Planning Urban Mobility within the UN Sustainable Development Goal Framework

Jenny María Chaverri Jiménez

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By: **Jenny María Chaverri Jiménez**
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Signed by the Final Examining Committee:

Dr. Andrea Schiffauerova, Chair

Dr. Ursula Eicker, Supervisor

Dr. Ketra Schmitt, Supervisor

Dr. Ciprian Alecsandru, Examiner

Dr. Fuzhan Nasiri, Examiner

Dr. Carmela Cucuzzella, Examiner

Dr. Gordon Lovegrove, External Examiner

Approved by

Dr. Mazdak Nik-Bakht, Graduate Program Director
Department of Building, Civil, and Environmental Engineering

May 11th, 2023

Mourad Debbabi, Dean
Gina Cody School of Engineering and Computer Science

ABSTRACT

Planning Urban Mobility within the UN Sustainable Development Goal Framework

Jenny Chaverri, Ph.D.

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Sustainable development is about raising human well-being and protecting the environment. In the context of urban sustainability, cities have prioritized cars leading to negative impacts on society and the environment. Some scholars are concerned that planners do not incorporate equity in the state of the practice. Individuals facing social exclusion are more vulnerable to low air quality, traffic collisions, and noise. Moreover, stronger mitigation measures are needed since the transport sector is the second largest contributor to emissions.

A conceptual investment framework was designed to interconnect the Sustainable Development Goals (SDGs) for planning and designing sustainable urban mobility under five strategic areas: social justice, health, climate change, economic development, and governance. Policies, modeling tools, and methodologies were reviewed to construct this framework under a systems approach.

To analyze the 2050 net-zero policy of changing the vehicle fleet from Internal Combustion Engines (ICE) to Electric Vehicles (EVs), a bottom-up regional average speed emission model relying on a four-step travel demand was developed. Four scenarios were explored: business as usual (BAU), low, moderate, and aggressive to evaluate the potential reduction of carbon dioxide (CO_2) emissions, Nitrogen Oxides (NOx), and Particulate Matter PM2.5. The emission model included vehicle speed and weight, fuel type, and vehicle emission standards. In the case study of Costa Rica, it was found that attaining zero CO_2 emissions by 2050 requires shifting to EVs at least 25% and 50% by 2030 and 2040, respectively. For ICE vehicles, changing the minimum vehicle emission standards from EURO 1 to EURO IV and EURO VI positively impacted the reduction of NOx and PM2.5 despite the growth of traffic volumes.

This research explored the barriers women face to having equal opportunities and differentiating urban mobility needs and patterns. A vertical equity transport planning approach that is pro-poor, gender-sensitive, and considers intermediary social health determinants is developed. This research is the first approach to incorporate the most at-risk demographics (material deprivation, disabilities, and single mothers' car ownership) and their exposure to NOx and PM2.5 in identifying high-priority areas.

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DEDICATION

“Earth”

“Tierra” by Danit

“Mountain, valley, forest, and sea. Flora and fauna, endless landscape

Stone cave, water lagoon. Seed, root, stem, and flower

How can it be that humans do not respect the Law of Life? Which is what sustains us

Honor the Earth, pray to the Sky. Love your siblings, lift the weight

Earth, the most beautiful of all. They want to sell your pretty body

Forgive them because they don't know that they are looking for power instead of love

Faith and strength. We lift our love to life

To the Earth, to the Sun and to the Moon, together to the Stars”

Excerpt from Medicine Song “Tierra” by Danit (Original in Spanish)

This dissertation is dedicated to Mother Earth (Pachamama), to the indigenous peoples as the guardians of Mother Earth and life, and to all the protectors of the environment and human rights

To my beloved cats Magic & Merlin, who passed away during my Ph.D. studies
To my soul brothers and sisters that were by my side during these challenging years
Thank you for your love, healing, and support

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Many blessings and love to all of you
“Only love is real”
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CONTRIBUTION OF AUTHORS

Miguel Del Pino collaborated with a literature review for the gender equality indexes. This led to a publication of a conference paper: Chaverri J., Del Pino M., Schmitt K., Eicker U. (2020). "A framework for gender equality for localizing the SDGs: A first approach from policy to implementation". 8th Annual International Conference on Sustainable Development (ICSD). New York, U.S.A.

Reza Ghobadpour collaborated on integrating and organizing the datasets for the Traffic Analysis Zones (TAZ) and connect the road system with TAZ.

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LIST OF ABBREVIATIONS

A	Activity system
AADT	Annual Average Daily Traffic
AADB	Annual Average Daily Bicycle
AADP	Annual Average Daily Pedestrian
ABM	Agent-based Models
AIC	Akaike Information Criterion
ASI	Avoid-Shift-Improve
BC	Black Carbon
BRT	Bus Rapid Transit
BAU	Business-As-Usual
CO_2	Carbon dioxide
CO	Carbon monoxide
CH4	Methane
CBA	Cost-Benefit Analyses
CBD	Central Business District
COPERT	Computer Programme to calculate Emissions from Road Transport
DOT	Department of Transportation
DUE	Deterministic User Equilibrium Assignment
EMISIA	European Environment Agency
EVs	Electric Vehicles
F	Flow patterns
GHG	Greenhouse gas emissions
GN	Grip Number
GDP	Gross Domestic Product
GVW	Gross Vehicle Weight
GII	Gender inequality index
GDI	Gender Development Index
GEI	Gender Equality Index
HDM-4	Highway Development and Management Model
HBW	Home-Based Work
HBS	Home-Based Study
HBO	Home-Based Others
HH-size	Household size
HC	Hydrocarbons
ICE	Internal Combustion Engine
IPCC	Inter-Governmental Panel on Climate Change
IRI	International Roughness Index
INAMU	Instituto Nacional de la Mujer (National Institute for Women)
LGBTQ	Lesbian, gay, bisexual, transgender and queer people
LCCA	Life-cycle cost analyses
LRT	Likelihood Ratio Test

MD	Model deviation
NDCs	Nationally Determined Contributions
NB	Negative Binomial
NO_2	Nitrogen Dioxide
NOx	Nitrogen oxides
NMVOCs	Non-methane volatile organic compounds
Number-Cars-HH	Number of cars per household
OD	Origin-Destination
OECD	Organization for Economic Cooperation and Development
PM2.5	Particulate Matter 2.5 μm
PM10	Particulate Matter 10 μm
PKM	Passenger Kilometer Traveled
PM	Performance measure
RMSE	Root Mean Square Error
R^2	Coefficient of determination
RMADEPM	Ratio material deprivation for men
RMADEPF	Ratio material deprivation for women
RDISABM	Ratio disability for men
RDISABF	Ratio disability for women
R2PARENTS-NOCAR	Ratio households with two-parents as head of family without automobile
RSMOM-NOCAR	Ratio households with single mothers as head of family without automobile
RSDAD-NOCAR	Ratio households with single fathers as head of family without automobile
SDGs	Sustainable Development Goals
SFC	Sideways force coefficient number
SUE	Stochastic User Equilibrium
Students-HH	Students per household
SO_2	Sulphur Dioxides
SOx	Sulfur Oxides
SO	System Optimum Assignment
T	Transport system
TAZ	Traffic Analysis Zones
TOD	Transit Oriented Development
Pi	Trip productions
Aj	Trip attractions
TKM	Tonne kilometers
THC	Total Hydrocarbon
VKT	Vehicle Kilometer Traveled
VMT	Vehicle Mile Traveled
VOC	Volatile Organic Carbon
UE	User Equilibrium Assignment

UN	United Nations
UNDESA	UN Department of Economics and Social Affairs
UNEP	UN Environment Programme
UN-Habitat	United Nations Human Settlements Programme
UN SDSN	UN Sustainable Development Solutions Network
UN ECLAC	United Nations Economic Commission for Latin America and the Caribbean
WHO	World Health Organization
Workers-HH	Workers per household

CHAPTER 1

Introduction

In 2015, United Nations Member States adopted the Sustainable Development Agenda. The SDGs embody four dimensions: human development and social inclusion, environmental protection, economic growth and prosperity, and good governance (Sachs, 2015). An SDG Index monitors progress, and it shows that the wealthiest countries present challenges in social inequalities and climate change while developing countries struggle with poverty, infrastructure, and environmental degradation (Schmidt-Traub et al., 2017). Cities account for 55% of the world's population, and by 2050 they will grow to 70% (UN Habitat, 2017). Transport and urban planners, researchers, city managers, and politicians have the moral responsibility to foster equity, combat climate change, and safeguard the transparency of public funds.

Lack of integration across sectors is an obstacle to attaining sustainable development in cities and their complex ecosystem (UNDESA, 2015). Planning and design require a cross-discipline approach supported by modeling tools to assist investment decisions and trade-off analyses while aligning programs, budgets, and stakeholders with the SDGs. Institutional fragmentation and the disconnection between transport and the built environment often limit solving for urban poverty traps, inequalities, urban sprawl, transport-related emissions and pollutants, and negative externalities related to health.

1.1 Policy Context for Sustainable Development and Cities

The increase in population in cities will demand affordable housing, efficient transport systems, and infrastructure. Currently, cities account for more than 80% of the Gross Domestic Product (GDP) and more than 70% of greenhouse gas emissions (GHG) (World Bank, 2020). Transport networks are the backbone of a city, and the built environment develops around them. Until recent years, a change of paradigm aims to shift from having motorization at the center of urban mobility to sustainable transport systems that prioritize the movement of people. Thus, shifting the traditional development frameworks.

The traditional approach for development has been based on economic growth and its metric Gross Domestic Product (GDP). It has been found that while income is one of the aspects of life satisfaction, it is only one of the components to achieve well-being. An alternative approach is sustainable development, which is not about raising income but about raising human well-being. This concept embodies four dimensions: (1) human development and social inclusion; (2) protection of environment; (3) economic growth and prosperity; (4) good governance, where governance involves good management of governments and private stakeholders (Sachs, 2015).

Development is sustainable when economic growth meets social needs without compromising the resources of future generations. It is emphasized that human development is at the center of development. Even though economic growth has the potential to reduce poverty and social problems, evidence has shown that this is not always the case. Economic growth can also create greater inequity, higher unemployment, weakened democracy, and overconsumption of resources. Slow human development can put an end to fast economic growth, and this growth pattern is labeled as a “dead end”. Some economists tend to agree that this growth is unsustainable (Soubbotina & Sheram, 2000).

The 2030 Agenda offers a holistic approach as to how society should be (Sachs, 2015). It places people and the environment at the center, where people should live with dignity and equality while protecting the planet through sustainable management of resources. In addition, attaining prosperity must ensure the preservation of the environment without compromising present and future generations (UNDESA, 2015). This agenda is based on 17 Sustainable Development Goals with 169 associated targets. These goals and targets are interlinked, shaping complex systems . In addition, the New Urban Agenda Habitat III (Habitat III, n.d.) and the Paris Climate Change Agreement (United Nations, 2016) provide new policies to change the business-as-usual.

The SDG Index is a composite index indicator with 56 metrics created to monitor progress on the Sustainable Development Goals (SDGs). It was created by Bertelsmann Stiftung and the UN Sustainable Development Solutions Network (SDSN) and presented at the United Nations High-level Political Forum on Sustainable Development in 2016, reporting results for 149 countries and European and American cities. This index identifies priorities, gaps and monitors progress for the 2030 Agenda (Sachs et al., 2016).

The Global North and Global South countries differentiate by their relative wealth and power, socio-economic and political traits. Global North countries are often industrialized nations of high income, such as the United States, Canada, most European countries, Australia, New Zealand, Singapore, Japan, and South Korea. The Global South depends more on primary exports and is developing. Some examples of the Global South include Latin America, Africa, China, developing countries in Asia, and Oceania (Cambridge, 2023) (Oxford, 2023) (Braff & Nelson, 2021).

The SDG Index has demonstrated that no Global North and Global South country has achieved the 2030 Agenda. Wealthiest countries present challenges in social inequalities, climate change, and biodiversity, while poor countries need to end extreme poverty, promote social inclusion, ensure access to essential infrastructure, tackle environmental degradation, and halt biodiversity loss (Schmidt-Traub et al., 2017). After COVID-19, a setback on the SDG Index showed a big toll on health and inequalities (Sachs et al., 2021; Sachs et al., 2020).

1.2 Sustainable Urban Mobility

Transport plays a crucial role in human development and economic growth. Worldwide we are facing challenges related to poverty reduction, social inclusiveness, and climate change. Urbanization is on the rise, and by 2050 the world population will increase by two billion people, most of whom will settle in urban areas (Habitat III, n.d.). Consequently, there will be an ever-increasing demand for mobility. At the same time, it has been recognized that the transport sector is one of the main contributors to greenhouse gas emissions. Under the current patterns of motorization and energy use, the transport sector will become the primary consumer of oil by 2030 (Kopp et al., 2013).

Transport is defined as the movement of people and goods. A city's competitiveness depends on the efficiency of moving people to jobs and services and delivering retail to run local economies. Transport planning and design shape cities, and poor designs can condition choices and travel behavior, limiting human and economic development. Highly congested cities harm city development. Adopting the SDGs in city planning can shift visions, policies, strategies, and investments towards equity, social inclusion, environment and health, and better allocation of resources for good governance.

1.3 Problem Statements

a) Implementing the SDGs in urban mobility faces a barrier of the need for more integration across sectors, which is an obstacle to attaining sustainable development in cities and their complex ecosystem. Planning and design require a cross-discipline approach supported by modeling tools to assist investment decisions and trade-off analyses while aligning programs, budgets, and stakeholders. Institutional fragmentation and the disconnection between transport and the built environment often limit solving for urban poverty traps, inequalities, urban sprawl, reduction of GHG emissions, and transport externalities related to health.

b) National decarbonization plans and monitoring strategies often rely on top-down emission models based on fuel consumption. However, a top-down approach is limited to forecasting and evaluating policy instruments such as shifting the Internal Combustion Engine vehicle fleet to Electric Vehicles (EVs). Bottom-up emission models that rely on travel demand models can forecast the movement of vehicles and disaggregate emissions per road segment. Relying on the consumer choice to attain net-zero emissions through the shift to EVs without implementing other climate policies such as transit, walking, and cycling must be evaluated proactively by setting long-term emission scenarios.

c) No country in the world has achieved gender equality. Key findings for the Global North and South are that transport planning and design must give more attention to transport poverty, gender equality, and multiple identities and their context in power relations. Integrating a gender-sensitive approach and negative environmental externalities in transport planning can redirect priorities toward inclusive cities promoting well-being.

1.4 Research Questions

a) How can the social, environmental, economic, and governance dimensions and the SDGs be integrated into planning and designing cities for the movement of people through the lens of sustainable development?

b) Can the 2050 climate change net-zero target be met by heavily relying on consumer choice in shifting vehicle technology to Electric Vehicles?

c) What is the relationship between gender equality and sustainable cities, and how can transport improvements be identified, given the relationship between social disadvantage groups and air pollution?

1.5 Research Objectives

a) Design a conceptual cross-discipline modeling framework for sustainable urban mobility that incorporates the SDGs in city planning for the urban movement of people.

b) Develop a bottom-up regional emission model supported by a macroscopic travel demand model to forecast traffic up to the year 2050 to analyze the Electric Vehicle penetration. The emission model will depend on vehicle speed, Gross Vehicle Weight, fuel type, and vehicle emission standards per road classification.

c) Develop a geospatial vertical equity planning approach to integrate gender-sensitive urban mobility and health dimensions for air quality into transport planning in a metropolitan city.

1.6 Overview and scope of research

The design of a conceptual cross-discipline modeling framework for sustainable urban mobility incorporates the SDGs and the SDG Index in disaggregated form. It classifies the SDGs into five strategic areas: social justice, health, climate change, economic development, and governance, and interconnects them. The objective is to provide a holistic view of how planning sustainable urban mobility should be. Proof of concept modeling to support the implementation of this proposed framework is required. Based on this framework, two case studies are developed for the environmental, social and health dimensions.

The geographical area of the case studies developed in this research is the metropolitan city of San José, Costa Rica. The metropolitan area of San José is 507.82 Km^2, and the total population is 1,517,537 for the year 2022. The population density of 2,988 persons per Km^2. In the year 2022, Costa Rica ranked 47 of 163 in the SDG Index with a score of 73.76 of 100 (SDSN, n.d.). According to the World Bank, the GDP per capita is USD$12,141 (World Bank, n.d.-b). There are scarce investments in sustainable transport, and most transport investments are allocated to favor the movement of cars.

The first case study develops a bottom-up regional emission model for the period 2022-2050. Four scenarios were explored: business as usual (BAU), low, moderate, and aggressive to evaluate the potential reduction of carbon dioxide (CO_2) emissions, Nitrogen Oxides (NOx), and Particulate Matter (PM2.5). The emission model included vehicle speed and weight, fuel type, and vehicle emission standards.

A macroscopic demand model was used to estimate traffic volumes; these volumes are used to estimate emissions. Travel demand models can be estimated based on vehicles or the movement of persons. The vehicle-based approach estimates the demand based on the vehicle fleet. The person-based approach requires the incorporation of transit and passenger demand. Given a lack of access to passenger data and transit systems, this travel demand model will use a vehicle-based approach.

The second case study develops a geospatial vertical equity planning approach to integrate gender-sensitive urban mobility and health dimensions for air quality. A geospatial equity analysis is performed by targeting disadvantaged population groups considering material deprivation, disabilities, and single mothers that do not own a car. Women face more barriers to equal opportunities for development than men and barriers in urban mobility (Madariaga & Neuman, 2020; (Knoll & Schwaninger, 2020) (Loukaitou-Sideris, 2016). Thus, statistical gender analysis of the population is performed to evaluate social disparities based on gender.

A vertical equity (social and environmental justice) approach was used to prioritize social disadvantage groups and air pollution exposure in San Jose for transport investments. For these groups, improving urban mobility and reducing air pollution compensate the disadvantage of households having the burden of low income plus the risk of developing illnesses associated to long-term exposure due to air pollution that is produced by their neighborhood. The methods used in this case study were geospatial and statistical analyses. Further research should incorporate accessibility and affordability analyses. Data availability limited the development of implementing further methods.

1.7 Expected Contributions

The cross-discipline modeling framework for sustainable urban mobility proposed in this research in Chapter 2 provides key elements and methods for researchers and transport planners to incorporate the SDGs in urban mobility. The Sustainable Development Solutions Network (SDSN) for the United Nations measures the SDGs through the SDG Index for countries and cities (SDSN, n.d.). The proposed framework provides a comprehensive approach for cities to advance on Agenda-2030. The Global North and Global South have different challenges.

In climate change, 75 percent of global GHG transport-related emissions are produced by the G20 members (UNEP, 2022). These countries have more resources than developing countries to invest in infrastructure to attain tangible climate targets. While the Global North countries have higher incomes, social inequalities have become challenging. These structural inequalities have become more visible with the COVID-19 pandemic (SDSN, n.d.) (McFarlane, 2020).

In the Global South, poverty is more visible, and transport projects conducted by developing Banks focus much on alleviating poverty and providing accessibility to the most disadvantaged (Peralta-Quirós & Mehndiratta, 2015). The Global South faces financing challenges and limitations of urban data for planning and designing transport projects. Countries such as Brazil and India produce high GHG emissions (UNEP, 2022) (World Bank, n.d.-a).; overall, air pollution is a topic of concern (IQAir, 2020). Road safety in developing countries performs poorly, with vulnerable road users having the most injuries and deaths (UN WHO, 2021a) (WHO, 2018).

The Global North and Global South face challenges in transport and implementation of the SDGs. Attaining sustainable development in cities is challenging due to the need for integration across sectors. Thus, the current review presented in Chapter 2 aims to understand the interconnectedness among the SDGs, transport, and the built environment in cities. A conceptual urban performance management system is proposed, and it is recommended to create an Urban Data Observatory for integrating sectors, improving decision-making, and monitoring the progress of the SDGs. Integration of sectors and disciplines is key to breaking down silos in government administration and academia.

The regional emission model developed in Chapter 3 aims to solve a practical problem. Top-down emission models based on fuel consumption are commonly used due to the accessibility to fuel consumption inventories, which allow monitoring of annual emissions. There are limitations to the top-down approach, such as the inability to forecast scenarios and incorporate specific climate mitigation actions.

On the other hand, bottom-up emission models are less common due to their complexity. Bottom-up emission models are disaggregated and presented in a spatial distribution. Emission models that rely on travel demand models allow for incorporating climate mitigation actions, identifying priorities, and evaluating climate policy instruments. Chapter 3 solves this practical problem and recommends a framework for a regional emission model supported by a case study through the lens of maturity levels that aims for process improvement and systems performance management, where policies and projects align with strategic goals and objectives.

Chapter 4 presents a case study, "Linking gender equality and transport planning for healthier cities." Some scholars in urban planning argue that "transport poverty" has not been given the proper attention by transport engineers and planners nor included in academia, policymaking, or infrastructure design (Lucas et al., 2016). Other scholars are concerned that transit projects need to consider equity, while in practice, the strategic goals focus mainly on promoting land developments (Linovski et al., 2018). This case study aims to address ¨transport poverty¨, gendered social disparities, and identify transport infrastructure priorities to improve urban mobility and health.

A case study in transport planning uses a gender-sensitive approach and incorporates air pollution. This research targets disadvantaged population groups to prioritize urban mobility in regions with the most vulnerable population. This research comprehensively analyzes the barriers women face to having equal opportunities to men, highlighting the difference in urban mobility patterns and needs between women and men. Thus, it aims to contribute to changing the business-as-usual in transport planning and incorporates a cross-discipline analysis by integrating gender equality and health. Planning cities using a vertical equity approach creates fair resource distribution, favoring socially disadvantaged groups to compensate for social inequalities.

CHAPTER 2

Planning and Design of Urban Mobility through the Lens of Sustainable Development: Review and Research Directions

Abstract

To implement the sustainable development goals (SDGs) in city planning and design for the mobility of people, a conceptual investment framework was designed to interconnect the SDGs under five strategic areas: social justice, health, climate change, economic development, and governance. Policies, modeling tools, and methodologies were reviewed to construct this framework under a systems approach. An Urban Data Observatory and the design of urban performance measures are recommended.

This review identifies critical design factors, modeling approaches, gaps, and research opportunities. Key findings for the Global North and South are that transport planning and design must give more attention to transport poverty, gender equality, and multiple identities and their context in power relations. More efforts are needed to mitigate traffic emissions to cope with climate change and health impacts on the population. Health social determinants and health outcomes are correlated. COVID-19 has brought into light structural social problems, in this case, how overcrowded housing conditions and social inequalities contribute to the rapid transmission of the disease.

Alignment of national and local governments is necessary to integrate transport and land use for climate change strategies, while policymakers should promote socially mixed compact housing developments around transit stations. Financial decisions for rapid transit should not rely only on land development or fostering wealth but on integrating equity, health, climate change, and local economies for all. More research is needed to quantify benefits based on the SDGs in economic analyses to support the decision-making of investments.

2.1 Sustainable development and urban mobility

Cities face challenges in urban mobility, rising car ownership, and congestion worldwide. In many cities, to overcome traffic gridlocks, the traditional solution has been to expand the infrastructure to accommodate cars. This approach is not sustainable and creates negative externalities for society and the environment. A limited number of cities have prioritized sustainable transport and concentrated on public transport, walking, and cycling.

Sustainable development embodies four dimensions: (1) human development and social inclusion; (2) protection of the environment; (3) economic growth and prosperity; (4) good governance. The Sustainable Development Goals (SDGs) offer a holistic approach ¨to how society should be¨ (J. D. Sachs, 2015). It places people and the environment at the center. Most cities have prioritized automobiles in their planning and design, leading to negative impacts on society and the environment, such as social exclusion, transport poverty, traffic collisions, air pollution, and noise (Lucas et al., 2016) (UN Habitat, 2013). Lack of integration across sectors is an obstacle to attaining sustainable development in cities and it is a barrier to implementing the SDGs (UNDESA, 2015).

This review aims to understand the relationship between sustainable development and urban mobility, embodying the sustainable development dimensions: social, environmental, economic growth, and good governance. The SDG Index measures progress in implementing Sustainable Development Goals (SDG) in cities (SDSN, n.d.) (Schmidt-Traub et al., 2017). The index is disaggregated and classified under the social and environmental dimensions to understand the key factors and metrics measured in cities. Modeling approaches are reviewed and associated with the SDG Index.

A conceptual sustainable urban performance-based management framework is proposed to support investment decisions and monitor and evaluate the performance of the transport systems and built environment. This framework aims to integrate the sustainable development dimensions. Future research requires proof of concept modeling under a cross-discipline approach.

2.2 Equity and Social Inclusion

Poverty is not limited to income but encompasses multiple dimensions (Alkire & Jahan, 2018). Furthermore, inequality is characterized by social exclusion. In the context of poverty, households are not just poor, but they cannot connect to jobs and services (Church et al., 2000).

Social exclusion is defined as the inability to participate in society, given a lack of access to opportunities (Preston & Rajé, 2007; Stanley & Lucas, 2008). Social exclusion can impact all socio-economic classes. Often, low-income groups suffer the most from social exclusion. However, a high-income individual with a disability can also experience it in the absence of Universal Design in transport facilities, or women can have mobility limitations due to unsafe public spaces (Church et al., 2000).

Seven contributing factors in the transport system have been classified as social exclusion (Lucas, 2012; Church et al., 2000):

I. Physical exclusion: physical barriers - inability to access transport systems due to physical and psychological difficulties, including age, impair mobility, language, and learning difficulties
II. Geographical exclusion: isolation of communities – lack of access to transport services
III. Exclusion from facilities: distance to access facilities due to time and income constraints - such as employment, education, health, shopping, sporting, leisure, and cultural activities
IV. Economic exclusion: cost of travel and distance to labor market
V. Time-based exclusion: time available for travel - balancing responsibilities between work and household
VI. Fear-based exclusion: Fear for personal safety at transport systems and public spaces
VII. Space exclusion: management of spaces, segregated spaces prevent access to specific public spaces (i.e., gated communities)

These barriers impact social-spatial inequities. In the absence of sufficient transit provision, it can also lead to transport-induced poverty. A city designed as car dependant can penalize low-income individuals. They can face trade-offs between car ownership, shelter security, and travel distance (UN Habitat, 2014), leading to "transport poverty". Where "Transport poverty" is experienced by people rather than households, and it is differentiated by gender (Lucas et al., 2016).

"Transport poverty" addresses the negative economic impact an individual experience given the transport system. It is classified in four dimensions (Lucas et al., 2016):

(1) Transport affordability is in the Global North, forcing car-ownership for more than travel costs can be afforded, or in the Global South where people cannot afford bus fares.
(2) Mobility poverty refers to the significant infrastructure investments that do not address the needs of the poorest. It is a correlation between low-income populations and lack of transport provision of services. Consequently, it generates or increases poverty by limiting people their mobility or isolate communities.
(3) Accessibility poverty refers to people accessing their key activities such as employment and services at a reasonable time, ease, and cost.
(4) Transport externalities or environmental justice is where people's health and lives are compromised due to road traffic casualties and chronic diseases generated by traffic pollution and noise.

In the Global North, low-income households are pushed to a "forced car ownership" behavior, where the households have no choice but to own a car, given the inadequate or non-existent transport alternatives to cope with the demands of life such as accessing employment. "Forced car ownership" implies transport costs for the investment of a car, insurance, and maintenance costs that will be a trade-off of other basic needs leading to transport poverty and affordability (Lucas et al., 2016; Currie et al., 2009). In the Global South, in the absence of public transport alternatives or inadequate service, informal transport can emerge, which will create informal employment, congestion, and safety issues. Thus, weakening ridership of public transport (Jönson & Tengström, 2005).

Some characteristics of urban sprawl are the urbanization of low-density, dispersed, and car-dependency. It separates people by race, ethnicity, and income. It results from poorly planned cities that reinforce motorized transport over long distances (UN Habitat, 2014), and contributes to spatial mismatches, which is the geographical mismatch where low-income households live in relation to where the formal jobs with livable wages are. In the United States, the poor live just outside the urban core, and jobs are on the periphery. In developing countries, most of the poor live in remote areas isolated from job opportunities. The spatial mismatch is even more pronounced on the Global South (Cervero, 2013). This leads to geographical exclusion (Church et al., 2000).

Urban sprawl is a consequence of the disconnection between transport and land use. Zhao (2013) argues that urban sprawl leads to social segregation. Thus, policymaking is needed to control urban sprawl supported by spatial planning to reduce segregation. In Europe and the USA, social segregation is characterized by race. In China, being a monoracial country, segregation is defined by rich and poor and the local and migrants.

2.2.1 Gender equality

No country in the world has achieved gender equality (Sachs et al., 2021). The first step to combat inequality is understanding the barriers. Based on the literature, Chaverri et al. (2020) classified six dimensions of gender equality where women experience barriers and exclusion: Workforce, Economics, Education, Health & Sexual Reproductive Rights, Empowerment, and Time (Forsberg & Stenbacka, 2018) (European Institute for Gender Equality, n.d.). Transport and the built environment significantly impact employment and economic well-being by facilitating access to employment (Guzman & Oviedo, 2018) (UN Habitat, 2013). Economic independence is an essential factor for women to have different choices (UN Women, 2015).

On a regional scale, congested cities and lack of transport supply can induce excessive travel times. In London-UK, there is evidence where job seekers express that they are willing to travel long travel times, but data from work journeys contradicts this statement, and work journeys are in shorter periods (Church et al., 2000). However, Gendered Travel Patterns show significant differences between men and women for travel distances and single versus multiple destinations, where women travel shorter distances to multiple trip chains given children and chores (Madariaga & Neuman, 2020) (Knoll & Schwaninger, 2020).

Research has consistently found transport as a barrier to employment (Blumenberg & Hess, 2003). Single mother's transport is a second barrier only to childcare as an obstacle for employment. Also, employment opportunities are affected by travel time and access to travel modes. In groups on welfare, jobs cannot be sustained in long-travel times (Blumenberg & Manville, 2004). Short travel times are more critical for lone parents that need to balance work, childcare, and home responsibilities.

On a neighborhood scale, women and girls can experience fear-based exclusion (Lucas, 2012; Church et al., 2000). The built environment and the quality of walkability can influence crime or perception of crime. In public spaces and transit systems, women can experience sexual harassment and sexual violence (Gonzalez et al., 2020). New metrics are necessary to assess mobility inequalities and incorporate Safety Audits and Gender Impact Assessments (Madariaga & Neuman, 2020).

2.2.2 Frameworks and modeling approaches for the social dimension

Accessibility analyses assess the ability of households or individuals to reach opportunities (i.e., jobs, services, social participation). Accessibility to opportunities integrates transport systems and land-use to reach destinations (Geurs & Van Wee, 2004). Accessibility should not be confused with mobility, where mobility refers to the physical ease of movement. Mobility attributes are travel distance, capacity, and speed. Mobility is the means to the end: accessibility to reach opportunities (Ducas, 2011). Accessibility to opportunities integrates four components: (1) Transport: travel time and cost; (2) Land-use: locations and opportunities; (3) Temporal: opening hours, services; (4) Individual (i.e., income, gender, car ownership) (Geurs & Van Wee, 2004).

Despite of the advantages that accessibility analyses can bring, Levy (2013) challenges planners to incorporate the social condition of individuals, given that they fail to address the multiple identities of men and women for gender, social class, ethnicity, religion, sexual orientation, age and physical/mental conditions, and their context in power relations. Thus, leading to socially constructed inequalities.

Social-spatial analyses can comprehensively address housing, neighborhoods and safety, poverty, social exclusion, gender equality. In addition, there are also “Leave no one behind indicators” used by the Sustainable Development Solutions Network United States (SDSN USA) that incorporate aspects such as population living below the poverty line, childhood poverty, working poor, Native American employment gap, racial segregation, and overcrowded housing (Lynch et al., 2019).

Understanding urban spatial inequalities can provide informed decisions to prioritize public investments to close inequality gaps. In this case, a vertical equity planning approach targets disadvantaged and marginalized populations. It establishes fairness in the distribution of resources favoring socially disadvantaged groups to compensate for social inequalities and negative transport externalities. A vertical approach differentiates from a horizontal approach; in the latest, equity refers to equal treatment of people and should not be favored by one particular group over another (Banister, 2018) (Litman, 2018).

Transport affordability analyses focus on transit fares, target population, and socioeconomic analyses to identify fare accessibility of vulnerable and marginalized populations. Affordability analyses can lead to defining or evaluating fare subsides to vulnerable groups (Guzman & Oviedo, 2018). Accessibility analyses per transport mode are also helpful in determining the accessibility to opportunities by automobile or transit (Peralta-Quirós & Mehndiratta, 2015). A city designed to depend on cars, will cause “force car ownership”, which means that people must buy a car to be able to access employment and services.

SDG target 11.2 defines that “by 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons” (UNDESA, 2015). Table 2.1 summarizes the main approaches used in modeling and their primary relationship with the SDG Index.

Table 2. 1 shows frameworks and modeling techniques for the urban social dimension and their relationship to the SDG Index and transport. The SDG Index reflects priority areas for development, and this table shows 20 out of 56 metrics that contribute to the SDG Index. Measuring the SDG Index in a city allows us to identify gaps that must be addressed to attain the 2030 Agenda. Modeling techniques have been classified in three groups: (1) accessibility to opportunities; (2) social spatial analyses to conduct transport equity assessments; and (3) affordability analyses.

Table 2. 1 Frameworks and modeling techniques for the urban social dimension and the SDG Index

APPROACH	METHODS: Planning and Design of Cities	SDG Index Cities (*)	SOURCE
ACCESIBILITY Transport and land-use	Isochrone accessibility: travel time, distance, or cost per transport mode Gravity-based: impedance function (time or cost) Utility-based: discrete choice analysis (logit model) Person-based: temporal and individual components	sdg5_emplogap sdg8_ltunemp sdg4_earlyleav sdg4_secondary sdg4_neet sdg4_earlyedu	(Sachs et al., 2016) (Lafortune et al., 2019) (Jeihani & Ardeshiri, 2017) (Ducas, 2011) (Geurs & Van Wee, 2004)
TRANSPORT EQUITY Social Spatial Analyses	Urban sprawl and social segregation analyses Vertical equity (across populations: disadvantaged and marginalized people are targeted) Horizontal equity (within populations: equal distribution of resources, except for subsidies) Spatial equity (between areas) Social equity (differential needs) Income equity (income groups) Economic metrics: Gini coefficient, pseudo-Palma ratio, Atkinson index, Theil index, etc. Global Multidimensional Poverty Index (MPI) Transport disadvantage (absence of provision of basic services or low transit frequency)	sdg1_depriv sdg1_povrisk sdg5_wgap sdg5_emplogap sdg8_ltunemp sdg9_intcon sdg10_gini sdg11_sathous sdg11_rburden sdg16_burglary sdg16_rob sdg16_homicide sdg16_safety	(Sachs et al., 2016) (Lafortune et al., 2019) (Geurs, 2020) (Litman, 2018) (Van Ham et al., 2021) (Guzman & Oviedo, 2018) (Alkire & Jahan, 2018) (Jaramillo et al., 2012)
AFFORDABILITY Transport poverty	Accessibility to opportunities & Transport equity metrics Transport disadvantage Indicators, Transport Social Needs Indicator, and Forced Car Ownership Transit fare analyses	sdg9_trains sdg11_satpubtran	(Sachs et al., 2016) (Lafortune et al., 2019) (Guzman & Oviedo, 2018) (Currie et al., 2009) (Jaramillo et al., 2012)

(*) SDG Index metrics related to the social dimension and transport: sdg1_depriv: Severe material deprivation rate in cities (%); sdg1_povrisk: People at risk of poverty or social exclusion (%); sdg4_earlyleav: Early leavers from education (% 18-24); sdg4_secondary: Adults with upper secondary education (% 25-64); sdg4_neet: NEET rate (% 15-24); sdg4_earlyedu: Four year-olds in early childhood education (%); sdg5_wgap: Gender wage gap (% male wage); sdg5_emplogap: Gender gap in unemployment (%); sdg8_ltunemp: Long term unemployment Rate (%); sdg9_intcon: Access to Internet at Home (%); sdg9_trains: Direct trains to other cities (per million pop.); sdg10_gini: Gini Coefficient (1-100); sdg11_satpubtran: Satisfaction public transport (%); sdg11_sathous: Satisfaction affordable housing (%); sdg16_burglary: Burglaries (per 100,000); sdg16_rob: Robberies (per 100,000); sdg16_homicide: Intentional homicides (per 100,000); sdg16_safety: Perception of neighborhood safety (%). Note: Leave no-one-behind indicators are not included (Lynch et al., 2019)

2.3. Environment and Healthy Cities

2.3.1 Climate change mitigation: driving and the built environment.

Worldwide transport greenhouse gas (GHG) emissions account for 28 percent of total end-use energy. The transport sector is the second largest contributor of emissions (Kooshian et al., 2018). Development demands mobility, and energy use in transport increases with per capita income. The highest-income countries are predominant transport-energy consumers (Kopp et al., 2013).

The thirteenth edition of the Emissions Gap Report published in 2022 reports that if the Nationally Determined Contributions (NDCs) for 2030 presented by countries are fully implemented, it will only reduce global emissions by 5 to 10 per cent. Furthermore, to limit global warming below 2.0°C and 1.5°C, require a reduction in emissions of 30 to 45 per cent by 2030 (UNEP, 2022).

For climate change mitigation in urban mobility and transport-related emission reduction, the Avoid-Shift-Improve (ASI) framework is recommended. At its core, the framework aims to "Avoid" or reduce travel by reducing the distance traveled by a person; "Shift" to more efficient energy modes (transit and active transport); and "Improve" vehicle efficiency through technology. In the "ASI" framework, A stands for Activity (travel demand); S for share by mode of transport; I for improving vehicle technology in terms of Energy Intensity and Fuel Mix per transport mode (Kooshian et al., 2018).

The "Avoid" strategy aims to reduce Vehicle Kilometer Travel (VKT or VMT in miles). Many regions of the world designed car-centered cities and created the urban sprawl that we see today. Decades of research in the United States have found that compact and mixed-use developments reinforce its ability to reduce Vehicle Mile Travel (VMT) and CO_2 emissions. VMT is a function of trip length, trip frequency, and mode choice. Compact cities increase the trip frequency but decrease trip length, and trip frequency increments do not negatively affect the VMT (National Research Council, 2009).

In compact developments, land use is referred to as the 5D's of the built environment. Table 2.2 describes the 5D's and shows the elasticity estimates of changes in VMT relative to changes in the built environment at a neighborhood and regional scale (Brownstone & Golob, 2009; Ewing & Cervero, 2001).

From Table 2.2, regional-scale research reveals that Destination accessibility (accessibility to opportunities) and Density have a more significant impact on VMT and CO_2. Compact mix-used developments can cluster destinations and improve access to opportunities. Achieving Density supports cost-effective transit projects as higher density areas tend to have higher ridership (Guerra & Cervero, 2011). Population and employment density can modify travel behaviors for location choices, car ownership, and modal choice. These are also affected by income, age, household size, and other socioeconomic variables (National Research Council, 2009; Badoe & Miller, 2000). Ding et al. (2017) argue that while there are benefits in reducing VMT and energy consumption given denser and mixed-used developments, density and car dependency can also offset the benefits by increased congestion and reduced speeds.

When planning to establish priorities among candidate projects for either urban rail or BRTs, Destination Accessibility, and Density significantly impact reducing VMT and CO_2 emissions at a regional scale. However, increasing population density can also come with challenges of housing affordability.

Table 2. 2 Relationship between the 5Ds of the built environment and VMT

5Ds	Description	Reduction VMT (neighborhood scale) (%)	Reduction VMT (regional scale) (%)
Density	Population & employment by geographic unit	5	12
Diversity (land use mix)	Mix land uses. Balance between residential, commercial, and jobs – housing balance in an area	5	-
Design	Neighborhood layout and street characteristics, connectivity, presence of sidewalks, design features, pedestrians & bicycle friendly	3	-
Destination accessibility	Ease of travel to destinations from point to origin	-	20
Distance to transit	Ease of access to transit from home to work (bus/ rail stop within 400 to 800 meters from trip origin)	-	-
Density + Diversity + Design		13	
All built environment variables		-	25

(National Research Council, 2009)

As a policy response on climate change mitigation, it is encouraged to design compact mixed-use developments. They can support the reduction of VMT, energy use, and CO_2 emissions. These transformations in the built environment will require sustained transport investments in the long term (National Research Council, 2009), long-term strategic urban planning for linking land development around stations and transit corridors (Cervero & Dai, 2014), and increase sustainable transport for mobility, vehicle efficiency and cleaner energies Kooshian et al., 2018).

2.3.2 Climate Change Adaptation: transport infrastructure, driving and CO_2 emissions

The consequences of climate change can create extreme events that can damage infrastructure and interrupt network connectivity for the mobility of people and goods (Kopp et al., 2013). Strategic planning and risk analyses for resilient transport infrastructure are necessary to cope with these challenges. In the absence or mismanagement of assets (i.e., pavements, bridges, culverts, and slopes), transport systems deteriorate and become more vulnerable to catastrophic failure, particularly when natural hazards strike. The deterioration comes from aging, overexposure, misuse, mismanagement, and neglect (Uddin et al., 2013). Without timely maintenance, road deterioration accelerates with time and weather (Kopp et al., 2013). Transport Asset Management Systems successfully manages planning and programming investments for construction and maintenance using life-cycle cost analyses (LCCA).

Contribution to GHG emissions is not limited to modal choice, travel demand, combustion engines, and fuel. Pavement-tire interaction contributes to energy consumption and emissions. Literature has consistently shown that pavement roughness is the major contributor to fuel consumption and less affected by pavement macrotexture and surface geometry (slope) as rolling resistance parameters (Ionescu, 2017). Correlations between pavement roughness (International Roughness Index - IRI), user costs, and CO_2 emissions can be found in the HDM-4 modeling tool developed by the World Bank (Ziyadi et al., 2018; Louhghalam et al., 2015).

For highways and the relationship between pavement roughness and CO_2 emissions, Ziyadi et al. (2018) has found that: (1) passenger vehicles are more sensitive to pavement roughness and speed than large trucks, demanding more fuel consumption when driving at higher speeds in more deteriorated pavements; (2) for every unit change of IRI (1 m/km), there is an average rise in fuel consumption of 3% at 105 km/h and 2% at 55 km/h.

2.3.3 Healthy Cities

City design can have a positive or negative impact on communicable and non-communicable diseases. In the context of urban mobility, populations face sedentary lifestyles in car-oriented cities that can contribute to obesity and cardiovascular disease. Respiratory diseases, mental health, and musculoskeletal injuries are a result of excessive vehicles. Congested cities take a toll on mental health, stress, depression, and well-being (UN Habitat, 2014). Long-term exposure to road traffic noise can create cardiovascular illness, cognitive impairment in children, insomnia, and emotional irritation (UN Habitat & WHO, 2020). Traffic volumes have a non-linear correlated to risk exposure to collisions, and the higher the traffic volumes the higher the crash exposure (Intini et al., 2021; Lyon et al., 2017; Hakkert & Braimaister, 2002).

Long-term exposure to air pollution can harm people's health and increase mortality rates. Transport is an anthropogenic activity that produces harmful pollutants in urban areas. The primary pollutants and effects from fossil combustion are (1) The predominant pollutant are Nitrogen oxides (NOx) and can lead to respiratory problems, and limited lung function; (2) Carbon monoxide (CO) affects oxygen absorption; (3) Particulate Matter (PM10 and PM2.5, for aerodynamic diameters of 10 and 2.5 µm respectively) is associated to cancer, cardiovascular illnesses, and breathing difficulties that are more severe with PM2.5 exposure; and (4) Ground-level ozone (combination of volatile organic compounds and NOx) have an impact on respiratory functions such as asthma and lung diseases (Molemaker et al., 2012; Krzyżanowski et al., 2005; Hertel et al., 1995).

The COVID-19 global pandemic is now turning more attention to communicable diseases in cities. Urban density and its impact on pandemics have been at the center of debate among urban planners. Climate change mitigation policies advocate for compact cities allowing better connectivity and accessibility to services through sustainable transport. However, questions have arisen if urban density contributes to the spread of the COVID-19 virus. UN Habitat (2020) argues that overcrowded housing conditions (not urban density) increase the rapid transmission of the virus. Overcrowded housing is the result of social exclusion and inequalities. Many research studies have found that urban density does not have a significant contribution to the spread of COVID-19 (Teller, 2021) and highlight the impact of social inequities, race, ethnicity, and poverty on mortality and morbidity (Dey & Dominici, 2021; Hamidi et al., 2020;). Evidence shows that the urban poor and vulnerable groups are the most affected by transport-related air pollution (UN Habitat, 2014).

In 913 U.S. metropolitan counties, the COVID-19 infection and mortality rates were studied by having explanatory variables as county density, socioeconomics (race, age, education), and health care infrastructure. It did not include pre-existing population health risk conditions. Findings revealed that: (1) connectivity (among counties and outside State) was more significant in the spread of COVID-19 rather than county density; (2) low-density areas had higher mortality rates and less access to health care facilities; (3) the most populated African American counties presented higher infections than other racial groups; and (4) people with education beyond high school had lower infection rates (Hamidi et al., 2020).

Studying the linkage between COVID-19, air pollution, and racial inequity in the U.S, Dey & Dominici (2021) found that African Americans consistently breathe higher levels of air pollution, while African Americans and Latinos are the racial/ethnic groups with higher mortality rates. Some underlying social conditions are pre-existing risk health conditions, lack of accessibility to healthcare, overcrowded housing conditions, and jobs limiting social distancing. The urban poor tend to have higher pre-existing health conditions and more exposure to air pollution (McFarlane, 2020; UN Habitat, 2014).

2.3.4 Frameworks and modeling approaches for the environmental dimension

Based on the composite SDG Index (Schmidt-Traub et al., 2017), Table 2.3 shows the metrics corresponding to Climate change mitigation (7 metrics) and adaptation (1 metric), health (20 metrics), and health equity (12 metrics). Climate change mitigation metrics reflect strategies for sustainable transport (transit and electric vehicles) and green spaces. Potential road accessibility has been classified under climate change adaptation through the lens of mobility disruption due to severe or extreme weather. Healthy cities classified the SDG metrics in two groups: (1) people's health; and (2) health equity as structural determinants affecting health outcomes. These metrics are summarized on Table 2.3 to highlight priorities and monitoring programs to attain the SDGs, as well as modeling approaches associated to these goals.

Modeling strategies for designing sustainable transport require the integration of transport and land use. Demand modeling and accessibility to opportunities analyses can address it while considering the 5Ds of the built environment for targeting VMT and GHG emissions reduction. The SDG metric contemplates electric vehicles.

The SDG Index is limited for climate change adaptation in transport infrastructure. However, infrastructure is the means to an end: people and the environment. Transport Asset Management Systems are used to manage infrastructure, including resiliency, risk, and uncertainty to extreme events (Liu et al., 2021). Pavement management systems can incorporate targets for smoothness to reduce GHG emissions and fuel consumption, reduce the noise produced by the interaction pavement-tire, and improve road safety by incorporating skid resistance (Van Dam et al., 2015).

Table 2. 3 Frameworks and modeling techniques for urban environmental dimension and SDG Index

APPROACH	METHODS: Planning and Design of Cities	SDG Index Cities (**)	SOURCE
Climate change mitigation	Transport Demand Models: 4-step model, Activity-based model, ABMs: UrbanSim, TranSims, MATSim Transport and Land Use Modeling: TRANUS Accessibility to opportunities analyses ASI Framework for climate change MOVES to estimate traffic emissions	sdg3_active sdg7_renenergy sdg11_evstations sdg11_satpubtran sdg13_co2 sdg15_nat2000 sdg15_urbgreen	(Sachs et al., 2016); (Lafortune et al., 2019); (US EPA, 2021); (Kooshian et al., 2018); (Jeihani & Ardeshiri, 2017) (Badland et al., 2013); (Ducas, 2011); (UrbanSim, n.d.); (MATSim, n.d.)
Climate Change Adaptation	Transport Asset Management Systems - TAMS (*) HDM-4, Linear programming MOVES Roughness-Speed Impact (RSI) model	sdg9_road	(US EPA, 2021); (Ziyadi et al., 2018) (World Bank Group, 2014); (Uddin et al., 2013)
Healthy Cities	**Urban and territorial planning health-centered:** Most at-risk populations: risk and uncertainty (spatial epidemiology analyses), spatial ecology, accessibility to health care facilities, ABMs: NetLogo **Air Pollution**: Transport demand modeling, air pollution models (MOVES, Health impact assessment of air pollution: AirQ+). Air quality management plans: low-emission zones and congestion charges **Social Spatial Analyses** (shown in table 2.1 under Transport Equity for spatial assessment of poverty/inequalities among populations, and accessibility analyses for health care facilities) **Noise pollution**: Traffic noise, congestion management, sustainable transport, pavement management for surface texture (pavement-tire interaction) **Mental Health and Wellbeing:** Travel demand management for traffic congestion, sustainable transport, design of liveable neighborhoods and green spaces **Road safety:** Roadway Safety Management: network screening & priorities; Swedish Vision Zero Framework	**Health:** sdg2_obesity sdg3_traffic sdg3_active sdg3_smoke sdg6_sectreat sdg6_consew sdg11_pm25 sdg11_nox sdg11_sathous sdg11_rburden sdg11_culture sdg11_sights sdg11_museums sdg11_concerts sdg15_nat2000 sdg15_urbgreen sdg16_homicide sdg16_safety sdg16_burglary sdg16_rob **Equity:** sdg1_depriv sdg1_povrisk sdg3_doctors sdg3_lifee sdg3_infmort sdg5_wgap sdg5_emplogap sdg8_ltunemp sdg10_gini sdg11_sathous sdg11_rburden	(Sachs et al., 2016) (Lafortune et al., 2019) (WHO Europe, 2020) (UN Habitat & WHO, 2020) (UN Habitat & WHO, 2016) (UN Habitat, 2014) (Huang & Brown, 2021) (NetLogo, n.d.) (Congdon, 2017) (Beale et al., 2008) (AASHTO, 2010) (Emissions of Air Pollutants from Transport — European Environment Agency, n.d.)

