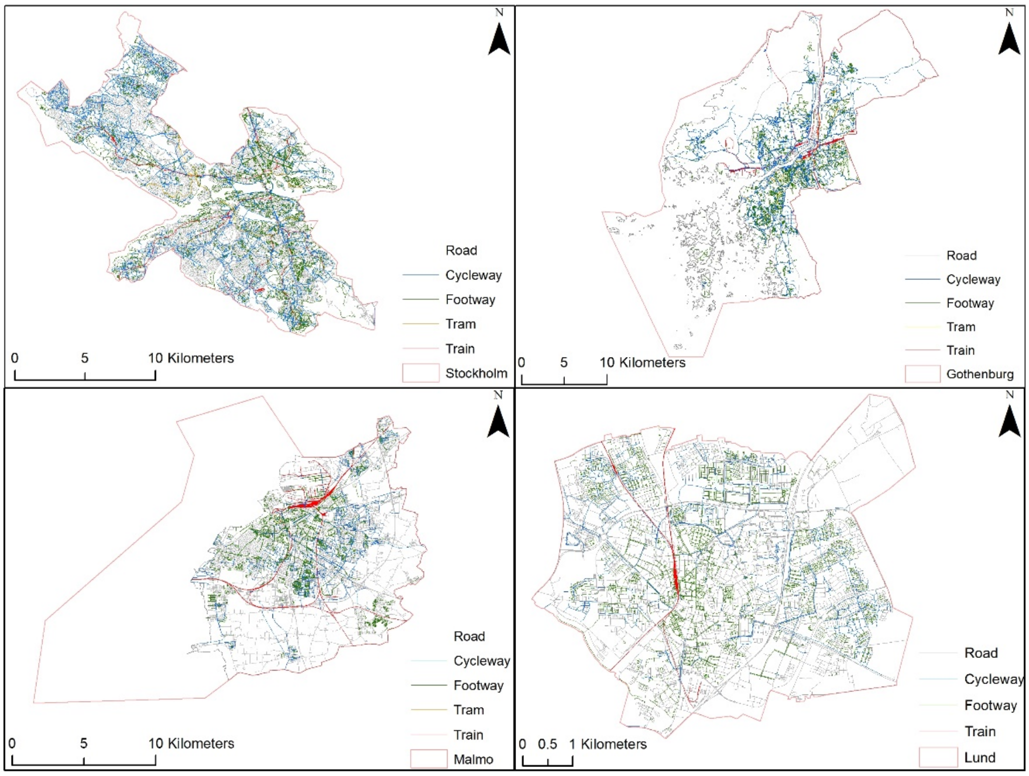

Figure 7.1 Linear vector data in Swedish cities.

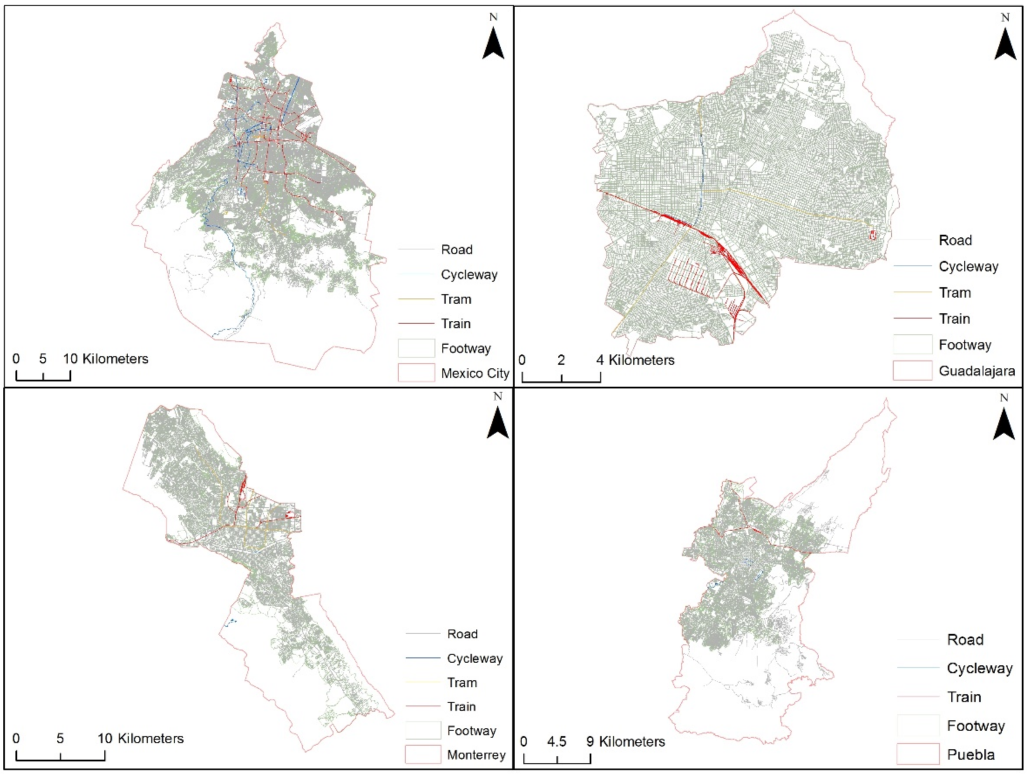

Figure 7.2 Linear vector data in Mexican cities

7.2 Polygon vector data

7.2.1 Parking lots

Parking lots are defined as polygons and therefore the unit of measurement is square meters. The information concerning the parking lots is found in the "park" and the "parking space" attributes in the "amenities" section within the attribute tables of OSM. Once the information is extracted, the parking lots within a structure are eliminated by selecting the "no" attribute in the "building" section. If the two criteria of "parking" and "building" are part of the same area/polygon, these are not taken into account for the study. This procedure was applied for the cities in this study for both countries. Figure 7.3 and 7.4 show the parking lots considered for this study.

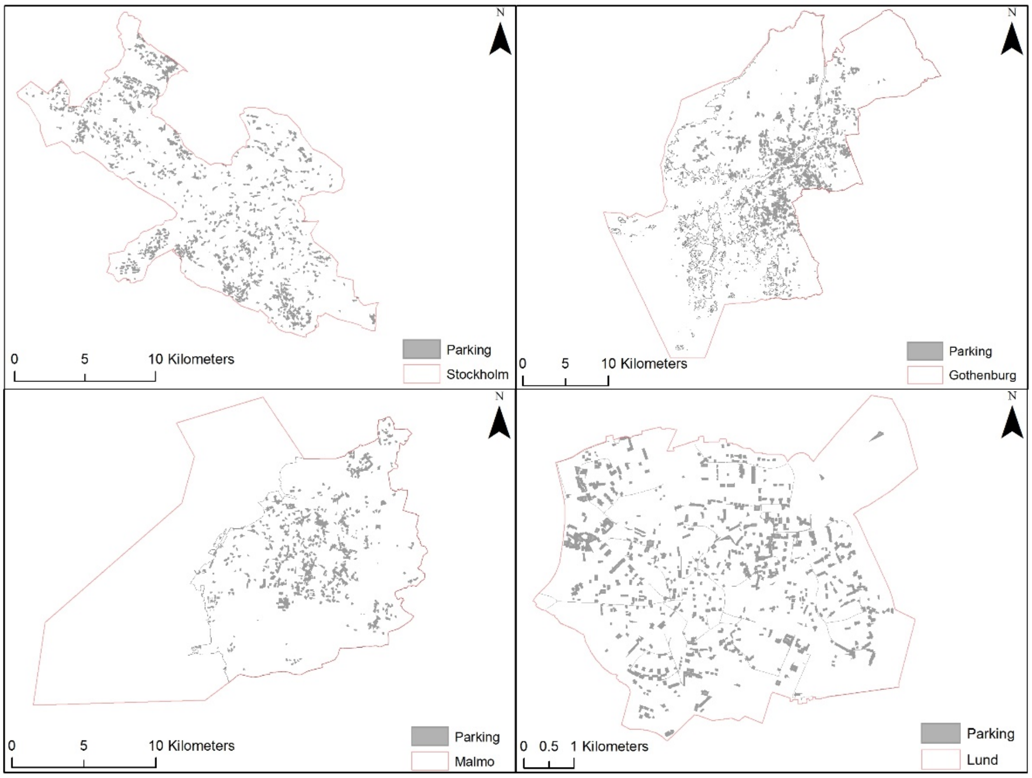

Figure 7.3 Polygon vector data in Swedish cities.

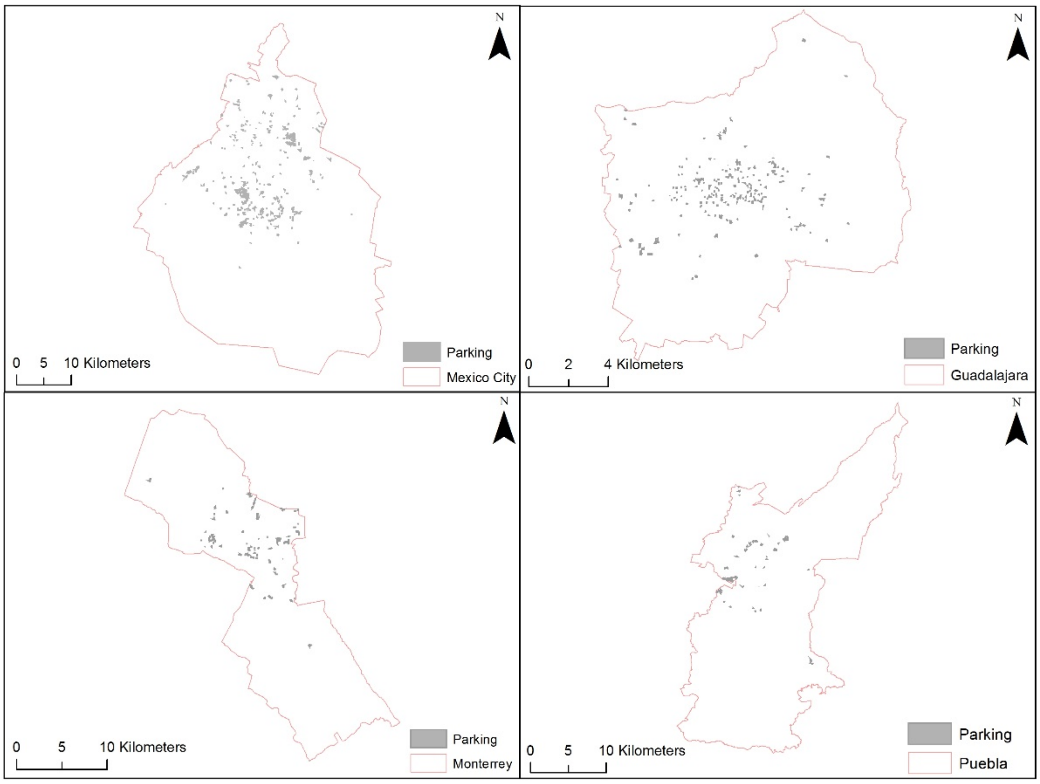

Figure 7.4 Polygon vector data in Mexican cities.

7.2.2 Subgrade materials

The subgrade materials for the Swedish roads design, were obtained from the Swedish University of Agricultural Sciences (SLU). The vector information of the cities was overlapped with SLU information in ArcMap. The small areas with neither clay nor bedrock, were neglected and grouped as the material closest. The different types of clay were grouped as one and the same was done for the different types of rocks, see Figure 7.5.

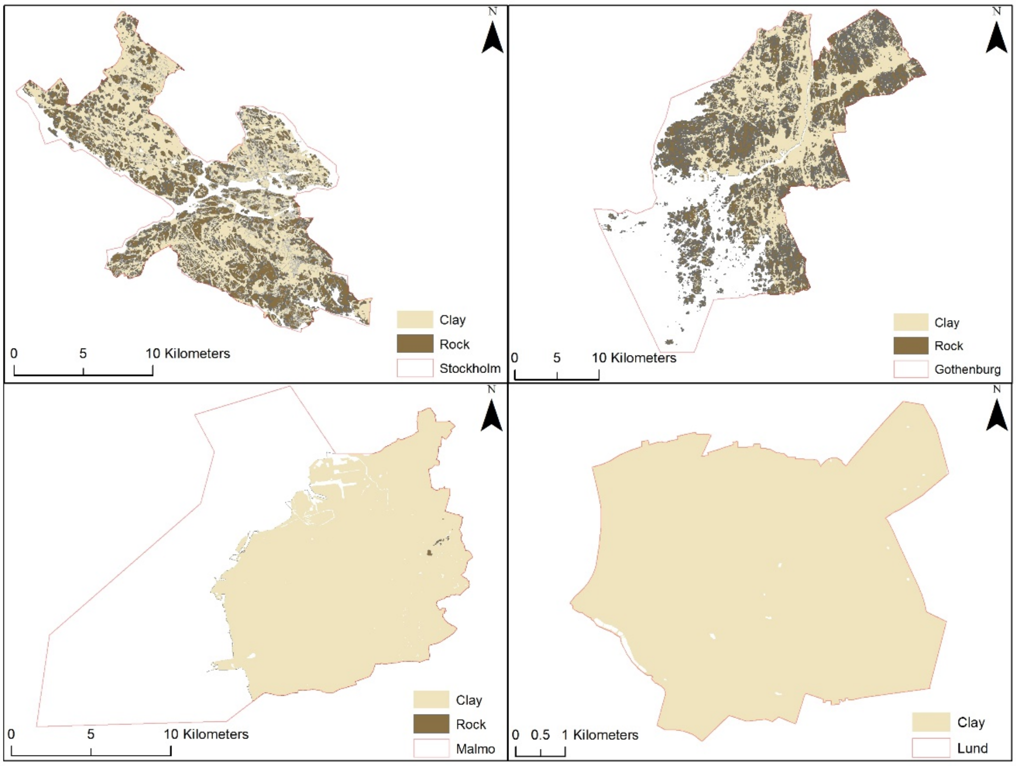

Figure 7.5 Subgrade materials in Swedish cities.

Table 7.1 Lengths and areas of the different types of infrastructures in Swedish cities.