(*) The scope of climate change adaptation was through the lens of interaction pavement-tire. However, it is recognized that Transport Asset Management (TAMS) must incorporate structural parameters for pavements, bridges, culverts, and slopes, and risk analyses for resilient infrastructure to cope with severe weather and disasters.
(**) SDG Index: Climate Change: sdg3_active: Active lifestyle (%), sdg7_renenergy: Renewable energy generated (%), sdg9_road: Potential road accessibility (adaptation), sdg11_evstations: Recharging stations (per 10,000 people), sdg11_satpubtran: Satisfaction public transport (%), sdg13_co2: CO2 Emissions (tonnes per capita), sdg15_nat2000: Natura 2000 Area in good quality (%), sdg15_urbgreen: Urban green area (%).
Healthy Cities: sdg2_obesity: Obesity rate (BMI <30), %, sdg3_traffic: Traffic fatalities (per 10,000 population), sdg3_active: Active lifestyle (%), sdg3_smoke : Daily smokers (%), sdg6_sectreat: Wastewater treated (%), sdg6_consew: Population connected to Sewerage Treatment (%), sdg11_pm25: Concentration PM2.5 (microgr/m3), sdg11_nox: Emission of nitrogen oxides (kg/km2), sdg11_sathous: Satisfaction affordable housing (%), sdg11_rburden: Housing cost overburden rate in urban areas (%), sdg11_culture: Satisfaction cultural facilities (%), sdg11_sights: Sights & landmarks (per 100,000), sdg11_museums: Museums (per 100,000), sdg11_concerts: Concerts & shows (per 100,000), sdg16_homicide: Intentional homicides (per 100,000), sdg16_safety: Perception of neighborhood safety (%), sdg16_burglary: Burglaries (per 100,000), sdg16_rob: Robberies (per 100,000).
Healthy Cities Equity: sdg1_depriv: Severe material deprivation rate in cities (%), sdg1_povrisk: People at risk of poverty or social exclusion (%), sdg3_doctors: General practitioners per (100,000 pop), sdg3_lifee: Life expectancy (years), sdg3_infmort: Infant mortality rate (under 1) per 1,000 births, sdg5_wgap: Gender wage gap (% male wage), sdg5_emplogap: Gender gap in unemployment (%), sdg8_ltunemp: Long term unemployment Rate (%), sdg10_gini: Gini Coefficient (1-100), sdg11_sathous: Satisfaction affordable housing (%), sdg11_rburden: Housing cost overburden rate in urban areas (%).

Urban and territorial planning should have people's health at the center, and the SDG Index reflects this priority. Healthy Cities present a higher level of complexity due to the interrelation among urban mobility, built environment, equity, affordable housing, and neighborhood liveability. Some modeling strategies include social-spatial analyses to identify inequities and exposure to air pollution and noise. Consideration of household overcrowding conditions as it plays a vital role in the spread of communicable diseases. Re-design of built environments towards liveable cities benefits mental health (improves safety perception and provides spaces for cultural activities). Reduction of congestion through sustainable transport can reduce stress and fatigue, air pollution, and noise.

2.4 Urban Governance and Economics

Governance defines policies, priorities and set norms, strategic vision, and goals at a high level. Good governance ensures processes that promote accountability, transparency, responsiveness, the rule of law, stability, equity and inclusiveness, empowerment, and participation. Governance sets goals for a system to operate and manage. It formulates policies and decision-making to allocate resources. Management refers to planning, implementing, and monitoring to support this governance to achieve the established vision and goals. It mobilizes the available resources: physical, human, and financial (UNESCO, 2015). In sustainability, sound governance principles are: (1) Accountability, meaning that metrics and indicators are needed to achieve the SDGs and report on them towards these goals; (2) Transparency; (3) Participation of citizens and stakeholders; (4) Polluter pays (social costs produced by companies and consumers) (Sachs, 2015).

The SDGs have set policies and a strategic vision for good governance, and an SDG Index monitors progress (Schmidt-Traub et al., 2017; UNDESA, 2015). Performance-management systems can support this vision and goals. In a structured framework for planning and design, there are four modules: (1) goals are transformed into performance measures or indicators;

(2) a systematic data collection program supports these performance measures for planning and monitoring; (3) modeling and analytical tools support investment programming and trade-off analyses; and (4) the system is monitored to determine if the targets are being met and provide feedback (Grant et al., 2013). Frameworks assist technical and policy decision-making with economic analyses to achieve strategic goals (Gudmundsson et al., 2015) for transparent and more efficient systems.

A system is a collection of elements that interact together as a whole, while systematic and systemic describe aspects of the system. Systematic refers to a methodological procedure, while systemic describes a phenomenon that influences the system (Merriam-Webster, n.d.; dictionary.com, 2022).

The elements of a city can be seen as a system (i.e., transport systems, built environment, people and their socioeconomic stratums). In the context of the SDGs, cities worldwide are being monitored with the SDG Index. The United States also includes Leave no-one-behind indicators (Lynch et al., 2019; Schmidt-Traub et al., 2017; Sachs et al., 2016). The 2030 Agenda is universal, and the SDG metrics must also be associated with engineering and urban planning metrics related to the city's elements that allow planning and designing for sustainable cities (Table 2.4 provides this relation). Monitoring progress and city planning requires systematic data collection. In addition, an example of the systemic concept is the systemic marginalization of groups and social exclusion due to the neglect of disadvantaged social groups in planning sustainable urban mobility.

"Lack of integration across sectors in terms of strategies, policies, and implementation has long been perceived as a major obstacle to achieving sustainable development" (UN Secretary-General, 2015). In transport agencies, branches are frequently disconnected, and the most robust program gets the more considerable funding (Sinha & Labi, 2007). The complexity increases when incorporating the SDGs in city planning and the need for integrating strategic goals to prioritize projects (i.e., social justice, health, climate change, and economic development). Performance management can be used as a governance tool to integrate the city elements as a system, as well as planning, implementing, and monitoring progress of the investments made.

Aligning national and local governments is necessary to integrate transport and land use. Evidence shows the benefits of integrating transport and the built environment in the economic performance of rapid transit systems. On the contrary, urban sprawl impacts transit systems' ridership and economic performance. Babalik-Sutcliffe (2002) studied five urban rail systems among cities in Canada and the US with similar car ownership per household. Vancouver had better economic performance due to increased ridership, with good municipal coordination promoting land developments. In contrast, Miami presented the lowest financial performance, as this city has street layouts, urban sprawl, and low density that promote car dependency.

Linovski et al. (2018) have shown concerns about incorporating equity in Bus Rapid Transit (BRT) Systems in metropolitan Canadian cities. A review of case studies showed that the state of the practice had been focused mainly on promoting land developments and attracting car drivers to transit rather than incorporating equity and measuring societal impacts.

Interviews revealed no clarity in defining equity, and often it has been understood as accessibility, mobility, and spatial coverage, without identifying transit drivers and demographics.

Another case study related to urban governance is the 45-years Curitiba-Brazil BRT. The urban management in municipalities related to the built environment affected the land surrounding the Curitiba BRT. As a result, housing is one of the most expensive in the city. Thus, BRT passengers come from the city's periphery and surrounding municipalities, given the unaffordable housing by the BRT stations for the medium and low-income groups (Duarte & Ultramari, 2012).

2.5. Modeling for Sustainable Urban Mobility: A Holistic Systems Approach

We propose a conceptual modeling framework through the lens of the SDGs by integrating cross-disciplines, as shown in Figure 2.1. This modeling framework will support performance-based management systems which require analytics. Thus, we aim to align public policy and modeling to attain the SDGs. Relating the SDGs and city planning, we categorized five strategic goals: (1) social justice, (2) health, (3) climate change, (4) economic development, and (5) governance.

Our first strategic goal is social justice. It is a fundamental pillar for planning and designing urban mobility systems, health, climate change, and economic development. Failing to address social exclusion and systemic discrimination in urbanization will only increase inequalities, poverty, and urban sprawl. The SDG Index for the Global North reports challenges in social inequalities (Schmidt-Traub et al., 2017). The Global South reflects a different scenario facing higher poverty rates (Schmidt-Traub et al., 2017), and developing banks are more progressive in urban designs for social inclusion (World Bank Group, n.d.; Buvinić et al., 2004).

Social inequities have a direct impact on health and well-being outcomes. There are structural determinants (socio-economic, political context, and social hierarchies) and intermediary social determinants (health system, exposure, and vulnerability of populations) related to health outcomes (WHO, 2021).

Physical & mental health and well-being outcomes depend on social health determinants (WHO, 2010), and climate change strategies are also affected by the neglect of social justice. Economic individual choices rely on income and affordability, which will impact the selection of vehicles and housing that potentially could contribute to urban sprawl. In some cases, individuals choose affordable housing in lands threatened by extreme climate events.

A common urban planning equity approach is accessibility to opportunities. It integrates transport systems with land use, and it can consider spatial-temporal characteristics of services and socioeconomics of individuals, allowing to identify of spatial mismatches (K. T. Geurs & Van Wee, 2004). However, spatial-social analyses at a micro-level analysis can better understand poverty, inequalities, social segregation, and urban sprawl and incorporate socioeconomic metrics (Zhao, 2013; Grant, 2010).

Our second strategic goal is health. Health social determinants and health outcomes go hand in hand (WHO, 2010). Thus, modeling for social justice is relevant to identify neighborhoods that are more exposed to communicable and non-communicable diseases. COVID-19 has brought into light structural social problems, in this case, how overcrowded housing conditions and social inequalities contribute to the rapid transmission of the disease (UN Habitat, 2021; Teller, 2021; Dey & Dominici, 2021; McFarlane, 2020).

Intermediary social determinants for health outcomes refer to the health system, exposure, and vulnerability of disadvantaged people (WHO, 2010). Communities are exposed to traffic-induced air pollution and noise. One approach is conducting a transport demand model to estimate traffic volumes in a city and calculate a spatial exposure of air pollution and noise. Social-spatial analyses can incorporate individuals' health pre-existing conditions, socioeconomics and find the most at-risk populations. Road safety is a thriving field in implementing comprehensive policymaking under a cross-disciple approach. However, research linking road safety and social inequalities is just emerging Webb et al., 2017; Steinbach et al., 2011).

Our third strategic goal is climate change. As a mitigation policy, the Avoid-Shift-Improve (ASI) Framework seeks to reduce travel, shift to sustainable transport, improve vehicle fuel efficiency and use cleaner energies. Climate change mitigation policies related to urban mobility and the built environment aim to invest in rapid transit systems and design for compact mixed-use developments. We recommend a combination of transport demand modeling and accessibility analyses. GHG emissions are also a result of vehicle activity (VKT, speed, and driving) and roadway conditions for pavement-tire interactions (pavement smoothness and speeds). Thus, pavement management systems must account for GHG emission reduction, also improving resilience for extreme climate events.

Our fourth strategic goal is economic development through the lens of sustainable development. Investment decisions must rely on human development, social inclusion, environmental protection, economic growth and prosperity, and good governance (Sachs, 2015). Our conceptual framework proposes conducting cost-benefit analyses (CBA), life cycle cost analyses (LCCA) and assessing social, health, and environmental impacts. In our framework, we highlight three economic development objectives: (1) Mobility poverty (individuals); (2) City economic development & equity for all; and (3) Good governance resource allocation.

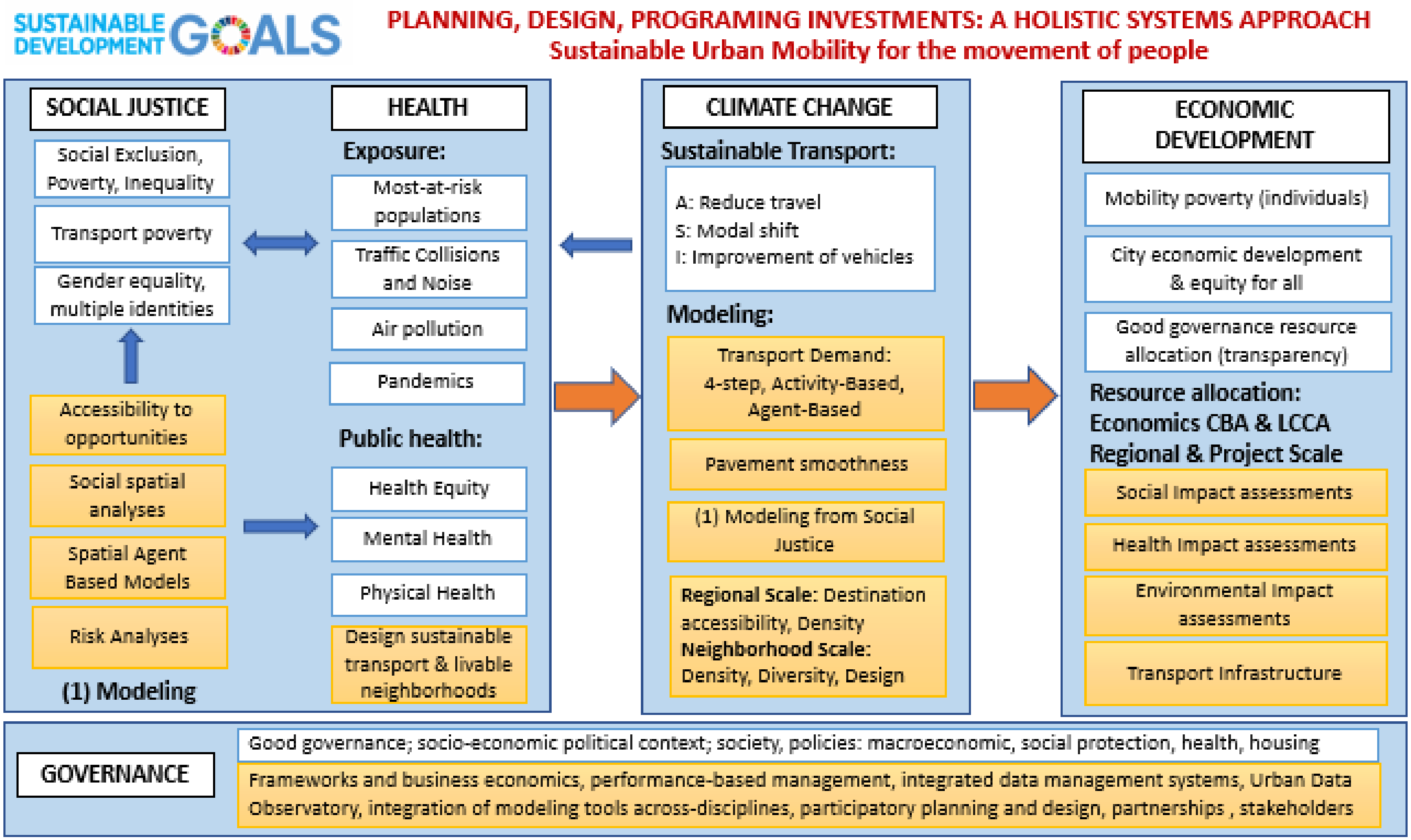
"Mobility poverty (individuals)" refers to significant infrastructure investments that do not address the needs of the poorest (Lucas et al., 2016). Neglecting social justice will result in transport poverty and forced car ownership. As a result, it limits improvements of cleaner vehicle fleets in a city and negatively impacts people's health. "City economic development & equity for all" refers to reshaping regions to build compact cities and neighborhoods to strengthen local economies, livability, and social cohesion. "Good governance resource allocation" refers to the transparent use of public funds for transit investments to attain equity, protect the environment, and allow economic growth for all. The use of public funds for sustainable transport should avoid favoring clusters of wealth in land developments and instead promote socially mixed housing developments for affordable housing and income diversity.

Our fifth strategic goal is good governance. Transit and active transport investments can transform the built environment and create sustainable cities (Suzuki et al., 2013). However, it requires long-term sustainable investments and good coordination between national and local governments to manage transport and land use. Transport is the movement of people and goods for development and an essential social service that National and Local Governments must provide.

A new economic era is emerging for sustainable development. Figure 2.1 shows a comprehensive conceptual framework to implement the SDGs in city planning for urban mobility, and a diversity of modeling approaches to support it. Future research is needed to develop proof of concept modeling through the lens of a cross-disciplinary research for the five strategic goals proposed: (1) social justice, (2) health, (3) climate change, and (4) economic development, (5) governance.

Table 2.4 shows key attributes for modeling sustainable urban mobility by linking transport and the built environment under the above strategic areas. The SDG Index shown in Tables 2.1 (social dimension) and 2.3 (environmental dimension) are universal metrics applicable to all industries. Thus, table 2.4 relates the SDG Index and research policy in transport and urban planning with specific metrics for planning and designing cities.

Figure 2. 1 Conceptual modeling framework for planning and design of sustainable cities using a cross-disciple approach.



ASI model = A: Activity (travel demand); S: Share by mode of transport; I: Improve vehicle technology
CBA: Cost Benefit Analysis; LCCA: Life Cycle Cost Analysis

Table 2. 4 Key Attributes for modeling Sustainable Urban Mobility

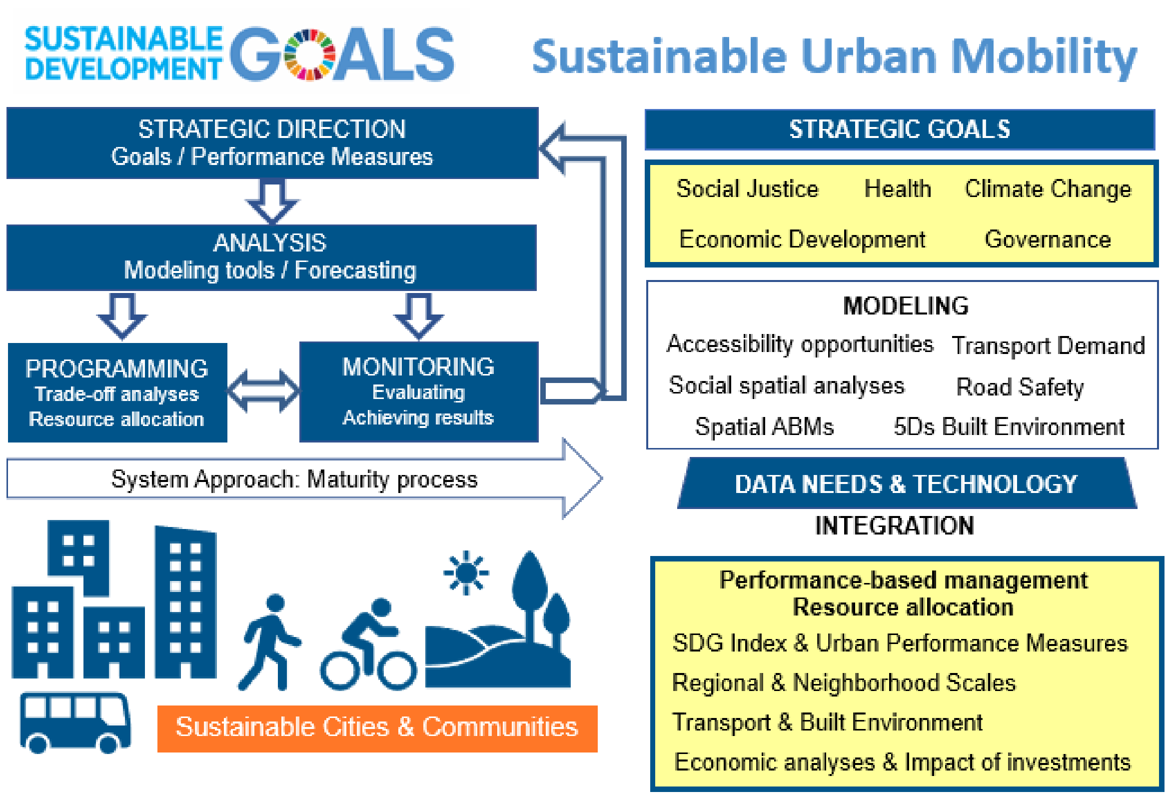
SDGs	Transport	Built environment and population
Social Justice	(1) Gender equality; (2) Multiple identities of men and women for gender, social class, ethnicity, religion, sexual orientation, age and physical/mental conditions, and their context in power relations; (3) Systemic discrimination; (4) Destination Accessibility: time, ease, cost per mode; (5) Transport poverty	Poverty and inequality Social exclusion: physical, geographic, facilities, economic, time-based, fear-based, space Urban poverty traps, social segregation, urban sprawl Destination Accessibility: land-use
Healthy Cities	<u>Congestion management:</u> Road traffic congestion index, car ownership Modal share (%), Vehicle technology (%) Air pollution: NOx, PM10, PM2.5 <u>Traffic noise:</u> Vehicle technology (%), Pavement surface macrotexture <u>Active transport</u>: AADP: Annual Average Daily Pedestrian AADB: Annual Average Daily Bicycle; Facilities (Km) AADT: Annual average daily traffic, Speed (Km/h) <u>Road Safety:</u> Collisions, AADT, AADP, AADB Factors: Human, road environment (road & built environment), vehicle. Congestion-ambulance travel time Pavement skid resistance: SFC = Sideways force coefficient number, GN = Grip Number	Social exclusion, poverty, inequality <u>Communicable disease:</u> Quality of density Accessibility: health care facilities Overcrowded housing Pre-existing conditions <u>Livability, Design, Diversity:</u> Design for crime and sexual harassment mitigation Design and road safety Design: walkability, cycling facilities, universal design, amenities Distance to transit Diversity: social cohesion
Climate change	<u>Mitigation (driving and CO2)</u>: VKT: Vehicle Kilometer Travel, Speed (Km/h) PKM: Passenger Kilometer in public transport, ridership Modal share (%), Vehicle technology (%), Fuel type per mode (%), CO2 Emissions, GHG Emissions <u>Adaptation (driving and CO2)</u>: IRI: International Roughness Index (pavements), VKT, AADT, CO2 Emissions, GHG Emissions	<u>Regional Scale:</u> Destination accessibility Density <u>Neighborhood Scale:</u> Diversity (land-use mix) Design Distance to transit Housing affordability
Economic Development	<u>Transport poverty & forced car ownership:</u> Car ownership, transit provision (coverage, frequency, quality), time-based exclusion (travel time, home-work balance), economic exclusion (transport affordability & distance). <u>Mobility poverty</u>: infrastructure investments that do not prioritize the poor <u>Local economies:</u> Transit Oriented Developments (TOD)	Social exclusion: physical, space, geographic, facilities (*), fear-based (personal safety) (*) Destination accessibility (opportunities) Density & Design: transit ridership, safe public spaces, and transport Housing affordability Diversity: local economies
Governance	<u>Breaking down silos in government administration:</u> Management systems and business economics, integrated data management systems Integration of modeling tools across-disciplines Financing sustainable development, public funds allocation, economics & impact on society National & local governments integration, citizen participation in planning and design <u>SDGs Implementation</u>: Frameworks and business models (1) Strategic Direction: Policies, SDGs, Performance Measures; (2) Analysis: Modeling tools, forecasting, data management; (3) Programming investments: trade-off analyses, resource allocation; (4) Measuring and monitoring: performance-based accountability and transparency	

We propose a cross-discipline urban performance-based management system for programming sustained investments and measuring social, health, and environmental impacts for strategic implementation of the SDGs in cities. Measuring a city's performance can support decision-making, identify trends and needs, make investments. We recommend creating an Urban Data Observatory for integrating sectors, decision-making, monitoring progress, and localizing the SDGs.

Figure 2.2 shows this conceptual framework, where investments decisions are made using performance measures (PMs), and project performance can be monitored through time. Some attributes performance measures have are: they should reflect at least one goal, data is accurate and reliable, comparable across time-periods and geographic regions, can communicate effectively to decision-makers and stakeholders, and forecastable for planning purposes (Sinha & Labi, 2007). Urban PMs can be related to the SDGs and report at the highest level using the SDG Index in cities and communities.

Figure 2.1 and Table 2.4 are the foundation for developing urban performance measures aligned with the SDGs. We recommend cross-discipline research to design urban performance measures and data acquisition, create an urban data management system, and proof of concept modeling through the lens of the SDGs. This framework is a tool for good governance, where the government sets goals and policies for decision-making to allocate resources, and management systems are created; to plan, implement, and monitor to support this governance to achieve the established vision and goals.

Figure 2. 2 Conceptual sustainable urban performance-based management framework



2.6. Conclusions

Transport is the backbone of a city and its development. The business-as-usual has led to poverty and social inequalities, making people ill and threatening climate change. Traditional transport planning has prioritized cars over sustainable transport. The urban sprawl results in the disconnection between transport and the built environment, reinforcing car-centered cities. There is evidence that some rapid transit systems foster land developments rather than human development. The 2030 Agenda is clear: we must place people and the environment at the center.

The transport sector is the second largest industry producing GHG emissions with slow progress towards attaining the IPCC 1.5°C target. Protecting the environment result from individual choices, city designs, and policymaking, and while climate change is a humanity threat around the corner, it goes hand in hand with human development. Individuals experiencing social inequalities and poverty have no choice but to prioritize survival over the environment in car-centered cities. They are also more exposed to health and climate risks and are most vulnerable to a humanitarian crisis. Urban and territorial planning for the most vulnerable improves the city's environmental resilience.

Attaining sustainable development in cities is challenging due to the lack of integration across sectors. Thus, the purpose of the current review was to understand the interconnectedness among the SDGs, transport, and the built environment in cities. We propose a conceptual urban performance management system and recommend creating an Urban Data Observatory for integrating sectors, decision-making, and monitoring progress. These systems must have modeling tools for evidence-based decisions to allocate resources. Thus, we examined frameworks and modeling approaches for social and environmental justice to support urban mobility investments, identified gaps, modeling tools, and future cross-discipline research. We proposed a conceptual modeling framework under five strategic areas: social justice, health, climate change, economic development, and governance.

In social justice, we found that transport planning must address "Transport poverty" for affordable transport, transparent investments to address the needs of the poor and avert "forced car ownership", accessible systems to reach opportunities, and reduce risks and costs associated with negative transport externalities, where health and lives are compromised. Poorly planned cities result in urban sprawl, social exclusion, and urban poverty traps. There is good evidence that urban sprawl generates social segregation, and that communicable and non-communicable disease are experienced differently by socioeconomic classes and racial and ethnic groups. Urban sprawl and congestion also reduce access to health care facilities that can be critical in emergency responses.

Women experience barriers and exclusion in the Workforce, Economics, Education, Health & Sexual Reproductive Rights, Empowerment, Time. Women represent half of the population, and urban mobility is the means to their development. However, limited research has been done in understanding their mobility in cities. Travel patterns are different from men, where women require to travel shorter distances to balance work-home responsibilities and sustain their jobs. Women also experience sexual harassment and violence in public spaces. The quality of walkability and safety can limit travel. In addition, transport planning requires an account for the multiple identities of men and women and their context in power relations. Failure to do this will lead to socially constructed inequalities.

Accessibility to opportunities is a modeling approach used to attain equity. It integrates transport and land use, allowing people to reach destinations and identify spatial mismatches. However, these analyses rely on the physical proximity from where people live to these opportunities. Accessibility to opportunities can undermine understanding social inequalities and segregation and why people remain poor in districts in time and space. Thus, spatial-social analyses best suit these goals by looking at demographics, socioeconomics, disadvantage and marginalized populations, provision of transit services, and economic indicators. In addition, transit affordability and forced car ownership analyses can explain the transport mode selected. A comprehensive study should integrate these three types of modeling approaches for better outcomes.

Health equity is key to health outcomes and well-being, and structural and intermediary social determinants define it. Thus, modeling approaches for social justice are necessary if designing for healthy cities to find the most at-risk populations, including their pre-existing health conditions. Traffic-related exposures are air pollution, noise, and traffic crashes. Air pollution is known for causing respiratory illnesses and is a predictor of COVID-19, where NOx and PM2.5 contribute the most to infections and deaths. Urban density does not contribute to the spread of the virus, but overcrowded housing resulting from social exclusion and inequalities. Social segregated communities in disadvantage have been found to be the most affected (i.e., African Americans breathe a lower air quality with higher mortality rates in the US). In some countries, the urban poor tends to have less healthcare access and more pre-existing health conditions. Having recognized that social determinants of health play a key role in health outcomes, regional planning of cities must strengthen analyses in integrating health equity and road safety.

Climate change mitigation strategies rely on reducing travel, shift modes to public and active transport, and improve vehicle efficiency. Transforming travel patterns and the built environment require high levels of investments that are sustained through time to halt forced car ownership. Since development demands mobility and the highest-income countries are the predominant contributors, increasing capital investments to transform cities should be feasible. The improvement of vehicle efficiency relies on the shift to renewable energy vehicles and smooth pavements due to the pavement-tire interaction.

Good governance uses management approaches to support decisions and allocate resources. Performance-based management systems are suitable for incorporating the SDG Index. The design of specific urban performance measures and data collection can be associated with the SDG Index. Modeling transport and urban systems are necessary to provide evidence-based analyses to support economic models. Often, a limitation for modeling cities is that datasets are disconnected or incomplete. Thus, an Urban Data Observatory under a comprehensive framework is recommended. There is evidence in the state of the practice that investment decisions and land management for rapid transit favors land developments rather than equity and urban mobility. Using the SDG Index with urban performance measures allows planning, designing, and monitoring progress in the long term.

The review undertaken here of sustainable development and cities through the lens of sustainable urban mobility has led to propose a conceptual modeling framework for planning, designing, and programming investments under five strategic areas: social justice, health, climate change, economic development, and governance. Recognizing the importance of integrating transport and the built environment, we provide key attributes for modeling and designing urban performance measures. This conceptual framework allows understanding the interconnectedness of the SDGs in people's movement and proposes new cross-discipline research directions to attain the most pressing needs in cities: human development and the environment.

This review and proposed frameworks provide insights for future research for modeling integration and designing a sustainable urban mobility performance-based management system with proof-of-concept modeling. Urban mobility is a systems challenge, and cities are urban ecosystems. Thus, planning and designs should use a systemic approach.

CHAPTER 3

A Bottom-Up Transport Emission Model For 2050 Policy Scenarios: Costa Rica Case Study

Abstract

The transport sector is the second-largest contributor to GHG emissions. According to the World Bank, under current motorization and energy use patterns, transport will become the primary oil consumer by 2030. The Avoid-Shift-Improve (ASI) Framework aims to decrease travel, shift to sustainable transport, and improve vehicle technology to combat climate change.

A case study of the metropolitan area of Costa Rica was used to evaluate the policy of shifting the vehicle fleet to Electric Vehicles (EVs). While the country's decarbonization strategic plan provides an ASI approach to attain net-zero urban mobility, institutional fragmentation has led to relying on the strategy to shift to EVs and charging stations. Given the low penetration of EVs adoption in the vehicle fleet (0.48% in 2022), a GDP per capita of USD$12,141, and scarce investments in sustainable transport, it is argued that achieving 2050 net-zero emissions by mainly relying on EVs might not be feasible under current patterns.

A regional average speed emission model relying on a macroscopic travel demand model was developed to analyze EVs penetration effect on traffic emissions up to the year 2050. Four scenarios are explored: the business as usual (BAU), low, moderate, and aggressive scenarios to evaluate the potential reduction of CO_2 emissions and air pollutants NOx and PM2.5. A regional emission model is developed for the province of San José - Costa Rica for highways, principal arterials, minor arterials, and collector roads. The emission model considers vehicle type and weight, average speed, and vehicle technology.

This research found that passenger cars and buses produce 61% of the vehicle fleet emissions, and these vehicle classes should be prioritized in emission reduction strategies. By 2050, the Business-As-Usual (BAU) scenario will increase 25% of CO_2 emissions due to traffic growth, resulting in a range of 949,453 and 997,893 CO_2, given speed scenarios and a change of vehicle emission standards from EURO I to EURO VI. Changing legislation in Internal Combustion Engine (ICE) vehicles to EURO VI results in a 58% reduction of NOx and PM2.5. For electric vehicles, a low scenario of shifting to 50% EVs results in 38% CO_2 and 79% NOx and PM2.5 reduction. A moderate scenario involving shifting to 75% EVs results in 69% CO2 and 90% NOx and PM2.5 reduction.

A framework under a systematic approach and performance management was proposed for a bottom-up regional emission model supported by travel demand modeling, and emission scenarios. As a decarbonization strategy, findings indicate that the Avoid-Shift-Improve Framework should be implemented to rely on a balanced solution.

3.1 Introduction

In 2015, the Paris Agreement on Climate Change agreed to keep the global average temperature rise below 2ºC above pre-industrial levels and seeks to limit temperature rise to 1.5 ºC (UNFCCC, 2015). The 2021 Inter-Governmental Panel on Climate Change (IPCC) assessment has found that under current trends, the average warming will exceed 1.5 ºC in the next 20 years (Masson-Delmotte et al., 2021). Globally, the Nationally Determined Contributions (NDCs) presented by United Nations Member States are insufficient, and countries are off track to attaining their NDCs. To get back on track to limit global warming to 1.5 ºC, greenhouse gas emissions must be reduced by 45 percent in eight years and pursue a rapid decline of emissions after 2030 (UNEP, 2022; UNDESA, 2021).

In 2020, the transport sector produced 24% of direct carbon dioxide emissions (CO_2), where passenger road vehicles are the largest contributor, followed by road freight vehicles (UNDESA, 2021). Carbon dioxide (CO_2), methane (CH4), and Black Carbon (BC) contribute significantly to global warming (Wei & Wang, 2020; Mascia et al., 2017). The top seven emitters are China, the 27 European Union countries, India, Indonesia, Brazil, the Russian Federation, and the United States of America. In addition, 75 percent of global GHG emissions are produced by the G20 members (UNEP, 2022).

Fossil fuel combustion emits harmful air pollutants such as Nitrogen Oxides (NOx), Nitrogen Dioxide (NO_2), Carbon monoxide (CO), and Particulate Matter (PM10 and PM2.5, for aerodynamic diameters of 10 and 2.5 μm respectively), Ground-level ozone (combination of volatile organic compounds and NOx), and Sulphur Dioxides (SO_2). Long-term exposure to road traffic-induced air pollution can cause respiratory and cardiovascular diseases, lung cancer, and diabetes (Molemaker et al., 2012; Krzyżanowski et al., 2005; Hertel et al., 1995).

Concerning traffic and carbon dioxide emissions (CO_2), the SDG Index incorporates an indicator for carbon dioxide emissions (CO_2) with SDG 13 for climate change. For air quality, Nitrogen Oxides (NOx) and Particulate Matter of 2.5 μm (PM2.5) are related to SDG 11 in sustainable cities (Schmidt-Traub et al., 2017). NOx and PM2.5 are significant pollutants harming health and have shown a positive correlation for populations exposed to the long-term and COVID-19 (Barnett-Itzhaki & Levi, 2021). Particulate Matter of 2.5 μm is more dangerous than 10 μm because it can go into the lungs and reach the bronchioles. These particulates are associated with lung cancer and respiratory and cardiovascular diseases (Molemaker et al., 2012).

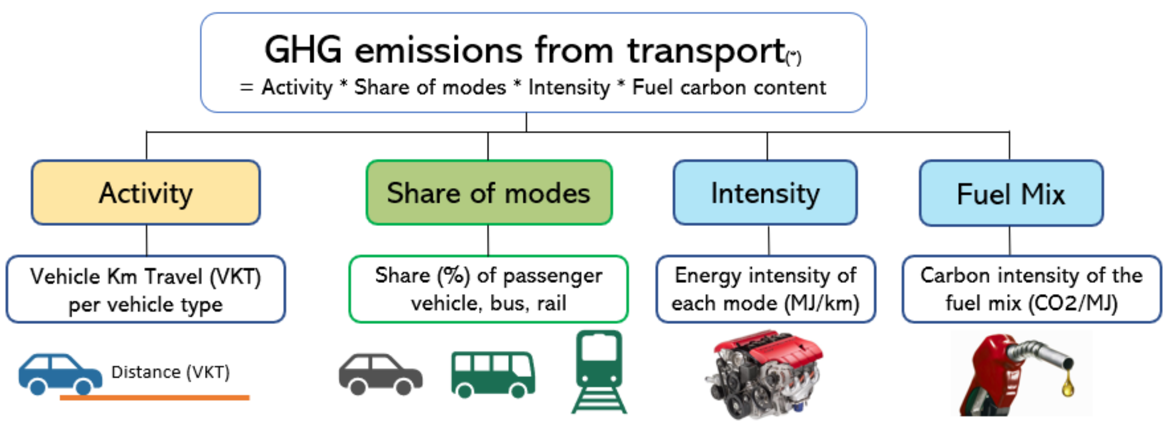
Transport emissions must be estimated to produce climate action planning and develop transport strategies. GHG emission analyses can prioritize policies, perform mitigation planning, and report results. There are two methods used: Top-down and Bottom-up. The most straightforward method is top-down, based on the fuel consumed. The fuel volume is multiplied by an emission factor per fuel type to estimate the emissions. As a result, traffic-related emissions can be monitored and, over time, determine if greenhouse gas (GHG) emissions are increasing or decreasing (Kooshian et al., 2018). There are limitations to the top-down approach, such as the inability to forecast scenarios and incorporate specific climate mitigation actions.

A bottom-up method is based on trips, people, and goods. This method considers the number of trips, the mode used, and vehicle fuel efficiency. Emission factors are used based on vehicle age or emission standards and fuel type. Travel demand models are used to determine the trips made between origin and destinations. These models demand high data input and processing for calibration for local conditions (Kooshian et al., 2018). A bottom-up approach is more complex. However, this approach allows forecasting scenarios and modeling the impact of future changes in the road network, which is an advantage over the top-down approach that is limited to forecasting.

Climate change mitigation strategies for sustainable urban mobility are summarized in the Avoid-Shift-Improve (ASI) Framework as shown in Figure 3.1. "Avoid" or reduce travel by reducing the distance traveled by a person aims to reduce Vehicle Kilometer Traveled (VKT) (Kooshian et al., 2018). VKT is a function of trip length, trip frequency, and mode choice. Compact and mixed-use developments and sustainable transport can reduce VKT and CO_2 (National Research Council, 2009).

"Shift" refers to a modal shift from passenger cars to more efficient energy modes (transit and active transport) (Kooshian et al., 2018). The modal choice depends on the following characteristics: demographic (i.e., car ownership, gender, socio-economics), journey (i.e., trip purpose, time of the day), and transport facility (i.e., travel time, fares, reliability, safety) (Ortúzar & Willumsen, 2011). "Improve" refers to the improvement of vehicle efficiency through technology, which is reflected in Energy Intensity (fuel efficiency) and Fuel Mix (type of fuel by mode) (Kooshian et al., 2018).

Figure 3. 1 Avoid-Shift-Improve (ASI) Framework



(Kooshian et al., 2018)

The "ASI" framework was applied to Brazil, India, Vietnam, and Kenya using a top-down approach. As a result, attaining an IPCC 1.5 °C scenario by 2050 for a target for land transport of 0.2 tCO_2 per capita requires more significant investments, dramatic changes in travel patterns and modal shifts to sustainable transport, near-zero carbon fuels, and urban planning solutions (Arioli et al., 2020).

Arioli et al. (2020) argued that the Nationally Determined Contributions (NDCs) of Brazil, India, Vietnam, and Kenya were inadequate. Thus, more robust measures must be taken. Brazil and India are more critical. Private vehicle travel must be reduced between 30 to 55%; public transport must double its passenger-km (PKM) per capita; and urban accessibility and active transport must improve (i.e., Activity and Share of Modes in the ASI Framework). In addition, shifting vehicle technology can significantly reduce CO_2 emissions through electric vehicles (EVs) and decarbonized electric systems, hydrogen vehicles, and biofuels. Brazil uses more biofuels than other countries, and indirect emissions due to land-use impacts must be considered.

3.2 Case Study: Metropolitan area of San José, Costa Rica

In 2019, the CO_2 emissions produced by all sectors in Costa Rica was 8,240 kilotons (kt). In a global scale, the contribution of CO_2 emissions is small when comparing it to the G20 countries. In 2019, China produced 10,707,220 kt and the United States 4,817,720 kt (World Bank, n.d.-a). The transport sector is the second largest contributor to emissions (Kooshian et al., 2018). Development demands mobility, and energy use in transport increases with per capita income. The highest-income countries are predominantly transport-energy consumers (Kopp et al., 2013).

The Costa Rican 2018-2050 decarbonization strategic plan follows the Avoid-Shift-Improve (ASI) Framework. The 2050 decarbonization vision aims to have a public transport system more efficient than traveling by automobile, changing the built environment to compact forms to reduce traveling and having a modal shift to non-motorized transport by 10%. In addition, the goal is to attain 85% of the bus fleet as zero emission vehicles (Meza et al., 2018).

The decarbonization plan also aims to shift passenger vehicle fleet from Internal Combustion Engines (ICE) to zero emissions and promote freight vehicles to adopt a similar shift. The transport sector consumes 66% of total end-use energy and is responsible for 54% of CO_2 emissions in the country. Air quality site instrumentation in the metropolitan city has shown that Particulate Matter PM2.5 and Nitrogen Dioxide (NO_2) exceed the international recommended limits. One advantage is that 98% of the electricity produced is renewable, and there is 99.4% coverage of the electricity system across the country. However, by 2022, only 0.48% of the vehicle fleet is electric MINAE, n.d.).

Despite decarbonization goals, the country's fiscal debt limit investments on public transport infrastructure, restricting the implementation of the "Avoid" and "Shift" strategies. The "Improve" strategy is based on shifting the ICE vehicle fleet to Electric Vehicles (EVs). Changing the vehicle is an individual consumer choice. Given the low penetration of EVs and a Gross Domestic Product per capita of USD$12,141, my analysis indicates that achieving 2050 net-zero emissions by relying mostly on EVs might not be feasible under current patterns.

This study aims to develop a bottom-up macroscopic travel demand model to forecast traffic and develop an emission model to analyze EVs penetration's effect on traffic emissions up to the year 2050 and design a regional emission framework for system performance evaluation. Four scenarios are explored: the business as usual (BAU), low, moderate, and aggressive scenarios to evaluate the potential reduction of CO_2 emissions and air pollutants NOx and PM2.5. A regional average speed emission model is developed for the province of San José - Costa Rica, for highways, principal arterials, minor arterials, and collector roads. The emission model considers vehicle type, weight, average speed, and technology. A baseline and scenarios of traffic emissions for a time horizon of 2050 can assist policymakers and planners in prioritization policies and climate mitigation actions for emission reduction. Figure 3.2 shows the methodology to analyze scenarios for Electric Vehicle (EVs) fleet penetration and forecast emissions for CO_2, NOx, and PM2.5.

The area of study is the metropolitan area of San José, the capital of Costa Rica. Two major components are developed. The first is a regional macroscopic travel demand model that estimates and forecasts traffic volumes. The travel demand is developed with the PTV Visum software and calibrated with local data.

The second component takes the PTV Visum output to develop an emission model for the road classification of highways, principal arterials, minor arterials, and collectors (residential roads are excluded from this analysis). The emission model was created in R Studio and classified the vehicle fleet by its average distribution, Gross Vehicle Weight (GVW), fuel type, vehicle emission standard, and average speed profile. These variables determine the choice of emission factors. Vehicle emission standards are EURO I, EURO IV, and EURO VI, and emission factors are obtained from COPERT Version 5.5.1 (Computer Programme to calculate Emissions from Road Transport) from the European Environment Agency (EMISIA et al., 2021).

Figure 3. 2 Methodology to analyze the EVs penetration for a 2050-time horizon

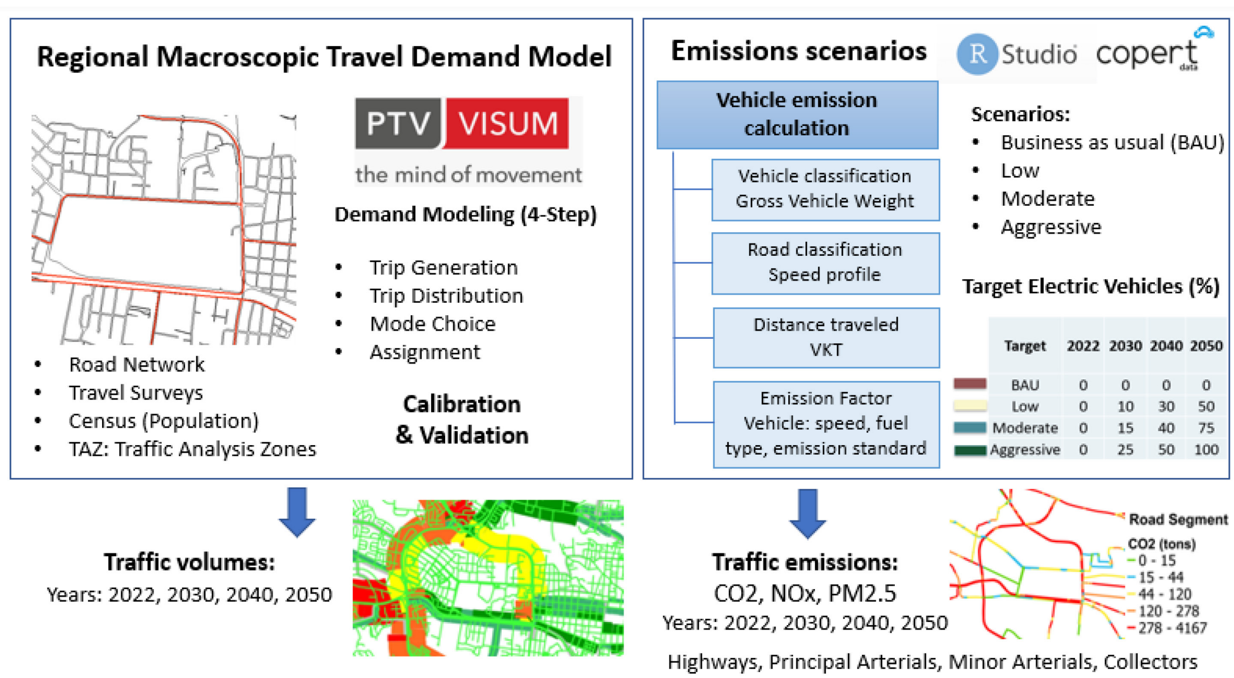


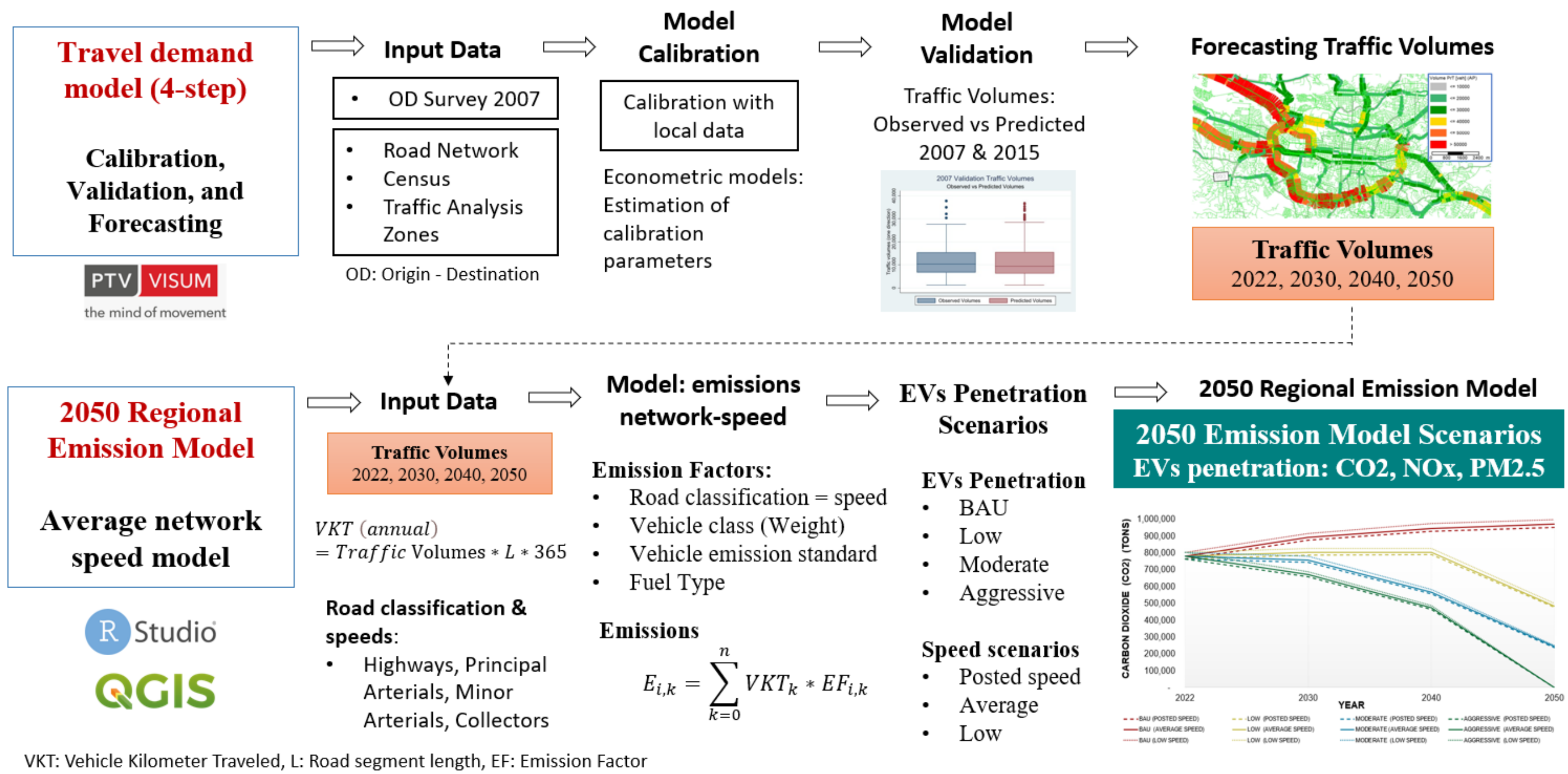
Figure 3.3 shows an extended view of the methodology. It has two main components: (1) the travel demand model and (2) the 2050 regional emission model. The input data in the travel demand model uses an origin-destination travel survey from 2007. This is a limitation as it is the only travel survey elaborated in the country (MIVAH, 2008a). In addition, the model requires the road network, Traffic Analysis Zones (TAZ), and population census. TAZ where defined by the Ministry of Human Settlements of Costa Rica (MIVAH, 2008a).

Based on the travel origin-destination survey, the calibration parameters are estimated using econometric models. The model is validated by using ground-truth data for the observed traffic data measured as the Annual Average Daily Traffic (AADT), which the Ministry of Transportation collects. For the case study, the most robust AADT dataset is from 2015. Beyond this year, data collection is minimal due to insufficient funding to replace malfunctioning equipment and maintenance. Thus, a first model is created corresponding to the year 2007 based on the 2007 origin-destination travel survey, and it is validated with the 2007 observed AADT. The model is forecasted to 2015 and validated with 2015 observed AADT. The 2015 traffic model is forecasted for 2022, 2030, 2040, and 2050.