		City			
Infrastructure	Built on	Stockholm	Gothenburg	Malmo	Lund
Class III [km]	Rock	71.83	79.03	0.37	0.00
	Clay	252.96	471.02	224.40	37.04
Class IV [km]	Rock	25.84	32.13	0.07	0.00
	Clay	152.82	299.11	144.22	47.35
Class VI [km]	Rock	40.80	83.89	0.13	0.00
	Clay	211.61	519.51	202.48	45.54
Class VII [km]	Rock	589.60	1064.29	0.00	0.00
	Clay	1260.88	2815.25	1159.53	378.24
Train [km]	Rock	153.34	22.20	0.00	0.00
	Clay	540.04	473.15	830.39	139.69
Parking lots [km^2]	Rock	546.02	1170.03	0.00	0.00
	Clay	1584.90	5962.75	2018.15	1147.20
Tram [km]*		134.67	606.92	1.80	0.00
Cycleway [km]*		859.12	1850.12	283.01	127.19
Footway [km]*		803.68	1613.51	487.03	243.53

*Dependency on the subgrade material was not included by the technical design.

Table 7.2 Lengths and areas of the different types of infrastructures in Mexican cities.

	City			
Infrastructure	Mexico City	Guadalajara	Monterrey	Puebla
Collector Roads [Km]	1,650.02	149.91	382.25	482.24
Minor Collector Roads [Km]	1,358.78	122.26	191.88	170.73
Sub-Collector Roads [Km]	1,098.68	106.87	267.54	136.94
Local Roads [Km]	10,065.07	2,501.26	2,692.45	3,135.97
BRTs [Km]	175.37	33.89	0.00	30.83
Train [Km]	139.26	225.04	75.63	56.10
Tram [Km]	278.02	22.77	51.30	0.00
Cycle way [km]	151.47	10.06	4.03	8.68
Footway [km]	26,789.90	5,253.51	6,228.35	6,855.29
Parking lots [km^2]	3.40	0.39	2.80	0.66

Table 7.3 Equivalences between OSM and official governmental data.

OSM	**Sweden**	**Mexico**
Cycleway	Cycleway	Cycleway
Footway	Footway	Footway
Living street	Class VII	Local
Motorway	Class III	Collector
Motorway link	Class III	Collector
Parking lots	Parking lots	Parking lots
Pedestrian	Footway	Footway
Primary	Class III	Collector
Primary link	Class III	Collector
Raceway	Class III	Collector
Railway	Railway	Railway
Residential	Class VII	Local
Road	Class VII	Local
Secondary	Class IV	Minor Collector
Secondary link	Class IV	Minor Collector
Service	Class VII	Local
Tertiary	Class VI	SubCollector
Tertiary link	Class VI	SubCollector
Tram	Tram	Tram
Trunk	Class III	Collector
Trunk link	Class III	Collector

8 Results and discussion

In the following chapter the calculated amount of material stock (MS) is shown followed by an analysis of the results.

8.1 Material Stock (MS)

The information obtained and shown in sections five to seven was used in the equation (3.1) and (3.2) to calculate the total material stock (MS).

8.1.1 Total material stock by material

The material stock by material type may indicate environmental impacts related to the extraction of raw materials and in their transformation into end-use stocks. Although the values shown in the Figure 8.1 are not normalized and a comparison between cities could not be objective, they can give us an idea of the overall materials that the cities have extracted to transform them into end-use stocks. It is important to mention that most of these materials might have been extracted some time ago and nowadays they are hibernating in the different infrastructures and in a near future they will turn into waste. In addition, the knowledge of the end-use stocks is the foundation of a potential transformation towards a sustainable and recycling society.

It can be observed that Mexico City is the city with the largest share of materials extracted and transformed with 215 million tonnes and therefore the city with the largest share of materials hibernating and likely to become in future waste. Mexico City is followed by Gothenburg (71.6 million tonnes), Puebla (54.6 million tonnes), Monterrey (52.4 million tonnes), Guadalajara (48.5 million tonnes), Stockholm (36.2 million tonnes), Malmo (30.2 million tonnes) and Lund (7.94 million tonnes).

The stone in its different aggregate size is the material with the largest share in the infrastructures. On average, it represents the largest material in use 69.4% in Mexican cities and 82.3% in Swedish cities. Followed by asphalt, concrete and steel, while the polymer accounts for a smaller part in the stock of cities.

Since the values correspond to materials being used, the cities will have to provide a good maintenance in order to prolong the lifetime of these materials and prevent large volumes of materials from becoming into future waste flows.

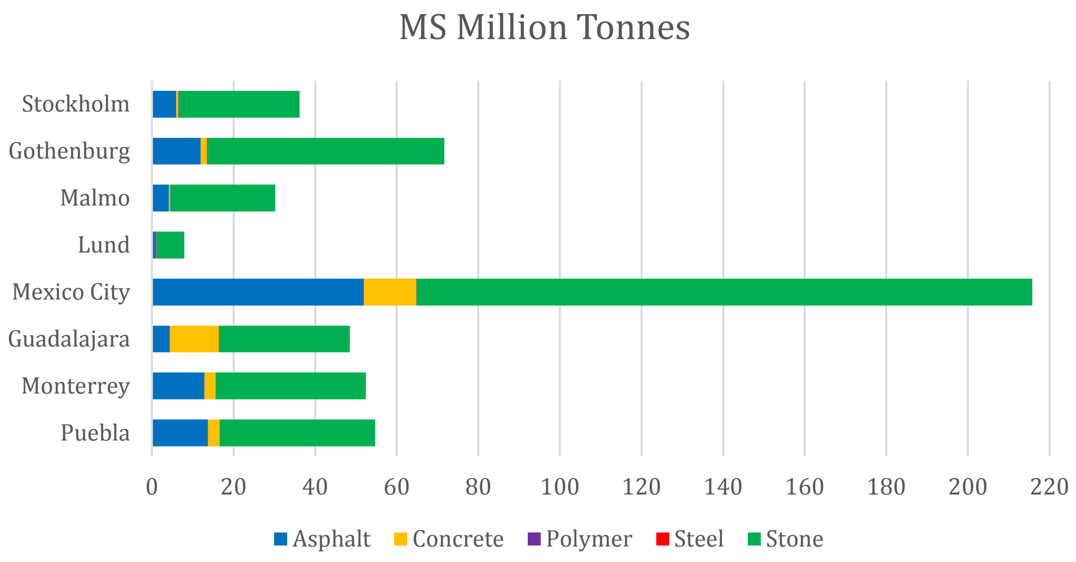

Figure 8.1 Material Stock (MS) in cities by material type

8.1.2 Total material stock per km^2 by material

In Figure 8.2, in order to analyze and compare the cities the material stock was normalized by square kilometer. As it can be seen, the stone represents the largest share of material stocked in the urban areas by square kilometer. The use of stone it is mainly based on two main reasons: First, the material used for the base and sub-base is suggested to be an economic material, abundant in the region and one fulfilling all the technical specifications. Therefore, in this study the regulations of both countries Trafikverket (Tekniska Handbok, 2016) in Sweden and the Secretariat of Communications and Transportation (SCT, 2016) in Mexico suggests the stone in its different grain size as a material to provide stability to the structures. Secondly, the thicknesses of the subbase are dependent on the type of soil on which the infrastructure is built, in the case of the Swedish cities the 80.5% of the roads were constructed on unstable soils and therefore major thicknesses and materials in the subbase layers were required.

The thicknesses of the base and subbase layers in Mexican cities unlike Sweden, are over-dimensioned. The foregoing is mainly due to the fact that authorities in Mexico lack a detailed inventory of the axle loads produced by cars and therefore the design it is only based on the assumption of the worst scenario for loads and for the most unstable soil, see section 5. The cities in Mexico might be less efficient in the use of stone. The latter can be observed in Guadalajara and Stockholm, both cities have approximately the same surface area with 151 km^2 and 187 km^2 respectively with a similar inventory of roads 2 880 km and 2 606 km respectively (see Table 6.1 and 6.2), nevertheless a difference in both cities in the tramlines and railways can be seen, Stockholm has a larger train infrastructure (three times greater) and also a larger tram line infrastructure (five times greater) in comparison with Guadalajara, as mentioned before, the infrastructure in Mexican cities might be over-dimensioned and therefore it is observed that Guadalajara has a large share of stone per square kilometer with 0.21 million tonnes per km^2 while Stockholm has 0.16 million tonnes per km^2.

In Sweden and particularly in Lund a more intensive use of this material is used in the infrastructure stock (0.26 million tonnes per km^2). The latter is due to the fact that the entire infrastructure in Lund is built on unstable soils, which has resulted in greater thicknesses and greater use of this material. The same can be observed in Stockholm and Malmo. Both cities have the same stock of stone per square kilometer (0.16 million tonnes), nevertheless Malmo has a lesser amount of roads in comparison with the city of Stockholm, therefore the prevailing unstable soils in Malmo might be the cause of such increase in the stock of stone.

In Mexico, the lack of precise statistical data might cause over-dimensioned infrastructures and an inefficiency in the use of the resources. As for stone, the city with the largest stock per square kilometer stands for the city with the less efficient use of this resource. Taking into account the above, Guadalajara is the city with the largest share of this material per square kilometer with 0.21 million tonnes, followed by Monterrey (0.11 million tonnes), Mexico City (0.10 million tonnes) and Puebla (0.06 million tonnes).

Therefore, cities with a large stock per square kilometer of this material may stand for an urban area with the following characteristics; Firstly, since the stone is stocked in all the infrastructures, a high amount of this material per square kilometer might suppose an area with a wide offer of infrastructure and therefore a well-connected city. Secondly, cities with an inefficient use of this natural resource in the base and subbase layers of the different types of infrastructures. Thirdly, cities with a large share of stone hibernating in the end-use stocks and therefore a future waste flow if a proper maintenance to the infrastructures is not applied.

As for asphalt, it is commonly used in roads due to its low construction and maintenance costs, its maintenance is easier to realize in comparison to the roads paved with concrete. In addition, the temperature during the construction of this type of roads play a less critical role in the final resistance of the roads. As can be seen in Table 6.1 and 6.2, the asphalt material intensity coefficient is higher in Mexican cities in comparison with Swedish cities. As explained in section 5, the asphalt thickness design is strongly dependent in the axle loads taken into account. Since Mexican authorities consider a standard high axle load value for the design of this layer an over-dimensioned layer of asphalt is considered in the construction of roads in Mexico. The latter can be observed in Puebla and Gothenburg, both cities have similar surface area 545 km^2 and 447 km^2 respectively, and Puebla has a lesser amount of roads with 3 925 km in comparison with the 5 364 km of Gothenburg. Nevertheless , in spite of the fact that Gothenburg has almost 1.3 times the roads of Puebla, both cities have similar stock of asphalt per square kilometer (0.027 million tonnes and 0.025 million tonnes respectively).

On the other hand, it can be seen that the city of Monterrey with 0.040 million tonnes per km^2 and the city of Lund with 0.043 million tonnes per km^2 have the largest share of asphalt. However, Monterrey has thirteen times the surface area of Lund and a larger stock of roads. The latter means that Lund has more roads per square kilometer and therefore, it could stand for a better connected city in comparison with the city of Monterrey.

Additionally, Puebla and Malmo have the smallest share of this material per square kilometer with 0.025 million tonnes and 0.026 million tonnes respectively. Even though Puebla has almost 2.3 times more stock of roads than Malmo and 3.4 more times its surface area, Malmo has a largest share of asphalt per square kilometer. The latter means that Malmo as Lund having more asphalt per square kilometer could have a better connectivity and accessibility than cities in Mexico.

A large stock of asphalt per square kilometer can mean the following; Firstly, urban areas with a large share of roads per square kilometer and therefore well connected cities. Secondly, urban areas with over-dimensioned roads and less resource use-efficiency. Thirdly, since the lifetime of asphalted roads are highly dependent in the maintenance, a major use of resources in order to prevent future waste flows in urban areas can be expected.

As regards to the concrete, in Guadalajara the stock of concrete per square kilometer stands out in relation to the rest of the cities (0.07 million tonnes per km^2). This is due to the fact that the city of Guadalajara has the largest share of paved roads with concrete. The preference for this material in this city is based on its low maintenance and the absence of deformations by high temperatures and by axle loads in comparison to the roads with asphalt. Although its cost is higher than asphalt, bad practices in the construction of asphalted roads and the high costs in the maintenance could have been a factor to change to concrete. Likewise the concrete is used in all cities in the compression layer of the tramlines and in the sleeper of the tramlines and trains. Based on the amount of concrete per square kilometer, it is difficult to predict whether the cities have a large number of roads or a large amount of trains and tramlines. The latter can be seen in the comparison between Guadalajara and Gothenburg. Both cities have the largest share of concrete per square kilometer (0.07 million tonnes and 0.003 million tonnes respectively) and have a large difference in the stock of tramlines and railways, Guadalajara has only the 3% of the inventory of railways and tramlines of Gothenburg. Therefore the main difference in the stock of this materials is represented by the roads paved with concrete.

The same can be observed in cities with the lowest share of this material per square kilometer. Puebla and Malmo have a concrete stock in their infrastructure of 0.005 million tonnes per km^2 and 0.001 million tonnes per km^2 respectively. Even though Puebla has only the 7% of the railway infrastructure of Malmo and although it lacks of a tramline infrastructure, Puebla has a large share of concrete in comparison with Malmo. This is due to the fact that Puebla has more roads paved with concrete and at the same time, instead of a tramline, Puebla has a Bus Rapid Transit System (BRT's) which infrastructure involves the use of concrete in the surface layer.

Therefore, unlike asphalt the amount of concrete per square kilometer is not enough evidence to determine the infrastructure to which it belongs. Nevertheless, having the stock of this material per square kilometer provide valuable information in order to account for the amount of concrete that has to be re-used once his lifetime has been fulfilled.

In regards to the steel, it is only used in trains and tramlines and it is stocked in the rails and in the rail clips. Therefore the larger the share of steel per square kilometer, the greater the amount of infrastructure for trains and tramlines in the same unit of area. The latter can be observed in Malmo and Guadalajara, both cities have similar surface areas with 156 km and 151 respectively and a difference in the stock of steel per square kilometer with 0.0005 million tonnes and 0.0002 million tonnes respectively. The difference in the steel stocks is a reflection of their rail stocks in which Malmo has three more times the stock of rails than the city of Guadalajara, see Table 7.1 and 7.2.

If the analysis of the type of material is analyzed per square kilometer, it is observed that cities in Sweden are more material intense in comparison with cities in Mexico. The city of Lund would be the city with the largest intensity of materials per square kilometer (0.31 million tonnes per km^2), followed by Stockholm and Malmo (0.19 million tonnes per km^2), and Gothenburg (0.15 million tonnes per km^2), while in Mexico , the city with the largest share per square kilometer of extracted and transformed natural resources is Guadalajara (0.32 million tonnes per km^2), followed by Monterrey (0.16 million tonnes per km^2), Mexico City (0.14 million tonnes per km^2) and Puebla (0.10 million tonnes per km^2). Likewise, cities should be aware that these stocks will fulfil their lifespan and will represent a future waste.