The traffic volumes obtained from 2022 to 2050 from the PTV Visum model are used as input for the regional emission model created in R Studio. The links and traffic volumes from the PTV Visum model are assigned to the road classification of the case study for highways, principal arterials, minor arterials, and collectors, and the Vehicle Kilometer Traveled (VKT) per link is estimated. Emission factors are selected based on average speed profile per road classification, Gross Vehicle Weight (GVW), fuel type, and vehicle emission standard. Traffic emissions are estimated based on the VKT, emission factors per vehicle type, and road classification. The functional unit of this emission model is vehicles. Thus, emissions are direct estimates from vehicle traveling, excluding additional emissions related to the pavement-tire interaction, or supply chain from vehicle's production and disposal.

Emission scenarios are estimated for 2022 until 2050: the business as usual (BAU), low, moderate, and aggressive scenarios to evaluate the potential reduction of CO2 emissions and air pollutants NOx and PM2.5. The emission scenarios depend on traffic growth expressed as Vehicle Kilometer Traveled (VKT); speed sensitivity (posted speed, average speed, low speed), which incorporates the effect of emission increment given reduced speeds due to congestion; change of vehicle emission standards (EURO); and target scenarios for the penetration of electric vehicles into the fleet. The long-term emission scenarios can provide findings to elaborate new policies and strategies and monitor the progress of reducing emissions and targets.

Figure 3. 3 Extended Methodology: Travel Demand Model and 2050 Regional Emission Model



3.2.1 Travel demand model

The case study is developed at the Great Metropolitan Area (GAM is the Spanish acronym) of Costa Rica. It is a polycentric city having four capital provinces, with the country's capital San José at its center. The travel demand model was created and calibrated for GAM, to later conduct decarbonization analyses for the province of San José.

The country's only Origin–Destination (OD) survey is from 2007 (MIVAH, 2008a). Thus, this year was used as a base model. A calibration based on the OD survey and validation of the model with ground-truth observed traffic volumes was conducted. The latest and most reliable observed traffic dataset collected by the Ministry of Transportation is from 2015. Thus, an average network traffic growth was applied to the 2007 model to estimate a 2015 model, and it was validated with observed traffic for the Annual Average Daily Traffic (AADT).

Given that Costa Rica has only made one OD survey, model parameters are assumed to remain unchanged through the future years. There were limitations of accessibility and incomplete datasets for public transport. Thus, the transport demand model was developed to conduct a vehicle fleet analysis, and passenger analyses were out of scope.

Figure 3.4 shows the Traffic Analysis Zones (TAZ) corresponding to GAM and includes San José (blue color). Travel demand from the neighboring provinces Alajuela, Heredia, and Cartago is estimated to calculate external trips and incoming traffic to San José. Figure 3.5 looks at the road classification: highways, principal arterials, minor arterials, and collectors.

Pre-existing Traffic Analysis Zones (TAZ) for residential, commercial, and industrial areas with an Origin-Destination (OD) travel survey were used (MIVAH, 2008b) for a total of 357 TAZ for a total area of 1,202.76 Km^2 for GAM. San José Metropolitan has 178 internal TAZ with an area of 551.49 Km^2. There was a geographical mismatch of coordinates between the TAZ created in 2007 and the new geographical system for the census tracks obtained at a block level. Additional work had to be performed to aggregate the census tracks within the TAZ boundaries.

Figure 3. 4 Traffic Analysis Zones for the Great Metropolitan Area of Costa Rica

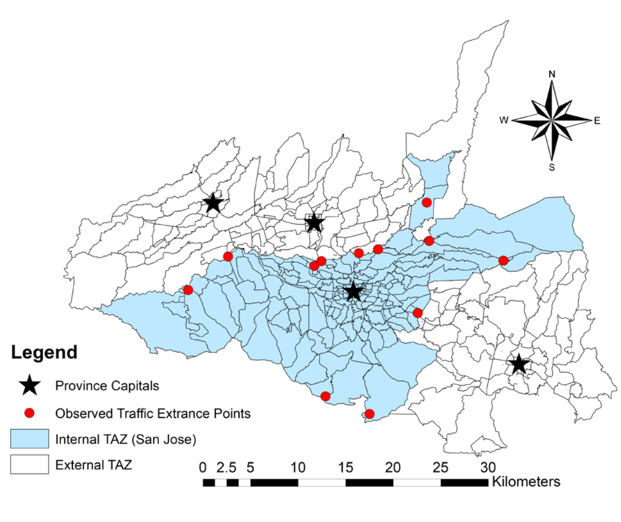
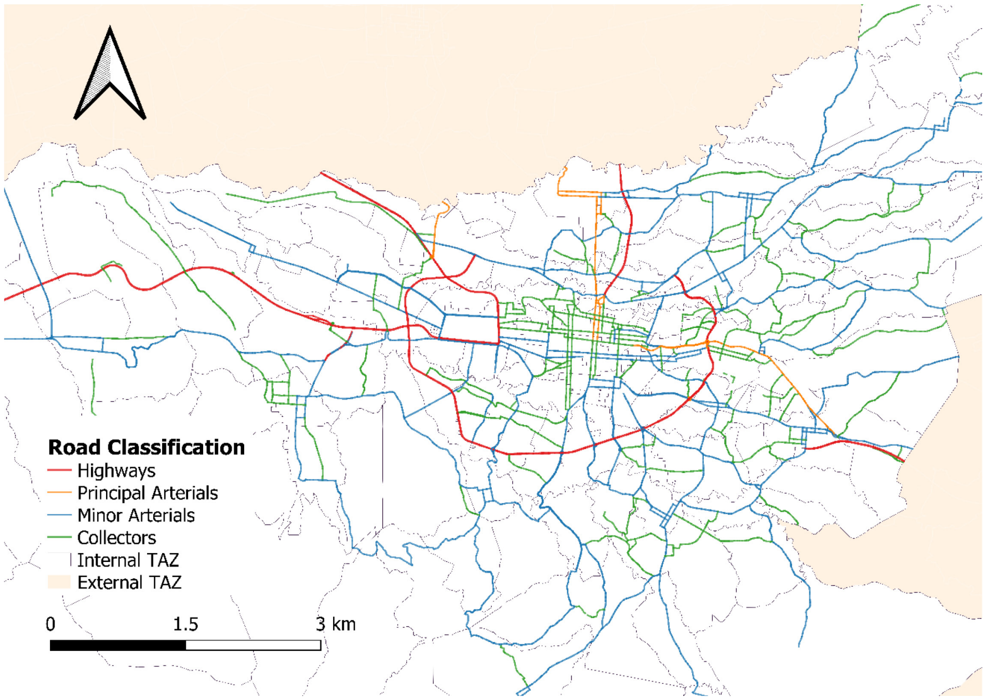


Figure 3. 5 Road Classification for internal TAZ



The Four-Step Demand Modeling is used. This model includes the following steps: (1) Trip Generation, (2) Trip Distribution, (3) Mode Choice, and (4) Network Assignment, as shown in Figures 3.6 and 3.7. Due to the complexity of travel demand, the model breaks down into four steps. The inputs are Origin-Destination travel surveys and census, socioeconomics and demographics, the transport network, and land use (Mansoureh & Ardeshiri, 2017).

Figure 3. 6 Four-step model applied to the case study of Costa Rica

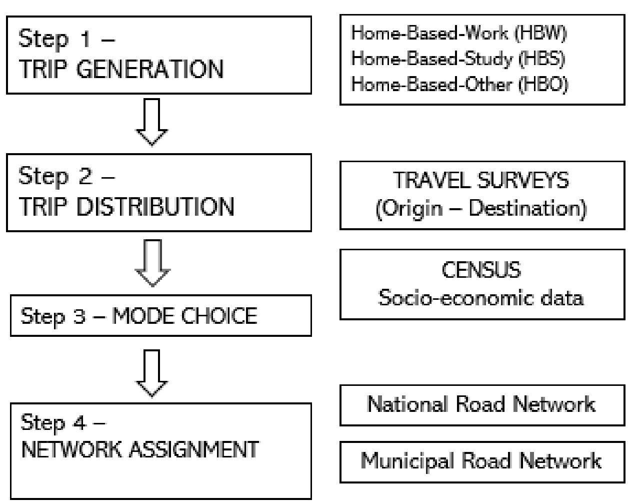
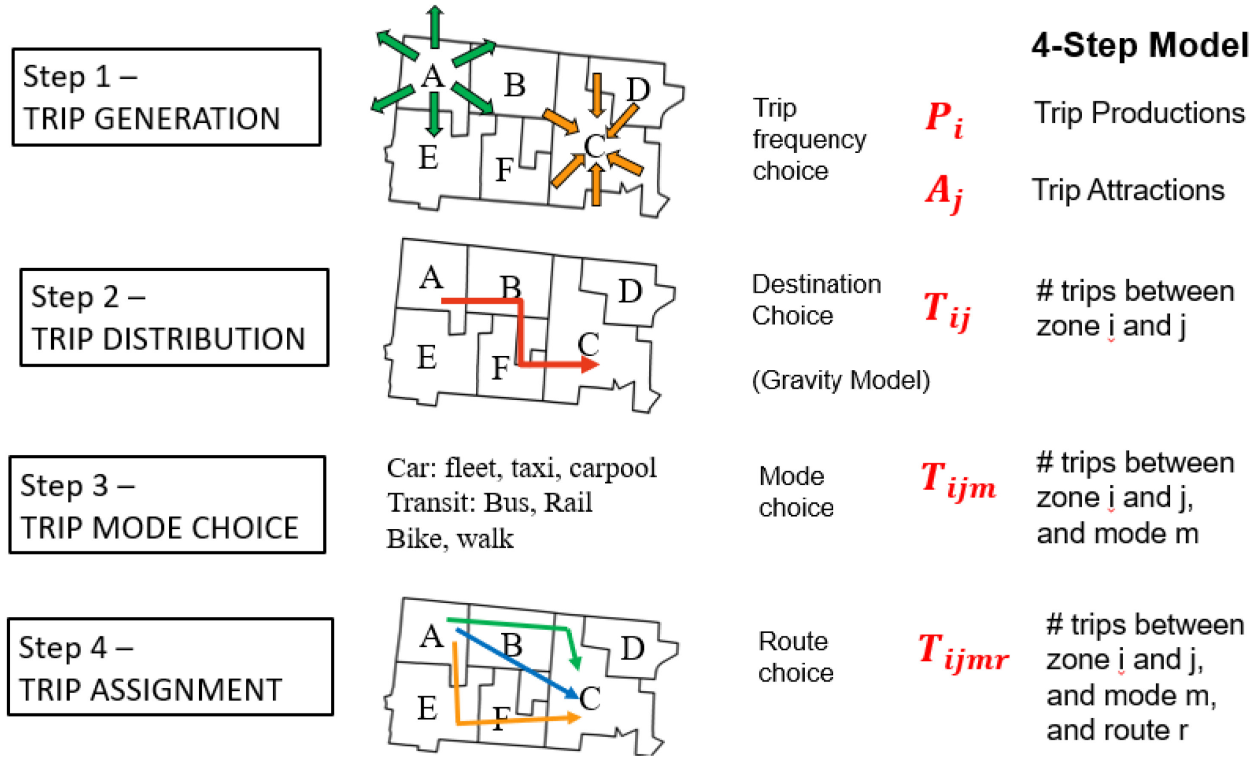


Figure 3. 7 Description of four-step model



(Van Nes, 2022)

3.2.1.1 Trip Generation Step

As shown in Figure 3.7, the Trip Generation Step estimates Trip Productions (P_i) (from zone i) and Trip Attractions (A_j) (to zone j), and it is assumed that there are no trip chains from an Origin-Destination matrix. Trip Generation is used to estimate the trips that are produced from an origin (i) and the trips that a zone attracts (j destinations) (Ortúzar & Willumsen, 2011).

In Trip Productions, travel behavior is influenced by income, car ownership, household structure, and family size (Ortúzar & Willumsen, 2011). In the case study, after removing inconsistent data and outliers, the travel survey had a sample size of 42,203 individuals. The four-step model aggregates data at the TAZ level. Thus, household information is aggregated by TAZ to use in regression analysis techniques. Household income is an important travel predictor. While the OD travel survey reports household income, the census datasets did not report this data at a block level. This reporting difference created a mismatch between travel surveys and census attributes.

Household car ownership was used due to the inability to incorporate income. Tables 3.1, 3.2, and 3.3 show correlation matrices based on the travel surveys. The strength of the correlation and collinearity are assessed to determine the regression model for the trip home-based work (HBW), home-based study (HBS), and home-based-others (HBO).

Table 3. 1 Correlation matrix for Home-Based-Work and Trip Productions

r / p-value	HBW Trips	HH-size	Workers-HH	Car-own-HH
HBW TripsP	1.0000			
HH-size	0.4108 0.0000 (*)	1.0000		
Workers-HH	0.7002 0.0000 (*)	0.5370 0.0000 (*)	1.0000	
Number-Cars-HH	0.1301 0.0000 (*)	0.0152 0.2111 (*)	0.1131 0.0000 (*)	1.0000

HBW TripsP: Home-Base-Work trip production; HH-size: Household size; Workers-HH: Workers per household; Number-Cars-HH: Number of cars per household; r: Pearson correlation coefficient; and (*) p-value at 5% significance level

Table 3. 2 Correlation matrix for Home-Based-Study and Trip Productions

r / p-value	HBS Trips	HH-size	Number-Cars-HH
HBS TripsP	1.0000		
Students-HH	0.6190 0.0000 (*)	1.0000	
Number-Cars-HH	0.0139 0.4351 (*)	0.0113 0.5282 (*)	1.000

HBS TripsP: Home-Base-Study trip production; Students-HH: students per household; Number-Cars-HH: Number of cars per household; r: Pearson correlation coefficient; and (*) p-value at 5% significance level

Table 3. 3 Correlation matrix for Home-Based-Others and Trip Productions

r / p-value	HBO Trips	People-HH	Number-Cars-HH
HBO TripsP	1.0000		
People-HH	0.2747 0.0000 (*)	1.0000	
Number-Cars-HH	0.0412 0.0858 (*)	-0.0377 0.1161 (*)	1.0000

HBO TripsP: Home-Based-Others trip production; People-HH: people per household; Number-Cars-HH: Number of cars per household; r: Pearson correlation coefficient; and (*) p-value at 5% significance level

In the case of Home-Based-Work (HBW) shown in Table 3.1, workers per household present a higher correlation (0.7002) with trip productions to work (HBW TripsP). There is collinearity between workers per household and household size. The number of cars per household presents a lower correlation with HBW TripsP, but it is significant.

Table 3.2 shows the correlation matrix for Home-Based-Study (HBS). The number of students per household is significant (p-value <0,05), and the correlation coefficient is 0.6190. The Number of cars per household is not a significant predictor of trips at a 5% significance level.

Home-Based-Others (HBO) correspond to trip purposes different than work or study. Table 3.3 shows that people per household have a higher correlation than car ownership per household.

Given the nature of travel data as non-negative integer values, a count data approach was used for Poisson and Negative Binomial regression models and tested for goodness of fit to analyze if data fits these models (Washington et al., 2003). Table 3.5 shows the estimated effects of explanatory variables on trips per household during peak-hour for each trip purpose.

In a Poisson regression model, the probability of zones i having y_i trips (where y_i is a non-negative integer). This is expressed as:

$$P(y_i) = \frac{EXP(-\lambda_i){\lambda_i}^{y_i}}{y_i!} \quad \text{Equation (3.1)}$$

$P(y_i)$ is the probability of zone *i* having y_i trips and λ_i is the Poisson parameter for zone *i*, which is equal to the expected number of trips at zone *i*, $E[y_i]$. The Poisson parameter λ_i is the mean of the expected count of events per period, and it is as a function of explanatory variables that were established in the correlation matrix analysis above and can be expressed as a function μ_i of site-specific attributes (Washington et al., 2003). Thus, a Poisson distribution with a mean per time unit of μ_i can be expressed as equations 3.1 and 3.2 (Miranda-Moreno, 2017).

$$Y_i|\mu_i, T_i \sim Poisson\ (T_i \cdot \mu_i), for\ i = 1, \ldots, n\ and\ \mu_i > 0 \quad \text{Equation (3.2)}$$

In the Poisson regression model, the conditional mean and variance of the count variable are constrained to be equal, that is

$$E[Y_i|\mu_i] = Var[Y_i|\mu_i] = \mu_i \quad \text{Equation (3.3)}$$

When this condition cannot be held, then the data is either under-dispersed ($E[Y_i|\mu_i] > Var[Y_i|\mu_i]$) or over-dispersed ($E[Y_i|\mu_i] < Var[Y_i|\mu_i]$. One of the main reasons of this is that variables influencing the Poisson regression were excluded. The Negative Binomial (NB) regression model can be used as the Poisson/Gamma model is not constraint to having the mean and variance to be equal (Miranda-Moreno, 2017; Washington et al., 2003).

$$P(y_i|\mu_i, \phi) = \frac{\Gamma(y_i + \phi)}{y_i!\,\Gamma(\phi)} (\frac{\phi}{\phi + \mu_i})^{\phi} (\frac{\mu_i}{\phi + \mu_i})^{y_i} \quad \text{Equation (3.4)}$$

Where $\Gamma(\cdot)$is the gamma function and $\phi = 1/\alpha$ is the dispersion parameter. If α equals zero, then this model becomes a Poisson regression model. Additionally, the mean and variance of the NB regression model is expressed as follows (Miranda-Moreno, 2017; Washington et al., 2003).

$$E(y_i|\mu_i, \alpha) = \mu_i \quad \text{Equation (3.5)}$$

$$Var(y_i|\mu_i, \alpha) = \mu_i + \alpha{\mu_i}^2 \quad \text{Equation (3.6)}$$

The Likelihood Ratio Test (LRT) of $\phi = 0$ is a test of the dispersion parameter that determines if there is dispersion. This test assesses the mean and variance of a Poisson distribution against the alternative hypothesis that the variance is different than the mean. If ϕ equals zero, then the data follows a Poisson regression model, if not, then the data follows a Negative Binomial distribution.

Thus, the null hypothesis is Ho: $\phi = 0$ where the dispersion parameter is zero, against the alternative hypothesis H_1: $\phi \neq 0$ where the dispersion parameter is not zero and there is a gamma function. To carry out the hypothesis testing, the Log Likelihood (LL) of the Poisson and Negative Binomial distribution must be estimated to conduct a chi-square test (Miranda-Moreno, 2017).

For the Poisson model, the log likelihood function is shown in Equation 3.7. X_i is a vector of the explanatory variables, β is a vector of the estimable parameters, and λ_i is the Poisson parameter for zone *i*. The expected number of trips per period at zone *i* is $E[y_i] = \lambda_i = EXP(\beta X_i)$ (Washington et al., 2003).

$$LL(\beta) = \sum_{i=1}^{n}[-EXP(\beta X_i) + y_i \beta X_i - LN(y_i!)] \qquad \text{Equation (3.7)}$$

Where,
$\beta X_i = \beta_0 + \beta_1 X_{1i} + \ldots + \beta_p X_{ip}$

For the Negative Binomial model, the log likelihood function is shown in Equation 3.8. $\Gamma(\cdot)$ is the gamma function and $\phi = 1/\alpha$ is the dispersion parameter (Washington et al., 2003).

$$LL(\lambda_i) = \prod_i \frac{\Gamma\left(\left(\frac{1}{\alpha}\right) + y_i\right)}{\Gamma\left(\frac{1}{\alpha}\right) y_i!} \left(\frac{1/\alpha}{\left(\frac{1}{\alpha}\right) + \lambda_i}\right)^{1/\alpha} \left(\frac{\lambda_i}{\left(\frac{1}{\alpha}\right) + \lambda_i}\right)^{y_i} \qquad \text{Equation (3.8)}$$

The LRT (Likelihood Ratio Test), that is, the LR statistic is shown in Equation 3.9 (Miranda-Moreno, 2017).

LRT = -2[LL (Poisson) – LL (Negative Binomial)] Equation (3.9)

Where,
LL (Poisson) is the log likelihood for the Poisson regression model
LL (Negative Binomial) is the log likelihood for the Negative Binomial regression model

A goodness-of-fit verifies if the data fits the model. This analysis measures if the observed data corresponds to the assumed model (fitted model) by comparing the observed values to the expected values (predicted or fitted). The Pearson chi-square statistic is commonly used in Poisson regression models. Equation 3.10 shows the Pearson chi-square statistic, where Y_i is the observed value and μ_i is the predicted value. It is calculated as the square difference between the observed and predicted values divided by the variance of predicted values (Spiegelman et al., 2011).

$$\chi^2 = \sum_{i=1}^{n} \frac{(Y_i - \mu_i)^2}{Var\ (\mu_i)} \qquad \text{Equation (3.10)}$$

The Pearson chi-square statistic has a chi-square distribution with degrees of freedom n – k which verifies if the data fits well the model. k is the number of parameters in the model. In the hypothesis test for goodness-of-fit, the null hypothesis (H_o) states that the data with k parameters fits well the model, and the alternative hypothesis (H_1) states that the data with k parameter does not fit the model.

For the trip productions (P_i) (from zone i), a regression model is used to predict trips for home-based work (HBW), home-based study (HBS) and home-based-others (HBO). A Likelihood Ratio Test (LRT) between a Poisson and Negative Binomial model is conducted to determine if the dispersion parameter (ϕ) is zero. This assessment will determine which data fits better the model. Table 3.4 shows the results for the hypothesis testing where H_o: $\phi = 0$, the dispersion parameter is zero and H_1: $\phi \neq 0$, the dispersion parameter is not zero, and there is a gamma function.

Seven models are developed. There is a HBW (model A) that includes households that own a car and households that don't own a car. This model is disaggregated in two models (B1 and B2) for workers owning a car and workers not owning a car, respectively. The same structure is applied to trips based on home-based others (Models D, E1, and E2). In the Likelihood Ratio Test (LRT), the p-values are larger than the significance level 5%. A p-value of 1.0 suggests that there is no statistically significant evidence to support the alternative hypothesis. Therefore, we can conclude that the null hypothesis is plausible, given the data we have observed. Thus, there is no significant evidence to reject H_o. Thus, a Poisson Model fits better the data, and it is suitable for estimating the regression parameters.

Table 3. 4 Likelihood Ratio Test (LRT) for dispersion analysis for trip productions per purpose

Model		**Purpose Group**	**(n)**	**LRT Test of ϕ=0 p-value**	**Ho vs H1**	**Regression**
A	HBW	Home-Based-Work (All)	6,798	1.000	No evidence to reject Ho	Poisson
B1	HBW-C	Home-Based-Work (Car)	3,295	1.000	No evidence to reject Ho	Poisson
B2	HBW-NC	Home-Based-Work (No Car)	3,503	1.000	No evidence to reject Ho	Poisson
C	HBS	Home-Based-Study	3,143	1.000	No evidence to reject Ho	Poisson
D	HBO	Home-Based-Others (All)	1,742	1.000	No evidence to reject Ho	Poisson
E1	HBO-C	Home-Based-Others (Car)	833	1.000	No evidence to reject Ho	Poisson
E2	HBO-NC	Home-Based-Others (No Car)	909	1.000	No evidence to reject Ho	Poisson

Ho: $\phi = 0$, the dispersion parameter is zero
H1: $\phi \neq 0$, the dispersion parameter is not zero, and there is a gamma function
n = Number of observations

A Poisson regression was applied to trip productions per purpose, as shown in Tables 3.5 and 3.6.

Table 3. 5 Estimated effects of explanatory variables on production trips per household

Model	Purpose Group	Variables	Number of observations (n)	Coefficient	Standard Error	z Stat	p-value	95% confidence interval	
A	HBW	Constant	6,798	-0.2027	0.02131	-9.51	0.000	-0.2444	-.16092
		Workers-HH		0.2904	0.00795	36.49	0.000	0.2748	0.3060
		Number-cars-HH		0.0331	0.01193	2.78	0.006	0.0097	0.0565
B1	HBW-C	Constant	3,295	-0.1579	0.02943	-5.36	0.000	-0.2155	-0.1002
		Workers-HH-Car		0.2905	0.01125	25.82	0.000	0.2684	0.3126
B2	HBW-NC	Constant	3,503	-0.2127	0.02858	-7.44	0.000	-0.2687	-0.1566
		Workers-HH-No-Car		0.2948	0.11090	26.58	0.000	0.2730	0.3165
C	HBS	Constant	3,143	-0.1800	0.03362	20.86	0.000	-0.2459	-0.1141
		Students-HH		0.2649	0.01270	-5.35	0.000	0.2399	0.2898
D	HBO	Constant	1,742	0.03427	0.04318	0.79	0.427	-0.0503	0.1189
		People-HH		0.07993	0.01272	6.28	0.000	0.0549	0.1048
E1	HBO-C	Constant	833	0.06883	0.06173	1.12	0.265	-0.0521	0.1898
		People-HH-Car		0.06706	0.17155	3.91	0.000	0.0334	0.1006
E2	HBO-NC	Constant	909	0.02684	0.05416	0.50	0.620	-0.0793	0.1330
		People-HH-No-Car		0.06857	0.01313	5.22	0.000	0.0428	0.0943

Estimates at 5% significance level

Table 3.5 shows the estimated effects of explanatory variables on production trips per household. The constant parameters of Model D, Model E1, and Model E2 have a p-value of 0.427, 0.265, and 0.620 respectively. Larger p-values suggest that changes in the predictor are not associated with the changes in the response. Thus, these predictors are not used in the travel demand model. On the other hand, a low p-value (p-value < 0.05) means that a predictor is likely to be meaningful to the model because changes in the predictor variable are related to changes in the response variable. Table 3. 6 shows the Poisson regression model for trip productions per purpose.

Table 3. 6 Poisson regression model for trip productions per purpose

Model	Purpose Group	Trip Production (TP) per purpose
A	Home-Based-Work	TP (A)= -0.2027 + 0.2904 * Workers-HH + 0.0331 * Number-cars-HH
B1	Home-Based-Work	TP (B1-car) = -0.1579 + 0.2905 * Workers-HH-Car
B2	Home-Based-Work	TP (B2-no-car) = -0.2127 + 0.2948 * Workers-HH-No-Car
C	Home-Based-Study	TP (C) = -0.1800 + 0.2649 * Students-HH
D	Home-Based-Others	TP (D) = 0.0799 * People-HH
E1	Home-Based-Others	TP (E1-car) = 0.06706 * People-HH-Car
E2	Home-Based-Others	TP (E2-no-car) = 0.06857 * People-HH-No-Car

By looking at the magnitude of the parameters of each model in Table 3.6, work purposes generate more traveling, followed by study trips. Trips related to other purposes (i.e., trips to government services, medical appointments) generate significant less trips than work and study.

A Pearson chi-square statistic was performed to evaluate the goodness-of-fit of the data in the model, as shown in Table 3.7. The null hypothesis (H_o) states that the model with k parameters fits well, and the alternative hypothesis (H_1) states that the model with k parameter does not fit. The p-values are larger than the significance level 5%, and there is no significance evidence to reject H_o. Thus, the model k parameters are accepted.

Table 3. 7 Goodness-of-fit Pearson Statistics for Poisson Regression Model

Model	Purpose Group	(n)	(k)	n - k	Pearson goodness-of-fit χ^2	p-value
A	HBW	6,798	3	6,795	1181.076	1.000
B1	HBW-C	3,295	2	3,293	599.1695	1.000
B2	HBW-NC	3,503	2	3,501	584.8324	1.000
C	HBS	3,143	2	3,141	591.6517	1.000
D	HBO	1,742	3	1,739	444.1944	1.000
E1	HBO-C	833	2	831	212.1851	1.000
E2	HBO-NC	909	2	907	299.9617	1.000

Ho states that the model with k parameters fits well, and the alternative hypothesis
H1 states that the model with k parameter foes not fit
Estimates at 5% significance level
n = Number of observations
k = Number of parameters in the model

In Trip Attractions, the land use typology will attract trips depending on their purpose for work, study or others. Examples of land use attributes affecting attractions are office space, schools, retail space, government institutions, and healthcare services characterized by areas or densities. In this case study, trip attraction rates were estimated based on trip destinations per purpose and land use expressed in areas in square kilometers (Km^2). Areas were calculated from Open Street Map datasets including offices, industrial areas, and shopping centers (OpenStreetMap, n.d.).

In the case of Home-Based-Work (HBW) purpose, the land use areas were estimated for mixed-used developments (offices and retail stores) and individual retail stores. In the case of Home-Base-Others (HBO) purpose, land-use areas incorporated mixed-used developments, individual retail stores, and hospitals. These areas were aggregated at a Traffic Analysis Zones (TAZ) level, for a total of 357 TAZ Tables 3.8 and 3.9 show a correlation matrix between trip destinations per TAZ and land use areas (Km^2). For the trip purpose of Home-Base-Study (HBS), lack of data availability limited the estimation of a regression model for local conditions. Thus, the attraction regression was selected from the Trip Generation Manual from the United States of America (ITE, 2012).

Tables 3.8 and 3.9 show the correlation matrices for trip attractions for HBW and HBO respectively. Both cases have a significant correlation (p-value < 0.05) and a positive correlation between trip destination and land use.

Table 3. 8 Correlation matrix corresponding to Trip Attractions (HBW)

Home-Base-Work and Land Use

r / p-value	HBW TripsD	Work-Land
HBW TripsD	1.0000	
Work-Land	0.4695 0.0000 (*)	1.0000

HBW TripsD: Trip Destinations for work purposes
Work-Land: Areas of land use for work
(*) p-value at 5% significance level

Table 3. 9 Correlation matrix corresponding to Trip Attractions for (HBO)

Home-Base-Others and Land Use

r / p-value	HBW TripsD	Others-Land
HBO TripsD	1.0000	
Others-Land	0.3616 0.0000 (*)	1.0000

HBO TripsD: Trip Destinations for other purposes
Others-Land: Areas of land use for other purposes
(*) p-value at 5% significance level

Table 3.10 shows the Likelihood Ratio Test (LRT) for dispersion analysis for trip attractions for HBW and HBO. In both cases, the p-values are smaller than $\alpha = 0.05$. Thus, the null hypothesis that assumes the dispersion parameter is zero is rejected, and a Negative Binomial regression model should be applied.

Table 3. 10 Likelihood Ratio Test (LRT) for dispersion analysis for trip attractions per purpose

Model	**Purpose Group**		**(n)**	**LRT Test of ϕ =0 p-value**	**Ho vs H1**	**Regression**
F	HBW(A)	Home-Based-Work (Attractions)	357	0.000	Reject Ho	NB
G	HBO(A)	Home-Based-Others (Attractions)	357	0.000	Reject Ho	NB

Ho: $\phi = 0$, the dispersion parameter is zero; H1: $\phi \neq 0$, the dispersion parameter is not zero, and there is a gamma function; n = Number of observations; NB = Negative Binomial

Tables 3.11 and 3.12 show the Negative Binomial (NB) regression for trip attractions for HBW and HBO. The Akaike Information Criterion (AIC) is used to test the performance of the NB model against the Poisson regression model. AIC is based on the maximum likelihood, and it is defined in Equation 3.8. The regression model with the lowest AIC performs better (Miranda-Moreno, 2017). Table 3.13 shows the results for AIC showing that Model F and G performed better with a Negative Binomial approach.

$$AIC = -2 \ln(L) + 2k \qquad \text{Equation (3.8)}$$

Where,
L: maximum likelihood
K: number of parameters in the model

Table 3. 11 Estimated effects of explanatory variables on attraction trips per household

Model	Purpose Group	Trip Attraction (TA) per purpose	Regression Approach
F	Home-Base-Work	TA (F)= 2.657 + 17.635 * (Areas work-land use)	Negative Binomial
G	Home-Base-Others	TA (G)= 0.955 + 19.267 * (Areas others-land use)	Negative Binomial
H	Home-Base-Students	TA (H) = 1.827+137.126*(Areas education)	(ITE, 2012)

Table 3. 12 Estimated effects of explanatory variables on attraction trips per household

Model	Purpose Group	Variables	(n)	Coefficient	Standard Error	z Stat	p-value	95% confidence interval	
F	HBW(A)	Intercept	357	2.657	0.0962	27.61	0.000	2.468	2.845
		Work-Land		17.635	2.3932	7.37	0.000	12.945	22.326
G	HBO(A)	Intercept	357	0.9553	0.1170	8.16	0.000	0.7260	1.1847
		Others-Land		19.267	2.7968	6.89	0.000	13.787	24.746

Estimates at 5% significance level; n = Number of observations

Table 3. 13 Akaike Information Criterion to test the performance of Poisson and Negative Binomial regression models

Model	Purpose Group	(n)	AIC Poisson Regression	AIC Negative Binomial Regression
F	Home-Base-Work	357	13,993.420	2,972.114
G	Home-Base-Others	357	4,508.047	1,841.186

AIC: Akaike Information Criterion
Estimates at 5% significance level; n = Number of observations

Trip productions and attractions regression models were estimated based on the OD travel survey. The PTV Visum uses numerical data, and census data must be introduced in these regression models. There are some limitations in the available data. The census does not report household income, which is an important predictor of trip production. Also, the census reports car ownership as owning one vehicle per household, which contributes to the model error. Trip attractions are based on land use for HBW and HBO uses the land use classification provided by Open Street Map. The lack of local data for the category school limited the estimation of a trip attraction regression model, and a regression model from the U.S. Trip Generation Manual was used (ITE, 2012).

3.2.1.2 Trip Distribution Step

Referring to Figure 3.7, the trip distribution (Tij) step uses trip productions (Pi) and attractions (Aj) and distributes them among the Traffic Analysis Zones (TAZ). The gravity model calculates the number of trips per purpose between two pairs of TAZ (T_{ij}). Trips are directly proportional to the trip ends and inversely proportional to the cost of travel, usually expressed as travel time (travel impedance). The larger the spatial separation between an origin and destination, the fewer trips are generated. TAZ containing more activities (attractions) will attract more trips. The gravity model is shown in Equation 3.9 (Mansoureh & Ardeshiri, 2017; Martin & Mcguckin, 1998).

$$T_{ij} = P_i * \frac{A_j * F_{ij} * K_{ij}}{\sum_{j=1}^{n} A_j * F_{ij} * K_{ij}}$$ Equation (3.9)

Where
T_{ij} = number of trips produced in zone i and attracted to zone j,
P_i = number of trips produced by zone i,
A_j = number of trips attracted to zone j,
F_{ij} = friction factor based on observed percentages of trip distributions (gamma-function)
K_{ij} = specific zone-to-zone adjustment factor

The travel impedance is addressed by the gamma-function as expressed in Equation 3.10 and it varies by trip purpose. It is a function that describes the relative willingness to travel as a function of travel time, travel distance, travel costs, or a combination of these attributes. This function reflects the travel behavior given the perception of distance in a trip (Martin & Mcguckin, 1998).

$$F_{ij}^{p} = a * t_{ij}^{b} * e^{c * t_{ij}}$$ Equation (3.10)

Where,
F_{ij} = friction factor between zones i and j
a, b, c = model coefficients
t_{ij} = travel time between zones i and j
e = the base of the natural logarithms

For the case study, the functions of travel impedance expressed as the relationship between trips and travel time per trip purpose are shown in Figure 3.8. To estimate the coefficients of friction factors, the gamma-function is transformed into a log-linear function as shown in Equation 3.11 (Martin & Mcguckin, 1998) resulting in the model parameters a, b, and c shown in Table 3.14.

$$\ln(f) = \ln(a) + b * \ln(t) + c * t$$ Equation (3.11)

Figure 3. 8 Travel impedance for the case study

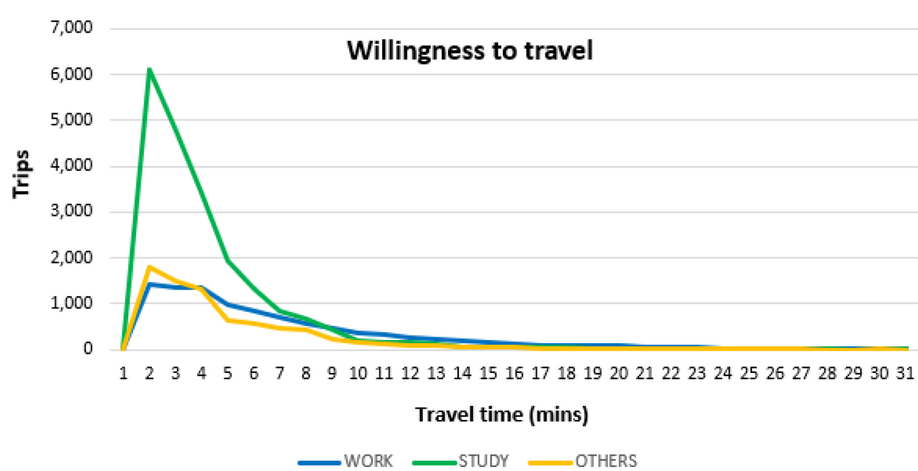


Table 3. 14 Gamma function coefficients for friction factors

Trip Purpose	a	b	c
HBW	2,572	-0.4442	-0.1116
HBS	14,380	-1.2108	-0.1434
HBO	3,137	-0.1583	-0.6447

3.2.1.3 Traffic Assignment Step

Referring to Figure 3.7, traffic assignment computes the traffic volumes on each link (road segment), which is the number of trips (T_{ijmr}) between zone i and j, and mode m, and route r (Mansoureh & Ardeshiri, 2017). This case study is a vehicle-trip-based model (i.e., vehicle trips rather than person trips), and there is no need to incorporate the mode choice (m) step.

Procedures for traffic assignment rely on the relationship of road capacity and travel times, expressed by a volume-delay function $t_l(v_l)$ shown in Equation 3.12, which is the average travel time t_l on link l with a traffic volume v_l on link l. The average travel time t_l is the free flow time t_0 multiplied by a congestion function *f(x)*. This congestion function relies on the volume/capacity ratio (*v/c*) (Spiess, 1990).

$$t_l(v_l) = t_0 * f\left(\frac{v}{c}\right)$$ Equation (3.12)

BPR developed by the U.S. Bureau of Public Roads is the most well-known volume-delay function, and it is expressed as follows (Mansoureh & Ardeshiri, 2017).

$$t_l(v_l) = t_{ol} * \left(1 + \alpha\left(\frac{v_l}{c_l}\right)^{\beta}\right)$$ Equation (3.13)

Where,
$t_l(v_l)$ = average travel time on link l with traffic volumes on link l
t_{ol} = free-flow travel time on link l
v_l = traffic volumes on link l
c_l = road capacity on link l
α and β = congestion parameters

When traffic volumes increase, speed decreases, and congestion increases (Martin & Mcguckin, 1998). The BPR function (U.S. Bureau of Public Roads) is not appropriate for traffic flow conditions near capacity and volume-delay functions because the travel time converges to infinity. Similarly, the Davidson's function presents limitations with calibration under these conditions (Mansoureh & Ardeshiri, 2017).

More volume-delay functions have been developed; however, it has been found that the Conical delay-function shown in Equation 14 has a better performance for congested road networks (P. A. PTV Visum, 2020). This function has similar results to the BPR function when the

Volume/Capacity ratio is less than 1. The Conical delay-function overcomes the BPR function disadvantages when the Volume/Capacity ratio is equal to or greater than 1. This function is expressed as follows (Spiess, 1990):

$$f^c(x) = 2 + \sqrt{\alpha^2(1-x)^2 + \beta^2} - \alpha(1-x) - \beta \qquad \text{Equation (3.14)}$$

Where β is given as

$$\beta = \frac{2\alpha - 1}{2\alpha - 2}$$

$f^c(x)$ = conical congestion function
x = Volume/Capacity
α = congestion parameter and it is larger than 1
β = congestion parameter as function of α

The case study is under congested conditions, and a conical delay-function is more appropriate. A literature review was undertaken to find the congestion parameters. A study from Bogotá-Colombia was found to have similar road geometry, speed, and capacity characteristics to the Costa Rican case study, and it is used as a reference.

For Bogotá-Colombia, Márquez et al. (2014) measured travel time at free-flow, speed, and capacity per hour per lane for six multilane roads. They estimated congestion parameters for a BPR and Conical volume-delay function. For the Conical function, the estimated α-values were between $2.027 < \alpha < 4.781$ for capacities between 1,620 and 1,750 passenger-car/hour/lane (pc/h/ln), respectively, and $3.094 < \alpha < 4.781$ for speeds between 78.45 km/h and 104.5 km/h. Highways from Costa Rica report higher capacities, and it is suggested to use higher values of α for road geometries that allow higher free-flow speeds. For the case study travel demand model, the congestion parameters used are shown in Table 3.15. The congestion parameters are increased due to the higher road capacities in the case study. In addition, the validation process of the model showed a better performance when using the α-values shown in Table 3.15.

Table 3. 15 Selected congestion parameters for the conical volume-delay function

Road classification	Number of lanes per direction	Posted speed (Km/h)(*)	Capacity (pc/h/ln)(**)	α Conical
Highways, 3 lanes	3	90	2,100	5
Highways, 2 lanes	2	90	2,000	4.7

(*) Posted speed taken as Free Flow Speed (FFS)
(**) pc/h/ln = passenger cars per hour per lane (flow rate)

The assignment algorithms aim to assign trips between origin and destination through the most convenient route. This step is where the demand (travel demand: trip productions and attractions) and the supply (transport system infrastructure) meet. A Deterministic User Equilibrium Assignment (DUE) was applied for this case study.

Static traffic assignment approaches are classified into User Equilibrium Assignment (UE) and System Optimum Assignment (SO). In the UE approach, users select the route based on their individual interest to minimize their travel time (it is a selfish choice); while in the SO, the selection of routes is according to the collective interest, and the travel time is minimized for the system (road network). A UE approach is commonly used as it is more realistic, while the SO approach can be used in traffic management by transport agencies (Alecsandru, 2018; Mansoureh & Ardeshiri, 2017).

User Equilibrium Assignment (UE) is based on Wardrop's equilibrium law: "All travelers choose their optimal route, such that no traveler can improve his/her travel time by unilaterally changing routes". The equilibrium is achieved when Wardrop's first principle is met: "All used routes have the same travel time, which is not greater than the travel time on any unused route". The System Optimum Assignment (SO) is based on Wardrop's second principle: "The average travel time is minimal" (Van Nes, 2022; Mansoureh & Ardeshiri, 2017).

For congested conditions, two main approaches in the User Equilibrium Assignment (UE) are the Deterministic User Equilibrium Assignment (DUE) and the Stochastic User Equilibrium (SUE). In the Deterministic User Equilibrium (DUE), users are assumed to have full knowledge of the traffic conditions and seek the minimum travel time. Travelers have accurate information regarding alternative paths and travel times, and they choose the right path and behave the same (Van Nes, 2022; Saberi, 2021; Mansoureh & Ardeshiri, 2017).

In the Stochastic User Equilibrium (SUE), the users seek the minimum "perceived" travel time, and they can make errors in their route choice (Van Nes, 2022; Saberi, 2021). SUE is a variant of DUE where Wardrop's first principle is relaxed by a lambda parameter that should be calibrated, which would account for the uncertainty of congested roads, perception errors, and using unfamiliar routes (TRB, 2022). When comparing SUE to DUE, SUE assigns traffic a small part of the demand to suboptimal routes, which lifts the strict constraint of Wardrop's first principle, which states that "all used routes have the same travel time, which is not greater than the travel time on any unused route" (P. G. PTV Visum, 2021).

3.2.1.4 Model Validation

After completing the trip assignment step, the external validation of a travel demand model is performed. The validation compares the predicted traffic volumes with observed traffic volumes collected through site traffic counts. There are several metrics to perform traffic volume-related checks: root mean square error (RMSE), coefficient of determination (R^2), and percent assignment error (model deviation) (CAMPO, 2013; Cambridge Systematics Inc., 2010).

The root mean square error (RMSE) measures the deviation between the predicted traffic volumes generated by the travel demand model and the observed traffic counts. The percentage of RMSE is shown in Equation 3.15. Larger percentages of RMSE indicate large deviations between the predicted and observed values, while smaller percentages imply small deviations between the predicted and observed values. Table 3.16 shows the acceptable RMSE adopted by many U.S. Departments of Transportation (DOT), such as the Oregon Department of Transportation, Montana Department of Transportation, and the State of Tennessee. The acceptable error is classified per volume classification, being highways and arterials stricter than roads with lower traffic volumes. The overall model must be under 30% of RMSE (CAMPO, 2013).

$$\%RMSE = \frac{100 * \sqrt{\frac{\sum_j (Model_j - Count_j)^2}{(Number\ of\ Counts - 1)}}}{(\frac{\sum_j Count_j}{Number\ of\ Counts})} \qquad \text{Equation (3.15)}$$

Where,
RMSE = Root Mean Square Error (%)
$Model_j$ = Simulation model traffic volumes
$Count_j$ = Observed traffic count volumes
Number of Counts = Number of traffic count observations

Table 3. 16 Acceptable RMSE by U.S. Departments of Transportation

Volume Classification	RMSE Guidelines (%)
Overall	< 30.00
Larger 20,000	< 25.40
10,000 - 19,999	< 28.30
5,000 – 9,999	< 43.10
< 5,000	< 115.80

The coefficient of determination R^2 shown in Equation 3.16 is used as a measure of goodness of fit statistic of the model. The interpretation is the proportion of the variance of the dependent variable y (model volumes) with respect to the variance of the independent variable x (observed traffic counts) (Washington et al., 2003).

When R^2 is 1, then all the variance is explained by the model and there is a strong relationship between the assigned volumes and traffic counts. When R^2 is 0, then there is no association between the predicted model volumes (y) and the observed traffic counts (x). For the overall model, a minimum R^2 of 0.88 is desired. Moreover, it is recommended to estimate the R^2 for road segments with similar characteristics, for instance, traffic volume group or facility type such as road classification (CAMPO, 2013; Cambridge Systematics Inc., 2010; Washington et al., 2003).

$$R^2 = \left(\frac{n \sum (x_i y_i) - (\sum x_i)(\sum y_i)}{\left[\sqrt{n \sum x_i^2 - (x_i)^2}\right] \left[\sqrt{n \sum y_i^2 - (y_i)^2}\right]} \right)^2 \qquad \text{Equation (3.16)}$$

Where,
x = observed traffic counts
y = simulated model volumes
n = number of counts

Model deviation or percent assignment error is the percentage of error between the predicted and observed values for individual road segments (links), as shown in Equation 3.17. A negative model deviation value indicates that the predictive volume is underestimated, while positive model deviations indicate that the predicted volume has been overestimated. Table 3.17 shows the suggested acceptable percent assignment error per functional class in the road network that is used in the United States of America (P. G. PTV Visum, 2021; CAMPO, 2013; Wegmann & Everett, n.d.).

$$Model\ Deviation\ (\%) = \left[\frac{(Predicted\ Volume - Observed\ Volume)}{Observed\ Volume}\right] * 100 \qquad \text{Equation (3.17)}$$

Table 3. 17 Acceptable percent of error per functional class

Functional Class	Suggested percent of error (range) FHWA	Michigan DOT
Overall	± 5 %	---
Highway	± 7 %	± 6 %
Principal Arterial	± 10%	± 7 %
Minor Arterials	± 15%	± 10%
Collector	± 25%	± 20%
Local	± 25%	---

FHWA: Federal Highway Administration, U.S.A.
DOT: Department of Transportation

For the case study, Figure 3.9 shows box plots and scatter plots for the models from 2007 and 2015 validated with observed traffic counts. Tables 3.18 and 3.19 show the RMSE, R^2, and Model Deviation (MD) for the 2007 model and 2015 model. The tables show the validation results for total of roads (overall) model and the road classification per volume groups express as Annual Average Daily Traffic (AADT) per direction, assuming a directional split of 50%.

Figure 3. 9 Model validation for years 2007 and 2015

(a) 2007 Model **(b) 2015 Model**

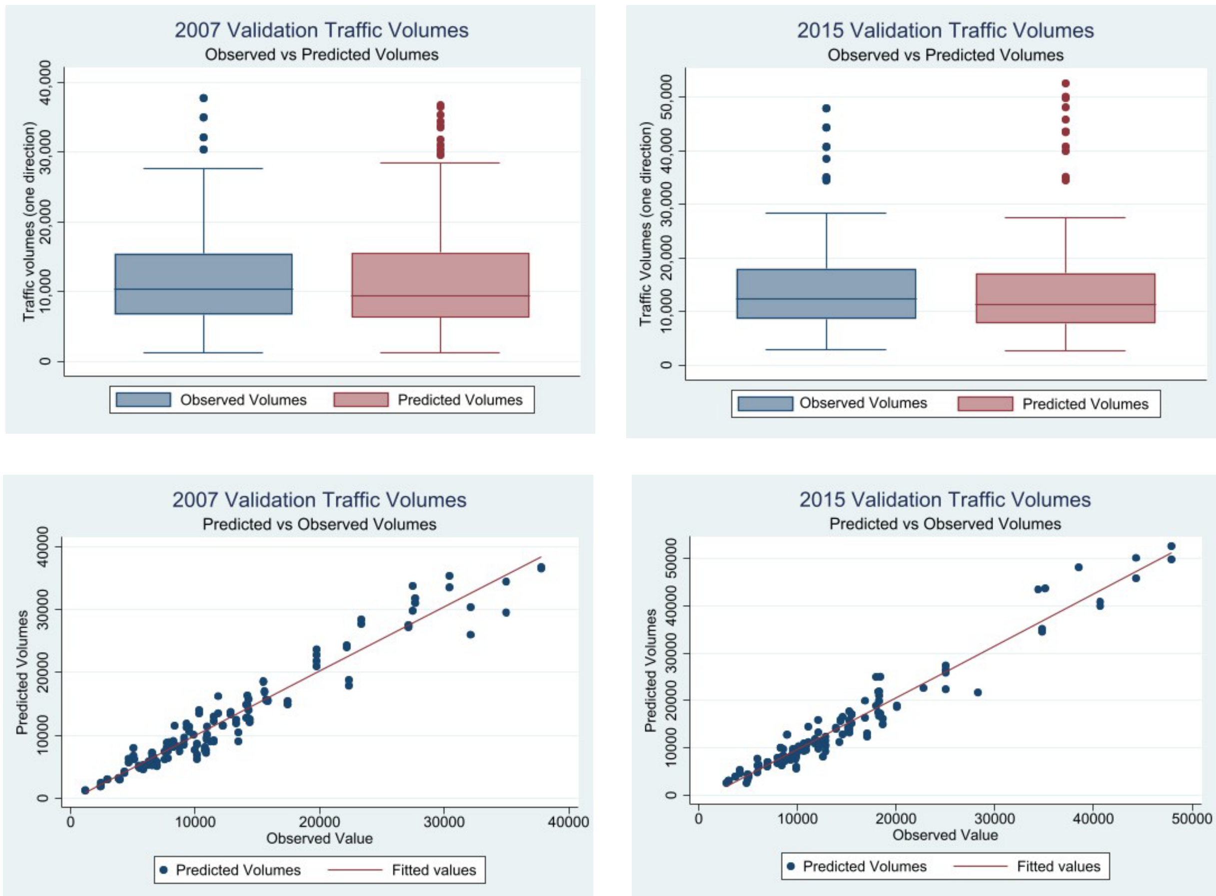


Table 3. 18 Model validation for 2007 year

Observed volumes Classification	**Number Observations** N	**RMSE Model** (%)	**RMSE Guidelines** (%)	**R^2**	**MD (%)** Mean	**Observed Volumes (*)** Mean	Std.Dev.	**Predicted Volumes** Mean	Std.Dev.
Overall	135	17.10	< 30.00	0.98	-1.38	12,407	8,102	12,380	8,586
Larger 20,000	20	13.20	< 25.40	0.87	3.14	28,539	5,161	29,252	5,296
10,000 - 19,999	52	16.60	< 28.30	0.93	-3.46	13,477	2,706	13,167	4,083
5,000 – 9,999	46	16.90	< 43.10	0.89	-0.21	7,361	1,466	7,361	2,041
< 5,000	16	21.40	< 115.80	0.94	-3.43	3,201	1,138	3,108	1,416

(*) Annual Average Daily Traffic (AADT) per direction
MD: Model deviation (%)

Table 3. 19 Model validation for 2015 year

Observed volumes Classification	Number Observations N	RMSE Model (%)	RMSE Guidelines (%)	R2	MD (%) Mean	Observed Volumes (*) Mean	Std.Dev.	Predicted Volumes Mean	Std.Dev.
Overall	122	17.89	< 30.00	0.99	-1.61	14,556	9,805	14,651	10,997
Larger 20,000	19	13.60	< 25.40	0.97	3.89	33,392	9,345	35,131	11,735
10,000 - 19,999	56	17.10	< 28.30	0.89	-1.30	14,503	2,657	14,410	4,004
5,000 – 9,999	34	20.02	< 43.10	0.77	-5.74	8,081	1,503	7,569	1,835
< 5,000	12	25.13	< 115.80	0.63	-3.67	3,787	826	3,577	867

(*) Annual Average Daily Traffic (AADT) per direction
MD: Model deviation (%)

The only origin-destination (OD) survey is from 2007 (MIVAH, 2008b). Thus, in this research a first baseline model was built based on this data and the model was validated with observed traffic. Based on the 2007 model, another model was built for 2015 to be validated with observed traffic counts. The Ministry of Transport is the stakeholder that collects these ground-truth traffic counts and provided the observed counts as Annual Average Daily Traffic (AADT). After 2015, traffic counts are scarce due to malfunctioning equipment and a lack of funding to replace them.