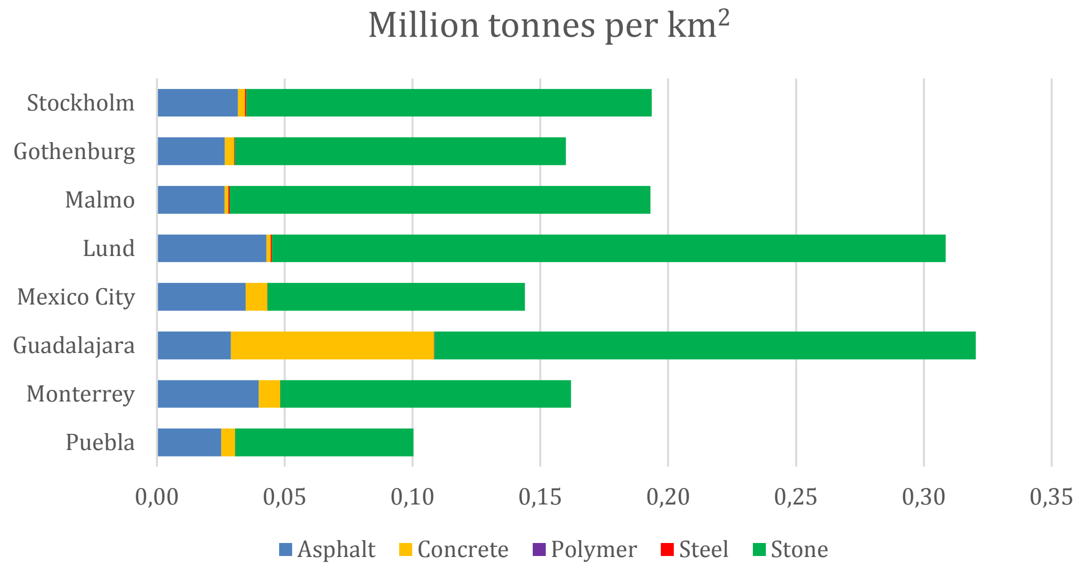

Figure 8.2 Material Stock (MS) in cities per Square Kilometer [km2] by material type.

8.1.3 Total material stock per km^2 by infrastructure

Road density is an indicator that is commonly used to determine the accessibility of cities, i.e. the proportion of linear kilometers of road per square kilometer (Sinchi, 2016). A city with a high density of roads stands for a city with high levels of accessibility and consequently a high socio-economic development of the territory. Therefore, the material stock per km^2 by infrastructure type could help us to understand the accessibility of the cities and the amount of natural resources required in order to achieve it, see Figure 8.3.

A large share of end-use stocks per square kilometer means that a large number of infrastructures in the same unit of area foster and encourage connectivity in a specific area and at the same time helps us to understand the allocation of the future waste flows. As can be seen, the city of Lund and Guadalajara have the largest share of end-use stocks per square kilometer with 0.31 million tonnes and 0.32 million tonnes respectively and both have the smallest surface area of the cities considered in this study (25 km^2 and 151 km^2). Based on their material stock density, we might assume that both cities are compact accessible cities. In other words, cities with proximity to the services, fostering the encounter of activities and enabling the development of life in community. Nevertheless, the fact that Lund has more end-use stocks in the cycle ways could stand for a sustainable spatial planning based on sustainable transportation modes. The latter can be also observed in the materials stocked in the roads, Guadalajara has 0.28 million tonnes per km^2 and Lund 0.21 million tonnes per km^2 which means that Guadalajara is either better connected with roads or its transportation policies are based on the use of the private car.

On the other hand, compared to the cities in Sweden, the cities of Monterrey, Puebla and Mexico City have less stock of infrastructure per square kilometer and a major road network. This is because the cities in Mexico are fragmented, which is due to certain housing policies and are characterized by an urban expansion in areas of low population density. Therefore, the low density of materials per square kilometer stocked in the infrastructure indicates that this type of cities have a bad accessibility and connectivity to the various services provided by them. Consider for example Gothenburg and Mexico City, both cities have the largest surface area in this study with 447 km^2 and 1,499 km^2 respectively (Table 4.1). In the case of Gothenburg, the material stock density in roads represent the 79.5% of the territory, followed by parking lots (10.2%), train (4.7%), tram (3.6%), cycle ways (1.0%) and footways (0.9 %), while in Mexico City, the stock density in roads represent the 84.9% of the territory , followed by footways (10.8%), tram (3.0%) , parking lots (1.2%), train (0.2%) and cycle ways (0%). As it is observed, the stock per square kilometer in cycle ways, tramlines and train lines is higher in Gothenburg, which means that the natural resources are used thinking in collective and sustainable transportation modes. In addition, the distribution of the stock in the different types of infrastructures in a square kilometer in cities can mean easier modal shifts from one transportation system to another.

With regard to Mexico City, the high percentage in the stock of roads and the low percentage in cycle ways, tramlines and trains, demonstrate the tendency in Mexican cities towards increasing motorization and a propensity to expand the network system of urban roads. This lack of stock in collective transport infrastructures in the cities of Mexico is due to several factors, such as; economic policies that maintain fuel subsidies, planning practices that incentivize an accelerated urban sprawl and at the same time ensured the car as an essential part of most transportation needs of people and as a status symbol which stands for affluence and success in life.

According to the National Institute of Statistics and Geography (2016) Mexico City and Monterrey have the largest amount of vehicles per 1000 inhabitants (410 vehicles) , followed by Guadalajara (350 vehicles) and Puebla (190 vehicles). In Sweden, Stockholm is the city with the largest amount of cars per 1000 inhabitants with 403 vehicles (County Administrative Board of Stockholm, 2016), followed by Malmo with 357 vehicles (Malmo Stad, 2016) and Gothenburg and Lund with 301 vehicles (Goteborg Stad, 2016) (Lund, 2016). Taking into account the number of inhabitants of each city and the number of vehicles per 1000 inhabitants, it can be concluded that the cities in Mexico have a greater number of vehicles in comparison with the Swedish cities. The large number of vehicles can mean a development focused on the use of the private vehicle and therefore a major development in road infrastructure as well as a solution due to the poor service and coverage in the infrastructure of mass transportation systems.

It should be noted that the density in the stocks of parking lots included in this study reflects only the single-level parking lots. Therefore, due to the high density of vehicles and inhabitants, parking lots could be found in multilevel structures and could not be taken into account in this study, thus, further analysis should be conducted in the future for this type of structures.

As can be seen, a large amount of construction materials have been used and transformed into different infrastructures causing environmental pressures, therefore conservation measures in order to prolong the lifetime of the infrastructures should be done. As explained before, a high amount of end-use stocks could stand for better connected cities, nevertheless having more infrastructure entails greater conservation measures in order to prolong the lifetime of the end-use stocks and avoid needs in infrastructure replacement and large amounts of waste flows.

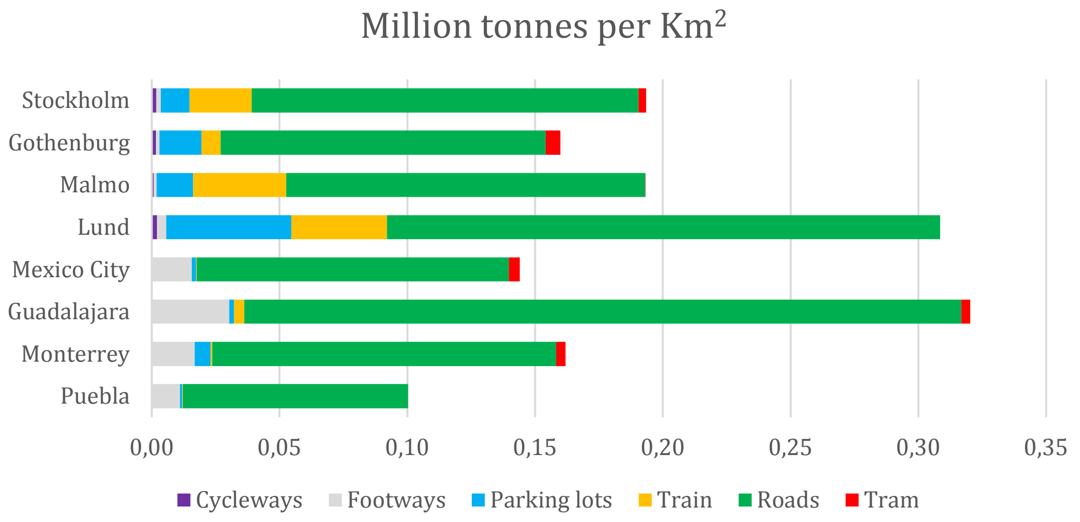

Figure 8.3 Material Stock (MS) in cities per Square Kilometer [km^2] by infrastructure type.

8.1.4 Total material stock per capita by infrastructure

The stock per capita by infrastructure type can be seen in Figure 8.4. In terms of infrastructures types, roads have the largest stock per capita for all cities considered in this study. The roads are the main infrastructure for mobility in different means such as public transportation or private car, and represent the place of access to housing, trade goods, employment and other services. It is therefore understandable that the construction of this infrastructure involves a larger stock per capita in order to improve the accessibility of all the inhabitants in urban areas. In addition, according to Glover and Simon (1975), the higher the population density, the higher the road density. With high population densities the cost per person is lower and the benefit/cost ratio is higher at higher population density. Therefore, following the benefit/cost ratio relation, it can be expected that roads represent the largest infrastructure being built in comparison with the other ones by having a lower cost and a faster return in the investment in urbanized area.

The stock per capita in trains and tramlines is lesser since these infrastructures represent a higher cost and need a larger population density in order to be considered a good investment. According to Guerra and Cervero (2011) , cities need an average of 3 000 inhabitants per km^2 in order to support reasonable cost-effective public transport services. A Bus Rapid Transit System (BRT's) system would need around 4000 inhabitants per km^2, while a light rail require at least 11 000 inhabitants per km^2 and a heavy-rail investment requires nearly 14,000 inhabitants per km^2. Therefore, even though cities in Mexico fulfil the suggested densities in order to build and encourage collective transportation systems, the lack of budget and political will might represent an obstacle in the development of these infrastructures. On the other hand, cities in Sweden due its solid economy are equipped with this type of infrastructure. Compare for example Puebla and Gothenburg, both cities have the lowest population density with 2 892 inhabitants and 1 190 inhabitants in an area of 545 km^2 and 447 km^2 respectively, see Table 4.1. Despite Puebla has a larger number of inhabitants per square kilometer and a larger surface area, the city lacks of a tram infrastructure, moreover the train system of Puebla represents the 0.68 % of the train infrastructure located in Gothenburg.

In regards to the largest stock per capita, Gothenburg is the city with the largest share with 134 tonnes per inhabitant and allocated as follows, 79.5% in roads, 10.2% tonnes in parking lots, 4.71% tonnes in trains, and 3.64% in tramlines, 1.03% in cycle ways and 0.88% in footways. If the stock per capita and the travelling modes in Gothenburg are compared, it can be observed that the end-use stock is related to the traveling behavior of the population. According to Göteborg Stads (2016) , in Gothenburg 44% of the travels are made using private car, 26% are by public transport, 6% by bicycle and 24% by walking. As regards to Monterrey, which is the city in Mexico with the largest stock per capita (47.3 tonnes per inhabitant), a different allocation of the materials in the different end-use stocks can be observed. 83.1% is stocked in roads, followed by footways (10.3%), tramlines (2.24%), trains (0.40 %) and cycle ways (0%). As can be seen 83% of the total stock per capita in Monterrey is stocked in roads. Unlike Gothenburg, in Monterrey the 50 % of the travels are made by private car and the other 50% in public transport (ONU Habitat, 2016). Nevertheless it can be observed that for both cities near the 50% of the travels are made by using private car, which means that urban mobility is dominated by motorization and particularly private motor vehicles as the preferred mean of mobility. Such travels habits and the large stock of roads per capita, are product of the spatial planning elaborated by local authorities which are ensuring the car as an essential part of transportation needs of people. This means that if the urban population is expected to grow and the travel habits prevail, the extraction and the wrong transformation of the natural resources into roads will be used as a solution for future traffic jams.

In what regards the capital cities, Stockholm has the lowest stock per capita in Sweden (41.1 tonnes), of which the 78.2 % is stocked in roads, 12.5% in trains, 5.80 % in parking lots ,1.60% in tramlines , 0.94% in cycle ways and 0.88% in footways. Unlike Gothenburg, in Stockholm in spite of the fact that the larger stock per capita is in roads, people make use more of the public transport. According to Stockholms Stad (2016), 59 % of the travels are made by public transport, 20 % by private car, 13% by foot and 6% by bicycle. This means that in Stockholm the stock per capita in the infrastructure of collective transport systems is more used in comparison with the infrastructure built for the vehicle. The high percentage of use of the public transport system can be due to the large traffic congestion of this city which has the largest number of vehicles (403 vehicles per 1000 inhabitants) and the largest population in Sweden (881 235 inhabitants) . On the other hand the congestion charges introduced by Stockholm and Gothenburg in August 2007 and January 2013 respectively (Centre for Transport Studies, 2016), it may be one of the reasons of the travel habits of the commuters.

As for the capital of Mexico, Mexico City has as well the lowest stock per capita (24.3 tonnes) with the largest number of inhabitants (8 851 080 inhabitants) and the largest share of vehicles per 1000 inhabitants (410 vehicles) . The distribution of the stock per capita in Mexico City is allocated as follow, the largest stock it is in roads with the 84.8 % of the stock, followed by footways (10.8%), tramlines (2.96%), parking lots (1.15%), train (0.18%) and cycle ways (0.03 %). In Mexico City as in Stockholm the travel habits are focused on mass transit systems. According to UN Habitat (2016), the 29 % of the travels are made by private vehicle, the 60.6 % by public transport concessioned of low capacity (Minibus, suburban bus and taxi) only 8% is done in integrated collective systems (Tramlines, BRT, Train) and a 2.4% by bicycle. Therefore, the stock per capita that serves to the infrastructure of mass transportation systems results in a better use than in those where the private vehicle is promoted.