The 2007 model has an overall RMSE of 17.1 %, an R^2 of 0.98, and an average model deviation of -1.38. In the overall assessment, the negative value of model deviation suggests that traffic has been underestimated for the whole network. By breaking down the model deviation into volume groups, highways and arterials with volumes per direction larger than 20,000 daily vehicles have a positive average model deviation of 3.14. Thus, the model overestimates traffic on roads with higher volumes or functional classes. On the contrary, road classes with volumes under 20,000 daily vehicles have negative values in the average model deviation. Thus, the predicted values are underestimated. Roads under 5,000 daily vehicles per direction have the larger RMSE (21.4 %).

Between 2007 and 2016, car ownership's annual growth was 6.7%, while the annual population growth was 1.2 % (PEN, 2018; Brenes Camacho et al., 2013). The car ownership growth rate reflects car dependency patterns and accelerated traffic growth. In addition, by looking at historical traffic data collected by the Ministry of Transport, a 3% compound traffic growth was applied to forecast traffic from 2007 to the 2015-year model.

The 2015 model has an overall RMSE of 17.89%, an R^2 of 0.99, and an average model deviation of -1.61. The 2015 model has a similar pattern of the model error to 2007. Volumes on highways and arterials are overpredicted, while roads with lower volumes are underpredicted. However, the magnitude of error in 2015 is slightly increased compared to 2007.

Several factors influence the errors found in the models. There is no external TAZ in the southbound of the model, and while low-volume roads characterize the south, there are more errors in the prediction of volumes due to the absence of external TAZ. The annual traffic growth of 3% between models is applied as an average for the whole network rather than individual road segments. There is an assumption of a 50% directional split in the Annual Average Daily Traffic (AADT).

Quality and updated data are essential to produce good models. Certainly, a dated OD survey and the reliability of traffic counts affect the outcome. Based on the OD survey, a local calibration of the trip generation step was applied, and it was assumed that the same behavior is maintained through the years. While the car dependency trend continues and the built environment has not significantly changed, it is recommended to update the OD surveys under a systematic approach.

The traffic assignment step uses a Deterministic User Equilibrium Assignment (DUE) approach, assigning traffic under the assumption that the drivers choose the minimum travel time routes. Unlike the stochastic approach (SUE), DUE does not assign part of the traffic to suboptimal routes. As a result, there is an overestimation in highways and arterials and an underestimation of traffic volumes per direction for roads of less than 20,000 daily vehicles.

The congestion parameters introduced in the volume-delay conical congestion function were assumed based on field studies in Colombia for multilane roads with similar geometric characteristics to Costa Rica. Further research needs to collect data and calibrate the congestion parameters to the local conditions of the model.

Table 3.20 shows the network average predicted traffic volumes for the baseline years 2007 and 2015. Roads classified as larger than 20,000 vehicles have more assigned traffic than lower ranges of volumes. Figure 3.9 shows the predicted traffic volumes for the models 2007 and 2015 per road link.

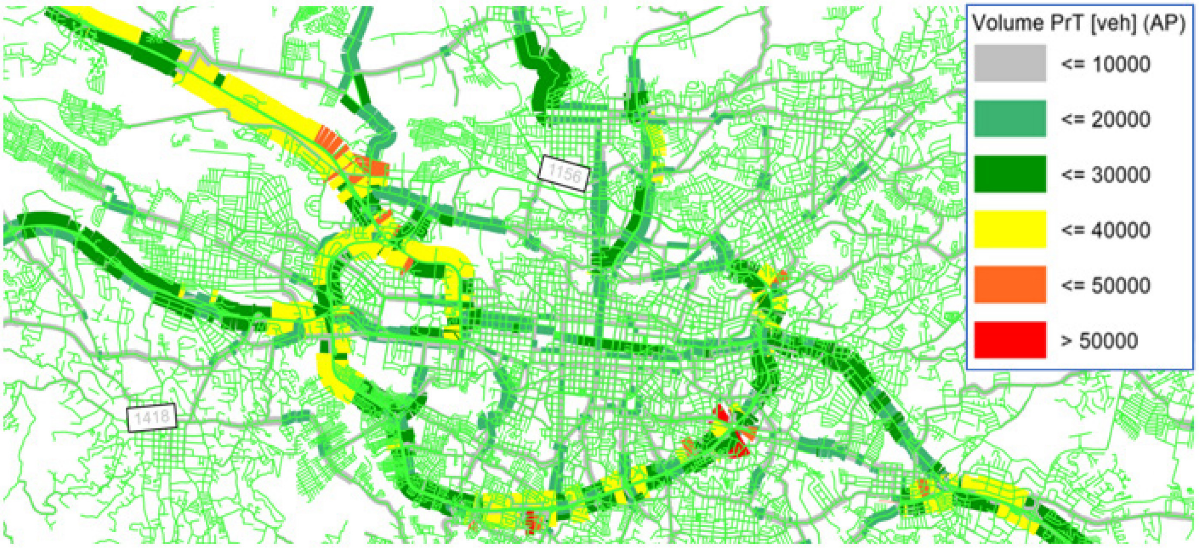
Table 3. 20 Traffic volumes for models 2007 and 2015

Volume Classification	**2007 Model Traffic Volumes (*)**				**2015 Model Traffic Volumes (*)**			
Range	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
Overall	10,773	9,091	21	46,716	12,635	12,636	9	50,520
Larger 20,000	29,647	8,196	20,047	46,716	32,327	10,266	20,013	50,520
10,000 - 19,999	13,921	2,721	10,007	19,999	14,538	2,983	10,011	19,953
5,000 – 9,999	7,196	1,405	5,002	9,994	7,507	1,404	5,015	9,956
< 5,000	3,051	1,194	21	4,998	2,243	1,495	9	4,999

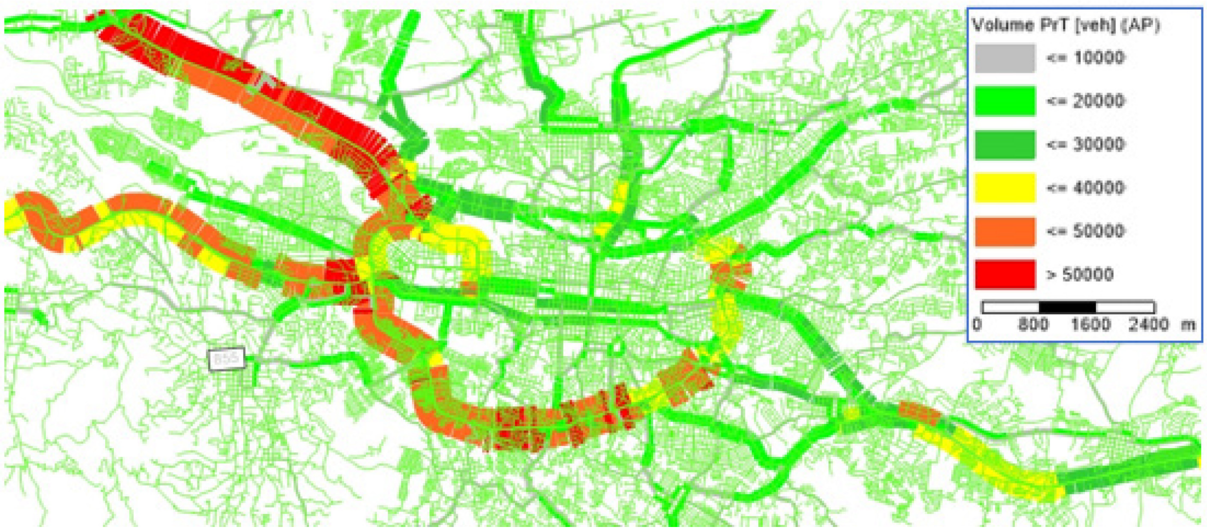
(*) Volumes per direction; Std.Dev: Standard Deviation
Min: minimum volume per volume classification
Max: maximum volume per volume classification

Figure 3. 10 Validated travel demand models for 2007 and 2015

2007 Travel Demand Model



2015 Travel Demand Model



3.2.1.5 Model Forecast

The complex political system of Costa Rica impacts the development of its transport system. Every electoral cycle has changes in priorities, policies, and goals. Thus, some projects are postponed or changed. As a result, transport designs become dated due to lack of implementation, and by the time these projects are actually implemented, new designs must be elaborated. Since 1985, attempts have been made to upgrade the regional metropolitan passenger rail system. While ten feasibility studies and designs have been conducted, one of these efforts has yet to succeed (PEN, 2018). This vicious cycle limits the implementation of transport investments regardless of whether an investment credit is approved, and construction of a new road can take between 20 to 40 years.

Investments are still focusing on the maintenance and development of infrastructure for improving motorization movements rather than people's movement. Apart from the potential regional rail system and integrated operational bus improvement plans to be implemented between 2020 and 2035, infrastructure investment plans to incorporate infrastructure massive rapid passenger movement such as Bus Rapid Transit (BRT) systems are not considered (MOPT, 2020). The past and current transport investments are mainly for allocating resources to pavement structures, and new infrastructure is built to improve the urban mobility of passenger cars. Thus, reinforcing car dependency in the city and motorization growth. In Latin America, Costa Rica ranks third with more passenger cars per capita, only succeeded by Argentina and Mexico (PEN, 2018).

The economic, social, and political context plays an essential role in urban development. Manheim (1979) views the urban mobility system as the result of three main components. The first is the transport system (i.e., roads and transit systems). The second is the activity system, where social and economic activities are developed in the built environment. The third is the flow patterns in the urban mobility system (i.e., origin and destinations).

Figure 3.11 shows the interrelationships among the transport system (T), the activity system (A), and the flow patterns (F). In relationship 1, the flow pattern (F) is determined by short-term equilibration of the Transport System (T) and Activity System (A). In relationship 2, the flow patterns lead to changes in the Activity System (A), and new socio-economic activities are developed given the flow patterns. In relationship 3, the Flow patterns (F) lead to changes in Transport System (T), which means incorporating transport infrastructure and operations given the traffic flows (Manheim, 1979).

In the forecasted models from 2022 to 2050, changes in the Transport System (T) were incorporated (see Figure 3.11). Between the period 2015 to 2022, the south ring highway had improvements through the construction of underpass roads at the roundabouts. Thus, improving local bottlenecks produced at the roundabouts. The 2030 model incorporated the new elevated north ring highway currently under construction (See Figure 3.11).

The activity system is related to the built environment. There are only two localized areas in the city with buildings of new mixed-use developments. These traffic analysis zones (TAZ) will produce and attract more trips. However, given the macroscopic scale of the model, the Activity System is assumed to be constant throughout the forecast modeling.

The 2015 travel demand model is a baseline to forecast traffic for 2022 until 2050. There are few traffic counts (AADT) post-2015 due to a lack of budget to replace the Ministry of Transportation's malfunctioning equipment. Thus, traffic counts posterior to the 2015 year are scarce. The existing traffic counts for the period from 2015 until 2021 was reviewed to determine an annual average network traffic growth, and 2% compound traffic growth was assumed to forecast traffic from 2015 to the 2022-year model. By following a logistic S-curve shape of traffic growth (Kucharavy & De Guio, 2015), it was assumed a compound traffic growth of 1.5 % for the period 2022-2030, 1% for the period 2030-2040, and 0.5% for the period 2040-2050. This assumption is based on a review of AADT historical data, and the decrease of traffic growth based on a logistic S-curve shape. The compound traffic growth is an average network growth.

Figure 3. 11 Travel forecast through the lens of Manheim´s model relationships

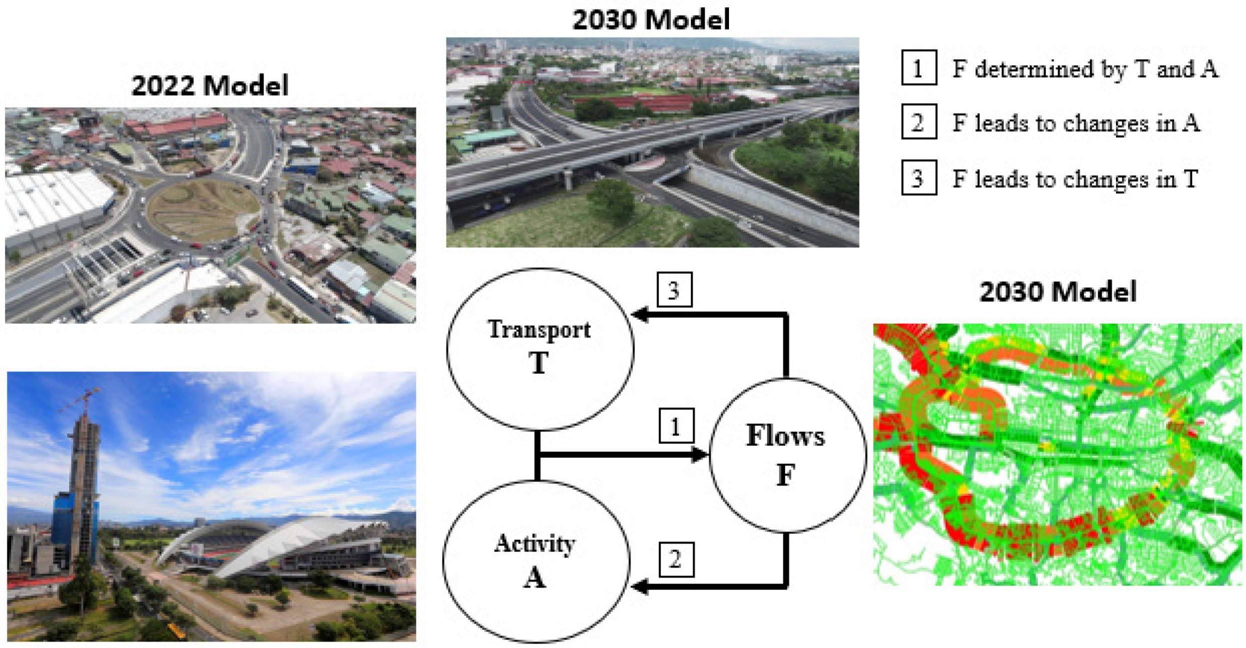


Table 3.21 shows the summary of traffic volumes for the models 2022, 2030, 2040, and 2050. Overall, the average traffic volume increases through the decades. However, the increment rate is reduced through each decade because the transport system is reaching its capacity and the annual traffic growth decreases. Figure 3.12 visualizes the differences in the models and traffic flows due to changes in the transport system (T) and traffic growth.

Models 2022, 2030, 2040, and 2050 follow the baseline model behavior where highways and arterials with volumes per direction larger than 20,000 daily vehicles increase their volumes through the decades at a larger rate than the other volume groups. The road class of lower volume ranges has a relatively average low traffic volume increment.

Table 3. 21 Traffic volumes for forecasted models 2022, 2030, 2040, and 2050

Volume Classification	2022 Model Traffic Volumes (*)				2030 Model Traffic Volumes (*)			
Range	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
Overall	13,967	13,428	23	51,912	15,626	14,353	26	54,219
Larger 20,000	32,996	10,932	20,004	51,912	34,435	11,307	20,004	54,219
10,000 - 19,999	14,204	2,872	10,001	19,987	14,119	2,993	10,013	19,987
5,000 – 9,999	7,186	1,519	5,000	9,972	7,090	1,438	5,010	9,992
< 5,000	2,319	1,571	23	4,991	2,270	1,464	26	4,999

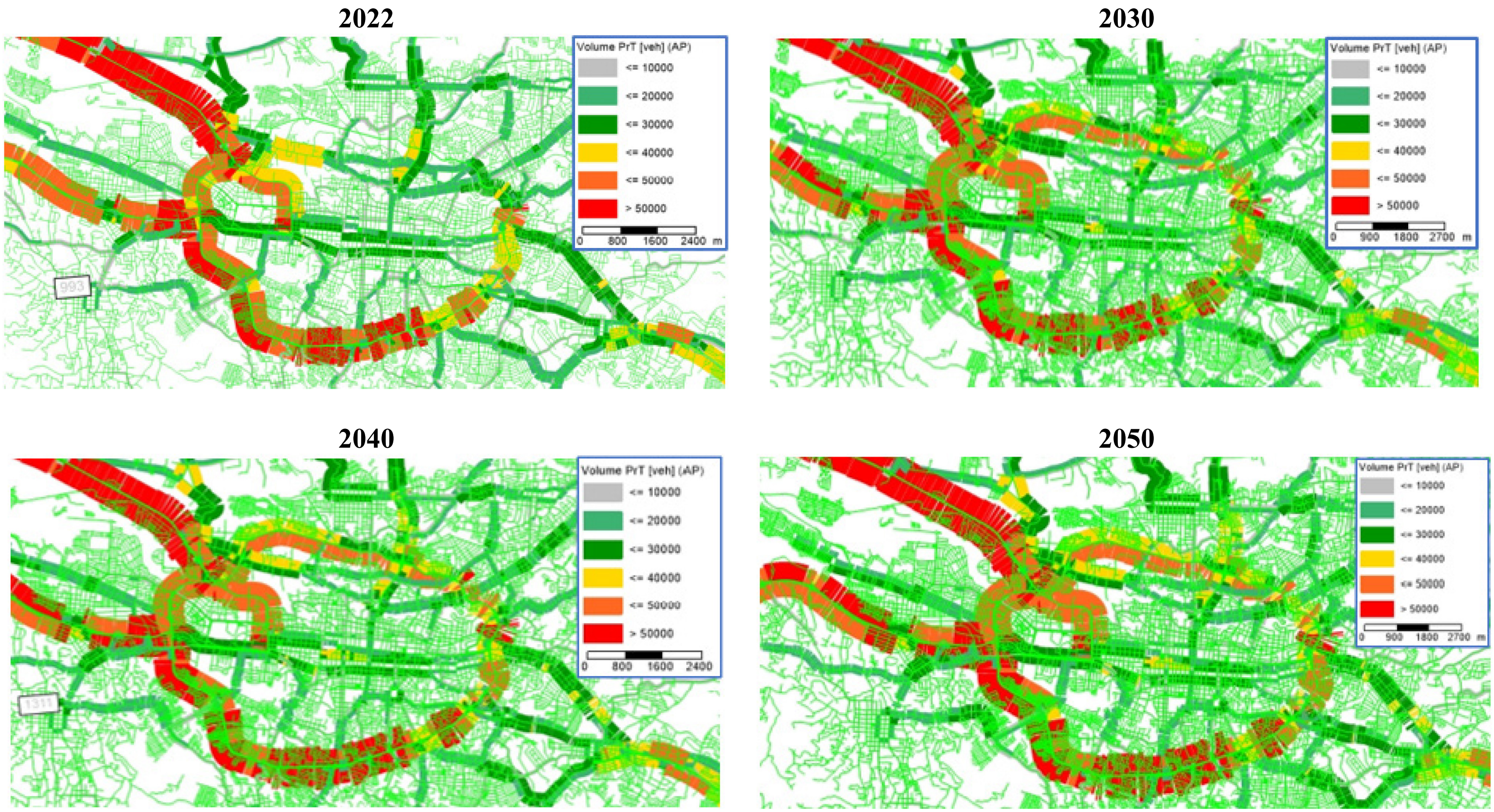
(*) Volumes per direction; Std.Dev: Standard Deviation
Min: minimum volume per volume classification
Max: maximum volume per volume classification

Table 3. 21 (cont). Traffic volumes for forecasted models 2022, 2030, 2040, and 2050

Volume Classification	**2040 Model Traffic Volumes (*)**				**2050 Model Traffic Volumes (*)**			
Range	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
Overall	16,593	14,879	35	55,084	17,055	15,101	38	56,327
Larger 20,000	34,987	11,520	20,000	55,084	35,147	11,613	20,003	56,327
10,000 - 19,999	14,260	2,899	10,002	19,950	14,267	2,787	10,003	19,995
5,000 – 9,999	7,237	1,337	5,009	9,987	7,145	1,349	5,004	9,988
< 5,000	2,289	1,483	35	4,990	2,188	1,391	38	4,984

(*) Volumes per direction; Std.Dev: Standard Deviation
Min: minimum volume per volume classification
Max: maximum volume per volume classification

Figure 3. 12 Forecasted travel demand models for 2022, 2030, 2040, 2050



Year	Annual Growth (period)	Traffic Volume Mean (*)	Std.Dev.	Year	Annual Growth (period)	Traffic Volume Mean (*)	Std.Dev.
2022	2.0 % (2015-2022)	13,967	13,428	**2040**	1.0 % (2030-2040)	16,593	14,879
2030	1.5 % (2022-2030)	15,626	14,353	**2050**	0.5 % (2040-2050)	17,055	15,101

(*) Volumes per direction; Std.Dev: Standard Deviation

3.3 Regional emission transport model

The main road transport emissions are Carbon Dioxide (CO_2), Nitrogen Oxides (NOx), Carbon Monoxide (CO), and Non-methane volatile organic compounds (NMVOCs), followed by Nitrous Oxide (N_2O), Methane (CH4), Hydrocarbons (HC), Particulate Matter (PM10 and PM2.5, for aerodynamic diameters of 10 and 2.5 µm respectively), and Black Carbon (BC) (Kirago et al., 2022;).

Carbon Dioxide (CO_2) is the main contributor to climate change. Black Carbon (BC) is a contributor to climate change. BC stays in the atmosphere for few weeks. BC absorbs sunlight and generates heat, and when BC is deposit on snow, it absorbs sunlight and accelerates melting. BC is produced through incomplete combustion of fossil fuels and emits particles with diameters less than 2.5 microns (PM2.5), threatening population's health (Kirago et al., 2022; Mascia et al., 2017; NZ Transport Agency, 2018; Cho, 2016; Eggleston & Walsh, n.d.).

Different emission models can be built depending on the complexity and purposes. For National Inventories, a top-down approach can be used based on the fuel consumed. These models aggregate the vehicle technology (i.e., motor fuel) and fuel purchased by users as the principal variable to estimate traffic emissions (Kooshian et al., 2018). The advantage of a top-down model based on fuel consumption inventories is the accuracy level in reporting and monitoring emissions. A disadvantage is that it limits the implementation of countermeasures to reduce emissions.

There are different types of bottom-up emission models using disaggregated variables. Transport activity or Vehicle Kilometer Traveled (VKT) is the main attribute in these models. An odometer-based approach quantifies the distance traveled per type of vehicle and fuel consumption. Average vehicle speed can be incorporated to select emission factors. The odometer approach can provide findings on the share of emissions per vehicle classification and create climate strategies to target specific groups (Grütter et al., 2016). An advantage is the ability to use a large scale of areas of study and, at the same time, incorporate disaggregated levels. A disadvantage is the inaccuracy of forecasting emissions given the annual growth of vehicles, street-level traffic flow, volume saturation due to congestion, and the inability to create a spatial model and interactions with the transport system and land use.

Other bottom-up approaches recommend using macroscopic travel demand models, which provide trip-based inputs based on origin and destinations for national and regional emission inventories. The model's disaggregation level is higher than the other emission approaches, as well as the complexity that travel demand models bring. Travel demand models provide details of current and future transport activity. Quantifying trips can be based on vehicle classification and travel activity, or persons and commodities per mode of transport (Kooshian et al., 2018; Grütter et al., 2016).

For national and regional scales, an average speed trip for the road network is recommended (NZ Transport Agency, 2018). An advantage of using macroscopic travel demand models is that it provides a spatial interaction between the transport activity and the transport infrastructure system. Mitigation strategies can be modeled to support climate actions. A disadvantage is that the input data requirements are intensive and complex, and updated data is only sometimes available, especially in developing countries. Low data quality can undermine the calibration parameters and compromise the accuracy of the travel demand models.

Microscopic traffic simulations can also deliver emission models at a project level. These applications can be used for environmental impact assessments and traffic management (NZ Transport Agency, 2018). Microscopic traffic simulations can model detailed movement of individual vehicles and their interactions (Austroads, n.d.). A microscopic approach can model choices and behaviors by individual drivers and capture the variation of speeds and acceleration rates to provide more accurate emissions based on variations of speed (Forehead & Huynh, 2018). Emissions are sensitive to speed and lower speeds produce larger emissions (NZ Transport Agency, 2018).

Building emission scenarios of future transport activity must include a Business-As-Usual scenario (BAU). A baseline scenario or BAU assumes that there will not be mitigation actions. This scenario is compared with other scenarios that incorporate potential emission reductions by implementing the Avoid-Shift-Improve (ASI) Framework (Kooshian et al., 2018). In this case study, the scenarios will evaluate the penetration of electric vehicles as an alternative fuel to the BAU scenario that relies on the fuel type of gasoline and diesel ("Improve") by using a macroscopic travel demand and average speed model.

The primary metric from traffic models in estimating traffic emissions is the Vehicle Kilometer Traveled (VKT), as shown in Equation 3.18. The annual VKT is the Annual Average Daily Traffic (AADT) or average daily traffic volumes multiplied by 365 days of the year, and the distance traveled.

$$VKT\ (annual) = AADT * L * 365 \qquad \text{Equation (3.18)}$$

Where,
AADT: Annual Average Daily Traffic
L: Length of road segment (Km)

The emissions per road segment (n) are estimated based on the Vehicle Kilometer Traveled (VKT) per vehicle type (k) and corresponding emission factors from the road transport emission model Copert version 5.5.1 from the European Environmental Agency (EMISIA et al., 2021) as shown in Equation 3.19.

$$E_{i,k} = \sum_{k=0}^{n} VKT_k * EF_{i,k} \qquad \text{Equation (3.19)}$$

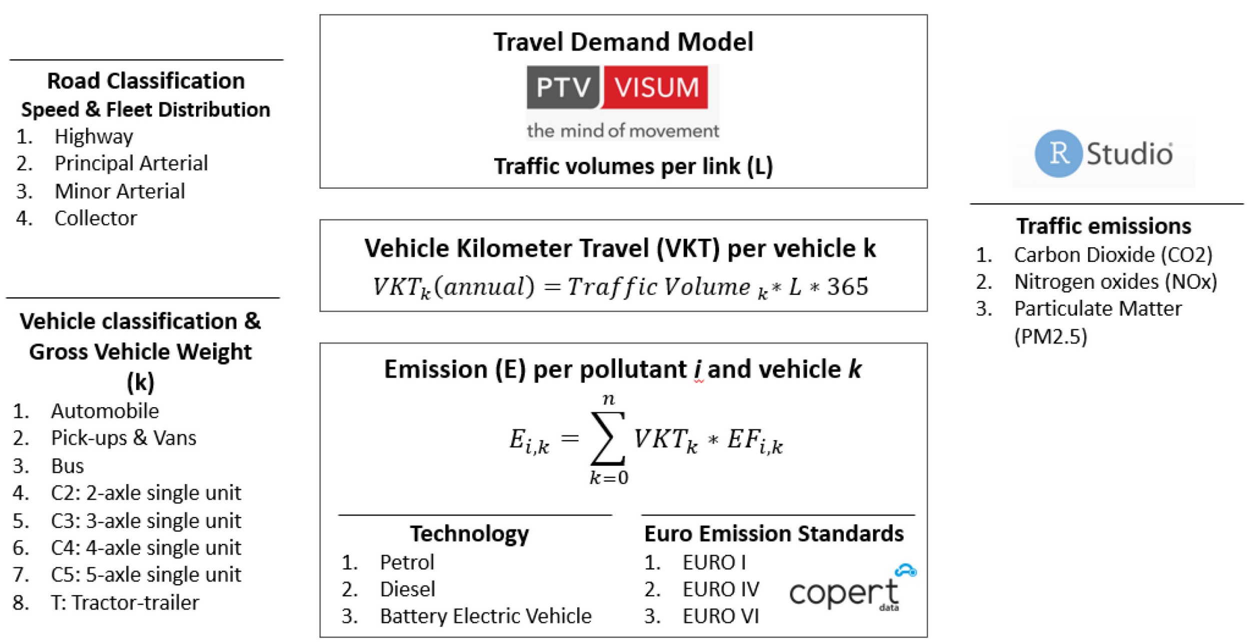
Where,
$E_{i,k}$: Emission for pollutant i and vehicle k
VKT_k: Vehicle Kilometer Travelled per vehicle type k (Km)
$EF_{i,k}$: Emission Factor per pollutant, per vehicle type k (g/Km)
i: pollutant (i.e. CO_2, NOx, PM2.5)

For the case study, given the lack of investment in transit and active transport infrastructure, it is desired to evaluate 2050 net-zero scenarios for a potential carbon dioxide (CO_2) reduction due to the shift from Internal Combustion Vehicles (ICE) to electric vehicles for the province of San José for highways, principal arterials, minor arterials, and collectors. Residential roads and motorcycles are not considered in the scope of this study.

Figure 3.13 shows the methodology to develop an average speed regional emission model. The output of the travel demand model is expressed as the annual average traffic volumes and the road segment (L) or link. The road segment length is the road link between intersections. An R Studio code was written to match the local road classification with the traffic volumes and links. Each road classification has different geometric characteristics, road capacity, and speeds.

The average vehicle classification percentage disaggregates the traffic volumes from PTV Visum. This distribution is based on the observed traffic counts measured by the Ministry of Transport and Public Works. The vehicle fleet is disaggregated into gasoline, diesel fuels, and electric. Emission factors are selected as described in Figure 3.13 to estimate the traffic emissions for CO_2, NOx, and PM2.5 by using equations 3.18 and 3.19.

Figure 3. 13 Methodology for an average speed regional emission model.



Overall, the total emissions from road transport are composed of vehicle emissions while driving, cold start emissions, and evaporative emissions. Cold star emissions are generated during the first minute due to the warm-up phase, and it generates the majority of Carbon Monoxide (CO) and Hydrocarbon (HC). These emissions increase at lower ambient temperatures (Weilenmann et al., 2009). Evaporative emissions release Volatile Organic Carbon (VOC) (Liu et al., 2015; Eggleston & Walsh, n.d.).

Another source of vehicle emissions is the road surface and pavement-tire interaction. Pavement roughness measured with the International Roughness Index (IRI in m/Km) impacts the fuel consumption rate. Passenger vehicles are more sensitive than large trucks. The combination of high speeds and advanced deteriorated pavements results in higher fuel consumption (Ziyadi et al., 2018). Pavement roughness is the major contributor to fuel consumption, while pavement macrotexture and surface geometry (slope) as rolling resistance parameters contribute less to fuel consumption (Ionescu, 2017). For the break and tire wear, there are non-exhaust emissions, which are a source of Particulate Matter PM10 and PM2.5. Highways produce less Particulate Matter emissions due to fewer braking events (Grigoratos & Martini, 2014).

The exhaust (tailpipe) emissions that are produced while the vehicle is driving depend on vehicle speed, road gradient (slope), truck loading, catalytic converter, fuel type, and vehicle legislation that defines the vehicle emission standards. Positive gradients (uphill) demand more power; as a result, NOx and CO_2 increase significantly than the other pollutants. Diesel vehicles tend to produce higher emissions of Particulate Matter and NOx, while gasoline vehicles produce larger amounts of CO and HC when compared to diesel vehicles (NZ Transport Agency, 2018; Weilenmann et al., 2009). Fully loaded trucks produce higher Carbon Dioxide (CO_2), Carbon Monoxide (CO), and Total Hydrocarbon (THC). However, loaded trucks discharge lower quantities of NOx due to the exhaust temperature (Wang et al., 2021). In the range of speeds between 5 to 90 Km/h, as speed decreases then CO_2 emissions increase, and speeds lower than 30 Km/h contribute to a significant increment in traffic emissions (Mrabti et al., 2022; Shahid et al., 2014; Barth et al., 2013).

For the case study, the selection of emission factors from the exhaust in driving conditions as a function of road and vehicle attributes is shown in Figure 3.14. The study aims to assess the shift from gasoline and diesel vehicles to electric vehicles. The vehicle classification is based on the truck size & weight legislation of Costa Rica (CONAVI, n.d.). A payload of 50% for freight trucks and a constant road slope of 0% are assumed. Monthly ambient temperature and relative humidity was considered (IMN, n.d.). By law, all vehicles must have a catalytic converter and comply with the emission specifications in the annual technical assessment (Riteve SyC, 2021).

Three-speed scenarios are considered for each road classification (highways, principal arterials, minor arterials, and collector); as a result, twelve speeds are considered in selecting exhaust (tailpipe) emission factors. Vehicle emission standards vary through the projection years. The current fleet is EURO I. Changes in legislation leads to a future renewal of vehicles to EURO IV and EURO VI. The attributes shown in Figure 3.14 are introduced in COPERT Version 5.5.1 to select the emission factors to estimate CO_2, NOx, and PM2.5 (EMISIA et al., 2021). The pavement-tire interaction is not considered.

Grütter et al. (2016) measured that in 2015, 100% of the vehicle fleet have emission standards of EURO I. For the construction of the scenarios in this study, it is assumed that the vehicle fleet is EURO I for 2022, EURO IV for 2030 and 2040, and EURO VI for 2050 as shown in Table 3.22.

Figure 3. 14 Selection of emission factors

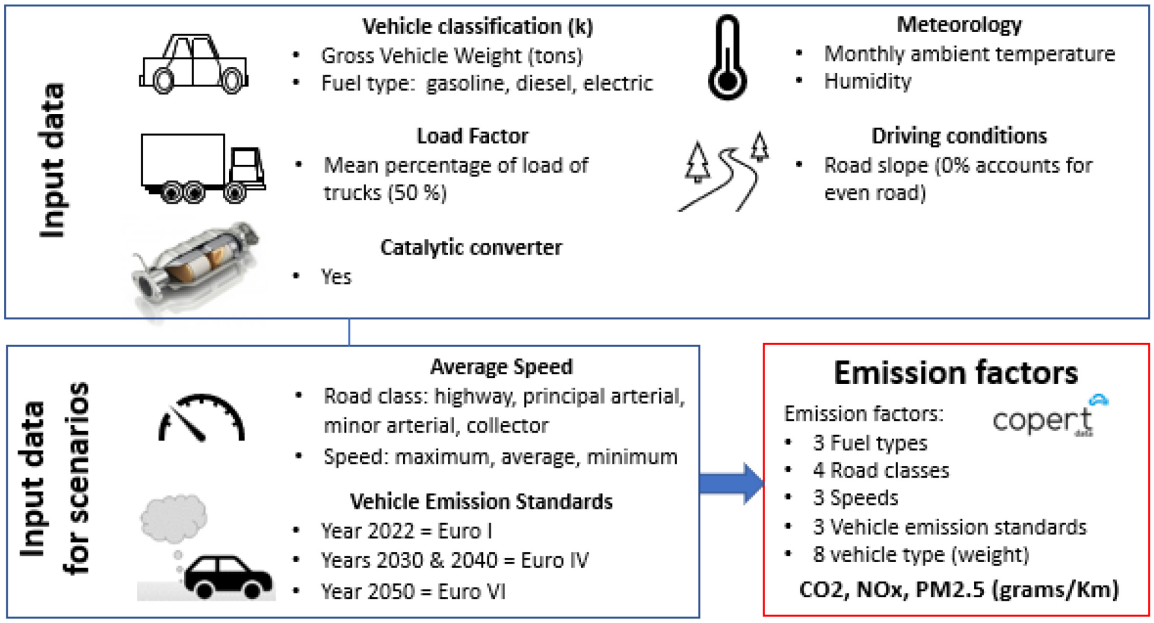
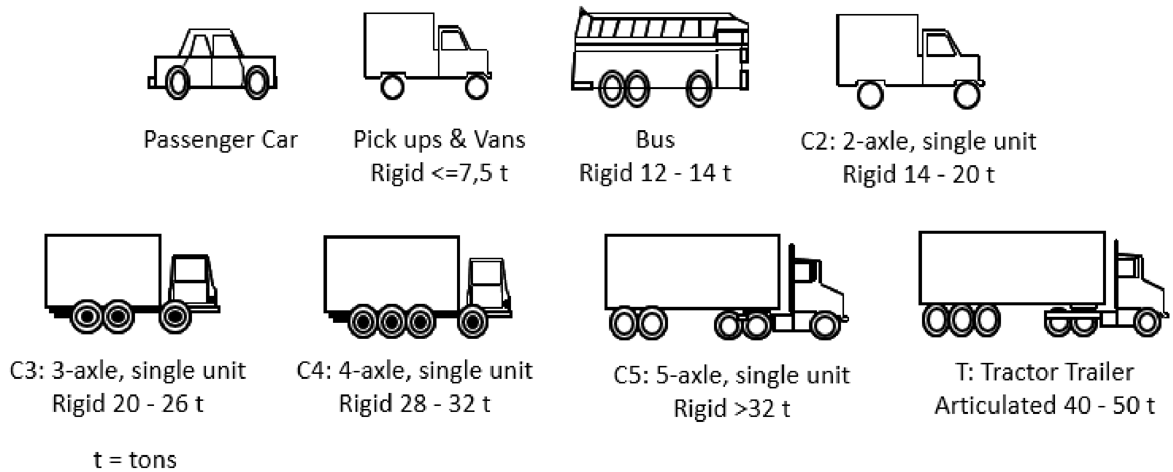


Table 3. 22 Vehicle classification and emission standards

Vehicle classification	Gross Vehicle Weight (t: tons)	EMEP/EEA air pollutant emission inventory	Euro Emission Standards
Automobile	Passenger Cars	Gasoline	EURO I, IV, VI
		Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
Pick-ups & Vans	Rigid <=7,5 t	Petrol	Conventional
		Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
Bus	Rigid 12 - 14 t	Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
C2: 2-axle single unit	Rigid 14 - 20 t	Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
C3: 3-axle single unit	Rigid 20 - 26 t	Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
C4: 4-axle single unit	Rigid 28 - 32 t	Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
C5: 5-axle single unit	Rigid >32 t	Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-
T: Tractor-trailer	Articulated 40 - 50 t	Diesel	EURO I, IV, VI
		Battery Electric Vehicle	-

EMEP: European Monitoring and Evaluation Programme; EEA: European Environment Agency

Figure 3. 15 Vehicle classification per Gross Vehicle Weight (GVW)



On average, the vehicle fleet in Costa Rica is 17 years old (Riteve SyC, 2021). The country has updated the minimum emission standards for imported vehicles to regulate vehicle emissions with a Gross Vehicle Weight (GVW) of less than 3.5 tons. From 2018 these vehicles must have the European Emission Standard EURO IV (Law No 39724 MOPT-MINAE-S, 2016), and from 2023 new vehicles must have the European Norm EURO VI (Law No 43166 MOPT-MINAE-S, 2021). The Costa Rican Law excludes trucks with GVW larger than 3.5 tons because the freight transport coming from Central American countries have different regulations, and they would not be able to comply with these new standards (Rodríguez, 2018).

The assumption for the construction of the scenarios in this study is that the vehicle fleet will change the emission standards for EURO I for 2022, EURO IV for 2030 and 2040, and EURO VI for 2050. If the assumption is not met, it will introduce an error in estimating the emission scenarios. In this case, it is recommended to update the scenarios.

The composition of fuel per vehicle fleet used to calculate the 2022 model is shown in Table 3.23. For automobiles, the fuel type is split into 84% gasoline and 16% diesel. The bus fleet and heavy vehicles larger than 3.5 tons use diesel. The heavy vehicles less than 3.5 tons of Gross Vehicle Weight is split into 14% gasoline and 62% diesel (PEN, 2020a).

Table 3. 23 Composition of fuel per Gross Vehicle Weight (GVW) for the year 2020

Vehicle class	Gasoline (%)	Diesel (%)	Battery Electric Vehicle (%)
Automobile	84	16	0
Bus	-	100	0
Heavy Vehicles < 3.5 t	14	62	0
Heavy Vehicles > 3.5 t	-	100	0

Source: (PEN, 2020a)

Travel activity (VKT) is disaggregated per vehicle class (k) and multiplied by the corresponding emission factor for the pollutant (i) and vehicle class (k), as shown in Equation 3.18. The Vehicle Kilometer Traveled per vehicle class (VKT_k) is calculated from the output of the travel demand model expressed in traffic volumes per direction. Traffic volumes are disaggregated by the mean percentage of the fleet composition per road classification, as shown in Table 3.24. The fleet composition was measured using traffic counts in the province of San José by the Ministry of Transport and Public Works from Costa Rica. The mean percentage of vehicle type (k) from Table 3.24 is used to calculate the annual traffic volume for vehicle (k) and estimate the Vehicle Kilometer Traveled per vehicle class (VKT_k).

Table 3. 24 Average fleet composition (%) per road classification for San José

Road Classification		Automobile	Pick-ups & Vans	Bus	C2 2-axle	C3 3-axle	C4 4-axle	C5 5-axle	T Tractor-trailer
Highway	Mean	73.61	15.11	3.06	5.40	1.00	0.24	1.17	0.41
	SD	5.78	3.28	1.89	1.79	0.39	0.16	0.62	0.22
Principal arterial	Mean	71.64	16.92	3.90	5.21	1.00	0.28	0.67	0.37
	SD	9.21	7.42	2.27	2.18	0.72	0.34	1.35	1.08
Minor arterial	Mean	76.51	13.93	4.72	3.91	0.59	0.13	0.16	0.04
	SD	6.30	3.97	2.77	1.88	0.51	0.23	0.26	0.08
Collector	Mean	74.96	15.20	4.18	4.07	0.70	0.26	0.38	0.27
	SD	10.37	5.58	3.24	3.10	1.73	1.31	1.18	0.85

SD: Standard Deviation

Grütter et al. (2016) analyzed speed profiles from the traffic navigation application WAZE for a sample of 6 days for Wednesdays from May to July 2015. For a period from 6:00 am until 6:00 pm. It was found that the average speed for all vehicle fleet was 42.5 km/h for principal arterials and 34.5 km/h for minor arterials and collectors. Based on these measurements and the posted speed per road classification, a speed profile was selected to produce the decarbonization scenarios, as shown in Table 3.25. This speed varies per road classification, and the scenarios consider three-speed variations (posted, average, and low). For the case of buses in principal arterial, minor arterial, and collectors, the speed used for buses is 17 Km/h (Grütter et al., 2016). Low-speed scenarios consider the average speed reduction due to congestion in future years.

Table 3. 25 Average network speed profile for emissions scenarios

Road Classification	Posted speed (km/h) (1)	Average speed (km/h) (2)	Low speed (km/h) (2)
Highway	100	85	70
Principal arterial	60	45	40
Minor arterial	40	35	30
Collector	40	35	30

(1) Source: Costa Rican Traffic Law on Public Land Roads, Version 41 of 41 (MOPT, 1993); (2) Assumed speed

3.3.1 Emission baseline and mitigation scenarios

The 2022-2050 models' total network length average is 508.62 Km, and the standard deviation is 7.46 Km for highways, principal arterials, minor arterials, and collectors. Table 3.26 shows the Vehicle Kilometer Traveled (VKT) corresponding to each target year. VKT increases due to traffic growth, but the growth rate decreases as traffic volumes reach road capacity. From 2022 to 2030, VKT increases by 373 million-Km; from 2030 to 2040, VKT increases by 196 million-Km; and from 2040 to 2050, VKT increases by 99 million-Km.

Table 3. 26 Vehicle Kilometer Traveled for demand models 2022 up to 2050

Year	Number Road Segments	Network Length (Km)	Length per link (meters)		Traffic Volume Per direction		VKT (million Km)
	N	Sum	Mean	Std.Dev.	Mean	Std.Dev.	Sum
2022	6,535	497.71	76.16	89.95	13,967	13,428	2,888
2030	6,774	510.08	75.30	88.70	15,626	14,353	3,261
2040	6,818	512.65	75.19	88.49	16,593	14,879	3,457
2050	6,837	514.06	75.19	88.41	17,055	15,101	3,556

To build the mitigation scenarios, Table 3.27 shows the percentages of penetration of Electric Vehicles (EVs). The percentage of EVs per decade changes the percentages of fuel vehicle for gasoline and diesel in Table 3.23 for the next decades.

Table 3. 27 Target Scenario to Electric Vehicles (%)

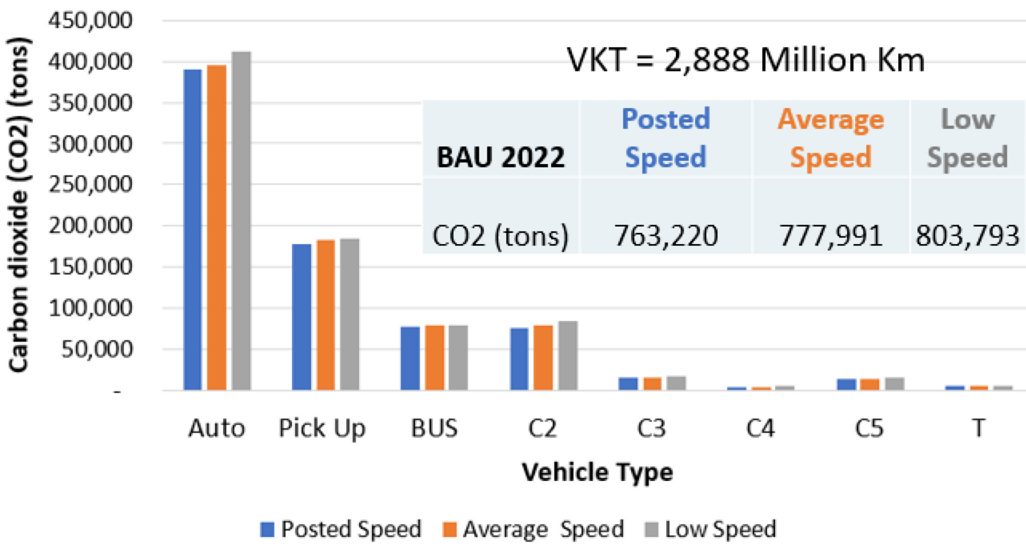
Target	2022	2030	2040	2050
BAU	0	0	0	0
Low	0	10	30	50
Moderate	0	15	40	75
Aggressive	0	25	50	100

Figure 3.16 shows the share of CO_2 emissions per vehicle class and speed for the emissions baseline scenario 2022 and a VKT of 2,888 million-Km. For the average speed scenario, automobiles produce 50.77% CO_2 emissions, and the bus fleet produces 10.22% CO_2. The combination of Pick-ups & Vans and 2-axle single units (C2) produce 33.6% of CO_2. These freight trucks under 20 tons of GVW travel within the city to deliver goods to shops and markets, while the heavy trucks between 20 tons and 50 tons represent 5.45% of CO_2 emissions.

Three-speed scenarios were calculated to account for speed reduction due to congestion that is expected to increase over time. Because lower speeds produce higher traffic emissions, they produce higher traffic emissions. This is valid for speeds between 5 to 90 Km/h, as speed decreases then CO_2 emissions increase, and speeds lower than 30 Km/h contribute to a significant increment in traffic emissions (Mrabti et al., 2022; Shahid et al., 2014; Barth et al., 2013).

The scenario 2022 shown in Figure 3.16 shows a difference of 25,802 tons of CO_2 between the average and low-speed scenarios; and 40,573 tons of CO_2 between the posted speed and low speed. Emission factors increase as speed decreases, and its rate increases significantly when speeds are below 30 km/h (EMISIA et al., 2021; NZ Transport Agency, 2018).

Figure 3. 16 Share of CO_2 emissions per vehicle class and speed for the 2022 scenario.



The share of traffic emissions per road classification for average speed for the emission baseline scenario 2022 is shown in Table 3.28. Highways and minor arterials have similar VKT and produce the most traffic emissions. In the case of highways, the length of the network is 88.01 Km, but it has more lanes and larger traffic volumes. Highways VKT is 1,260 million-Km. Minor Arterials have a lower capacity and fewer traffic volumes; however, the 238.69 Km of roads produce 1,231 million-Km of VKT. Figure 3.17 shows the Vehicle Kilometer Traveled (VKT) for the emission baseline scenario 2022 in San José.