A minor stock per capita means that a greater number of people are being benefited of the materials stored in certain infrastructure. Therefore due to rapid urban growth and from a resource-use point of view, what is sought is the creation of compact cities, areas highly densified where the extracted and transformed materials into in-use stocks serve a large number of inhabitants.

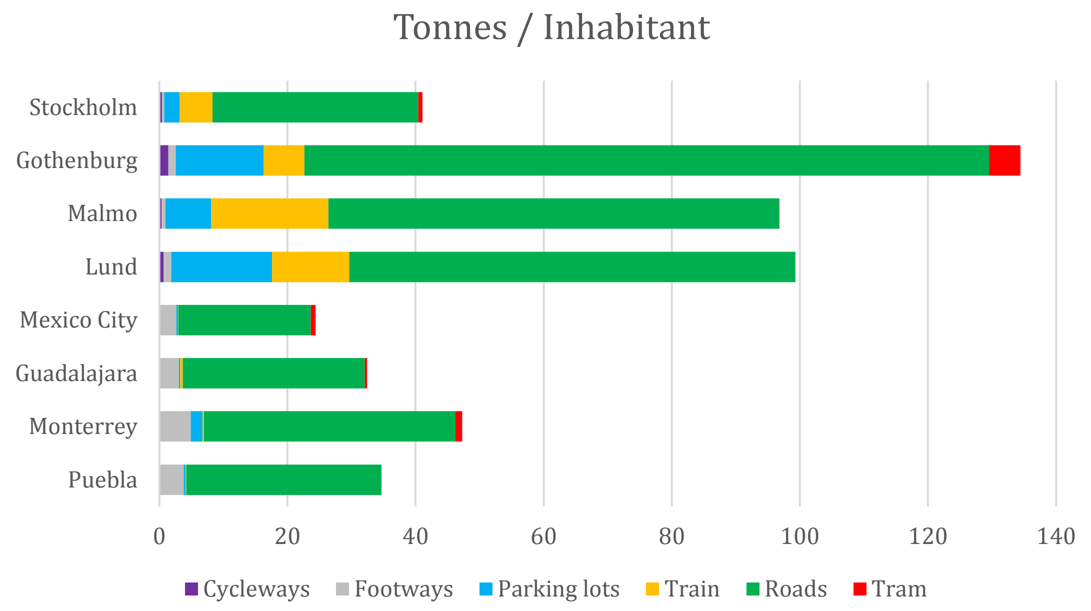

Figure 8.4 Material stock (MS) per capita by infrastructure.

8.2 Comparison with relevant studies

To some extent, aspects included by other authors were not taken into account in this study. For example, in order to avoid double counting Guo and colleagues (2014) took into account the intersections between roads in the road network system in Beijing, China. Tanikawa and colleagues (2009) considered more elements such as warning devices and crossing barriers in the railway system. In addition, the rail system was divided into four subtypes based on the type of rail and sleepers. Wiedenhofer and colleagues (2015) included the materials in the maintenance for roads and railways. Han and Xiang (2012) examined the temporal and spatial patterns of the stocks. With regard to the materials, studies are based on official government data of each region and which differ from those shown in this study as follows : Guo and colleagues (2014) , incorporated more materials to their study such as, flyash, mineral powder, polyurethane plastics and "atactic polypropylene" as part of the stock in roads. While Han and Xiang (2012) included steel as a reinforcing material in concrete roads.

The obtained material intensity coefficients are in similar ranges to values in studies conducted by different authors in the last decade. In Japan, Tanikawa and Hashimoto (2009) applied the material intensity coefficient of 292 [kg/m] for concrete sleepers and 158 [kg/m] for the steel used in railways, while in Sweden and Mexico were 281.54 [kg/m] and 326.39 [kg/m] for concrete sleepers, and 101.08 [kg/m] and 115.06 [kg/m] regarding steel. Concerning the ballast of the superstructure and substructure in the railways, Tanikawa and Hashimoto (2009) used 2340 [kg/m] for Japan and 3000 [kg/m] for the United Kingdom. In Sweden and Mexico the values obtained were 5200 [kg/m] and 2310 [kg/m] respectively. As for the superstructure and substructure of roads, Han and Xiang (2012) included material intensity coefficients ranging from 330 [kg/m2] to 440 [kg/m2]. While for Japan, Tanikawa and Hashimoto (2009) considered values from 312 [kg/m2] to 1786 [kg/m2] For Sweden values of 460 [kg/m2] in roads constructed on rock and values from 1000 [kg/m2] to 1380 [kg/m2] in constructed on clay. In Mexico the material intensity obtained for the substructure was of 1100 [kg/m2].

The material intensity in paved roads has a greater range of variation. For asphalted roads in Japan, Tanikawa and Hashimoto (2009) considered asphalt coefficients between 47 [kg/m2] and 211 [kg/m2] depending on the road class. In the same study, values for roads paved in United Kingdom range from 46.00 [kg/m2] up to 462 [kg/m2]. Values considered in this study for Sweden range from 88.00 [kg/m2] to 352.00 [kg/m2] and for Mexico from 131.20 [kg/m2] to 419.84 [kg/m2].

8.3 Sensitivity Analysis

A sensitivity analysis was conducted to determine the variable with greater consequences in the final stock. In the analysis, a five centimeters increase factor was considered for widths, lengths and thicknesses. The initial conditions are defined by the values corresponding to the roads class III of Stockholm and shown in the section (5.1.1), when the increase factor was applied to a variable the others remained with the baseline dimensions. Figure 8.5 illustrates the sensitivity analysis on the asphalt layer in the class III roads of Stockholm. As can be seen, the variation of the cross sectional variable has the largest impact on the scale of the material stock, even over the width and length of the structures. The difference in the stock can be noticed in the first increment factor applied. The thickness had an increment of 31% in the final stock with the first increment factor while with the same increment in the width and length of the roads, the total stock did not suffer a considerable increase.

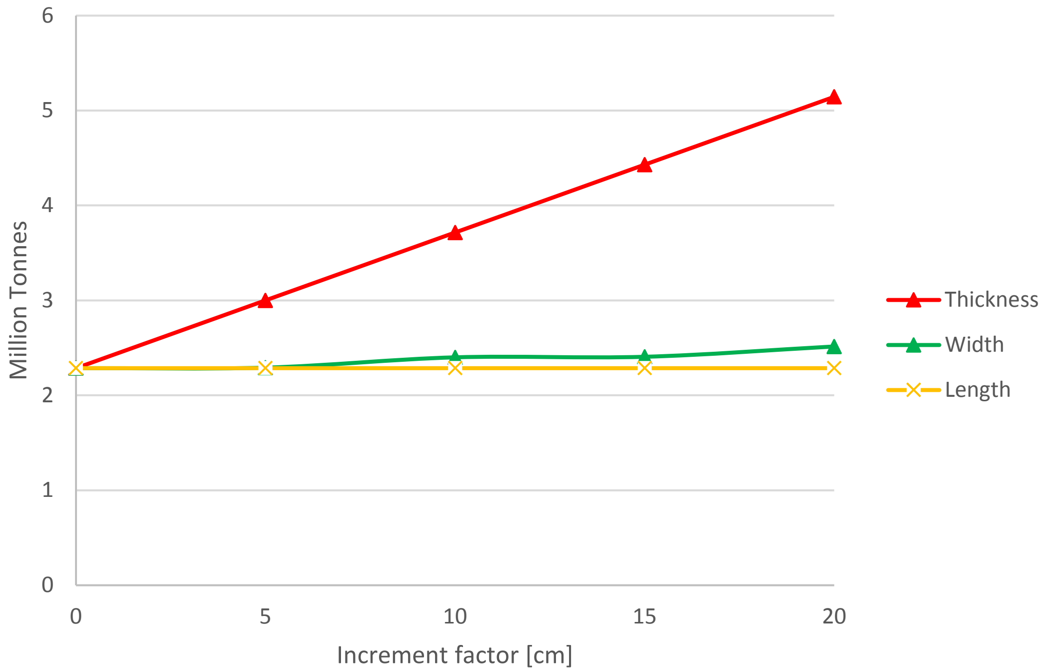

Figure 8.5 Sensitivity analysis on the asphalt layer in the class III roads of Stockholm.