Table 3. 28 Share of traffic emissions per road classification for average speed for the emission baseline scenario 2022

Road Classification	Traffic Volume Per direction		Road Length	VKT	CO_2	NOx	PM2.5
	Mean	Std. Dev.	(Km)	(Million-Km)	(tons)	(tons)	(Kg)
Highways	36,923	13,953	88.01	1,260	309,362	1,986	69,980
Principal Arterials	21,797	15,939	22.25	178	49,872	313	13,591
Minor Arterials	14,077	9,822	238.69	1,231	354,397	1,955	90,569
Collectors	4,358	4,675	148.76	219	64,359	366	16,667
		Summatory	497.71	2,888	777,991	4,620	190,808

Figure 3. 17 Vehicle Kilometer Traveled for the emission baseline scenario 2022 San José

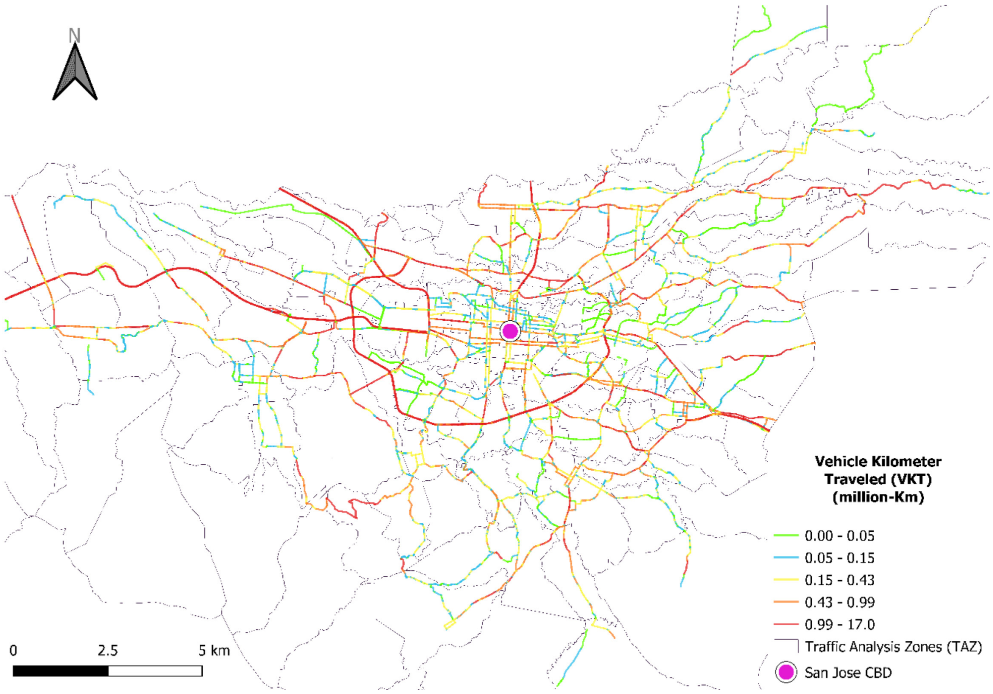


Figure 3. 18 shows the attributes considered for the estimation of emission scenarios. The scenarios are as function of VKT that increases due to the traffic growth, and EVs penetration into the fleet that will replace gasoline and diesel vehicles and will reduce emissions. For ICE vehicles, emissions will also be reduced by shifting from EURO I to EURO IV by 2030 and from EURO IV to EURO VI by 2050. These variables are applied to three speed scenarios to shape emissions scenarios for business as usual (BAU), low, moderate, and an aggressive scenario to evaluate the potential reduction of CO_2 emissions and air pollutants NOx and PM2.5.

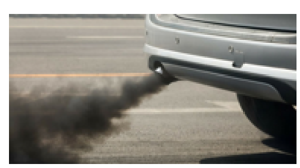
Figure 3. 18 Attributes considered for the estimation of emission scenarios.

1 **Traffic Growth**
VKT: Vehicle Kilometer Traveled

2 **Speed sensitivity**

Road Class	Posted speed (km/h)	Average speed (km/h)	Low speed (km/h)
Highway	100	85	70
Principal arterial	60	45	40
Minor arterial	40	35	30
Collector	40	35	30

3 **Vehicle Emission Standards (EURO)**



Year	EURO
2022	I
2030	IV
2040	IV
2050	VI

4 **Target scenarios EVs (%)**

Target	2022	2030	2040	2050
BAU	0	0	0	0
Low	0	10	30	50
Moderate	0	15	40	75
Aggressive	0	25	50	100

The emission baseline and mitigation scenarios and the spatial distribution are shown from Figure 3.19 to Figure 3.24. Table 3.29 shows the percentage of reduction of pollution with respect to the baseline 2022 for the average speed scenario. The Business-As-Usual (BAU) scenario is composed by 100% ICE vehicles (Figure 3.17). By 2050 the CO_2 emissions increase by 24.6% due to the traffic growth expressed in VKT. However, NOx decreases by 58.7% and PM2.5 decreases by 58.4%. The air pollutants NOx and PM2.5 decrease due to the change from EURO I to EURO IV despite the increase of VKT, and it can be seen in Figures 3.21 and 3.23.

By 2050, the low scenario in which 50% of the vehicle fleet becomes electric would result in a 37.7% CO_2 reduction, while a shift towards 75% of EVs (Moderate scenario) would result in a 68.9% CO_2 reduction. The low scenario reduces 79.4% of NOx, and the moderate scenario reduces 89.9% of NOx. Similarly, the low scenario reduces 79.2% of PM2.5 emissions, while the moderate scenario reduces 89.6% of PM2.5 emissions.

The NOx and PM2.5 emissions outcome also account for the emission standards change for the ICE vehicle fleet from EURO I to EURO IV by the end of 2050. Thus, by 2050, 50% of ICE vehicles will be EURO VI for the Low scenario, while 25% of ICE vehicles will be EURO VI in the Moderate scenario.

Table 3. 29 Percentage of reduction of pollution with respect to the baseline 2022 for average speed scenario

Pollutant	CO_2 (% change)			NOx (% change)			PM2.5 (% change)		
Year	2030	2040	2050	2030	2040	2050	2030	2040	2050
VKT (Million Km)	3,261	3,457	3,556	3,261	3,457	3,556	3,261	3,457	3,556
Vehicle Standard (*)	EURO I	EURO IV	EURO VI	EURO I	EURO IV	EURO VI	EURO I	EURO IV	EURO VI
BAU (%)	14.4	21.5	24.6	-27.6	-23.3	-58.7	-49.3	-46.1	-58.4
Low (%)	3.0	3.2	-37.7	-34.9	-34.6	-79.4	-54.5	-54.0	-79.2
Moderate (%)	-2.8	-27.2	-68.9	-38.3	-53.9	-89.9	-56.8	-67.5	-89.6
Aggressive (%)	-13.9	-39.3	-100	-45.4	-61.6	-100	-61.8	-73.0	-100

(*) Vehicle emissions standard for ICE vehicles

Figure 3. 19 Carbon Dioxide (CO_2) emission scenarios 2022-2050

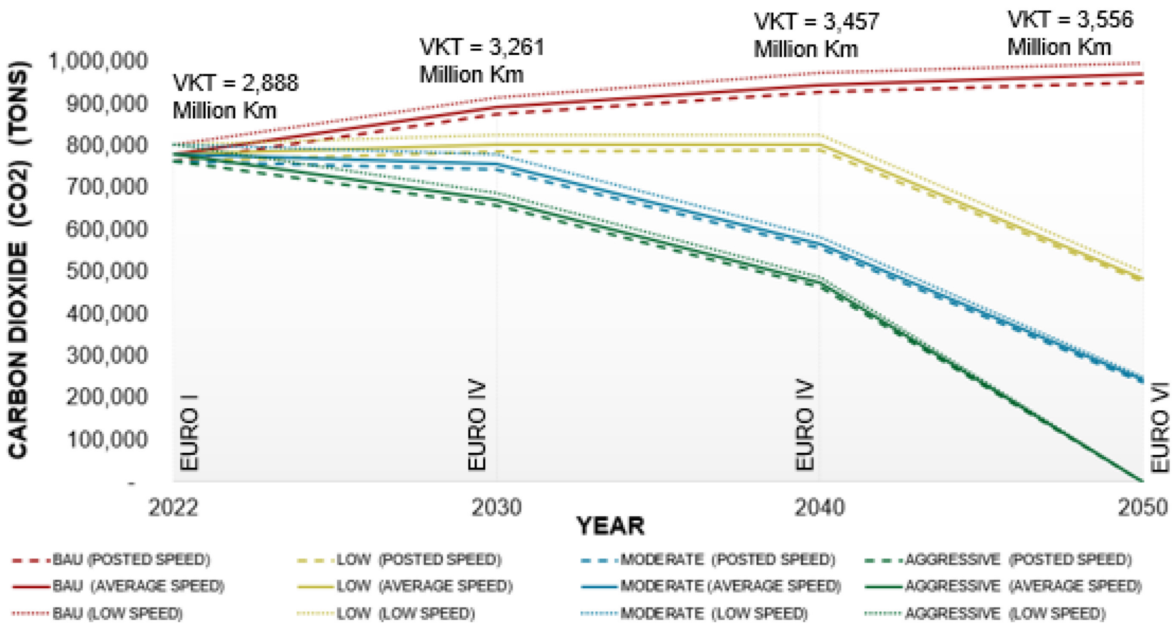


Figure 3. 20 Spatial distribution of Carbon Dioxide (CO_2) (tons) from 2022 model and average speed

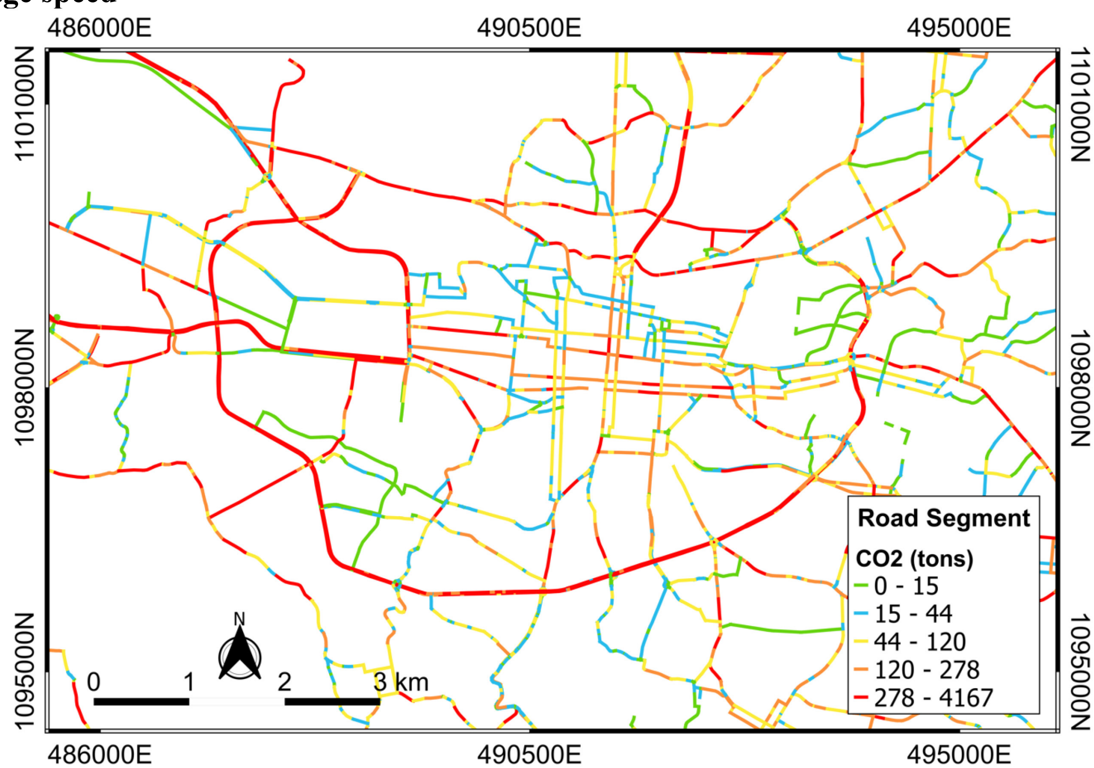


Figure 3. 21 Nitrogen oxides (NOx) emission scenarios 2022-2050

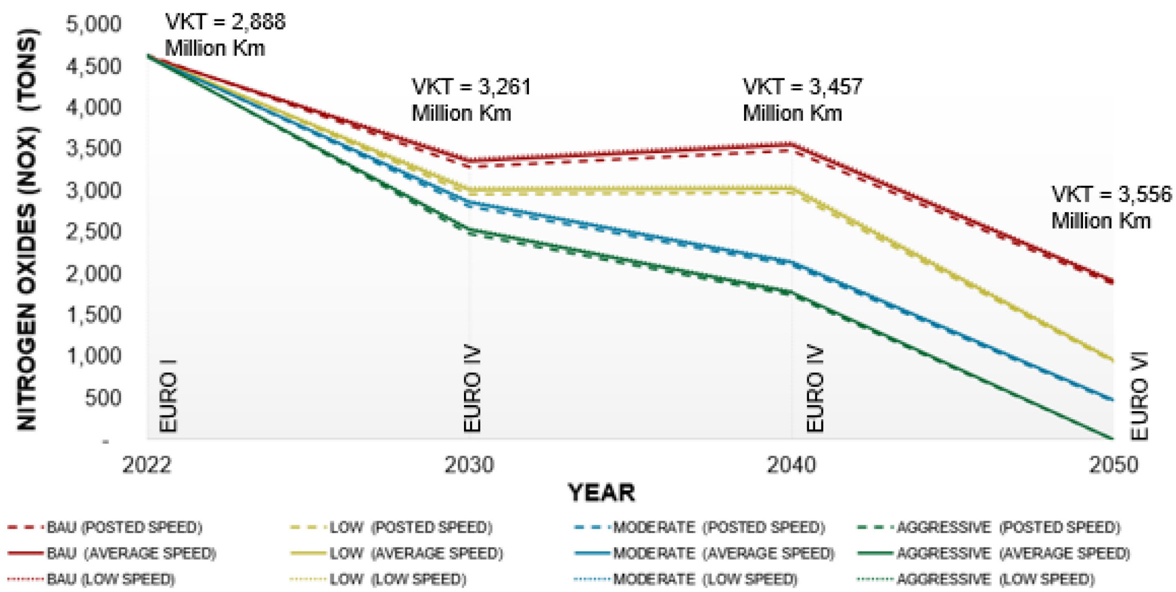


Figure 3. 22 Spatial distribution of Nitrogen Oxides (NOx) (tons) from 2022 model and average speed

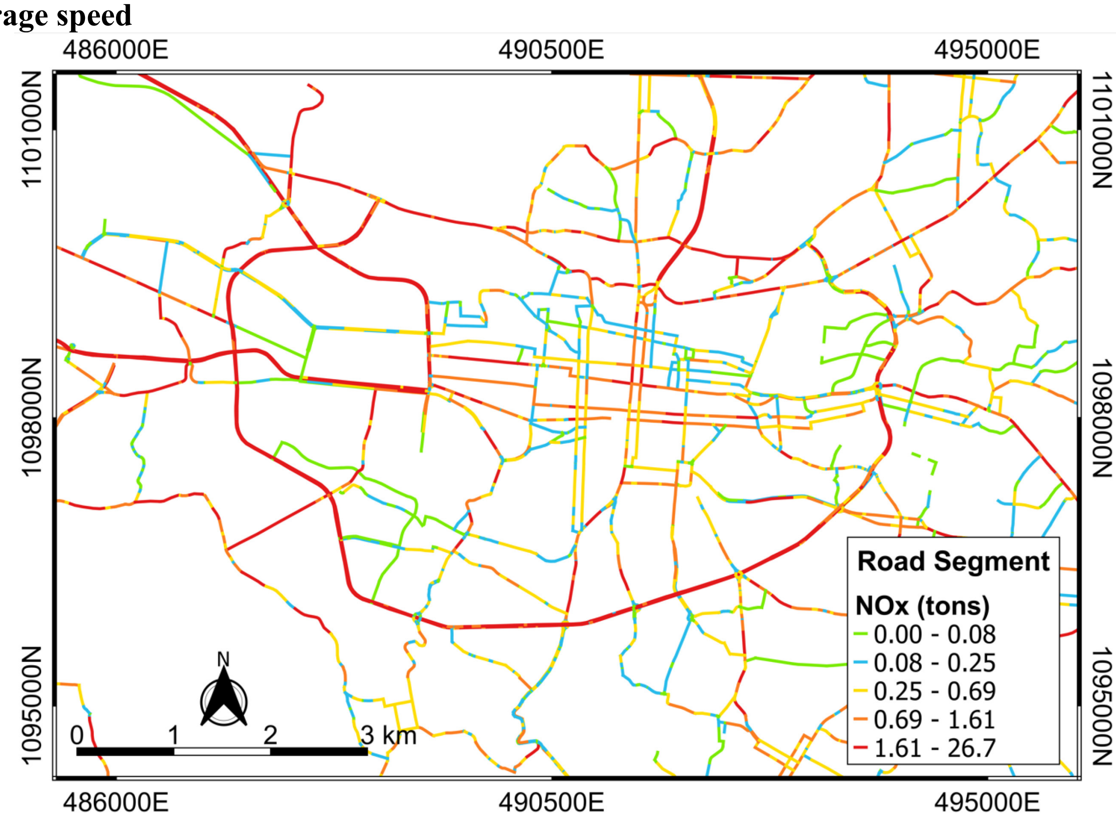


Figure 3. 23 Particulate Matter (PM 2.5) emission scenarios 2022-2050

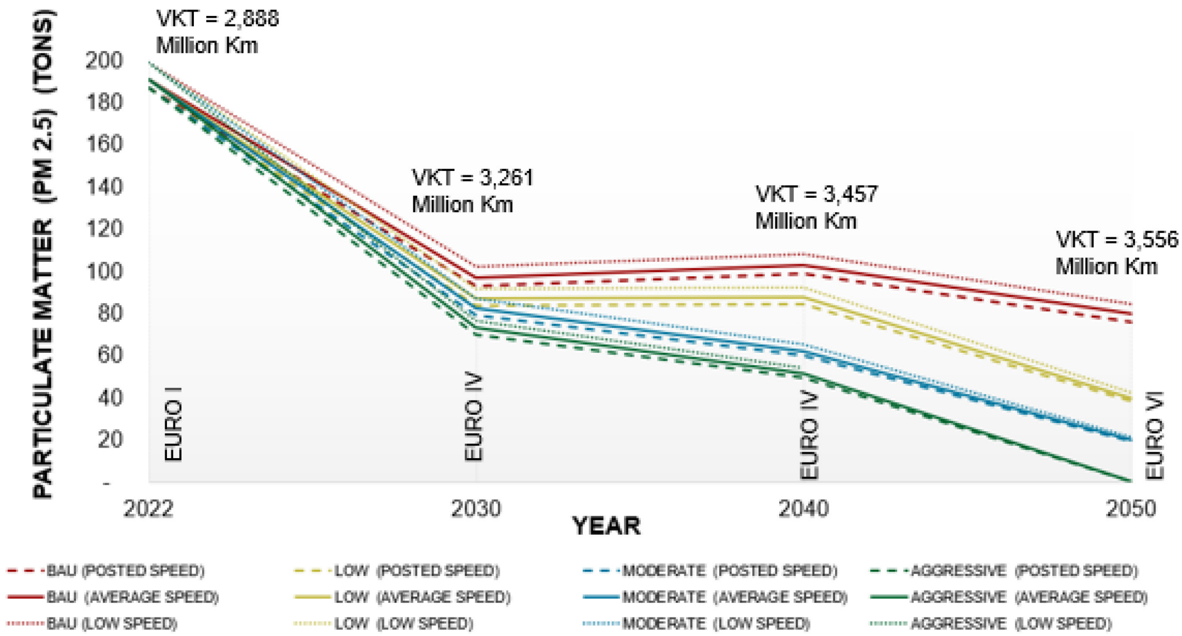
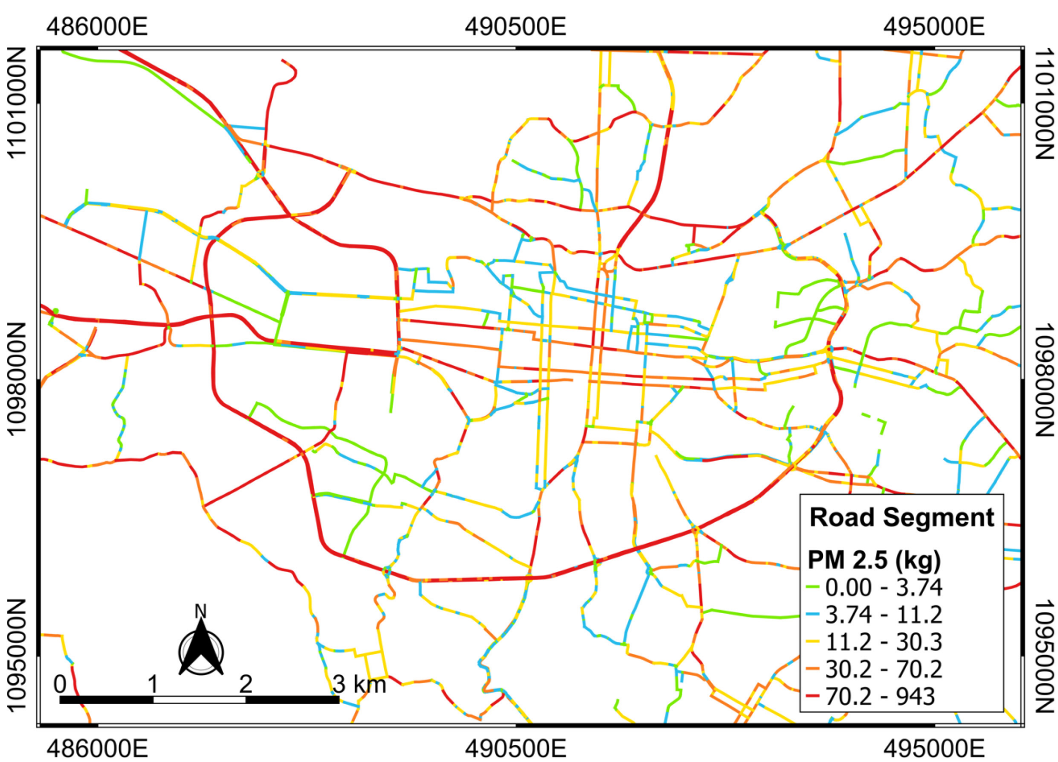


Figure 3. 24 Particulate Matter (PM 2.5) (Kg) from 2022 model and average speed



3.4 Discussion

Traditional transport planning has contributed to the dominance and growth of motorization in cities. The dominant use of cars, spatial segregation, and urban sprawl continue to reinforce car dependency. In the car culture, there is much attention to increasing highway capacity and investing in infrastructure to mobilize cars rather than other transport modes. Motorization produces adverse outcomes for society, health, and climate change. Investing in sustainable transport, such as high-quality public transport, walking, and cycling, is a countermeasure that just has begun in recent years (TUMI et al., 2020).

The Costa Rica case study is an example of traditional transport planning and investment decisions favoring the movement of cars. Overcoming institutional fragmentation plays an essential role in implementing strategies and policies. Decarbonization plans presented by the Ministry of Environment in Costa Rica incorporate the Avoid-Shift-Improve Framework (ASI) (Meza et al., 2018). However, investments in transport infrastructure continue to focus on increasing highway capacity (MOPT, 2020; PEN, 2018). The United Nations highlights that lack of integration across sectors is a significant obstacle to attaining sustainable development (UN Secretary-General, 2015).

From an environmental dimension in urban mobility, the country focuses mainly on the "Improve" measures toward changing the vehicle fleet to Electric Vehicles (EVs). This measure relies heavily on individual consumer choices. In 2021, the Gross Domestic Product (GDP) per capita was USD $12,472.4 (World Bank, 2021). In 2022, only 0.48% of the vehicle fleet was electric (MINAE, n.d.). Given the low penetration of EVs, income per capita, and low investments in sustainable transport, a regional emission model was developed to assess the potential reduction of CO_2 emissions and air pollutants NOx and PM2.5.

CO_2 traffic emissions in the year 2022 range between 763,220 and 803,763 tons. Passenger cars produce 51% of CO_2 emissions, followed by pick-up trucks with 23% CO_2, buses with 10%, 2-axle trucks with 10% CO_2, and heavy vehicles with a less significant contribution.

By 2050, the Business-As-Usual (BAU) scenario will increase 25% of CO_2 emissions due to traffic growth, resulting in a range of 949,453 and 997,893 CO_2. However, NOx and PM2.5 decreased by 58% due to the change of emission standard vehicles from EURO I to EURO IV and VI. Thus, even in the BAU scenario of having ICE vehicles, a regulation change and enforcement of vehicle emission standards can improve air quality. By 2050, NOx emissions will range between 1,872 and 1,919 tons, or a 58% reduction. PM2.5 emissions will range between 76 and 84 tons, or a 58% reduction.

By 2050, a low scenario requires a shift to EVs of 50% of the fleet, and the ICE fleet must be EURO VI, resulting in a range of 474,727 to 498,947 CO_2 emissions or 38% CO_2 emission reduction. By 2050 NOx emissions will range between 936 and 960 tons, or a 79% reduction. PM2.5 emissions will range between 38 and 42 tons, or a 79% reduction.

Likewise, by 2050, a moderate scenario requires a shift to EVs of 75% of the fleet, and the ICE fleet must be EURO VI, resulting in a range of 236,944 to 248,970 CO_2 emissions or 69% CO_2 emission reduction. By 2050 NOx emissions will range between 456 and 468 tons, or a 90% reduction. PM2.5 emissions will range between 19 and 21 tons, or a 90% reduction.

While the benefits of improving vehicle technology towards net-zero emissions are evident, relying only on the "Improve" measure from the ASIF framework is not recommended because of its weak feasibility to reach the target. The countermeasure to car dependency is to provide greater priority to public transport, walking, and cycling. These new sustainable transport networks and the integration of the urban form can shape new urban livable spaces. As a result, travel distances between origin and destinations can be reduced by changing the Activity System around new Transport Systems ("Avoid" measure), and travel behaviors can change by shifting from passenger cars to public transport, cycling, and walking ("Shift" measure). Internal Combustion Engines (ICE) for passenger cars and buses correspond to 61% CO_2 emissions. Thus, targeting these groups through the lens of ASI Framework should be a priority in achieving a net-zero scenario.

In the Global South, the lack of data availability on transportation limits the development of transport planning and projects (TUMI et al., 2020). A travel demand model aims to simulate the reality for which local calibration and validation are essential. Inadequate data contribute to the error in the model. In the case study, the only OD survey of the case study is from the year 2007. The travel behavior might not have varied significantly because there are no significant changes in the transport and activity systems. Under these circumstances, it is safe to assume that parameters and travel behavior estimated from the 2007 OD survey might not have varied significantly. However, in the state of practice, transport agencies collect OD surveys every five years (ARTM, n.d.) to provide a good representation of travel behaviors. There is a need to collect data to update the calibration parameters (i.e., the conical-delay function); centralize and make the data accessible.

The model went through external validation, and the trip assignment step was validated with observed traffic data collected by traffic counts. The dataset had many issues, such as the unavailability of count stations, given the limited budget for maintenance of malfunctioning equipment since the year 2015. Thus, the year 2015 was used for external validation.

Two approaches of validation checks were performed: (1) Comparisons of the base year model with observed values; and (2) Temporal validation (Cambridge Systematics Inc., 2010). The first validation approach is considered the "traditional" validation. It compares the model results with an independent dataset, such as traffic counts. The model 2007 was taken as the base year model and validated with traffic counts data. The second approach was applied by forecasting the 2007 model to 2015 and validated with observed traffic counts from 2015.

Overall, the 2007 model had an RMSE of 17.10%, and the 2015 model had an RMSE of 17.89%. However, when disaggregating the error per volume groups, the error is more significant for roads with less than 5,000 daily vehicles per direction. The models overpredict traffic on volume groups larger than 20,000 daily vehicles per direction, and underpredict traffic on roads with volumes lower than 20,000 daily vehicles per direction. Volume groups with less than 5,000 daily vehicles per direction have larger errors. It is expected to carry on with this pattern for the forecasted models.

The assignment step used a Deterministic User Equilibrium Assignment (DUE) approach, which has a set of assumptions that assigns traffic believing that all drivers know the traffic conditions and will choose the route with minimal travel time. On the other hand, the Stochastic User Equilibrium Assignment (SUE) approach assumes that the driver seeks the minimum "perceived" travel time, and they can make errors in the route choice. Thus, also selecting suboptimal routes. Given the RMSE per volume group, in future models, it is recommended to evaluate the performance of the Stochastic User Equilibrium Assignment (SUE) for this case study.

The potential for reduction of emissions and air pollutants was estimated given the "improve" measure towards shifting to electric vehicles. A set of emission scenarios were evaluated, and the reduction of emissions was calculated for a time horizon of 2050. The scenarios allow agencies to monitor the EVs penetration progress and compare it with targets.

Instead of a fixed scenario estimation, this modeling should be seen through a systems maturity process lens. Thus, the model should be dynamic and updated with new datasets and improved techniques from the initial model to estimate new scenarios.

Figure 3.25 shows the proposed maturity process for the regional emission model. In data management, OD surveys should be collected every five years or less, the census and OD survey attributes should be matched, the transport system and land use database should be integrated, local data for calibration must be updated, and traffic counts should be collected on an annual basis.

Two approaches can be used to estimate traffic emissions: vehicle-based, which estimates the Vehicle Kilometer Traveled (VKT); and person & goods-based, which estimates the Passenger Kilometer Traveled (PKM) and Tonne kilometers (TKM) of cargo transported (Kooshian et al., 2018). A vehicle-based approach was used in this model to estimate emission scenarios. A vehicle-based approach demands fewer data than the person & goods approach. However, the person & goods approach can allow for evaluating strategies regarding shifting transport modes, or the "Avoid" and "Shift" measures (Kooshian et al., 2018; Grütter et al., 2016).

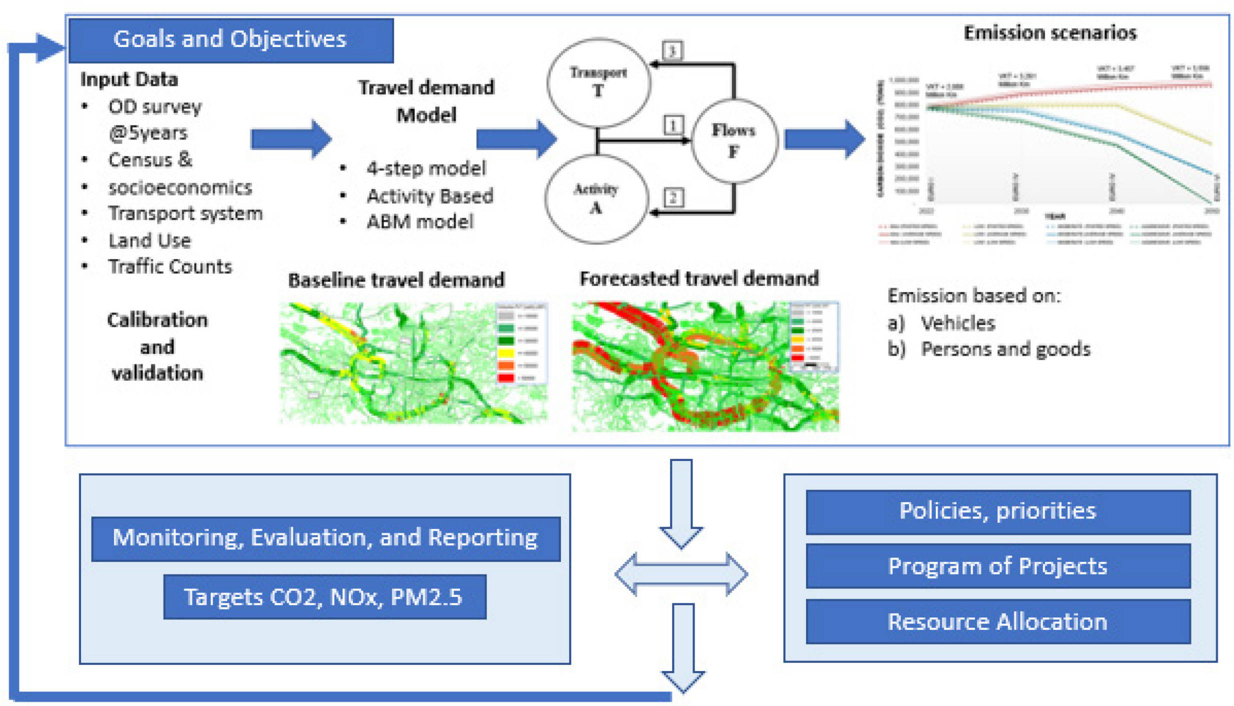
Part of the maturity process is to increase the level of modeling tools' complexity, which also demands more complex data collection. A four-step travel model is a trip-based approach that aggregates trip activities leading to a trip-based model. In a four-step model, trips are made from home to a destination activity and vice versa, such as home-based work. However, most people do a chain of trips, and a four-step model would result in overestimating and underestimating trips (Mansoureh & Ardeshiri, 2017).

Another travel model approach is the activity-based travel model is a tour-based model which considers trip chaining that considers the daily itinerary. For example, the person leaves home, drops the children at school, goes to work, leaves the office for lunch, goes back to work, picks up the children from school, goes grocery shopping, and gets home. The disaggregate nature of an activity-based modeling allows for designing environmental policies such as congestion charging and tolling measures to disincentive car use (Mansoureh & Ardeshiri, 2017).

Another travel modeling approach is the agent-based travel demand models, which can incorporate individual travel behaviors at a microscopic level and develop macroscopic travel patterns. The travel demand model has three types of agents: node, arc, and traveler. Nodes entail demographics and socioeconomics, arc refers to the connectors between nodes, and the traveler agent aims to find an activity at the lowest travel cost. There are behavioral rules, and agents can change their behavior and evolve. Some behavioral rules are the interaction between agents and the environment (i.e., free-flow driving or changing lanes). Agent-based models are disaggregated and consider human behavior (Mansoureh & Ardeshiri, 2017; Zhang & Levinson, 2004). Disaggregate or behavioral models such as activity-based and agent-based models (ABM) can be a closer simulation to reality by travel decision-making and person-environment interactions. Activity-based models can be integrated into agent-based models (Bekhor et al., 2011) (Zhang & Levinson, 2004).

Improving the travel demand model is not the objective of this research. Instead, developing a framework for a regional emission model supported by a case study through the lens of maturity levels that aims for process improvement and systems performance management. Thus, data management and simulation model techniques can improve over time to deliver improved models that can capture travel behaviors and interactions more realistically. Figure 3.25 shows the maturity process for this regional emission model, where policies and projects are in alignment with strategic goals and objectives.

Figure 3. 25 Regional Emission Framework and Maturity Process



OD survey: Origin-Destination survey; @5years: every five years; ABM: Agent-based model

Future research should define targets for CO_2, NOx, and PM2.5 to include in a monitoring system and formulate policies, priorities, projects, and resource allocation. A monitoring process of emissions should evaluate project performance to determine if the goals and targets were achieved. The transport and emission modeling process begins again, incorporating the outcomes and new goals. There is a need to incorporate Life Cycle Cost Analyses (LCCA) for project development.

3.5 Conclusions

A bottom-up regional emission traffic model was created and supported by a four-step travel demand model with a Costa Rica case study. The objective was to evaluate the potential reduction of CO_2 emissions and air pollutants NOx and PM2.5 given the EVs' penetration effect on the vehicle fleet for a time horizon of 2022 – 2050. The emission model considered vehicle type and weight, average speed, and vehicle technology, and the analysis was disaggregated per road classification for highways, principal arterials, minor arterials, and collectors.

A framework under a systemic approach and performance management was proposed for a bottom-up regional emission model supported by travel demand modeling. Setting long-term emission scenarios allows the framework to measure network performance by monitoring EV penetration. The process of monitoring, evaluating, and reporting allows for identifying trends and targets and the definition of new policy instruments and priorities for climate actions toward achieving the 2050 goals.

The systemic approach of this framework is a dynamic process where agencies can make improvements over time and deliver improved datasets and travel demand methods. Disaggregate or behavioral models such as activity-based and agent-based models (ABM) can be a closer simulation to reality by travel decision-making and person-environment interactions. The disaggregation of trips can reduce the error of overestimating and underestimating traffic flows, a limitation of the four-step models. Future research should define targets for CO_2, NOx, and PM2.5 and incorporate Life Cycle Cost Analyses (LCCA).

For the case study of San José – Costa Rica, the four-step travel demand model overestimates traffic on roads with volume groups larger than 20,000 daily vehicles per direction and underestimates traffic with volume groups lower than 20,000 daily vehicles per direction. Volume groups with less than 5,000 daily vehicles per direction have more significant errors. It is expected to carry on with this pattern for the forecasted models.

Several factors influence the errors found in the travel models. There is no external TAZ in the southbound of the model, and while low-volume roads characterize the south, there are more errors in the prediction of volumes due to the absence of external TAZ. The annual traffic growth applied to the forecasted models is a network average rather than individual road segments. There is an assumption of a 50% directional split in the daily traffic volumes. The OD survey is from the year 2007, and traffic counts are scarce after the year 2015.

The case study of San José showed that by 2050, the Business-As-Usual (BAU) scenario would increase 25% of CO_2 emissions due to traffic growth. This scenario was mitigated by including the effect of the change of vehicle emission standards of ICE vehicles from EURO I to EURO VI, given the current changes in legislation. As a result, air quality shows improvements with a 58% reduction of NOx, and PM2.5.

The low scenario (50 % EVs) and moderate scenario (75 % EVs) reduce 38% CO_2 and 69% CO_2 emissions, respectively. For air quality, the low scenario attains 79% NOx and PM2.5 reduction, while the moderate scenario achieves a 90% reduction of NOx and PM2.5.

By taking global benchmarks, the United Nations recommends that by the year 2030, a 45% reduction of greenhouse gas emissions (GHG) to get back on track to limit global warming to 1.5ºC (UNEP, 2022; UNDESA, 2021). On a global scale, Costa Rica is not a significant contributor to GHG. However, on a local scale, air pollution in the metropolitan city exceeds the health limits, and air quality must be a priority.

In the year 2022, the model of this research showed that passenger cars are the largest contributor to CO_2 emissions, with 51%. After passenger cars, pick-up trucks produce 23% CO_2 and buses 10% CO_2. It is not recommended to rely only on the consumer to shift to EVs ("improve" measure), which depends on psychological factors, socio-economic factors, and policy instruments (i.e., financial, lifting driving restrictions).

Moreover, addressing other climate countermeasures such as rapid transit, cycling, and walking ("avoid" and "shift" measures) can target 61% of CO_2 emissions produced by passenger cars and buses. Addressing climate change and air pollution requires real implementation of the Avoid-Shift-Improve Framework (ASI). Sustainable urban mobility plans should align national and municipal efforts toward common goals and strategies and reduce car dependency and motorization levels.

CHAPTER 4

Linking gender equality and transport planning for healthier cities

Abstract

This research explores the geospatial urban interdependence among gender and vulnerable groups and their exposure to traffic-induced air pollution estimated from a four-step travel demand model. Six dimensions of gender equality were identified for managing gender barriers: Workforce, Economics, Education, Health & Sexual Reproductive Rights, Empowerment, and Time. There is intersectionality among dimensions, and its relationship to urban mobility is explored.

A case study for San José - Costa Rica identified areas of high priority based on a vertical equity urban planning approach. It was found that the population experiencing material deprivation is 11.07% women and 10.02% men. The population with disabilities is 6.16% women and 4.92% men. An assessment of the ratios per population found no statistically significant difference (p-value < 0.05) for material deprivation based on gender, but there was a statistically significant difference in disabilities, where women have larger disability ratios. Analyzing household composition that does not own a car, there are 8.90% of single mothers, 0,83% of single fathers, and 45.56% of households having two parents. Comparing the ratios per population of these variables (p-value < 0.05), there was no significant difference between two parents and single fathers, but there was a significant difference between single mothers when compared with two parents and single fathers. There is a larger ratio of single mothers without automobiles than the other variables. The case study is a car-dependent city, and accessibility to opportunities are limited in the absent of owning a car.

From a geospatial approach, it was found that there is a close match between women with material deprivation and single mothers that do not own a car. High priority areas for improving urban mobility were identified. The Central Business District (CBD) has higher ratios of women with disabilities and high levels of air pollution. The inner city has higher ratios of women with material deprivation, single mothers who do not own a car, and high levels of air pollution. The Southbound produces intermediate levels of pollution and has high ratios of women with material deprivation, single mothers that do not own a car, and the higher population density of the city, which supports investments for transit infrastructure.

Reducing air pollution requires reducing the Vehicle Kilometer Traveled from highways. This network attracts trips from outer provinces that commute to the city. Thus, rapid regional public transport and carpooling should be considered. A modal shift would reduce air pollution in the inner city and CBD. In addition, the city's Southbound should be a priority to improve urban mobility as it has a lower socioeconomic stratum and higher population density. The CBD and inner city have higher ratios of women with disabilities. Further research and data collection are needed to understand the mobility needs of this demographic group.

This analysis is a first approach to integrate gender-sensitive transport planning and a health dimension in a metropolitan city. Furthermore, accessibility to opportunity analyses should be conducted to integrate transport and land use, and affordability analyses.

4.1 Introduction

The Sustainable Development Goals (SDGs) seek to put people and the environment at the center of decision-making. It aims to promote economic prosperity and good governance for social development with the core principle of "leaving no one behind" (Sachs, 2015). In urbanization, key lessons from the COVID-19 pandemic highlight the need to plan for resilient cities and strengthen equity to tackle social inequalities and adverse health outcomes (UN Habitat, 2022). In addition to the SDGs, other policies from the United Nations call for incorporating a gender perspective in transport planning and healthier cities (UN WHO, 2021b).

SDG 3 focuses on ensuring healthy lives and promoting well-being for all. Urban planning and transport can have positive or negative health implications. Incorporating health in the planning and design of cities can contribute to managing preparedness for epidemiological events. Social inequalities go hand-in-hand with the spread of infectious diseases and exposure to transport negative externalities such as air pollution, noise, traffic injuries and deaths. There are structural determinants (socio-economic, political context, and social hierarchies) and intermediary social determinants (health system, exposure, and vulnerability of populations) related to health outcomes. Recognizing the role of cities in health outcomes, cities must address social inequalities, and underlying social, economic, environmental, and political determinants of health (UN WHO & UN Habitat, 2016).

SDG 5 is to "Achieve gender equality and empower all women and girls" is an ambitious goal that no nation has yet achieved (Sachs et al., 2022). Nine targets have been set to achieve this goal. The first seven of these targets map directly to women's day-to-day challenges, including ending harassment, violence, early marriage and genital mutilation; highlighting and valuing unpaid labor; empowering women in leadership roles in all walks of life; and rights to reproductive health and economic resources. The last two targets, however, offer a vision of how gender equality can be achieved and maintained (UNDESA, 2015).

This research explores the geospatial urban interdependence among gender and vulnerable groups and their exposure to traffic-induced air pollution estimated from a four-step travel demand model for Costa Rica. The first objective is to review the barriers women experience to attain equal opportunities to men and their connection to urban mobility. The second objective is to perform a demographic analysis and tackle inequalities in urban health and air pollution for Nitrogen Oxides (NOx) and Particulate Matter (PM2.5). These analyses explore how to incorporate equity, gender, and environmental externalities into urban mobility planning.

4.2 Gender Equality

Achieving gender equality is a complex challenge that requires a systemic and strategic approach, which is particularly critical to implement at regional and local levels. Barriers to gender equality cross socio-economic boundaries.

Gender intersects with economic empowerment, especially through poverty, access to good work, education and the rights to safety and environmental sustainability. Here it is presented a highly abbreviated review of some important aspects of these intersections.

In addition, planned and unplanned pregnancy influences the available economic opportunities and employment available to women. Sexual reproductive health and education are key to support their economic development. Early age pregnancies disrupt women and girls' ability to finish high school or pursue a university education. These educational disruptions are often compounded by domestic violence. According to the World Health Organization, worldwide, 35% of women have experienced physical or sexual violence (UN WHO, 2022).

Gender equality is sometimes narrowly defined, as equal pay, reproductive choice, or living without violence or harassment. In fact, gender equality intersects with a large number of other foundational concepts of social exclusion. In order to achieve equality, women must have basic freedoms met, such as the ability to direct their own lives and choices, the ability to access education and work, and the ability to access and direct their healthcare and reproductive choices. But these freedoms must be coupled with equitable opportunities, meaning freedom from discrimination, equal pay, and freedom from sexual harassment and violence both in and out of the workplace and transport systems.

4.2.1 Barriers in achieving gender equality

One policy tool that has been used to increase women's representation in politics are gender-based parity and quota policies. Latin American nations which have adopted these policies require anywhere from 30% to 50% of candidates are female (Bárcena et al., 2017).

These policies have been quite successful in increasing representation, particularly at the federal level (WEF, 2022). However, even for countries which have been successful in increasing gender representation at the federal level, that gender progress does not necessarily extend to more local levels of government.

Often, the arguments made for increased gender representation are tied to representation and empowerment. Indeed, seeing women representatives at the parliamentary level is important representation for women, particularly when it comes to laws and regulations that disproportionately impact women. The most glaring example are reproductive rights, and particularly abortion rights. But the importance of women in powerful positions extends beyond parliament. Representation among judges, prosecutors and defence lawyers is critical in protecting women's parental and personal safety rights. At the local level this includes gender equality in police departments and local government.

Equal representation matters beyond government. In Costa Rica, the majority of university graduates are now women. Yet, university boards of directors remain overwhelmingly male. The same holds true for boards of government for crown corporations (Salas-Calderón et al., 2019).

Six dimensions of gender equality are analyzed, as shown later in Table 1. These dimensions are workforce participation, economic power, education, health & sexual reproductive rights, time, and empowerment.

There are significant data gaps in the measurement of these dimensions. For example, women-owned businesses are important not just for economic power, but for empowerment. Pay equity can be measured directly, or through adjusted data. When directly comparing median earnings between men and women, the gender gap for OECD countries is roughly 13%. However, Canada and the United States of America have much similar and higher gender income differences of 17.6% and 18.5%, respectively (OECD, 2020).

Work-life balance is often discussed as a gendered issue, in which women can optimize their work life and home life. In the popular media, women are given helpful tricks or "hacks" to make their lives work. But these popular narratives of work life balance belie the time limitations women face and the impacts these limits pose for women's access to the workplace and advancements. While in some workplaces women's additional burdens for childcare and home-work responsibilities are formally recognized (Bakker & Jacobs, 2016).

The barriers to women's participation in the workforce need to be better understood. This is particularly important in the Costa Rican context, where economic parity is limited by women's ability to access the labor market, rather than education or solely a wage gap. Costa Rica has significant programs to ensure access to childcare and schools, including free school lunches and subsidized or free childcare for mothers to access work and school (Salas-Calderón et al., 2019). Underlying this disparity is the disproportionate amount of homework and childcare that women take on, meaning that these barriers limit women's economic participation more substantially or solely.

This additional burden of home and child labor that women face challenges the ability to obtain work, good work, promotion, advancement, or participate in entrepreneurship or politics. When childcare is not available, or when a child is ill, the care burden falls on women rather than men. According with UN Department of Economics and Social Affairs (UNDESA), "On average, women spend approximately three times as many hours in unpaid domestic and care work as men, and significantly more if they have children" (UNDESA, 2022).

These additional burdens further relate to transport and safety. When neighborhoods are not safe or accessible, women may be forced to reduce their travel in order to access work, childcare or education.

Single working mothers need to balance work and household responsibilities (Blumenberg & Manville, 2004). Research in the United Kingdom has found that shorter travel distances are correlated with higher performance, while longer travel times lead to difficulties in sustaining jobs (Church et al., 2000a).

Social exclusion comes in many forms, but all involve an inability to participate in civil society (Preston & Rajé, 2007b; Stanley & Lucas, 2008b). For gender equality related to sustainable cities, an important aspect of social exclusion is limitation of access due to time deficits and fear, translated as the freedom of movement.

Time-based exclusion refers to time available for travel, while balancing responsibilities between work and household. At the neighborhood-scale consider fear-based exclusion means the fear for personal safety in transport systems and public spaces (Church et al., 2000a; Lucas, 2012a).

4.2.2 Trends in the Americas

Gender equality is multi-faceted. Four aspects of gender equality are compared: gendered violence, pay equity, equal representation, and home-work balance in an abbreviated review of gender equality in the Americas.

4.2.2.1 Gender equality in Canada

The Canadian Government aims to create federal policies and programs that are more responsive to the differential needs of diverse groups recognizing the intersectional nature of the SDGs. Federal policy specifically targets indigenous women and girls, migrant and refugee women and girls, women and girls in rural and remote communities, women and girls with disabilities and LGBTQ and non-binary persons (Global Affairs Canada, 2018).

Despite this federal focus on equality, Canada has ongoing challenges related to achieving gender equality. The Canada's Implementation of the 2030 Agenda for Sustainable Development: Voluntary National Review reports that harassment and sexual violence in workplaces are under-reported and ineffectively managed. Women in Canada remain under-represented in politics and leadership roles. Canadian women also earn less than men (Canadian women earned $0.87 for every dollar earned by men in 2017), and experience high rates of harassment and gender-based violence—nearly 1 in 3 women experienced sexual harassment in the workplace. Gendered violence also persists in Canada. While this exists across demographic groups, there is an especially severe problem of violence towards indigenous women and girls (Global Affairs Canada, 2018).

4.2.2.2 Gender equality in the United States of America

The situation in the USA is largely similar to Canada. However, the government policy is not explicitly oriented toward promoting equality and inclusion for women or minority or oppressed communities. Evidence suggests that while significant advances toward gender equality occurred in the 1970s and 1980s, improvement has either slowed or stopped. As of 2018, women earned $0.83 per dollar earned by a man (England et al., 2020). Polls indicate that 42% of women experience gender discrimination at work (Parker & Funk, 2017) and depending on the source, anywhere from 25-85% of women experience sexual harassment at work (Durana et al., 2018). While discussions of sexual harassment and violence have increased with the #MeToo movement, it remains to be seen whether or not this discussion will manifest lasting societal change.