Additionally, a sensitivity analysis was carried out in the road system of Stockholm to observe the differences in the total stock depending on the subgrade on which they were built. Figure 8.6 depicts the total stock in the road system of Stockholm taking into account three different considerations. The “base line” criterion, takes into account the Swedish norms and standards regarding the thicknesses of the base and subbase layers either built on rock or clay. The "rock" and “clay” criteria, considers the construction of the roads built 100% on rock and on clay respectively.

Roads constructed on clay had an 11.2 % increase in the total stock, while the roads built on rock have a 36.7% decrease in the total stock of the road system of Stockholm. Therefore, it can be seen from the analysis that roads built on clay have a greater impact in the total stock. Since clay is more instable than rock, more materials are used in order to provide stability to the structure. The same can be expected for railways and parking lots, which design is dependent on the subgrade material and explained in section 5.

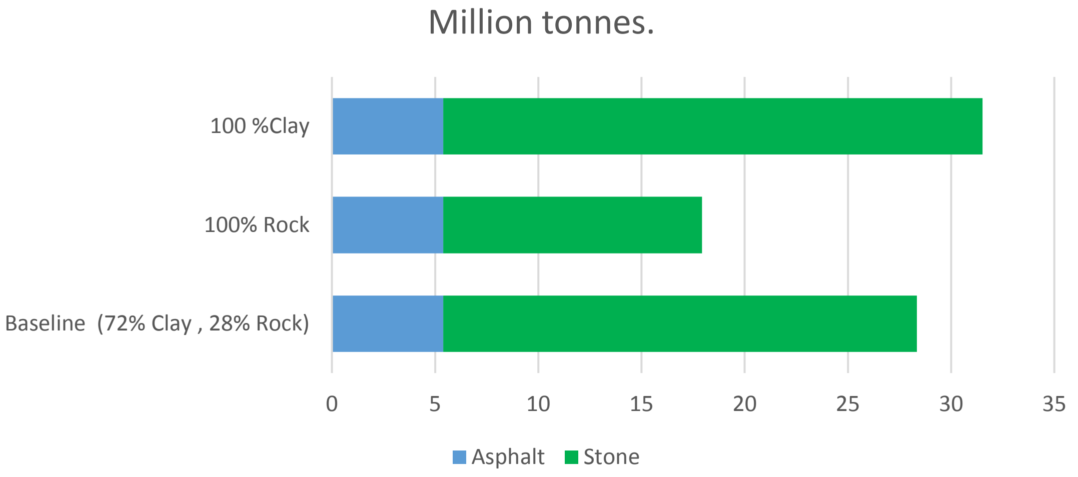

Figure 8.6 Sensitivity analysis in the stock of the roads of Stockholm regarding the materials on which they were built.

8.4 Limitations

Three potentials sources of limitations are present in this study. First, the information by construction year of each infrastructure was not available. Second, the amount of materials added in the maintenance phase was not included. Third, demolition rates were neglected as well. These type of constraints hinder temporal analysis of the accumulated stocks, furthermore, the forecasts of resource use peaks and infrastructures peaks such as those conducted by Shi and colleagues (2012) could not be performed.

8.5 The future of material stock research

In spite of the several existing methods to calculate the material stock of cities, the methods are strongly dependent on the statistical information provided by local authorities. The challenge then, is to create awareness among policy makers in order to create reliable statistical data. Moreover, local authorities need to understand that the first step towards a sustainable city is to determine the amount of materials that are being extracted and transformed into end-use stocks which will fulfill their life span and therefore will become in future waste flows.

9 Conclusions

In this study, due to the significant environmental impact in the extraction of raw materials and their transformation into end-use stocks, five types of materials stocked in six major infrastructures for four cities in Sweden and Mexico have been estimated. The results were showed by material and infrastructure type per square kilometer and per inhabitant by infrastructure type. In contrast to other studies, a bottom-up method integrated with Geographical Information Systems (GIS) from OpenStreetMap ArcMap extension tool (2016) was used to calculate the total material stock. On the other hand, the inclusion of OpenStreetMap ArcMap extension tool, served as a viable option to obtain the inventories of the different types of the infrastructures in urban areas. Then, several sensitivity analysis were made to interpret the contribution of the different variables in the total final stock.

The major findings obtained in this study are as follows:

1. The material stock methodology used in this study can be applied for other cities.
2. Data quality and availability in Mexican cities is not as good as in Swedish cities.
3. Mexico City is the city with the largest share of materials extracted and transformed with 215 million tonnes and therefore the city with the largest share of materials hibernating and likely to become the future waste. Mexico City is followed by Gothenburg (71.6 million tonnes), Puebla (54.6 million tonnes), Monterrey (52.4 million tonnes), Guadalajara (48.5 million tonnes), Stockholm (36.2 million tonnes), Malmo (30.2 million tonnes) and Lund (7.94 million tonnes).
4. The largest share of materials is stocked in roads in all the cities of both countries. On average, the roads in Mexican cities represent the 85.4 % of the total end-use stock followed by footways (10.6%), tramlines (2.2%), parking lots (1.4%) and rail lines (0.4%), while in Sweden roads are 77.3% of the system, followed by rail lines (10%), parking lots (8.8%), tramlines (2.2%), footways (0.9%) and cycle ways (0.8%).
5. The stone is the material with the largest stock contained within the infrastructure of all cities in both countries, while asphalt, concrete, steel and polymer account for smaller parts in the stocks of the cities.
6. In Mexican cities, the roads are over-dimensioned by considering high axle loads and unstable subgrade soils in their design causing an inefficient use in the transformation of the materials.
7. In Sweden, Lund has the largest share of material stock per square kilometer (0.31 million tonnes), followed by Stockholm (0.19 million tonnes), Malmo (0.19 million tonnes) and Gothenburg (0.16 million tonnes), while for Mexico, Guadalajara has the largest share per square kilometer (0.32 million tonnes), followed by Monterrey (0.16 million tonnes), Mexico City (0.14 million tonnes) and Puebla (0.10 million tonnes). The highest stock per square kilometer is in roads in all the cities for both countries, while for the other infrastructures variation among cities could be observed.
8. The variation in the cross sectional variable, which is strongly dependent in the subgrade soil, represented the largest impact on the accumulation in the material stock, even over the width and length of the structures.

Finally, in order to move towards a resource-efficiency society, major efforts should be carried out in the maintenance of all the end-use stocks to prevent large amount of new inputs and waste flows. In addition, since raw materials are limited, the present stocks should be seen as secondary resource after they have fulfilled their service lifetime.

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