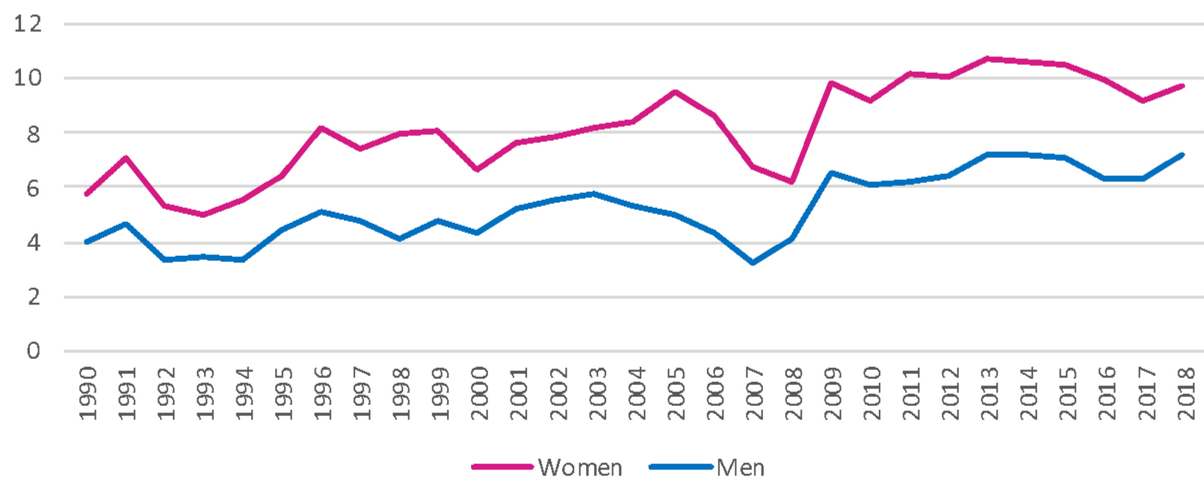
4.2.2.3 Gender Equality in Costa Rica

Costa Rica has uneven performance in gender equality. Recent progress in the number of women in Parliament and high educational achievement, as well as access to health care and contraception all compare favorably to much of Latin America (WEF, 2022). In addition to the programs ratified by Costa Rica, the country has added new rights to scale up gender equality (Salas-Calderón et al., 2019) Costa Rica is ranked 58th out of 191 countries in the Gender Inequality Index (GII) conducted in 2021 (UNDP, n.d.-a).

The difference in higher educational achievement and participation in the labor market highlight this uneven performance. Between 2009 and 2016, the proportion of graduated women was 60% (Salas-Calderón et al., 2019). Yet, women experience disadvantages when it comes down to participation in the labor market and leadership positions.

Costa Rica's State of the Nation reveals a consistent difference on unemployment rate between men and women between 1990 to 2018 (PEN, 2020b). Figure 4.1 shows this trend as the percentage of the unemployed population with respect to the labor force (15 years or more).

Figure 4. 1 Unemployment rate per gender in Costa Rica



Source: (PEN, 2020b)

COVID-19 has led to rising levels of poverty with a direct impact on the most vulnerable and disadvantaged populations. Using data from Statistics National Institute of Costa Rica (INEC), Baiocchi et al. (2020) highlighted that during the period of July and August 2020, poverty levels reached 26.2% of households, and extreme poverty increased by 8.5%, the highest values reported since 1992.

COVID -19's impact is also gendered; the latest unemployment rate is 30.4% for women and 20% for men. The most affected group are women with incomplete primary education, whose labor participation dropped 54% (Baiocchi et al., 2020).

While data gaps prevent a full assessment of the gender pay gap, existing estimates vary wildly. The Organisation for Economic Co-operation and Development (OECD), for example, reports the Costa Rica wage gap is less than 4% (OECD, 2020). Local reporters estimate gender wage gap up to 27% (Arias, 2017). The highest estimate found for the wage gap is 34%, meaning a woman makes $0.66 cents for every dollar earned by a man in Costa Rica (Romero, 2022). Most likely, this discrepancy stems from both low participation in the labor market as well as an hourly wage gap.

United Nations ECLAC (Economic Commission for Latin America and the Caribbean) collects data on ministerial positions by nation as a measure of gender equality, Costa Rica has a participation of 50% women in ministerial cabinets (UN ECLAC, 2022). In Costa Rica, the National Institute for Women (INAMU) also includes data related to members of Parliament. There is a gender parity with a ratio of 26 to 31 female to male members (Salas-Calderón et al., 2019). Municipal governance demonstrates a much different picture of gender equality than the national data. At the municipal level significant differences are found in the proportion of female and male mayors with a ratio of 12 to 69 (Salas-Calderón et al., 2019).

4.3 Sustainable Cities and Gender Equality

4.3.1 Gender equality dimensions and localizing the SDGs

Cities and transport play a fundamental role in the socioeconomic development of the population. A Sustainable Development Goals Index (SDG Index) was created to monitor the progress of cities and countries in attaining the SDGs. The SDG comprises indicators in inequalities, employment and income, gender equality, housing affordability, accessibility to sustainable transport, climate change, and renewable energies. Urban health includes air quality and mental health associated with neighborhood safety and livability. The SDG Index includes traffic fatalities and obesity as well (Schmidt-Traub et al., 2017).

The Sustainable Development Goals (SDGs) set global policies with a core message of "leave no one behind". In addition to gender equality, literature shows that this is measured by a combination of work, education, economy, local politics, health, family, and businesses (Forsberg & Stenbacka, 2018) (UNDP, n.d.-b).

Three relevant indexes in gender equality were identified and are shown in Table 4.1, presented by the United Nations and an index from the European Institute for Gender Equality:

(1) Gender inequality index (GII) seeks to measure and reflect gender inequality and considers three dimensions: health, empowerment, and labor market. GII also includes specific indicators relevant to each dimension, such as maternal mortality ratio, female and male shares of parliamentary seats, and female and male labor force participation rates, among others (UNDP, n.d.-b);

(2) Gender Development Index (GDI) looks at gender gaps and considers three basic dimensions of human development, healthy life, knowledge, and living standards (UNDP, n.d.-a); and

(3) Gender Equality Index (GEI) measures the progress of gender equality in 28 European Union countries using 31 indicators (European Institute for Gender Equality, n.d.). GEI considers six core domains enumerated in Table 4.1.

Forsberg & Stenbacka (2018) classified seven gender dimensions to evaluate municipal-level gender equality considering Work, Education, Economy, Local politics, Health, Family, and Business. These dimensions are similar to the GEI index (European Institute for Gender Equality, n.d.).

Table 4. 1 Dimensions of the indices in relation to the gender specific SDG goals

Gender inequality index (GII) dimensions (1)	Gender Development Index (GDI) dimensions (2)	Gender Equality Index domains (3)
Health	Long and healthy life	Health
Empowerment	Knowledge	Knowledge
Labor market	Standard of living	Work
		Power
		Money
		Time
		Violence against women*
		Intersecting inequalities*

Source: (1) (UNDP, n.d.-b); (2)(UNDP, n.d.-a); (3) (European Institute for Gender Equality, n.d.)
Notes: *Additional domains

UN Women stresses the importance of disaggregated data across gender dimensions, including income, sex, age, race, ethnicity, migration status, disability, and geographic location. Data gaps can limit the visibility of the most at-risk populations. Data must also be of high quality and timely to reflect the reality of the most disadvantaged groups. Accurate and reliable data systems can support efficient evidence-based decisions, strategies, and resource allocation (UN Women, 2015). Federal and local governments need policies, programs, and allocation of resources to respond to differential needs, but they often lack sufficiently granular data to do so.

From a top-down approach, countries rely on international gender equality indicators to monitor progress on gender equality. These indicators are reported at a high level with aggregated data. Localizing the SDGs is necessary to implement solutions beyond monitoring progress. Gender indicators and data at a block level with geospatial coordinates are necessary to incorporate gender equality in city planning and account for the intersectionality across variables.

Performance measures allow organizations to achieve their goals by developing metrics and monitoring progress. These Performance Measures (PM) allow agencies and stakeholders to monitor progress over time towards achieving a specific target (Grant et al., 2013).

Performance-based decision making relies on a set of goals, objectives and targets tied to measurable metrics, and quantifies the impact of policies, programs, and projects (AASHTO & U.S. FHWA, 2013; Grant et al., 2013a). Some properties of a good performance measure are Sinha & Labi, 2007):

- Appropriateness – PM should be an adequate reflection of at least one goal
- Measurability - Measure PM in an objective manner, with an acceptable degree of accuracy and reliability
- Dimensionality – Comparable across time periods or geographic regions
- Realistic – It should be possible to collect, generate, or extract reliable data
- Defensible – Clear and concise. It can be communicated effectively within a circle of decision makers, stakeholders and general public
- Forecastable – For planning purposes, it should be able to use existing forecasting tools

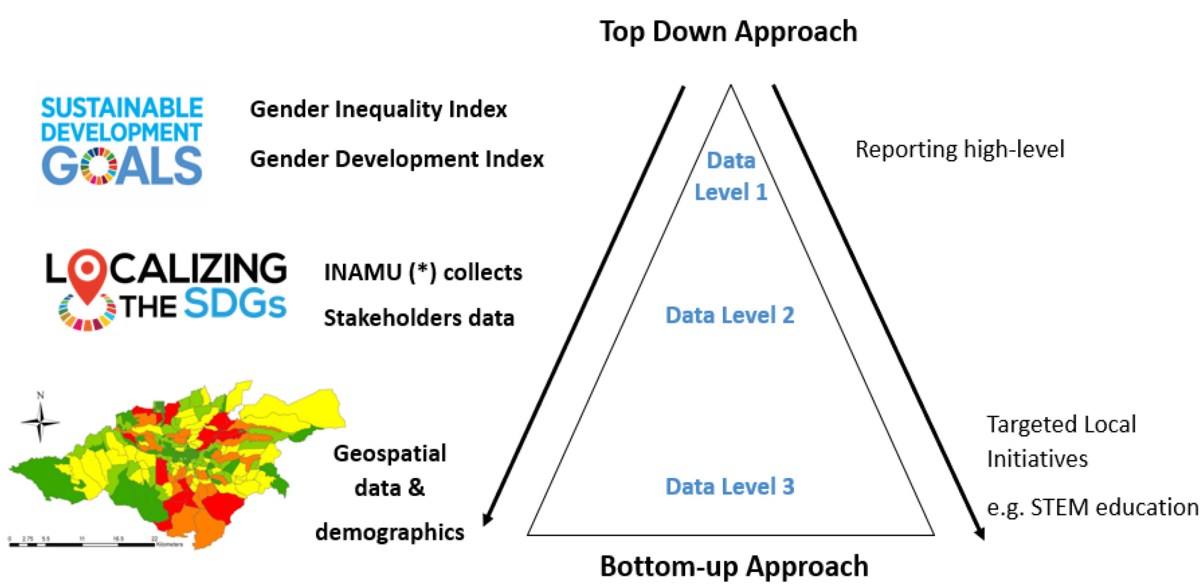
The gender indices reviewed allowed us to classify six dimensions of gender equality: "Workforce, Economics, Education, Health & Sexual Reproductive Rights, Time, and Empowerment" (European Institute for Gender Equality, n.d.; UNDP, n.d.-a; UNDP, n.d.-b).

Recognizing the need for implementing gender equality policies, the United Nations ECLAC (Economic Commission for Latin America and the Caribbean) has created a Gender Equality Observatory for Latin America and the Caribbean (Bárcena Ibarra, 2017). In 2018, the Government of Canada announced the creation of a Centre for Gender, Diversity and Inclusion Statistics (Global Affairs Canada, 2018).

The National Institute for Women (INAMU: Instituto Nacional de la Mujer) from Costa Rica collects data from government stakeholders in the most disaggregated form (Salas-Calderón et al., 2019). It is a comprehensive database. However, just like the international datasets reviewed, it lacks geographic coordinates and granular level of disaggregation that limits geospatial analyses to identify the most vulnerable and marginalized households, communities or districts in need for specific interventions in the city.

Figure 4.2 illustrates the difference between the two approaches for monitoring progress through indicators: (1) a top-down approach generating and reporting indicators at a high level; and (2) bottom-up approach using granular geospatial data in the most disaggregated form (block level in a neighborhood can be an appropriate unit of measurement). A bottom-up approach allows for identifying data gaps and performance measures aligned with the SDGs.

Figure 4. 2 Top-down and bottom-up approaches for monitoring progress of goals and objectives



4.3.2 Gender equality and transport planning

The 2030 Agenda encourages the creation of "sound policy frameworks at the national, regional and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions". Lack of integration across sectors in terms of strategies, policies and implementation has long been perceived as a major obstacle to achieving sustainable development (UNDESA, 2015).

A framework organizes information following a purpose to assist both technical and policy decision-making by presenting trade-offs in terms of benefits and costs to achieve strategic goals (Gudmundsson et al., 2015) (Uddin et al., 2013). Frameworks should assist policies and decision-making by relying on evidence and economic evaluations.

In a structured framework under performance management principles: (1) goals are transformed into performance measures or indicators; (2) a systematic data collection program supports these performance measures for planning and monitoring; (3) modeling and analytical tools are developed to support investment programming; and (4) the system is monitored to determine if the targets are being met and provide feedback (Grant et al., 2013).

The first step to develop a framework is establishing a Vision Statement, goals and objectives. The Vision is a statement of desired outcomes, linked to goals and objectives that will allow identifying data needs. Based on the gender equality UN policies and the SDGs, a vision statement was created. Table 2 presents the goals and objectives to incorporate Gender Equality and categorized under the six dimensions that are interrelated to the SDGs, with performance measures in urban mobility and cities.

VISION STATEMENT

"By 2030, create a world having gender equality and empowerment for all women and girls, with special attention to the most-at risk populations, generating equal opportunities and accessibility to the workforce, economic empowerment, education, sexual and reproductive health, leadership and decision-making, and home-work balance"

Table 4. 2 Goals, dimensions and metrics for Gender Equality through the lens of the SDGs in urban mobility

Overall goal	Goal	Objectives	Performance measures in urban mobility and cities
Workforce	Equal access to decent work and entrepreneurship	By 2030, ensure equal access to employment and decent work, entrepreneurship, innovation, including access to childcare and financial access for micro-small-medium enterprises	- Accessibility to opportunities: work, education, and services - Modal travel split for men and women - Trip chains for men and women - Geographical exclusion (transit: time and frequency) - People at risk of poverty or social exclusion - Exclusion from facilities (distance and time) - Economic exclusion (transport affordability) - Accessibility to childcare (government services) - Participation to the workforce (gender gap and wage gap) - Long term unemployment rate - Women/men living in poverty or extreme poverty - Single mothers living in poverty or extreme poverty - Unemployment for women/men having disabilities - Severe material deprivation rate in cities
Economics	Eradicate poverty and reduce inequality	By 2030, eradicate extreme poverty, reduce inequality, and provide equal rights to economic resources	
Education	Equal access to education for all	By 2030, provide equal access and opportunities to education for all, with special attention to low-income households, girls with early pregnancies, people´s with disabilities, immigrants, and diversity (ethnicity and sexual orientation)	
Health & Sexual Reproductive Rights	Healthy lives, well-being, and safe & accountable institutions	By 2030, provide universal access to health services and coverage, eliminate all forms of violence against all women and girls, and ensure safe and accountable systems for reported sexual harassment and femicides in all institutions	- Physical exclusion: infrastructure barriers - Walkability through the lens of road safety and citizen safety - Fear-based exclusion in public spaces and transport facilities: Perception of neighborhood safety (%) - Burglaries, Robberies, Intentional homicides per population - Reported sexual harassment and court cases for rape - Space exclusion (segregated spaces preventing access) - Exposure to air pollution for Nitrogen Oxides (NOx) and Particulate Matter PM2.5 - Traffic fatalities and exposure per transport mode and gender - Transport time-based exclusion (home-work balance) - Car ownership single working mothers and fathers
Time	Ensure availability of decent housing, safe cities, home-work balance	By 2030, ensure availability of decent housing, and safe, efficient and reliable sustainable transportation, safe public spaces By 2030, implement social protection policies and strategies, and design communication strategies for the promotion of shared responsibility within the household	
Empowerment	Inclusive leadership and decision-making	By 2030, ensure responsive, inclusive, participatory and representative decision-making at all levels	- Women/men leading research positions in industry, innovation, and infrastructure - University degree on STEM: Science, Technology, Engineering, and Mathematics disciplines - Elected city majors (women/men) municipalities - Management positions in the workforce (women/men) - Government ministers (women/men) - Board of directors in corporations, universities (women/men)

Source performance measures: Chaverri et al., 2020; Salas-Calderón et al., 2019; Global Affairs Canada, 2018; Schmidt-Traub et al., 2017; UN Women, 2015; Church et al., 2000a

Gender equality has been classified into six dimensions: “Workforce, Economics, Education, Health & Sexual Reproductive Rights, Time and Empowerment”. Transport plays an essential role in social development. A transport system that provides adequate access to opportunities will allow people to access employment, education, and services. Mobility is the ease of movement, but accessibility means the ability to reach destinations, and it should be differentiated per mode of transport (i.e., automobile and transit) (Peralta-Quirós & Mehndiratta, 2015; Ducas, 2011).

The SDG 11.2 target requires that a transport network should allow people to reach their destinations with ease. The transport network should be safe, reliable, and affordable, with special attention to women, children, persons with disabilities, and older persons (UNDESA, 2015). Women have different mobility needs and travel patterns than men. Transport policies, travel surveys, and assessments of the built environment often ignore women’s needs (Madariaga & Neuman, 2020; Knoll & Schwaninger, 2020; Loukaitou-Sideris, 2016).

Loukaitou-Sideris (2016) claims that urban mobility has cultural, economic, physical, and psychological constraints, varying depending on socioeconomic levels and geography. Cultural barriers include religion, and excessive workload of unpaid household chores and caring for children and elders. Economic barriers include unaffordable transport which occurs when affected individuals cannot afford to own automobiles or live in centralized locations where cars are less necessary, but instead are forced to live in the periphery of the city due to unaffordable housing. Physical barriers are car-oriented cities and urban sprawl, low quality of walkability, and limited transit service. Psychological barriers include fear of sexual harassment and violence. These barriers contribute to different forms of social exclusion such as physical and geographical exclusion from facilities, as well as economic, time, and fear-based exclusion in response to a lack of safety in transport systems and public spaces (Lucas, 2012; Church et al., 2000).

Women responsible for caring for children and elders have complex day-to-day trips. Seeking to accommodate time slots for these responsibilities, women might choose part-time or low-pay jobs or not take management positions (Knoll & Schwaninger, 2020). Commuting from work to home, women have multiple trip chains such as picking up children, shopping, or attending medical appointments. As a result, women need to travel shorter distances to address multiple trip chains and chores (Madariaga & Neuman, 2020). Geographical mismatches between home and work lead to long travel times. Long travel times are an obstacle to accessing employment and makes sustaining jobs difficult (Blumenberg & Manville, 2004; Church et al., 2000). The gender equality “time dimension” due to household responsibilities and long travel times is a barrier to empowering women to participate in managerial positions and politics.

Another barrier for caregivers is when they face a low quality of public transport services, such as mismatching timetables, lack of connectivity between routes, and fixed-route service that increase travel time reaching a destination. In a car-oriented city and given work-home responsibilities, low-income women who do not have access to a car are at a greater disadvantage (Blumenberg, 2016). On the other hand, when low-income women can afford to own a car, they can face a transport poverty scenario where they have to face trade-offs among automobile, housing, and providing for essential goods (Lucas et al., 2016; UN Habitat, 2014). In the case of single mothers, lack of efficient transport is the second barrier to access employment, after the first obstacle, childcare. Single mothers without access to automobiles may be the most spatially isolated (Blumenberg & Manville, 2004; Blumenberg & Hess, 2003).

There is a dichotomy between sustainable transport policies that seek carless cities and the growing evidence of low-income women in need of owning a car. In the context of the U.S.A, Schmitt (2014) argues that American policies of subsidizing cars to low-income families to fight poverty reinforce car dependency and increase congestion and transit travel times. This policy might help individual households, but it would harm others already on the road. Blumenberg (2016) argues that in the short-term until accessibility to opportunities using transit becomes a better option than automobile, low-income travelers should not be prevented from owning a car. In fact, those driving on the road that would be affected by more cars are disproportionally high-income groups.

Fear-based social exclusion plays an essential role in women's and girls' urban mobility. Women face challenges in public spaces and transit systems due to crime, sexual harassment, and sexual violence, which limits the freedom of movement in a city. Surveys show evidence that 17% of women in two outer suburbs in Paris had experienced sexual harassment on trains. 99.3% of women in Cairo-Egypt and 80% of women in Mumbai-India had experience harassment in public transport. Perceptions of crime and violence are significantly different between genders. Women have more exposure to crime as they are seen as "easy targets." As a result, and for safety reasons, women prefer automobiles. Women who do not have access to automobile experience restrictions in their areas of travel, social interactions, and employment choices (Gonzalez et al., 2020).

4.4 Linking air pollution to gender equality for transport planning

Road traffic is an important contributor to air pollution in urban areas, negatively affecting people's health. Vehicles with Internal Combustion Engines (ICE) produce harmful mixtures of toxicity, emitting chemical compounds such as Nitrogen Oxides (NOx), Nitrogen Dioxide (NO2), Particulate Matter (PM2.5 and PM10), Non-methane volatile organic compounds (NMVOC), Carbon monoxide (CO), Sulfur oxides (SOx) (Čokorilo et al., 2019; Nadadur & Hollingsworth, 2015).

Long-term exposure to air pollution can bring undesirable health outcomes. Nitrogen oxides (NOx) can lead to respiratory problems. Particulate Matter (PM2.5, for aerodynamic diameters of 2.5 μm) is associated with cancer, cardiovascular illnesses, diabetes, and breathing difficulties. These particulates may move to the lungs and circulation (Nadadur & Hollingsworth, 2015). Ground-level ozone (volatile organic compounds and NOx) contributes to asthma and lung diseases. Carbon monoxide (CO) affects oxygen absorption (Huang & Brown, 2021; UN Habitat, 2014; Molemaker et al., 2012; Krzyżanowski et al., 2005; Hertel et al., 1995). Long-term exposure to NOx and PM2.5 in a city are predictors of Covid-19 (UN Habitat, 2021; Travaglio et al., 2021; Barnett-Itzhaki & Levi, 2021).

In the United States, it has been found that communities with social disparities are more exposed to air pollution. African Americans breathe more polluted air, followed by Latinos, a positive relationship between their exposure to air pollution and higher Covid-19 mortality rates has been identified Hamidi et al., 2020). In addition to the racial disparity, lower socio-economic stratums and people with disabilities have been found to be more exposed to PM2.5 (Chakraborty et al., 2022).

The urban poor and vulnerable groups are more disadvantaged in being exposed to air pollution and the health impacts associated with this toxicity (McFarlane, 2020; Dey & Dominici, 2021; UN Habitat, 2014). In urban health, social disparities experienced by the most at-risk populations are reflected in their socioeconomic conditions such as overcrowded housing conditions, poverty, material deprivation, pre-existing health conditions, age, ethnicity, and accessibility to healthcare (Chakraborty et al., 2022; McFarlane, 2020).

In terms of gender disadvantage, barriers and dimensions that women experience to have equal opportunities than men were reviewed. Gender equality means that men and women, boys and girls have equal rights and opportunities. Social inequalities for women directly impact households, economies, child development, cities, and communities. These conditions are more critical for single mothers, as they are heads of the family and the primary income provider in the household. Long travel times and multiple trip chains influence accessibility to employment and services, which becomes more challenging if single mothers rely on inadequate public transport provisions as different types of social exclusion can develop. For this population group, being exposed to high levels of air pollution brings another disadvantage due to the potential of developing health conditions related to traffic pollution, which will directly impact household income and childcare responsibilities.

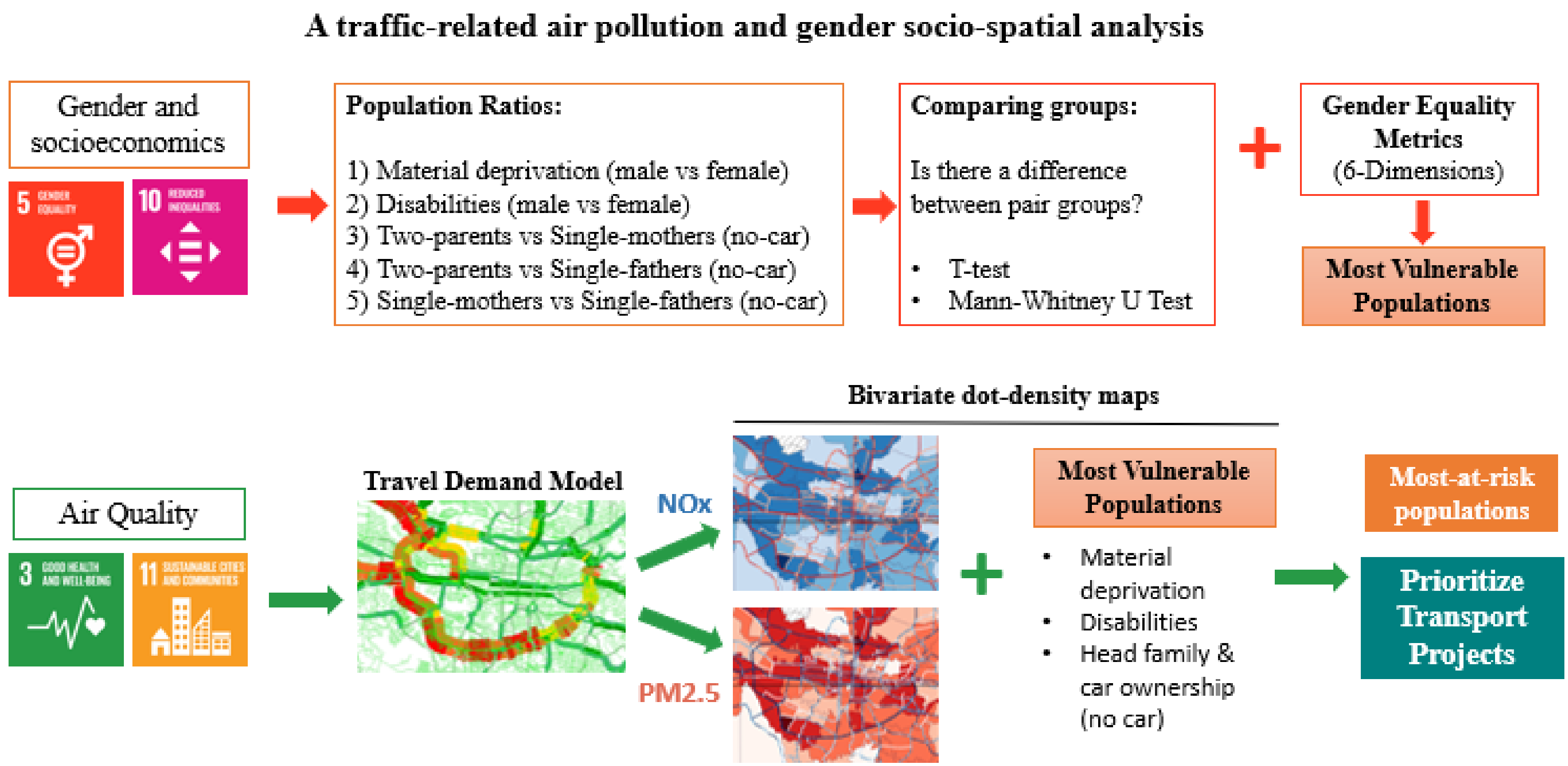
4.4.1 Analyzing gender equality in transport planning for the case study San José

It is desired to examine spatial demographic patterns focused on vulnerable groups and their exposure to air pollution at a regional scale for the metropolitan area of the province of San José.

Figure 4.3 shows the methodology to conduct a traffic-related air pollution and gender socio-spatial analysis. The first part of the method is based on a statistical and geospatial analysis to identify where people spatially live and understand who is being "left behind". Social disadvantage groups per gender (male/female) for material deprivation, disabilities, and households with single mothers and car ownership are studied in a geospatial setting. A T-test or a Mann-Whitney U Test compares population ratios for these social disadvantage groups to determine if there is a difference between pair groups. In addition, gender equality indicators and the state of gender equality elaborated by the Government of Costa Rica is analyzed (Salas-Calderón et al., 2019). This process will identify the most vulnerable populations and understand who is being "left behind".

The second part of the method estimates the production of air pollutants per Traffic Analyzes Zones (TAZ). The produced emissions per road segment by traffic are aggregated within each TAZ and normalized per area (Km2) (details of this method is shown in Figure 4.6). Bivariate dot-density maps are elaborated to combine the most vulnerable population groups identified in the gender and socio-economic analyses. Having the combination of these vulnerable groups and air pollution exposure allows to identify the most-at-risk populations for planning urban mobility under a vertical equity approach, which prioritizes socially disadvantaged groups.

Figure 4. 3 Methodology: traffic-related air pollution and gender socio-spatial analysis



Referring to the Sustainable Development Goals (SDGs), the SDG Index for cities and air pollution monitors Nitrogen Oxides (NOx) and Particulate Matter with a diameter of 2.5 µm (PM2.5) (Schmidt-Traub et al., 2017). This research incorporates SDG 1 (No poverty), SDG 3 (Good Health), SDG 5 (Gender Equality), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Cities) (UNDESA, 2015).

The case study is developed for the metropolitan area of San José, as shown in Figure 4.4. San José is part of a polycentric metropolitan city with four capital cities from four provinces. Population from these outer provinces commute to San José for work and government services, and these provinces were included in the model travel demand. The geographic unit is Traffic Analysis Zones (TAZ).

The Traffic Analysis Zones (TAZ) are predefined by the Ministry of Housing and Human Settlements (MIVAH, 2008b). They have been classified per land use typology for residential, commercial, and industrial settlements. Traffic Analysis Zones are used in travel demand models, which divide the analysis area into homogeneous land use and socio-economic characteristics while minimizing intra-zonal trips (Mansoureh & Ardeshiri, 2017). TAZ aggregate population and similar spatial attributes to represent areas of origin and attractions to distribute trips (Miller, 2021).

In this case study for the metropolitan area of San José, the geospatial demographic analysis will use 166 TAZ and aggregate population groups per this geographic unit. Figure 4.5 shows the Central Business District and surrounding areas. The road network includes highways, principal arterials, minor arterials, and collectors. Residential roads are excluded from this analysis.

Figure 4. 4 Area of study for the Metropolitan Area of San José and Traffic Analysis Zones (TAZ)

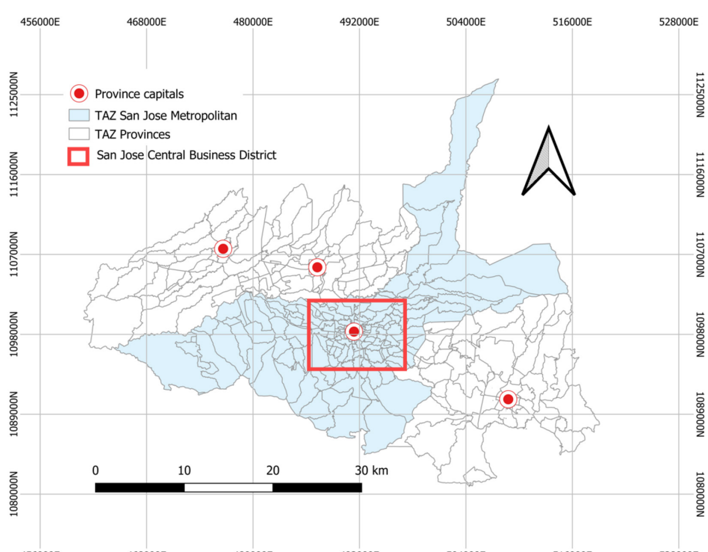


Figure 4. 5 San José Central Business District (CBD), surroundings and Traffic Analysis Zones (TAZ)

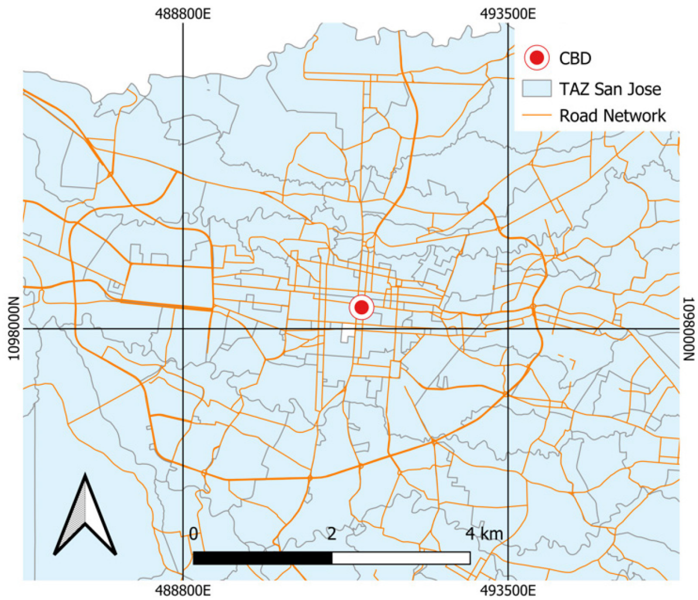


Figure 4.6 shows the methodology for estimating Nitrogen Oxides (NOx) and Particulate Matter (PM2.5). The traffic emissions per road segment are estimated from a four-step travel demand model for Costa Rica for the year 2022 for an average speed scenario (85km/h for highways, 45 km/h for principal arterials, and 35 km/h for minor arterials and collectors). Vehicle Kilometer Traveled (VKT) is estimated per road segment based on annual traffic volumes (Equation 4.1). The emissions per road segment are estimated based on the VKT and corresponding emission factors per pollutant per type of vehicle for emission standards corresponding to EURO I as shown in equation 4.2. The emission factors used are from the road transport emission model Copert version 5.5.1 from the European Environmental Agency (EMISIA et al., 2021).

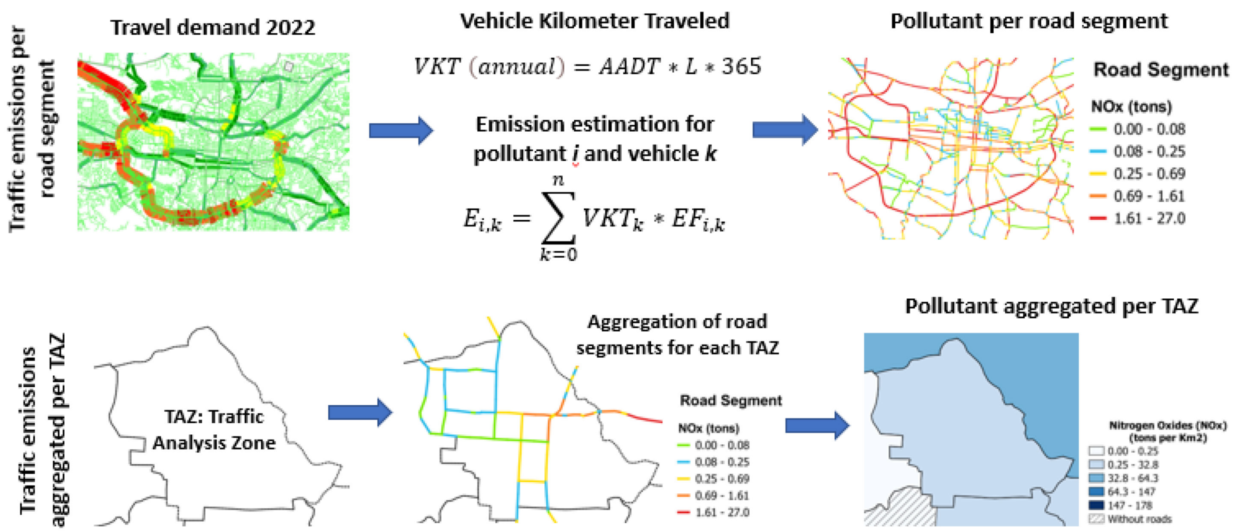
$$VKT\ (annual) = AADT * L * 365 \quad \text{Equation (4.1)}$$

$$E_{i,k} = \sum_{k=0}^{n} VKT_k * EF_{i,k} \quad \text{Equation (4.2)}$$

Where,
$E_{i,k}$: Emission for pollutant i and vehicle k
VKT_k: Vehicle Kilometer Travelled per vehicle type k (Km)
$EF_{i,k}$: Emission Factor per pollutant, per vehicle type k (g/Km)
i: pollutant (i.e. NOx, PM2.5)

Each pollutant (NOx and PM2.5) is aggregated per Traffic Analysis Zone (TAZ) and normalized per square kilometer. Census tract at a block level is used and aggregated per TAZ. The population was estimated from the Census from the year 2011, and it was applied an annual population growth of 1.2 % based on the projections calculated by the Institute of Census of Costa Rica (Brenes Camacho et al., 2013).

Figure 4. 6 Methodology for estimating Nitrogen Oxides (NOx) and Particulate Matter (PM2.5)



4.4.2 Model results

4.4.2.1 Travel demand model and air pollution

A travel demand model was built with PTV Visum and calibrated for the metropolitan area of Costa Rica. The San José Metropolitan area has 6,535 road segments with an average length of 76.16 meters. The network average traffic volume per direction is 13,967 average vehicles per year, and the total Vehicle Kilometer Traveled is 2,888 million-Km.

An R Studio code was written to classify the PTV Visum output of the road network per highways, principal arterials, minor arterials, and collectors as defined by the Ministry of Transport of Costa Rica (MOPT) and matches the traffic volumes from the travel demand model. The speed profile used for highways was 85 Km/h, 45 km/h for principal arterials, and 35 km/h for minor arterials and collectors. Based on traffic counts measured by MOPT, the average distribution of vehicles was estimated for each road classification. Then, the vehicle type is classified per Gross Vehicle Weight (GVW) into eight categories (passenger cars, pick-ups, buses, and heavy vehicles from 14 to 50 tons). The traffic volumes are disaggregated per vehicle type per road classification to estimate traffic emissions. The emission factors (grams per kilometer) correspond to EURO I emission standards (EMISIA et al., 2021).

Table 4.3 shows summary statistics for the traffic emission model for San José Metropolitan per road classification. Highways and minor arterials have the highest VKT (1,260 million-Km and 1,231 million-Km, respectively). The total length of highways is 88.01 Km, but highways have larger capacity and traffic volumes. On the other hand, the total length of minor arterials is 238.69 Km, with a lower capacity for traffic. The emission factors are sensitive to speed. Higher emissions are produced at lower speeds. In this case, highways have a speed of 85 km/h, minor arterials are

35 km/h. Minor arterials produce more Particulate Matter (PM2.5) for the totality of the area of study.

Table 4. 3 Summary statistic for the traffic emission model for San José Metropolitan per road class

Road Classification	Traffic Volume (*)		Total Road Length	Average speed	VKT (**)	NOx	PM2.5
	Mean	Std. Dev.	(Km)	(Km/h)	(million-Km)	(tons)	(Kg)
Highways	36,923	13,953	88.01	85	1,260	1,985.88	69,980
Principal Arterials	21,797	15,939	22.25	45	178	312.52	13,591
Minor Arterials	14,077	9,822	238.69	35	1,231	1,955.43	90,569
Collectors	4,358	4,675	148.76	35	219	365.91	16,667
Summatory	-	-	497.71	-	2,888	4,619.74	190,808

(*) Traffic volume per direction estimated from a travel demand model for 2022
(**) VKT: Vehicle Kilometer Traveled

Table 4.4 shows a summary of statistics of traffic emissions per road segment. In a road segment, the maximum value for NOx is 26.75 tons, and PM2.5 is 942.57 Kg. Figures 4.7 and 4.8 illustrate the spatial distribution of NOx and PM2.5, respectively. The ranges are based on quartiles, as shown in Table 4.4. Highways produce more pollutants per road segment in both cases (NOx and PM2.5).

Table 4. 4 Summary statistics of pollutants per road segment

	Road Segment	Pollutants per road segment		Levels of pollution per road segment (ranges)		
Statistics and Quartiles	**Length (Km)**	**NOx (tons)**	**PM2.5 (Kg)**	**Level**	**NOx (tons)**	**PM2.5 (Kg)**
N (observations)	6,535	6,535	6535	-	-	-
Mean	0.0762	0.71	29.20	-	-	-
Std. Dev.	0.0899	1.53	57.10	-	-	-
Minimum	0.001	0.00	0.00	-	-	-
Q1 (25th percentile)	0.027	0.08	3.74	L1	0 – 0.08	0.00 – 3.74
Q2 (median)	0.052	0.25	11.17	L2	0.08 – 0.25	3.74 – 11.2
Q3 (75th percentile)	0.095	0.69	30.33	L3	0.25 – 0.69	11.2 – 30.3
Q3 + (1.5*IQR)	0.197	1.61	70.22	L4	0.69 – 1.61	30.3 – 70.2
Maximum	1.642	26.75	942.57	L5	1.61 – 27.0	70.2 - 943
Summatory	497.71	4,619.74	190,808	-	-	-

Figure 4. 7 Nitrogen Oxides (NOx) per road segment

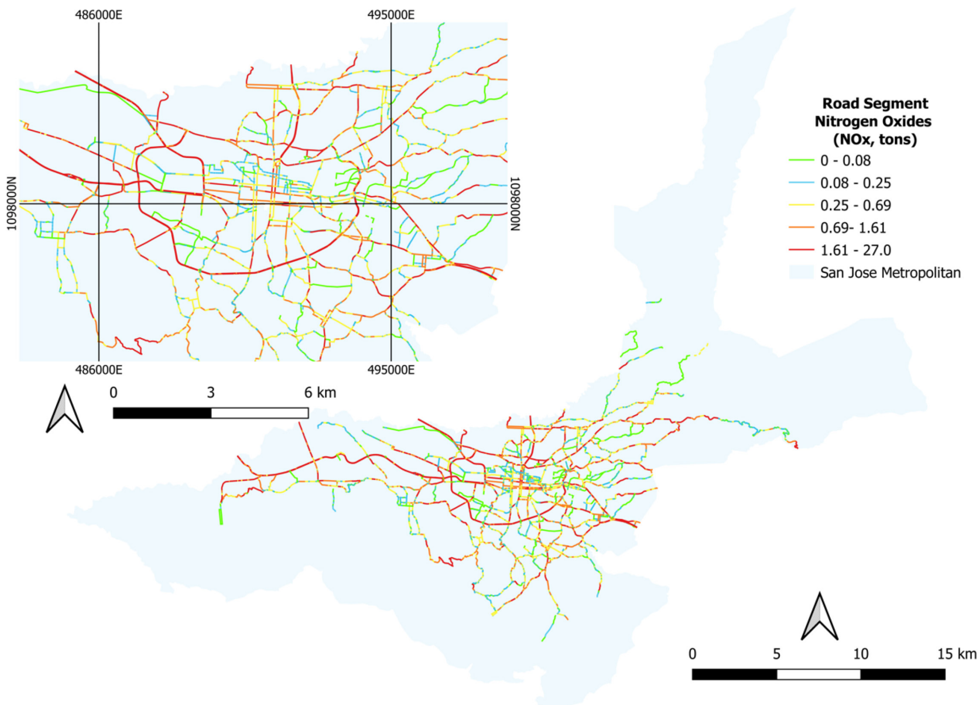
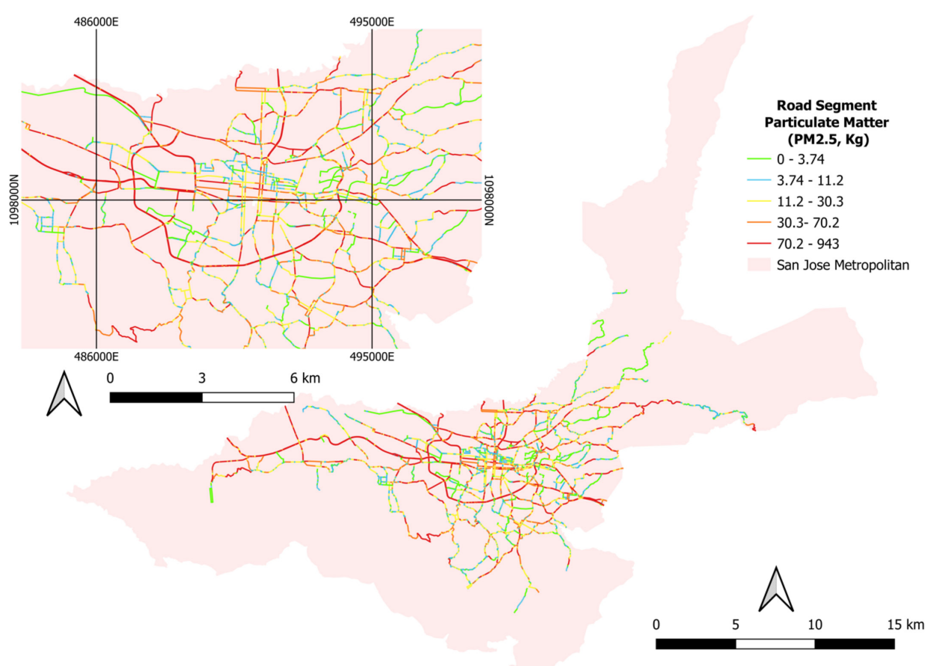


Figure 4. 8 Particulate Matter (PM2.5) per road segment



Traffic pollution per road segment is aggregated per TAZ and normalized per area in square kilometers for comparison among zones. Table 4.5 shows the summary statistics of pollutants and population per Traffic Analysis Zones (TAZ). On average, there are 44.89 road segments per TAZ.

The average area of TAZ is 3.06 Km^2, and the population by census blocks is aggregated per TAZ. There are 166 TAZ producing an average of 42.16 tons per Km^2 of NOx and a maximum value of 177.18 tons per Km^2. For the case of PM2.5, the 166 zones have an average of 1,778.12 Kg per Km^2 and a maximum value of 7,745.10 Kg per Km^2.

Table 4. 5 Summary statistics of pollutants and population per Traffic Analysis Zones (TAZ)

Statistics	Road.Seg. (count)	NOx (tons per Km^2)	PM2.5 (Kg per Km^2)	Population (TAZ)	Area (Km^2)	Population density (TAZ)
N (observations)	166	166	166	166	166	166
Mean	44.89	42.16	1778.12	9,141	3.06	8,371.65
Std. Dev.	38.50	38.45	1586.25	9,582	7.64	9,939.74
Min	1.00	0.01	0.41	183	0.02	29.12
Median	36.50	32.75	1346.86	5,393	0.98	6,870.61
Max	189.00	177.18	7745.10	51,171	68.01	82,595.21
IQR	47.00	54.87	2185.91	10,815	2.09	7,397.09

Road.Seg: Road Segment; NOx: Nitrogen Oxides; PM2.5: Particulate Matter 2.5 μm;
Population density (population/area in Km^2); Population: Total population per TAZ

The zone air pollution is a direct estimate of the traffic emissions on the roads within the zones. One limitation is that wind is not considered, and these traffic emissions are static. Quartiles classified the data for NOx and PM2.5 and based on these metrics; pollution levels were classified (L1 to L5), as shown in Table 4.6. Figures 4.9 and 4.11 show NOx and PM2.5 per TAZ with the road network expressed by Vehicle Kilometer Traveled (VKT). Both cases show similar spatial patterns.

Table 4. 6 Statistics for NOx and PM2.5 and levels of pollution per Traffic Analysis Zones (TAZ)

	Pollutants aggregated per TAZ		**Levels of pollution (ranges)**		
Quartiles	**NOx** (tons per Km^2)	**PM2.5** (Kg per Km^2)	**Level**	**NOx** (tons per KM^2)	**PM2.5** (Kg per KM^2)
Minimum	0.01	0.41	L1	0.00 – 0.25	0.00 – 437
Q1 (25^{th} percentile)	0.25	436.66	L2	0.25 – 32.8	437 – 1,347
Q2 (median)	32.75	1,346.86	L3	32.8 – 64.3	1,347 – 2,623
Q3 (75^{th} percentile)	64.30	2,622.57	L4	64.3 – 147	2,623 - 5,902
Q3 + (1.5*IQR)	146.60	5,901.43	L5	147 - 178	5,902 - 7,746
Maximum	177.18	7,745.10			

There is higher air pollution production around the Central Business District (CBD) (at coordinates 1098000N, and between 486000E and 495000E as shown in Figure 4.9). TAZ associated with highways with VKT between 0.43 and 17 million-Km also has higher pollution levels. These highways connect provinces with San José with a confluence around the CBD in the Great Metropolitan Area.

An assessment of the normality of data is performed for the two pollutants. Figure 4.10 shows a histogram and normal quantile plots for Nitrogen Oxides (NOx). The histogram shows a right-skewed distribution, and the normal quantile plot shows a curve-shape line suggesting that the data is not normally distributed. A skewness-kurtosis test of normality Jarque-Bera tests is performed where the null hypothesis states that the data is normally distributed and the alternative hypothesis states that the data is not normally distributed at a 5% significance level. Table 4.7 shows the results of this test. A chi-square test is performed, resulting in a p-value smaller than $\alpha = 0.05$. Thus, the null hypothesis that assumes that the distribution is normal is rejected, and there is not enough evidence to conclude that the data is normally distributed.

A similar procedure is conducted to assess the normality of the data for Particulate Matter (PM2.5). Figure 4.12 shows the histogram and normal quantile plot, and Table 4.8 shows the results for the skewness-kurtosis test of normality. The shape of the histogram and normal quantile plot suggests that the data is not normally distributed. The skewness-kurtosis test of normality results in a p-value that is smaller than $\alpha = 0.05$. Thus, there is not enough evidence that the PM2.5 data is normally distributed.

Figure 4. 9 Nitrogen Oxides (NOx) aggregated per Traffic Analysis Zones (TAZ)

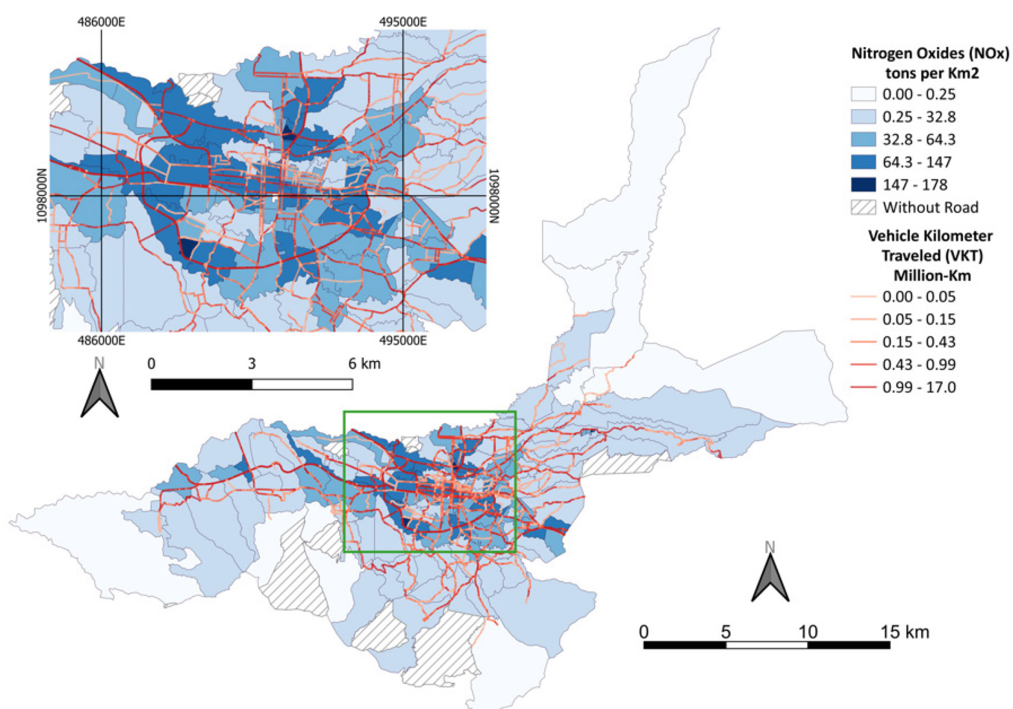


Figure 4. 10 Histogram and normal quantile plots for Nitrogen Oxides (NOx)

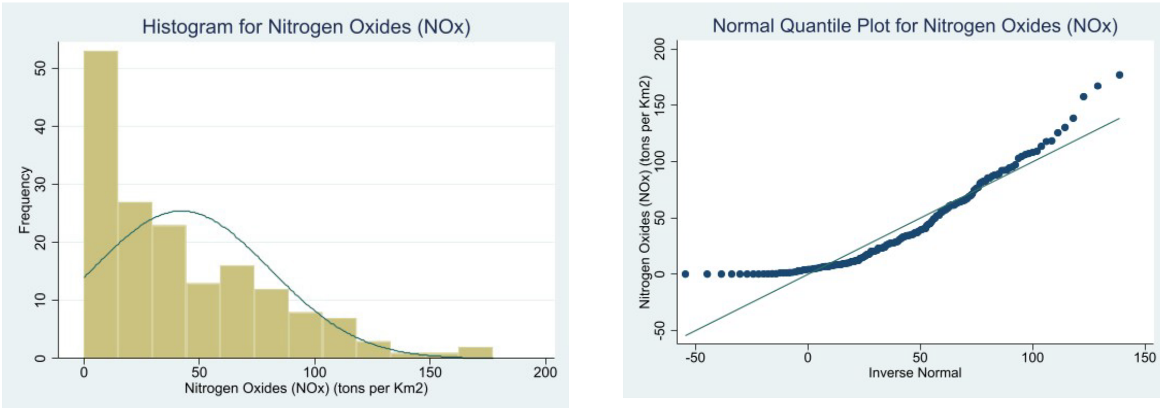


Table 4. 7 Skewness and kurtosis tests for normality for Nitrogen Oxides (NOx)

Observations	Mean	Skewness	Kurtosis	Pr (skewness)	Pr (kurtosis)	Adj chi2(2)	Prob>chi2
166	42.157	1.0717	3.7472	0.0000	0.0666	21.96	0.0000

Significance level α = 0.05

Figure 4. 11 Particulate Matter (PM2.5) aggregated per Traffic Analysis Zones (TAZ)

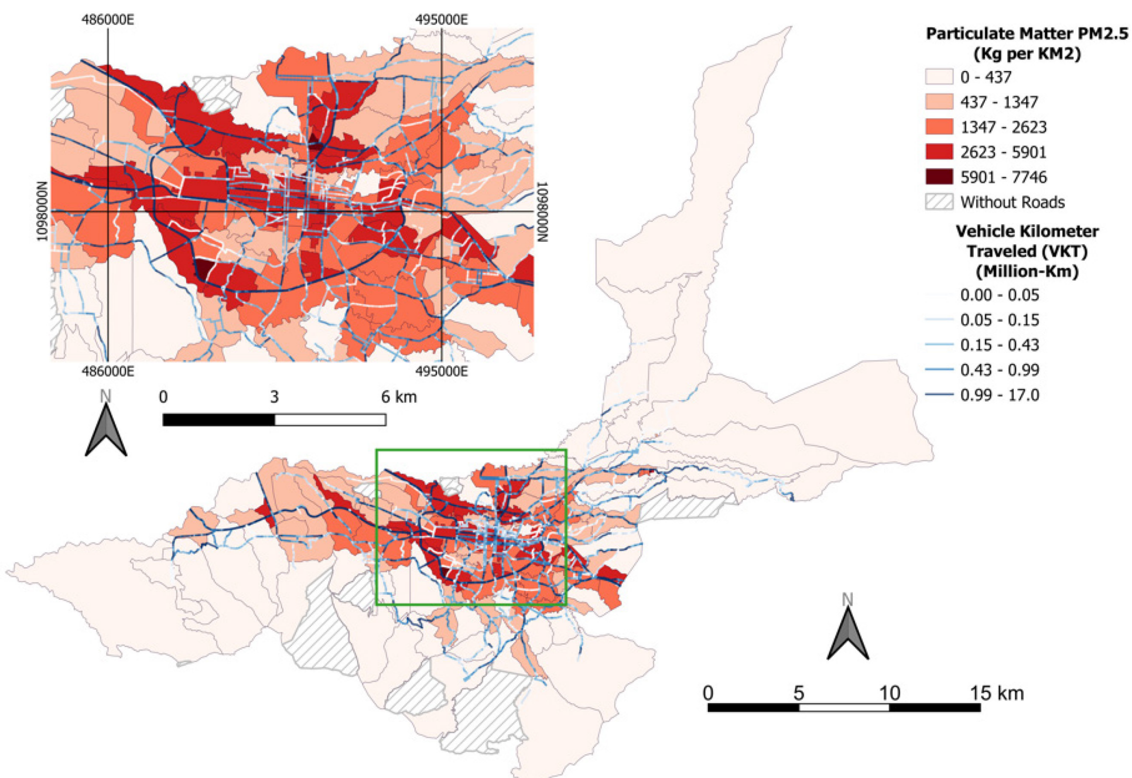


Figure 4. 12 Histogram and normal quantile plots for Particulate Matter (PM2.5)

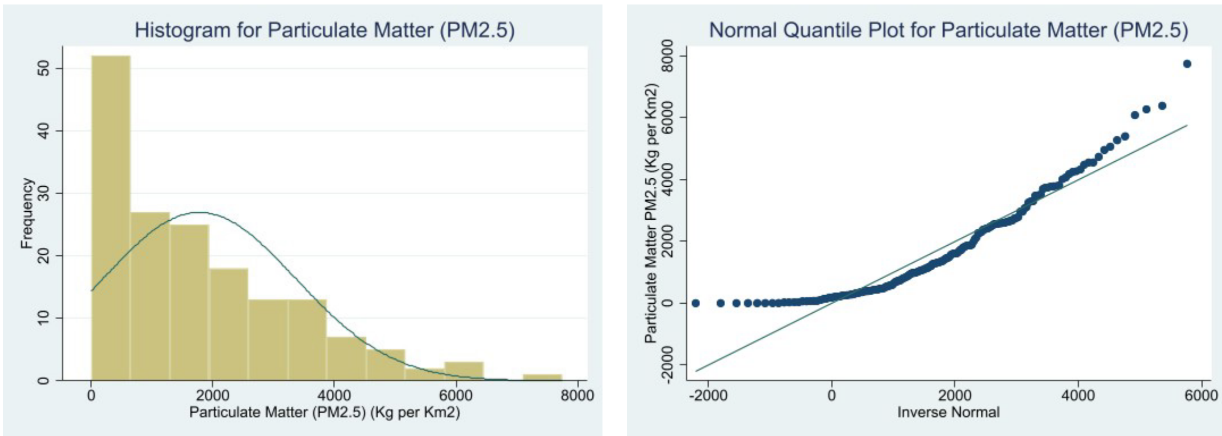


Table 4. 8 Skewness and kurtosis tests for normality for Particulate Matter (PM2.5)

Observations	Mean	Skewness	Kurtosis	Pr (skewness)	Pr (kurtosis)	Adj chi2(2)	Prob>chi2
166	1778.114	1.058247	3.8015	0.0000	0.0547	21.86	0.0000

Significance level α = 0.05

4.4.2.2 Descriptive statistics for population and vulnerable groups

The metropolitan area of San José is 507.82 Km^2, and the total population is 1,517,537 for the year 2022. The population density of 2,988 persons per Km^2 for 2022 indicates that the city has urban sprawl. For the population estimate, the census from 2011 was used, and applied an annual population growth of 1.2% as projected by the Census Institute of Costa Rica (Brenes Camacho et al., 2013).

There is 166 TAZ associated with Nitrogen oxides (NOx) and Particulate Matter of 2.5 μm (PM2.5). Datasets are disaggregated per gender (male/female) and focus on material deprivation and disabilities per TAZ. It is desired to explore the absence of car ownership of single mothers, since they are at a greater disadvantage in coping with work-home responsibilities and can experience time-based social exclusion. This is due to the combination of travel times, multiple trip chains, and home responsibilities for caring for children and elders. Car ownership of single fathers and two-parents household is also explored.

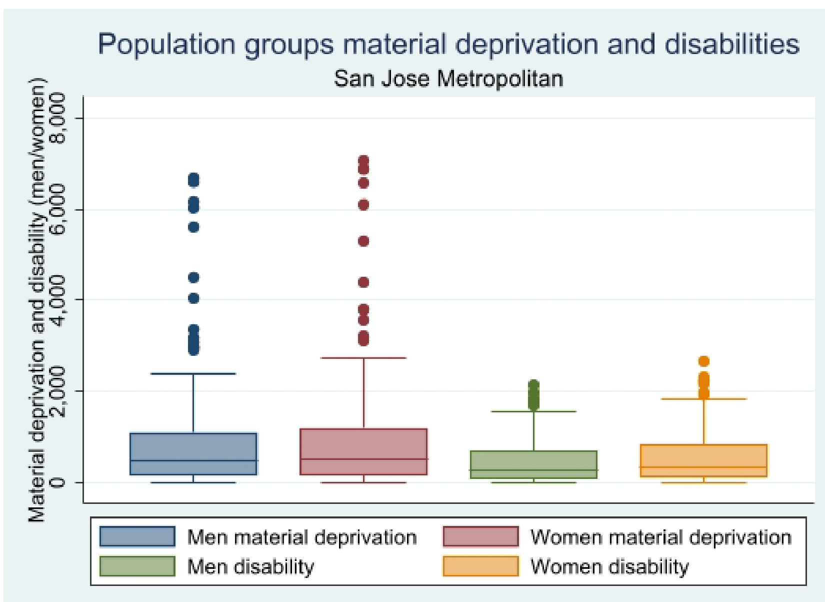
Table 4.9 shows a summary statistic for material deprivation and disability per gender for the study area. For 166 TAZ in San José Metropolitan, 11.07% of women experience material deprivation, while men present 10.02%. There is a total of 21.09% of people with material deprivation in San José. In addition, 4.92% of males and 6.16% of women experiencing a disability, and 11.09% of the total population have a disability. Figure 4.13 shows a box plot for population counts for material deprivation and disability per gender aggregated per TAZ.

Table 4. 9 Summary statistic for material deprivation and disability per gender

Statistics	Population per TAZ	Men Material Deprivation	Women Material Deprivation	Men Disabilities	Women Disabilities
N (observations)	166	166	166	166	166
Mean	9,140.70	915.69	1,011.70	449.86	563.40
Std. Dev.	9,582.20	1,258.74	1,374.21	469.51	592.92
Min	183	5	3	9	12
Median	5,392.50	486.00	517.50	276.50	353.50
Max	51,171	6,687	7,067	2,138	2,665
IQR	10,815.00	941.00	1,045.00	605.00	709.00
Total TAZ (*)	1,517,357	152,004	167,942	74,677	93,525

(*) Total TAZ is the summatory of all individuals from the 166 Traffic Analysis Zones (TAZ)

Figure 4. 13 Box plot for material deprivation and disability per gender (counts)



It is desired to compare groups to determine if there is a significant difference between population groups. For this comparison, ratios aggregated per TAZ are estimated as shown in equations 4.3 to 4.6, for ratios of material deprivation (male vs. female), and ratios of disability (male vs. female).

$$RMADEPM = \frac{Population\ of\ men\ with\ material\ deprivation}{Population\ of\ men} * 100$$ Equation (4.3)

$$RMADEPF = \frac{Population\ of\ women\ with\ material\ deprivation}{Population\ of\ women} * 100$$ Equation (4.4)

$$RDISABM = \frac{Population\ of\ men\ with\ disabilities}{Population\ of\ men} * 100$$ Equation (4.5)

$$RDISABF = \frac{Population\ of\ women\ with\ disabilities}{Population\ of\ women} * 100$$ Equation (4.6)

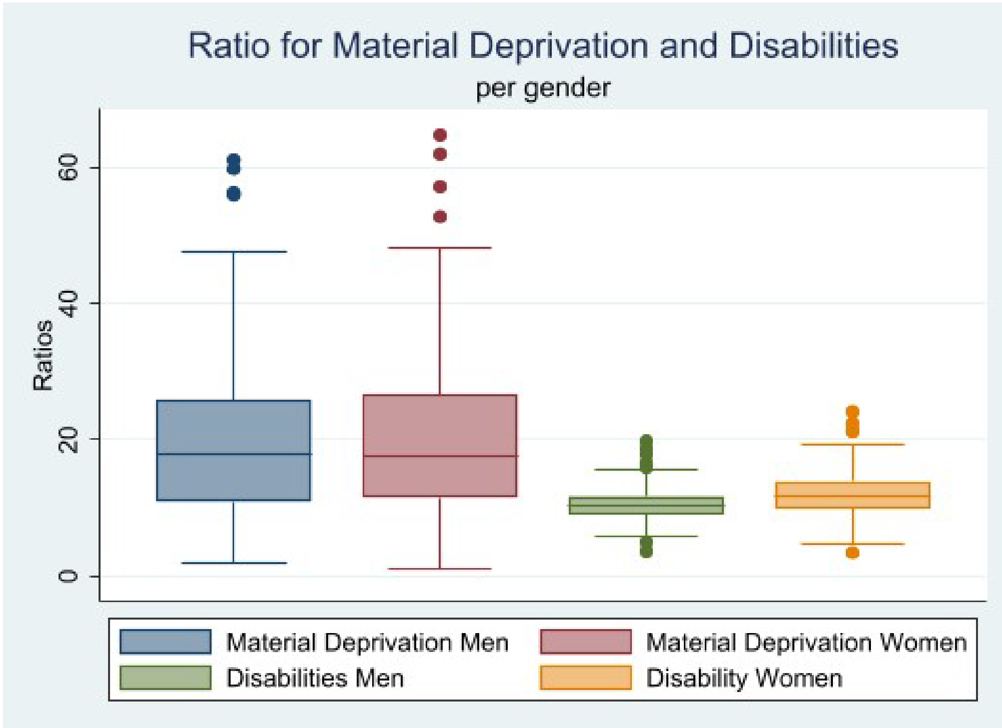
Where,
RMADEPM = Ratio material deprivation for men
RMADEPF = Ratio material deprivation for women
RDISABM = Ratio disability for men
RDISABF= Ratio disability for women

Table 4.10 shows the summary statistics for ratios for material deprivation and disabilities per gender, and Figure 4.14 shows a box plot for these variables. The mean for women for each variable is larger than men. It is desired to compare if there is a significant difference between gender groups.

Table 4. 10 Descriptive statistics of ratios for material deprivation and disabilities per gender

Statistics	Ratio Men Material Deprivation	Ratio Women Material Deprivation	Ratio Men Disabilities	Ratio Women Disabilities
N (observations)	166	166	166	166
Mean	19.94	20.02	10.61	12.12
Std. Dev.	11.54	11.72	2.55	3.42
Min	2.03	1.14	3.68	3.47
Median	17.81	17.67	10.40	11.70
Max	61.05	64.7	19.74	24.17
IQR	14.88	15.08	2.57	3.94

Figure 4. 14 Box plot for ratios material deprivation and disability per gender



An assessment of the normality of data and homogeneity of variances is a prerequisite to meeting the assumptions in parametric testing for performing T-Test for independent samples. Figure 4.15 shows normal quantile plots and histograms for the ratios of material deprivation and disability per gender aggregated per TAZ. The histograms show a positively skewed distribution. It is more pronounced for material deprivation than disabilities. The normal quantile plots for both variables suggest that the data do not follow a normal distribution. A skewness-kurtosis test for normality is conducted to find an overall test statistic based on skewness and kurtosis.

In the skewness-kurtosis test for normality, the null hypothesis (H0) declares that the data follows a normal distribution, while the alternative hypothesis (H1) is that the data do not follow a normal distribution. This hypothesis testing is applied to the ratios of material deprivation and disability differentiated by gender. The results of this test are shown in Table 4.11. In each case, the p-values are smaller than the significance level $\alpha = 0.05$. Thus, there is evidence that the data tested are not normally distributed.

Figure 4. 15 Normal quantile plots and histograms for ratios of material deprivation and disability per gender

Material Deprivation per Gender | **Disabilities per Gender**

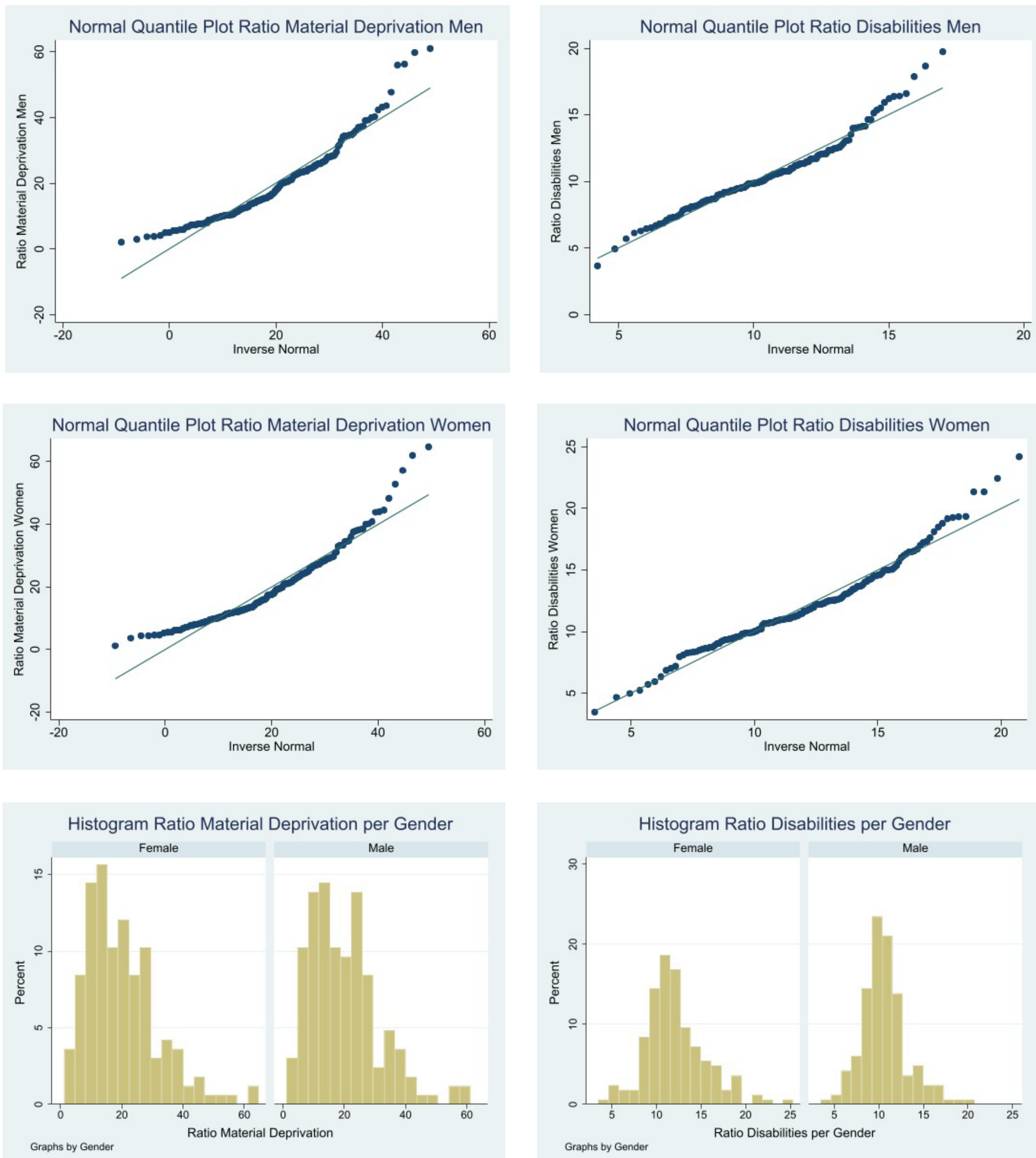


Table 4. 11 Skewness-kurtosis tests for normality for ratios of material deprivation and disabilities per gender

Gender	Observations	Skewness	Kurtosis	Pr (skewness)	Pr (kurtosis)	Adj chi2(2)	Prob>chi2
Ratios Material deprivation							
Male	166	1.1019	4.4080	0.0000	0.0062	25.63	0.0000
Female	166	1.1687	4.6551	0.0000	0.0027	28.36	0.0000
Ratios Disabilities							
Male	166	0.6850	4.3218	0.0006	0.0084	15.49	0.0004
Female	166	0.6317	4.0635	0.0013	0.0212	13.16	0.0014

Significance level α = 0.05

A similar analysis is conducted on two groups related to the household composition that do not own a car. The groups are households as head of family for two-parents, single mothers, and single fathers. Table 4.12 summarizes the statistics. For households that do not own a car, 45.56% are two-parent households, 8.90 % are single mothers and 0.83% are single fathers. Only 4.32% of households with single mothers own an automobile.

Table 4. 12 Descriptive statistics of counts for heads of households without owning a car

Statistics	Men	Women	HH Total	HH Two-Parents No Car	HH Single Mothers Total	HH Single Mother No Car	HH Single Fathers No Car
N (observations)	166	166	166	166	166	166	166
Mean	4,343.1	4,797.6	2,674.30	1,218.47	353.47	237.88	22.22
Std. Dev.	4,570.6	5,014.3	2,668.22	1,347.21	377.09	285.68	25.74
Min	69	114	83	37	6	2	0
Median	2,607	2,936	1,756	716.5	224.5	141.5	14
Max	24,332	26,839	14,026	7167	1.917	1,500	134
IQR	4,969	5,866	3,345	1,339	447	287	29
Total TAZ (*)	720,962	796,395	443,934	202,266	58,676	39,488	3,689

(*) Total TAZ is the summatory of all individuals from the 166 Traffic Analysis Zones (TAZ)
Men: Total population of men per TAZ, Women: Total population of women per TAZ
HH Total: Total Head of Household for men and women;
HH Two-parents No Car: Households with two parents without automobile
HH Single Mothers: Single mothers as head of household
HH Single Mother No Car: Households Single Mother without automobile
HH Single Father No Car: Households Single Father without automobile

Ratios are estimated for households as head of family that do not own an automobile as shown in equations 4.7 to 4.9 for households with two-parents, single mothers and single fathers. Table 4.13 shows descriptive statistics and Figure 4.16 shows a box plot. Ratios corresponding to single mothers have a larger mean than two-parents and single fathers.

$$R2PARENTS - NOCAR = \frac{Number\ of\ households\ with\ two\ parents\ without\ car}{Total\ number\ of\ households\ with\ two\ parents} * 100 \quad \text{Equation (4.7)}$$

$$RSMOM - NOCAR = \frac{Number\ of\ households\ with\ single\ mothers\ without\ car}{Total\ number\ of\ households\ with\ single\ mothers} * 100 \quad \text{Equation (4.8)}$$

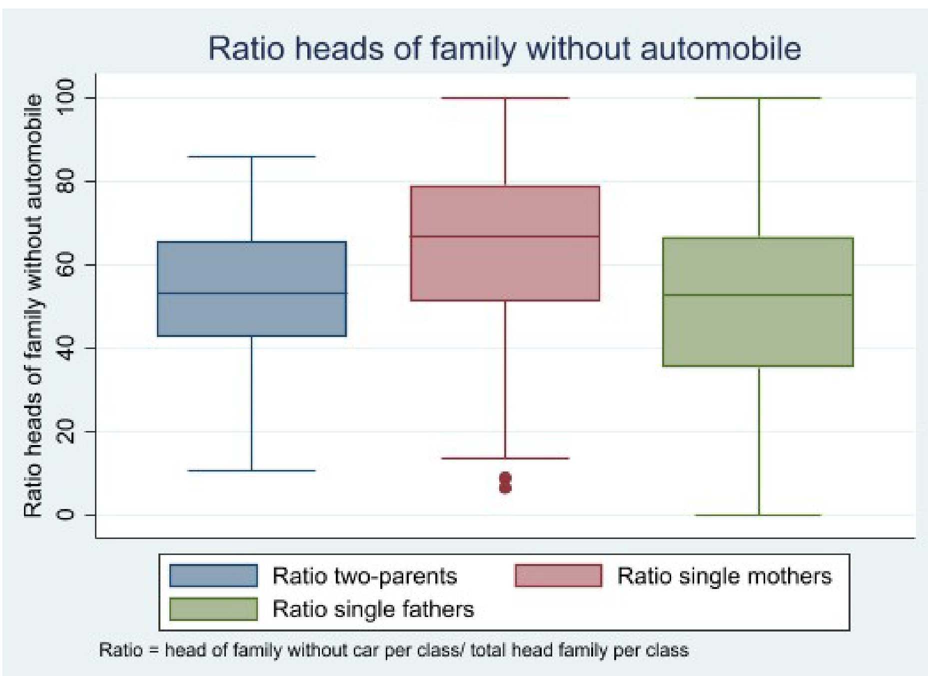
$$RSDAD - NOCAR = \frac{Number\ of\ households\ with\ single\ fathers\ without\ car}{Total\ number\ of\ households\ with\ single\ fathers} * 100 \quad \text{Equation (4.9)}$$

Where,
R2PARENTS-NOCAR = Ratio households with two-parents as head of family without automobile
RSMOM-NOCAR = Ratio households with single mothers as head of family without automobile
RSDAD-NOCAR = Ratio households with single fathers as head of family without automobile

Table 4. 13 Descriptive statistics of ratios for household composition and car ownership

Variable	N	Mean	Std. Dev.	Min	Median	Max	IQR
R2PARENTS-NOCAR	166	53.26	16.31	10.53	53.06	85.98	22.81
RSMOM-NOCAR	166	63.66	19.68	6.41	66.85	100	27.71
RSDAD-NOCAR	166	50.73	23.88	0	52.63	100	31.38

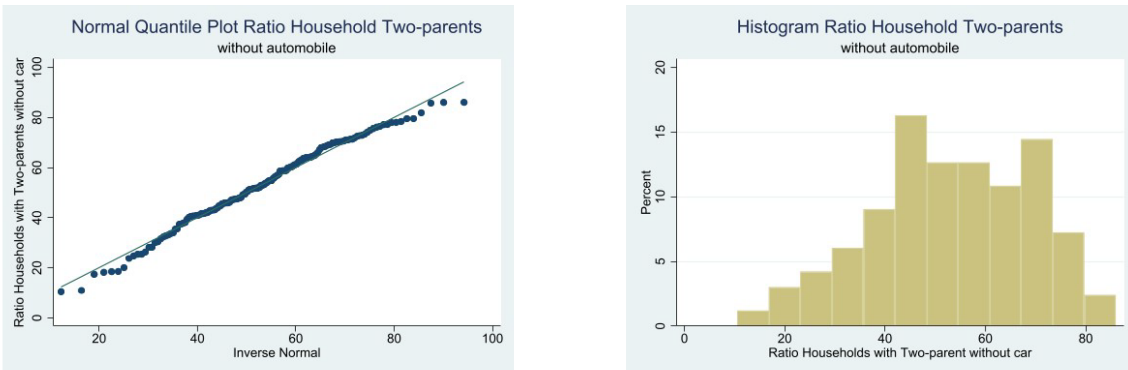
Figure 4. 16 Box plot for ratios of household composition without owning a car



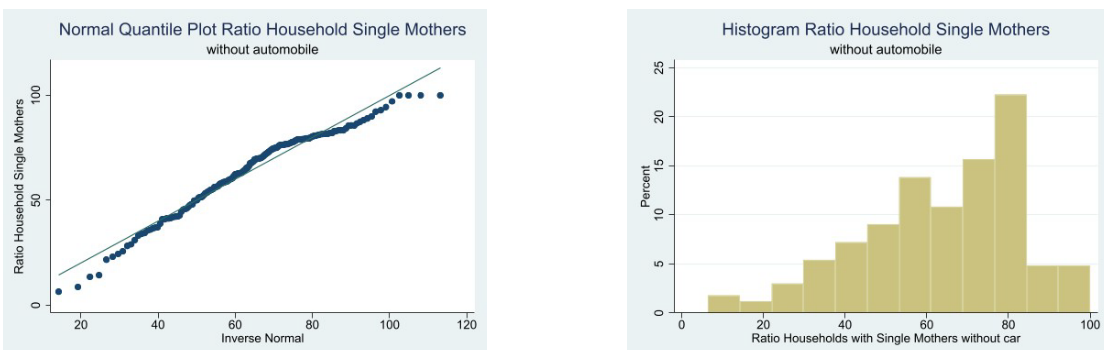
To assess the normal distribution of household composition, Figure 4.17 shows the normal quantile plots and histograms for two-parents, single mothers and single fathers.

Figure 4. 17 Normal quantile plots and histogram for ratios of household composition without automobile

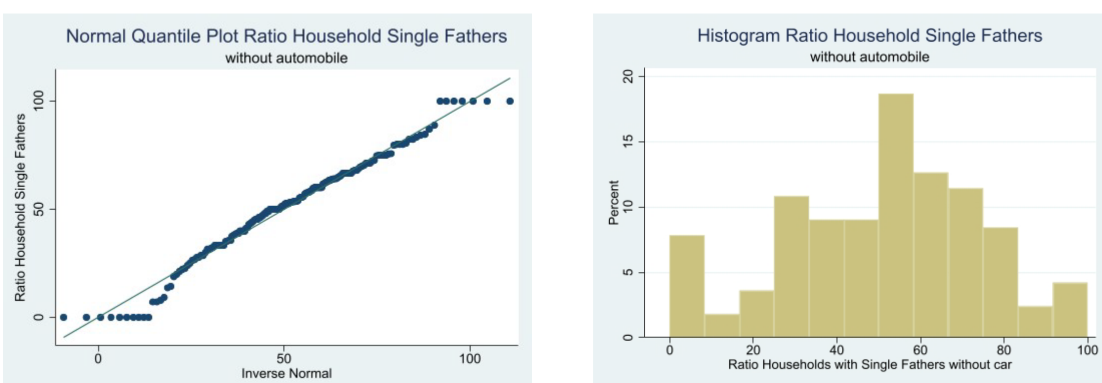
Ratio Households with Two-parents without automobile



Ratio Households Single Mothers without automobile



Ratio Households Single Fathers without automobile



For the three variables in Figure 4.17, the histograms show a negatively skewed distribution, and the normal quantile plots suggest that the data follows a normal distribution. A skewness-kurtosis test for normality for two-parents, single mothers and single fathers without automobile is shown in Table 4.14. The null hypothesis (H0) declares that the data follows a normal distribution, while the alternative hypothesis (H1) is that the data do not follow a normal distribution. In each case, the p-values are larger than the significance level α = 0.05, and the null hypothesis cannot be rejected. Thus, there is evidence that the data tested are normally distributed.

Table 4. 14 Skewness-kurtosis tests for normality for ratios of household head of family composition without car

Variable	Observations	Skewness	Kurtosis	Pr (skewness)	Pr (kurtosis)	Adj chi2(2)	Prob>chi2
Two-parents	166	-0.2919	2.6374	0.1164	0.3465	3.40	0.1828
Single Mothers	166	-0.5786	2.9128	0.0030	0.9927	8.05	0.0179
Single Fathers	166	-0.2533	2.8354	0.1711	0.8170	1.95	0.3766

Significance level α = 0.05

A Levene's test for equal variances between groups is conducted to compare: (1) Ratios of material deprivation between men and women; (2) Ratios for disabilities between men and women; (3) Ratios between households of two-parents and single mothers without car; (4) Ratios between households of two-parents and single fathers without car; and (5) Ratios between households of single mothers and single fathers without car. Table 4.15 shows the results for the Levene's test for equal variances. The null hypothesis (H0) states that the groups have equal variances, while the alternative hypothesis (H1) is that the groups have different variances. (DATAtab, 2022a).

Table 4. 15 Levene's test for equal variances for comparing ratios between groups

Test statistic Levene's test	(1) **Material deprivation Male vs female**	(2) **Disabilities Male vs female**	(3) **Two-parents vs Single mothers (without car)**	(4) **Two-parents vs Single fathers (without car)**	(5) **Single mothers vs Single fathers (without car)**
	P-value	P-value	P-value	P-value	P-value
W0 (mean)	0.8789	0.0019	0.0131	0.0001	0.0711
W50 (median)	0.9467	0.0028	0.0197	0.0001	0.0756
W10 (10% trim mean)	0.9346	0.0023	0.0168	0.0001	0.0714
Ho vs H1 (*)	Cannot reject Ho	Reject Ho	Cannot reject Ho	Reject Ho	Cannot reject Ho

(*) H0: Groups have equal variances, H1: Groups have different variances, Significance level α = 0.05

Referring to Table 4.15 and the Levene's test for equal variances for comparing ratios between groups, the hypothesis testing for paired groups (1) ratio material deprivation (male vs. female), group (3) two-parents and single mothers, and group (5) single mothers and single fathers showed that the p-values are larger than the significance level α = 0.05, and the null hypothesis cannot be rejected. This means that the homogeneity assumption of the variance is met between each pair of groups.

For paired groups (2) ratio disabilities (male vs female) and (4) ratio of two-parents and single fathers, the p-values are smaller than the significance level $\alpha = 0.05$, and the null hypothesis is rejected. Thus, the variances are significantly different, and the homogeneity assumption of the variance is not met for each pair of groups.

4.4.2.3 Checking assumptions for the T-test and Mann-Whitney U-Test

A T-Test for independent samples is used to compare the means of two independent samples to verify if there is statistical evidence that the population means are different. This parametric test requires that the data meet the assumptions of having a normal distribution and the variances between the samples should be similar (Kent State University, 2022). When these assumptions are not met, then the non-parametric Mann-Whitney U-Test can be used to test if there is a difference between two samples (groups) (DATAtab, 2022b).

Table 4.16 shows a summary of the findings for testing for normality and homogeneity of variance and the corresponding test for comparing groups between two independent samples.

Table 4. 16 Summary of assumptions of normality and homogeneity of variance for comparing two independent samples

Comparison between two independent samples (Ratios)	Normal distribution	Variance between independent samples	Test
(1) Material deprivation Male vs female	RMADEPM = No RMADEPF = No	Homogeneity = Yes	Mann-Whitney U Test
(2) Disabilities Male vs female	RDISABM = No RDISABF = No	Homogeneity = No	Mann-Whitney U Test
(3) Two-parents vs Single mothers (Without car)	R2PARENTS-NOCAR = Yes RSMOM-NOCAR = Yes	Homogeneity = Yes	T-test
(4) Two-parents vs Single fathers (Without car)	R2PARENTS-NOCAR = Yes RSDAD-NOCAR = Yes	Homogeneity = No	Mann-Whitney U Test
(5) Single mothers vs Single fathers (Without car)	RSMOM-NOCAR = Yes RSDAD-NOCAR = Yes	Homogeneity = Yes	T-test

The normality tests shown in Table 4.14 indicated that the ratios for two-parents, single mothers, and single fathers have a normal distribution; and the test of homogeneity of variances between the variables for (3) two-parents and single mothers and (5) single mothers and single fathers show homogeneity of variances (Table 4.15). Thus, the assumptions are met to conduct a T-Test for independent samples. Table 4.16 summarizes these conditions.

A violation of assumptions to conduct a T-Test for independent samples is when the sample does not follow a normal distribution or there is not homogeneity of variances in the samples between groups. It has been found that (1) ratio material deprivation (male vs. female), (2) ratio disabilities (male vs female), and (4) ratio of two-parents and single fathers violate these assumptions (Table 4.16). Thus, the lack of validity of assumptions for normality and variance indicates that a non-parametric test must be conducted. Thus, the Mann-Whitney U Test is used to compare two independent samples.

4.4.2.4 Testing statistical differences between groups

A T-Test for independent samples is a parametric test used to compare the means of two independent groups to verify if there is statistical evidence that the population means are different. (Kent State University, 2022). The hypothesis test states a null hypothesis (H0) that there is no mean difference between the two groups, and the alternative hypothesis (H1) declares that there is a mean difference between the two groups (DATAtab, 2022).

The Mann-Whitney U Test is a non-parametric test. The hypothesis test states a null hypothesis (H0) that there is no difference (in terms of central tendency) between the two groups in the population; and the alternative hypothesis (H1) declares that there is a difference (with respect to the central tendency) between the two samples in the population (DATAtab, 2022; Washington et al., 2003). Table 4.17 shows the results for each hypothesis test.

Table 4.17 shows that the p-value for (1) ratio material deprivation (male vs. female) is larger than the significance level $\alpha = 0.05$. Thus, there is no evidence that there is a significant difference in gender in the case of ratios of population with material deprivation. However, in the case of males and females with disabilities, it was found that the p-value is smaller than the significance level $\alpha = 0.05$. Thus, the null hypothesis can be rejected and there is significant evidence that the ratios of populations of men and women with disabilities are different.

For the case of household composition as head of family without automobile, p-values smaller than the significance level $\alpha = 0.05$ were found in comparing (3) two-parents and single mothers and (5) single mothers with single fathers. Thus, the null hypothesis can be rejected and there is significant evidence that the ratios between two-parents and single mothers are different. Similarly, the ratios between the samples of single mothers and single fathers are different.

In the case of comparison between two-parents and single fathers, the p-value is larger than the significance level $\alpha = 0.05$. Thus, there is no evidence that there is a significant difference between two-parents and single fathers.

This analysis aimed to determine whether males and females differ regarding demographic variables for material deprivation and disabilities for the San José Metropolitan case study. Similarly, it was desired to understand if there was a difference in the household composition of not owning a car for two-parents, single mothers and single fathers.

Table 4. 17 Results for Hypothesis Testing comparing two independent samples

Comparing two independent samples	Hypothesis test	Test	P-value	Ho vs H1 (*)
(1) Material deprivation Male vs female	Ho: the sum of rankings in the between the ratios of male and female presenting material deprivation does not differ H1: the sum of rankings in the between the ratios of male and female presenting material deprivation differ	Mann-Whitney U Test	0.9820	Cannot reject Ho
(2) Disabilities Male vs female	Ho: the sum of rankings in the between the ratios of male and female presenting disabilities does not differ H1: the sum of rankings in the between the ratios of male and female for material deprivation differ	Mann-Whitney U Test	0.0000	Reject Ho
(3) Two-parents vs Single mothers (Without car)	Ho: There is no mean difference between the two groups of ratios for two-parents and single mothers without car (H_0: $\mu_1 = \mu_2$) H1: There is a mean difference between the two groups of ratios for two-parents and single mothers without car (H_1: $\mu_1 \neq \mu_2$)	T-test	0.0000	Reject Ho
(4) Two-parents vs Single fathers (Without car)	Ho: the sum of rankings in the between the ratios of household composition two-parents without car, and household composition of single fathers without car does not differ H1: the sum of rankings in the between the ratios of household composition two-parents without car, and household composition of single fathers without car differ	Mann-Whitney U Test	0.4100	Cannot reject Ho
(5) Single mothers vs Single fathers (Without car)	Ho: There is no mean difference between the two groups of ratios for single mothers and single fathers (H_0: $\mu_1 = \mu_2$) H1: There is a mean difference between the two groups of ratios for single mothers and single fathers (H_1: $\mu_1 \neq \mu_2$)	T-test	0.0000	Reject Ho

Significance level $\alpha = 0.05$

It was found that 21.09% of the population experience material deprivation, where 11.07% are women and 10.02% are men. The mean of ratios for men with material deprivation is 19.94 and for women is 20.02. When comparing ratios aggregated per TAZ, the results showed no statistically significant difference based on gender at the significance level $\alpha = 0.05$.

Regarding people with disabilities, 11.09% of the population present a form of disability, where 6.16% are women, and 4.92% are men. The mean for ratio of men with disabilities is 10.61 and 12.12 for women. The ratios differentiated per gender showed that there is a statistically significant difference between men and women. There is a larger ratio of women with disabilities than men.

For the case of household composition as head of family without automobile, 45.56% are two-parent households, 8.90 % are single mothers and 0.83% are single fathers. The ratios are 53.26 for two-parents, 63.66 for single mothers, and 50.73 for single fathers. In the case of comparing two-parents and single fathers, there was no significant difference. Comparing samples for single mothers revealed that this group is significantly different with two-parent households and with single fathers. There is a larger ratio of single mothers without automobile than the other variables.

4.4.2.5 Geospatial demographic analysis and air pollution

The Great Metropolitan Area of Costa Rica is a polycentric city of low population density and is heavily car dependent. The bus service is low quality, and there are limited trip frequencies of the regional train. Highways are the central connectors for people to commute to work or to access government services from the outer provinces to the capital San José.

The San José Central Business District (CBD) is characterized by centralizing offices for the government and private sector. In most of the inner city, the housing landscape is of poor quality with low-income residentials. Slums and informal settlements are at the periphery of the province of San José, predominantly in the South, northeast, and northwest. Wealthier neighborhoods are on the east and west (from 49600E to Eastbound on 109800N; and the west from 48800E to westbound on 109800N, as shown in Figure 4.18).

The CBD road network also serves as a connector for regional travel from East to West and vice versa. There is a road network in the shape of a ring around the CBD. It is the most important road network that connects highways from the outer provinces and the districts within San José. Figure 4.18 shows the Vehicle Kilometer Traveled (VKT) for San José Central Business District (CBD) and its surroundings. The upper level of VKT (from 0.99 to 17.0 million-Kms) is related to the highways connecting the outer provinces to the capital and the highways and main arterials connected to the ring network in San José.

Geospatial equity analysis is performed by targeting disadvantaged population groups. It has been argued that women face barriers to equal opportunities for development. Differentiating per gender, women experience additional barriers to urban mobility. Women have to invest more time in household responsibilities. Long travel times, car dependency, and low-quality transit services are additional challenges to balancing work-home responsibilities. Lack of citizen safety (crime and sexual harassment) can limit the freedom to travel (Knoll & Schwaninger, 2020; Gonzalez et al., 2020; Loukaitou-Sideris, 2016).

The statistical analysis shows no significant evidence between populations groups differentiated per gender for ratios of material deprivation (p-value < 0.05), but there was a significant difference in disabilities per gender, where women experienced larger mean ratios. A similar situation was found with single mothers without automobile, presenting larger mean ratios and significantly different than households with two-parents and single fathers. In addition, gender equality indicators of Costa Rica show that the female population is more disadvantaged. Some disadvantages are related to employment opportunities, the gender wage gap, and time due to childcare responsibilities for children and elders that falls on women rather than men (Salas-Calderón et al., 2019).

Based on this evidence, this geospatial equity analysis aims to target women living with material deprivation, disabilities, single mothers who do not own a car, and their exposure to air pollution. The goal is to identify high-priority areas for urban mobility improvements. Bivariate dot-density maps using TAZ as geographic units are generated to contrast these population groups with air pollution. For each demographic variable, census tracks per block are aggregated per TAZ.

Figure 4. 18 Vehicle Kilometer Traveled for San José Central Business District (CBD) and surroundings

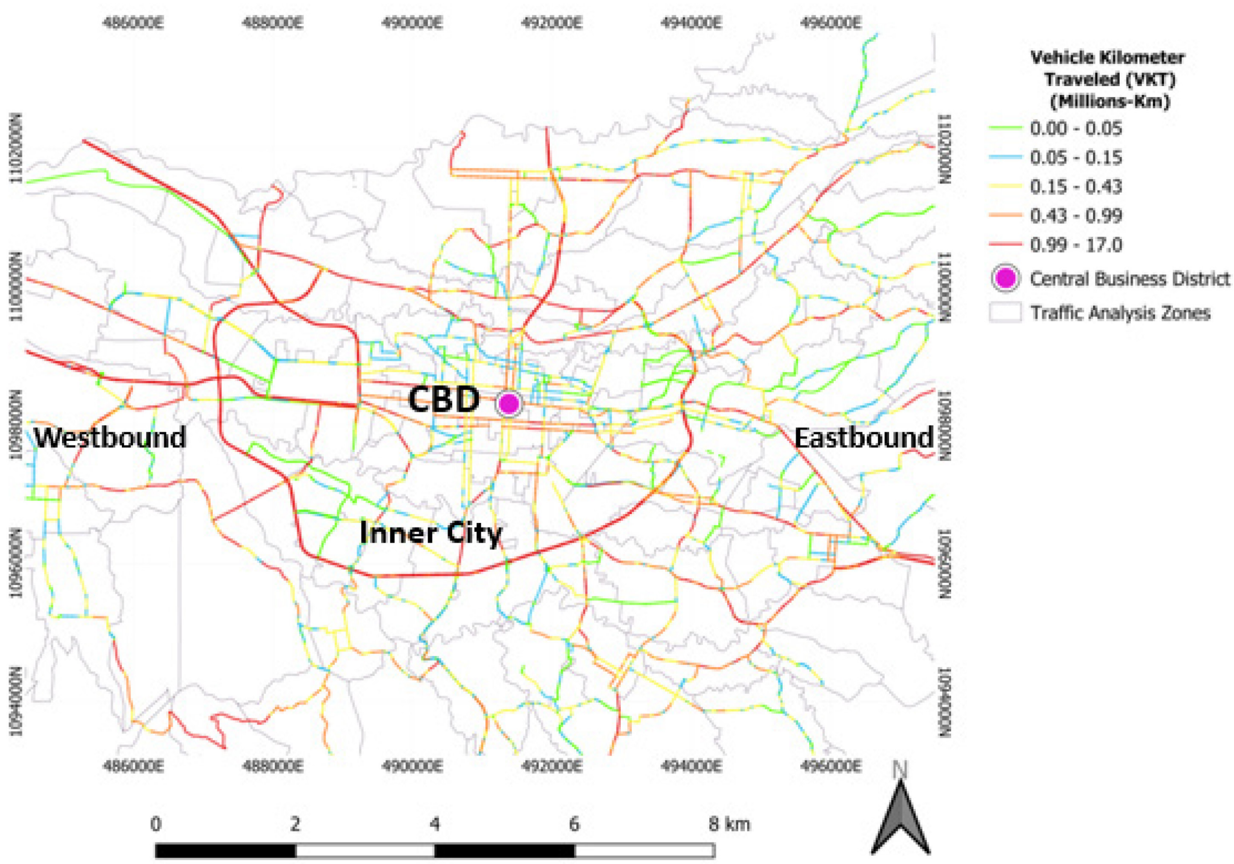


Table 4.18 shows the ratio for women with material deprivation, women with disabilities, single mothers without a car aggregated per TAZ by Percentiles of 25%, 50%, and 75%. For screening potential social disparities, maps are produced by assigning three ranges from (1) from the minimum value to Percentile 25%, (2) Percentile 25% to Percentile 50%, and (3) Percentile 75% to the maximum value (upper 25% and more critical). Table 4.6 showed the classification of air pollution (NOx and PM2.5) produced in each TAZ, normalized per square kilometer, and classified by Levels (L1 to L5). Each air pollutant and demographic variable are used to produce a bivariate map to assess air pollution exposure in vulnerable groups. This is shown in Figure 4.19 to Figure 4.22.

Table 4. 18 Ratios for women with material deprivation, women with disabilities, and single mothers without car aggregated per TAZ

Variable	N	Mean	Std. Dev.	Min	P25	P50	P75	Max	IQR
RMADEPF	166	20.02	11.72	1.14	11.57	17.68	26.65	64.7	15.08
RDISABF	166	12.12	3.42	3.47	9.92	11.71	13.86	24.17	3.94
RSMOM-NOCAR	166	63.66	19.68	6.41	51.26	66.85	78.97	100	27.71

RMADEPF: Ratio Material deprivation for women
RDISABF: Ratio Disabilities for women
RSMOM-NOCAR: Ratio Single mothers without owning a car

N: Number of observations (166 TAZ)
P25: Percentile 25th, P50: Percentile 50th,
P75: Percentile 75th, IQR: Interquartile range

The spatial distribution of air pollution shows a similar pattern of pollutants NOx and PM2.5 produced in each TAZ. Roads with higher VKT produce higher levels of pollution (L4 and L5). Higher levels of pollution are located in the Central Business District (CBD) and inner-city. TAZ with L4 and L5 levels are characterized by involving highways. These highways connect the outer provinces to the capital and main arterials that intersect with the ring-shaped network. These zones hold 25% upper ratios for women with material deprivation, women with disabilities, and single mothers without automobile.

There is a close match between the spatial distribution of ratios for women with material deprivation and single mothers without a car. The 25% upper ratio for material deprivation lies between 26 and 65, while the 25% upper ratio for single mothers without a car is between 79 and 100. In addition to the CBD and inner city, these population groups also are allocated in the Southbound of the city and localized areas in the northwest and northeast with air pollution concentration Levels type L2.

The upper 25% for ratios of women with disabilities lie between 13.9 and 23.0. They are in the Central Business District and exposed to a concentration of NOx and PM2.5 class L4 and L5. They are also located around the south ring-shaped road network with NOx and PM2.5 class L4. The northwest and northeast also contain the highest ratios of disabilities with levels of pollution type L2.

Looking at the population density per zone, the Southbound and localized areas in the northwest and the northeast have higher population density (higher than 10,265 persons per Km^2) which supports transit investments by offering higher demand. Since these areas have the highest ratios for single mothers without a car and disabilities, these areas should be considered a priority when planning rapid transit investments from a social exclusion perspective.

The Central Business District (CBD) has lower population densities (from 2,868 to 10,265 persons per Km^2). CBD is a center of attraction for government services and employment, and its road network serves as a connector for regional urban mobility. As a result, traffic produces high concentrations of air pollution.

Figures 4.23 and 4.24 show a different perspective of bivariate maps showing material deprivation with the 25% upper ratios of single mothers without a car and women with disabilities. It also shows the slums identified by the Ministry of Housing and Human Settlements. It is noticeable that slums lie on the periphery of the city.

The highest ratio of people with disabilities lives in the CBD (upper 25%). By looking at the intermediate ratios between Percentiles 50th and 75th, prioritizing investments for improving urban mobility and reducing air pollution in the CBD, inner-city, and the Southbound also benefits this second population level. This population also lives in the outer TAZ of the province of San José. Further data collection and analyses are necessary for better understanding the urban mobility needs, modes of transport used, and origin and destinations through the lens of social exclusion.

Figure 4. 19 Spatial distribution of exposure of Nitrogen Oxides (NOx) for women as vulnerable groups and population close to the CBD

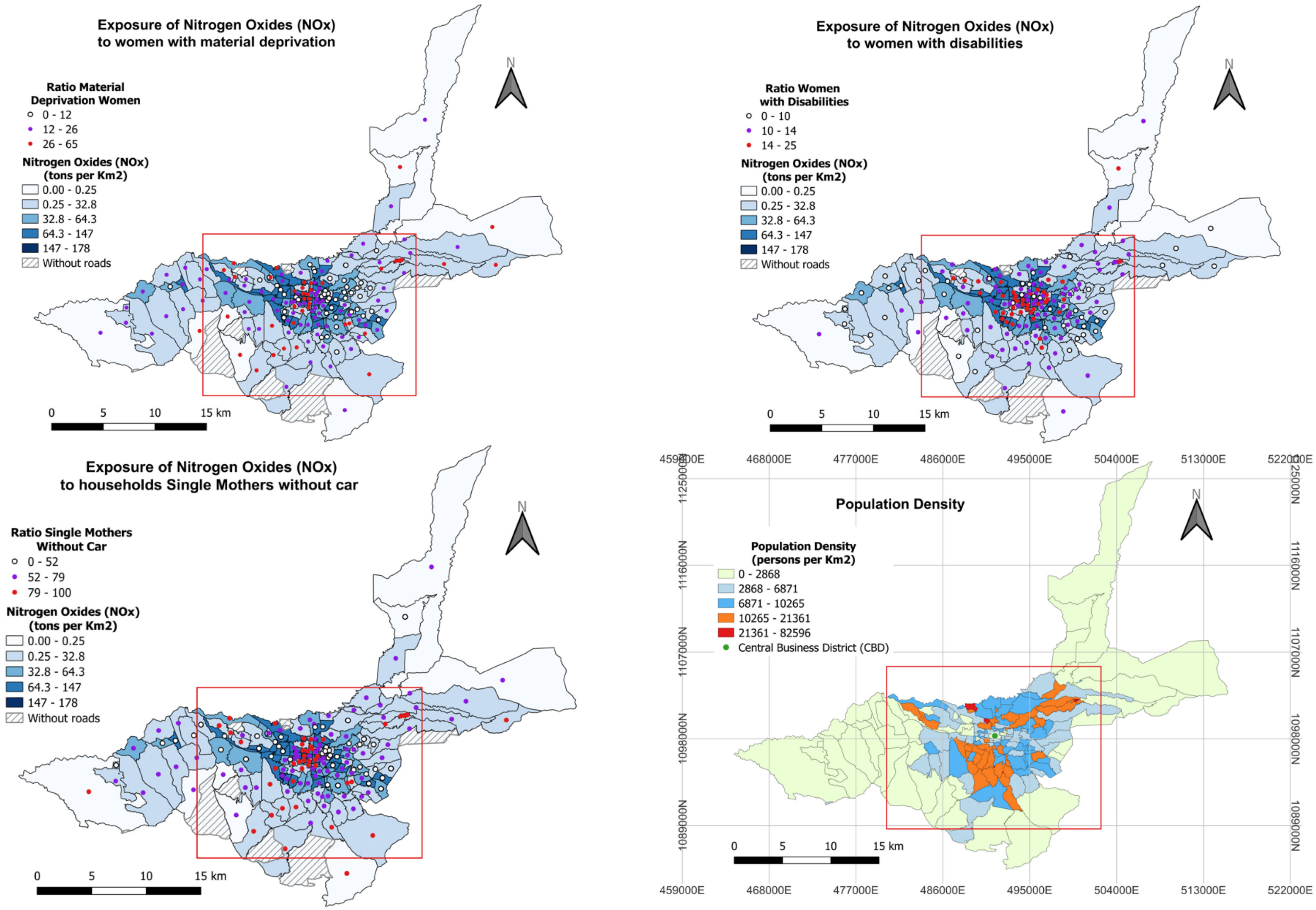


Figure 4. 20 Spatial distribution of exposure of Nitrogen Oxides (NOx) for women as vulnerable groups and population close to the CBD

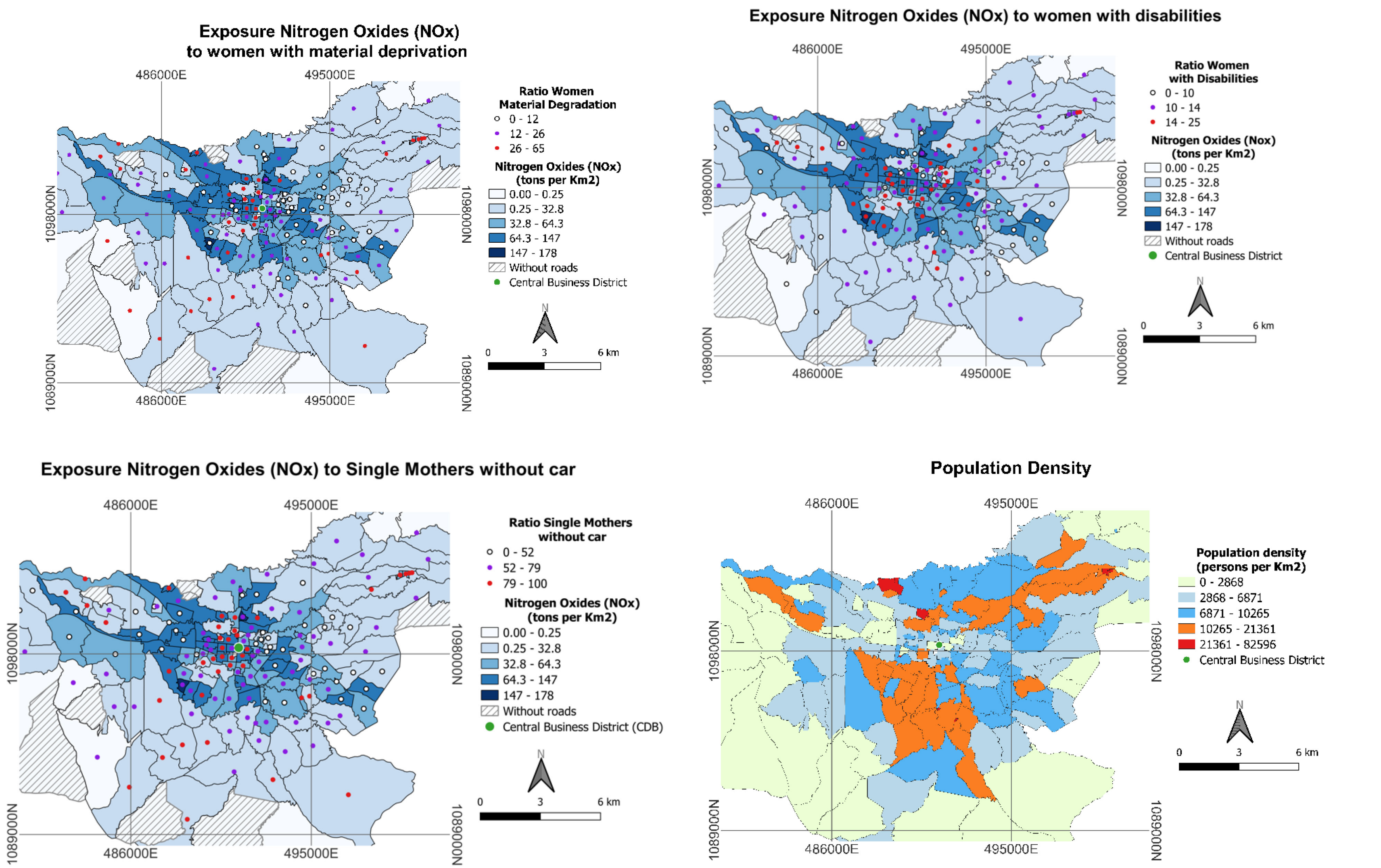


Figure 4. 21 Spatial distribution of exposure of Particulate Matter (PM2.5) for women as vulnerable groups and population

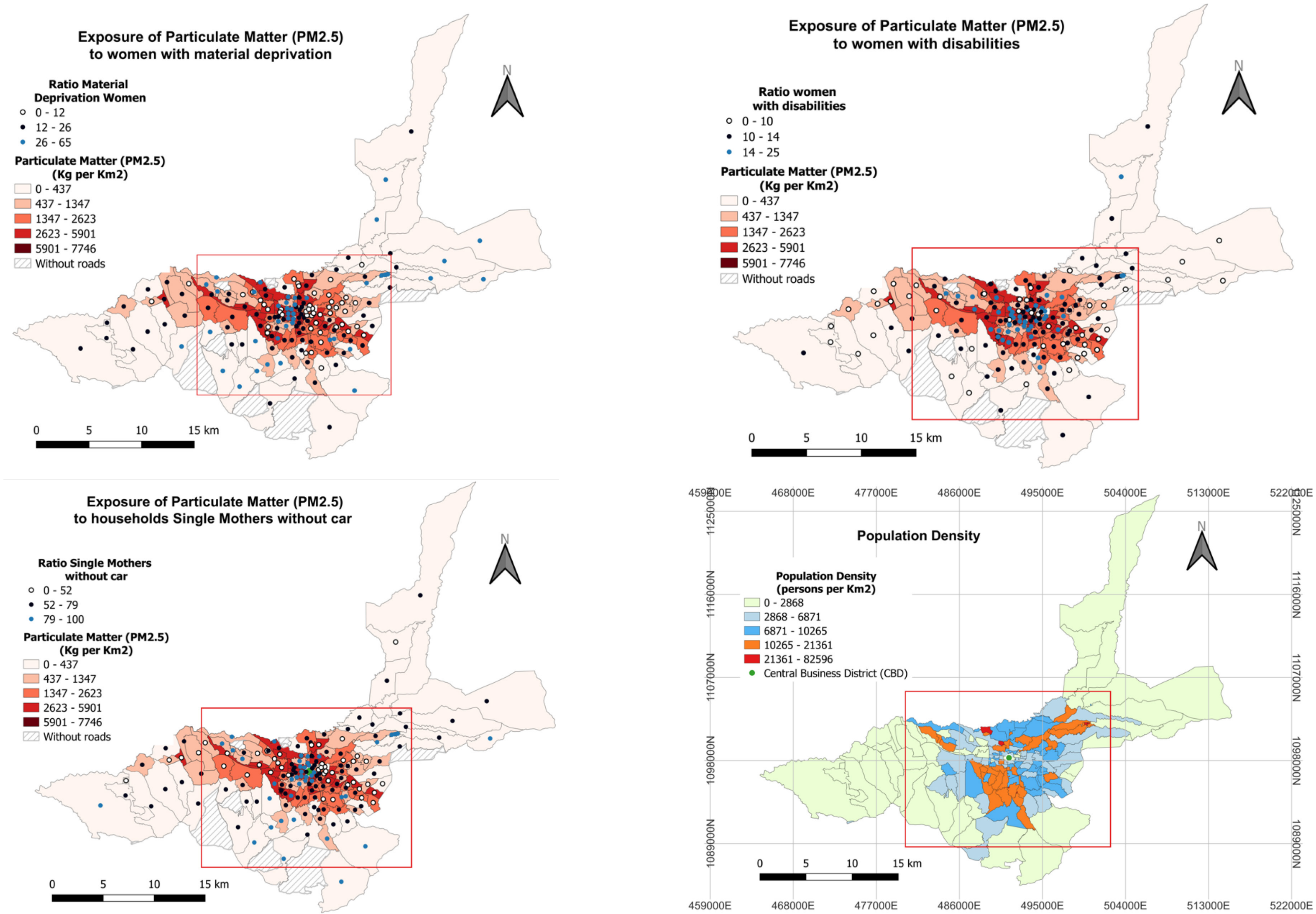


Figure 4. 22 Spatial distribution of exposure of Particulate Matter (PM2.5) for women as vulnerable groups and population close to the CBD

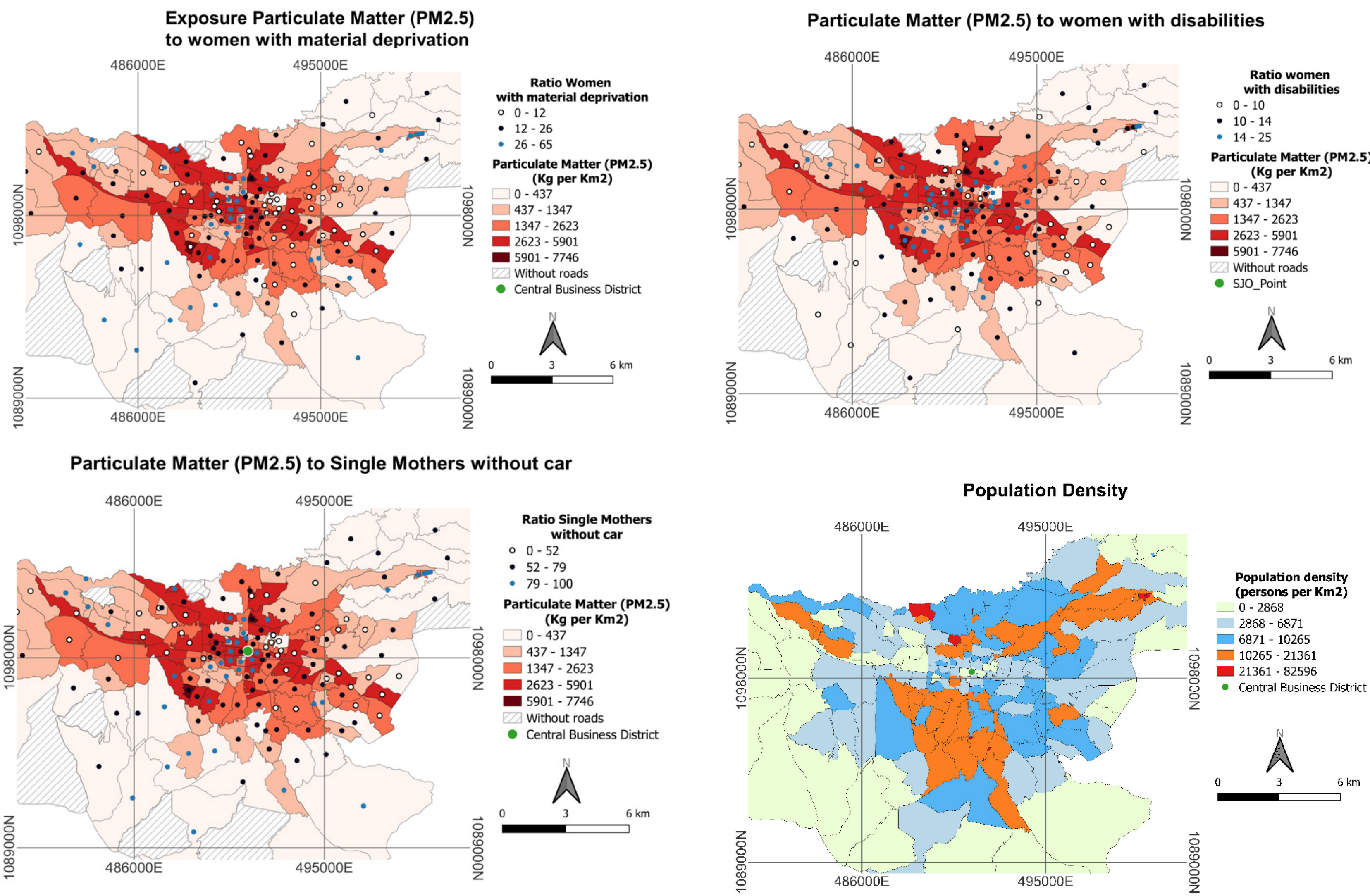


Figure 4. 23 Material deprivation, slums, and upper 25% ratio for single mothers not owning a car

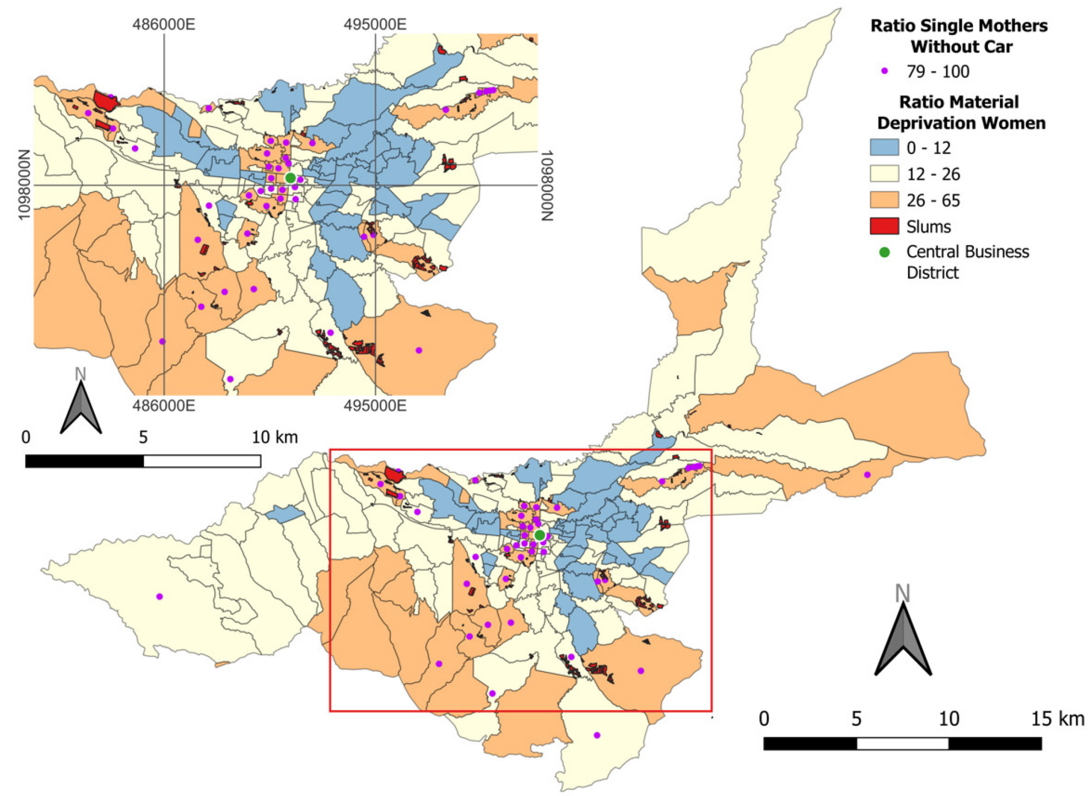
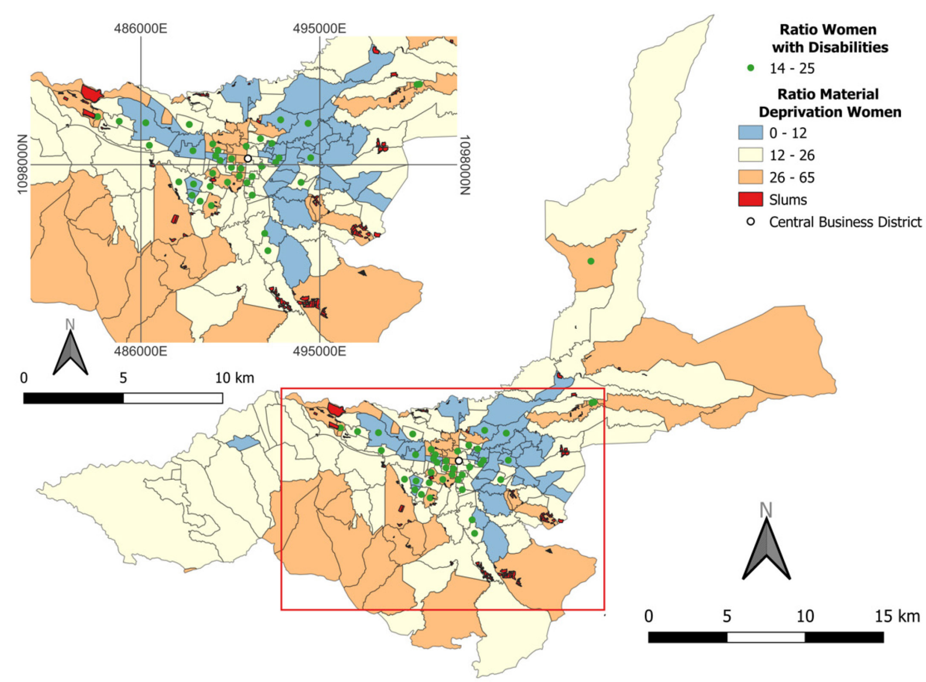


Figure 4. 24 Material deprivation, slums, and upper 25% ratio for women with disabilities



4.4.2.6 High-priority areas in urban mobility through the lens of social and environmental justice

Most cities of the world were designed for the mobility of cars leaving behind safe and adequate infrastructure for other modes of transport. In this context, people who do not own a car or cannot drive a car are disadvantaged in accessing desired destinations. One of the tasks of transport planners and politicians is to ensure a fair allocation of resources, and address issues of fairness, equality, and justice (Banister, 2018).

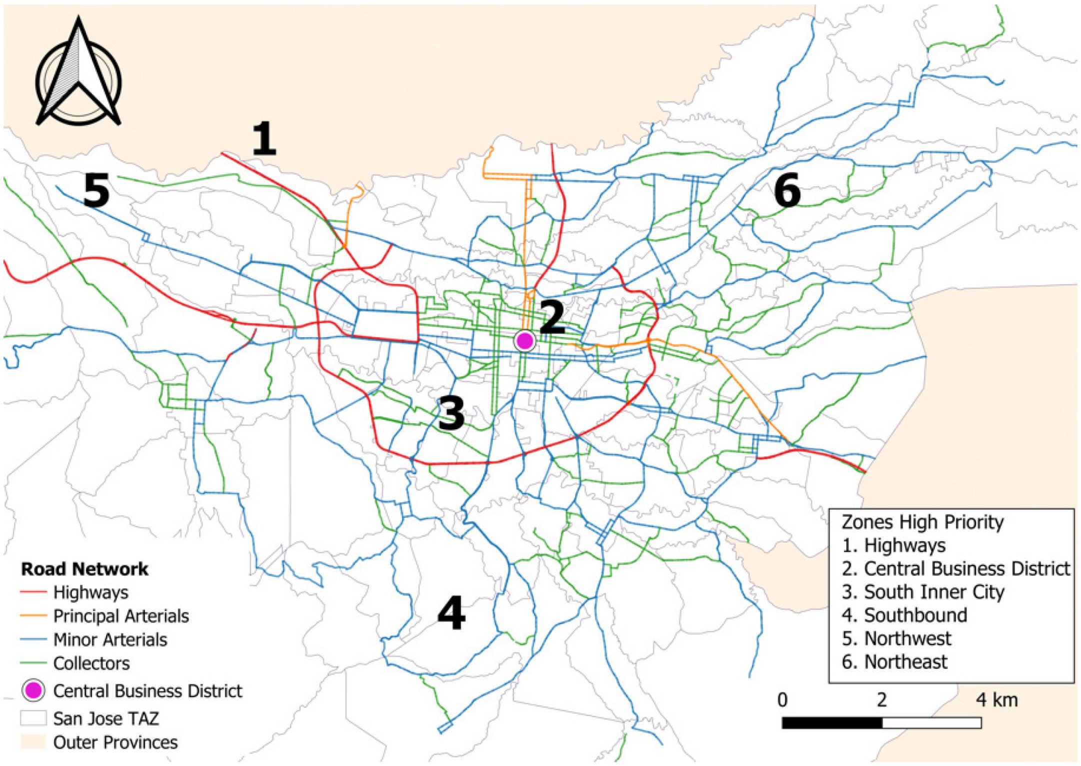
In city planning, there are two approaches to equity: horizontal and vertical. Horizontal equity refers to equal treatment of people and should not be favored by one particular group over another. There is equality in the service provided across communities, and the service is provided according to demand. On the other hand, vertical equity establishes fairness in the distribution of resources favoring socially disadvantaged groups to compensate for social inequalities and negative transport externalities such as air pollution, traffic collisions, and noise (Banister, 2018; Litman, 2018).

Vertical equity (social and environmental justice) approach was used to prioritize social disadvantage groups and air pollution exposure in San José for transport investments. For these groups, improving urban mobility and reducing air pollution compensate the disadvantage of households having the burden of low income plus the risk of developing illnesses associated to long-term exposure due to air pollution that is produced by their neighborhood. This potential scenario can also impact the household economy by increasing health expenses or the loss of income due to the inability to work. Single mothers are the most vulnerable in this scenario as they are the primary source of income in the household and the caregivers of children and elders. Based on demographic and geospatial assessments, high priority areas have been identified as shown in Figure 4.25.

In Figure 4.25, traffic emissions from zones 1, 2, and 3 are higher, which contain the highway network and its connectors. As a strategy, reducing the VKT on the highways is necessary. Some solutions to explore are regional rapid transit that must be connected to the bus network as a feeder to increase ridership; there is also carpooling, and High Occupancy Vehicle Lanes. Given that the road network lacks redundancy, new infrastructure investments are needed to accommodate any rapid transit system. Zones 2 and 3 (CBD and Inner city) have higher and intermediate ratios of women with disabilities and are exposed to levels of air pollution L3, L4, and L5, and should be taken as a priority for improvements in transit and universal design.

Zones 4, 5, and 6 have higher population densities, ratios of material deprivation, and single mothers without cars. These zones contain lower levels of air pollution (L2), but demographic characteristics show that these populations are disadvantaged in a city that is highly dependent on cars. Zone 4 (southbound) could be a candidate for a rapid transit system.

Figure 4. 25 High-priority areas in urban mobility through the lens of social and environmental justice



Modeling the travel demand has allowed for estimating the mobility patterns and air pollution produced per road segment. This research has identified that highways generate higher concentrations of pollutants. The CBD and inner-city produce higher levels of air pollution as these zones have a road network connects the highways to distribute traffic to their destinations. There are strategies to decrease traffic emissions, such as shifting towards zero-emissions vehicles, carpooling, improving public transport for people to shift modes from car to transit, and improving local mobility with active transport. Other strategies include avoiding traveling by changing the built environment with mixed-use developments, and teleworking.

High-priority areas based on equity and health have been evaluated as factors to be included in the planning process and project selection of transport investments through the lens of equity for poverty, mobility for the transport disadvantaged, gender, and healthy cities (air pollution). Further studies must incorporate accessibility to opportunities to access the labor market, education, and services per transport mode. Traffic safety and city safety are essential to include in allocating investments. Safer roads are required to reduce traffic injuries and deaths, while city safety strategies and investments can reduce crime and sexual harassment on the streets. Safety is essential to reduce car dependency, shift to transit and walking, and reduce traffic emissions. These elements should be incorporated as a criterion for prioritizing and evaluating projects (Madariaga & Neuman, 2020; Gonzalez et al., 2020).

In this case study, over the last two decades, there has been a debate about whether it is worth investing in rail rapid transit systems given the city's low population density that does not produce enough demand to pay the service cost fully. Besides rail, Bus Rapid Transit Systems offer a more affordable option under lower demand conditions. Either way, under this argument, only direct costs are being considered. Social costs should be incorporated in the state of the practice.

Managing a transport system without considering climate change (local and global) and air pollution can increase costs to governments, as they must cope with social and healthcare costs when there is long-term exposure to air pollution. Also, in the absence of implementing strategies to climate change (mitigation and adaptation), the consequences of costs in infrastructure and lives when extreme events strike can be significant. Further research is needed for Cost Benefit Analyses to incorporate equity, health, and the environment through the lens of the Sustainable Development Goals.

4.5 Conclusions

Business as usual in transportation has led to negative externalities such as greenhouse gas emissions, air pollution, noise, and road traffic injuries and deaths. Traditional planning of transport systems has prioritized the movement of vehicles over the movement of people. The social implications of exclusion are not always considered. The COVID-19 pandemic has highlighted the importance of incorporating social inequalities and air pollution in the planning and design of cities. Social inequalities go together with the spread of communicable diseases. In addition, communities exposed to long-term air pollution are more-at-risk of developing respiratory and cardiovascular illnesses such as cancer, COVID-19, diabetes, asthma, and lung diseases.

Planning cities using a vertical equity approach creates fairness in resource distribution, favoring socially disadvantaged groups to compensate for social inequalities. Some scholars argue that transport planning must give more attention to transport poverty, gender equality, and their context in power relations. The United Nations SDGs have a core message of “leave no one behind” and give much attention to vulnerable populations to attain the 2030 targets. The new UN agenda Decade of Action for Road Safety 2021 – 2030 mandates the incorporation of a gender perspective in transport planning since there are differences in aspects of the design and construction of transport infrastructure.

A gender and air pollution geospatial analysis was performed for a case study of San José - Costa Rica, through the lens of vertical equity planning for identifying priority areas in urban mobility. The first objective reviewed barriers women experience to attain equal opportunities to men and their relation to urban mobility. The second objective analyzed demographics and geospatial social disparities, including material deprivation and disabilities for women and single mothers’ car ownership. Evidence shows that women are at a disadvantage compared to men. Thus, geospatial analysis of the female population with social disparities and their exposure to traffic-induced air pollution was performed with the goal of incorporating this perspective into transport planning.

Women's social and economic empowerment depends on the ability to attain gender equality, where men and women, boys and girls, have equal rights and opportunities. Six dimensions of gender equality were identified: "workforce participation, economic empowerment, education, health & sexual reproductive rights, time, and empowerment." These dimensions are interrelated, and barriers can lead to social exclusion. Workforce participation can be limited due to barriers to childcare availability and transport due to long travel times or low perception of safety, accessibility to opportunities on automobile versus transit, and the multiple travel trip chains women must make after work when they have children or elders under their care. Performing these tasks becomes challenging when women deal with low-quality public transport services that increase travel times or lack safety from a door-to-door journey.

On average, women spend three times as many hours in unpaid domestic and care work as men, and significantly more if they have children. In some cases, women might choose part-time or low-pay jobs or not take management positions to attend to household responsibilities. Limited free time is also a barrier to political participation, education, and empowerment.

Low-income single-working mothers that do not own a car are at a more significant disadvantage. The U.S.A. has established policies to subsidize automobiles for this group to overcome poverty. There is a debate about this policy between advocates of sustainable transport who do not want to enhance the car culture. At the same time, urban planners focusing on social inequalities, gender, and poverty argue that until transit becomes a better option than automobiles, low-income travelers should not be prevented from owning a car. Higher-income groups are the ones disproportionally driving on the roads.

The health & sexual reproductive rights dimension is related to women and girls facing challenges in public spaces and transit systems due to crime, sexual harassment, and sexual violence. Violence limits the freedom of movement in a city and creates fear-based exclusion of public spaces and public transport systems. As a result, and for safety reasons, women prefer automobiles if they can afford them. Nevertheless, low-income groups in need of automobiles can experience “transport poverty”; in need to buy a car to access employment and services; they can face trade-offs between owning a car, shelter security, and travel distance.

Another form of “transport poverty” is when expenses or loss of income compromise individuals due to chronic diseases, injuries, or death related to transport externalities such as air pollution and road traffic collisions. Communities with social disparities, for example, breathing low-quality air or experiencing higher exposure to traffic collisions are at greater disadvantage. Low-income single mothers face additional disadvantage due to the potential of developing health conditions related to negative traffic externalities, which will directly impact household income and childcare responsibilities.

Gender equality is reported through global indices in an aggregated form. Collecting data with geographic coordinates and a granular level of disaggregation is necessary. Thus, geospatial analyses can be performed to identify the most vulnerable and marginalized households, communities, or districts in need of specific interventions in the city. Travel surveys must also be differentiated by gender and capture the chain of multiple trip activities. A gender-based data collection associated with the six dimensions of gender equality and the SDG Index should be collected annually to produce performance measures in urban mobility and cities.

The case study of San José – Costa Rica, performs a gender demographic assessment and measures geospatial social disparities based on female material deprivation, females with disabilities, single mothers that do not own a car, and their exposure to traffic-induced air pollution. 11.07% of women and 10.02% of men experience material deprivation, and 6.16% of women and 4.92% of men have disabilities. The mean of ratio for men with material deprivation is 19.94 and for women is 20.02, and the mean for the ratio of men with disabilities is 10.61 and 12.12 for women. When comparing ratios for gender groups at the significance level $\alpha = 0.05$, it was found that there is no significant difference between genders for material deprivation. However, there was a significant difference in genders for ratios for disabilities. The mean ratio of women with disabilities is larger than men.

For the household composition as head of family without automobile, 45.56% are two-parent households, 8.90 % are single mothers and 0.83% are single fathers, while the percentage of households owning a car is 44.71%. The ratios are 53.26 for two-parents, 63.66 for single mothers, and 50.73 for single fathers. In the case of comparing two-parents and single fathers, there was no significant difference. Comparing samples for single mothers revealed that this group is statistically significantly different with two-parent households and with single fathers. There is a larger mean ratio of single mothers without automobile than the other variables.

The statistical findings show that the ratios of women with disabilities are larger and significantly different than men, while there was no significant difference for gender and material deprivation. For the household composition and car ownership, single mothers have a larger mean ratio and is significantly different than two-parents and single fathers.

High-priority areas for improving urban mobility were identified. The Central Business District (CBD) has higher ratios of women with disabilities and high levels of air pollution. The inner city has higher ratios of women with material deprivation, single mothers who do not own a car, and high levels of air pollution. The Southbound produces intermediate levels of pollution and has high ratios of women with material deprivation, single mothers that do not own a car, and the higher population density of the city, which supports investments for transit infrastructure.

Reducing air pollution requires reducing the Vehicle Kilometer Traveled from highways. Thus, rapid regional public transport and carpooling should be considered. This strategy would also impact the CBD and inner city towards reducing air pollution. The city's Southbound has a lower socioeconomic stratum and car ownership, higher population density, and intermediary air pollution levels. Thus, rapid transit systems should be considered to improve mobility. Accessibility to opportunities and road safety analyses should be conducted. Further data is needed to understand the mobility needs of people with disabilities and elders, sexual harassment and sexual violence in public spaces and transit systems, and crime.

CHAPTER 5

Conclusions

Sustainable development is about raising human well-being. This concept embodies four dimensions: (1) human development and social inclusion; (2) protection of the environment; (3) economic growth and prosperity; (4) good governance. The 2030 Agenda offers a holistic approach to how society should be. The SDG Index is a composite index indicator with 56 metrics created to monitor progress on the Sustainable Development Goals (SDGs). This index identifies priorities, gaps, and monitors progress for the 2030 Agenda. The SDG Index has demonstrated that no Global North and Global South country has achieved the 2030 Agenda.

Implementing the SDGs in urban mobility faces a barrier of the need for more integration across sectors, which is an obstacle to attaining sustainable development in cities. This research proposes a conceptual urban performance management system under five strategic areas: social justice, health, climate change, economic development, and governance. A literature review was conducted to analyze the interconnectedness among the SDGs, transport, and the built environment in cities. An Urban Data Observatory for integrating sectors is recommended to support improved policies, decision-making and monitor progress of the 2030 Agenda and transport goals.

Urban and territorial planning for the most vulnerable improves the city's environmental resilience, health outcomes and closes the gap in inequalities, and poverty reduction. Modeling tools to address the social dimension of sustainable development were classified in three groups: (1) Accessibility analyses, which integrates transport and land use to improve access to employment, education, and services; (2) Transport equity, which elaborates social-spatial analyses including demographics and socioeconomics, can identify vulnerable populations; (3) Affordability, which analyses "transport poverty", transit fare analyses and forced car ownership. A comprehensive study should integrate these three types of modeling approaches for better outcomes.

Health equity is key to health outcomes and well-being, and structural and intermediary social determinants define it. There is evidence of how intermediary social determinants (health system, exposure, and vulnerability of populations) play a fundamental role in health outcomes. Scholars found that overcrowded housing conditions (not urban density) increase the rapid transmission of the virus COVID-19. Overcrowded housing is the result of social exclusion and inequalities. Structural determinants (socio-economic, political context, and social hierarchies) also played a role in COVID-19. Scholars found in the U.S. that African Americans consistently breathe higher levels of air pollution, while African Americans and Latinos are the racial/ethnic groups with higher mortality rates.

As a policy response to climate change mitigation, it is encouraged to design compact mixed-use developments. They can support the reduction of VKT, energy use, and CO_2 emissions. Destination Accessibility and Density significantly impact reducing VKT and CO_2 emissions at a regional scale. However, increasing population density can also come with challenges in housing affordability. In Curitiba-Brazil, housing around the BRT lines is one of the most expensive in the city. In Canada, scholars have found that the state of the practice had been focused mainly on promoting land developments and attracting car drivers to transit rather than incorporating equity and measuring societal impacts.

In climate change, as a mitigation policy, the Avoid-Shift-Improve Framework (ASI) seeks to reduce travel, shift to sustainable transport, improve vehicle fuel efficiency, and use cleaner energies. In this review, it is recommended a combination of transport demand modeling and accessibility analyses. GHG emissions are also a result of vehicle activity (VKT, speed, and driving) and roadway conditions for pavement-tire interactions (pavement smoothness and speeds). Thus, pavement management systems must account for GHG emission reduction, also improving resilience for extreme climate events.

In economic development through the lens of sustainable development, investment decisions must rely on human development, social inclusion, environmental protection, economic growth and prosperity, and good governance. Good coordination between national and local governments is required to manage transport and land use for desired outcomes.

The literature review and proposed frameworks provide insights for future research for modeling integration and designing a sustainable urban mobility performance-based management system with proof-of-concept modeling. Urban mobility is a systems challenge, and cities are urban ecosystems. Thus, planning and designs should use a systematic approach. In this regard, two case studies were developed for the metropolitan area of San José - Costa Rica.

The first case study of the metropolitan area of Costa Rica was used to evaluate the policy of shifting the vehicle fleet to Electric Vehicles (EVs). A regional average speed emission model relying on a macroscopic four-step travel demand model was developed to analyze EVs penetration effect on traffic emissions up to the year 2050. Four scenarios are explored: the business as usual (BAU), low, moderate, and aggressive scenarios to evaluate the potential reduction of CO_2 emissions and air pollutants NOx and PM2.5. A regional emission model is developed for the province of San José - Costa Rica for highways, principal arterials, minor arterials, and collector roads. The emission model considered vehicle type and weight, average speed, and vehicle technology.

There are two approaches for emission models: top-down and bottom-up. Top-down emission models based on fuel consumption are commonly used due to the accessibility to fuel consumption inventories, which allow monitoring of annual emissions. There are limitations to the top-down approach, such as the inability to forecast scenarios and incorporate specific climate mitigation actions.

On the other hand, bottom-up emission models are less common due to their complexity. Bottom-up emission models are disaggregated and presented in a spatial distribution, and emission models that rely on travel demand models allow for incorporating climate mitigation actions, identifying priorities, and evaluating climate policy instruments. The bottom-up emission model relied on a four-step travel demand model. This model was calibrated and validated with local data. A limitation of the model was that the Origin-Destination survey was from the year 2007 to be used for the calibration process. Observed traffic volumes are used for the validation process relied on traffic counts from the years 2007 and 2015. After 2015, traffic counts are scarce.

Overall, the 2007 model had an RMSE of 17.10%, and the 2015 model had an RMSE of 17.89%. However, when disaggregating the error per volume groups, the error is more significant for roads with less than 5,000 daily vehicles per direction. The models overpredict traffic on volume groups larger than 20,000 daily vehicles per direction, and underpredict traffic on roads with volumes lower than 20,000 daily vehicles per direction. Volume groups with less than 5,000 daily vehicles per direction have larger errors. It is expected to carry on with this pattern for the forecasted models.

A framework under a systematic approach and performance management was proposed for a bottom-up regional emission model supported by travel demand modeling. Setting long-term emission scenarios allows the framework to measure network performance by monitoring EV penetration. The process of monitoring, evaluating, and reporting allows for identifying trends and targets and the definition of new policy instruments and priorities for climate actions toward achieving the 2050 goals.

For the bottom-up regional emission model, the emission scenarios depend on four factors: (1) Traffic growth, expressed as Vehicle Kilometer Traveled (VKT); (2) Speed scenarios, where three-speed profiles were tested given the variation of speed due to an increase of congestion; (3) Vehicle emission standards EURO I, EURO IV and EURO VI. The emission standards are regulated by legislation; (4) Electric vehicle percentage of penetration through time for four target scenarios: Business-As-Usual, low, moderate, and aggressive.

For the case study of San José, by 2050, the Business-As-Usual (BAU) scenario would increase 25% of CO_2 emissions due to traffic growth. This scenario was mitigated by including the effect of the change of vehicle emission standards of ICE vehicles from EURO I to EURO VI, given the current changes in legislation. As a result, air quality shows improvements with a 58% reduction of NOx, and PM2.5.

The low scenario (50 % EVs) and moderate scenario (75 % EVs) reduce 38% CO_2 and 69% CO_2 emissions, respectively. For air quality, the low scenario attains 79% NOx and PM2.5 reduction, while the moderate scenario achieves a 90% reduction of NOx and PM2.5. The aggressive scenario targets 100% EVs by 2050.

While the Costa Rican 2018-2050 decarbonization strategic plan follows the Avoid-Shift-Improve Framework (ASI), the country's fiscal debt limit investments in public transport infrastructure, restricting the implementation of the "Avoid" and "Shift" strategies. Most of the available funds are invested in infrastructure to improve traffic operations and improved motorization movements. Thus, the current state of the practice of decarbonization relies on the "Improved" strategy, and by 2022, 0.48% of the vehicle fleet was electric.

In the year 2022, the model of this research showed that passenger cars are the largest contributor to CO_2 emissions, with 51%. After passenger cars, pick-up trucks produce 23% CO_2 and buses 10% CO_2. It is not recommended to rely only on the consumer to shift to EVs ("improve" measure), which depends on psychological factors, socio-economic factors, and policy instruments (i.e., financial, lifting driving restrictions). The "Avoid" and "Shift" strategies bring the advantage of improving urban mobility by focusing on the built environment for enhancing Density and investing in public transport, cycling, and walking. The “Improve” strategy focuses on improving vehicle technology, and using only this strategy will reinforce motorization, urban sprawl, forced car ownership, and “transport poverty”.

By taking global benchmarks, the United Nations recommends that by the year 2030, a 45% reduction of greenhouse gas emissions (GHG) to get back on track to limit global warming to 1.5ºC. On a global scale, Costa Rica is not a significant contributor to GHG. However, more efforts should be made to decrease traffic emissions. On a local scale, air pollution in the metropolitan city exceeds the health limits, and air quality must be a priority.

The second case study of the metropolitan area of Costa Rica aimed to integrate into transport planning gender equality and air quality. This research explores the geospatial urban interdependence among gender and vulnerable groups and their exposure to traffic-induced air pollution estimated from a four-step travel demand model.

The first objective reviewed barriers women experience to attain equal opportunities to men and their relation to urban mobility. The second objective analyzed demographics. to assess populations with material deprivation and disabilities per gender. In addition, household composition and car ownership for single mothers, two-parents, and single fathers. Geospatial analyses selected the most critical variables and developed bivariate dot-density maps to contrast population groups with air pollution. The most critical groups were material deprivation and disabilities for women and single mothers’ car ownership.

Women's social and economic empowerment depends on the ability to attain gender equality, where men and women, boys and girls, have equal rights and opportunities. Six dimensions of gender equality were identified: "workforce participation, economic empowerment, education, health & sexual reproductive rights, time, and empowerment." These dimensions are interrelated, and barriers can lead to social exclusion.

Work-life balance is a gender issue. On average, women spend three times as many hours in unpaid domestic and care work than men, and significantly more if they have children. In some cases, women might choose part-time or low-pay jobs or not take management positions to attend to household responsibilities. Women struggle to have equal pay to men and can experience sexual harassment in the workplace. Another barrier to women's workforce participation is childcare and long travel times to access employment can challenge balancing household responsibilities.

Women responsible for caring for children and elders have complex day-to-day trips. Commuting from work to home, women have multiple trip chains such as picking up children, shopping, or attending medical appointments. As a result, women need to travel shorter distances to address multiple trip chains and chores. In the case of single mothers, lack of efficient transport is the second barrier to access employment, after the first obstacle, childcare. Single mothers without access to automobiles may be the most spatially isolated. Some scholars argue that until accessibility to opportunities using transit becomes a better option than automobile, low-income travelers should not be prevented from owning a car. In fact, they support subsidizing car ownership.

Social exclusion is the inability to participate in civil society. In urban mobility, women often experience time-based exclusion or time available for travel to balance work-home responsibilities; and fear-based exclusion or fear for personal safety at transport systems and public spaces. Women's urban mobility has cultural, economic, physical, and psychological constraints, varying depending on socioeconomic levels and geography. Cultural barriers include religion, and excessive workload of unpaid household chores and caring for children and elders. Economic barriers include unaffordable transport. Physical barriers are car-oriented cities and urban sprawl, low quality of walkability, and limited transit service. Psychological barriers include fear of sexual harassment and violence.

In the case study, demographic statistical analysis were conducted to assess populations with material deprivation and disabilities per gender. In addition, household composition and car ownership for single mothers, two-parents, and single fathers. The statistical analysis shows no significant evidence between populations groups differentiated per gender for ratios of material deprivation (p-value < 0.05). However, there was a significant difference in disabilities per gender, where women experienced larger mean ratios. A similar situation was found with single mothers without an automobile, presenting larger mean ratios and significantly different than households with two parents and single fathers. In addition, gender equality indicators of Costa Rica show that the female population is more disadvantaged. Some disadvantages are related to employment opportunities, the gender wage gap, and time due to childcare responsibilities for children and elders that falls on women rather than men.

Based on this evidence, the geospatial equity analysis aims to target women living with material deprivation, disabilities, single mothers who do not own a car, and their exposure to air pollution. The goal is to identify high-priority areas for urban mobility improvements. Bivariate dot-density maps using TAZ as geographic units were generated to contrast these population groups with air pollution. For each demographic variable, census tracks per block were aggregated per TAZ.

For transport investments, a vertical equity approach was used to prioritize social disadvantage groups and air pollution exposure in San José. For these groups, improving urban mobility and reducing air pollution compensate the disadvantage of households having the burden of low income plus the risk of developing illnesses associated to long-term exposure due to air pollution that is produced by their neighborhood. This potential scenario can also impact the household economy by increasing health expenses or the loss of income due to the inability to work. Single mothers are the most vulnerable in this scenario as they are the primary source of income in the household and the caregivers of children and elders.

The Central Business District (CBD) has higher ratios of women with disabilities and high levels of air pollution. The inner city has higher ratios of women with material deprivation, single mothers who do not own a car, and high levels of air pollution. The Southbound produces intermediate levels of pollution and has high ratios of women with material deprivation, single mothers that do not own a car, and the higher population density of the city, which supports investments for transit infrastructure. Future research should include accessibility to opportunity analyses and affordability analyses.

As contributions from this research, a cross-discipline modeling framework for sustainable urban mobility was proposed based on performance management principles. The United Nations 2030 Agenda provides policies and priorities, and the SDG Index measures progress. The SDGs are a universal agenda and must be localized to specific disciplines and contexts. In this case, transport and the built environment metrics were associated with the SDGs for planning and designing sustainable urban mobility. This conceptual framework allows an understanding of the interconnectedness of the SDGs under five strategic areas: social justice, health, climate change, economic development, and governance.

Governance sets goals for a system to operate and manage. It formulates policies and decision-making to allocate resources. Management refers to planning, implementing, and monitoring to support this governance to achieve the established vision and goals. The proposed sustainable urban mobility framework is a tool for good governance where social and environmental justice is integrated into strategic planning to allocate investments and monitor progress.

Future research must integrate modeling and analytical tools under these five strategic areas: social justice, health, climate change, economic development, and governance, and develop proof-of-concept modeling. In addition, economic analyses must incorporate environmental and social analyses.

The case study for the 2050 bottom-up transport emission model based on a travel demand model overcomes the limitations of top-down emission approaches. Top-down emission models based on fuel consumption are commonly used due to the accessibility to fuel consumption inventories, which allow monitoring of annual emissions. There are limitations to the top-down approach, such as the inability to forecast scenarios and incorporate specific climate mitigation actions.

Bottom-up emission models are disaggregated and presented in a spatial distribution. Emission models that rely on travel demand models allow for incorporating climate mitigation actions, identifying priorities, and evaluating climate policy instruments. The travel demand model was validated with ground-truth traffic data for the case study, and emissions were estimated from the traffic volumes. A top-down emission approach could be used as an additional method to validate the emission model.

In this case study, the travel demand model is a vehicle-based model, which estimates the Vehicle Kilometer Traveled (VKT), rather than a person & goods-based, which estimates the Passenger Kilometer Traveled (PKM). A vehicle-based model was elaborated due to limited access to public transport data. The emissions can be estimated based on these two approaches, but the difference lies in assessing the impact of emissions reduction when transit systems or cycling networks are incorporated. Future work should incorporate a person & goods-based travel demand model in the emission model to evaluate the effect of implementing new sustainable transport systems other than electric vehicles.

The case study linking gender equality and transport planning for healthier cities is a traffic-related air pollution and gender socio-spatial analysis. This research contributes to incorporating gender equality to deliver a pro-poor and gender-sensitive approach to transport planning and urban health. This research comprehensively analyzes the barriers women face to having equal opportunities to men, highlighting the difference in urban mobility patterns and needs between women and men.

It has been argued that integration is needed for the proposed sustainable urban mobility framework to break down silos across sectors. The proposed framework needs to develop proof-of-concept modeling and analytical tools. In this case study, the social, environmental, and health dimensions are integrated, identifying priority areas based on a vertical equity approach. Thus, the urban mobility priorities establish fairness in the distribution of resources favoring socially disadvantaged groups to compensate for social inequalities and negative transport externalities of air pollution. Future research requires incorporating additional equity analyses, such as accessibility to opportunities and affordability analyses, for a comprehensive assessment.

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